Project[1] Number: 824093

Project Acronym: STRONG-2020

Project title: The strong interaction at the frontier of knowledge: fundamental research and applications

Periodic Technical Report

Part B

Period covered by the report: from 01/06/2022 to 31/07/2024

Periodic report: 3rd

[1] The term 'project' used in this template equates to an 'action' in certain other Horizon 2020 documentation

TABLE OF CONTENTS

1. Explanation of the work carried out by the beneficiaries and Overview of the progress

1.1 Objectives

The following part gives the descriptions of the objectives as fixed in the Description of the Action (DoA) and explains how the project has progressed towards these objectives during the first Reporting Period. The objectives are organized around the following three pillars: low- and high-energy frontier studies, and instrumentation as defined in the Grant Agreement (GA).

As stated in the GA, the objectives of this Action are to federate leading experimental and theoretical groups in EU in order to carry out new fundamental and applied research studies at the frontier of our current knowledge of the strong interaction, the force that binds together quarks and gluons and, ultimately, forms the visible baryon matter of our universe. The underlying quantum field theory that describes the strong interaction, quantum chromodynamics (QCD), has an extremely rich dynamical content (asymptotic freedom, confinement, approximate chiral symmetry, non-trivial vacuum topology…). This translates into a very diverse many-body phenomenology at various limits: at high temperatures the Quark-Gluon-Plasma (QGP), at large quark densities the colour superconductivity, at very low parton fractional momenta the colour glass condensate (CGC), etc. Also, many of the fundamental parameters of the Standard Model (SM) like the strong coupling constant, the quark masses, the matrix elements of the Cabibbo-Kobayashi-Maskawa mixing (CKM) are also directly connected to QCD. A good understanding of the interaction between light-, heavy-quarks, and gluons is crucial for searches of physics beyond the SM. The study of QCD is mostly carried out through electron-positron (e+e-), lepton-proton (e-p, mu-p), electron-nucleus (e-A), protonproton (p-p), antiproton-proton, proton-nucleus (p-A), antiproton-nucleus and nucleus-nucleus (A-A) collisions at low (<20 GeV) and high (>20 GeV) center-of-mass (c.m.) energies in world-class experimental facilities for which Transnational Access (TA) is requested.

The detailed progress towards concrete objectives of each thematic field achieved during the second Reporting Period is presented in the table below.

Objective	Results
Low-Energy frontier	
JRA - Precision Tests of the Standard Model (PrecisionSM) Precise determination of the muon anomalous magnetic moment (g-2)μ; extraction of the CKM matrix element Vud from beta decay, and of the weak mixing angle from	In order to calculate the Standard Model prediction for the anomalous magnetic moment of the muon, a_μ, a database with experimental data for the low-energy process $e^+e^-\to$hadrons, called PrecisionSM, was created: https://precision-sm.github.io/. It contains information about the datasets, systematic uncertainties and the treatment of radiative corrections. For the work on the theory calculations, a dedicated collaboration RadioMonteCarLow2 was started and three workshops were organized.

parity-violating electron scattering (PVES)	MUonE collaboration carried out a test-beam campaign at the CERN M2 beamline on the prototype detector and demonstrated the ability of the detector to sustain a 160 GeV muon beam intensity of 40 MHz and thereby delivered a major milestone to proceed towards the Technical Proposal to the SPSC asking for a technical run with three stations in 2025. A complete re-evaluation of the entire body of radiative corrections to V_{ud} and V_{us} with new formalism and with new modern tools has been achieved. At present, there is a 3σ deficit in the first-row CKM unitarity. New nuclear effects in combination with improved experimental measurements of neutron decay, much more stringent constraints on possible BSM explanations of the CKM unitarity deficit can be expected in the next few years. New directions in experimental studies of PVES on nuclei have been studied, which can be measured at the new MESA facility at Mainz, currently under construction. Two comprehensive reviews (D21.3) have been published. Hyperon decays at e^+e^- colliders with polarized electron beam at the J/ψ resonance showed an enhanced sensitivity to CPV signatures compared to the unpolarized case. This motivates the construction of future facilities.
NA - Proton Radius European Network (PREN) Address the “proton-radius puzzle” via combined data-theory analyses of new results in atomic spectroscopy and very-low momentum transfer (Q2) lepton-proton elastic scattering at various energies	The collaboration between groups working in similar fields has been enhanced by the active contribution of the PREN leaders to a 2 weeks data taking campaign of ULQ2 (UltraLow Q^2) experiment at Tohoku University / ELPH (Sendaï, Japan) (09 - 06/10/2024). The ULQ2 experiment aims to determine the proton and the deuteron charge radius from measurements at very low Q^2 ([3x10^{-5}; 0.013] (GeV/c)^2) relying on relative cross section measurements (elastic electron proton/electron Carbon scattering). This close collaboration took its origin within the Proton Radius European Network. Also, three workshops have been organized within the PREN umbrella, such as the PREN2022 Convention: • International STRONG-2020 workshop on the proton charge radius and related topics, 20 – 23/06/2022, Paris, France; • PREN2023 + μASTI (Muonic Atom Spectroscopy Theory Initiative), 26 - 30/06/2023, Mainz, Germany; • NREC (Nuclear Radius Extraction Collaboration) Kick-off meeting, 6 – 10/05/2024, Stony Brook, USA.

	This new collaboration was created to extend the STRONG-2020 Proton Radius European Network. As highlights of the objectives of this period, two publications can be named: Phys.Rev.C, 2024,110(1), pp.01520; and Nuclear Theory, Vol. 40 (2023). Moreover, the COVID acute period (2020) allowed the collaboration to write a report entitled "The proton size", Nature Rev.Phys., 2020, 2 (11), pp.601-614, acting as the PREN White paper deliverable (D15.2).
NA - LatticeHadrons (LatticeHadrons) Development of combined software, data sharing, and methodologies in lattice QCD theory across Europe for hadron spectroscopy and structure, hadrons under extreme conditions, hadrons in the SM and beyond, and novel numerical algorithms and computing for lattice hadron physics	Good progress was made regarding the planned objectives due to the return to travel to and from the Dublin node after the pandemic. The lattice community in Europe formed a new consortium based on the STRONG-2020 LatticeHadrons network to build an experimental online training platform. This platform is called the Lattice Virtual Academy (LaVA) and is launched. To date a set of introductory modules have been recoreded and made available by Profs Margarita Garcia Perez, Simon Hands and Christoph Gattringer. A first workshop was organised at the ECT* site (Trento) from 20-24 February 2023. The meeting was fully funded as part of the LatticeHadrons STRONG-2020 initiative. With regards to thematic workshops, all meetings planned by the network were delivered. During the reporting period, the following meetings were held: 24-27 April 2023 – Edinburgh, Scotland - Algorithms and computing for lattice hadron physics; 12-16 June 2023 – Madrid, Spain - Lattice Gauge Theory contributions to new physics searches (Hadrons in the Standard Model and Beyond); 4-7 July 2024 – Dublin, Ireland – Hadron spectroscopy and structure. All attracted a significant number of participants from across the network and were successful. In addition, a small number of research exchanges between nodes commenced following the pandemic and the STRONG-2020 network was able to restart activity in this direction.
JRA-Light-and heavy-quark hadron spectroscopy (HaSP)	The groups of the JRA7-HaSp have continued in this third period a productive collaboration. The HaSP activity has

Development of a common data-theory analysis framework to determine exotic hadrons properties by fitting new experimental data to lattice QCD and effective-field-theory predictions	boosted the coordination of different institutions active in hadron spectroscopy leading to the development of new tools for the analysis of hadron spectrum, reaction data, and interpretation of physics results. As remarkable achieved objectives of the working package, the calculation of the generalized Wilson loop containing the QCD force on the lattice using gradient flow carried out can be highlighted. The study provides the one loop renormalization in gradient flow of lattice QCD operators appearing in the heavy quark effective theory and non relativistic QCD. There has also been a significant progress in the understanding of quarkonium hybrids, tetraquarks, baryons and pentaquark in the systematic framework of the Born-Oppenheimer effective field theory. The improved analysis of $e+e-\longrightarrow\pi+\pi-$, including radiative corrections provides an important step towards reducing further the theoretical uncertainties of the hadronic vacuum polarisation contribution to the muon $(g-2)$. A model-independent dispersive analysis of $\pi\pi\longrightarrow KK$- allowed to achieve a reasonable description of the CP violation effect measured recently by LHCb while being consistent with the measured scattering amplitude and confirming the prominent role of hadronic final state interactions. The $DD*$ system has been investigated at unphysical quark masses in the context of LQCD studies of the exotic $T(3875)+$. We showed that at slightly higher than physical pion mass, the $D*$ gets stable and the system develops a left-hand cut that calls for significant modifications to be applied to the methods used to analyze lattice spectra. Moreover, the LHCb $T\psi\psi$ tetraquark candidate was studied in a quark model framework as a possible molecule of two hidden charm mesons. Candidates for the experimentally seen $T(6200)$, $T\psi\psi(6600)$, $T\psi\psi(6700)$, $T\psi\psi(6900)$ and $T\psi\psi(7200)$ were also predicted. There has also been LQCD works exploring a wide range of interpolating operators: dibaryon operators built from products of plane-wave nucleons, hexaquark operators built from six localized quarks, and quasi-local operators inspired by two-nucleon bound-state wavefunctions in low-energy effective

	theories and provided for the first-time upper bounds on two-nucleon energy levels, though for a quite heavier pion mass. The NPLQCD collaboration is currently working to obtain results closer to the chiral limit. In this third period, the study of two-hadron correlation functions from high multiplicity collisions has been a highlight activity, as measured in experiments like ALICE at LHC. An interesting new line of research, is that the study of high-energy collisions between protons and nuclei can provide information on hadron interactions. Femtoscopy technique was developed as a tool to study the possible creation and properties of the quark-gluon plasma in relativistic heavy-ion collisions through the particle correlations (CF) in momentum space for any hadron-hadron pair. The experimental component of HaSp kept working on data collection and data analysis. LHCb, experiment at CERN, GlueX, CLAS12 at Jefferson Lab, BES-III in China, A2-Mami in Mainz, and CB-Elsa and BGOOD in Bonn, collected hadron (standard and exotics) production and decay data that will be used to extend the existing statistics and cover new territories (e.g. using polarized nuclear targets such as the HD). Studies also focused on the future with predictions for spectroscopy at the EIC. A combination of these techniques led to a more precise determination of the resonance pole position. A similar multi-channel approach used in the baryon sector (SAID) led to an improved determination of resonance parameters. New photo and electro-production data were used to refine models and extend them to heavy quark systems. It is worth mentioning that the current effort of experimental groups focuses on data collection and analysis of exotic configurations such as di-baryon, tetraquarks, and pentaquarks. The experimental activity produced interest in the theory community in a virtuous spiral of defining new observables and subsequent interpretations. Pentaquarks, in particular, were studied in different ways (decay and production) trying to set a common interpretation of the rich phenomenology studies at hadron colliders (e.g. LHCb), e+e- colliders (e.g. BES-III) and high-intensity lepton beam experiments (e.g. GlueX). Finally, we had a significant improvement in our understanding of dibaryonic degrees of freedom in neutron stars, EoS and neutron stars dynamics.

	Workshops organized by HaSp collaborators (e.g. NSTAR series) gathered together experimentalists and theorists, in the spirit of the STRONG-2020 initiative. Members of the STRONG-2020 working group participated in a comprehensive review of both the theory and experimental successes of Quantum Chromodynamics. This review included a presentation of the present situation regarding determinations of the fundamental constants of QCD, as well as an introductory discussion of lattice QCD and effective field theories among other topics.
NA - QCD physics at GSI/FAIR (FAIRnet) Multi-prong improved data selection plus distributed physics analysis for rare signal events under high background conditions in anti-p-p, anti-p-A, and A-A collisions for the PANDA and CBM experiments at the future FAIR facility	An ASIC integrated circuit, called ToASt, has been developed for the readout of the Silicon strip detector in the Micro-Vertex Detector of PANDA experiment. The chip has been characterized and tested for radiation tolerance. The communication protocol, called Aurora, was also tested for time synchronization. Results have been discussed in a workshop in June 2024. A demonstrator of the PANDA experiment was setup at COSY: the forward endcap electromagnetic calorimeter, a prototype of the luminosity detector and the Micro-Vertex Detector were operated together. The operations went smooth and 220TB of data were recorded and reconstructed. A PANDA EMC meeting was held in Feb 2024. A second demonstrator was operated at GSI/FAIR. The CBM mCBM setup was upgraded for the runs in 2024/25 with detector hardware and Frontend Electronics but in particular with an improved STS, TRD and TOF hit reconstruction for the CA track reconstruction, which is essential for the online selection of events with a Λ candidate. The CBM CA track reconstruction could be improved and is the input for the CBM KFParticle package, which identifies Λ candidates. The reconstruction of Λs could be nicely demonstrated offline with the 2022 Ni+Ni data. The PAWIAN (PArtial Wave Interactive ANalysis Software) was further developed and applied to the data analysis. The package supports different reactions from antiproton-proton annihilation, pion-proton, pion-pion, central production, e+e- annihilation, and two-photon fusion. Progress on the track

	reconstruction and identification of the Λ candidates are also highlighted. The teaching activities and school visits to the laboratory were ramped up.
NA-Strange Hadrons and the Equation-of-State of Compact Stars (THEIA) Address the "neutron stars hyperon puzzle" through combined theoretical and experimental studies of (anti)hypernuclei and bound strange-meson systems produced in hadronic collisions at various c.m. energies	There has been a tremendous advance in all objectives of the working package, from addressing the hypertriton puzzle, the study of antihyperons in nuclei at PHASE-1 of PANDA to theoretical and experimental studies of bound mesonic systems. Among them, we should highlight the following: The lightest hypernucleus $^{3}_{\Lambda}H$. A profound understanding of the lightest hypernuclei is a cornerstone for any strong interaction theory dealing with strange baryons. Indeed, the hypertriton consisting of a proton, a neutron and a Λ hyperon, was addressed in several activities of THEIA: new data of ALICE and STAR were presented, suggesting a binding energy only slightly above the old emulsion data; a new and accurate measurements of the $^{3}_{\Lambda}H$ binding energy was successfully performed at the Mainz Mikrotron (MAMI); and measured lifetimes of the hypertriton by ALICE indicate a lifetime closer to the free Λ lifetime. Thus, the hypertriton puzzle as it existed at the start of THEIA 5 years ago, has turned into a quantitative problem, calling for precision studies, on the experimental as well as on the theoretical side. Members of the networking activity THEIA made substantial contributions to this progress. Kaonic atoms. Among strange exotic atoms the kaonic ones play a special role, since they permit linking the isospin-dependent scattering lengths to the kaon-nucleus potential below threshold. At the DAFNE collider at INFN-LNF the SIDDHARTA-2 collaboration performed the first measurement of the kaonic deuterium transitions, which will help to separate the isoscalar and isovector parts of the antikaon-nucleon scattering length. Future measurements, along the whole periodic table, going from light to heavy exotic strange atoms will be possible by using a series of complementary radiation detector systems recently developed. The new data base of kaonic atoms will thus become a bedrock for low-energy QCD. Several annual workshops have been also held, with the final workshop organized by THEIA in May 13-17, 2024 at ECT* SPICE – Strange hadrons as a Precision tool for strongly

	InteraCting systEms (https://indico.ectstar.eu/event/203/) These workshops turned out to be the most important and fruitful meetings for the scientific community of THEIA in the past years. Particularly the international web seminars during the corona crises were important to keep up the coherence of the community and to foster the continuous collaborations. In all these meetings, young scientists and students played a dominant role, giving on average more than 50% of the presentations. At the final workshop at ECT* in 2024 there was a unanimous consensus, that the community will try to continue with these annual meetings also beyond STRONG-2020.
High-Energy Frontier	
VA - Automated perturbative NLO calculations for heavy ions and quarkonia (NLOAccess) Extension of the MadGraph automated on-line code for the novel computation of perturbative QCD cross sections in high-energy hadronic collisions at next-to-leading-order accuracy, using meson and heavy-ion beams, and for quarkonia final-states.	The fact this VA exceeded the initial objectives and expectations was already mentioned in the former periodic report. During this last reporting period, the NLOAccess team maintained and even improved and consolidated the access to the facility via the portal website (https://nloaccess.in2p3.fr). This includes not only developments of the different computing codes (MadGraph5 and Helac-onia) but an update of all major software packages used for the platform workflow, the addition of clear description of the access and its objectives as well as references and scientific news (publications, presentations and internships). All major packages of NLOAccess were updated, and the portal website was enriched with, inter alia, a description of the VA, a selection of references and of scientific news. The structure and usage of the platform was described in a dedicated publication. The extension of automated NLO computations to asymmetric hadronic collisions was implemented in MADGRAPH5 and the inclusive NLO photoproduction was validated. The integration of extra single purpose codes is being considered to enrich the platform. As noted by the International Assessment Board, the results of the VA outperformed the initial objectives. It gave rise to several publications and conference talks crucially relying on computations made with the platform. The scientific output includes many publications and reviews (including a 100-page one on quarkonium physics at the High

	Luminosity LHC) in major nuclear and particle physics journals as well as proceedings related to more than 70 oral communications in top conferences and workshops in the field. Seven PhD theses were directly related to NLOAccess. Additional articles from users of the facility still at a drafting stage will further increase the prolific scientific outcome of this VA. Half of the users work in European institutions, and the majority of the remaining users almost equally shares between North America and Asia. As of July 2024, NLOAccess hosted 662 registered users (to be compared to 247 after the second report and 89 after the first) with 52.27% from Europe, 22.21% from Asia, 1.51% from Africa, 21.14% from North America, 2.72% from South America and 0.15% from Oceania respectively).
VA - Virtual Access to 3DPartons (3DPartons) Development of a new combined framework to extract generalized (GPDs) and transverse momentum-dependent (TMDs) parton distributions, with higher-order fixed and twist corrections, from fits to experimental e-p and p-p data	Version 4 of PARTONS was released. With respect to physics, it provides more physical observables and GPD models; with respect to computing functionalities, it provides a docker image and a Python wrapper. The PARTONS website was updated with links provided to all interoperable computing codes of the PARTONS ecosystem. Of specific interest to experimentalists is the generic event generator EpIC, which is designed to generate events for all exclusive processes implemented in PARTONS. The interoperability of PDF, GPD and TMD codes is perhaps best demonstrated in the versatile use of the QCD evolution equations solver APFEL and a pioneering study on the determination of GTMDs. Many physics results were obtained in conjunction with JRA4 TMD-neXt and JRA5 GPT-ACT. The PARTONS website is mostly accessed from the US (EIC and Jefferson Lab users), Europe (most developers are European) and China (EIcC). Most of the visitors seem assiduous users, suggesting the presence of a robust community of users worldwide.
JRA- Generalized Parton Distributions (GPD-ACT) Extraction of GPDs from new high-precision QCD	A prototype of the ALERT detector was constructed and tested in 2023 and a full detector constructed and delivered to JLab in spring 2024 – data taking starting in the second half of 2024. CLAS12 measured DVCS beam spin asymmetry on unpolarized LH2 target, previous data improve precision of

analyses of novel high-statistics e-p and p-p measurements at fixed-target and collider energies.	Compton form factor fits. Also, measurements with deuteron targets allowed a clean quark-flavor separation of Compton form factors. COMPASS performed analysis of pi0 production in polarized muon-proton scattering with good agreement with models. Exclusive pi0 production was presented in conferences and the publication is coming. Spin density matrix elements in exclusive rho meson production are published. The publication of DVCS measurements could not be completed, since the first analysis of the considered data exhibited a marked difference with a past similar measurement also made at COMPASS. The need to cross-check the analysis of both datasets and a shortage of workforce delayed the finalization of this analysis. This constitutes the only significant deviation from the original plan. These, and other, experimental results help constraining the models for GPDs and extract them from data, including also lattice QCD inputs. Several theoretical developments have been produced, including the relation of exclusive measurements to small-x PDFs; the computation of the full set of one-loop corrections to the off-forward matching function and evolution equations for GPDs – in collaboration with VA2-3DPartons. NLO DVMP and multichannel fits are performed; twist-3 contributions to DVMP are included. Public codes are developed and released, in collaboration with VA2-3DPartons.
JRA - 3D structure of the nucleon in momentum space (TMD-neXt) Extraction of unpolarized and polarized TMDs and parton fragmentation functions (FFs) from new high-precision QCD analyses of novel high-statistics measurements at e+e-, e-p and p-p at fixed-target and collider energies.	Several analyses of Drell-Yan data have been released, both in COMPASS and CMS. The analysis of transverse spin asymmetries lead to a Silvers asymmetry in agreement with the sign-change hypothesis. Preliminary results measured in ammonia, aluminium and tungsten have been presented in conferences. The final analysis of DY transverse momentum spectra has been published by CMS. Analyses of semi-inclusive DIS (SIDIS) data at COMPASS and CLAS are finished – data taking with transversely polarized targets – or near to completion – unidentified hadrons off proton target, and the analysis of the data with longitudinal polarized target. The analysis of Belle e+e- data is slowly progressing and is not complete yet, although most of the analysis steps have already been cross-checked. This task presents the most significant

	deviation with respect to the original plans of the WP, which otherwise progressed as expected. On the other hand, several analyses relevant for quark TMD extractions have been published, as the extraction of the pion TMD from DY; the extraction of unpolarized proton TMDs at N4LL; extraction of unpolarized proton TMDs and fragmentation functions with flavor decomposition; etc. Similar progress has been taken place in the gluon TMD studies, with several published works, as the TMD shape function from J/ψ production in SIDIS and the gluon transverse momentum-dependent FF at NLO into heavy quarkonium; a model calculation of the T-odd gluon TMDs; a detailed phenomenological study of J/ψ polarization in SIDIS. Many determinations of TMDs or FFs were made possible using software developed in VA2-3DPartons.
JRA - Challenges for next generation DIS facilities (next-DIS) Development of new Monte Carlo tools and studies of benchmark channels, for e-A collisions at future deep-inelastic experiments. Optimisation of associated detector designs for high-resolution tracking, vertexing, photon, and PID.	A new simulation study for exclusive processes at the Electron-Ion collider (EIC) was completed and contributed to the EIC Yellow Report. The focus in the period has been the simulation of the ePIC detector to be installed at EIC in Brookhaven. The development and characterization of a new hybrid MPGD with a very low ion-back-flow has been completed in 2023. The focus has been on design, development and simulation of a cylindrical Micromegas layer for the tracking system of ePIC. In particular its resistive layer and a 2D readout pattern are being optimized. The ePIC silicon tracker, also developed in this WP, will be complemented by layers of MPGDs. The design and status of R&D was presented in March 2024. Another task of this WP aims to implement a dual-radiator ring imaging Cherenkov detector (dRICH) for the hadron separation. A small-scale prototype has been installed at CERN for a test beam, during which a better separation of the Cherenkov rings was achieved. Also, studies of the geometry and integration of dRICH detector in ePIC have been made. New generation depleted MAPS sensors have been studied, in collaboration with ALICE ITS3, to satisfy the stringent requirements on vertex and tracking at EIC, several prototypes have been developed and tested. The definition of the detector

	layout, the study of its performance and the development of associated tracking software has been continued and are key contributions to the ePIC tracker. Physics simulations concentrated on expanding previous work on reconstruction of DIS kinematic variables, combining a knowledge of cross section and initial state radiation with the detector resolution. The method has been valiated using H1 data. All deliverables and milestones were achieved during the grant period.
NA - Small-x Physics at the LHC and future DIS experiments (Small-x) Extraction of high-precision nuclear parton distribution functions through global fits including the latest LHC p-A and A-A data. Extension of current gluon-saturation calculations to NLO accuracy with resummation corrections, for observables with three jets and with heavy-quarks. Calculation of multi-particle correlations issuing from initial-state PDF effects to separate them from final-state hydrodynamic effects in small systems	New constraints to the parton distribution functions (PDFs) have been found for the future EIC data as well as ultraperipheral collisions at the LHC. At the same time, a new way to implement the QCD evolution directly in physical observables – rather than the not-observable PDFs – has been developed. Important advances on the Color Glass Condensate (CGC) treatment of the small-x parton distributions have been published, as improvements in the evolution equations; impact parameter dependence; NLO calculations; or next-to-eikonal corrections. Also phenomenological studies on the possibility to disentangle saturation in exclusive vector meson production in ultraperipheral collisions; the extraction of initial conditions for non-linear evaluation; or its influence on extracting the parton densities. Several studies of interest for future colliders, including EIC and FCC, have also been performed. Works on the relation of TMD and small-x evolution, towards a unified description of both, have been performed. This activities are related with those in JRA4 (GPDs) and JRA5 (TMDs). Finally, works on the onset of thermalization have also been addressed.
JRA - Fixed Target Experiments at the LHC (FTE@LHC) Development of novel gas-target techniques to be able	The last period counts many major achievements for the three main tasks of this JRA, i.e. i) feasibility studies in ALICE; ii) Gas-target developments in LHCb; iii) Phenomenological and theoretical studies associated to fixed target experiments and programme at the Large Hadron Collider. Between June 2022

to carry out the most energetic fixed-target collisions ever performed in the laboratory, using the LHC beams at ALICE and LHCb. Evaluation of the novel expected constraints on PDFs at high-x in the proton and nucleus, parton spin dynamics, as well as QGP properties via unique quarkonia measurements.	and January 2023, significant efforts and progress were made related to the first task. Both the conceptual design and the performed simulations showed that a fixed target system would be a strong asset for the ALICE physics programme, even putting within reach new physics. However, due to strong integration constraints from other ongoing projects of the experiment, aggressive timelines originating from the collider operation as well as manpower issues for coordinating the activities, it was decided not to pursue with the implementation phase. Concerning the second point dealing with Gas-target development in LHCb, all initial objectives were implemented and successfully accomplished: the unpolarized target for LHCb has been designed, installed, and is currently fully operational, with collecting data during simultaneous data-taking with beam-beam collisions. When operating LHCb with the unpolarized target, the full detector occupancy and data flow only increase by a few percents. The design of a new polarized target has also been completed, with CAD drawings illustrating the implementation of the target and its components within the LHCb spectrometer. Related to the third point, significant progress was made and discussed in several major workshops and conferences, including a dedicated one organized at Aussois in January 2023. Overall, more than 30 oral communications and about 20 publications, including proceedings participate to the strong scientific outcome of the JRA. The technical developments and implementation within LHCb will certainly lead to additional publications both in a short and a long timescale.
NA - Quark-Gluon-Plasma characterisation with jets (Jet-QGP) Development of novel experimental and theoretical techniques for jet physics in A-A collisions, providing a reference implementation of jet interactions in a QGP via a full heavy-ion Monte	The first task of this theory/phenomenology/inter-experiment NA was already completed for the former reporting period: it consisted in the evaluation of several models then the selection of the JEWEL event generator as a well-defined reference implementation for jet-QGP dynamics. A broad set of 31 jet shape observables has then been benchmarked using machine-learning methods. Several of these observables were clearly identified as sensitive to specific scales/features of jet-QGP interaction, which was the main objective of the second task. In particular, it was found that

Carlo event generator. Definition of new observables and development of new tools with increased sensitivity to the physical mechanisms involved in jet-QGP interactions.	these jet substructure observables actually consist of two or three main classes and that the most relevant information about jets can be captured by selecting one observable from each class. Whereas the first angularity moment rz_{SD} and the groomed 2-subjettiness are found to be most sensitive to quenching effects, a few other observables, like the groomed number of constituents, higher angular moments and subjettiness measures, as well as the largest kT in softdrop declustering, presented similar sensitivity. All the results of the study have been discussed in detail in the open-access publication SciPost Phys. 16 (2024) 1, 015 corresponding to Deliverable D14.3 with slightly less than a year delay with respect to initial planning (MS16 delivered month 47 instead of month 36). On the other hand, Deliverable D14.4 which consisted in the analysis algorithms for selected observables was delivered just one month later (month 48 instead of the initially planned month 56) i.e. 8 months in advance. A full 'User's manual' was also released publicly, under the terms of the MIT license, on the GitLab platform: https://gitlab.com/lip_ml/jet-substructure-observables-ml-analysis. The software can be freely modified by users as to be extended to cases not covered in the publication. In addition, two other main results should be noted as major scientific output: i) Energy-energy correlators define a set of novel jet observable that are particularly amenable to theoretical calculations and have recently raised a large interest in the community. A calculation method was developed consequently for decreasing the computation time needed for the evaluation of higher-order energy-energy correlators. A manuscript describing the method is available on the preprint online server (arXiv:2406.08577) and has been submitted for publication; ii) a discussion session at a recent workshop at the European Center for Nuclear Physics Theory (ECT*) was dedicated to jet observables as part of the NA3 activities. A white paper summarizing the discussion and future directions has been released also as a preprint: arXiv:2409.03017.
NA - Quark-Gluon Plasma characterisation with heavy flavour probes (Hf-QGP)	There has been an excellent progress in all tasks in order to reach the desired objectives. With regard to the task on the interpretation of LHC results by the development of the necessary theory and preparation of next run, the interpretation of the LHC results and theory

Extraction of QGP transport coefficients from new high-precision theoretical calculations and experimental measurements of the production of open and closed heavy flavour (HF) quarks in A-A collisions at the LHC. Accurate measurements of total c-cbar, b-bbar cross sections in p-p, p-A and A-A collisions. Development of a new data-theory interface to compare event-by-event experimental results to MC predictions	developments were well advanced already, and their finalization progressed smoothly over the period covered by this report. A very intense work was done in this period for the preparation for the HI-IL LHC runs. The original deliverable (and associated milestone) related to this activity was a paper with recommendation for the dedicated heavy-ion periods of LHC. It was agreed in the amendment of the grant to postpone the due date for this deliverable (from month 26 to the end of the project) and to focus on the study of LHC Run 5 and beyond. The opportunity to have LHC periods with lighter collision systems than Pb-Pb was investigated in detail. In particular, two benchmark observables were selected: multi-charmed baryon production and azimuthal angular correlation of D and Dbar mesons. On the one hand new theoretical studies have been conducted to provide predictions in different collision systems (O-O, Ar-Ar, Ca-Ca, In-In, Xe-Xe, etc…) for these two observables by two different groups. On the other hand, the expected performance for an experimental apparatus analogue to the new proposed ALICE 3, which is supposed to replace ALICE in the LHC Long Shutdown 4, was studied considering the previously mentioned colliding systems. The study demonstrated the impressive potentiality of lighter colliding systems as a tool to understand the mechanism by which heavy quarks tend to reach equilibrium with the lighter (and equilibrated) partons of the QGP. This in turn has the potential to further elucidate the properties of the expanding QGP, the key objective of the experimental study of ultra-relativistic heavy-ion collisions. Therefore, also the remaining task was fully completed at the end of the project. As for the interactive framework for theory-data comparison, both sub-tasks were completed already before the start of the period covered by this report. In the period from 1 June 2022 to 31 July 2024, there has been some remaining work to include a few further analysis (published results from the ALICE Collaboration) in the Rivet DB, previously developed for proper treatment of Heavy Ion physics. In particular, the analyses and results are documented in these papers: Prompt and non-prompt J/y production at midrapidity in Pb–Pb collisions at = 5.02 TeV, 10.1007/JHEP02(2024)066; Measurement of non-prompt D-meson elliptic flow in Pb–Pb collisions at TeV, 10.1140/epjc/s10052-023-12259-3;

	Measurement of the J/ψ Polarization with Respect to the Event Plane in Pb-Pb Collisions at the LHC, 10.1103/PhysRevLett.131.042303. And, finally, as for the organization of meetings and workshops, the second network workshop was held from 28 September to 4 October 2023 in Giardini Naxos, Sicily, Italy. It included two series of lectures about "Exploring the phase diagram of strong-interaction matter with QCD inspired models" by M. Buballa, and "Jets in strongly interacting matter" by K. Tywoniuk. The workshop was attended by 54 participants. Every participant gave a talk. http://theory.gsi.de/~ebratkov/Conferences/HFHF-STRONG-2023/index.html. Also, support was granted for the participations of students at the "11th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions" 26–31 March 2023, one of the major conference of the field, was given by this Network activity. See https://indico.uni-muenster.de/event/1409/page/48-supported-by
JRA - Inter-experiment combination of heavy-ion measurements at the LHC (LHCCombine) Combination of key LHC (ALICE, ATLAS, CMS, LHCb) measurements in p-p, p-A, and/or A-A collisions to achieve high-precision constraints on nuclear PDFs, QGP properties, SM parameters, and/or searches of physics beyond the SM. Examples include gauge bosons and jets differential cross sections to constrain nPDF, light-by-light scattering to constrain new physics searches, open charm or bottom hadron cross	The first (2010-12) and second (2016-18) long periods of data taking of the Large Hadron Collider (LHC) at CERN provided a wealth of results from hadronic collisions including heavy-ions. The four large LHC collaborations, ALICE, ATLAS, CMS and LHCb, contribute to the LHC physics programme with very different and complementary capabilities, both in terms of angular coverage and particle identification. The aim of this JRA is to improve communication between the four collaborations in the heavy-ion physics field, and establish an LHC data-combination working group. These objectives are split into two tasks: establishing and animating of a common forum (task 1) to ensure regular communication between the four collaborations; nurturing cross-experiment combination work (task 2), such as detailed comparisons of techniques or optimized statistical combination of results, leading to common publications. During the first reporting period and concerning the first task, 14 topical meetings occurred involving a core of 120 persons identified with a dedicated mailing list. This success led to the creation, during the second reporting period, of a heavy-ion

sections to determine QGP transport coefficients	working group within the LHC Physics Center at CERN (https://lpcc.web.cern.ch) upon the initiative of the spokespersons of this JRA (who, together with two theorists and an extra person from each collaboration, acted as first conveners of this officialized supported activity at CERN). This was a very important milestone since such new group insures the perennity of the JRA activity beyond the scope of the STRONG-2020 project. Moreover, it can be gathered when official endorsement is needed from the collaborations. The legitimacy of coordinating the activities started within the current JRA now falls in that group. During reporting period 3, two of the collaborations rotated the convenorship as a common practice in the field and new individuals were identified to steer the group. The group was less active during the third reporting period concurrent to the beginning of a new period of data taking at the LHC requiring more involvement of participants within their collaboration. However, the group convened when needed and four meetings occurred with 20 to 50 persons attending. As for the second task, all the cross-experiment topics identified at the beginning of the JRA were discussed: this includes constraining nuclear parton distribution functions (nPDFs), light-by-light scattering, open charm cross sections and quarkonia production and feed-downs. Open charm cross section and quarkonium feed-downs were identified as a priority and subgroups are working on combining data. Light-by-light scattering was identified as a third priority meanwhile other topics such as top quark and jet production were also reviewed. During the period 3, new topics such as electroweak bosons, di-tau or global observables (centrality and high multiplicity events) were also discussed with strong contributions of the four hired postdoctoral fellows in the framework of STRONG-2020. The main deliverable reports are related to light-by-light scattering cross-section measurements at LHC and Open charm production cross section from combined LHC experiments in pp collisions at $\sqrt{s}$ = 5.02 TeV. Both were made available and published during the third reporting period in Acta Physica Polonica B Proceedings Supplement (2022) arXiv:2204.02845 and Eur. Phys. J. Plus 139, 593 (2024) arXiv:2311.11426, respectively.

Instrumentation	
JRA - Micropattern Gaseous Detectors for Hadron Physics (MPGD_HP) Development of new gas detectors with improved capabilities in tracking, charged particle identification, photon detection, and timing in the picosecond region, capable of operating under very high beam intensity conditions.	The prototype for the high-rate TPC including a laser calibration system was built and tested successfully (Deliverable D32.3). The TPC is designed for standard-sized 10× 10 cm2 amplification structures employing GEM foils. A system to calibrate the electric drift field using the photoelectric effect was implemented, with the main goal of measuring static field distortions. The drift time of photoelectrons was measured varying the detector pressure in order to derive a drift velocity calibration. The concept can easily be extended to future TPCs to be used at high-luminosity fixed-target or collider experiments. One of the future applications of a high-rate TPC is a new detector (multiple time projection chamber, mTPC) that is being designed for upcoming meson structure studies in tagged deep inelastic scattering at Jefferson Lab Hall A. For this detector, GEANT4 and GARFIELD++ simulations were performed and completed to optimize the TPC design. Based on the simulations, a prototype detector was built by colleagues at University of Virginia and the device is currently being tested at JLab. The simulations on energy ranges and resolutions in an active-target TPC were completed (Deliverable D32.4). The layout of the TPC Pad Plane was updated to make use of all 64 available readout channels. The simulations of the muon reconstruction were extended to study the geometrical acceptance as well as the efficiencies and resolutions over a wide range of the squared four-momentum transfer Q^2. The TPC trigger threshold from the Pilot Run 2021 was studied and used to update the expected number of events for this measurement. The Modular Minipad Photon Detector Demonstrator was built and fully characterized (Deliverable D32.1). To equip the modular hybrid MPGD with readout electronics suitable for triggerless streaming data taking a second prototype has been built and tested in the laboratory using both APV25-based frontend and VMM3-based frontend. The comparison of performance demonstrated the full compatibility of VMM3-based readout with hybrid MPGD photon detectors. Alternative photocathode materials were investigated. A prototype detector was built and tested with different gas mixtures up to gains of 50×10^3. The systematics of the response of H-ND in different gas mixtures was tested. A new campaign

	of H-ND photocathode tests has been performed, with the production of semi-transparent photocathodes deposited on MgF2 substrates, with different H-ND thickness, to optimize their performance in the context of fast-timing gaseous photon detector development. A large 10×10 cm^2 prototype of the Picosec detector was built, to achieve a time resolution of the order of a few 10 ps for charged particles. To realize this resolution over a larger area requires extremely uniform gaps and a flatness of electrode structures better than 10 µm. For the first prototype, a ceramic board was employed, which, however, is not suitable for applications in hadron physics experiments because of the large material budget. The Picosec FR4 prototype makes use of a printed circuit board made of FR4 material instead. The detectors are built from PCB boards of two thicknesses, 0.8 and 1.6mm, stiffened with a 1-cm thick Rohacell layer. Their active areas are covered with a diamond-like carbon (DLC) layer manufactured at CERN, while the bulk Micromegas structure was added at Saclay. A preliminary value for the time resolution for the DLC layer was measured on a few channels at the level of 44ps. Even though this value is a bit worse than the prototypes with ceramic board and CsI photoconverter, the feasibility of such detector was demonstrated (D32.2).
JRA - Tracking and Ions Identifications with Minimal Material budget (TIIMM) Development of new silicon detectors based on Monolithic Active Pixel Sensors (MAPS) for high-precision tracking, and energy loss measurement for advanced particle identification.	This JRA focuses on MAPS technological innovation in the field of tracking detectors for a broad range of experiments primarily in the hadron physics area. Such innovation and corresponding developments are instrumental for the ALICE experiment, and in the more general area of LHC particle physics experiments at CERN, but also in the low energy range ion tracking and identification, as needed in the patient particle treatment in medical physics for instance. A common need to those applications is to combine a precision tracking with energy loss measurement to be used for particle identification (PID), and very low level of crossed material to minimize multiple scattering. The final goal of the JRA was to demonstrate the PID capability of a precise tracking device with a low crossed material then evaluate the final sensor with dedicated tests. The definition of requirements for the sensor was completed in 2020 (interim report M60), the design of the prototype sensors (TIMM-1A/B)

	was achieved in 2021 (M61) and the sensors were fabricated in 2021. The sensors have been under test since late 2021 and the characterization of the TIMM-1 prototypes have validated two important goals: - obtention of a large dynamic of the sensors from minimum ionizing particles with signal of about 1000 e^- to heavy ionizing charged ions with signal exceeding 800 ke^-; - ability of the sensor to generate differentiated signals from various ion species, allowing for the identification of these species. After a period of steady progress, two main difficulties arose in the last reporting period (June 2022 – July 2024) and prevented a full achievement of the WP's final objectives: - two recruitment attempts were unsuccessful and this led to a lack of personnel expected to contribute to the project at the INFN site of the Frascati laboratories; - serious personal problem of the WP responsible effectively stopped the activities mainly depending on him during the last ten months. Despite the aforementioned difficulties, the second prototype was built as planned and the relevant functionality measurements were carried out at different beam energies (2, 3, 6 and 25 MeV). A clear correlation was obtained between the charge measured by the prototype and the numerically simulated charge (SRIM) released in the epitaxial layer of the sensor. Additional measurements with beams at higher energy and with higher atomic number ion would nevertheless be needed to reach the latest milestone of the project (MS62 - final device working and characterized).
JRA - Advanced ultra-fast solid STate detectors for high precision RAdiation spectroscopy (ASTRA) Development of beyond state-of-art radiation detectors based on semiconductors able to perform high-precision measurements of X-ray and	CNR-IMEM performed several simulations in order to identify the best detector shape and electrodes configuration. Commercially available CdTe material with characteristics matching the simulation outcomes has been purchased. The tests carried out at CNR-IMEM on these detectors revealed that 1 mm custom CZT detectors realized in Redlen material show the same or even better performance than CdTe. So, for all the future activities CZT (or CdZnTe) detectors have been developed and used.

gamma-ray photons in different environments and conditions.	Several additional tests have been carried on with a 4-channel system, first, and with an 8-channel one in the latest phase. These measurements have proven the great capabilities of such devices when operated in a high background environment such as an e+e- collider; in particular, the background rejection capabilities, the linearity and stabilization of the system, the possible arising of radiation damage, the timing and energy resolutions as well as the possibility to operate the detectors with an external trigger have been extensively studied. Finally, thanks to the good performances reached, the first ever spectra of kaonic atoms measured with CdZnTe detectors have been obtained. The list of the positive outcomes of the preliminary tests on the CZT detectors includes: 1) Good energy resolution, in the range of a few percent, have been obtained in the first laboratory tests with typical Cs, Am, and Co sources. 2) The good energy resolutions, as well as a linearity below a few permille, have been also confirmed in the DAFNE accelerator environment. 3) Tests performed in the laboratory, after the first data taking in DAFNE, confirmed that no radiation damage was observed. 4) Two electronics modules, a Time to Analog Converter and a Mean Timer, have been implemented in the CdZnTe DAQ chain to detect Kaons and MIPs, exploiting the Luminosity Monitor system of the SIDDHARTA-2 experiment hosting the CdZnTe tests in parasitic mode. This test allowed to assess the background rejection factor to be of the order of 105-6, depending on the timing performances of the detectors, matching that of the SIDDHARTA-2 experiment. 5) The energy calibration fitting function has been optimized, resulting in residuals (deviation of the nominal value of a calibration peak with respect to the one obtained from the calibration function) below 0,4%. 6) “In-situ” detector calibration procedure has been successfully established, allowing for an efficient alternative calibration method with respect to the employment of radioactive sources. 7) Thanks to the fast readout of the CdZnTe detectors, a timing coincidence of a few tens of ns between the external trigger and the detectors have been optimized.

	8) This coincidence window has been then used in a data taking run with a Cu target, from which the first ever signals of kaonic atoms measured with such devices were obtained.
JRA - Cryogenic Polarized Target Applications (CryPTA) Production of polarized nucleon targets (at the prototype level) using solid state materials combined with superconducting high-field magnets and the Dynamic Nuclear Polarization method.	During the final two years of the funding period (2022-2024), the team made significant progress in developing a combined coil concept for a polarized target. The design includes a solenoid and dipole coil, allowing the polarization direction to be adjusted within a magnetic field for the frozen spin mode. This setup could be particularly useful for future measurements involving elliptically polarized photons, as it enables switching field orientations during experiments. The combined coil concept involves nesting the solenoid and racetrack dipole geometries to achieve both longitudinal and transverse functionalities. The challenge is to maintain sufficient field strength without increasing the radiation material budget. Using MATLAB and finite element analysis, the team optimized the coil configuration, reducing the solenoid by two layers while maintaining the necessary field strength. The racetrack coil geometry was also optimized, balancing field strength, material budget, and uniformity. The result is a design for a combined holding coil that adds only one extra layer compared to current coils. Next steps include manufacturing and testing a prototype at the University of Bonn, with the potential to achieve arbitrary angle polarization using this configuration. During the reporting period, the Mainz group advanced the development of new prototypes for an active polarized target. Originally, tests were planned in collaboration with the Joint Institute for Nuclear Research in Dubna, Russia, but due to the political situation, these activities were conducted in Mainz by expanding the local team. The team set up a test box for scintillators with fiber and SiPM readouts, which were tested both in the lab and in the MAMI photon beam. Components were produced locally, and a cryogenic test box was constructed, enabling successful tests at 77K with liquid nitrogen in 07/2024. The results were documented in a deliverable report.
JRA - Cryogenically cooled particle streams from nano- to micrometer-	Numerical simulations on the evaporation of microspheres, i.e. clusters, droplets and pellets, in vacuum have been further developed and compared with data from experiment. These

size for internal targets at accelerators (CRYOJET) Development of cryogenically-cooled cluster/pellet/microjet sources to be used as targets in a variety of collision setups (storage ring experiments, electron accelerators, or laser-driven hadron accelerators).	studies led to a good understanding of the vacuum situation for experiments using hydrogen cluster beams. Moreover, these calculations give important information about the freeze-out time of the droplets in vacuum and by this with the known particle velocity about the freeze-out position in the target device. The obtained results could be compared to measurements using droplets produced in a 10 µm droplet nozzle. Diagnostic tools to investigate the properties and quality of cluster-jet beams have been improved significantly. In detail, a new MCP detection system with a phosphor screen has been tested at COSY. It was found that ionized hydrogen clusters can lead to long-term damage of the phosphor layer. According to this, a chemically more robust scintillating YAG:Ce screen has been used instead. A new droplet generator has been built and set into operation. The properties of the produced droplet streams were studied by using a new laser diagnostic system. It could be shown that by switching off the piezo transducer a stable frozen hydrogen filament can be produced. Such filaments are of high interest for future hadron physics experiments, such as MAGIX at MESA. A long-term measurement showed that such filaments can be produced for more than 100 hours without interruption. An implementation and proof of concept of a real-time pellet tracking system have been done. A pellet tracking section with four detection modules has been completely equipped with line scan cameras and lasers. The fine adjustment and alignment are almost finished. A collimator system with 0.16 mm hole diameter is being prepared. The system allows the prediction of when a pellet will be present in the nominal interaction region with high accuracy. This information can be provided to a pulsed laser as a trigger signal. Furthermore, a system to study the influence of laser light pulses on the droplet production has been prepared and tested at the pellet generator at Uppsala University. The system consists of a point focused, pulsed laser, a CCD camera monitoring the droplet formation chamber, and a line scan camera monitoring the pellet stream after vacuum injection. The studies included different droplet production frequencies and laser power setting. During these runs, no significant effects from applying the laser pulses could be observed in the

	droplet formation chamber. The offline analysis of the data from the line scan cameras confirmed these results. To achieve an effect a further increase in laser power or additional laser is required.
JRA - Spin for FAIR (SPINFORFAIR) Optimization of the polarization of protons and antiprotons beams and targets for the GSI/FAIR storage ring	The first Siberian Snake commissioning beam time took place in March 2020 at the COSY Storage Ring. The test evidenced that the solenoidal field, acting quadratically on the betatron tunes, introduces a strong phase space coupling creating a tune split around the $\nu x - \nu y = 0$ resonance, inhibiting the possibility of operating the ring in this region of the phase space. The $\nu x = \nu y$ is essential for the obtainment of the long beam lifetime conditions required for the spin-filtering experiment. Subsequently, progresses were made in understanding the effect on the beam dynamics caused by the presence of the soleonidal magnetic field. Dedicated developments have been initiated in view of second commissioning test. The long shutdown due the COVID pandemic, combined with the budget restrictions causing a reduction of the available beam time at the COSY ring and its premature shutdown at the end of 2023, did not allow the completion of the physics program. The final detector commissioning, as well as the beam polarization measurement, was planned together with the final Siberian Snake commissioning, taking into account the beam availability at the COSY facility and the PAX interaction point availability, now occupied by the RF Wien Filter needed for the EDM precursor experiment performed by the JEDI collaboration, whose schedule was heavily affected by the pandemic as well. the long shutdown due the COVID pandemic, combined with the budget restrictions causing a reduction of the available beam time at the COSY ring and its premature shutdown at the end of 2023, did not allow the completion of the physics program.
JRA - Polarized Electrons, Positrons and Polarimetry (P3E) Optimization of high-intensity polarized electron and positron beam sources, and full design of the Hydro-Møller polarimeter detector using high-voltage	The charge lifetimes of a high polarization photocathode were measured over two years, demonstrating an improvement >50% when the photo-gun anode is biased. A new simulation code to model the measurements was created and compared successfully. The results were submitted to Phys. Rev. Accel. And Beams and are in review. The publication of the JLab Positron White Paper as a 2022 topical issue of the European Physics Journal A was a major achievement of a group of physicists including JRA13-P3E partners, which goes much beyond the boundaries of the

monolithic active pixel sensors (HV-MAPS).	STRONG-2020 program. However, this result was a major step in the scientific motivation of the $Ce^{+}BAF$ positron injector which was further assessed and confirmed by the approval of positron beam experiments by the JLab PAC (PAC51). The full design and evaluation of the new positron injector for CEBAF has also been a significant step not-only with respect to the objectives of the JRA13-P3E but also for the whole $Ce^{+}BAF$ project, particularly showing that an optimized design is capable to achieve high enough performances to efficiently complete the proposed JLab positron experimental program. The completion of a finite element modelling of a positron production target has been an essential step into the practical evaluation of a conceptual target, the identification of the different technical/mechanical/thermal issues, and the validation of possible solutions. It was shown that a disk rotating with a moderate speed of 4 turn/s and cooled by water is able to dissipate the 17 kW thermal power deposited by the electron beam in the target. The expected life-time of such a system corresponds to about one year of $Ce^{+}BAF$ operation. The mechanical and thermal properties of the positron production material are particularly important to optimize the life-time of a target. An electron beam traversing the target produce a high level of radiation and may also activate the target material which result in a progressive destruction of the target. The first experiments to identify the damages to materials resulting from exposure to an electron beam were performed at MAMI and further characterized at PETRA-III. An unexpected signal of the unsensitivity of Tantalum under the $Ce^{+}BAF$ operating conditions was obtained, opening new prospects for positron target materials. A detailed simulation framework for Møller polarimeters using large solenoidal magnetic fields was created; the physics models used for Møller and Mott scattering were thoroughly validated; a working geometry for collimators and magnets to be used in the polarimeter was developed, delivering excellent signal to noise ratios; HV-MAPS sensors suitable for the detection system were developed and are being produced; the polarimeter design was summarized in a technical design report.

1.2 Explanation of the work carried per WP

1.2.1 Work Package 1

Activity Type	Management and Monitoring
Work package title	Project Management and Coordination (MAN)
Lead beneficiary	1 – CNRS

Project objectives

MAN takes in charge the effective management, the steering of the whole project and the monitoring of the progress of all Work Packages, including the planned scientific activities, industrial developments and applications, and society issues. The management team ensures the contractual and administrative implementation. It oversees the use of resources and prepares Periodic and Final Reports.

The other objective of MAN is to coordinate the overall Integrating Activity and ensure the links with the European Commission from one side and the large community involved in the scientific programs focused on Transnational and Virtual Access from the other side.

Progress made during the reporting period towards objectives

Task 1: Management. MAN is responsible for setting up the organizational consistent and efficient structures and decision-making mechanisms.
MAN is responsible for establishing of the Consortium Agreement (CA) between the Coordinator and the participants of the Consortium.
Another important objective of MAN is to organize meetings at different levels of STRONG-2020. MAN takes care of the organization of Kick-off meeting in the beginning of the project as well as regular Annual Meetings.
MAN is entitled to represent the project and ensure the regular interactions with the European Commission, the Transnational and Virtual Infrastructures, the spokespersons of the WPs and the persons in charge of scientific, administrative and legal aspects in the organization of the participant institutions.

During the third reporting period, MAN continued its role as coordinator between the different decision-making mechanisms already established at the beginning of the project. This includes Governing Board (GB), Coordination Board (CB), Executive Board (EB) and Facility Coordination Panel (FCP). There were no major changes in the composition or functioning of these structures. A close collaboration was also in place with the Dissemination Board (DB) established by DISCO Work Package (WP2).

As for the Consortium Agreement, there were no modifications of the document adopted during the first reporting period.
Given the extended duration of the third period, MAN organized three annual meetings:

The 2022 edition of STRONG-2020 Annual Meeting took place in hybrid mode, on 18-19 October at the CNRS headquarters in Paris, Michel-Ange :
https://indico.in2p3.fr/event/27767/

The 2023 edition of the STRONG-2020 Annual Meeting was held on 20–22 November at CERN, Switzerland:
https://indico.cern.ch/event/1264833/

The final Annual Meeting of STRONG-2020 was held from 20 to 22 June 2024 at National Laboratory of Frascati (LNF) of INFN in Italy:
https://indico.in2p3.fr/event/32198/

In addition to these regular Annual Meetings, MAN has also organized two Workshops, as it was foreseen in the frame of MS3:

The first Workshop co-organized with the STRONG-2020 support took place on 17 October 2022, in Orsay, France (Institut Pascal):
https://indico.in2p3.fr/event/27767/timetable/#20221017.detailed

The second Workshop, held on 17-19 June 2024 at LNF of INFN in Italy, was co-organized with the DISCO Work Package and was entitled "Present and Future of Hadron Physics":
https://agenda.infn.it/event/38467/

MAN continued to fulfil its role in relay of information by ensuring transparent and timely communication between the EU Commission and the Consortium representatives. This organization of communication has proven its effectiveness throughout the project, whether for resolving specific issues for a concerned partner or during the processes involving many partners, such as amendments of the project. MAN also ensures communication with scientific, administrative and legal representatives of each beneficiary using distribution lists organized by categories of interlocutors (one list for each category).

Task 2: Reporting. This task supposes the coordination of the preparation of the Periodic and Final Reports to the European Commission documenting the progress in all the activities and the financial status of the project.

MAN fulfils its role of centralization for the preparation of Periodic Reports, ensuring thus their consistency and compliance with the EU Commission rules and standards. During the third reporting period, that lasted 26 months, MAN also prepared and submitted a special deliverable, Report on cumulative expenditure, prepared with the participation of all the Administrative representatives of the project beneficiaries.

In the frame of the same task, MAN ensures the internal reporting as well as by producing reports on the results of Annual Meetings. For restricted meetings, organized with decision-making bodies of the project, minutes are regularly drafted and distributed to the concerned participants. Finally, the results of the reviews in the frame of the project monitoring are also disseminated to all members of the Consortium.

Highlights of significant results

1. Continuous monitoring

One of the regular responsibilities of the MAN Work Package consists in the monitoring of the activity of important decision-making mechanisms/bodies established from the very beginning of the project: Governing Board (GB), Coordination Board (CB), Facility Coordination Panel (FCP) and Executive Board (EB). Another structure formed by the DISCO Work Package, that is Dissemination Board (DB), also closely collaborates with MAN on matters related in particular to the communication with general public, updates of the project web page, dissemination of scientific results, preparation and publication of the Newsletters.

The same task of continuous monitoring includes regular updates of information in the Participant Portal. This supposes the submission of the deliverables, the validation of the dates of completion for milestones, the updates of information on communication and dissemination activities, the validation and manual addition of the publications/open data, as well as the update of sections relating to gender and intellectual property.

During the RP3, MAN prepared and submitted a Report on cumulative expenditure, a mandatory deliverable for reporting periods exceeding 18 months. The requested information on annual expenditures of all the beneficiaries was collected and submitted in time for the further evaluation by the PO.

In view of ongoing support for the participants, MAN fulfills the role of consultation and advisory body by providing advises and answers to all the issues addressed by the Consortium members.

1. Targeted communication

From the beginning of the project, MAN set the goal of making the communication efficient and targeted by avoiding overloading emails to participants not concerned by the given issue. To this end, MAN established several mailing lists according to the roles of the participants. Thus, first of all, the distribution lists for decision-making bodies have been created: Governing Board, Coordination Board, Facility Coordination Panel, Dissemination Board and Executive Board mailing lists. Secondly, each participant institution provided contact information per category of responsible personnel: legal, administrative/financial and scientific contact. Dedicated mailing lists have been created for these “category contacts” that enabled a smooth and efficient communication.

As part of this mission, MAN also informed the relevant WP leaders about the deadlines for deliverables and milestones, assisted DISCO in collecting the necessary information as regards the communication and other activities aimed at the dissemination of the obtained results (Workshops, Conferences, etc.). Targeted communication also concerns the interactions with the Commission where MAN is responsible for transmission, on behalf of the participants, of the questions addressed by the beneficiaries to the PO or, conversely, to inform the concerned beneficiaries of the requests for information coming from the PO.

2. Meetings Organization

As mentioned above, given the extended duration of the third period (26 months), three Annual Meetings were organized by MAN.

The first one, the 2022 edition of Annual Meeting, took place in hybrid mode, on 18-19 October at the CNRS headquarters in Paris, Michel-Ange:

https://indico.in2p3.fr/event/27767/

The presentations made by each WP during this meeting can be consulted at this page.

This meeting marked an important moment of sharing and exchange for the participants of the project. It was an opportunity to meet in person (after a long COVID shutdown period) with the leaders of WPs and to welcome some young participants who could benefit from the support of the project.

A detailed description of the work performed by different WPs was exposed during the two days of plenary sessions. These presentations were given following the classification by thematic category adopted for STRONG-2020:

- Research Infrastructures: Transnational Access
- Research Infrastructures: Virtual Access
- GPD (generalized parton distributions)/TMD (transverse momentum distributions)/PDFs (parton distribution functions)
- Hadron Physics
- Precision Physics
- Instrumentation Activities

The progress and future perspectives were discussed in details during restricted sessions of the Annual Meeting: Facility Coordination Panel Meeting, Governing Board Meeting and Executive Board Meeting. These sessions were organized and managed by MAN and they were restricted to the members of the relevant decision-making bodies. These closed sessions were scheduled on 18, 19 and 20 October 2022 respectively, and participation to these meetings was possible in-person and remotely.

This meeting was preceded by the Workshop co-organized with the STRONG-2020 support, that took place on 17 October 2022, in Orsay, France (Institut Pascal):

https://indico.in2p3.fr/event/27767/timetable/#20221017.detailed

The Workshop has shown a great involvement of young researchers, both engaged in the STRONG-2020 project and in other research initiatives, who had the opportunity to expose results of their work and to discuss them with experienced counterparts. The information on this Workshop and the presentations can be found on the page mentioned above.

The 2023 edition of the STRONG-2020 Annual Meeting took place on 20–22 November 2023 at CERN, Switzerland:

https://indico.cern.ch/event/1264833/

This meeting was organized in a very important for many participants infrastructure: CERN. We invited Sari Vartiainen-Mathieu, the Head of Unit of REA, the Executive Research Agency responsible for the monitoring of the project at the EU Commission level. She gave an explanatory talk on the European Research Executive Agency as a funding body in the Horizon Europe (HE) as well as on Research Infrastructures (RI), their role in the implementation of Horizon 2020 and Horizon Europe, and future perspectives for the RI-related projects.

The presentations of the WP leaders followed the same logic as for the previous year edition. They delivered their vision of the results achieved during the past year, the important highlights of the performed work, as well as future plans and the remaining tasks until the end of the project. At the end of the two-day plenary presentations, a special session was held by the Project Coordinator to discuss the role of Hadron Physics in Horizon Europe. The new features of the Horizon Europe framework, as well as the major changes for our pillar (Research Infrastructures), were presented to the members of the Consortium.

Three restricted meetings were scheduled during that annual meeting as follows: Facility Coordination Panel (FCP) Meeting on 20 November, Governing Board (GB) Meeting on 21 November and the Meeting of the members of Executive Board (EB) on 22 November. Here again, some specific questions were addressed and future perspectives of STRONG-2020 in the frame of Horizon Europe were discussed. It was also the time to analyze the remaining tasks before the end of the project and to address the questions of the organization of two last major events, the details of which are given below.

The final Annual Meeting of STRONG-2020 was held from 20 to 22 June 2024 at National Laboratory of Frascati (LNF) of INFN in Italy:

https://indico.in2p3.fr/event/32198/

This meeting brought together the entire Consortium to review the accomplishments and discuss the future of Hadron physics in Europe. This last meeting was of utmost importance not only to conclude the achievements but also to expose the plans for the future. In addition to the presentation of the scientific progress made during the five years of the project, it was also an opportunity to define the main research directions for the future. Indeed, most of the WP leaders expressed their high hopes and willingness to take part in a new project, built on the successes of STRONG-2020 that could be submitted in the frame of Horizon Europe.

The second Workshop, held on 17-19 June 2024 at LNF of INFN in Italy, was co-organized with DISCO WP and was entitled "Present and Future of Hadron Physics":

https://agenda.infn.it/event/38467/

The Workshop lasted three days, with thematic presentations of the most recent worldwide results by scientists including both project participants and external invited speakers. It began with talks of young researchers, providing a platform for the next generation of scientists to present their work. The following two days were dedicated to the presentations of senior researchers who exposed the current and future programs of the large-scale infrastructures in Europe, US and Japan, as well as advances in areas such as hadron spectroscopy, the physics of quark-gluon plasma, exotic atoms and nuclei, and rare decays. These presentations highlighted both the progress made by the STRONG-2020 project and the many open questions that remain in the field of Hadron Physics.

Other meetings with the members of decision-making bodies held either via ZOOM or in-person were also organized based on the needs of the project.

4. Project Amendments

During the last reporting period, MAN prepared and submitted two Amendments that had a major impact on the implementation of the project.

The first Amendment, launched on 31 March 2023, contained the request for a second extension of 8 months. As a result of this extension, the total duration of the project became 62 months, with the last Reporting Period (RP3) of a total duration of 26 months, from month 37 (June 2022) to month 62 (July 2024).

The preparation of this Amendment required the collection of information from all the beneficiaries to objectively assess the progress of their tasks and properly justify the request for the extension. This collection of information included the arguments in favor of the extension, the quantified estimates of the tasks already performed and those to be accomplished, and the new schedule for the completion of the deliverables and milestones for the WPs concerned.

The Amendment was approved by the Commission and was finally accepted on 15 June 2023.

The second Amendment, requested during RP3, concerned the modifications of work program for some of the WPs, as well as financial transfers to ensure the optimal finalization of the tasks by all the beneficiaries. It was launched on 26 March 2024.

This Amendment was also of utmost importance for the Consortium because the required modifications aimed to ensure the optimal conditions for the completion of the project tasks and the valorization of the obtained scientific results. Indeed, the unspent by few beneficiaries funds were redistributed to the partners that needed additional resources to accomplish their tasks. Some transfers between cost categories enabled the implementation of additional work and the optimized use of TAs budgets permitted the support for young researchers. It also allowed for last modifications of the work programs for some of the work packages.

After a detailed study of the requested modifications, the Commission accepted this amendment on 13 May 2024.

Deliverables due in RP3.

D1.3 Strategic road map – Achieved

The document describing the overall context and objectives of the project, the scientific results and the future perspectives for RI developments, as well as the plans for the future potential project in the frame of Hiorizon Europe, was submitted in the Portal.

Milestones due in RP3.

MS3 Workshops – Achieved

MS4 Mid-term review – Achieved

MS5 Presentations at NuPECC – Achieved

MS6 Preparation of periodical reports – Achieved

1.2.2 Work Package 2

Activity Type	Communication and Dissemination
Work package title	Dissemination and Communication (DISCO)
Lead beneficiary	30 - INFN

Project objectives

During the second reporting period the main objective of the DISCO Work Package was to continue to promote and realize efficient and targeted dissemination, exploitation of results and communication activities resulting from the dedicated research and transnational activities performed within STRONG-2020.

DISCO is a transversal and integrated activity, which involves all the other WPs of the project. The overarching objective of DISCO was to promote and realize dissemination and communication of the results coming from the project, by using various methods, actions and platforms, towards:

- the scientific community of specialists in hadron physics: DISCO presented the main results coming from the project activities during the reporting period, as well as the opportunities and outcomes from the research infrastructures dedicated to the strong interaction studies, both within the researchers community involved in the project, as well as to those researchers in hadron physics who are not directly involved in the project;
- the wider scientific community: DISCO disseminated the main results coming from the project activities and the research infrastructures to those researchers who are not directly involved in research in strong interaction physics;
- the general public, industry representatives and policy makers: DISCO disseminated the main results coming from the project activities and the research infrastructures with the aim of raising the awareness about this type of research and related infrastructures, to promote a new generation of scientists and enhance future financing opportunities.

Progress made during the reporting period towards objectives

Task 1: Realization of activities with impact on the scientific community of specialists in strong interaction physics
During the reporting period, the DISCO activities were organized and coordinated by the Dissemination Board (DB) representing the various research areas and industries present in the project, as a continuation of the activities started and active in the previous reporting period. All the dissemination and communication activities were discussed within regular (about one per month) DB meetings. In particular, during the reporting period, an overall number of 22 DB meetings were held online; all these meetings have associated Minutes. Considering the high number of researchers involved in STRONG-2020 (more than 2500) and an even larger community studying the strong interaction but not directly participating in STRONG-2020, it was important to have an efficient tool for disseminating the news/achievements/activities towards the scientific community. In this context, the events

and achievements coming from the STRONG-2020 activities were timely disseminated to the hadron physics community, both the one directly involved in the project, as well as researchers not directly involved in the project.
The main tool used for extended dissemination was the continuous implementation and updating of the project dedicated web page with the news, events and activities and results coming from the project:
http://www.strong-2020.eu/

The web page contains an updated description of the project and useful information related to the activities with impact on the scientific community of specialists in strong interaction physics. This web page contains information related to the whole project, with updated details provided by WP leaders, containing a description of events (including meetings), participants, news and documents and was a very useful instrument for all the STRONG-2020 community.

The section of events was updated and enriched continuously during the reporting period. It presently contains information regarding the organized meetings, divided in categories reflecting the project activities: Heavy Ions; GPD/TMD/PDFs; Hadron physics; Lattice QCD; Precision Physics.

The web page was also a useful dissemination instrument for the community of specialists in strong interaction physics, beyond the community strictly involved in STRONG-2020 project.

In the reporting period, the DB organized, coordinated and promoted the following dissemination activities:
- we have prepared and published a Newsletter, in May 2023, containing scientific information, dissemination information, interviews and news coming from the project WPs. This newsletter was published on the dedicated STRONG-2020 web-site, under News and Documents section:
http://www.strong-2020.eu/news-documents/newsletter.html

Another very important activity in the reporting period was the organization of the final Workshop of STRONG-2020: "Present and Future Perspectives in Hadron Physics", for which the DB was playing a fundamental role, being active in the Organizing Committee.

The Workshop was organized in the period 17-19 June 2024 and held at INFN-LNF, Frascati. All information related to the workshop can be found at the dedicated web-site:
https://agenda.infn.it/event/38467/overview

Task 2: Realization of activities with impact on the wider scientific community, such as (but not limited to): publications of the general findings of the project in top journals, participation to conferences and workshops attended by a broad scientific audience; exploration of dissemination channels offered by participating Institutions

A series of activities with impact on the wider scientific community were organized and coordinated by the DB. The main platform for providing information to the wider scientific community of the project was the web-page that publicized by the members of STRONG-2020 and outside of the hadron physics community

A very successful instrument to disseminate the STRONG-2020 activities and results in the reporting period was the online dissemination channel offered by ECT* which was broadly used and where the Newsletter and other outreach documents were (re)posted; workshops, seminars and colloquia organized with the STRONG-2020 support were also regularly posted:
https://www.ectstar.eu/

Task 3: Realization of activities with impact on general public, such as (but not limited to): dedicated STRONG-2020eb-page for public, seminars and conferences in schools and universities; hands-on experiments in the framework of stages for students; dedicated video-channel for presentation of the STRONG-2020 activities, etc.

The web-page is accessible to the general public and contains dedicated information on activities, which are organized, such as the section of Life Events that are also important for educated public interested in science and, in particular, in the STRONG-2020 outcomes.

A very important tool within Task 3 were the dedicated STRONG-2020 public lectures, initiated originally during the pandemic lockdown. This instrument proved to be very efficient, so was continued also in the reporting period. Specifically, the DB organized and held a series of 8 public lectures online and one virtual visit on the dedicated YouTube channel on related activities:
https://www.youtube.com/playlist?list=PLRuUrPCVPFIqjT_o4A7iPEPj26N_OOA6s

Speakers were identified within the DB meetings, then they were invited to give the talks. Consequently, the platform was organized, posters prepared and publicized within the STRONG-2020 community, broader community and schools. At the end of the lectures, an interactive session with participants, where they could get answers from experts, was organized. The videos were then registered, edited and posted on the dedicated channels.

Transversal to all dissemination activities (including Task 1 and Task 2) is the section on the web page under Events – i.e. Pictures gallery – where a gallery picture of participants in various events:
http://www.strong-2020.eu/events/pictures-gallery.html

A dedicated public event was organized and held in occasion of the final STRONG-2020 workshop, Present and Future Perspectives in Hadron Physics, the public conference:

Dai quark alle stele. Il fascino della fisica adronica, held on 19th June 2024 at Scuderie ldobrandini in Frascati. More than 100 participants (schools, students and general ublic) took actively part:
https://agenda.infn.it/event/38467/overview

Another important type of activities was that dedicated to schools. Among these activities, the most important ones were organized within the INSPYRE International Schools, 2023 and 2024 editions, organized online by LNF-INFN, with support from STRONG-2020.

Task 4: Realization of activities with impact on potential partners in industry, such as (but not limited to): technical reports containing innovation in technology resulting from STRONG-2020 for the potential industrial partners; meetings, symposia, visits and

discussions both in the institutes and research infrastructures participating in STRONG-2020 and in the potentially interested industry partners
Related to this Task, Dr. Catalina Curceanu gave various talks (see Highlights), where representatives of industries and SME were also present. Various WPs, especially those developing detector systems, were in contact with potential industrial partners (see reports WPs) for possible use of their technologies in other sectors. For example, within ASTRA project, the CdZnTe detectors are being discussed for possible applications in industry – quality check and agrifood. Also, during the project, various meetings and discussions were organized with FBK (Italy) for collaboration in radiation detectors development. During the final Workshop "Present and future perspectives in Hadron Physics", which was held in June 2024 at INFN-LNF, at the public event "Il fascino della fisica adronica", held on 19 June at Scuderie Aldobrandini in Frascati, there were various representatives of SME with whom possible future collaborations were discussed.
Task 5: Realization of activities with impact on policy makers, such as (but not limited to): realization of documents summarizing STRONG-2020 findings and perspectives, to be distributed at national, European and international levels; visits of policy makers to the STRONG-2020 research infrastructures; communication with the European Commission
Activity of communication with the European Commission was task of the Project Coordinator, Dr. Barbara Erazmus, who was in permanent contact with the Commission. Part of the activities within Task 5 were organized during the Annual Meetings held in the reporting period. These include: the 2023 annual meeting, held at CERN in November 2023: https://indico.cern.ch/event/1264833/ Other activities took place during the final Workshop "Present and future perspectives in Hadron Physics", held in Frascati in June 2024. Finally, more activities in this context were organized during the final Annual meeting (20-22 June 2024) at LNF-INFN where final discussions took place: https://indico.in2p3.fr/event/32198/

Highlights of significant results

The activities within DISCO were organized by the Dissemination Board (DB). The DB had the total of 22 online meetings lead by DISCO WP leader (Curceanu); during these meetings the dissemination and communication activities were organized, including: the update of the STRONG-2020 web-page with latest activities; the organization and preparation of the Newsletters; the organization and preparation of public lectures; the organization of the final workshop, etc.

During the reporting period, the following activities together with their results towards the objectives were achieved:

1) Continuous update and implementation of the dedicated web-page materials pertinent to the description of the project and useful information related to the activities with impact on the scientific community of specialists in strong interaction physics, on wider scientific community and general public:

http://www.strong-2020.eu/

2) Preparation and release of a Newsletter, containing scientific information, dissemination information, interviews and news coming from STRONG-2020 WPs.

http://www.strong-2020.eu/news-documents/newsletter.html

This Newsletter contained as main articles:

- Report on the 2022 edition of the STRONG-2020 Annual Meeting: a new stage of return to normal operation and impressive results
- A featuring article: LHCb goes to fixed target
- A second featuring article: Kaonic atoms at the DAΦNE collider with the SIDDHARTA-2 experiment
- News and updates on various WPs
- Public dissemination information
- An Interview with Dr. Mostafa Hoballah, researcher of WP23 (JRA5)

3) The organization of the final Workshop: Present and Future Perspectives in Hadron Physics, for which the DB was playing a fundamental role, being active in the Organizing Committee.

The Workshop was organized in the period 17-19 June 2024 and held at INFN-LNF, Frascati:

https://agenda.infn.it/event/38467/overview

84 participants were registered to the workshop, both from STRONG-2020 as well as from the enlarged scientific community. The timetable can be found at:

https://agenda.infn.it/event/38467/timetable/#20240617

The list of contributions is available at:

https://agenda.infn.it/event/38467/contributions/

Two competitions were organized and held in correspondence with the workshop:

- Best Young Talks researchers' award:

https://agenda.infn.it/event/38467/page/9103-best-young-researchers-talk-award

- Photo competition, with information at:

https://agenda.infn.it/event/38467/page/9104-strong-2020-best-picture-award

4) Organization of dedicated STRONG-2020 public lectures: the DB proposed and discussed the public lectures, using a dedicated platform; this was especially useful during the pandemic emergency. The lectures were addressed to the general public, specially targeting the schools:

http://www.strong-2020.eu/news-documents/live-events.html

The 8 public lectures and a virtual visit, as well as their related videos were realized with support from LNF-INFN Educational service, and they can be found on:

- How progress is made in fundamental science cutting-edge instrumentation, having nearly 1000 views; https://www.youtube.com/watch?v=J8TJRosPasg&list=PLRuUrPCVPFIqjT_o4A7iPEPj26N_OOA6s&index=9&t=3044s&pp=iAQB

- Virtual MAMI tour http://www.strong-2020.eu/events/live-events.html

- I Buchi Neri, la Quantistica e…i segreti di Babbo Natale, with more than 3800 views: https://www.youtube.com/watch?v=rB0FIrl0KSI&list=PLRuUrPCVPFIqjT_o4A7iPEPj26N_OOA6s&index=8

- The heart of matter : the secret inner life of protons with more than 600 views: https://www.youtube.com/watch?v=OANoxeGOGus&list=PLRuUrPCVPFIqjT_o4A7iPEPj26N_OOA6s&index=7ttps://www.youtube.com/watch?v=ie3Gj0WvRlk&t=292s

- Machine learning the history of the Universe with more than 1000 views https://www.youtube.com/watch?v=6BnwlxO1KKo&list=PLRuUrPCVPFIqjT_o4A7iPEPj26N_OOA6s&index=6

- Navigating uncharted territories with strangeness with SIDDHARTA-2 at DSFNE with more than 800 views: https://www.youtube.com/watch?v=b7OuJHnwaKs&list=PLRuUrPCVPFIqjT_o4A7iPEPj26N_OOA6s&index=5

- Science, policy and Truth (special lecture) with more than 600 views: https://www.youtube.com/watch?v=ikBtifkNV1Y&list=PLRuUrPCVPFIqjT_o4A7iPEPj26N_OOA6s&index=4&t=1s

- May the Strong Force be with you – DB special public lecture with more than 1000 views: https://www.youtube.com/watch?v=Oc6F4ysHS1w&list=PLRuUrPCVPFIqjT_o4A7iPEPj26N_OOA6s&index=1

- Computing the heart of matter with nore than 700 views: https://www.youtube.com/watch?v=zIoU4UXZxiM&list=PLRuUrPCVPFIqjT_o4A7iPEPj26N_OOA6s&index=2&t=3357s

The overall number of visualizations is more than 10000 for the lectures and visits, showing the interest of the general public in the issues related to the project activities.

The lectures are posted on the STRONG-2020 web page:

http://www.strong-2020.eu/events/live-events.html

5) Organization of the INSPYRE International Schools, 2023 and 2024 Editions, online by LNF-INFN, with support from STRONG-2020:

https://edu.lnf.infn.it/inspyre-2023/

https://comedu.lnf.infn.it/inspyre-2024/

Moreover, reports on the INSPYRE schools, as well as other dissemination events, can be found in the Newsletters.

6) Events organized for schools and general public:

- 7 affascinanti rompicapi della Fisica Moderna: dai buchi neri al gatto di Schrödinger

Talk given by C. Curceanu to 200 students from Italy on 14 June 2024 at LNF-INFN

- La magia degli acceleratori di particelle: dalla caccia alla materia oscuRa alla terapia dei tumori

Talk given by C. Curceanu on 5-6 April 2024 at Serra San Bruno for schools (120 participants)

- L'affascinante vita di una stella

Talk given by C. Curceanu on 23 March 2024 for students at Istituto Comprensivo di Falerna - Nocera Terinese (100 participants)

- I misteri dell'Universo

Talk given by C. Curceanu on 22 March 2024 for general public at Aula Magna di Nocera Terinese (250 participants)

- Evoluzione quantistica. Dal Big Bang ai Buchi Neri Quo Vadis Universo?

Talk given by C Curceanu on 16 March 2024 at Udine library for general public (50 participants)

- A tu per tu con i fisici nucleari

Public event at Sala Degli Specchi, Frascati, 28 November 2023 (50 participants)

- Atomi Kaonici a DAΦNE: L'esperimento SIDDHARTA-2

By C. Curceanu, 30 September 2023 – Researchers Night event – Testaccio Roma

- The greatest puzzles of Modern Physics: from the Dark Matter to the Black Holes

By C. Curceanu at Tradate High School, 6 February 2023 (250 participants)

- L'incredibile mondo della fisica quantistica

By C. Curceanu on 19 April 2023 at Ladispoli high school (120 participants)

In addition and similar to the talks above C. Curceanu gave other about 10 lectures in high-schools in the reporting period for more than 1000 students.

7) During the final Workshop on the topic "Present and future perspectives in Hadron Physics", which was held in June 2024 at INFN-LNF, at the public event "Il fascino della fisica adronica, held on 19th June 2024 at Scuderie Aldobrandini in Frascati" there were various representatives of some SME with whom possible future collaborations were discussed.

Deliverables due in RP3.

D2.4 Proceedings of the Workshop - Achieved

Proceedings of the Workshop contain the contributions of young participants. The file of the proceedings can be found on the web page:
https://agenda.infn.it/event/38467/contributions/contributions.pdf

D2.5 Article in Nuclear Physics News International (NUPECC) and in CERN Courier on the results of the project - Achieved

The article STRONG-2020: Advancing Our Understanding of the Strong Interaction and Shaping the Future of European Hadron Physics was written and is being submitted to NuPECC News.

Another article (in French) was published in the Newsletter of IN2P3:
https://www.in2p3.cnrs.fr/fr/cnrsinfo/la-physique-hadronique-europeenne-se-projette-dans-le-futur

Milestones due in RP3.

MS9 Preparation of the Workshop "Present and future perspectives in Hadron Physics in the 21st Century" - Achieved

1.2.3 Work Package 12

Activity Type	Networking activity
Work package title	QCD physics at GSI/FAIR (NA1-FAIRnet)
Lead beneficiaries	6 – FAIR, 11 – RUB, 12 - UHEI

Project objectives

The FAIRnet networking activity will foster the interchange of ideas and methods on dead time free front-end electronics, FPGA based feature extraction, hard- and software for online event selection on heterogeneous multi-core systems (CPU+GPU), and data acquisition networks as well as physics analysis methods.

Progress made during the reporting period towards objectives

Task 1: Front-end, DAQ and On-line

The ToASt ASIC is a 64-channel integrated circuit developed for the readout of the Silicon strip detector project designed to be placed in the Micro-Vertex Detector of the PANDA experiment. The ASIC has been developed in the framework of this work package. ToASt is implemented in a commercial 110 nm CMOS technology and can provide information on the position, time, and deposited energy of the particle passing through the detector. Its time resolution is given by its 160 MHz master clock. During the reporting period the chip has been characterized electrically both standalone and coupled with sensors, with focus on its noise performances. It has also been tested for radiation tolerance, both in terms of total ionizing dose and single event upset. The results are published (G. Mazza et al., JINST 18, C01020, 2023; F. Lenta et al., JINST 19, C04047, 2024).

The ToASt ASIC was tested successfully with beam (cf. Task 2, and section 1.3 Highlights).

The Aurora Protocol, which is a link layer communications protocol for use on point-to-point serial links was successfully evaluated for time synchronization purposes. Data transport is performed in 8b/10b encoding. The AMC data concentrator board, which was produced during the last reporting period, was combined with 64 channel, 14 bits, 80 MSPS sampling ADCs of the PANDA experiment. An excellent timing synchronization of 160 ps between two SADC modules was achieved.

In June 2024, a front electronics and data acquisition workshop took place within the PANDA collaboration meeting. It was dedicated to the FAIR experiments with emphasis on the PANDA experiment and the CBM experiment. Further options for future common projects were identified.

Task 2: Demonstrator

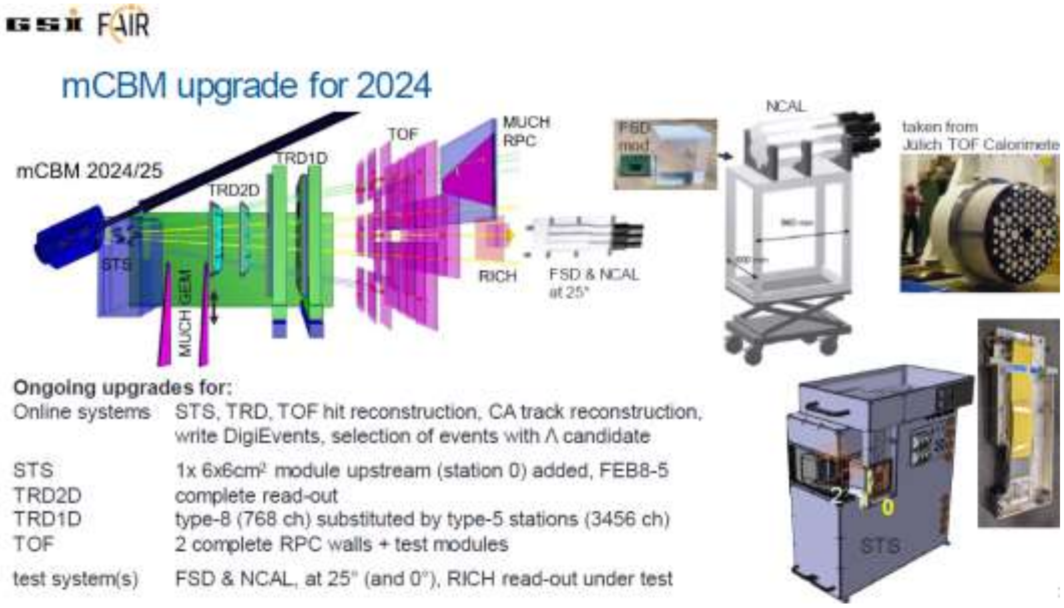
As planned, a demonstrator for the PANDA experiment was set up at the COSY accelerator at the FZK, Jülich, Germany. In a combined test beam in August and September 2023 the forward endcap electromagnetic calorimeter, a prototype of the luminosity detector and of the Micro Vertex Detec¬tor were operated together. At the COSY-TOF hall stable running with a high intensity (108/s) beam of 2.74 GeV/c protons on a plastic target was achieved. The silicon vertex detector was read out with the ToASt front end (cf. task 1). For the luminosity detector two sensors of the HV-MAPS MuPix sensors were read out together. The forward endcap lead tungstate electromagnetic calorime¬ter was for the first time put into operation as common system under the temperature of -25ºC as planned for its usage at the PANDA experiment. The detector modules were read-out via VPTTs and pertly with APD-readout, connected through pre-amplifiers to the SADC modules. The operation of the data acquisition system went smooth and in total 220 TB of data were recorded, including full waveform information for further analysis. The data reconstruction showed in the two photon invariant mass a clear neutral pion signal. A great success of the beam time. A PANDA EMC meeting was held in Februray 2024 dedicated to the forward endcap, data analysis of the beam time and related issues. Further analysis of the valuable data is ongoing to improve the simulation and analysis software as well as the feature extraction methods. First results were presented at the Calor 2024 conference in Tsukuba, Japan in May 2024 by T. Held.

The second demonstrator was operated at GSI/FAIR. With a full-system sandbox with detector prototypes and pre-series components the free-streaming CBM data transport was developed and tested in the framework of the mCBM experiment. It allows realistic set ups with high rate studies up to 10 MHz collision rate in nucleus-nucleus collisions. During the runs in 2021 and 2022 all data was written to disk and no online-processing was performed. During the reporting period, the online processing chain was successfully developed, and the online processing chain was first tested with a re-play of archived raw data. In March 2024 the online procession was applied for the first time during data taking with a minimum bias trigger. Finally, the full online reconstruction and trigger on displaced vertices for the selection of lambda particles was applied during the Ni on Ni beam time in May 2024. See also section 1.3 Highlights.
Task 3: Data analysis challenge
The vast amount of data requires high-level data analysis tools and sophisticated partial wave analysis tools (PWA). During the reporting period, the PAWIAN (PArtial Wave Interactive ANalysis Software) was further developed and applied to data analysis. The package supports different reactions from antiproton-proton annihilation (PANDA experiment), pion-proton scattering, pi-pi scattering data, central production, positron-electron annihilation, and two-photon fusion. Its special feature is the coupled channel PWA, were several reaction channels are combined, to put constraints on the resonances. In particular, searching and investigating exotic states, e.g. glueballs, hybrids and tetraquarks is a challenge among the many broad and overlapping resonances. Sophisticated dynamical models are applied respecting unitarity and analyticity. Results of a coupled channel analysis with PAWIAN were discussed in a workshop about "The present and future of heavy flavour and exotic hadron spectroscopy (Munich, May 2023) by M. Küßner and B. Kopf and presented at the HADRON 2023 conference, Genua, Italy by M. Küßner in June 2023. Progress on the track reconstruction and identification of Λ candidates is depicted in the highlights sections.
Task 4: Education and outreach
During the third reporting period, the teaching activities and lab visits for school children were ramped up. As Covid-19 restrictions were released, larger events for the public could again take place. For example in the framework of the German year of the universe 2023, a special event for the general public named "big bang in the city" took place at the center of the city of Bochum, Germany.

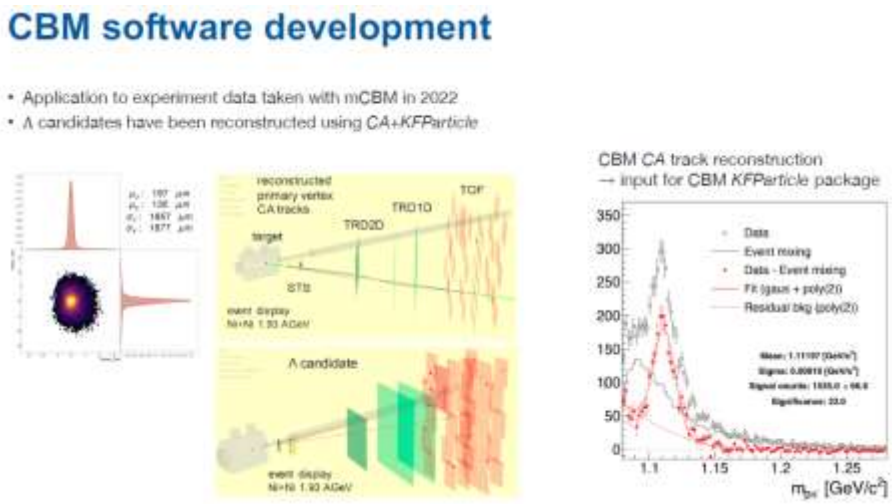
Highlights of significant results

Two successful beam tests of the ToASt AISC were performed at COSY (see also Task 2: Demonstrator) and showed excellent performance. Preliminary results were presented at several conferences (G. Mazza, TREDI workshop on Advanced Silicon Radiation Detectors, Torino, Italy, February 2024; G. Mazza, Pisa Meeting on Advanced Detectors, May 2024, La Biodola, Italy).

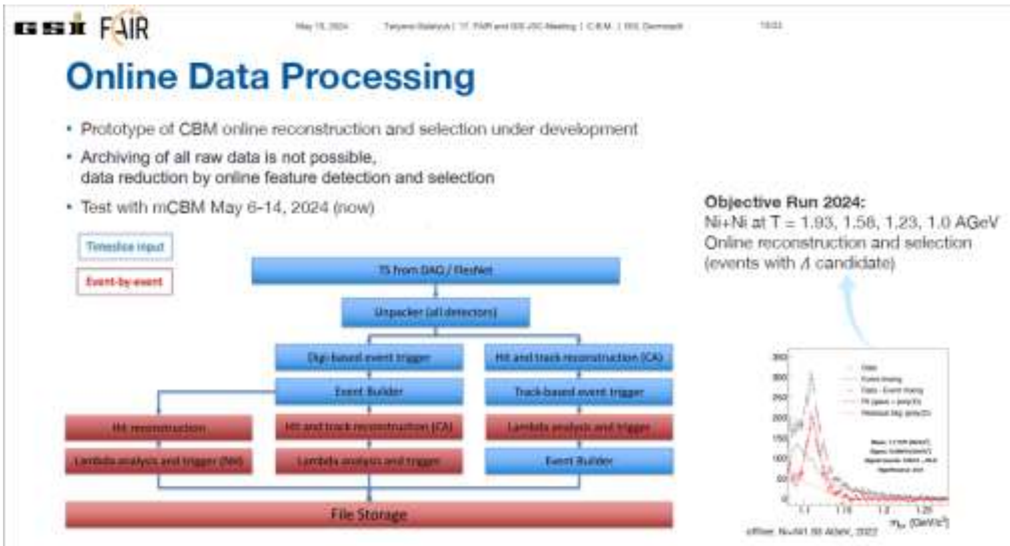
The CBM mCBM setup was upgraded for the runs in 2024/25 with detector hardware and Frontend Electronics but in particular, with an improved STS, TRD and TOF hit reconstruction for the CA track reconstruction, which is essential for the online selection of events with a Λ candidate.



The CBM CA track reconstruction could be improved and is the input for the CBM KFParticle package, which identifies Λ candidates. The reconstruction of Λs could be nicely demonstrated offline with the 2022 Ni+Ni data.



Based on the results of the work package, the prototype of CBM online reconstruction and selection is under further development. Everything is under well preparation to reach the objective for the upcoming runs, the successful online reconstruction of events with a Λ candidate.



Deliverables due in RP3.

D12.1 Report on detector tests, FEE, DAQ and data analysis; user manuals on FEE and DAQ software - Achieved

The document of deliverable D12.1 consists of the following publications, reports and user manuals:

1. G. Mazza, “ToASt v1 User’s Guide”, 2024.
2. Francesca Lenta et al., “Characterization of the radiation tolerant ToASt ASIC for the readout of the PANDA MVD strip detector”, 2024, JINST 19 C04047.
3. P.Marcinieweski, T. Johansson, “PANDA Forward EMC Sampling ADC”, Uppsala University, 2023.
4. M. Preston a, S. Bukreeva b, S. Diehl, P. Marciniewski, R.W. Novotny, S. Ryzhikov, P.A. Semenov P.-E. Tegnér on behalf of the PANDA Collaboration, “A feature-extraction and pile-up reconstruction algorithm for the forward-spectrometer EMC of the PANDA experiment”, Nuclear Inst. and Methods in Physics Research, A 1011 (2021) 165601.
5. Radim Dvořák and Lukáš Chlad for the CBM collaboration, “Performance studies for the mCBM experiment campaigns in 2022”, PoS(FAIRness2022)013.
6. V. Sidorenko et al, “Time error accumulation in a hierarchical time and clock distribution network with deterministic optical links”, 2024 JINST 19 C03014.
7. V. Sidorenko et al, “Evaluation of GBT-FPGA for timing and fast control in CBM experiment”, 2023 JINST 18 C02052.
8. V. Sidorenko et al, “Prototype design of a timing and fast control system in the CBM experiment” 2022 JINST 17 C05008.
9. CBM Progress Report 2023, Contributions on DAQ/FLES and Computing.
10. G. Barucca et al,”Feasibility studies for the measurement of time-like proton electromagnetic form factors from $\bar{p}p \rightarrow \mu^+\mu^-$ at PANDA at FAIR”, Eur. Phys. J. A (2021) 57:30.
11. G. Barucca et al (PANDA collaboration), “PANDA Phase One”, Eur. Phys. J. A (2021) 57:184.

12. G. Barucca et al, “Study of excited Ξ baryons with the PANDA detector”, Eur. Phys. J. A (2021) 57:149.

D12.2 Repository of software components - Achieved

The repository, accessible via the web site https://strong-2020.ep1.rub.de/category/repository/ contains a collection of software developed in the framework of the experiments at FAIR/GSI, especially CBM and PANDA. The following software package are available not only for experiments at FAIR/GSI, but also provide valuable algorithms for future hadron physics experiments and beyond.

FAIRroot: The FairRoot framework is an object oriented simulation, reconstruction and data analysis framework. It includes core services for detector simulation and offline analysis of particle physics data. FairRoot is the standard simulation, reconstruction and data analysis framework for the FAIR experiments at GSI Darmstadt. The framework enables the users to design and/or construct their detectors and /or analysis tasks in a simple way, it also delivers some general functionality like track visualization. The basic idea of FairRoot is to provide a unified package with generic mechanisms to deal with most commonly used tasks in HEP. FairRoot allow the physicist to:

- Focus on physics deliverables while reusing pre-tested software components.
- Do not submerge into low-level details, use pre-built and well-tested code for common tasks.
- Allows physicists to concentrate on detector performance details, avoiding purely software engineering issues like storage, retrieval, code organization etc.

CbmRoot: CbmRoot is the software package for simulation, reconstruction, and data analysis for the CBM experiment.

PandaRoot: PandaRoot is the software package for simulation, reconstruction, and data analysis for the PANDA experiment.

TRB3: The TRB-family contains a versatile FPGA-platform, TDC-in-FPGA technology with 10ps precision, front-end electronics and a complete set of data acquisition and control software.

PAWIAN PArtial Wave Interactive Analysis: PAWIAN is a powerful, user-friendly and highly modular partial wave analysis software package with the aim to support analyses for a multitude of different physics cases at hadron physics experiments. Real data originating from the pbar p annihilation process and from e+ e- reactions are currently under investigation with PAWIAN. It is possible to define complicated decay trees, to choose different spin formalisms and resonance dynamics as well as to set up numerous other parameters via a simple plain text configuration file without modifying and compiling any code.

Parameters that can be set in the configuration file include, among many more:

- The amplitudes can be described with different formalisms.
- The widely used helicity, canonical and the Lorentz-invariant Rarita-Schwinger formalisms are supported so far
- A couple of different descriptions for the dynamics of resonances can be chosen, e.g. the Breit-Wigner parametrization with or without barrier factors, the Flatté-formalism and the K-matrix formalism

- The minimization is realized with an event-based maximum likelihood fit. It makes use of the MINUIT2 minimization package. In addition, one can start with a pre-fitter based on a genetic algorithm
- To improve the performance for the very time-consuming fit procedure the applications can be run in parallel on multi-core CPUs (multi-threading) and/or on computer clusters (networking)
- Coupled channel analyses are supported
- The analyst can generate events based on the user-defined decay model or on the fit result obtained with real data
- Tools for quality assurance, histogramming and for extracting values of different goodness-of-fit criteria are also available.

PAWIAN is written in C++ and follows an object-oriented approach with a wide range of flexibility. The code therefore allows to be easily extended for further decay models, complete amplitudes and also other descriptions for the dynamics.

Milestones due in RP3.

No milestones due in the RP3

1.2.4 Work Package 13

Activity Type	Networking activity
Work package title	Small-x Physics at the LHC and future DIS experiments (NA2-Small-x)
Lead beneficiaries	1 – CNRS, 20 – USC, 23 – JYU, 37 - IFJ PAN

Project objectives

The objective of this WP is the strengthening the communication and collaboration between the European groups involved in theoretical and phenomenological studies in small-x physics. Understanding the dynamics of the strong interaction at high energies is one of the central topics in nuclear and particle physics. A genuinely new, non-linear regime of QCD is expected to occur at high energies. Here, the Color Glass Condensate (CGC) effective theory provides a controlled weak coupling description applicable in spite of the non-perturbatively large gluonic field strengths. Hints of the breaking of fixed-order perturbation theory have been found at HERA and RHIC, but only data from the LHC and future DIS experiments can unambiguously establish the existence of the non-linear regime. The behavior of gluons carrying only a small fraction x of the proton and nuclear momentum determines the bulk of particle production in relativistic heavy ion collisions. These gluons provide the initial conditions for the subsequent evolution towards a quark-gluon plasma in nuclear collisions at the LHC. A good control of these initial conditions is paramount for understanding the emergence of collectivity at the macroscopic level from the microscopic QCD dynamics.

Progress made during the reporting period towards objectives

Task 1: Nuclear PDFs. The determination of parton densities inside nuclei and the searches for collinear factorization breaking effects at small x, both by refining the methods for PDF extraction and by using new data sets from the LHC and RHIC will be improved

During the reporting period, the activities on this task can be divided into three directions. First, we have developed a new way to implement QCD evolution directly on physical observables and not on PDFs, as developed in the paper Eur. Phys. J. C 84 (2024) 1, 84.
Second, studies of the future impact of EIC data on the determination of proton and nuclear PDFs, were developed in Phys. Rev. D 109 (2024) 5, 5.
Third, studies of the possibilities and uncertainties for constraining nuclear parton densities in ultraperipheral collisions at the LHC, were developed in Eur. Phys. J. C 83 (2023) 8, 758.

Many of these developments are summarized in the review *Nuclear PDFs After the First Decade of LHC Data*, e-Print: 2311.00450 [hep-ph], M. Klasen, H. Paukkunen (JYV), to appear in Ann. Rev. Nucl. Part. Sci.

Task 2: New NLO-based precision phenomenology in CGC and BFKL.

Concerning technical aspects in the CGC and BFKL, several lines have been pursued:

- On the CGC side, there have been works on the interpretation of improvements on evolution (feasibility of a Langevin implementation at NLO in JHEP 03 (2024), 131; impact parameter dependence in Phys. Lett. B 848 (2024) 138360), NLO implementation of forward particle production (Phys. Rev. D 109 (2024) 3, 034018), several works on NLO calculations for diffraction, either inclusive (JHEP 05 (2024) 024; Phys. Rev. D 108 (2023) 11, 114023) or exclusive (e-Print: 2311.09146 [hep-ph]; JHEP 02 (2024) 165; Eur. Phys. J. C 83 (2023) 11, 1078), and on the implementation of non-eikonal corrections (JHEP 07 (2024) 137).
- On the BFKL side, theory computations at higher order for evolution (JHEP 04 (2024) 078; JHEP 04 (2023) 137) and impact factors (JHEP 01 (2024) 106).

On a more phenomenological side, several studies on the possibility to disentangle saturation in exclusive vector meson production in ultraperipheral collisions (Phys. Rev. D 109 (2024) 7, L071504; Phys. Lett. B 852 (2024) 138613) and dijet production in pA collisions (Eur. Phys. J. C 83 (2023) 10, 947), as well as extractions of initial conditions for non-linear evolution (Phys. Rev. D 109 (2024) 5, 054018) and its influence on the extraction of parton densities (Phys. Rev. D 109 (2024) 9, 094004).

Finally, there has been several theoretical studies relevant for future facilities concerning diffraction at the EIC (e-Print: 2406.02227 [hep-ph], to appear in Phys. Rev. D), production of exotic hadrons in high energy factorization (2405.14773 [hep-ph]; Phys. Lett. B 848 (2024) 138406) and new evolution equations including the electro-weak sector at ultrahigh energies (e-Print: 2403.08583 [hep-ph]).

Task 3: TMDs at small x

On this task, and related with activities in JRA4 and JRA5, there has been work on the relation between TMD and small x evolutions and the possibility of obtaining a consistent TMD-factorized form for the cross sections at small x (e-Print: 2406.04238 [hep-ph]; e-Print: 2406.08277 [hep-ph]).

Furthermore, and as a new deliverable, TMD factorization has been established for diffractive dijet production in photoproduction on nuclei at next-to-leading order: *TMD factorisation for diffractive jets in photon-nucleus interactions,* JHEP 06 (2024) 180, S. Hauksson, E. Iancu (CEA), A. H. Mueller, D. N. Triantafyllopoulos (ECT*), S. Y. Wei.

Task 4: Multi-particle correlations & Thermalization

Concerning this task, there has been activities on three directions: First, initial state explanations of long range two-particle correlations in hadronic collisions, i.e., the ridge, in the CGC (JHEP 10 (2023) 159; Universe 10 (2024) 2, 58; arXiv:2405.12062 [hep-ph]).

Second, entanglement and entropy in the hadronic wave functions and the influence of small-x evolution (e-Print: 2310.18510 [hep-ph]; Phys. Rev. D 109 (2024) 5, 054015).

Finally, studies of the onset of thermalization or isotropization in the early stages of hadronic collisions using transport equations or Glasma simulations, with several different aspects:

- Theoretical aspects like the existence of attractors (Phys. Lett. B 852 (2024) 138623) and the form of the energy momentum tensor (Eur. Phys. J. C 84 (2024) 4, 36).
- Studies of momentum broadening of light and heavy partons in the initial stages (Phys. Rev. D 110 (2024) 3, 034019; Phys. Rev. D 109 (2024) 1, 014025; Phys. Lett. B 850 (2024) 138525).
- Studies of the influence of quarks in the equilibration process (JHEP 06 (2024) 145).

Highlights of significant results

The highlight concerning Task 1 for this reporting period is the development of a framework to make the QCD evolution incarnated in the DGLAP equations, directly for physical quantities like structure functions in DIS, and not on quantities like parton densities which are dependent on the choice of scheme separation between short and long distance pieces in the physical observables, and on the renormalization scheme. This work, reflected in the publication *Evolution of structure functions in momentum space,* Eur. Phys. J. C 84 (2024) 1, 84, T. Lappi, H. Mäntysaari, H. Paukkunen, M. Tevio (JYV), allows the elimination of ambiguities in evolution, while yielding the same result as the traditional approach checked up to next-to-leading order.

The highlight of Task 2 is the complete calculation of diffractive structure functions and cross sections in DIS at next-to-leading order, including both real and virtual corrections. The calculation, made in the framework of the CGC and the dipole model, and contained in the publication *Diffractive deep inelastic scattering at NLO in the dipole picture*, JHEP 05 (2024) 024, G. Beuf, T. Lappi, H. Mäntysaari, R. Paatelainen, J. Penttala (JYV), is a step forward in precision for the comparison of experimental data from HERA and the future EIC or eventual new DIS colliders, with QCD predictions implementing high-energy evolution and saturation. It required the development of several techniques to deal with the existing singularities, techniques that will become of wider use.

Concerning Task 3, the highlight of the period is establising TMD factorization at next-to-leading order in dijet photoproduction off nuclei, as shown in publication *TMD factorisation for diffractive jets in photon-nucleus interactions*, JHEP 06 (2024) 180, S. Hauksson, E. Iancu

(CEA), A. H. Mueller, D. N. Triantafyllopoulos (ECT*), S. Y. Wei. Establishing such factorisation is one of the expected deliverables (D13.3) of WP13 and complements in a different system the efforts in inclusive DIS to clarify the different divergences and the corresponding evolutions, finding a strong interplay between small-x and standard TMD evolution, see the corresponding publications above.

Finally, the highlight for Task 4 is the study on entanglement, decoherence and evolution of entropy in the BFKL framework, reflected in publication *Von Neumann entropy and Lindblad decoherence in the high energy limit of strong interactions*, Phys. Rev. D 109 (2024) 5, 054015, G. Chachamis, M. Hentschinski, A. Sabio Vera (UAM-LIP). In this work a rigorous approach to evolution in the BFKL setup was adopted, which demanded a regulation in the infrared. It complements more phenomenological studies and offers a link with the physics of open quantum systems through the Lindblad equation.

Deliverables due in RP3.

D13.1 NPDFs – Achieved

Deliverable 13.1 is a new set of nuclear parton densities, EPPS21, which, for the first time, includes in the fit data from pPb collisions at the LHC Run 2 and considers the uncertainties in the proton baseline. The set is made publicly available in the web page https://research.hip.fi/qcdtheory/nuclear-pdfs/, and also in the LHAPDF tool (the standard in high-energy physics). This set constitutes a new benchmark to which all other sets are compared, and the description of the work was contained in publication *Nuclear PDFs with new LHC Run 2 data plus proton baseline uncertainties*, Eur. Phys. J. C 82 (2022) 5, 413, K. J. Eskola, P. Paakkinen, H. Paukkunen, C. A. Salgado (JYV-USC); it has already achieved 114 citations in the INSPIRE database.

D13.3 TMD factorization – Achieved

Deliverable 13.3 is the derivation of TMD factorization at next-to-leading order in dijet photoproduction of nuclei, as shown in publication *TMD factorisation for diffractive jets in photon-nucleus interactions*, JHEP 06 (2024) 180, S. Hauksson, E. Iancu (CEA), A. H. Mueller, D. N. Triantafyllopoulos (ECT*), S. Y. Wei. Establishing such factorisation complements in a different system the efforts in inclusive DIS to clarify the different divergencies and the corresponding evolutions, finding a strong interplay between small-x and standard TMD evolution. By itself it is a most important result and means the culmination of many works at next-to-leading order of the same group and others within WP13, like JHEP 10 (2022) 184, e-Print: 2406.08277 [hep-ph], Phys. Rev. Lett. 128 (2022) 20, 202001, JHEP 10 (2022) 103, Eur. Phys. J. C 83 (2023) 11, 1078 and e-Print: 2406.04238 [hep-ph], and multitude of previous works not including next-to-leading virtual corrections.

Milestones due in RP3.

No Milestones in the RP3.

1.2.5 Work Package 14

Activity Type	Networking activity
Work package title	Quark-Gluon Plasma characterization with jets (NA3-Jet-QGP)
Lead beneficiaries	34 – Nikhef, 39 - LIP

Project objectives

The aim of this Work Package is to establish a theory/phenomenology/inter-experiment working group, with synergies with related communities (most notably, machine learning/data science and high-energy pp physics) to develop and deploy novel experimental and theoretical techniques and tools for jet physics in heavy ion collisions and enhance the impact of the European groups in the worldwide heavy-ion jet programme.

The modification of QCD jets in the medium is the prime tool for the clarification of the microscopic structure and degrees of freedom of the QGP. Jets developing within the QGP probe its structure and dynamics at specific identifiable spatio-temporal and momentum scales.

Progress made during the reporting period towards objectives

Task 1: Reference implementation of jet-QGP dynamics in a full heavy-ion simulation. The participating theoretical groups have developed independent approaches that describe the various aspects of the relevant physics, using different starting points or approximations. To enable a productive discussion and compare the different approaches the working group will define and implement a common benchmark model of jet-QGP dynamics from which reference data-samples will be generated
This task was completed in the previous reporting period. The JEWEL event generator was selected as the reference model.
Task 2: Identification of jet substructure observables sensitive to specific scales/features of jet-QGP interaction
A broad set of 31 jet shape observables has been benchmarked using machine-learning methods. The results of the study have been published in *SciPost Phys.* 16 (2024) 1, 015. It was found that the full set of 31 observables consists of two or three main classes of observables and the most of the relevant information about jets can captured by selecting one observable from each class. While the first angularity moment rz_{SD} and the groomed 2-subjettiness are found to be most sensitive to quenching effects, a few other observables, like the groomed number of constituents, higher angular moments and subjettiness measures, and the largest k_{T} in softdrop declustering, have similar sensitivity.

Highlights of significant results

Besides the results listed above, two other main results should be noted:

1. Energy-energy correlators are a set of novel jet observable that are particularly amenable to theoretical calculations and have recently raised a large interest in the community.

We developed a calculation method to decrease the computation time needed for the evaluation of higher-order energy-energy correlators. A manuscript describing the method is available as a preprint (arXiv:2406.08577) and has been submitted for publication.

2. A discussion session at a recent workshop at the European Center for Nuclear Physics Theory (ECT*) was dedicated to jet observables as part of the NA3 activities. A white paper summarizing the discussion and future directions has been released as a preprint: arXiv:2409.03017.

Deliverables due in RP3.

D14.3 Report on the survey of observables – Achieved

The report on the survey of observables was published in SciPost Phys. 16 (2024) 1, 015 (doi: 10.21468/SciPostPhys.16.1.015) in open access.

We reproduce here the abstract for context:

"We present a survey of a comprehensive set of jet substructure observables commonly used to study the modifications of jets resulting from interactions with the Quark Gluon Plasma in Heavy Ion Collisions. The JEWEL event generator is used to produce simulated samples of quenched and unquenched jets. Three distinct analyses using Machine Learning techniques on the jet substructure observables have been performed to identify both linear and non-linear relations between the observables, and to distinguish the Quenched and Unquenched jet samples. We find that most of the observables are highly correlated, and that their information content can be captured by a small set of observables. We also find that the correlations between observables are resilient to quenching effects and that specific pairs of observables exhaust the full sensitivity to quenching effects. The code, the datasets, and instructions on how to reproduce this work are also provided."

D14.4 Analysis algorithms for selected observables – Achieved

The full analysis algorithms supporting the work summarized in SciPost Phys. 16 (2024) 1, 015 (doi: 10.21468/SciPostPhys.16.1.015), together with a full "User manual", were released publicly, under the terms of the MIT license, on the GitLab platform:

https://gitlab.com/lip_ml/jet-substructure-observables-ml-analysis

This software can be freely modified by users as to be extended to cases not covered in the publication.

Milestones due in RP3.

MS16 Delivery of D14.3 – Achieved

1.2.6 Work Package 15

Activity Type	Networking activity
Work package title	Proton Radius European Network (NA4-PREN)
Lead beneficiaries	1 - CNRS, 9 - JGU MAINZ

Project objectives

This network represents a reinforced worldwide effort, both experimental and theoretical to shed light on the so-called "proton radius puzzle". It combines atomic spectroscopy and lepton scattering, each involving both electrons and muons. The international effort on this matter concerns several leading groups in Europe. The PREN network constitutes the critically missing forum between atomic spectroscopy and lepton scattering communities. It will provide the ideal framework to develop synergies, to draw common strategies and to enhance constructive collaborative theoretical and experimental research activities in order to converge together in attempting to understand the proton charge radius puzzle.

Progress made during the reporting period towards objectives

Task 1.1: PREN-Collaboration: Enhance collaboration between groups working in similar fields ("competing" groups), by funding exchanges of scientists, e.g. for participation in beam times / measurements, or joint analyses or publications. To allow outstanding Postdoctoral fellows and PhD students to spend several months at a "competing" group. The aim is to migrate knowledge between different groups and provide new input to established procedures in these groups
- 17/09 - 06/10/2024: active contribution from D. Marchand and E. Voutier (IJCLab, France) to a 2 weeks data taking campaign of ULQ2 (UltraLow Q2) experiment at Tohoku University/ELPH (Sendaï, Japan). The ULQ2 experiment aims to determine the proton and the deuteron charge radius from measurements at very low Q2 ([3x10-5 ; 0.013] (GeV/c)2) relying on relative cross section measurements (elastic electron proton / electron Carbon scattering). Apart from daily 8 hour shifts, D. Marchand and E. Voutier have taken part to analysis meetings. This close collaboration took its origin within the Proton Radius European Network.
Task 1.2: PREN-Study: help fund extra studies (experimental and theoretical), e.g. for supporting systematics studies of experiments or comprehensive theory studies, e.g. in two-photon physics
At Mainz, an experiment has been set up to measure the 1S-2S transition in atomic H, D and T in a gas cell. We are currently looking for a spectroscopy signal using optigalvanic spectroscopy. In Garching, we are in the advanced stages of the analsis for several new transitions in atomic H and D. Deuterium, in particular, will yeld an independent check of the Rydberg constant and the nuclear polarizability contributions.

The most recent proton radius value comes from MPQ Garching team [5], and was published at the end of 2020. The 2-photon UV direct frequency comb spectroscopy was measured on the 1S-3S transition in atomic hydrogen. Combining with the 1S-2S transition previously measured, they obtained a proton radius value, which is in better agreement with the muonic hydrogen values and more precise compared to the same transition investigated by the LKB group.

The recent publication of results from muonic helium-4 ions [3] demonstrates excellent agreement with the scattering results on helium-4, ruling out most of the remaining Beyond the Standard Model solutions entertained for the solution of the proton radius puzzle. PREN funds were used for inviting researchers from Amsterdam to Mainz for the final analysis of these muonic helium results.

The understanding of the physics puzzle has been evolving in several directions over the past years. One of it implies the comparison between electron and positron elastic scattering off a proton to investigate the still opened question of Two Photon Exchange. Following the precision success of the PRad experiment at Jefferson Lab, the collaboration is planning such measurements with the future CEBAF positron beam [4] as soon as available. The development of this beam is part of the STRONG-2020 scientific acitivity, for which the IJCLab team is currently designing a high-power positron production target.

Task 2.1: PREN-Conventions: a kick-off meeting to identify the most pressing questions. Two more workshops will be organized where all PREN groups will present results. Detailed discussions and targeted sessions will scrutinize the results in great detail, and provide guidance for more in-depth studies

- PREN2022 Convention: International STRONG-2020 workshop on the proton charge radius and related topics, 20 – 23/06/2022, Paris, France.

- PREN2023 + µASTI (Muonic Atom Spectroscopy Theory Initiative), 26 - 30/06/2023, Mainz, Germany.

- NREC (Nuclear Radius Extraction Collaboration) Kick-off meeting, 6 – 10/05/2024, Stony Brook, USA. This new collaboration was created to extend the STRONG-2020 Proton Radius European Network.

Task 2.2: PREN-Meetings: organization of working meetings or targeted workshops dedicated to specific sub-topics relevant for the proton radius puzzle

PREN-related researchers have taken part in several virtual meetings over the second reporting period. Within the framework of STRONG-2020 outreach and dissemination activities, PREN members, J.C. Bernauer and R. Pohl, gave the first public lecture (December 16, 2020), https://www.youtube.com/watch?v=C5B_ZfGy4d0

Another online talk on the same topic was presented on April 4, 20222 by J.C. Bernauer and R. Pohl within the Internationtional School on modern Physics and Research (INSPYRE) organized at INFN Frascati. It aims at students around the world.

http://edu.lnf.infn.it/inspyre-2022/

Highlights of significant results

- "Determination of the moments of the proton charge density", M. Atoui, M.B. Barbaro, M. Hoballah, C. Keyrouz, M. Lassaut, D. Marchand, G. Quéméner, E. Voutier, *Phys.Rev.C*, 2024, 110 (1), pp.01520.
⟨10.1103/PhysRevC.110.015207⟩. ⟨hal-04093642⟩ https://arxiv.org/pdf/2304.13521

- "Determination of the moments of the proton charge density: is there a proton radius puzzle?", M. Atoui, M.B. Barbaro, M. Hoballah, C. Keyrouz, R. Kunne, M. Lassaut, D. Marchand, G. Quéméner, E. Voutier, J. van de Wiele, NUCLEAR THEORY, Vol. 40 (2023), eds. M. Gaidarov, N. Minkov, Heron Press, Sofia. Proceedings of the 40th International Workshop on Nuclear Theory (IWNT), Rila Mountains, July 2023.

Deliverables due in RP3.

D15.2 PREN-WP - Achieved

We took advantage of the COVID acute period (2020) to write a report entitled "The proton size" (Jean-Philippe Karr, Dominique Marchand, Eric Voutier. Nature Rev. Phys., 2020, 2 (11), pp.601-614. DOI: 10.1038/s42254-020-0229-x, hal-03011020, acting as the PREN White paper deliverable (D15.2)

Abstract:

The proton charge radius has been measured since the 1950s using elastic electron–proton scattering and ordinary hydrogen atomic spectroscopy. In 2010, a highly accurate measurement of the proton charge radius using, for the first time, muonic hydrogen spectroscopy unexpectedly led to controversy, as the value disagreed with the previously accepted one. Since then, atomic and nuclear physicists have been trying to understand this discrepancy by checking theories, questioning experimental methods and performing new experiments. Recently, two measurements from electron scattering and ordinary hydrogen spectroscopy were found to agree with results from muonic atom spectroscopy. Is the protonradius puzzle' now resolved? In this Review, we scrutinize the experimental studies of the proton radius to gain insight on this issue. We provide a brief history of the proton before describing the techniques used to measure its radius and the current status of the field. We assess the precision and reliability of available experimental data, with particular focus on the most recent results. Finally, we discuss the forthcoming new generation of refined experiments and theoretical calculations that aim to definitely end the debate on the proton.

Milestones due in RP3.

MS18 Conventions - Achieved

- PREN2022 Convention: International STRONG-2020 workshop on the proton charge radius and related topics, 20 – 23/06/2022, Paris, France.

MS19 Meetings - Achieved

PREN2023 + µASTI (Muonic Atom Spectroscopy Theory Initiative), 26 - 30/06/2023, Mainz, Germany.

1.2.7 Work Package 16

Activity Type	Networking activity
Work package title	Strange Hadrons and the Equation-of-State of Compact Stars (NA5-THEIA)
Lead beneficiary	9 - JGU MAINZ

Project objectives

In a neutron star, the occurrence of hyperons emerges rather naturally at nuclear densities larger than about two times the nuclear density. The difficult reconciliation of the recent observations of neutron stars having about twice the solar mass with the presence of hyperons is referred to as the “hyperon puzzle”.

The cooperation of world-leading experimentalists and theoreticians in the field of strangeness nuclear physics with experts of the neutron star community is the aim of the networking activity THEIA, which will allow to critically assess the status of our present understanding and to determine the impact of terrestrial observations on the hadronic Equation of State (EOS).

Progress made during the reporting period towards objectives

Task 1: A=3 hypernuclei: The hypertriton puzzle and its implication for fragment formation in heavy ion reactions. Does a neutral A=3 hypernucleus exist?
The two experimentally established lightest hypernuclei ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ are important cornerstones in the field of strangeness nuclear physics. On one hand, the production of these nuclei in relativistic heavy ion collisions allows new insight in the production mechanism of complex clusters. On the other hand, the detailed structure of particularly the hypertriton is an important benchmark for our understanding of the strong hyperon-nucleon and multibaryon interaction with strange baryons (hypertriton puzzle). It thus can impact our understanding of more complicated systems involving hyperons, such as the interior of neutron stars. The existence or non-existence of a neutral A=3 hypernucleus nnΛ is another open issue. During the last 2 years, new data on the hypertriton became available from ALICE and STAR. A new precision experiment was successfully performed at MAMI. Also, the theoretical understanding of these systems continuously improves. Indeed, in the coming years, several experiments are planned, which will produce even more precise and accurate lifetime and binding energy data. These data are expected to serve as benchmarks for any hypernuclear structure calculation. A few highlights are summarized in the following:

Hypertriton puzzle: binding energy vs. Lifetime (experimental results):

In a three body system, when any pair of particles is close together, the third particle is, on the average, relatively far away from them. Therefore, a small total Λ binding energy of the hypertriton $^{3}_{\Lambda}H$ implies that the Λ-hyperon has an extended wave function with respect to the deuteron core with a typical size of about 10fm. As a consequence of the extremeΛ-halo, the Λ particle in $^{3}_{\Lambda}H$ should have properties similar to the free Λ. In fact, all available calculations of the hypertriton lifeti predict values, which deviate no more than about 10% from the free Λ decay. Indeed, bubble chamber and emulsion data from the 60s and 70s were – albeit with large uncertainties - consistent with these expectations. However, the first series of heavy ion collision experiments before 2019 at STAR@RHIC, HypHI@GSI and ALICE@LHC b found consistent with each other a lifetime, which is about 30-40% shorter than the free Λ-hyperon, which was significantly below all present theoretical expectations. The combination of its unexpected short lifetime and its small Λ binding energy was one of the most intriguing puzzles in hypernuclear physics when STRONG2020 started and was referred to as the *hypertriton puzzle*. Indeed, this puzzle was in the center of many experimental and theoretical activities of THEIA.

Concerning the hypertriton production in heavy ion reactions, the ALICE collaboration at CERN presented new data https://doi.org/10.1103/PhysRevLett.128.202301 on the production of $^{3}_{\Lambda}H$ in Pb–Pb collisions at $\sqrt{s}$= 5.02 TeV. They found for in this new lifetime measurement a value of 253 ± 11 (stat.) ± 6 (syst.) ps which is still compatible with the latest lifetime measurement of STAR of 221±15(stat.)±19(syst.) ps. However, the deduced binding energy of 0.102 ± 0.063 (stat.) ± 0.067 (syst.) MeV found by ALICE are in tension with the STAR data from 2020, which was remarkably high 0.406 ± 0.120 (stat.) ± 0.110 (syst.) MeV https://www.nature.com/articles/s41567-020-0799-7. It is, however, interesting, that the latest (still preliminary) analysis of d-Λ correlation functions by STAR in 3GeV Au+Au collisions suggest a low hypertriton binding energy of 0.185 ± 0.145 MeV (95%CL), corresponding to 0.185 ± 0.075 MeV https://doi.org/10.48550/arXiv.2401.00319. [Frankfurt]

At the Mainz Mikrotron (MAMI), a new high precision and accuracy pion spectroscopy experiment aims at a measurement with a systematic uncertainty which is comparable to the statistical error of ≤ 20 keV https://pos.sissa.it/380/201/. The high accuracy will be made possible by measuring the absolute value of the beam energy with a novel undulator light interference method. The method is based on the analysis of the intensity oscillation length in the synchrotron spectrum from two collinear sources, which are realized by two undulators and the electron beam of MAMI https://doi.org/10.1088/1742-6596/2482/1/012016. The time delay between the two wave packets can be controlled by changing the distance between the two undulators. This new decay-pion spectroscopy experiment was delayed because of the Covid pandemic and was performed in summer 2022. The detailed calibration of all three spectrometers of the A1 setup by the undulator technique was performed in spring 2024. The analysis is still ongoing. The present status of the analysis has been presented at the SPICE workshop of THEIA https://indico.ectstar.eu/event/203/. [Mainz]

Hypertriton puzzle: binding energy vs. Lifetime (theoretical results):

A comparison of light hypernuclei production, from UrQMD+coalescence and the thermal model, in heavy ion collisions over a wide range of beam energies and system sizes was performed in https://doi.org/10.1103/PhysRevC.107.014912. It was found that both approaches provide generally similar results, with differences in specific details. Especially the ratios of hypertriton to Λ are affected by both the source radius Δr of the coalescence procedure as well as canonical effects. On the other hand, the double ratio called S3 is almost independent of canonical effects, which is in contrast to coalescence. Thus, both the beam energy dependence and centrality dependence of S3 can be used to constrain the hypertriton source radius. The predictions further suggest that the existence of the H-dibaryon (ΛΛ) seems to be ruled out by ALICE data. [Frankfurt]

In https://doi.org/10.1103/PhysRevC.109.044913, the Ultra-relativistic Quantum Molecular Dynamics model is employed to simulate π^-+C and π^-+W collisions at p_{lab} =1.7 GeV motivated by the recent HADES results. By comparing the proton and Λ transverse momentum spectra, it was observed that the data and transport model calculation show a good agreement, if cluster formation is included to obtain the free proton spectra. Predictions of light cluster (d, t ^{3}He, ^{4}He, as well as $^3_\Lambda$H and ΞN) multiplicities and spectra are made using a coalescence mechanism. The resulting multiplicities suggest that the pion beam experiment can produce a substantial amount of $^3_\Lambda$H, especially in π^-+W collisions due to the stopping of the Λ inside the large tungsten nucleus. The findings are supplemented by a statistical multi-fragmentation analysis suggesting that even larger hyper-fragments are produced copiously. It is suggested that even double strange hypernuclei are in reach and might be studied in more detail using a slightly higher pion beam momentum. [Frankfurt]

In https://doi.org/10.1051/epjconf/202227101002, the hypertriton puzzle was revisited theoretically, using $^3_\Lambda$H and ^{3}He wave functions computed within the abinitio no-core shell model employing interactions derived from chiral effective field theory to calculate the two-body decay rate $\Gamma(^3_\Lambda\text{H}\to{}^3\text{He}+\pi-)$. Significant but opposing contributions arising from ΣNN admixtures in $^3_\Lambda$H and from $\pi-$–^{3}He final-state interaction were found. To derive $\tau(^3_\Lambda\text{H})$, the inclusive $\pi-$ decay rate $\Gamma_{\pi-}(^3_\Lambda\text{H})$ was evaluated by using the measured branching ratio $\Gamma(^3_\Lambda\text{H}\to{}^3\text{He}+\pi-)/\Gamma_{\pi-}(^3_\Lambda\text{H})$ and added the π^0 contributions through the ΔI=1/2 rule. The resulting $\tau(^3_\Lambda\text{H})$ varies strongly with the rather poorly known Λ separation energy $E_{sep}(^3_\Lambda\text{H})$ and it is thus possible to associate each one of the distinct heavy ion $\tau(^3_\Lambda\text{H})$ measurements with its own underlying value of $E_{sep}(^3_\Lambda\text{H})$.

In https://doi.org/10.1103/PhysRevC.109.024001, the same group noted the good agreement between the lifetime value $\tau(^3_\Lambda\text{H})$=238(27) ps computed at the lowest value B_Λ=66 keV reached by us and the very recent ALICE measured lifetime value $\tau_{ALICE}(^3_\Lambda\text{H})$=253(11)(6) ps associated with the ALICE measured B_Λ value B_{ALICE}=102(63)(67) keV. [Barcelona, Jerusalem, Prague]

A hyperon-nucleon potential for the strangeness S=−1 sector (ΛN, ΣN) up to third order in the chiral expansion is presented https://doi.org/10.1140/epja/s10050-023-00960-6. SU(3) flavor symmetry is imposed for constructing the interaction, however, the explicit SU(3) symmetry breaking by the physical masses of the pseudoscalar mesons and in the leading-order contact terms is taken into account. A novel regularization scheme is employed which has already been successfully used in studies of the nucleon-nucleon interaction within chiral effective field theory up to high orders. An excellent description of the low-energy Λp, Σ−p and Σ+p scattering data is achieved. New data from J-PARC on angular distributions for the

ΣN channels are analyzed. Results for the hypertriton and A=4 hyper-nuclear separation energies are presented. An uncertainty estimate for the chiral expansion is performed for selected hyperon-nucleon observables. [Bonn, Jülich]

Separation energies of light Λ hypernuclei ($A\leq5$) and their theoretical uncertainties are investigated in https://doi.org/10.48550/arXiv.2308.01756. Few-body calculations are performed within the Faddeev-Yakubovsky scheme and the no-core shell model. Thereby, modern and up-to-date *NN* and *YN* potentials derived within chiral effective field theory are employed. It is found that the numerical uncertainties of the few-body methods are well under control and an accuracy of around 1 keV for the hypertriton and of less than 20 keV for the separation energies of the $^{4}{}_{\Lambda}$He and $^{5}{}_{\Lambda}$He hypernuclei can be achieved. Variations caused by differences in the *NN* interaction are in the order of 10 keV for $^{3}{}_{\Lambda}$H and no more than 110 keV for A=4,5 Λ hypernuclei, when recent high-precision potentials up to fifth order in the chiral expansion are employed. The variations are smaller than expected contributions from chiral *YNN* three-body forces (3BFs) which arise at the chiral order of state-of-the-art *YN* potentials. Estimates for those 3BFs are deduced from a study of the truncation uncertainties in the chiral expansion. [Bonn, Jülich]

In https://doi.org/10.48550/arXiv.2309.12822, the contribution of pionic final state interactions (FSI) in the weak decay of the hypertriton is investigated. Focusing on the ^{3}He channel, we find a contribution of the pionic FSI of the order of 18%. Assuming a fixed value for the branching ratio $R3$ for the decay width into ^{3}He over the decay width into ^{3}He and *pd* final states, values were found for the hypertriton lifetime that are consistent with the world average as well as recent measurements by the ALICE Collaboration. [Darmstadt, FAIR, Jülich]

To summarize, several new data on the A=3 hypertriton were presented during the duration of the THEIA networking activity of STRONG2020. With the most recent heavy ion data, the best estimate of the lifetime has moved closer to the freeΛ lifetime. At the same time, our theoretical understanding of this system has significantly improved. Thus, the hypertriton puzzle has turned into a quantitative problem, calling for precision studies, on the experimental as well as on the theoretical side.

Does a neutral hypernucleus nnΛ exist?

The small binding energy of the hypertrition leads to predictions of the non-existence of bound hypernuclei for isotriplet three-body systems such as nnΛ. However, invariant mass spectroscopy at GSI has reported events that may be interpreted as the bound nnΛ state (Phys. Rev. C 88, 041001(R)). Theoretically, this nucleus is likely to be unbound, though no firm predictions of its stability can be made. Clearly, an experimental clarification is required. At J-Lab, the nnΛ state was sought by missing-mass spectroscopy via the (e,e′K+) reaction at Jefferson Lab's experimental Hall A. No significant structures were observed with the acceptance cuts, and only upper limits of the production cross-section of the nnΛ state were obtained (Prog. Theor. Exp. Phys. 2022, 013D01 (2022)). Following the tentative observation at GSI, the search for the nnΛ system in the ^{6}Li+^{12}C reaction was repeated with an improved setup at the GSI, making use of the fragment separator facility and the WASA detector. The experiment was successfully performed between March 9th and March 19th, 2022 (see MS20). The analysis has started. A first - still preliminary - status report on the experiment was delivered during the HYP22 conference in Prague in June 2022. During the 2024 THEIA meeting at ECT* the ongoing progress of the analysis was shown, but unfortunately no final results have been released by the WASA Collaboration as yet. [Gießen, GSI, Mainz and others]

Task 2: Study of antihyperons in nuclei at PHASE-1 of PANDA

The first measurement of the antihyperon potential in complex nuclei is part of the PANDA Phase-one program, which has been published in European Physics Journal A57, 44 (2021) https://doi.org/10.1140/epja/s10050-021-00475-y. During the Phase-1 of PANDA, we plan to study antiproton-^{20}Ne $\to\Lambda\Lambda$ interactions close to threshold. The development of the reconstruction software has been continued. Major effort was devoted to the reconstruction of very low-momentum decay products within the PANDA framework, which until now was only treated under so-called ideal conditions. We also study of the pA $\to$ ΛΛ +X and the pA $\to\Sigma^{-}$ Λ +X reactions. In nuclear targets, these reactions probe the proton and neutron distributions, respectively, and may allow to determine both the Σ^{-} potential but also the neutron variation of the skin thickness in different isotopes of e.g. Kr or Xe.

During this reporting period, extensive simulations with a modern transport model for the reaction p +^{20}Ne $\to\Lambda\Lambda$ were performed. Besides the reconstruction of the true ΛΛ pairs within the customized PANDA analysis framework, the efficient background suppression was a major task. Since a suppression by a factor 10^7 is required, in total about 4 billion inclusive events had to be generated for our study, making use of the High Power Computing Cluster HIMster located at the Helmholtz-Institute Mainz. By applying conventional successive cuts, the goal can already be reached. Modern machine learning methods (multilayer perceptron neural network or boosted decision tree method), lead to a further significant improvement of the signal to background ratio. A report on that work was submitted in February 2024 (see deliverable D16.2 and MS21). [Mainz]

Task 3: Theoretical and experimental studies of bound mesonic systems

SIDDHARTA-2 represents a state-of-the-art experiment designed to perform dedicated measurements of kaonic atoms, which are particular exotic atom configurations composed of a negatively charged kaon and a nucleus. Investigating these atoms provides an exceptional tool to comprehend the strong interactions in the non-perturbative regime involving strangeness.

The experiment is installed at the DAΦNE electron-positron collider, of the INFN National Laboratory of Frascati (INFN-LNF) in Italy. His prime goal is to perform the first-ever measurement of the 2p → 1s X-ray transitions in kaonic deuterium, a crucial step towards determining the isospin-dependent antikaon-nucleon scattering lengths. Based on the experience gained with the previous SIDDHARTA experiment, which performed the most precise measurement of the kaonic hydrogen 2p → 1s X-ray transitions, the present apparatus has been upgraded with innovative Silicon Drift Detectors (SDDs), distributed around a cryogenic gaseous target placed in a vacuum chamber at a short distance above the interaction region of the collider. A comprehensive description of the SIDDHARTA-2 setup including the optimization of its various components during the commissioning phase of the collider is presented in https://doi.org/10.48550/arXiv.2311.16144.

During summer 2021, the installation of the SIDDHARTA-2 apparatus has successfully been concluded during the commissioning phase of the DAFNE collider. Data taking was resumed in spring 2022 with a kaonic helium run https://doi.org/10.48550/arXiv.2310.20584 for optimization of final degrader. In 2023 and 2024, the SIDDHARTA-2 experiment was taking data for the measurement of kaonic deuterium, aiming to collect 800 pb^{-1} of data. The experiment will provide a kaonic deuterium measurement at the same level of precision as the kaonic hydrogen one. First, very preliminary results for K-d at SIDDHARTA-2 were presented by Francesco Sgaramella during the THEIA workshop SPICE at ECT* https://indico.ectstar.eu/event/203/. [Frascati, Krakow, Munich, Roma, Palermo, Vienna, Zagreb]

Task 4: What role can a mini antiproton-proton collider at FAIR play for strangeness nuclear physics?

Considering the present situation at FAIR and in Europe, an antiproton-protn collider can only be a long-term perspective. Concerning the physics addressed by THEIA, the low energy regime with $\sqrt{s}$ up to about 5 GeV is relevant. The physics program at such a collider is based on hyperon-antihyperon pair production, which may provide tagged low-momentum hyperons and antihyperons. Possible physics topics are:

- Hyperatom and antihyperatom production
- Low momentum scattering of hyperons or antihyperons in a secondary target.
- Production of doubly strange systems

The advantage of an antiproton-proton collider is the lower background and the controlled (anti)hyperon momenta, the major problem is the lower luminosity. Still insecure is a possible detection system for such low momentum particles.

Since the PANDA detector at FAIR is significantly delayed, it became clear that work on such future project cannot reach the necessary attention in the present situation. We hope that once a firm timescale for the realization of the antiproton storage ring at FAIR has been established, the possibility of such a collider at FAIR will gain new momentum. [Mainz, Frankfurt, Jülich]

Task 5: Annual workshops organized by THEIA will bring together scientists and students with complementary expertise

- The first THEIA workshop was held at Speyer, Germany, end of 2019, just before the corona crisis started. https://indico.gsi.de/event/8950/.
- The second workshop was planned to take place in October 2020 in Greece. Due to the Corona pandemic, this workshop had to be canceled. Also throughout 2021 and until spring of 2022 no meeting in person could be held. Instead, we organize two web-seminars with weekly talks:
- Joint THEIA-STRONG-2020 and JAEA/Mainz REIMEI Web-Seminar 2020/2021 October 2020 – May 2021; 46 talks https://indico.gsi.de/category/513/
- Joint THEIA-STRONG-2020 and JAEA/Mainz REIMEI Web-Seminar 2021/2022 October 2021 – March 2022; 18 talks https://indico.gsi.de/category/571/
- The HYP22 conference, which is the major periodic conference of our community, took place in hybrid from in Prague in June 2022, and was to a large extent supported by THEIA http ://rafael.ujf.cas.cz/hyp2022/

- Finally, THEIA organized a workshop in May 13-17, 2024 at ECT*
  SPICE – Strange hadrons as a Precision tool for strongly InteraCting systEms.
  https://indico.ectstar.eu/event/203/

These workshops turned out to be the most important and fruitful meetings for the scientific community of THEIA in the past years. Particularly the international web seminars during the corona crises were important to keep up the coherence of the community and to foster the continuous collaborations. In all these meetings, young scientists and students played a dominant role, giving on average more than 50% of the presentations

At the final workshop at ECT* in 2024 there was a unanimous consensus, that the community will try to continue with these annual meetings also beyond STRONG-2020. [All participating institutions]

Highlights of significant results

The lightest hypernucleus ${}^{3}_{\Lambda}$H

A profound understanding of the lightest hypernuclei is a cornerstone for any strong interaction theory dealing with strange baryons. Indeed, the hypertriton consisting of a proton, a neutron and a Λ hyperon, was addressed in several activities of THEIA:

- New data of ALICE and STAR were presented, suggesting a binding energy only slightly above the old emulsion data.
- A new and accurate measurements of the ${}^{3}_{\Lambda}$H binding energy was successfully performed at the Mainz Mikrotron (MAMI).
- Measured lifetimes of the hypertriton by ALICE indicate a lifetime closer to the free Λ lifetime.

Thus, the hypertriton puzzle as it existed at the start of THEIA 5 years ago, has turned into a quantitative problem, calling for precision studies, on the experimental as well as on the theoretical side. Members of the networking activity THEIA made substantial contributions to this progress.

Kaonic atoms

Among strange exotic atoms, the kaonic ones play a special role, since they permit linking the isospin-dependent scattering lengths to the kaon-nucleus potential below threshold. At the DAFNE collider at INFN-LNF, the SIDDHARTA-2 collaboration performed the first measurement of the kaonic deuterium transitions, which will help to separate the isoscalar and isovector parts of the antikaon-nucleon scattering length. Future measurements, along the whole periodic table, going from light to heavy exotic strange atoms will be possible by using a series of complementary radiation detector systems recently developed. The new database of kaonic atoms will thus become a bedrock for low-energy QCD

Thirdly, an important highlight was the final workshop organized by THEIA in May 13-17, 2024 at ECT* SPICE – Strange hadrons as a Precision tool for strongly InteraCting systEms. https://indico.ectstar.eu/event/203/

Deliverables due in RP3.

D16.2 Antihyperons in nuclei, PANDA sofware tools – Achieved

Antiproton-nucleon annihilations represent the most effective way to produce low momentu hyperons and antihyperons under controlled kinematic conditions, which is a prerequisite for the formation of bound hyperonic systems. Combined with large cross sections for the production of associated hyperon-antihyperon pairs, antiprotons circulating in a storage ring are ideally suited for exploring strange baryonic systems.

Antihyperons annihilate quickly in nuclei and conventional spectroscopic studies of bound systems are not feasible. Quantitative information about the antihyperon potentials may be obtained via exclusive antihyperon-hyperon pair production close to threshold in antiproton-nucleus interactions. In such reactions, the transverse momenta of the baryon and antibaryon should be opposite and equal at the point of their production inside the nucleus. Once these hyperons leave the nucleus and are detected, their asymptotic momentum distributions will reflect the depth of the respective potentials. A deep potential for one species could result in a momentum distribution of antihyperons, which differs from that of the coincident hyperon. The main task of the present project is the development of the $\Lambda\Lambda$ reconstruction software for the PANDA setup. This is a prerequisite to explore how the finite acceptance and resolution of the experimental PANDA apparatus affects the experimental observables. The second objective is development of the software tools, which allow the required suppression of background events.

The PANDA Collaboration is developing the PandaRoot framework based on Root as part of the FairRoot project. It is used both for the physics simulation and data analysis. Root is an object-oriented software framework developed at CERN since 1995 and is one of the premier software for particle physics analysis. Root is capable of handling large amounts of data and can be used either as compiled code or using interpreted C++ macros. The presented results used ROOT in version 6.22/08.

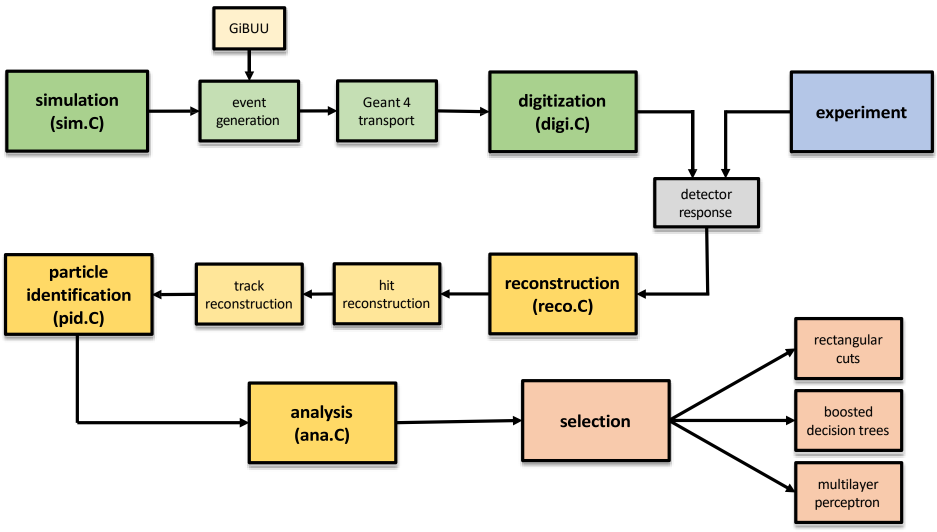


Fig. 1: Workflow of the PandaRoot simulation stages. In green: simulation of the Panda detector in operation. The output corresponds to the same data format that would be recorded in an experimental measurement (blue). In yellow, the analysis by PandaRoot, which is identical for both measurement and simulation.

PandaRoot is an extension of FairRoot, developed for the needs of the PANDA experiment. It is used both for the simulation of the complete pp annihilation inside the PANDA detector and the subsequent data analysis of both simulated and future experimental data. The software works in a modular way, where each detector subsystem has its own software routines, handling digitization, hit or cluster generation. The data from all subsystem is then combined in the analysis routines where the detector responses are used for track reconstruction and particle identification. A flow diagram of the event generation, reconstruction and analysis software is shown in Figure 1. Each PandaRoot simulation follows a chain of five stages in which the stage specific tasks are completed:

1. Simulation (green part): The simulation stage works in several steps. In the firs step physical events either for a signal channel or generic background are generated. For this purpose, PandaRoot usually has several event generators implemented. However, in this work none of the original generators are used, instead the event generation is done externally using GiBUU. A custom written generator then adds the GiBUU tracks into PandaRoot.
   The second step is the particle transport through the PANDA geometries and materials using the GEANT package. The GEANT toolkit is used for the simulation of particle propagation through matter. It can handle a large set of long-lived particles over a wide energy range from keV up to TeV and their interaction with matter in complex geometries taking into account a comprehensive range of physical processes.
   In the digitization stage, the Monte Carlo information from the simulation stage is used to reproduce the signals that can be measured at the detector in reality. The data stored in this way are in the same format as experimental data measured later at the PANDA detector.
2. Reconstruction (yellow part in Figure 1): In the reconstruction step, the particle tracks, with their positions and momentum, are determined from the physical detector data. Once the tracks have been reconstructed, the particle species that gave rise to the tracks have to be identified. To achieve this, the information from the particle identification detectors (PID) is correlated with the reconstructed tracks to form charged candidates.
3. Event reconstruction (red part in Figure 1): In the last step, the composite particles, in this case Λ or Λ which decayed during the simulation and whose daughter particles could be reconstructed, are calculated. PandaRoot contains all necessary tools for further analysis by supporting combinatorial calculations, mass selection and kinematic fitting.

In the present study, more than 4 billion events were generated with the high-performance computing cluster HIMster at the Helmholtz Institute Mainz.

The major task of this project was the background suppression to reach a high signal: background ratio. Besides conventional sequential cuts, we also applied machine-learning algorithms. Indeed, the so-called boosted decision tree method significantly improves the number of true events by more than 50% for the same signal to background ratio. It could be shown that after filtering the generated $\Lambda\Lambda$ pairs with the developed software, the sensitivity of e.g. the transverse momentum asymmetry to the antihyperon potential persists, thus proving the feasibility of the proposed measurement.

The analysis software has been uploaded to the PandaRoot software repository at FAIR and can be applied by other PANDA users.

A detailed review was uploaded; see MS21.

D16.3 Bound mesonic systems – Achieved

High precision light kaonic atoms X-ray spectroscopy is a unique tool for performing experiments equivalent to scattering at vanishing relative energies, to determine the antikaon–nucleus interaction at threshold without the need of extrapolation to zero energy. The SIDDHARTA-2 collaboration is going to perform the first measurement of kaonic deuterium transitions to the fundamental level, which is mandatory to extract the isospin dependent antikaon–nucleon scattering lengths.

In the previous period (up to M22) the SIDDHARTA-2 setup in its Phase 1 version was installed and in operation on the DAFNE collider. Since January 2021 to July 2021 the beam was used for:

- Measurement of machine luminosity with SIDDHARTA-2 luminometer
- Background optimization by use of shielding
- Kaonic helium measurements at 2 densities: 1.5% liquid and 0.75 % liquid densities which produces (papers in preparation) the most precise measurement of KHe transitions to 2p level in gas; see Fig. 2 for preliminary spectrum.

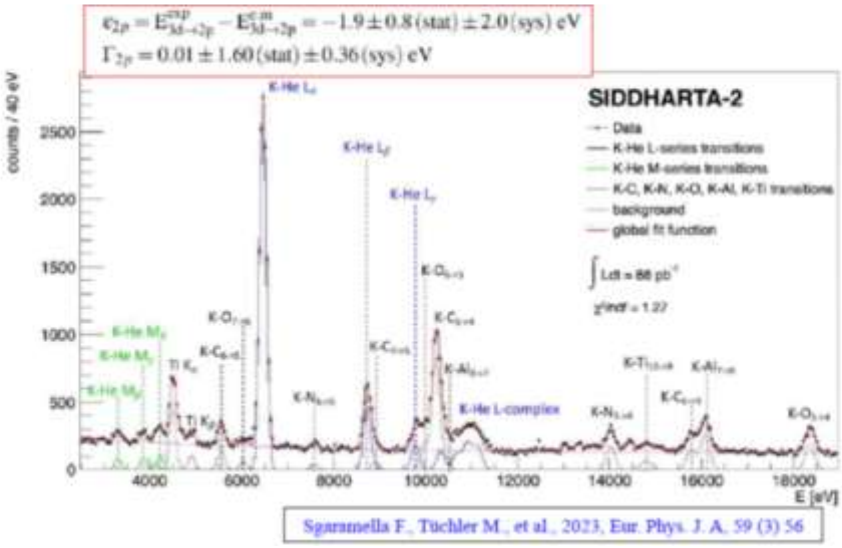


Fig 2: Kaonic Helium spectrum measured by SIDDHARTA-2 with a gaseous target.

The prime goal of SIDDHARTA-2 is to perform the first-ever measurement of the 2p → 1s X-ray transitions in kaonic deuterium, a crucial step towards determining the isospin-dependent antikaon-nucleon scattering lengths. Based on the experience gained with the previous SIDDHARTA experiment, which performed the most precise measurement of the kaonic hydrogen 2p → 1s X-ray transitions, the present apparatus has been upgraded with innovative Silicon Drift Detectors (SDDs), distributed around a cryogenic gaseous target placed in a vacuum chamber at a short distance above the interaction region of the collider. A comprehensive description of the SIDDHARTA-2 setup including the optimization of its various components during the commissioning phase of the collider is presented in https://doi.org/10.48550/arXiv.2311.16144.

During summer 2021, the installation of the SIDDHARTA-2 apparatus has successfully been concluded during the commissioning phase of the DAFNE collider. Data taking was resumed in spring 2022 with a kaonic helium run https://doi.org/10.48550/arXiv.2310.20584 for optimization of final degrader. In 2023 and 2024, the SIDDHARTA-2 experiment was taking data for the measurement of kaonic deuterium, aiming to collect 800 pb−1 of data. The experiment will provide a kaonic deuterium measurement at the same level of precision as the kaonic hydrogen one. First, very preliminary results for K-d at SIDDHARTA-2 were presented by Francesco Sgaramella (see Fig. 3) during the THEIA workshop SPICE at ECT* https://indico.ectstar.eu/event/203/

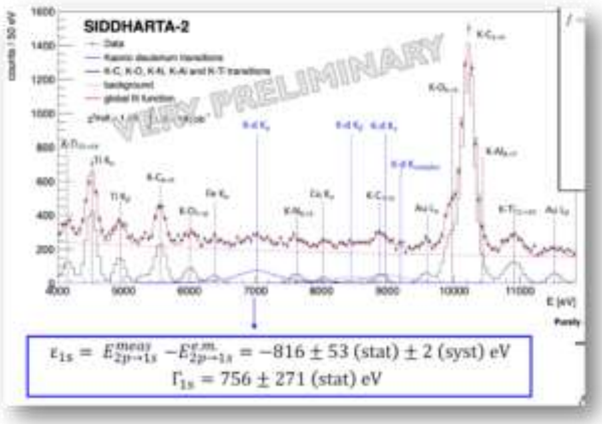


Fig 3: Preliminary Kaonic deuterium spectrum measured by SIDDHARTA-2

A very detailed review about SIDDHARTA 2 experiment can be found at https://doi.org/10.48550/arXiv.2311.16144

D16.4 Hypernuclear database – Achieved

Due to the delays of planned experiments caused by the full or at least partial shut downs of experimental facilities like MAMI, we started to setup a hypernuclear database at MAMI. This interactive database allows the community to quickly evaluate the impact of new data and will thus help in the planning of new experiments. Furthermore, it provides standardized numbers and plots to the community, which will lay out the basis for all theoretical discussions.

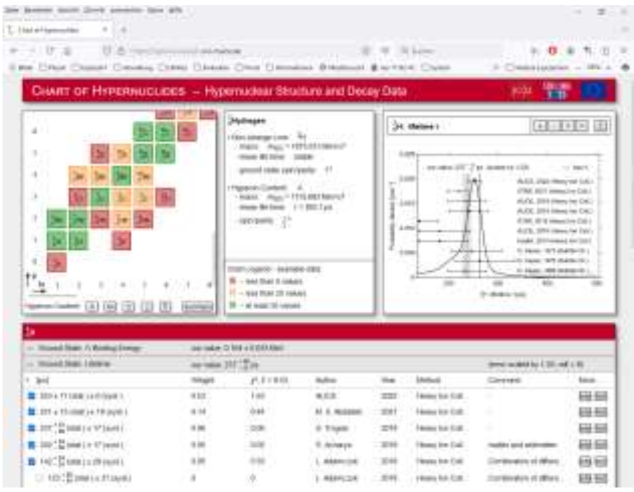


Fig 4: Screenshot of the interactive webpage of the hypernuclear data.

The database is hosted by the Mainz University in the meantime on-line available for the scientific community at https://hypernuclei.kph.uni-mainz.de/ It will continuously be updated when new data are published. In order to guarantee a continuous maintenance of the web page for the community, we are preparing a mirror of the webpage at the Tohoku University in Japan https://lambda.phys.tohoku.ac.jp/HypernuclearDatabase/

Milestones due in RP3.

MS21 Design report for antihyperons in nuclei ready – Achieved

MS22 SIDDHARTA-2 progress report – Achieved

1.2.8 Work Package 17

Activity Type	Networking activity
Work package title	Lattice Hadrons (NA6-LatticeHadrons)
Lead beneficiaries	15 – UREG, 17 – UAM, 27 – TCD, 43 - UEDIN

Project objectives

The network, spanning 34 partner research institutions, aims to embed existing lattice field theory expertise more deeply into the European hadron physics community, enhance access across the network to research expertise, data and new developments and exploit new links between research in lattice field theory, experimental and phenomenological hadron physics and high-performance computing and data analytics.

Progress made during the reporting period towards objectives

The work, distributed across the partners in the network in collaboration with many research partner institutions across Europe, can be broken down into the following tasks:
Task 1: Coordinate research secondments, visits and exchanges

With the return to travel following the pandemic, some visitor and exchange activity recommenced, including visitors to and from the Dublin node.

The switch to online teaching and training resulting from the pandemic resulted in many research and teaching staff quickly learning to deliver online modules and recorded material. To exploit this new expertise, the lattice community in Europe formed a new consortium based on the STRONG-2020 LatticeHadrons network to build an experimental online training platform. This platform is called the Lattice Virtual Academy (LaVA) and is close to launch. To date a set of introductory modules have been recoreded and made available by Profs Margarita Garcia Perez, Simon Hands and Christoph Gattringer.

To initiate the project a first workshop was organised at the ECT* site (Trento) from 20-24 February 2023. The meeting was fully funded as part of the LatticeHadrons STRONG-2020 initiative. During the week, the team developed the first plan for content and began creating the material to record.

Task 2: Arrange thematic workshops. The network will organize focused workshops to expand research expertise in lattice field theory across Europe and address open challenges for hadronic physics in four themes: ***1. Hadron spectroscopy and structure.*** ***2. Hadrons under extreme conditions.*** ***3. Hadrons in the standard model and beyond.*** ***4. Numerical algorithms and computing for lattice hadron physics***
In spite of delays due to pandemic travel restrictions, all meetings planned by the network were delivered. During the reporting period, the following meetings were held : 24-27 April 2023 – Edinburgh, Scotland - Algorithms and computing for lattice hadron physics 12-16 June 2023 – Madrid, Spain - Lattice Gauge Theory contributions to new physics searches (Hadrons in the Standard Model and Beyond) 4-7 July 2024 – Dublin, Ireland – Hadron spectroscopy and structure. All attracted significant participants from across the network and were successful.
Task 3: Develop software, data sharing and analytics methodologies
A small number of research exchanges between nodes commenced following the pandemic and the STRONG-2020 network was able to restart activity in this direction.

Highlights of significant results

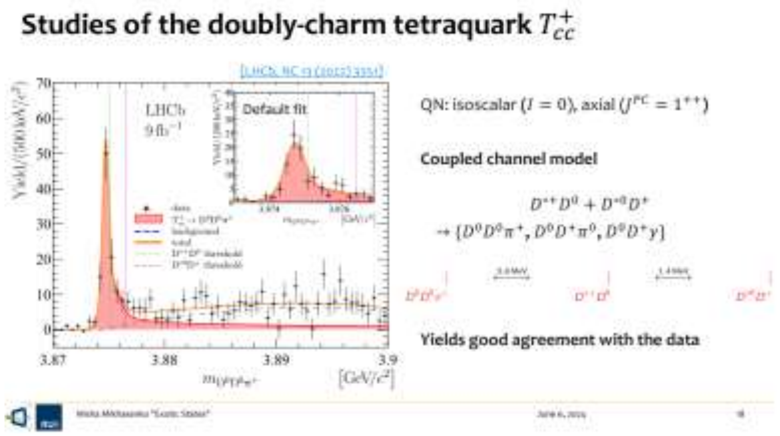
The most significant output from the network was the formation of the LaVA online training intiative. This is now growing and is supported by ECT*, which will host the web material generated for the project. Discussions with senior colleagues in NUPECC on how to proeceed have been initialised and have generated useful connections and feedback.

Deliverables due in RP3.

D17.1 Report on the status and future research directions - Achieved

Workshop on hadron spectroscopy and structure. Dublin, Ireland, 4-7 June 2024.

The final workshop of the Network was successfully hosted at Trinity College Dublin. On the first two days, the meeting focussed on gradient flow and renormalisation, discussing important new developments in both the perturbative and non-perturbative theoretical treatment of fundamental parameters in the Standard Model, specifically aimed at understanding heavy quark dynamics. On Day 3, hadron spectroscopy was discussed, including a presentation on the experimental status of recent exotic hadrons seen in LHCb (Talk by Mikhail Mikhasenko, Ruhr Uni Bochum). In the afternoon, short presentations by early-stage researcher enabled them to showcase their work on machine-learning applications and theoretical developments in the technical precision of lattice calculations. On Friday, the meeting closed with further discussions on charm meson scattering and resonances in charmonium.



D17.2 Report on the status and future research directions for investigations of hadrons under extreme conditions - Achieved

The publication corresponding to the D17.2 has been published and the manuscript is submitted in the Portal.

The publication is also available in open access online, on arXive at https://arxiv.org/pdf/2301.04382.pdf

D17.3 Report on the status and future research directions for investigations of precision physics in the Standard Model and studies of strongly interacting quantum field theories relevant for physics beyond the SM - Achieved

Workshop on Algorithms for Lattice Gauge Theory for Contributions to New Physics Searches, Madrid, 12-16 June 2023.

https://indico.ift.uam-csic.es/event/19/

A crucial goal for the lattice community in Europe is to provide theory insights and input to constraint searches for physics beyond the standard model of particle physics. The workshop in Madrid brought together experts in these calculations to discuss new developments and the limitations and constraints on precision that can be provided from the state-of-the-art lattice calculations.

The meeting drew together 38 participants and covered topics such as

- Muon g-2
- Flavor Physics
- Axions & EDMs
- BSM & New Developments

The meeting encouraged a mixture of formal presentations and open discussion sessions framed by questions of broad interest to the community.

D17.4 Report on the status and future research directions of algorithms for large-scale numerical computing - Achieved

Numerical algorithms and computing for lattice hadron physics. Edinburgh, Scotland 24-27 April 2023

The workshop on algorithms was hosted in Edinburgh and brought together experts in the numerical and data-analytic techniques relevant to large-scale Monte Carlo calculations that are at the core of lattice QCD research. External speakers came from DeepMind (David Barrett) and Nvidia (Kate Clark). The workshop covered the latest developments in

- Master Field simulations
- Multilevel algorithms
- Machine Learning
- Quantum Computing
- Implementation on current and future hardware (exascale projects)
- Energy efficiency
- Mathematical foundations

The first speaker of the meeting was Martin Luescher, an internationally recognised expert in the discipline who presented his new ideas for multilevel techniques, which have the potential to accelerate lattice computations and enable theory to address a broader scope of experimental questions. The future of High-Performance Computing and its application to Lattice QCD calculations was discussed by experts on exascale computing. The mathematical foundations of the numerical techniques and in particular the linear algebra methods needed to compute the effects of quark propagation on a gluon background were reviewed in detail.

D17.5 White paper on the near-future challenges in lattice hadron physics and the links to other aspects of phenomenology and large-scale numerical computing – Cancelled

The travel and secondments that were to take place over the course of the project were disrupted by the COVID-19 pandemic and could not be restarted. In the end, this was to be the main driver for input into the white paper and so it will not be a valuable document if the WP members proceed. The WP members pivoted to focus on setting up LaVA, an online virtual training platform from the experiences during the lock-down, and this is progressing as a positive output from NA6 that replaced the in-person interactions. This has mitigated the impact of the cancellation on the overall Work Program. The white paper was to be written by senior staff in the network, so no resources were costed to the budget.

Milestones due in RP3.

MS23 Workshop on hadron spectroscopy and structure – Achieved

MS25 Workshop on hadrons in the standard model and beyond – Achieved

MS26 Workshop on algorithms for lattice field theory – Achieved

MS27 Enhanced integration of lattice field theory in European hadron physics community – Achieved

1.2.9 Work Package 18

Activity Type	Networking activity
Work package title	Quark-Gluon Plasma characterization with heavy flavor probes (NA7-Hf-QGP)
Lead beneficiaries	1 – CNRS, 30 - INFN

Project objectives

Heavy flavor (HF) quarks (charm and beauty) have been identified in the last years as a reliable mean to study the properties of the Quark Gluon Plasma (QGP), which is created in ultra-relativistic heavy ion collisions at the LHC. The reasons are the following: heavy quarks are produced in hard processes with very short formation time. They hence experience the early phase of the QGP and the full evolution of the system. Heavy quarks with large transverse momentum, which do not come to equilibrium, are unique probes to study the parton energy loss mechanism in the QGP, and its dependence on the parton type (gluon vs. quark and light vs. heavy quarks, respectively).

On the theoretical side, several approaches have been proposed which describe the few presently available open HF data within the still large experimental uncertainties.

Objective of the present WP is a systematic comparison of these different approaches to discriminate between them and to eliminate uncertainties like details of the expansion of the QGP, initial state fluctuations or the influence of nuclear shadowing. The second main objective is to advance the understanding of hidden charm and bottom mesons in ultra-relativistic heavy ion reactions. The description of hidden HF production is even more challenging. One of the main difficulties in this sector is the multi-disciplinary aspect of the problems.

Progress made during the reporting period towards objectives

The NA7 will start by assigning tasks to working groups in view of the review paper. Both theoreticians and experimentalists of different experiments will be nominated to coordinate each working group. Two working groups "Open HF" and "Quarkonia" will be formed.

Task 1: Open heavy flavor. The work will start with an assessment of the numerical models (Catania, Frankfurt, GSI and Nantes) that describe the dynamical variables of open heavy flavor hadrons

Please note that Task 1 in the Gantt Chart reads:

1. Interpretation of LHC results development of the necessary theory and preparation of next run

1.1 Interpretation of LHC results

1.2 Preparation for HI-IL LHC runs

1.3 Theory developments

We refer to these tasks 1.1, 1.2. and 1.3 in the following

Tasks 1.1 and 1.3 were well advanced already, and their finalization progressed smoothly over the period covered by this report.

A very intense work was done in this period for task 1.2. The original deliverables (and associated milestone) related to this activity was a paper with recommendation for the dedicated heavy-ion periods of LHC. It was agreed in the amendment of the grant to post-pone the due date for this deliverable (from month 26 to the end of the project) and the study had it focus on LHC Run 5 and beyond. The opportunity to have LHC periods with lighter collision systems than Pb-Pb was investigated in detail. In particular, two benchmark observables were selected: multi-charmed baryon production and azimuthal angular correlation of D and Dbar mesons.

On the one hand new theoretical studies have been conducted to provide predictions in different collision systems (O-O, Ar-Ar, Ca-Ca, In-In, Xe-Xe, etc…) for these two observables by two different groups. On the other hand, the expected performance for an experimental apparatus analogue to the new proposed ALICE 3, which is supposed to replace ALICE in the LHC Long Shutdown 4. was studied considering the previously mentioned colliding systems. The study demonstrated the impressive potentiality of lighter colliding systems as tool to understand the mechanism by which heavy quarks tend to reach equilibrium with the lighter (and equilibrated) partons of the QGP. This in turn has the potential to further elucidate the properties of the expanding QGP, the key objective of the experimental study of ultra-relativistic heavy-ion collisions. Therefore, also the remaining task 1.2 was fully completed at the end of the project.

Task 2: Hidden heavy flavor. The theory for hidden heavy flavour production in heavy ion collisions is even more complex and therefore less developed. It needs a multidisciplinary approach of different subfields to solve the questions at hand, which include the stability of quarkonia at high density and temperature, the recombination of c and cbars from different primary vertices, their hadronization and their final interaction with hadronic matter

<u>Please note that Task 2 in the Gantt Chart reads</u>:
2. Interactive Framework for Theory-Data comparison
2.1 Theory data-base development
2.2 Retrieving of and matching to Experimental Data

We refer to Tasks 2.1 and Task 2.2 in the following

Both sub-tasks were completed already before the start of the period covered by this report. In the period from 1 June 2022 to 31 July 2024, there has been some remaining work to include a few further analysis (published results from the ALICE Collaboration) in the Rivet DB, previously developed for proper treatment of Heavy Ion physics. In particular, the analyses and results documented in these papers:

- **Prompt and non-prompt J/y production at midrapidity in Pb–Pb collisions at = 5.02 TeV** DOI/journal: 10.1007/JHEP02(2024)066
- **Measurement of non-prompt D-meson elliptic flow in Pb–Pb collisions at TeV** DOI/journal: 10.1140/epjc/s10052-023-12259-3
- **Measurement of the J/ψ Polarization with Respect to the Event Plane in Pb-Pb Collisions at the LHC** DOI/journal: 10.1103/PhysRevLett.131.042303

Task 3: Workshops. Significant progress can only be expected from a common effort. The three network workshops will bring the driving forces of the different subfields together. The objective is that these workshops are seeds for future collaborations
In this case, in the Gantt Chart this task reads properly, i.e.:
3. Meeting & workshop
3.1 Network meetings
*3.2 Ordinary workshop at ECT**

The second network workshop was held from 28 September to 4 October 2023 in Giardini Naxos, Sicily, Italy. It included two series of lectures about "Exploring the phase diagram of strong-interaction matter with QCD inspired models" by M. Buballa, and "Jets in strongly interacting matter" by K. Tywoniuk. The workshop was attended by 54 participants. Every participant gave a talk.

http://theory.gsi.de/~ebratkov/Conferences/HFHF-STRONG-2023/index.html

Overall, in the full period, two theory workshops were held, plus the main workshop held at ECT* in Trento. Other standard, online or hybrid workshops were organized and/or supported. This is the full list:

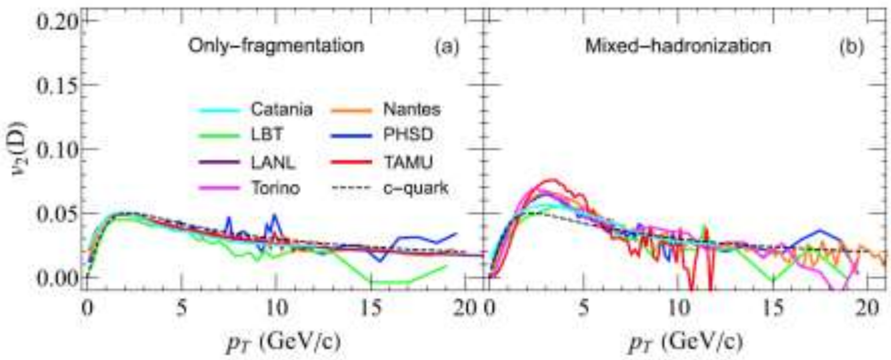
- First theory workshop: 4.10 – 8.10 2021 Crete (Greece) *http://theory.gsi.de/~ebratkov/Conferences/STRONG2021/index.html*
- *Second theory workshop:* 28.9 – 4.10 2023 Giardini di Naxos (Italy) http://theory.gsi.de/~ebratkov/Conferences/HFHF-STRONG-2023/index.html
- Main workshop: 15-19 November 2021 ECT* Trento (Italy) *https://www.ectstar.eu/workshops/quark-gluon-plasmacharacterisation-with-heavy-flavour-probes/*
- Hybrid workshop “Heavy-flavour hadronization in pp and heavy ion collisions at the LHC” 2–3 Mar 2020 (CERN) https://indico.cern.ch/event/866418/overview

- Online workshop “HF-QGP: theory meets experiments for the usage of RIVET”: 8.4.2021
  https://indico.cern.ch/event/1022351/
- Support for the participations of students at the “11th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions” 26–31 March 2023, one of the major conference of the field, was given by this Network activity. See https://indico.uni-muenster.de/event/1409/page/48-supported-by

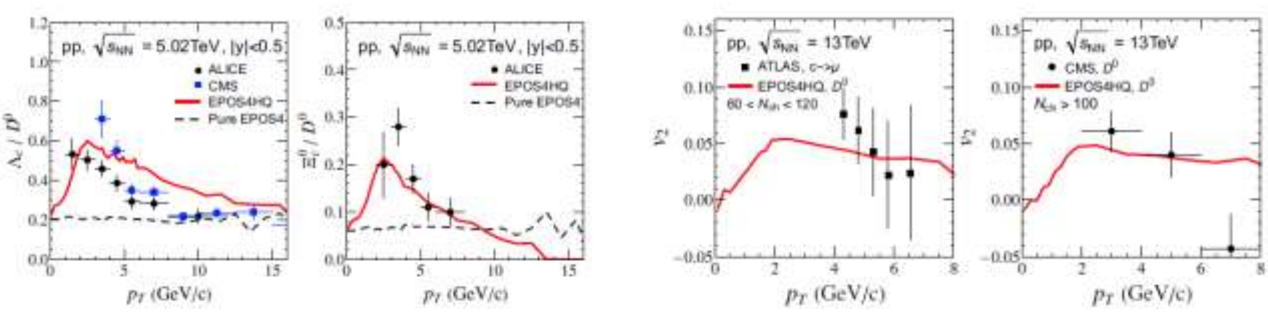
Highlights of significant results

Few highlights for this period are the following:

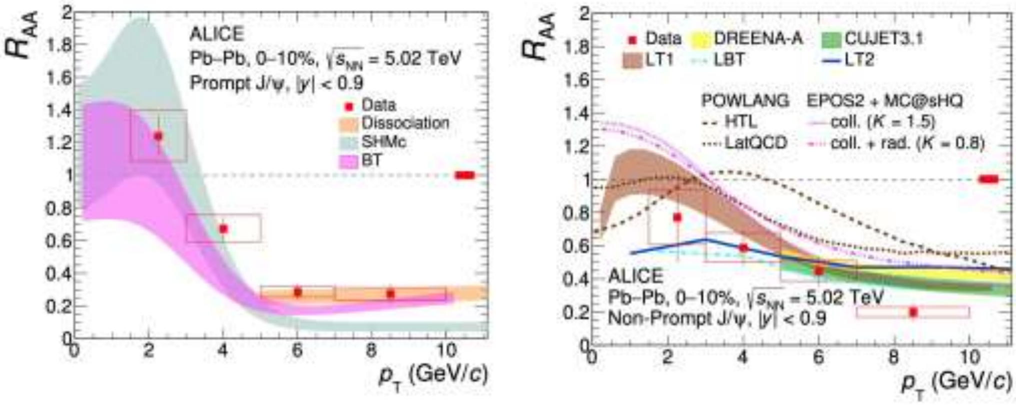
- Paper with title “Hadronization of heavy quarks “, Phys. Rev. C 109, 054912 (2024), where the differences in the hadronization processes due to the assumptions each approach have been studied in detail, which paved the way to unify the hadronization procedures in the different codes. This is the paper of the systematic comparison of transport approaches for heavy quarks/hadrons. The plots below shows the v_2 coefficient, which quantifies the elliptic flow of D mesons, as a function of transverse momentum for the different models.



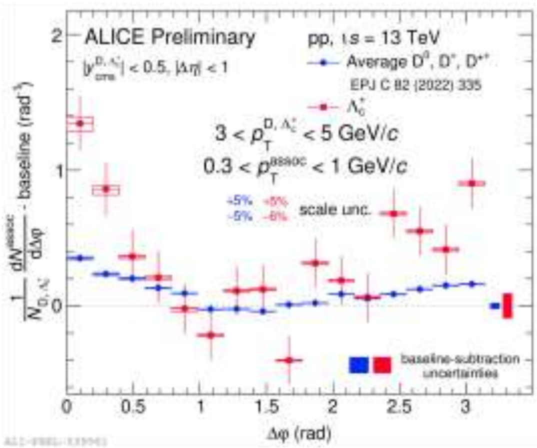
- The results of the paper “Phys.Rev.D 109 (2024) 5, 054011 (& arXiv:2401.17096)” , about the study in small colliding systems with EPOS4HQ approach. The surprising enhancement of HF baryons over mesons and the appearance of an elliptic flow which has been observed in proton-proton data can be understood assuming that also in p-p collisions at the LHC a quark gluon plasma is formed if critical energy density of 0.57 GeV/fm3 is obtained. The plots below show a comparison between the model and the data.



- Results of prompt and non-prompt J/y production in Pb-Pb collisions at mid-rapidity down to very low transverse momentum, results presented EPS-HEP 2023, Hamburg. Significantly better precision w.r.t. LHC run 1 data. The plots below show the nuclear modification factor for prompt (left) and non-prompt (right) J/ψ versus the transverse momentum. Non prompt J/ψ production originates from beauty hadron decays.



- First study ever of azimuthal angular correlation between a Lambda_c baryon and charged particles. Preliminary results based on ALICE data and a paper ready for publication. The result below show the comparison between D meson and Lambda_c.



Deliverables due in RP3.

D18.2 Talks delivered at the workshop/meetings published at the webpage – Achieved

The second Workshop of NA7 was held from 28 September to 4 October 2023, in Giardini Naxos, Sicily, Italy.

The NA7-HF-QGP Network is a common network of theorists and experimentalists to address all topics, which are of relevance for the physics of heavy quarks in pp, pA and AA collisions. The Network topics include the production of heavy quarks in elementary collisions, the stopping of strongly interacting matter in the entrance channel, the formation and expansion of a quark gluon plasma (QGP) and the study of its properties by different probes and on the lattice, the elementary interactions of heavy quarks with the QGP, the hadronization of the QGP and of heavy quarks the final state interaction among the hadrons.

The HFHF Retreat brought together the theory groups from different German universities working on physics of FAIR. The key topics include the dynamical descriptions of heavy-ion collisions in terms of microscopic transport approaches and hydrodynamics, the properties of the quark-gluon plasma (QGP), the phase transition, the chiral symmetry restoration, the properties of hadrons in hot and dense medium.

The talks were given by leading researchers and young scientists (PhD students and young postdocs); the format of the meeting provided possibilities for free discussions, exchange of opinions and ideas. All the talks of this Workshop can be downloaded from the homepage of the workshop:

http://theory.gsi.de/~ebratkov/Conferences/HFHF-STRONG-2023/talks.html

D18.3 Paper with recommendation for the dedicated heavy-ion periods of LHC after the 2nd Long Shutdown for the different LHC experiments – Achieved

The report was provided on the 30th of July 2024, it includes a published papers and another paper submitted as a preprint to arXive. The report without the two papers is 11 pages, the full report with the paper is 38 pages. The text of the report was submitted in the Portal

Milestones due in the RP3.

MS31 Draft of strategy paper for next LHC Runs – Achieved

1.2.10 Work Package 19

Activity Type	Joint Research Activity
Work package title	Inter-experiment combination of heavy-ion measurements at the LHC (JRA1-LHCCombine)
Lead beneficiaries	1 – CNRS, 30 – INFN, 37 - IFJ PAN, 45 - AGH UST

Project objectives

The first (2010-12) and second (2016-18) runs of the Large Hadron Collider at CERN provide a wealth of results from heavy-ion collisions. The four large LHC collaborations, ALICE, ATLAS, CMS and LHCb, contribute to this programme with very different and complementary capabilities, both in terms of angular coverage and particle identification. The aim of this WP is to improve communication between the four collaborations in the heavy-ion field, and to establish an LHC data-combination working group. These objectives can be split into two tasks: the animation of a common forum (task 1) to ensure a regular communication between the four collaborations; and cross-experiment combination work (task 2), such as detailed comparisons of techniques or optimized statistical combination of results, leading to common publications.

Progress made during the reporting period towards objectives

Task 1: Creation of a forum to guarantee a regular communication of information between the four collaborations
Done during period 1, 14 topical meetings occurred involving a core of 120 people identified with a dedicated mailing list. This success led to the creation, during the second reporting period,, of a heavy-ion working group within the LHC Physics Center at CERN (https://lpcc.web.cern.ch) upon the initiative of the spokespersons of this JRA (who, together with two theorists and an extra person from each collaboration, acted as first conveners of this officialized activity at CERN). This was a very important milestone, although not expected initially, since such new group insures **the perennity of the JRA activity** beyond the scope of the STRONG-2020 project., Moreover, it can also be gathered when official endorsement is needed from the collaborations. The legitimacy of coordinating the activities started within the current JRA now falls in that group. During period 3, two of the collaborations rotated the convenership as a common practice in the field and new individuals were identified to steer the group. It is worth noting that the group was not very active during the reporting period, since a) people are very busy within their collaborations, b) some work was still going on within the current WP. However, the group exists and can be summoned when needed.
Task 2: Comparisons of techniques or optimized statistical combination of results. Examples : ***• Constrain nuclear parton distribution function (nPDFs)*** ***• Light-by-light scattering*** ***• Open charm cross sections*** ***• Quarkonia et al topics*** ***The activity will start by hiring one postdoctoral position per each experiment, for 12-18 months. The postdoctoral fellows will thus spend continuously, during three years, a third of their time on cross-experiment projects, the two other third being used to convey work in their collaboration.***
All of the above-mentioned examples were discussed in meetings. The first one (nPDF) was judged not worth starting a working group, since fitters already exist and incorporate new data in nPDF sets. The two others (open charm cross section and quarkonium feed-downs) were identified as a priority, and subgroups are working on combining data. Other topics were also reviewed (top quarks, jets…) and one of them (light-by-light scattering) was identified as a third priority. During period 3, new topics were discussed (electroweak bosons, ditau…) as well as global observables : centrality and high multiplicity. Additional ideas emerged: listing and solving tensions in published results; producing and endorsing comparison plots. After having been delayed for several administrative and sanitary reasons, the hiring of postdocs occurred: • Florian Damas (from Alice) in CMS @ Polytechnique joined in Feb. 21 • Sándor Lökös in ALICE @ INP Krakow, started in Sep. 21

- Yuriy Volkotrub in ATLAS @ AGH UST Krakow, started in Nov. 21
- Jiayin Sun in LHCb @ INFN Cagliari, started in Sep. 21, hired before on other funds

  Though not all of them were still paid by Strong-2020, they were mostly active during period 3.

Highlights of significant results

The JRA held 18 meetings (https://indico.cern.ch/category/11797/), with 20 to 50 people attending which is in itself an achievement taking into account the pandemic. Moreover, the creation of a perennial LPCC working group, corresponding to some extent to an endorsement of this activity by CERN can be seen as the first highlight.

Another highlight is that a first combination work) was terminated (individuals from ATLAS and CMS) with a parallel talk (https://indico.cern.ch/event/895086/contributions/4703027/) given at the Quark Matter conference, and an article (few authors) submitted to the preprint server:

- https://arxiv.org/abs/2204.02845

During period 3, a second combination work paper was terminated, and published (individuals from ALICE, CMS, LHCb and Theory). An invitation to present the result to the DIS conference was also received.

- *Eur.Phys.J.Plus* 139 (2024) 7, 593 ; https://arxiv.org/abs/2311.11426

Other work, including an advanced study on quarkonium feed-down fractions was kept internal.

Deliverables due in RP3.

D19.3 Cross-experiment papers – Achieved

Three studies were pushed to an advanced level, one of them published, another one publicly released, the third one kept internal.

- Light-by-light scattering cross-section measurements at LHC, G. K. Krintiras, I. Grabowska-Bold, M. Kłusek-Gawenda, É. Chapon, R. Chudasama, R. Granier de Cassagnac, https://arxiv.org/abs/2204.02845
- Open charm production cross section from combined LHC experiments in pp collisions at $\sqrt{s}$=5.02 TeV, Christian Bierlich, Jeremy Wilkinson, Jiayin Sun, Giulia Manca, Raphael Granier de Cassagnac, Jacek Otwinowski, Eur.Phys.J.Plus 139 (2024) 7, 593 ; https://arxiv.org/abs/2311.11426

D19.4 Outlook report paper – Achieved

The paper was submitted in the Portal.

Milestones due in the RP3.

No Milestones in the RP3

1.2.11 Work Package 20

Activity Type	Joint Research Activity
Work package title	Fixed Target Experiments at the LHC (JRA2- FTE@LHC)
Lead beneficiaries	1 – CNRS, 7 – FZJ, 20 – USC, 30 – INFN, 35 – NCBJ, 36 – WUT, 39 – LIP

Project objectives

The objectives of the WP are to investigate and implement fixed-target experiments at the LHC with the ALICE and LHCb detectors.
In order to achieve these objectives, three tasks were defined:
1. Feasibility studies in ALICE
2. Gas-target development in LHCb
3. Phenomenological and theoretical studies.
In the third period of STRONG-2020, the remaining objectives were achieved as described in Table 1.2

Progress made during the reporting period towards objectives

Task 1: feasibilities studies in ALICE. • ***Study on the gas-jet target implementation and study of the L3 magnetic field constraints on a polarised setup;*** • ***Integration of a solid target internal to the beam pipe;*** • ***Estimation of the detector performance with a vertex shifted from the nominal interaction point;*** • ***Full simulations of selected soft and hard processes with the ALICE setup***
On the ALICE side, the feasibility studies planned in the WP20 were already achieved in the previous reporting periods. The activities related to ALICE project were very dense in June 2022 to January 2023. The conceptual design was achieved and the realistic simulations performed showed the capabilities of the fixed target system to bring new physics in ALICE. There was no showstopper. Funding was granted from a French ANR and the budget was in place to hire two postdocs to perform detailed studies on vacuum constraints around the target system in the LHC beam pipe and on beam impedance. However, in February 2023, the ALICE management decided not to pursue this activity due to a lack of manpower needed from the ALICE technical coordination side to follow the implementation of the project.
Task 2: gas-target development in LHCb. • ***Design and construction of the unpolarised target for LHCb;*** • ***Standalone tests on gas polarisation ;*** • ***Design of the new polarised gas target;*** • ***Full simulation for the detector performances with a vertex shifted from the nominal interaction point;*** • ***Implementation of the new trigger and tracking reconstruction code;*** • ***Full simulations of selected hard processes with the LHCb setup.***

All the items listed above have been successfully accomplished. The unpolarized target for LHCb has been designed, installed, and is currently operational, collecting data during simultaneous data-taking with beam-beam collisions.

This data taking involves the implementation of trigger lines and simulations of the physics channels. In particular, the shifted primary vertex has been included in the reconstruction algorithms, demonstrating the important result that the efficiency for beam-gas collisions and beam-beam collisions is the same. The particle reconstruction resolution remains unchanged, and the two collision points work independently, behaving as separate primary vertices.
When operating with the unpolarized target, the full detector occupancy and data flow only increase by a few percent. The design of a new polarized target has also been completed, with CAD drawings illustrating the implementation of the target and its components within the LHCb spectrometer.
All these results have been published and presented at international workshops and conferences.

Task 3: phenomenological and theoretical studies

On the theory and phenomenological side, the studies were quite active and new papers have been published on various topics related to fixed target at LHC, as it can be seen in section 1.3. The studies were also discussed in workshops and conferences (see section 1.3).

Highlights of significant results

All the studies performed in this WP were extensively discussed during the workshop organized at Aussois in January 2023.

References and publications:

Published proceedings and contributions:

- “Heavy flavour studies with a high-luminosity fixed-target experiment at the LHC”, B.Trzeciak et al. PoS HardProbes2020 (2021) 190
- "White Paper on Forward Physics, BFKL, Saturation Physics and Diffraction", M. Hentschinski et.al., https://arxiv.org/abs/2203.08129

Published papers with topics related to the WP20:

- "Revisiting NLO QCD corrections to total inclusive J/ψ and Y photoproduction cross sections in lepton-proton collisions", A. Colpani Serri et al., Phys.Lett.B 835 (2022) 137556
- “Matching next-to-leading-order and high-energy-resummed calculations of heavy-quarkonium-hadroproduction cross sections », M.Nefedov et al., JHEP 05 (2022) 083
- “Antiproton production with a fixed target and search for superheavy particles at the LHC”, A.B. Kurepin et al., J.Mod.Phys.13(2022)1093
- “Curing the high-energy perturbative instability of vector-quarkonium-photoproduction cross section at alpha.alphaS^3 with high-energy factorization”, M. Nefedov et al., EPJC 84 (2024) 4, 351

- “A potential approach to the X(3872) thermal behavior”, E. G. Ferreiro et al., Phys.Lett.B 854 (2024) 138760
- “An experiment for electron-hadron scattering at the LHC”, E. G. Ferreiro et al., Eur.Phys. J. C (2022) 82:40
- “Simple model to include initial-state and hot-medium effects in the computation of quarkonium nuclear modification factor”, Phys.Rev.D 105, 014019;
- “The LHCspin project: A polarized fixed target for LHC” B. Passalacqua et al., Nuovo Cim.C 47 (2022) 121;
- “The LHCspin project: A polarized target experiment at LHC”, L.L.Pappalardo et al., Nuovo Cim.C 47 (2024) 4, 235;
- “The LHCspin project A polarised gas target at the Large Hadron Collider”, M. Santimaria et al., EPJ Web of Conferences 276, 05007 (2023);
- “The LHCspin project”, P. Di Nezza et al., Acta Phys.Polon.Supp. 16 (2023) 7, 7-A4;
- “The LHCspin project”, P. Di Nezza et al., PoS (PSTP2022)001;
- “LHCspin: Unpolarized gas target SMOG2, and prospects for a polarized gas target at the LHC”, E. Steffens et al., PoS (PSTP2022)002;
- “Fixed Target Program at the LHC”, P. Di Nezza et al., PoS SPIN2023 (2024) 036;
- “A neural-network-defined Gaussian mixture model for particle identification applied to the LHCb fixed-target programme”, S. Mariani et al., Journal of Physics 2438 (2023) 012107;
- “A high-density gas target at the LHCb experiment”, O. Boente et al., arXiv:2407.1420, in print on Physics Review Accelerators and Beams;
- “Amorphous carbon-coated storage cell tests for the polarized gas target at LHCb”, T. El-Kordy et al., Nuclear Instruments and Methods A 1068 (2024) 169707;

Communications to Workshop/Conference

-Update on ALICE Fixed Target project, Daniel Kikola, PBC annual meeting, Nov. 2022
-Organization of the FTE@LHC workshop at Centre Paul Langevin, Aussois, France January 5-7 2023 : https://indico.cern.ch/event/1222068/ and related talks
-"Quarkonia as tools 2023", Centre Paul Langevin, Aussois, France, 4-14 January 2023, "Inclusive quarkonium production phenomenology and tools overview" (09.01) [https://indico.cern.ch/event/1213416/timetable/#20230109.detailed]
-"QCD Evolution workshop 2023", IJClab, Orsay, France, 22-26 May 2023, "High-Energy factorization and matching to NLO for quarkonium production" (26.05) [https://indico.cern.ch/event/1239374/timetable/#20230526.detailed]
-"26th High-Energy Physics International Conference in Quantum Chromodynamics (QCD23)", University of Montpellier, France, 10-14 July 2023, "On the High-Energy instability of quarkonium production cross sections" (10.07) [https://qcd23.sciencesconf.org/]
-"EPS-HEP2023 Conference", Hamburg University, Hamburg, Germany, 20-25 August 2023, "Resolving the perturbative instability of p_T-integrated quarkonium production cross section with High-Energy Factorisation" (23.08) [https://indico.desy.de/event/34916/timetable/#all.detailed]
-"Low-x 2023", Leros Island, Greece, 3-8 September 2023, "Computing one-loop corrections to quarkonium production impact-factors with Lipatov's EFT" (08.09) [https://indico.cern.ch/event/1214186/timetable/#all.detailed]

-"General assembly of the GDR QCD", IPHC, Strasbourg, France, 27-29 September 2023, "Computing heavy quarkonium production cross sections at high energy with the matching between collinear and high-energy factorisations" (28.09) [https://indico.in2p3.fr/event/30003/timetable/#all.detailed]

-“Fixed targets at LHC”, P. Di Nezza, APCTP Focus Program in Nuclear Physics, POSCO Korea, Jul 18 – 23, 2022

-“The LHCspin project”, L.L. Pappalardo, Fixed-target experiments at LHC – STRONG2020 workshop, CERN, 22-24 Jun 2022

-“The LHCspin project”, M. Santimaria, The 20th International Conference on Strangeness in Quark Matter, Busan, Jun 2022

-“Fixed target at LHCb”, M. Santimaria, CFSN Workshop, Stony Brook, Jun 2024

-“The LHCspin project”, M. Santimaria, Diffraction and low-x 2022, Corigliano Calabro, Jun 2024

-“LHC fixed target experiments”, P. Di Nezza, IWHSS Cern Aug 2022;

-“The LHCspin project: a Polarized Fixed-Target Experiment at the LHC”, L.L. Pappalardo, 24th Gordon Research Conference on Photonuclear Reactions, Holderness, NH (USA), Aug 2022

-“The LHCspin project”, P. Di Nezza, Workshop on Polarized Sources Targets and Polarimetry 2022 (PSTP22) Mainz, Sep 2022

-“Fixed target experiments at LHC”, P. Di Nezza, Workshop Opportunities with JLab Energy and Luminosity upgrade, ECT* Trento, Oct 2022

-“Status of the LHCspin project”, P. Di Nezza, Workshop Fixed target experiments at LHC, Aussois, Jan 2023

-“Polarised physics at the LHC”, P. Di Nezza, Epiphany conference Gen 2023, Krakow, Jan 2023

-“LHCspin (SMOG3): considerations for IP8”, P. Di Nezza, Velo-II Upgrade workshop, Amsterdam, Feb 2023

-“Fixed Target and Heavy-Ion Results at LHCb”, P. Di Nezza, LISHEP 2023 Conference, Rio de Janeiro, Mar 2023

-“Spin Physics with LHCspin”, P. Di Nezza, LISHEP 2023 Conference, Rio de Janeiro, Mar 2023

-“The LHCspin project: a polarized target experiment at LHC“, L.L. Pappalardo, HADRON 2023, Genova, Jun 2023

-“The LHCspin project”, M. Santimaria, International Workshop on Hadron Structure and Spectroscopy, Prague, Jun 2023

-“Polarised physics at LHC: the LHCspin project”, P. Di Nezza, Sar WorS 2023, Cagliari, Jun 2023

-“The fixed target program at the LHC”, P. Di Nezza, SPIN 2023 Conference, Durham, Sep 2023

-“The LHCspin project”, M. Santimaria, Low-x 2023 conferencce, Leros, Sep 2023

-“The LHCspin project”, M. Santimaria, Joint ECFA-NuPECC-APPEC, DESY, Dec 2023

-“The physics case of LHCspin“, L.L. Pappalardo, Workshop COMAP- VIII, CERN, May 2024

-“The LHCspin proposal“, P. Di Nezza, Workshop COMAP- VIII, CERN, May 2024

-“LHCspin simulations”, M. Santimaria, COMAP-VIII; CERN, May 2024

-“Fixed target experiments at the LHC”, P. Di Nezza, STRONG-2020 workshop, Frascati June 2024

Deliverables due in RP3.

D20.6 Internal reports Design of the polarised gas target for LHCb – Achieved

For the deliverable D20.6, the design of a new polarized target has been completed for all its components: the vacuum chamber, the Atomic Beam Source, and the Breit-Rabi polarimeter. Starting from the system used in the HERMES experiments, modifications were studied and implemented to comply with CERN requirements. CAD drawings illustrate the integration of the target and its components within the LHCb spectrometer and along the LHC beamline. A detailed technical note, 'Design of a Polarized Gas Target for LHC', P. Di Nezza et al., note INFN-23-33/LNF, was published in 2023. Additionally, these results have been published and presented at international workshops and conferences.

Published papers and proceedings about the delivery D20.6:

- “Design of a polarized gas target for LHC”, P. Di Nezza et al., note INFN-23-33/LNF

- “The LHCspin project: A polarized fixed target for LHC” B. Passalacqua et al., Nuovo Cim.C 47 (2022) 121;

- “The LHCspin project: A polarized target experiment at LHC”, L.L.Pappalardo et al., Nuovo Cim.C 47 (2024) 4, 235;

- “The LHCspin project A polarised gas target at the Large Hadron Collider”, M. Santimaria et al., EPJ Web of Conferences 276, 05007 (2023);

- “The LHCspin project”, P. Di Nezza et al., Acta Phys.Polon.Supp. 16 (2023) 7, 7-A4;

- “The LHCspin project”, P. Di Nezza et al., PoS (PSTP2022)001;

D20.7 Peer-reviewed paper Phenomenology and theory papers for high-x, spin and QGP physics – Achieved

For the deliverable D20.7, several phenomenological and theory reports have been published. Those works concern physics topics that motivate the use of a fixed target system at the LHC, or theory development that are useful for the calculations of observables that can motivate a fixed target experiment at the LHC.

Published proceedings:

- “Heavy flavour studies with a high-luminosity fixed-target experiment at the LHC”, B.Trzeciak et al. PoS HardProbes2020 (2021) 190

- “Exclusive production of a large mass photon pair”, J. Wagner et al, PoS DIS2019 (2019) 196

- Contribution to SnowMass 2021 (on arXiv) "White Paper on Forward Physics, BFKL, Saturation Physics and Diffraction", M. Hentschinski et.al., https://arxiv.org/abs/2203.08129

Published papers:

- “Data-driven study of timelike Compton scattering”, J. Wagner et al., EPJC80 (2020) 2, 171

-“Electroproduction of a large invariant mass photon pair”, J. Wagner et al., Phys.Rev.D101 (2020) 11, 114027

- “A fixed-target programme at the LHC: Physics case and projected performance for heavy-ion, hadron, spin and astroparticle studies”, C. Hadjidakis et al. Phys.Rept.911 (2021)1-83

- "Curing the unphysical behaviour of NLO quarkonium production at the LHC and its relevance to constrain the gluon PDF at low scales", J.-P. Lansberg and M.A. Ozcelik, Eur. Phys.J. C 81 (2021) 497

- "Revisiting NLO QCD corrections to total inclusive J/ψ and Y photoproduction cross sections in lepton-proton collisions", A. Colpani Serri et al., Phys.Lett.B 835 (2022) 137556

- “Matching next-to-leading-order and high-energy-resummed calculations of heavy-quarkonium-hadroproduction cross sections”, M.Nefedov et al., JHEP 05 (2022) 083

- “Antiproton production with a fixed target and search for superheavy particles at the LHC”, A.B. Kurepin et al., J.Mod.Phys.13 (2022)1093

- “Curing the high-energy perturbative instability of vector-quarkonium-photoproduction cross section at alpha.alphaS^3 with high-energy factorization”, M. Nefedov et al., EPJC 84 (2024) 4, 351

- "A potential approach to the X(3872) thermal behavior", E. G. Ferreiro et al., Phys.Lett.B 854 (2024) 138760

-“An experiment for electron-hadron scattering at the LHC”, E. G. Ferreiro et al., Eur.Phys. J. C (2022) 82:40.

Milestones due in the RP3.

MS35 Code for full simulation in LHCb – Achieved

MS36 Gas target and detector setup ready for gas polarisation and dissociation studies – Achieved

1.2.12 Work Package 21

Activity Type	Joint Research Activity
Work package title	Precision Tests of the Standard Model (JRA3-PrecisionSM)
Lead beneficiaries	9 - JGU MAINZ, 30 – INFN, 41 - UU

Project objectives

The experimental programs that define the context of this Work Package are: precise determination of the muon anomalous magnetic moment (g-2)μ; extraction of the CKM matrix element Vud from beta decay, and of the weak mixing angle from parity-violating electron scattering (PVES).

Progress made during the reporting period towards objectives

Task 1: Hadronic effects in precision tests of the weak sector of SM
In the past 2 years, the WP members made major contributions in the field of radiative and nuclear corrections to V_{ud} from neutron and nuclear beta decays and tests of Cabibbo unitarity, and in precision determination of the weak mixing angle with PV electron scattering. Publications [1-3, 7-9] reassessed the ft-values and nuclear corrections δ_{NS} and δ_C to superallowed nuclear β decays. [1] related δ_C to combinations of nuclear radii across the superallowed isotriplet providing a framework for data-driven uncertainty estimate of this correction. [3] set up the formalism to compute δ_C with ab-initio methods. [7] demonstrated that isospin symmetry constrains the nuclear charge and weak radii; applying this new formalism to the computation of the integrated β decay spectra (ft-values) we found a significant systematic effect that was missed in the literature and must be studied further. [2] developed a new dispersion theory-based formalism for the nuclear structure correction δ_{NS}, applied to an ab-initio calculation for the $^{10}C \rightarrow ^{10}B$ decay [9]. This lightest superallowed transition has the largest sensitivity to scalar currents beyond the SM. All novel developments by our JRA3 and other groups were reviewed in [8]. The newly established connection between nuclear radii and nuclear corrections to β decays requires that the charge and weak radii of selected nuclear isotopes be known to high precision. Until now, no experimental information on weak nuclear radii was available for nuclei relevant for V_{ud} extraction. In [10] we demonstrated that a combination of two measurements of the parity-violating asymmetry in elastic electron-carbon scattering at the future MESA facility in Mainz will allow for 0.3-0.5% determination of the weak radius of ^{12}C alongside a similar determination of its weak charge which is directly proportional to the weak mixing angle. This study motivates the future PVES program on stable daughter nuclei pertinent to superallowed transitions, building upon the formalism developed in [1,7]. The use of PVES to measure nuclear weak radii until now has been concentrating on neutron-rich isotopes in the context of constraining the nuclear equation of state. Our work showed how this program can be applied to nearly symmetric nuclei and connected to precision electroweak tests and isospin-breaking corrections to V_{ud}. Likewise, for the free neutron decay we performed lattice QCD studies that complete the works performed in the previous funding period. Isospin breaking effects from the LQCD perspective were addressed in [4]. The very first direct LQCD calculation of the electroweak box on the nucleon at the physical pion mass was performed in [6]. It confirmed the earlier dispersion-theory based calculations, which led to the CKM unitarity deficit in the first row. A comprehensive review of the recent progress in neutron decay was published in [5]. Two articles on weak decays of strange baryons [11,12] developed a new formalism to analyze hadronic and semileptonic modes at existing and future e+e- colliders. They show that the electron beam polarization, if implemented in e+e- colliders, will boost sensitivity to CP-violating observables by a factor 4-5, motivating future experimental programs. Most of these results go beyond the original plans of this WP. Importantly, they open new directions for the future research at existing and future experimental facilities.
Task 2: Hadronic effects in precision tests of the electromagnetic sector of the Standard Model

The JRA has been guiding the global effort necessary to interpret the Muon g-2 experiment at Fermilab. The first (Run-1) of the muon g-2 FNAL experiment was published in 2021, confirming the BNL results, strengthening the observed discrepancy with the SM calculations, compiled in 2020 under the Muon g-2 Theory Initiative, to 4.2σ. In 2023, data-taking came to an end with the completion of Run-5. The published result [13,14] showed excellent agreement with the previous result, bringing the uncertainty of a_μ=(g-2)/2 to an unprecedented accuracy of 190 ppb, a_μ = 0.001 165 920 59(22).

The Standard Model prediction for the anomalous magnetic moment of the muon relies on theoretical calculations and on experimental data for relevant hadronic processes. At present, Of the prime importance is the correct and accurate evaluation of the hadronic vacuum polarization (HVP) contribution, which appears at the order $O(\alpha^2)$ in the electromagnetic constant, and of the $O(\alpha^3)$ hadronic light-by-light scattering (HLbL) contribution. Given the low characteristic scale of the muon g-2, these contributions have to be calculated with nonperturbative methods. The main effort is concentrated on improving the calculation of these two contributions with either a data-driven, dispersive approach, or a first-principle, lattice-QCD approach. For the data-driven approach, a unified database comprising all relevant experimental hadronic data is mandatory. Data base https://precision-sm.github.io/ (D21.4) was announced at workshop at Liverpool U. https://indico.ph.liv.ac.uk/event/731 Nov 7 – 9, 2022 (presenter Alberto Luisiani) https://indico.ph.liv.ac.uk/event/731/contributions/4387/attachments/2246/2977/alusiani-muon-prec-phys-nov22.pdf

Due to new results from CMD-3 Collaboration *Phys.Rev.Lett.* 132 (2024) 23, 231903 which deviates from all other measurement of the pion form factor, the scope of the project was extended. After finishing the database for experimental data, it was necessary to recheck computer codes that evaluate radiative corrections. As the starting event for this effort, 5th Workstop / Thinkstart: Radiative corrections and Monte Carlo tools for Strong 2020 was organized 5-9 June 2023 at University of Zurich. https://indico.psi.ch/event/13707/

The Workstop included STRONG-2020 Workshop on "Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e+e- collisions » 7-9 June 2023, Zurich https://indico.psi.ch/event/13708/ .

With the finished work on the database, the focus shifted to the comparison of the event generators and new analysis of the pion form factor with the KLOE data. The progress was reported on 2nd Liverpool Workshop on Muon Precision Physics 2023 (MPP2023) https://indico.ph.liv.ac.uk/event/1297/

The scope of the event generator comparison is beyond planed work within STRONG2020. Therefore, to continue this crucial work after finishing the project a dedicated Collaboration RadioMonteCarLow2 was created. The publication of the first results by the collaboration is planned for the fall 2024.

As a complementary approach to HVP, the MUonE experiment at CERN was proposed which would directly access the HVP contribution in the kinematics relevant for muon g-2. In August/September 2023 a test-beam campaign at the CERN M2 beamline on the prototype detector, composed of two tracking stations, equipped with CMS strip modules, and a calorimeter demonstrated, for the first time, the ability of the detector to sustain a 160 GeV muon beam intensity of 40 MHz and thereby delivered a major milestone to proceed towards the Technical Proposal to the SPSC asking for a technical run with three stations in 2025. Data analysis was presented at several conferences. A publication is in preparation [17].

Work on the next White Paper on “Standard Model predictions for muon g-2” is ongoing to include all new developments; the White Paper is expected to appear on the arXiv in late 2024. It will supplant the previous one, “The anomalous magnetic moment of the muon in the Standard Model” T. Aoyama. et al. Phys.Rept. 887 (2020) 1-166

Highlights of significant results

Precision tests in the electroweak sector:

By the end of activities within JRA3, the WP provided a re-evaluation of the entire body of radiative corrections to V_{ud} and V_{us} with new formalism and with new modern tools. This led to an appearance of the 3σ deficit in the first-row CKM unitarity. New nuclear effects found on the way, joined with improved experimental measurements of neutron decay, resulted in a situation when much more stringent constraints on possible BSM explanations of the CKM unitarity deficit can be expected in the next few years. We also defined new directions in experimental studies of PVES on nuclei, which can be undertaken at the new MESA facility at Mainz, currently under construction. All these new findings were summarized in two comprehensive reviews (D21.3). Hyperon decays at e^+e^- colliders with polarized electron beam at the J/ψ resonance showed an enhanced sensitivity to CPV signatures compared to the unpolarized case. This motivates the construction of future facilities.

Precision tests in the electromagnetic sector:

The muon g-2 FNAL experiment with strong involvement of JRA3 and STRONG2020 brought the uncertainty of $(g\text{-}2)_\mu$ to the unprecedented 190 ppb [13,14], a_μ = 0.001 165 920 59(22).
For the purpose of calculating, the Standard Model prediction for a_μ with the needed accuracy, PrecisionSM, a database for low-energy $e^+e^-\to$hadrons data, was created https://precision-sm.github.io/. It contains information about the datasets, systematic uncertainties and the treatment of radiative corrections. For the latter, a dedicated collaboration RadioMonteCarLow2 was started and several workshops were organized.
MUonE collaboration carried out a test-beam campaign at the CERN M2 beamline on the prototype detector and demonstrated the ability of the detector to sustain a 160 GeV muon beam intensity of 40 MHz and thereby, delivered a major milestone to proceed towards the Technical Proposal to the SPSC asking for a technical run with three stations in 2025.

Workshops organized:

Probing baryon weak decays - from experiment to lattice QCD
https://indico.cern.ch/event/1245077/, 6–7 March 2023, Warsaw

Baryon weak decays - from experiment to lattice QCD
https://indico.cern.ch/event/1361025/, March 4-5, 2024 Warsaw

Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e+e-collisions
https://indico.psi.ch/event/13708/, 7-9 June 2023, Zurich

Publications:

[1] C.Y. Seng, M. Gorchtein, «Electroweak nuclear radii constrain the isospin breaking correction to V_{ud}», *Phys. Lett. B* 838 (2023) 137654

[2] C.Y. Seng, M. Gorchtein, «Dispersive formalism for the nuclear structure correction δ_{NS} to the β decay», *Phys. Rev. C107 (2023) 3, 035503*

[3] C.Y. Seng, M. Gorchtein, «Toward ab-initio nuclear theory calculations of δ_C», *Phys. Rev. C109 (2024) 4 044302*

[4] C.Y. Seng, V. Cirigliano, X. Feng, M. Gorchtein, L. Jin, «Quark mass difference effects in hadronic Fermi matrix elements from first principles», *Phys. Lett. B* 846 (2023) 137259

[5] M. Gorchtein, C.Y. Seng, «The Standard Model theory of neutron beta decay», Universe 9 (2023) 9, 422

[6] P.X. Ma, X. Feng, M. Gorchtein, L. Jin, K.F. Liu, C.Y. Seng, «Lattice QCD calculation of electroweak box contributions to superallowed nuclear and neutron beta decays», *Phys. Rev. Lett. 132* (2024) 19, 191901

[7] C.Y. Seng, M. Gorchtein, «Data-driven reevaluation of ft-values in superallowed β decay», *Phys. Rev. C109 (2024) 4, 045501*

[8] M. Gorchtein, C.Y. Seng, «Superallowed nuclear beta decays and precision tests of the Standard Model», Ann. Rev. Nucl. Part. Sci. 74 (2024) 23-47

[9] M. Gennari, M. Drissi, M. Gorchtein, P. Navratil, C.Y. Seng, «An ab-initio recipe for taming nuclear-structure dependence of V_{ud} : the $^{10}C \rightarrow {}^{10}B$ superallowed transition », arXiv : 2405.19281

[10] M. Cadeddu, N. Cargioli, J. Erler, M. Gorchtein, J. Piekarewicz, X. Roca Maza, H. Spiesberger, «Simultaneous extraction of the weak radius and weak mixing angle from PVES on ^{12}C » *Phys.Rev.C* 110 (2024) 3, 035501

[11] N. Salone, P. Adlarson, V. Batozskaya, A. Kupsc, S. Leupold, and J. Tandean, « Study of CP violation in hyperon decays at super-charm-tau factories with a polarized electron beam », Phys. Rev. D 105, 116022

[12] V. Batozskaya, A. Kupsc, N. Salone, and J. Wiechnik, « Semileptonic decays of spin-entangled baryon-antibaryon pairs », Phys. Rev. D 108, 016011

[13] D. P. Aguillard et al. [Muon g-2] "Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm" Phys. Rev. Letters 131 (2023) 161802

[14] D. P. Aguillard et al. [Muon g-2], "Detailed report on the measurement of the positive muon anomalous magnetic moment to 0.20~ppm" Phys. Rev. D 110 (2024) no.3, 032009

[15] A. Driutti [Strong2020 and Radio MonteCarLow], "The Strong2020 and Radio MonteCarLow activities", PoS ICHEP2022 (2022), 920

[16] A. Driutti, "PrecisionSM: an annotated database for low-energy positrons-electrons into hadrons" PoS EPS-HEP2023 (2024), 376

[17] A. Driutti, "The detector for the MUonE experiment at CERN", to be published in NIMA

[18] A. Driutti, "PrecisionSM: an annotated database for low-energy positron-electron hadronic cross sections" to be published in POS ICHEP2024

[19] L. Cotrozzi "The STRONG2020 and Radio MonteCarLow activities,", JINST 18 (2023) no.09, C09004

[20] G. Venanzoni, "Towards a full NNLO Monte Carlo generator for low energy e+e- data into leptons and hadrons" PoS EPS-HEP2023 (2024), 330

Deliverables due in RP3.

D21.3 Report on hadronic corrections to precision tests in the weak sector - Achieved

Two review articles in high-impact international peer-reviewed journals, “The Standard Model theory of neutron beta decay”, Universe 9 (2023) 9, 422, and “Superallowed nuclear beta decays and precision tests of the Standard Model”, Ann. Rev. Nucl. Part. Sci. 74 (2024) 23-47, summarize the current status of the field of beta decays and are largely based on the innovative work carried out within WP21 on precision tests in the electroweak sector.

D21.4 Database on hadronic processes relevant for HVP and HLbL - Achieved

PrecisionSM (precision Standard Model) is an annotated database for low-energy electron-positron into hadrons data. The database relies on a custom-made website that contains an up-to-date list of the published measurements with links to their HEPData locations and some examples of tools to elaborate them. The database contains information about the datasets, the systematic uncertainties and the treatment of radiative corrections. This information is important for precision tests of the Standard Model like the calculation of anomalous magnetic moment of the muon whose accuracy relies on the quality of $e^+e^- \to$ hadrons data.

The database structure has been reported in several conferences. Few key members involved in this WP has signed of the second result on the muon g-2 experiment, which measured the muon g.-2 with unprecedented precision, see:

https://inspirehep.net/files/9be71b2e43649e094007444d2afe0f75
https://inspirehep.net/files/7cdf823e057c10f9c9c64830cd66bf1a

Milestones due in the RP3.

MS39 New Pi production MC event generator - not achieved

Monte Carlo generator for pion production in neutrino scattering experiments:
During COVID the MAID collaboration consisting mostly of senior researchers effectively dissolved due to unanticipated early retirements. This affected the amount of manpower, which could be dedicated to the work on MC generator for pion production in neutrino experiments. The only active member of MAID collaboration, Mikhail Gorchtein, was unable to travel to Fermilab since the beginning of the Russia-Ukraine war (MG is a Russian citizen). Extended visits of MG to Fermilab were necessary to kickstart the work on that task, and according to the plan of the project, the JGU-FNAL agreement for mutual visits was favoring these. Since within the framework and timeline of STRONG-2020 neither the composition of the MAID collaboration nor the international situation could be changed, MS39 had to be dropped for now. The work on the MC event generator will be continued in the future.

Nonetheless, the rest of objectives was met, and in many aspects, the obtained results exceeded the original plans. The muon g-2 experiment confirmed the previous measurements and improved their precision, while an ongoing progress in reducing the hadronic uncertainties has resulted in one White Paper published in 2020 and the next one is planned in late 2024. Unanticipated fundings from lattice QCD and from the CMD3 experiment sparked a renewed interest of the community, and JRA3 has been pivotal in coordinating this global effort. A complete re-evaluation of the radiative corrections to beta decays of free and bound nucleons and kaons led to improved theoretical uncertainties and resulted in an apparent deficit of CKM unitarity in the first row. Here, new formalisms have been developed, and new connections between various experimental programs established, e.g. to muonic X-ray program at PSI and PVES and neutron skin program at the future MESA facility.

MS40 Database for hadronic processes relevant to HVP and HLbL – Achieved

1.2.13 Work Package 22

Activity Type	Joint Research Activity
Work package title	3D structure of the nucleon in momentum space (JRA4-TMD-neXt)
Lead beneficiaries	18 – UCM, 21 - UPV/EHU, 30 – INFN, 32 - UOM

Project objectives

The exploration of the internal structure of hadrons is one of the core missions of hadronic physics. TMD-neXt will join together a network of experimentalists and theorists with the aim of mapping the distributions of partons inside hadrons in momentum space, including their dependence on spin. The complete three-dimensional information on these distributions is encoded in Transverse-Momentum Dependent Parton-Distribution Functions (TMD PDFs). In experimental observables, they are often combined with Transverse-Momentum Dependent Fragmentation Functions (TMD FFs).

TMD-neXt will open the way to the next-generation extractions of Transverse-Momentum Distributions (TMDs). In the envisaged four years' running of the work package, TMD-neXt plans to:
- increase the amount of data available for TMD studies,
- test the validity and limits of applicability of the TMD framework,
- extract TMDs from available data,
- extend the formalism in particular to gluon-dominated processes.

Progress made during the reporting period towards objectives

Task 1: Analysis of Drell-Yan (DY) data. The COMPASS collaboration will analyze unpolarized and polarized DY data, suitable for the study of unpolarized TMDs and the Sivers polarized TMD in the range 4 GeV < Q < 9 GeV. Of particular importance is the experimental verification of the sign-reversal property of the Sivers function in polarized Drell-Yan processes, which is a crucial test of the validity of TMD factorization.
1.1) COMPASS: The analysis of transverse spin asymmetries from 2015 and 2018 data taking in the dimuon high mass range (4.3 GeV/c^2 - 8.5 GeV/c^2) has been published (arxiv.org/abs/2312.17379). The Sivers asymmetry is found to be one standard deviation above zero, which is in agreement with the sign-change hypothesis.

Drell-Yan unpolarized cross sections have been measured in ammonia, aluminum and tungsten. Preliminary results were shown at SPIN 2023, 24-29 September 2023

1.2) CMS: The final analysis of DY transverse-momentum spectra measured by CMS was published in Eur.Phys.J.C 83 (2023) 7, 628.

Task 2: Analysis of semi-inclusive DIS data

2.1) At COMPASS the analysis of unidentified hadrons off proton target is near to completion and preliminary results have been presented at international conferences. Progress has been achieved on the analysis of data with identified hadrons using the RICH detectors.

2.2) At COMPASS, the data taking with transversely polarized target has been performed in 2022 and results published in Phys.Rev.Lett. 133 (2024) 10, 101903.

2.3) At CLAS, the longitudinal polarized target has been installed and data was taken in 2022-2023. The analysis is in progress and preliminary data have been presented at conferences (see, e.g., https://agenda.infn.it/event/38132/contributions/234391/). Progress with the RICH detector have been documented in Nucl.Instrum.Meth.A 1057 (2023) 168758.

Task 3: Analysis of electron-positron data

3.1) The analysis of Belle e^+e^- is slowly progressing. Most of the intermediate analysis steps have been cross-checked. A framework for tuning Pythia MC generator was developed and published, with the aim of reducing strong Pythia model dependence of systematics.

Task 4: Quark TMD extractions

The MAP22 extraction of pion TMDs from Drell-Yan data has been published (e-Print: 2210.01733 [hep-ph]).

The ART23 extraction of unpolarized proton TMDs at N4LL has been published (e-Print: 2305.07473 [hep-ph]).

The MAP24 extraction of unpolarized proton TMDs and unpolarized fragmentation functions, including their flavor dependence, was published (e-Print: 2405.13833 [hep-ph])

A parametrization of unpolarized TMD fragmentation functions was published (e-Print: 2306.02937 [hep-ph]).

Apart from these improved extractions of quark TMD PDFs and FFs, several other related achievements took place:

Benchmarking of available codes, especially for Drell-Yan precision physics (see CERN EW precision working group)

Global reweighting of Sivers, transversity, and Collins functions from azimuthal asymmetries (arxiv.org/abs/2402.12322)

Alternative approach to TMD parametrization (HSO) (arxiv.org/abs/2401.14266)

Study of transverse momentum with parton branching approach (arxiv.org/abs/2312.08655, arxiv.org/abs/2404.04088)

Task 5: Gluon TMD studies
5.1) The TMD shape functions for J/ψ production in SIDIS have been studied (arxiv.org/abs/2304.09473). The gluon transverse-momentum-dependent fragmentation function (TMDFF) at next-to-leading order (NLO) into heavy quarkonium was computed (https://arxiv.org/abs/2308.12356v3) Matching coefficients of gluon TMDs have been calculated (arxiv.org/abs/2306.15052) 5.2) A model calculation of T-odd gluon TMDs was completed (arxiv.org/abs/2402.17556). This can help to make predictions for experimental observables. 5.3) A detailed phenomenological study of J/ψ polarization in semi-inclusive deep inelastic scattering processes has been published (arXiv:2301.11987 [hep-ph]). An analysis of single and double spin asymmetries for C-even quarkonium production was performed (arxiv.org/abs/2403.20017)

Highlights of significant results

New data suitable for TMD studies have been collected in all processes of interest (Drell-Yan, semi-inclusive DIS, for e+e− annihilation to hadrons) and almost all published. At COMPASS and CLAS, polarized targets have been installed and data taking has been performed in 2022-2023.

New extractions of TMD distribution and fragmentation functions (unpolarized and polarized) have been completed and published. The results have been made available through the TMDlib interface (https://arxiv.org/abs/2103.09741)

Several theoretical and phenomenological studies of gluon TMDs have been published.

Overall, all tasks have been completed, with the exception of Tasks 3.1 and 3.2.

Deliverables due in RP3.

D22.1 TMD data from DY, SIDIS, e+e− – Achieved

Publications containing data from DY

[CMS] Eur.Phys.J.C 83 (2023) 7, 628, e-Print: 2205.04897 [hep-ex]

[COMPASS DY unpol] Pion-induced Drell-Yan cross section [Paper in drafting. Results were shown at SPIN 2023, 24-29 September 2023]

[COMPASS DY transverse] Phys.Rev.Lett. 133 (2024) 7, 071902; e-Print: 2312.17379 [hep-ex]

Publications containing data from SIDIS

[CLAS A_LU] Phys.Rev.Lett. 130 (2023) 2, 022501; e-Print: 2208.05086 [hep-ex]

[COMPASS] Int.J.Mod.Phys.A 37 (2022) 07, 2240005; DOI: 10.1142/s0217751x2240005x

[COMPASS A_UT] Phys.Rev.Lett. 133 (2024) 10, 101903; e-Print: 2401.00309 [hep-ex]

Publications containing data from e+e-

[BELLE] Phys. Rev. D 100 (2019) 9, 092008; e-Print: 1909.01857 [hep-ex]

D22.2 Parametrizations of TMD PDFs and FFs – Achieved

Publications containing parametrizations of TMD PDFs

[PDF bias] JHEP 10 (2022) 118; e-Print: 2201.07114 [hep-ph]

[PionTMDs] Phys.Rev.D 107 (2023) 1, 014014; e-Print: 2210.01733 [hep-ph]

[ART 23] JHEP 05 (2024) 036; e-Print: 2305.07473 [hep-ph]

[PV Sivers] Phys.Lett.B 827 (2022) 136961; e-Print: 2004.14278 [hep-ph]

Publications containing parametrizations of FFs

[TO1] Phys.Rev.D 106 (2022) 7, 074024; e-Print: 2206.08876 [hep-ph]

[TO2] JHEP 09 (2023) 006; e-Print: 2306.02937 [hep-ph]

Publications containing parametrizations of both

[SV 20] JHEP 06 (2020) 137; e-Print: 1912.06532

[MAP 22] JHEP 10 (2022) 127; e-Print: 2206.07598 [hep-ph]

[MAP 24] JHEP 08 (2024) 232; e-Print: 2405.13833 [hep-ph]

D22.3 Estimates of quarkonium production in SIDIS – Achieved

Publications containing estimates of quarkonium production in SIDIS

[Dijet] JHEP 03 (2022) 047; e-Print: 2111.03703 [hep-ph]

[J/Psi] Phys.Rev.D 106 (2022) 1, 014030; e-Print: 2204.01527 [hep-ph]

[J/Psi pol] Phys. Rev. D 107 (2023), 114001, e-Print: 2301.11987 [hep-ph]

Milestones due in the RP3.

MS42 Implementation of polarized target at CLAS12run – Achieved

The polarized target has been commissioned, and data taking started in May 20.

1.2.14 Work Package 23

Activity Type	Joint Research Activity
Work package title	Generalized Parton Distributions (JRA5-GPD-ACT)
Lead beneficiaries	1 – CNRS, 24 – CEA, 30 - INFN

Project objectives

The concept of Generalized Parton Distributions (GPDs) allows to study the structure of nucleons in terms of quarks and gluons (partons) at a previously unexpected level. GPDs give information, for instance, on the correlation between the transverse spatial distributions and longitudinal momentum distributions of the partons, thus providing a three-dimensional mapping of the nucleon. They are related also to the orbital angular momentum contribution of partons to the nucleon's spin.

It is the objective of this WP to access GPDs experimentally through hard exclusive reactions such as the lepto-production of a photon ("Deep Virtual Compton Scattering", DVCS) or of a meson ("Deep Virtual Meson Production", DVMP) or in photo-production of a lepton pair ("Time-like Compton Scattering", TCS). These exclusive reactions have been measured in certain kinematical regions and one particular objective of this WP is the analysis of the numerous data already collected these past years at COMPASS and TJNAF and not published.

Progress made during the reporting period towards objectives

Task 1: GPD experiments at TJNAF@12 GeV
A prototype of ALERT was constructed and tested in magnetic field during 2023. The full detector was constructed and delivered to JLab in the spring 2024, for data taking to start in the second half of 2024. CLAS12 measured DVCS beam spin asymmetry on unpolarized LH2 target in a kinematic region never covered before. In the previously measured kinematics, the new data are shown to be in good agreement with existing data and they improve the precision of GPD fits. (Phys. Rev. Lett. 130, 211902 (2023)). CLAS12 measured DVCS beam spin asymmetry on deuteron target and determined this asymmetry for DVCS on neutron. The extracted beam-spin asymmetries, combined with DVCS observables measured on the proton, allowed a clean quark-flavor separation of the imaginary parts of the Compton form factors H and E. (arXiv:2406.15539, submitted to Phys. Rev. Lett.)
Task 2: Analysis of COMPASS data
COMPASS collaboration performed analysis of exclusive pi0 production data collected in 2016 in polarized muon - proton scattering, demonstrating good agreement with GK model predictions.

Exclusive pi0 production results are presented on several conferences and a publication is due soon. Spin Density Matrix Elements in exclusive rho meson production have been published (EPJC (2023) 83 924; hep-ex/2211.00093).
Task 3: Building models, analysis of processes and extraction from data
There is an advancement in the combining lattice QCD and phenomenological inputs on GPDs at moderate skewness (arXiv:2306.01647, *Eur.Phys.J.C* 84 (2024) 2, 201). It was shown how to relate exclusive measurements to PDFs small Bjorken xB based on evolution equations (arXiv:2302.07861, *Phys.Rev.D* 107 (2023) 11, 114019). The operator definition of generalised transverse-momentum-dependent (GTMD) distributions is exploited to compute for the first time the full set of one-loop corrections to the off-forward matching functions. (arXiv: 2207.09526, *Eur.Phys.J.C* 82 (2022) 10, 941), and evolution equations for GPDs were recalculated (arXiv:2206.01412, *Eur.Phys.J.C* 82 (2022) 10, 888) and implemented in the code. This was done in collaboration with VA2-3DPartons virtual access workpackage of H2020-STRONG. Other exclusive processes were studied and found to be good candidates for GPD extraction. (arXiv:2212.00655, JHEP 03 (2003) 241. NLO DVMP and multichannel fits (in combination with DIS and DVCS) were performed and the importance of inlusion of NLO corrections to DVMP amplitude was shown (arXiv:2310.13837, JHEP 12 (2023) 192, JHEP 02 (2024) 225 (erratum)). Twist-3 contributions to the DVMP of pions are determined and favorable comparison to Jlab and COMPASS measurements was demonstrated (arXiv: 2312.13164, PRD 109, 034008 (2024)) Public analysis code Gepard released in previous reporting period is completed by a public server serving numerical results in graphical and numerical form (in collaboration with VA2-3DPartons virtual access workpackage). See Sect. 4.3 for details on this.

Highlights of significant results

On the experimental side, highlights are construction of a low energy recoil tracker (ALERT) increasing precision of measurements of GPD-related and other processes at JLab and publications of results on DVCS on proton (and soon neutron) in unprecedented kinematical span. (Phys. Rev. Lett. 130, 211902 (2023)).

On the theory side, it was demonstrated that exclusive photoproduction of photon-pion pair with large invariant mass can be used to access chiral-even quark GPDs (JHEP 03 (2003) 241.)

On the phenomenology side, Gepard code for GPD analysis has been completed with public server https://gepard.phy.hr/ and used for first multichannel NLO fit of DIS, DVCS and DVMP data (JHEP 12 (2023) 192, JHEP 02 (2024) 225 (erratum))

Deliverables due in RP3.

D23.2 Publication of COMPASS results – Achieved

This deliverable was partially realized. It was originally a very ambitious deliverable, promising "Publication of COMPASS results. Using the data taken in 2016-17 with a liquid hydrogen target, a recoil detector, and polarized mu+ and mu- beams: sum and difference of DVCS cross section, with study of the slope of dSigma_DVCS/dt and of the D term; Pi, Rho, Omega, Phi, J/psi cross section and evolution in W, Q2 and t."

The main problem was that the DVCS analysis using the last data taken in 2016 was surprisingly not in agreement with a result obtained with test run data from 2012. The new result obtained using the data taken in 2016 is more precise and exhibits a difference of about 3 sigma with respect to the 2012 data. This then required a lot of extra work to recheck everything and with the help of several PhD students the analysis was further refined and the new result is now confirmed to be 2 sigma different from the 2012 results. For this latest results the cross check is still ongoing due to shortage of manpower. In the meantime, a new group joined the analysis allowing COMPASS collaboration to proceed with the analysis of the complete set of data. A paper presenting the results is expected to be completed in the following months.

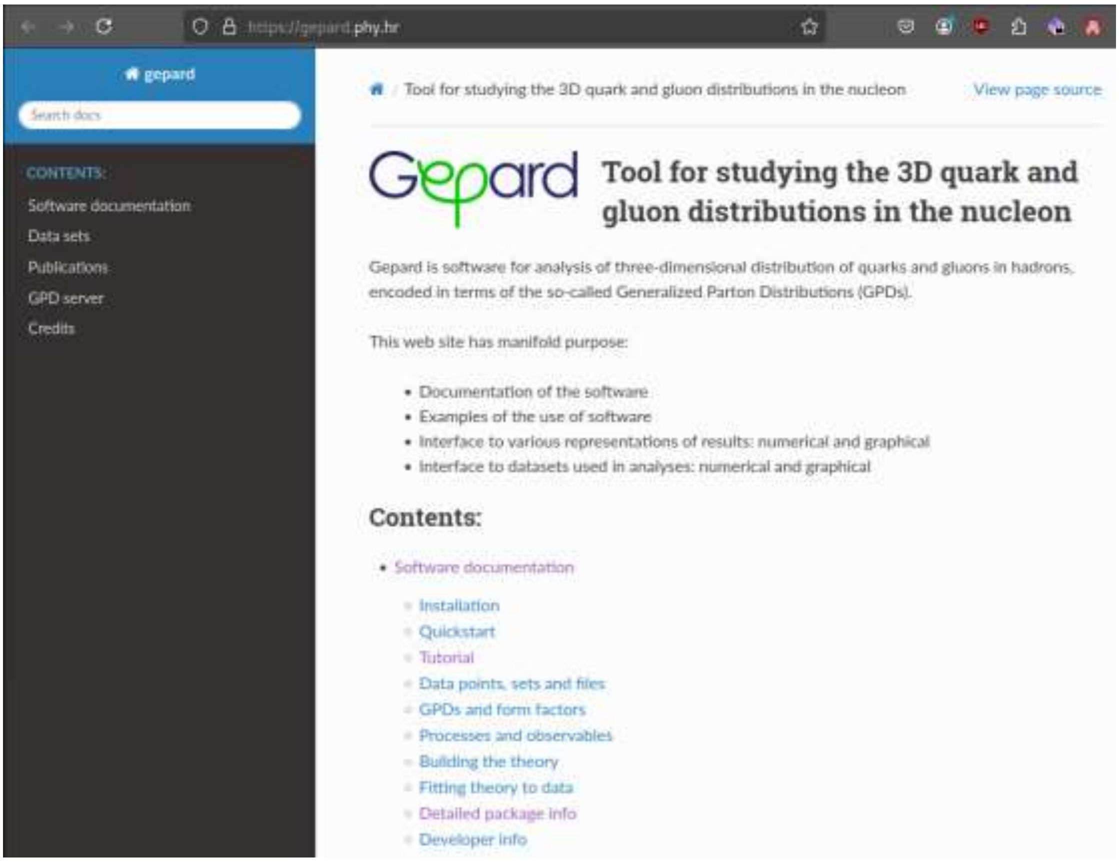
In the last two years collaboration found many improvements in the pi0 analysis, which are also applicable to the other channels. As a result, parts of the analysis chains had to be redone. Presently the exclusive pi0 analysis data are released and publication is prepared, and the exclusive phi meson analysis is also in the final phase.

Spin Density Matrix Elements (SDME) for the exclusive rho0 production have been published (EPJC (2023) 83 924; hep-ex/2211.00093) This result is by itself very important for the objectives of this workpackage, because SDME enable separation of transversal and longitudinal parts of the cross-section which are described by different GPDs.

Even if this deliverable is not yet formally delivered as promised, i.e. in terms of journal publications, results have been presented in many (10-15) international conferences and workshops, so community is well informed about these measurements and the resulting advancement in the understanding of GPD physics.

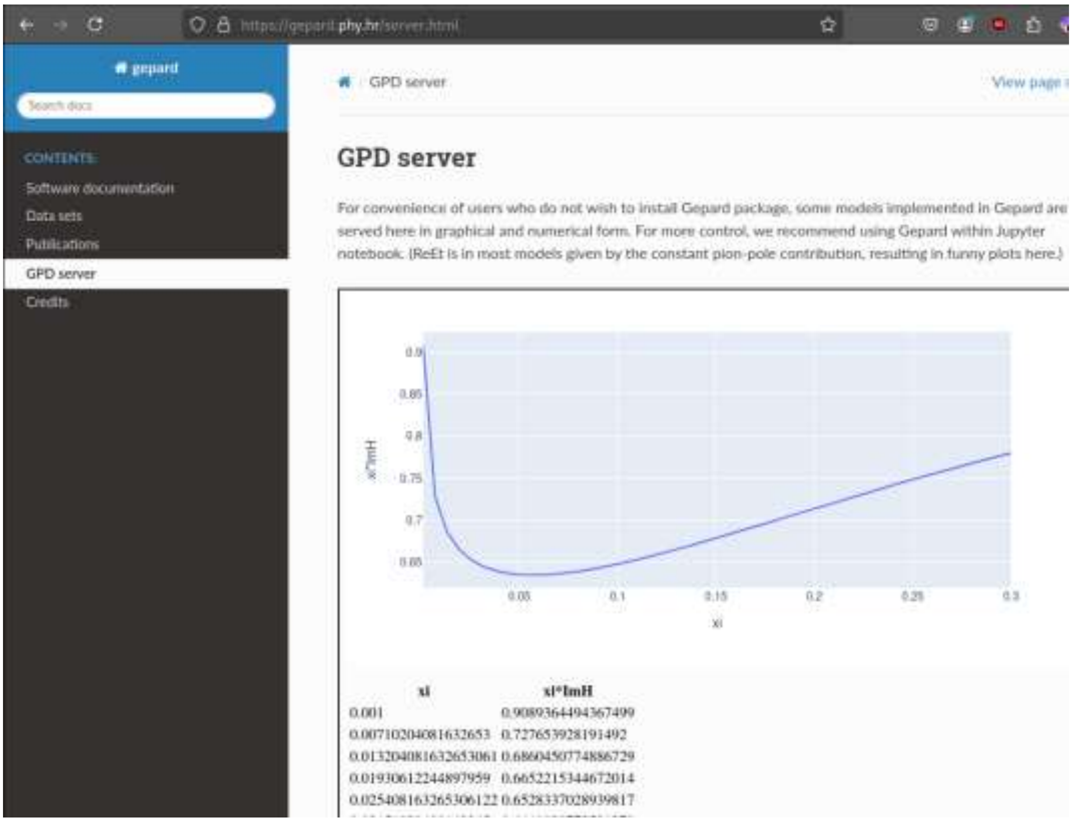
D23.3 Public software serving GPD fit results – Achieved

Gepard Python package, together with the related WWW site gepard.phy.hr, developed within the JRA5-GPD-ACT workpackage of STRONG-H2020 project, using also the framework provided by VA2-3DPartons virtual access workpackage, is providing the community the multi-purpose tool for studying the 3D quark-gluon structure of hadrons, as encoded in terms of Generalized Parton Distributions (GPDs).



Gepard Python package is hosted on PyPI repository, and is directly installable on Linux, Windows, and MacOS platforms, while its source code is open and hosted on github.com. By installing the package user can easily build models of GPDs and DVCS and DVMP form factors, calculate related observables (light vector meson DVMP cross-sections, DVCS cross-sections and asymmetries) and compare to the available experimental measurements graphically and by using standard statistical tools (MINUIT fitting). Development version (available via github) provides also the possibility of extraction of structure functions usin PyTorch neural network library. Many experimental measurements by HERA and JLab collaborations are also provided, as well as models known to be in good agreement with this data (GK, KM), so Gepard can be used to make predictions and impact of future experiments.

WWW site gepard.phy.hr is hosting simple usage tutorials, detailed Gepard package information, and developer information. A GPD server, serving the Compton Form Factors in graphical and numerical form is also provided for convenience of users who do not wish to install the Gepard Python package.



In separate [github.com repositories](https://github.com), Jupyter notebooks are provided with example calculations corresponding to published GPD studies.

Milestones due in the RP3.

MS46 Construction of ALERT, NPS, and FT-hodoscope electronics – Achieved

Month 58 is for delivery of ALERT drift chamber. NPS and FT-hodoscope were delivered before that.

1.2.15 Work Package 24

Activity Type	Joint Research Activity
Work package title	Challenges for next generation DIS facilities (JRA6-next-DIS)
Lead beneficiaries	24 – CEA, 30 – INFN, 42 – UOB, 44 - UGLASGOW

Project objectives

High precision Monte Carlo (MC) simulations of the physics processes are essential to design the interaction region, identify the optimal detector configurations and refine their parameters. Modern time projection chambers (TPCs) used for charged particle tracking, are designed to operate at high collisions rates. Their main limitation is the amount of positive ions, created during the electron amplification processes that drift back from the readout detectors into the TPC's drift volume (ion back-flow, or IBF). Minimising this becomes a priority of TPC design. Photon detectors for particle identification: the reconstruction of many reactions of interest depends on the ability to identify particles, which cannot be distinguished kinematically at high momenta, such as pions and kaons. In this kinematic regime, particle identification is most effectively achieved with ring-imaging Cherenkov (RICH) detectors, whose performance crucially depends on the photon detection.

The extremely high resolution required for vertex reconstruction in the EIC can be achieved using silicon pixel sensors and this WP proposes to develop a prototype for central and forward/backward tracking and vertexing, which will exploit the advantages of depleted MAPS technologies (DMAPS).

Progress made during the reporting period towards objectives

Task 1: Monte Carlo Simulations
The deliverable for this task, namely a simulation study of exclusive processes at the Electron-Ion Collider, was completed and formed section 8.4 of the EIC Yellow Report (Nucl.Phys.A 1026 (2022) 122447). In this reporting period, the focus has been on simulation for the EIC detector (ePIC) on two main aspects. On the one hand, simulations of exclusive processes have continued as they are instrumental for the optimization of the ePIC design. On the other hand, GEANT4 simulations of the Low-Q2 tagger based on the Timepix technology have continued at UGLASGOW in collaboration with the UK's Nuclear Physics Cross Community Support Group based at Daresbury Laboratory.
Task 2: Very low ion-back-flow detectors for high-flux TPC
The development and characterisation of a new hybrid MPGD (micro-pattern gaseous detector) detector with very low ion-back-flow (IBF) has been completed in 2023 with the publication of the results in Nucl.Instrum.Meth.A 1051 (2023) 168134. Results have shown that a hybrid structure Micromegas-GEM-micromesh can achieve IBF values as low as 0.2% for detector gains around 2000. During this reporting period, the activities focused on the design, development and simulation of a cylindrical Micromegas layer for the tracking system of the EIC detector (ePIC). The ePIC silicon vertex tracker, developed in Task 4, will be complemented by layers of MPGDs to provide redundancy for tracking and patter recognition. An MPGD layer in EIC must be light in material budget, fit in a tight environment, work in high a magnetic field, and have 2D readout capabilities. Therefore, the activity focused on the upgrade of the 1D-readout cylindrical Micromegas technology developed for the CLAS12 experiment at Jefferson Lab: the choice of a 2D readout pattern and the resistive layer are being optimized for the ePIC needs. In March 2024, the design and the status of the R&D have been presented at the EIC Project Preliminary Design Review of the Tracking system. In parallel, a realistic description of the cylindrical Micromegas layer has been implement in the ePIC simulation framework: this allow for further optimization of the detector design.
Task 3: Photon detectors for particle identification using RICH

The main goal of this task is the implementation of a dual-radiator ring imaging Cherenkov detector (dRICH) for the hadron separation over the 3 GeV/c to 60 GeV/c momentum range, and the electron identification up to 15 GeV/c, for the EIC detector (ePIC).

In this reporting period, the small-scale prototype (D24.3, in the previous achieved in the previous reporting cycle) has been brought to beam test at CERN for further studies. In particular, it was equipped with eight improved photo-detectors and tested with various Aerogel samples and two gas radiators. The SiPM sensors have been operated at two working point temperatures of -40C and -20C. The temperature of the radiator chamber has been continuously monitored. In this beam test campaign, a better separation of the Cherenkov rings has been achieved.

Also in this reporting period, careful studies of the geometry and the integration of the dRICH detector in ePIC have been made in strict collaboration with the EIC Project engineers: the complex and compact design of ePIC imposes constraints on the geometry and interferences with the other subsystems had to be resolved.

Task 4: Depleted MAPS for tracking

During the reporting period work towards the realization of the first EIC silicon detector, the ePIC Silicon Vertex Tracker (SVT) has been carried out on three topics.

Sensor development continued in collaboration with the ALICE ITS3 project to develop a new generation depleted MAPS sensor in 65 nm to satisfy the stringent requirements on vertex and tracking measurements at the EIC. During the reported period, the ITS3 collaboration with contributions from ePIC institutes developed prototypes for technology exploration (MLR1 prototypes) and for learning of stitching methodology (ER1 prototype) towards the realization of the wafer scale sensor for ITS3 and ePIC. Within this effort, the University of Birmingham worked on the characterization of the analogue pixel test structures (APTS) prototype to assess the charge collection properties of the technology and hence its suitability for a production sensor. In particular, lab characterization with radioactive sources was performed on 14 different flavors of APTS. These were combinations of different pixel sizes, pixel designs and process parameters. They have been tested, with signals injected via pulse generators and radioactive sources. Results highlighted how the optimizations in pixel design and process parameters achieve a larger depletion volume and shape the electric field lines leading to excellent charge collection properties with a pixel size in the order of 20 um, making the technology suitable to develop the sensor for the ePIC SVT. (More details are given in the deliverable report in 4.1)

In the **tracking and vertexing** context, work in Birmingham continued on the definition of the detector layout, the study of its performance, and the development of the associated tracking software with key contributions to the development of the ePIC tracker. The work proceeded through successive versions of the tracking detector and the evaluation of their impact on momentum and vertex resolutions. In particular: the position of the silicon vertex layers was optimized to maximize vertexing performance; trade-offs have been identified between redundancy and material for the silicon disk configurations in the forward and backward directions; the impact of the MPGD detectors in terms of their contribution to the tracker resolution and redundancy was investigated, highlighting their main role for track pattern recognition. Following up on work from the ePIC Background Task Force, first estimates of radiation levels and hit rates in the SVT were provided. In terms of more general contributions, Birmingham maintained an up-to-date parametrization of the vertex and momentum resolution of the ePIC detector at each new iteration of the geometry and contributed to the development of the track reconstruction software via benchmarking studies of realistic seeding versus truth seeding.

Physics simulations concentrated on expanding previous work on reconstruction of DIS kinematic variables with a reconstruction method developed in Birmingham. This uses a combination of knowledge of the cross-section for the kinematic variables x and y, and initial state radiation, with the detector resolution on the measured electron and hadron final states to improve the reconstruction. This method yields, in addition to the DIS kinematic variables, the energy of a possible photon radiated from the incoming electron beam, which allows to get better resolution. Applying this method to ePIC simulated data showed its performance matches that of the best standard reconstruction method across the kinematic range. The method has been validated using with H1 simulation and data, showing good agreement. H1 simulations also show that hard ISR can be identified with good resolution and efficiency. Hard ISR results in a lower energy electron beam and extends the kinematic reach if identified. The distributions of reconstructed ISR in simulation and data also show good agreement.

Highlights of significant results

Task 4: Demonstration of the suitability of the selected 65 nm CMOS imaging process for the development of the wafer scale ePIC SVT MAPS sensor through the evaluation of prototypes.

Deliverables due in RP3.

D24.4 EIC DMAPS prototype and characterization – Achieved

During the grant period, Birmingham worked on the development of prototypes for the ePIC SVT depleted MAPS sensor. The activity focused on the characterization of prototype structures to assess the charge collection properties of the devices. In total 14 different flavors of analogue pixel test structures were characterized. Flavors differ by pixel size, pixel design and process parameters.

Figure 1 shows a schematic of the pixel cross-section for the three different pixel designs. Flavor (a) is the standard process as used in previous generation MAPS (such as the ALPIDE sensor), where the depletion region grows only around the n-well collection electrode. In flavor (b), the use of a deep n-well implant achieves full depletion of the pixel volume, extending the depletion region below the p-well containing the electronics. Finally, flavor (c) introduces a gap in the deep n-well between pixels to shape the electric field at the edges for a more complete charge collection in the entire pixel.

These three flavors come in up to four splits, where each split contains optimizations of the geometry and size of both the collection electrode and the electronics p-well to further enhance charge collection properties. The combinations of pixel design and splits are implemented on pixel sizes between 10 and 25 μm.

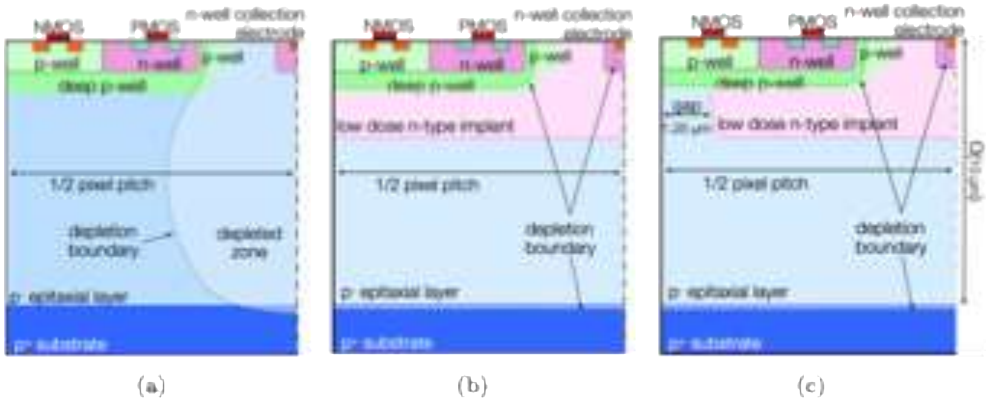


Figure 1: APTS pixel designs [1]. (a) standard process; (b) modified process with deep n-well; (c) modified process with deep n-well with gap.

Figure 2 shows the results of an example measurement with an ^{55}Fe source. The plot on the left shows the results on sensors implemented in the standard process from split 1 and 4. The plot on the right shows the results on sensors implemented in the modified process with gap for all four splits. The pixel pitch is 15 µm. With the process modifications, the ^{55}Fe spectra is clearly visible demonstrating the improved charge collection with respect to the standard process.

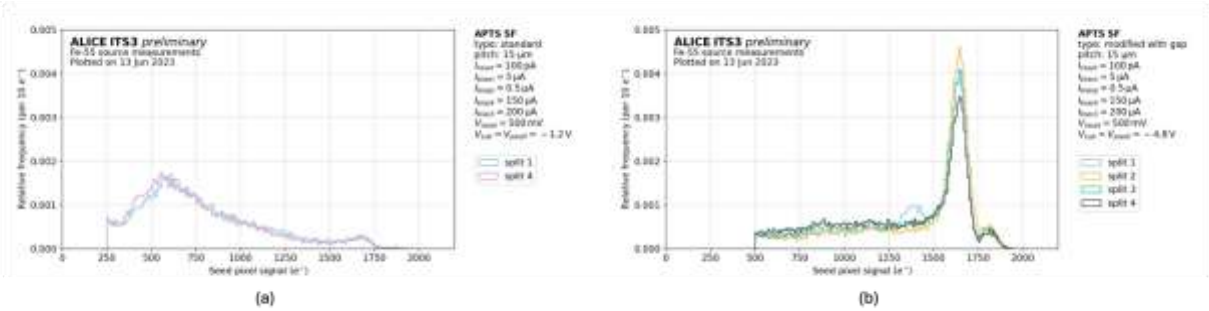


Figure 2: Comparison of different pixel designs and process optimisations (splits) for 15 μm pitch APTS sensors.

The results obtained in this study are publicly available as part of a publication currently on the arxiv and under review by NIMA [1] and have also been presented at an EIC UK meeting [2].
[1] https://arxiv.org/abs/2403.08952
[2]https://indico.jlab.org/event/760/contributions/14248/attachments/10697/16836/ePIC_SVT_sensor_development_Long_NEW.pdf

Milestones due in the RP3.

MS51 First functional tests of the EIC DMAPS chip - Achieved

1.2.16 Work Package 25

Activity Type	Joint Research Activity
Work package title	Light-and heavy-quark hadron spectroscopy (JRA7-HaSP)
Lead beneficiaries	12 – UHEI, 13 – TUM, 18 – UCM, 19 – USAL, 22 – UVEG, 30 – INFN, 43 - UEDIN

Project objectives

The HaSP network activity aims to coordinate the leading European institutions active in hadron spectroscopy with the objective of making progress in the development of theoretical, phenomenological, and computational foundations for amplitude; establishment of best practices for accessing systematic uncertainties in the analysis of hadron reaction data and interpretation of physics results.

Progress made during the reporting period towards objectives

Task 1. Precision calculations in non-perturbative QCD (I)

QCD symmetries at the hadron level are used to construct EFT's able to describe the low energy hadronic phenomenology. Dispersion relations provide rigorous constraints to theoretical predictions that can be used to obtain accurate properties of excited states. Especially when combined with EFT's, they provide a very powerful connection between the Hadronic and QCD realms.

T1.1 Development and application of Effective Field Theories (EFTs)
There were various different activities within the task that are below sorted under a few headlines.

1. *Understanding the hadron spectrum from data*

- The Jülich-Bonn dynamical coupled-channel (JüBo DCC) model is employed to extract the N^*- and Δ-spectrum. For this, the data base was extended by including recent data for η-photoproduction for the observables $d\sigma/d\Omega$ and Σ by the LEPS2/BGOegg Collaboration as well as recent data for the processes $\gamma p \to \pi^0 p$ and $\gamma p \to \pi^+ n$ for the double polarization observable G by the CLAS Collaboration and data for $\gamma p \to \pi^0 p$ on the double spin polarization observable E. With these newly included datasets an updated fit result was produced. Furthermore, the coupled channel model allows us to extract the individual contributions from each channel to physical observables. This was used to analyse the different contributions to the Gerasimov-Drell-Hearn (GDH) sum rule. The new fit result as well as the GHD sum rule determination were already presented at the international conference PWA13/ATHOS8 in the USA and a publication is in preparation.
- An effective field theory for the $DD\pi$ system was constructed in [Du:2021zzh] to analyse the LHCb data for $pp \to DD\pi X$, where X denotes other, undetected hadrons, showing a pronounced signal of a resonance dubbed $T_{cc}(3875)$ in the $DD\pi$ invariant mass distribution. It is in particular demonstrated that a complete non-perturbative treatment of the $DD\pi$ intermediate state is necessary to get a reliable extraction of not only the pole parameters of the exotic state but also the effective range parameters for DD^*scattering that from a crucial input to deduce the nature of the studied state [Baru:2021ldu].
- In Ref. [Ji:2022vdj] it was argued that the signals labeled as $X(3915)$, seen in the $J/\psi\omega$ channel, are from the same state as the $\chi_{c2}(3930)$. Moreover, analyzing various data sets with a $D\bar{D}, D_s\bar{D}_s, D^*\bar{D}^*$ and $D_s^*\bar{D}_s^*$ coupled channel amplitude revealed in total four scalar isoscalar states of molecular type in the mass range from 3.7-4.3 GeV.

- There is still no consensus in the literature on how to properly define branching ratios for overlapping resonances. A comparison of different methods as well as an attempt to connect partial widths and branching fractions more directly to resonance properties like pole locations and residues is provided in Ref. [Burkert:2022bqo].
- For a long time, it was unclear, if the scalar resonance $f_0(1370)$, seen in some experimental analyses and not in others, exists. A thorough application of dispersion theory and data analysis allows for a clear identification of the pole of this state that can now be assumed as established [Pelaez:2022qby].
- The impact of non-perturbative interactions of two light vector mesons on the $\bar{K}K$ spectrum in the decay $J/\psi \rightarrow \phi K\bar{K}$ is studied in Ref. [Abreu:2023xvw]. In particular it is argued that in addition to the signatures of the pertinent resonances also kinematic effects can distort the spectra.

2. *Effective field theory studies to connect lattice data to observables*

- In a follow up study of Ref. [Du:2021zzh], we investigated the DD^* system a unphysical quark masses [Du:2023hlu]. Here it is important to note that at slightly higher than physical pion mass, the D^* gets stable and the system develops a left-hand cut that calls for significant modifications to be applied to the methods used to analyze lattice spectra.

3. *Systematic studies to connect lattice data to low energy constants of the effective field theory*

- A systematic approach for calculating the matching from the gradient-flow scheme to the MS scheme in the limit of small flow time for off-light cone Wilson-line operators was presented in Ref. [Brambilla:2023vwm]. This will be crucial to use the lattice gradient flow calculations of the low energy correlators in the nonrelativistic effective field theories for quarkonium and exotics.
- A calculation for the generalized Wilson loop containing the QCD force on the lattice using gradient flow was presented [Brambilla:2023fsi]. This is an important preliminary result that opens the possibility to calculate on the lattice all correlators emerging in the nonrelativistic effective field theory, including pNRQCD and BOEFT.

4. *Construction of a Born-Oppenheimer EFT for doubly heavy exotics*

- A lot of effort was put into a construction of a Born-Oppenheimer effective field theory making use of the static quark-antiquark potentials calculated using lattice QCD. A certain application of the method is already provided in Ref. [Brambilla:2022hhi]. A long paper capturing all the various aspects of the methods as well as the different structures of the exotics accessible is in preparation.

5. *Emergence of exotic states from Goldstone-boson heavy state scattering*

- The lightest positive parity open charm states are good candidates for owing their existence to the non-perturbative nature of the Goldstone-boson heavy source interactions largely controlled by chiral symmetry. In recent studies the imprint those states should leave in two-particle correlations accessible employing femtoscopy were investigated [Albaladejo:2023pzq, Torres-Rincon:2023qll]. ALICE correlation function data was also used in [Sarti:2023wlg] to constrain the low-energy $S=-2$ meson-baryon interaction. Other works predicting correlation functions have been done.

- Analogously to the emergence of two hadron states from the scattering of Goldstone bosons off heavy mesons, the same non-perturbative dynamics also drives the generation of exotic baryons. In Ref. [Feijoo:2023wua], $\Xi(1620)$ and $\Xi(1690)$ are conjectured to emerge from the scattering of kaons and pions or eta mesons off singly and doubly strange baryons, respectively.

6. *Further studies for the emergence of two-hadron states*

- While the above look at Goldstone boson heavy particle-scattering, which is controlled to some extend by chiral symmetry, there are also studies for the scattering of light vector mesons off D mesons. Also, these studies naturally lead to the appearance of two-hadron states as demonstrated in Ref. [Molina:2022jcd].

7. *Exotic states in many body systems*

- In Ref. [Montana:2023sft] a formalism is provided that allows for a consistent treatment of finite temperature amplitudes and vacuum scattering amplitudes. The method is applied to the amplitudes derived in unitarised chiral perturbation theory and thus provides access to the thermal properties of the emerging two-hadron states. In Ref. [Montana:2022inz] it is demonstrated that the thermal properties of the $X(3872)$ and its predicted spin partner state *X(4014),* assumed to be hadronic molecules composed of $D\bar{D}^*$ and $D^*\bar{D}^*$, respectively, follow closely those of the constituents. These observations should be testable in heavy ion collisions. Then there are quite a few works looking at doubly heavy exotics in different reactions. Also, here there is still quite some work to be done.
- The πK elastic scattering amplitude at finite temperature in Chiral Perturbation Theory has been calculated, and its unitarized version through the Inverse Amplitude Method has been obtained, which allows one to generate the $K_0^*(700)$ and $K^*(890)$ poles [GomezNicola:2023rqi]. In this work, the thermal evolutions of these states have been studied. The analysis performed, which extends the finite-temperature scattering to unequal masses, as well as to thermal unitarity, opens many future lines for analysis of scattering and resonances within the light hadron multiplets.
- Hadronic molecules typically have very small binding energies that translate to large sizes. It is therefore important to study their properties at finite densities for a comparison to experimental data might reveal a new independent access to the structure of the states. In Ref. [Montesinos:2023qbx] the in medium properties of the $T_{cc}(3875)^+$ and its antiparticle are calculated and it is demonstrated that the molecular structure has an impact on the in medium properties. A similar study is carried out in [Montesinos:2024uhq] for the $D_{s0}^*(2317)^{\pm}$ exotic states.

8. *Studies of the light quark sector*

- Systematic applications of dispersion theory form a sound basis to the analysis of CP violation visible in the decays of heavy hadrons into few light hadron final states. As is demonstrated in Ref. [Garrote:2022uub] in this way the uncertainties in the analyses can be reduced drastically.
- The pion-nucleon sigma term is an important quantity since it encodes the effect of the masses of the light quarks on the nucleon mass. A controlled theoretical access to it requires sophisticated theoretical tools that are presented in Ref. [Hoferichter:2023ptl].
- A reliable determination of the pole parameters and residues of nucleon resonances have been achieved [Hoferichter:2023mgy]. In this work, a comprehensive analysis is presented, accessible with Roy–Steiner equations for pion–nucleon scattering—a set of partial-wave dispersion relations that combines the constraints from analyticity, unitarity, and crossing symmetry.

9. *Systematic studies of hadronic contributions to the muon $(g-2)$*

- There is currently a striking discrepancy between the hadronic vacuum polarization derived using dispersion theory from experimental data and calculated using lattice QCD. A possible candidate could be isospin breaking corrections either driven by QCD or by electromagnetism. In Ref. [Hoferichter:2023sli] it is demonstrated, however, that those differences are too small to explain the discrepancy.
- In Ref. [Colangelo:2022lzg] an improved analysis of $e^+e^- \to \pi^+\pi^-$ is provided including radiative corrections. In particular special emphasis is put on the cancellation of infrared singularities. This work provides an important step towards reducing further the theoretical uncertainties of the hadronic vacuum polarisation contribution to the muon $(g-2)$.

T1.2 Hadron decays

1. *Semi-inclusive heavy hibrids decays into quarkonium*

- Semi-inclusive decays of heavy quarkonium hybrids have been evaluated in the framework of non-relativistic Effective Field Theories. The leading and sub-leading powers in the heavy-quark mass have been computed and have been compared with experimental data for candidates of heavy quarkonium hybrids [Brambilla:2022hhi]
  The same formalism will be applied to the study of tetraquark decays.

2. *Decays of heavy mesons*

- B decay modes where one can find a peak for a $D\bar{D}$ bound state have been analyzed [Brandao:2023vyg]. The $B^+ \longrightarrow K^+\eta\eta$ goes through a $D_s^*\bar{D}^0$ pair with the $D_s^* \to D^0K^+$ and a posterior fusion of the $D^0\bar{D}^0$ to $\eta\eta$. A neat peak in the $\eta\eta$ mass distribution is found.
- The LHCb collaboration has recently reported the largest CP violation effect from a single amplitude in several $B-$meson decays into three

charmless light mesons. The recent model-independent dispersive analysis of $\pi\pi \longrightarrow K\bar{K}$ data have been implemented in the LHCb formalism and leads to a more accurate description of the asymmetry, while being consistent with the measured scattering amplitude and confirming the prominent role of hadronic final state interactions [Garrote:2022uub].

3. *Light meson decays*

- An improved phenomenological model that describes $V \to P\gamma$ and $P \to V\gamma$ decays including isospin-symmetry breaking was presented in Ref. [Escribano:2020jdy]. Statistical fits to the most recent experimental data for the radiative transitions and estimations for the mixing angles amongst the three pseudoscalar states $\pi^0\eta\eta'$ with vanishing third-component of isospin are obtained. The experimental uncertainties allowed for isospin-symmetry violations with a confidence level of approximately 2.5σ. In this third period, further studies of the $\eta' \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$ [Escribano:2022njt] and $\eta' \to \pi^0\ell^+\ell^-$ and $\eta' \to \eta\ell^+\ell^-$ [Escribano:2022zgm] decays have been carried out searching for new physics signatures.

4. *Study of reactions disclosing the nature of the low-lying scalar mesons*

- The role of $f_0(980)$ and $a_0(980)$ in low $K\bar{K}$ invariant mass region of B −meson decays have been analyzed. Results have been compared with LHCb data and shows that the $I = 0$ component tied to the $f_0(9809$ generates the main contribution [Abreu:2023hts]. Decays of the J/ψ into ω, ϕ, K^{*0} and a scalar or tensor resonance have been considered. New ratios relating the scalar and tensor meson productions have been also estimated. The results suggest that the D −wave mechanism of tensor production is a relevant contribution [Abreu:2023yvf]. The decay into $\phi K\bar{K}$ is also analyzed looking for differences in the charged and neutral channels. Some isospin violation appears, although due to the large width of the K^*, the final isospin violation is very small [Abreu:2023xvw]. On the other hand, the J/ψ decay into three pions has been also studied in the Khuri-Treiman framework. Experimental dipion mass distributions in the $\rho^0(770)$ mass region from BESIII are well reproduced and predictions on the transition form factor of the decay into $\pi^0\gamma^*$ are provided [JPAC:2023nhq].

5. *Search for tetraquak and pentaquark signals*

- The $D^0D^0\pi^+$ line shape for the recently discovered T_{cc}^+ tetraquark candidate have been analyzed in the framework of the chiral quark model. Results are in good agreement with LHCb data and the state is compatible with a loosely D^0D^{*+} bound state [Ortega:2022efc]. Hidden-charm pentaquark-like states have been also analyzed in the same framework as possible meson-baryon molecules [Ortega:2022uyu]. States compatible with experimental measurements are found in the *JP(I)=1/2(0)*. Other states, nor observed experimentally are also reported.

- The $T_{\psi\psi}$ tetraquark candidate has been studied in a quark model framework as a possible molecule of two hidden charm mesons in Ref. [Ortega:2023pmr]. Candidates for the experimentally seen $T_{\psi\psi}(6200)$, $T_{\psi\psi}(6600)$, $T_{\psi\psi}(6700)$, $T_{\psi\psi}(6900)$ and $T_{\psi\psi}(7200)$ have been also proposed in that work.
- A model based on unitarized meson-baryon amplitudes obtained from vector-meson exchange interactions has predicted the existence of pentaquarks with double strangeness, at about 4500 and 4600 MeV [Marse-Valera:2022khy]

REFERENCES

[Du:2021zzh] Coupled-channel approach to T_{cc}^{+} including three-body effects. M.L.Du, V.Baru, X.K.Dong, A.Filin, F.K.Guo, C.Hanhart, A.Nefediev, J.Nieves and Q. Wang. Phys. Rev. D105 (2022) 014024.

[Baru:2021ldu] Effective range expansion for narrow near-threshold resonances. V. Baru, X. K. Dong, M. L. Du, A. Filin, F. K. Guo, C. Hanhart, A. Nefediev, J. Nieves and Q. Wang. Phys. Lett. B 833 (2022) 137290.

[Ji:2022vdj] Understanding the 0^{++} and 3^{++} charmonium(-like) states near 3.9 GeV. T. Ji, X. K. Dong, M. Albaladejo, M.L.Du, F.K. Guo, J. Nieves and B. S. Zou, Sci. Bull. 68 (2023) 688.

[Burkert:2022bqo] Note on the definitions of branching ratios of overlapping resonances. V. Burkert, V. Crede, E. Klempt, K. V. Nikonov, J. A. Oller, J. R. Peláez, J. R. de Elvira, A. V. Sarantsev, L. Tiator and U. Thoma, et al. Phys. Lett. B844 (2023) 138070.

[Pelaez:2022qby] $f_0(1370)$ Controversy from dispersive meson-meson scattering data analyses. J.R. Pelaez, A. Rodas and J. R.de Elvira. Phys. Rev. Lett. 130 (2023) 051902.

[Abreu:2023xvw] Traces of the new $a_0(1780)$ resonance in the $J/\psi \to \phi K^+K^-(K^0\bar{K}^0)$ reaction,
L. M. Abreu, W. F. Wang and E. Oset. Eur. Phys. J. C83 (2023) 243.

[Du:2023hlu] Role of left-hand cut contributions on pole extractions from lattice data: case study for $T_{cc}(3875)^+$. M. L. Du, A. Filin, V. Baru, X. K. Dong, E. Epelbaum, F. K. Guo, C. Hanhart, A. Nefediev, J. Nieves and Q. Wang. Phys. Rev. Lett. 131 (2023) 131903

[Brambilla:2023vwm] Off-lightcone Wilson-line operators in gradient flow. N. Brambilla and X. P. Wang. JHEP 06 (2024) 210.

[Brambilla:2023fsi] Static force from generalized Wilson loops on the lattice using the gradient flow.
N. Brambilla, V. Leino, J. Mayer-Steudte and A. Vairo. Phys. Rev. D109 (2024) 114517.

[Brambilla:2022hhi] Heavy hybrid decays to quarkonia. N. Brambilla, W. K. Lai, A. Mohapatra and A. Vairo, Phys. Rev. D107 (2023) 054034.

[Albaladejo:2023pzq] Femtoscopic signatures of the lightest S −wave scalar open-charm mesons. M. Albaladejo, J. Nieves and E. Ruiz-Arriola. Phys. Rev. D108 (2023) 014020-

[Torres-Rincon:2023qll] Femtoscopy of D mesons and light mesons upon unitarized effective field theories. J. M. Torres-Rincon, À. Ramos and L. Tolos. Phys. Rev. D108 (2023) 096008.

[Sarti:2023wlg] Constraining the low-energy $S = -2$ meson-baryon interaction with two-particle correlations. V. M. Sarti, A. Feijoo, I. Vidaña, A. Ramos, F. Giacosa, T. Hyodo and Y. Kamiya. Phys. Rev. D110 (2024) L011505.
[Feijoo:2023wua] The $\Xi(1620)$ and $\Xi(1690)$ molecular states from $S = -2$ meson-baryon interaction up to next-to-leading order. A. Feijoo, V. Valcarce Cadenas and V. K. Magas. Phys. Lett. B841 (2023) 137927.
[Molina:2022jcd] $T_{cs}(2900)$ as a threshold effect from the interaction of the D^*K^*, $D_s^*\rho$ channels. R. Molina and E. Oset. Phys. Rev. D107 (2023) 056015.
[Montana:2023sft] Recent progress on in-medium properties of heavy mesons from finite-temperature EFTs. G. Montaña, A. Ramos, L. Tolos and J. M. Torres-Rincon. Front. in Phys. 11 (2023) 1250939.
[Montana:2022inz] $X(3872), X(4014)$, and their bottom partners at finite temperature. G. Montaña, A. Ramos, L. Tolos and J.M. Torres-Rincon. Phys. Rev. D107 (2023) 054014.
[GomezNicola:2023rqi] The pion-kaon scattering amplitude and the $K_0^*(700)$ and $K^*(892)$ resonances at finite temperature. A. Gómez Nicola, J. Ruiz de Elvira and A. Vioque-Rodríguez. JHEP 08 (2023) 148.
[Montesinos:2023qbx] Properties of the $T_{cc}(3875)^+$ and the $T_{\bar{c}\bar{c}}(3875)^-$and their heavy-quark spin partners in nuclear matter. V. Montesinos, M. Albaladejo, J. Nieves and L. Tolos, Phys. Rev. C108 (2023) 035205.
[Montesinos:2024uhq] Charge-conjugation asymmetry and molecular content: The $D_{s0}^*(2317)^{\pm}$ in matter. V. Montesinos, M. Albaladejo, J. Nieves and L. Tolos, Phys. Lett. B853 (2024) 138656.
[Garrote:2022uub] Dispersive $\pi\pi \to K\bar{K}$ amplitude and giant CP Violation in B to three light-meson decays at LHCb. R. A. Garrote, J. Cuervo, P. C. Magalhaes and J.R. Peláez, Phys. Rev. Lett. 130 (2023) 201901.
[Hoferichter:2023ptl] On the role of isospin violation in the pion-nucleon σ −term. M. Hoferichter, J. R. de Elvira, B. Kubis and U. G. Meissner. Phys. Lett. B843 (2023) 138001.
[Hoferichter:2023mgy] Nucleon resonance parameters from Roy-Steiner equations. M. Hoferichter, J. Ruiz de Elvira, B. Kubis, Ulf-G. Meißner. Phys. Lett. B 853 (2024) 138698.
[Hoferichter:2023sli] Phenomenological estimate of isospin breaking in hadronic vacuum polarization. M. Hoferichter, G. Colangelo, B. L. Hoid, B. Kubis, J. R. de Elvira, D. Schuh, D. Stamen and P. Stoffer. Phys. Rev. Lett. 131 (2023) 161905.
[Colangelo:2022lzg] Radiative corrections to the forward-backward asymmetry in $e^+e^- \to \pi^+\pi^-$. G. Colangelo, M. Hoferichter, J. Monnard and J. R. de Elvira. JHEP 08 (2022) 295.
[Brandao:2023vyg] B^+decay to $K^+\eta\eta$ with $(\eta\eta)$ from the $D\bar{D}(3720)$ bound state. P. C. S. Brandão, J. Song, L. M. Abreu, and E. Oset. Phys. Rev.D108 (2023) 054004.
[Escribano:2020jdy] $\pi^0 - \eta - \eta'$ mixing from $V \to P\gamma$ and $P \to V\gamma$ decays. R. Escribano and E. Royo. Phys.Lett.B 807 (2020) 135534.
[Escribano:2022njt] Sensitivity of the $\eta^{(\prime)} \to \pi^0\gamma\gamma$ and $\eta^{(\prime)} \to \eta\gamma\gamma$ to a sub-GeV leptophobic $U(1)_B$ boson. R. Escribano, S. González-Solís and E. Royo. Phys. Rev. D106 (2022) 114007.
[Escribano:2022zgm] New-physics signatures via CP violation in $\eta^{(\prime)} \to \pi^0\mu^+\mu^-$ and $\eta^{(\prime)} \to \eta\mu^+\mu^-$decays. R. Escribano, E. Royo and P. Sánchez-Puertas. JHEP 05 (2022) 147.

[Abreu:2023hts] Role of the $f_0(980)$ and $a_0(980)$ in the $B^- \to \pi^- K^+ K^-$ and $B^- \to \pi^- \bar{K}^0 K^0$ reactions. L. M. Abreu, N. Ikeno and E. Oset. Phys. Rev. D108 (2023) 016007.
[Abreu:2023yvf] J/ψ decay to ω, ϕ, K^{*0} plus $f_0(1370), f_0(1710), K_0^*(1430)$, $f_2(1270), f_2'(1525)$ and $K_2^*(1430)$: Role of the D −wave for tensor production. L.M. Abreu, L. Dai and E. Oset, Phys. Lett. B843 (2023) 137999.
[JPAC:2023nhq] Khuri-Treiman analysis of $J/\psi \longrightarrow \pi^+\pi^-\pi^0$. M. Albaladejo et al. [JPAC]. Phys. Rev. D108 (2023).
[Ortega:2022efc] Nature of the doubly-charmed tetraquark T_{cc}^+ in a constituent quark model. P.G. Ortega, J. Segovia, D.R. Entem and F. Fernández. Phys. Lett. B841 (2023) 137918.
[Ortega:2022uyu] Strange hidden-charm $P_{\psi_s}^{\Lambda}(4459)$ and $P_{\psi_s}^{\Lambda}(4438)$ pentaquarks and additional $P_{\psi_s}^{\Lambda}, P_{\psi_s}^{\Sigma}$ and $P_{\psi_{ss}}^{N}$ candidates in a quark model approach. P.G. Ortega, D.R. Entem and F. Fernández. Phys. Lett. B838 (2023) 137747.
[Ortega:2023pmr] Exploring $T_{\psi\psi}$ tetraquark candidates in a coupled-channels formalism. P.G. Ortega, D. R. Entem, and F. Fernández, Phys. Rev. D 108 (2023) 094023.
[Marse-Valera:2022khy] Double-Strangeness Molecular-Type Pentaquarks from Coupled-Channel Dynamics. J.A. Marsé-Valera, V.K. Magas and A. Ramos, Phys. Rev. Lett. 130 (2023) 9.

Task 2. Precision calculations in non-perturbative QCD (II)

T2.1 Hadron resonances, form factors, LECs, fundamental parameters of QCD and light nuclei spectroscopy

1. *Precision QCD parameter determinations*

- It has been shown in Ref. [Bris:2022cdr] that in the process $e^+e^- \to \bar{Q}Q + X$, finite bottom-mass effects provide important corrections and therefore cannot be neglected in precision studies, since they are not damped by a power of the strong coupling.
- The discrepancy between the fixed-order and contour-improved (CIPT) perturbative expansions for τ −lepton decay hadronic spectral function moments had been affecting the precision of α_S determinations. The origin of the CIPT inconsistency is exposed as well as the reasons for its apparent good convergence at low orders in [Gracia:2023qdy].
- Important progress on calibrating the top quark mass has been achieved in the study carried out in [Dehnadi:2023msm]. There, a precise relation is found between the parameter entering Monte Carlo simulations (determined in experimental analysis) with the mass defined in QFT maintaining next-to-next-to leading logarithm contributions.
- Significant progress on the precise extraction determination of α_S from QCD static energy has been achieved in a Refs. [Brambilla:2022jxg, Brambilla:2022het, Leino:2021vop, Mayer-Steudte:2022uih, Brambilla:2023fsi, Brambilla:2023vwm]. The comparison of lattice calculations of the QCD static energy with 2+1+1 active light quark with a perturbative calculation of the same quantity in QCD at NNNLO, has allowed the precise extraction of α_S. In addition, measures of the static energy up to distances of 1 fm have made possible to perform a scale setting at scales r_0, r_1, and r_2 simultaneously, and then, determine

their ratios. It is observed that, comparing to 2+1 flavor static potential scales, the short distance scales r_2 and r_1 are affected by the charm mass, while the large distance scale r_0 is not. No charm mass effect is observed on the measure of the string tension. Furthermore, comparison of the static potential to a perturbation theory of the static energy with 3 massless quarks and a massive charm correction shows that this formulation of the static energy that includes the massive charm quark, describes the data better than 3 or 4 massless flavor equations, which only describe the large or small distance regimes respectively.
The information about α_S is contained in the force, which may be determined by numerically taking the derivative of the static energy, which requires its precise determination. An alternative determination consists in computing a Wilson loop with a chromoelectric field insertion. When this quantity is computed in lattice QCD, it shows a slow convergence towards the continuum limit, limit which may be inferred from the spatial derivative of the static energy that is the common way to compute the force. The gradient flow algorithm on the lattice is a novel approach to compute the force between a static quark-antiquark pair. When this algorithm, which typically cuts off exponentially high momenta regions, is used in the calculation of the expectation value of the chromoelectric field in the Wilson loop, the convergence towards the continuum limit is much faster. The scale governing the exponential cut off is the flow time. The zero flow time limit corresponds to QCD. The continuum QCD result is recovered from the lattice gradient flow result by performing the continuum limit before the zero flow time limit. Indeed, preliminary lattice data obtained by the TUM group show a fast convergence towards the continuum limit. Eventually the zero gradient flow limit may be extrapolated at short distances from the analytical one loop expression of the force at finite flow time.

- Calculation of the heavy quark diffusion coefficient on pure gauge lattice QCD has been also performed [Brambilla:2022xbd]. Comparing this calculation to previous works, the $1/M$ correction to this quantity was added, described by a correlator of two chromomagnetic fields. Another new aspect is the change in the measurement algorithm, from multilevel to gradient flow, which offers better renormalization properties. The mass suppressed effects to the heavy quark momentum diffusion coefficient are about 20% for bottom quarks and 35% for the charm quarks.
- A public C++ library, "Revolver" (with Python and Mathematica wrappers), has been published [Hoang:2021fhn]. The library systematically accounts for the renormalization group evolution of low-scale short-distance masses which depend linearly on the renormalization scale and sums logarithmic terms of high and low scales that are missed by the common logarithmic renormalization scale evolution.

2. *Hadron resonances and hadron interactions in extreme conditions*

- The study of spin quantum numbers of particle-antiparticle pairs produced in intense fields is relevant in scenarios such those appearing in heavy ion collisions (featuring intense color fields) or neutron stars (where magnetic fields are very intense). With this in mind, the role of a light quark-antiquark pair with zero total angular momentum from Landau-gauge Green’s functions has been discussed in [Alkofer:2023syz].

- A generalized effective string rope model has been developed in order to take into account fluctuations in the initial state of relativistic heavy ion collisions, following the Glauber Monte Carlo approach [Ramirez:2022obv]. This model will allow for further hydrodynamical calculations. Results from symmetric nucleus-nucleus collisions at different impact parameters are also presented at energies available at heavy-ion colliders.

3. *Lepton flavor universality violation and New Physics*

- Using input from lattice QCD calculations (form factors) and heavy quark effective theory, a study of new physics effects on τ −semileptonic decays of $\bar{B}_s$ by comparing tau spin, angular and spin-angular asymmetry distributions obtained within the Standard Model and different New Physics (NP) scenarios, has been performed in Ref. [Penalva:2023snz]. The analysis of these reactions is already able to discriminate between some of the NP scenarios and its potentiality will certainly improve when more precise form factors are available.

4. *Lattice QCD calculations of hadronic and nuclear systems*

- Variational methods have been applied in lattice QCD calculations to constrain the low-energy spectra of two-nucleon systems in a single lattice spacing, and two different finite volumes with quark masses corresponding to a pion mass of 806 MeV. This study [Amarasinghe:2021lqa, Tews:2022yfb, Detmold:2024iwz] uses a wide range of interpolating operators: dibaryon operators built from products of plane-wave nucleons, hexaquark operators built from six localized quarks, and quasi-local operators inspired by two-nucleon bound-state wavefunctions in low-energy effective theories, providing upper bounds on two-nucleon energy levels. Additionally, the same spectroscopy analysis on two nucleons and two Λ's is being performed, with larger variational basis, multiple volumes, and a pion mass of ~ 170 MeV. This study represents a step toward reliable nuclear spectroscopy from the underlying Standard Model of particle physics.
- Lattice QCD calculations of correlation functions for systems with the quantum numbers of many identical mesons have been performed [Abbott:2023coj]. A new algorithm is presented, which has been applied to calculations of correlation functions with up to 6144 π's using two ensembles of gauge field configurations, corresponding to two different volumes and generated with quark masses corresponding to a pion mass of 170 MeV. From the extracted energies, the large-isospin-density, zero-baryon-density region of the QCD phase diagram is explored. The results indicate that the isospin chemical potential must be large for the system to be well described by an ideal gas or perturbative QCD. Furthermore, a determination of the equation of state (EoS) of isospin-dense matter for the complete range of isospin chemical potential at zero temperature is presented for the first time in [Abbott:2024vhj]. To achieve this, continuum limit LQCD calculations are combined with perturbative QCD (pQCD) calculations and Chiral Perturbation Theory through a model-mixing approach in overlapping regions of isospin chemical potential. Comparison to pQCD enables a determination of the superconducting gap, and QCD inequalities translate the isospin-dense EoS into rigorous bounds on the nuclear EoS relevant for astrophysical environments.

5. *Neutrino-nucleus interactions*

- The future long baseline experimental programs, DUNE and T2HK, which will measure neutrino oscillations with an unprecedented accuracy, will require a much better understanding of neutrino-nucleus interactions, being one of the main sources of systematic uncertainty. Calculations within the coupled cluster framework for electromagnetic nuclear responses employ nuclear forces derived from the chiral perturbation theory (both for 2- and 3-body forces at N2LO, using either Δ-full or Δ-less interactions). Progress in this topic has showed that working within this approach one is able to assess the error introduced by truncation at a given chiral order. The results for the longitudinal response both for a light system, (^{4}He) and a medium-mass region (^{40}Ca), stay in an excellent agreement with the data up to 400 MeV/c [Sobczyk:2022ezo].
- The analysis of the energy and angular distributions of the tau decay visible products, which depend on the components of the tau-polarization vector, can be used to obtain information on the dynamics of the $\nu_\tau(\bar{\nu}_\tau)A_Z \longrightarrow \tau^{\mp}X$ nuclear process. The general expression for the outgoing hadron (pion or rho meson) energy and angular differential cross section for the sequential reactions involving tau decays has been given, for the first time in Ref. [Hernandez:2022nmp]. In addition to its potential impact on neutrino oscillation analyses, this result can be used to further test different nuclear models, since these observables provide complementary information to that obtained by means of the inclusive nuclear weak charged-current differential cross section.

6. *The nuclear matter equation of state*

- Neutron stars, which contain the universe's most dense nuclear materials, can now be probed in whole new ways from gravitational waves to satellite X-ray telescopes, providing an opportunity to test the high-density and low-temperature regime of matter that is not currently accessible by terrestrial experiments. We derived the equation of state of infinite neutron matter as obtained from highly realistic Hamiltonians that include nucleon-nucleon and three-nucleon coordinate-space potentials [Lovato:2022apd]. We benchmarked three independent many-body methods: Brueckner-Bethe-Goldstone (BBG), Fermi hypernetted chain/single-operator chain (FHNC/SOC), and auxiliary-field diffusion Monte Carlo (AFDMC). We find them to provide similar equations of state when the Argonne v18 and the Argonne v6′ nucleon-nucleon potentials are used in combination with the Urbana IX three-body force. The AFDMC calculations carried out with all of the Norfolk potentials fitted to reproduce the experimental trinucleon ground-state energies and nd doublet scattering length yield unphysically bound neutron matter, associated with the formation of neutron droplets. Including tritium β decay in the fitting procedure, as in the second family of Norfolk potentials, mitigates but does not completely resolve this problem. An excellent agreement between the BBG and AFDMC results is found for the subset of Norfolk interactions that do not make neutron-matter collapse.

7. *Neural network quantum states*

- The complexity of many-body quantum wave functions is a central aspect of several fields in physics and chemistry, particularly where non-perturbative interactions are significant. Artificial neural networks have proven to be a versatile tool for approximating quantum many-body states in condensed matter and chemistry problems. We have developed increasingly sophisticated neural network quantum states that solve the quantum many-body problem with unprecedented accuracy and polynomial computational cost in relation to the number of nucleons [Gnech:2021wfn, Gnech:2023prs]. For finite nuclei, in addition to calculating ground-state energies and radii, we have devised a novel computational protocol to determine their magnetic moments. For infinite systems, we introduced a translation-invariant ansatz that outperforms the state-of-the-art auxiliary-field diffusion Monte Carlo method in both pure neutron matter and beta-equilibrated matter at a fraction of the computational cost.

T2.2 Computation of heavy-quark, hybrid and tetraquark potentials

In the third reporting period, there has been significant progress in the understanding of the heavy quark dynamics underlying quarkonium exotics. Some of them have already been mentioned due to their clear interrelation with the objectives of previous subtasks.

- In the framework of the Born-Oppenheimer effective field theory (BOEFT), this dynamics is described by potentials encoding the light degrees of freedom (light quarks and gluons) and their excitations. The potentials are computed in lattice QCD. Potentials may mix giving rise to a dynamics described by coupled Schrödinger equations. In Ref. [Brambilla:2022hhi], we have computed in the framework of BOEFT hybrid to quarkonium transition widths. In this way, we could exclude some of the XYZ states as possible hybrid candidates, while suggesting some other XYZ states as possible hybrid candidates. In Ref. [Berwein:2024ztx], we have worked out a complete theoretical description of quarkonium hybrids, tetraquarks, baryons and pentaquark based on BOEFT. We point out that potentials mix at short distances, a phenomenon highlighted in our previous hybrid work, due to the restoration of the spherical symmetry, but they also mix at large distances with threshold states due to the avoided level crossing mechanism. These two mixing mechanisms enlarge the set of coupled Schrödinger equations needed to properly describe tetraquarks and hybrids leading to a rich and complex dynamics. Recent lattice data of the hybrid and tetraquark potentials get a clear interpretation in view of these findings, which we comment in our work.
- In [Brambilla:2022het], the TUMQCD lattice QCD collaboration provided the most accurate determination of the quarkonium static potential with 2+1+1 active flavours up to date. The determination shows the dynamical role played by the charm quark contributing as a massless light quark to the running coupling constant at short distances, while decoupling at large distances.

T2.3 Computation of matrix elements for in medium quarkonium evolution

In this subtask, we have also achieved significant progress. We highlight:

- In Ref. [Brambilla:2024tqg], the effects of the three-loop corrections to the static quark-antiquark potential and its leading short-distance nonperturbative correction have been added to the evolution equations of quarkonium in the medium formed in heavy-ion collisions. This has led to an accurate description of the quarkonium nuclear modification factor measured at the LHC, a determination of the quarkonium thermal decay width in agreement with lattice QCD computations and a determination of the in vacuum bottomonium spectrum consistent with data.
- In Ref. [Brambilla:2022xbd], a systematic one loop study of several nonrelativistic operators with gradient flow was started. As mentioned above, gradient flow is a very convenient scheme for lattice calculations, as it automatically renormalises composite operators and improves the continuum limit. Because of these properties, gradient flow is increasingly more often used in lattice QCD calculations.

Related to the activity of T2.3, in March 2024, we have organised the 2nd edition of the workshop
"Quarkonia meet Dark Matter" (https://indico.ph.tum.de/event/7422/) meant to favour a transfer of knowledge between experts on the behaviour of quarkonium in a thermal medium and researcher on dark matter, where in a large variety of models threshold effects in the thermal environment provided by the early universe play a crucial role in the determination of the relic dark matter density.

REFERENCES

[Bris:2022cdr] NLO oriented event-shape distributions for massive quarks. A. Bris, N.G. Gracia, V. Mateu. J. High Energ. Phys 02 (2023).

[Gracia:2023qdy] Mathematical aspects of the asymptotic expansion in contour improved perturbation theory for hadronic tau decays. N.G. Gracia, A.H. Hoang, V. Mateu, Phys. Rev. D108 (2023) 034013.

[Dehnadi:2023msm] Top quark mass calibration for Monte Carlo event generators: An update. B. Dehnadi, A.H. Hoang, O.L. Jin, V. Mateu, J. High Energ. Phys. 12 (2023) 065.

[Brambilla:2022jxg] Charm mass effects in the static energy computed in 2+1+1 flavor lattice QCD.
TUMQCD Collaboration, N. Brambilla et al., PoS LATTICE2022 (2023) 089.

[Brambilla:2022het] Static energy in 2+1+1 flavor lattice QCD: Scale setting and charm effects,
TUMQCD Collaboration, N. Brambilla et al., Phys. Rev. D107 (2023) 074503.

[Leino:2021vop] The static force from generalized Wilson loops using gradient flow. V. Leino, N. Brambilla, J. Mayer-Steudte, and A. Vairo. EPJ Web Conf. 258, 04009 (2022).

[Mayer-Steudte:2022uih] Implications of gradient flow on the static force. J. Mayer-Steudte, N. Brambilla, V. Leino, and A. Vairo. PoS LATTICE2022, 353 (2023).

[Brambilla:2023fsi] The static force from generalized Wilson loops on the lattice using gradient flow. N. Brambilla, V. Leino, J. Mayer-Steudte, and A. Vairo. Phys. Rev. D109 (2024) 114517.

[Brambilla:2023vwm] Off-lightcone Wilson-line operators in gradient flow. N. Bambrilla, X-P Wang, J. High Energ. Phys. 06 (2024) 210.

[Brambilla:2022xbd] Heavy quark diffusion coefficient with gradient flow. N. Brambilla, V. Leino, J. Mayer-Steudte, and P. Petreczky (TUMQCD Collaboration), Phys. Rev. D107 (2023) 054508.

[Hoang:2021fhn] REvolver: Automated running and matching of couplings and masses in QCD. A. H. Hoang, C. Lepenik, V. Mateu. Comput. Phys. Commun. 270 (2022) 108145

[Alkofer:2023syz] Supporting $^3P_0$ quark-pair creation from Landau-gauge Green's functions. R. Alkofer, F. J. Llanes-Estrada, A. Salas-Bernardez. Phys. Rev. D 109 (2024) 074015.

[Penalva:2023snz] Study of new physics effects in $\bar{B}_s \to D_s^{(*)} \tau^- \overline{\upsilon_\tau}$ semileptonic decays using lattice QCD form factors and heavy quark effective theory. N. Penalva, J.M. Flynn, E. Hernández, and J. Nieves. JHEP 01 (2024) 163.

[Amarasinghe:2021lqa] S. Amarasinghe, R. Baghdadi, Z. Davoudi, W. Detmold, M. Illa, A. Parreño, A.V. Pochinsky, P.E. Shanahan, and M.L. Wagman (NPLQCD Collaboration), Phys. Rev. D 107 (2023) 094508

[Tews:2022yfb] Nuclear Forces for Precision Nuclear Physics: a collection of perspectives. I. Tews et al., Few-Body Systems 63 (2022) 67.

[Detmold:2024iwz] Constraints on the finite volume two-nucleon spectrum at m_π 806 MeV. W. Detmold, M. Illa, W.I. Jay, A. Parreño, R.J. Perry, P.E. Shanahan, and M.L. Wagman, (NPLQCD Collaboration), arXiv:2404.12039 [hep-lat].

[Abbott:2023coj] Lattice quantum chromodynamics at large isospin density: 6144 pions in a box. R. Abbott, W. Detmold, F. Romero-López, Z. Davoudi, M. Illa, A. Parreño, R.J. Perry, P.E. Shanahan,and M.L. Wagman (NPLQCD Collaboration). Phys. Rev. D108 (2023) 114506.

[Abbott:2024vhj] QCD constraints on isospin-dense matter and the nuclear equation of state. R. Abbott, W. Detmold, M. Illa, A. Parreño, R.J. Perry, F. Romero-López, P.E. Shanahan,and M.L. Wagman (NPLQCD Collaboration), arXiv:2406.09273 [hep-lat].

[Sobczyk:2022ezo] Spectral function for ^4He using the Chebyshev expansion in coupled-cluster theory, J.E. Sobczyk, S. Bacca, G. Hagen, T. Papenbrock. Phys. Rev. C 106 (2022) 034310.

[Hernandez:2022nmp] Tau longitudinal and transverse polarizations from visible kinematics in (anti-)neutrino nucleus scattering. E. Hernández, J. Nieves, F. Sánchez, J.E. Sobczyk. Phys. Lett. B 829 (2022) 137046; Erratum Phys. Lett. B 836 (2023).

[Ramirez:2022obv] Generalized Effective String Rope Model for the initial stages of Ultra-Relativistic Heavy Ion Collisions. A. Reina Ramirez, V.K. Magas, L.P. Csernai and D. Strottman.
Phys. Rev. C107 (2023) 034915.

[Lovato:2022apd] Benchmark calculations of infinite neutron matter with realistic two- and three-nucleon potentials. A. Lovato, I. Bombaci , D. Logoteta, M. Piarulli, and R. B. Wiringa. Phys. Rev. C105 (2022) 055808.

[Gnech:2021wfn] Nuclei with up to A=6 nucleons with artificial neural network wave functions. A. Gnech, C. Adams, N. Brawand, G. Carleo, A. Lovato, and N. Rocco, Few Body Syst. 63 (2022) 7.

[Gnech:2023prs] Distilling the essential elements of nuclear binding via neural-network quantum states. A. Gnech, B. Fore, and A. Lovato. Phys. Rev. Lett. (in press); e-Print: 2308.16266 [nucl-th].

[Brambilla:2022hhi] Heavy hybrid decays to quarkonia. N. Brambilla, W. K. Lai, A. Mohapatra and A. Vairo. Phys. Rev. D107 (2023) 054034.

[Berwein:2024ztx] One Born-Oppenheimer effective theory to rule them all: hybrids, tetraquarks, pentaquarks, doubly heavy baryons and quarkonium. M. Berwein, N. Brambilla, A. Mohapatra and A. Vairo. e-Print: arXiv:2408.04719 [hep-ph]

[Brambilla:2024tqg] Bottomonium suppression from the three-loop QCD potential. T. Magorsch, M. Strickland, A. Vairo and P. Vander Griend. Phys. Rev. D109 (2024) 114016.

Task 3. Meson Spectroscopy analysis of new and exotic states

T3.1 Search for and study of light exotic mesons, charmonium and strangeonium

The GlueX collaboration released a estimation of the lightest isovector exotic meson photoproduction [Afz24]. We published several reports concerning the production of charm exotic XYZ mesons at the future EIC facility. [Abd22, Bur23, Byl23]. Making the physics case for an upgraded beam energy at Jefferson Lab which is ideal for X and Z spectroscopy [Acc23]. We also investigate heavy exotic meson decays and productions in [Bra22] and [Bra23]. The BESIII collaboration has reported the first observation of the lightest isoscalar exotic meson in [BESIII].

Finally, we study the problem of ambiguities in extracting partial waves from photoproduction [Smi23].

REFERENCES

[Smi23] W. Smith et al [JPAC], Phys. Rev. D108 076001 (2023)

[Afz24] F. Afzal et al [GlueX], arXiv : 2407.03316

[Bur23] V.D. Burkert et al, Prog. Part. Nucl. Ph. 131, 104032 (2023)

[Byl23] A. Bylinkin et al Nuclear Instruments and Methods in Physics Research Section A 1052, 168238 (2023)

[Acc23] A. Accardi et al. arXiv : 2306.09360

[Abd22] R. Abdul Khalek et al, Nuclear Physics A 1026, 122447 (2022)

[Bra23] N. Brambila et al, *Phys.Rev.D* 107 (2023) 5, 054034

[Bra22] N. Brambila et al, arXiv:2203.16583

[BESIII] BESIII collaboration, PRL **129**, 192002 (2022), PRD **106**,072012 (2022), PRD **107**,079901 (2023)

T3.2 Spectroscopy of low-lying scalars, strange mesons and strangeonia

The two lightest isoscalar-scalar resonances are σ/f0(500) and f0(980). The quark model predicts two other scalars below 2 GeV while three, f0(1370), f0(1500) and f0(1710), are observed. This stimulated heightened interest in identifying one of these three resonances as the long-sought glueball.

One approach uses a large collection of reaction amplitudes to determine the fundamental parameters of resonances produced as intermediate states of these reactions, with reduced model bias. The challenge lies in the large number of resonances seen in the data with multiple open thresholds. Scalar and tensor resonances are studied in J/ψ radiative decays by performing a systematic analysis of the J/ψ→γπ0π0 and →γK0SK0S partial waves measured by BESIII. The physical properties of seven scalar and tensor resonances in the 1-2.5 GeV mass range have been determined. These include the well known f0(1500) and f0(1710) that are considered to be the primary glueball candidates. Here, f0(1370) is not considered well established from two meson final states. The hierarchy of resonance couplings determined from this analysis favors f0(1710) as having the largest glueball component.

Dispersive and analytic methods are used to establish the existence of the long-debated f0(1370) resonance in the dispersive analyses of meson-meson scattering data. The f0(1370) candidate would be needed to complete the controversial scalar nonet above 1 GeV and is of interest for studies of the lightest glueball and its mixing scheme. The challenge in identifying this resonance had been the strong model dependence of previous works.

Resonance poles can be determined from data with forward Dispersion Relations and analytic continuation methods. A novel approach using forward dispersion relations, valid for generic inelastic resonances, reveals its pole at (1245±40)−i(300+30−70) MeV in ππ scattering.

Also, a pole at (1390+40−50)−i(220+60−40) MeV is found in the ππ→KK¯ data analysis with partial-wave dispersion relations. Despite settling its existence, the model-independent dispersive and analytic methods still show a lingering tension between pole parameters from the ππ and KK¯ channels. Given the reduced model dependence, the tension should be due to inconsistencies between ππ→ππ and ππ→KK data sets.

REFERENCES

[Ro22] A. Rodas et al. (JPAC), Eur. Phys. J. C 82, 80 (2022)
[Pe23] J. R. Peláez, A.Rodas, J.Ruiz de Elvira, Phys. Rev. Lett. 130, 051902 (2023)

Task 4. Baryon Spectroscopy

T4.1 Resonance parameter determination

This task focuses on the determination of baryon resonance parameters from experimental data, in particular from new results in meson photoproduction from the CB-ELSA, BGOOD, CLAS, CLAS12, GlueX and A2-MAMI collaborations. Analyses within the Jülich-Bonn-Washington coupled channel approach, the Bonn-Gatchina multi-channel analyses and the Mainz-Tusla-Zagreb initiatives based on the MAID model and truncated partial wave analyses are connected via this network. Projects with people from different groups and the scientific exchange between the groups were supported.

The SAID partial-wave analysis of pion photoproduction has been extended and updated by including new experimental data as well as recent research in model independent single-energy analyses [Bri23]. Pion production above the resonance region has been studied within Regge phenomenology [Str23]. A model independent approach in single-energy partial-wave analysis has been applied to kaon-hyperon photoproduction. The results were compared to existing muli-channel analyses and a modified Laurent-expansion was applied in order to determine resonance pole parameters [Sv22, Sv23]. The dynamical coupled-channel Jülich-Bonn-Washington model has been updated and extended by including recent photo- and even electroproduction data [Mai22, Mai23, Roe22]. Furthermore, these sophisticated dynamical coupled-channel methods were applied to heavy-quark systems, in particular new data from LHC-B [Wa22, Sha24].

Two NSTAR workshops (NSTAR2022, Santa Margherita Ligure, Genova and NSTAR2024, York) were held during the reporting period. The NSTAR workshop series aims at the exchange between theory and experiment in the field of exited nucleons. In particular, the participation of A. Svarc (Zagreb) and students from Basel would not have been possible without the support of this project. They reported on new methods in single-channel, single-energy partial wave analysis [Sv22, Sv23] and new experimental results on 2-pion photoproduction [Gho23]. Another important meeting in the field of hadron resonance parameters is the PWA13/Athos8 workshop, which took place from 28 May to 1 June in Williamsburg, USA. The focus of this workshop is on methods and tools for data analysis in hadron spectroscopy. Furthermore, contributions to other conferences on hadron physics were supported, e.g. the 59. International Winter Meeting on Nuclear Physics (Bormio 2023) and the Physics at Amber Workshop (PAW2024, Geneva).

In addition to this support for scientific exchange, the participation of undergraduate students in training for data taking and data analysis was supported.

REFERENCES

[Bri23] Extended SAID partial-wave analysis of pion photoproduction, William J. Briscoe et al., DOI: 10.1103/PhysRevC.108.065205, Phys.Rev.C 108 (2023) 6, 065205

[Gho23] Helicity dependent cross sections for the photoproduction of π0π± pairs from quasi-free nucleons, D. Ghosal (Basel U.) et al. DOI: 10.1016/j.physletb.2023.138273, Phys.Lett.B 847 (2023), 138273

[Mai22] Coupled-channels analysis of pion and η electroproduction within the Jülich-Bonn-Washington model Maxim Mai et al., DOI: 10.1103/PhysRevC.106.015201, Phys.Rev.C 106 (2022) **1**

[Mai23] Inclusion of $K\Lambda $ electroproduction data in a coupled channel analysis, M. Mai et al., DOI: 10.1140/epja/s10050-023-01188-0, Eur.Phys.J.A 59 (2023) 12, 286

[Roe22] Light baryon resonances from a coupled-channel study including $\mathbf {K\Sigma }$ photoproduction, Deborah Rönchen et al., DOI: 10.1140/epja/s10050-022-00852-1, Eur.Phys.J.A 58 (2022) 11, 229

[Sh24] Exploration of the LHCb P_c states and possible resonances in a unitary coupled-channel model , Chao-Wei Shen, DOI: 10.1140/epjc/s10052-024-13139-0, Eur.Phys.J.C 84 (2024) 7, 764

[Str23] Pseudoscalar and scalar meson photoproduction interpreted by Regge phenomenology, Igor I. Strakovsky et al., DOI: 10.1103/PhysRevC.107.015203, Phys.Rev.C 107 (2023) 1, 015203

[Sv22] Application of the single-channel, single-energy amplitude and partial-wave analysis method to K+Λ photoproduction A. Švarc et al. Phys.Rev.C 105 (2022) 2, 024614, DOI: 10.1103/PhysRevC.105.024614, Phys.Rev.C 105 (2022) 2, 024614

[Sv23] Laurent+Pietarinen partial-wave analysis , A. Švarc, R.L. Workman, Phys.Rev.C 108 (2023) 1, 014615, DOI: 10.1103/PhysRevC.108.014615, Phys.Rev.C 108 (2023) 1, 014615

[Wa22] Resonances in heavy meson–heavy baryon coupled-channel interactions, Zheng-Li Wang , DOI: 10.1140/epjc/s10052-022-10462-2, Eur.Phys.J.C 82 (2022) 5, 497

T4.2 Diffractive and annihilation production and exotic baryon

One of the still open problems in the description of the baryon spectrum by Quark Models or lattice QCD is the missing observation of a sizable number of nucleonic resonances.
Significant progress has been made in recent years and is evident in several new entries of N* and Δ* states in the latest editions of the Review of Particle Properties (PDG), as well as the inclusion of the transition form factor measurement for several excited states.

State	PDG	PDG	KΛ	KΣ	Nγ	Np
N(1710)1/2$^+$	***	****	**	*	****	****
N(1880)1/2$^+$		***	**	*	**	*
N(2100)1/2$^+$	*	***	*		**	***
N(1895)1/2$^-$		****	**	**	****	*
N(1900)3/2$^+$	**	****	**	**	****	**
N(1875)3/2$^-$		***	*	*	**	**

N(2120)3/2$^-$		***	**	*	***	**
N(2060)5/2$^-$		***	*	*	***	**
Δ(1600)3/2$^+$	***	****			****	***
Δ (1900)1/2$^-$	**	***		**	***	***
Δ (2200)7/2$^-$	*	***		**	**	***

Figure 1. Recently discovered or upgraded N* and Δ resonances in the mass range 1700-2200 MeV

Most of the newly discovered states have masses in the range 1.85 GeV to 2.1 GeV where precise photoproduction data were driving the new observations, however the mass region above 2.1 GeV has hardly been studied. This is the region where the gluonic excitations are expected to occur, representing the focus of the task in the search of exotic baryons.

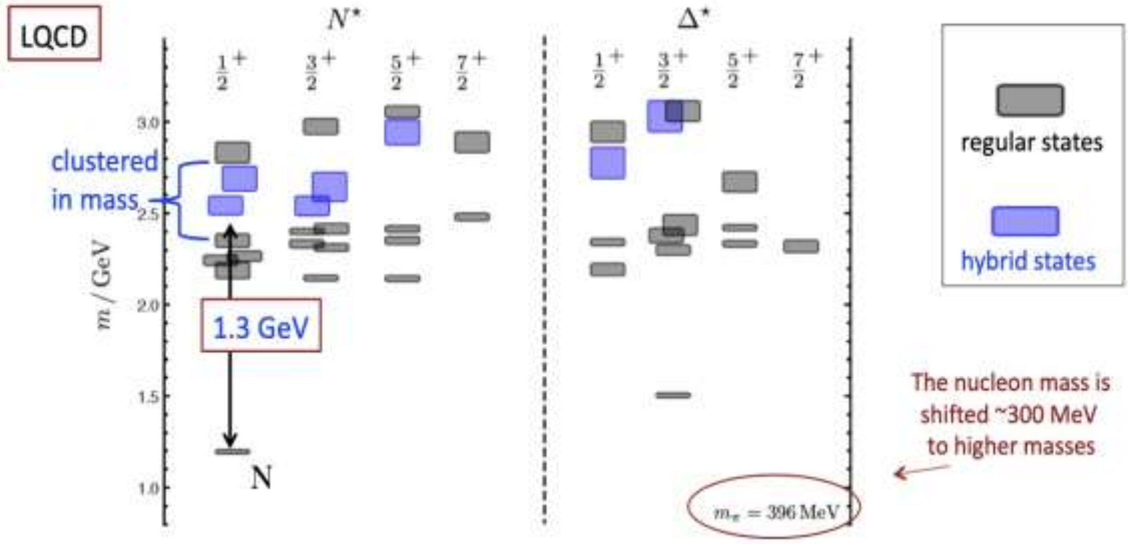


Figure 2. Lattice QCD prediction of light baryons spectrum, including states with dominant gluonic degrees of freedom. [J.J. Dudek and R.G. Edwards, PRD85, 054016 (2012)]

The existence of “exotic baryons” whose structure is more complex than a simple three-quarks state not only is compatible with QCD predictions, but it has been experimentally observed at LHCb, where evidence of penta-quark states has been obtained [LHCb].
In the search for “missing resonances”, with the scope of a better understanding the nucleon dynamics, new important information can be provided by precision electromagnetic machines operating polarized beams.
The availability of polarized photon beams impinging on polarized targets provide access to single and double polarization observables of meson photo-production processes, which strongly constrain the reaction amplitudes and proved to be the new key information in the discovery of the new resonances, reported in Table 1.

Electro-production of the same mesons-baryon final states produced in photoreactions allows for the extraction of the resonance electro-couplings and the study of their evolution as a function of the Q^2 photon virtuality. This additional information allows to picture the evolution of the effective-degrees N* freedom as a function of the distance scale and to assess the possible hybrid nature of new resonances.

The combined analysis of photo-induced and electron-induced meson production has proven to be an effective strategy to exploit the discovery potential of electromagnetic machines operating polarized beams.

Photo-induced mesons production. In the past decade, CLAS at CEBAF ran dedicated data takings with circularly polarized photon beams, of energy up to 5 GeV, on longitudinally polarized targets. These data are fundamental to study the trend of single- and double polarization observables as a function of the available energy W and the angles of the emitted products: such observables provide alternative tools, complementary to PWA, to resolve and characterize possible baryonic missing states. Several final states with particles of different flavor content can be analyzed to extract information on the couplings of the new baryonic resonances and their dependence on flavors. For instance, studies were carried on to extract the E beam-target helicity asymmetry in the $\gamma n \rightarrow K^+\Sigma^+$ reaction on a HD target [Za20]: the trend of this variable cannot be easily reproduced in the framework of QCD quark models without additional hypotheses on the interference patterns and on the couplings between the photon and the known low-mass baryonic resonances, as well as the inclusion of at least one new resonant state.

The same HD target, with different degrees of longitudinal polarization, is used to extract the single- and double-polarization asymmetries for the $\vec{\gamma} + p \rightarrow \pi^+ + \pi^- + \pi^0$ reactions, both on protons and neutrons. This analysis is still in progress: preliminary results show a good agreement for the trend of the $I^{\odot}$ beam asymmetry for reactions on both protons and neutrons, as a function of the φ helicity angle and invariant energy W; the expected parity-odd trend, with some modulations, is followed in every step of W in the range 1.6-2.2 GeV. From the fit of this distribution the relative weight of the J=½ and 3/2 amplitudes can be inferred. The concurrent extraction of the P_z and $P_z^{\odot}$ polarization asymmetries is currently underway.

Search for di-baryons states made of six quarks is also underway. Data analysis from A2 collaboration at MAMI of coherent photoproduction of π-pairs from the deuteron is being finalized to elucidate on the possible role an exotic baryon in the reaction mechanism.

Electro-induced mesons production. Data taking with polarized electron beams at 6.5 GeV and 7.5 GeV energies on unpolarized proton target occurred at the CLAS12 upgraded facility at CEBAF in December 2018. Data have been calibrated and reconstructed. Kinematical coverage of available data spans in the 0.05 - 4.0 GeV^2 range in Q^2 and in the 0.95-3GeV range in W, covering all the invariant phase-space of interest for the study of baryons resonance structure.

Data analysis of $ep \rightarrow eK^+Y$ and $ep \rightarrow e\pi^+\pi^-$ reaction channels is underway with the aim of measuring un-separated cross sections and polarization observables with final statistics which surpasses the world database by one order of magnitude.

Data Analysis and Interpretation. Waiting for the first CLAS12 experiments to provide high-precision data on inclusive electron scattering observables the modeling of the resonant contributions to the inclusive electron scattering observables has been published [Hi19]. As input, the existing CLAS electro-coupling results obtained from exclusive meson electro-production data off protons have been used to evaluate for the first time the resonant contributions based on the experimental results on the nucleon resonance electro-excitation.

The uncertainties are given by the data and duly propagated through a Monte Carlo approach. In this way, estimates for the resonant contributions have been obtained, important for insight into the nucleon parton distributions in the resonance region and for the studies of quark-hadron duality.

The properties of the hidden-charm pentaquark-like resonances first observed by the LHCb Collaboration in 2015, have been studied estimating the sensitivity of the polarization transfer K_{LL} to the pentaquark photocouplings and hadronic branching ratios. Predictions to the case of the initial-state helicity correlation A_{LL}, using a polarized target have been deduced. These results serve as a benchmark for the SBS experiment at Jefferson Lab, which proposes to measure for the first time the helicity correlations A_{LL} and K_{LL} in J/ψ exclusive photoproduction, to determine the pentaquark photocouplings and branching ratios [Wi19]. Finally the nature of the new signal reported by LHCb in the J/ψp spectrum has been studied using a minimum-bias analysis of the underlying reaction amplitude, based on the S-matrix principles and focusing on the analytic properties that can be related to the microscopic origin of the $Pc(4312)^+$ peak. By exploring several amplitude parametrizations, evidence for the attractive effect of the $\Sigma^+c\bar{}D0$ channel has been found, which is not strong enough, however, to form a bound state [Fe19].

REFERENCES

[Za 20] CLAS Collaboration, N. Zachariou et al., Phys. Lett. B880 (2020), 135662
[Hi19] A. N. Hiller Blin et al. Phys. Rev. C 100 (2019), 035201
[Wi19] (Joint Physics Analysis Center) D. Winney, et al. Phys. Rev. D 100 (2019), 034019 (2019)
[Fe19] (Joint Physics Analysis Center) C. Fernández-Ramírez, et al. Phys. Rev. Lett. 123, (2019) 092001
[LHCb] R. Aaig. et at (LHCb collaboration), Phys. Rev. Lett. 115 (2015) 072001.

T4.3 Di-baryon structure and parameter determination

There was a lot of progress in last year in a field of dibaryons both on theoretical side and in experiments. To consolidate activities and cross-feed the efforts we have organized a dibaryon miniworkshop as a part of NSTAR 2024 conference with a dedicated dibaryon session.

The 14th International Conference on the Physics of excited nucleons (NSTAR) was organised and hosted by the University of York Hadron Physics Group (Organising Committee Chairperson: Nick Zachariou) between June 17-21st. The successful workshop brought together more than 100 delegates from Europe, the Americas, and Asia to discuss the current progress and future prospects on the physics of the Baryon spectrum and the structure of excited nucleons. The workshop focused on highlighting new experimental results utilising photo-, electro-, and hadron- production reactions, as well as e+e- and ion collisions to study aspects of the baryon spectrum, including reaction amplitudes, electrocouplings, and the excited nucleon structure. Advancements in theoretical approaches, using effective field theories, QCD-inspired models, Schwinger-Dyson approaches to QCD, and first principle calculations (lattice QCD) were also discussed in detail, and the workshop provided an invaluable venue for synergies between theory and experiments
A link to a conference and a STRONG2020 funding allowed to bring dibaryon researchers from all over the globe – China, India, EU, US and all kind of areas: quark models,

LatticeQCD, functional theory, experiment, which otherwise are very difficult to bring together.

The dedicated Dibaryon session at NSTAR was well received by the NSTAR community: the dibaryon parallel session room was completely full - with several people standing to watch the talks. This activity catalyzed new collaborations in dibaryon theory and dibaryon astrophysical areas.

Highlights of significant results

The groups of the JRA7-HaSp WP25 have continued in this third period a productive collaboration. Experimentalists working in the world-leading nuclear physics facilities and theorists keep working together to run experiments, collect data, set an analysis framework, and provide a sound interpretation to reveal the basic mechanisms of hadronic interaction.

As it has been clear in the details of the activities and main results reported above, the collaboration between the different teams working on the subtasks in WP25 has been remarkable. We have several researchers working on projects with different subtasks. The HaSP activity has boosted the coordination of different institutions active in hadron spectroscopy leading to the development of new tools for the analysis of hadron spectrum, reaction data, and interpretation of physics results.

First, we highlight the calculation of the generalized Wilson loop containing the QCD force on the lattice using gradient flow carried out in [Brambilla:2023fsi]. This is an important result that opens the possibility of calculating on the lattice all correlators emerging in the nonrelativistic effective field theory, including pNRQCD and BOEFT. Actually, the gradient flow is a very convenient scheme for lattice calculations, as it automatically renormalizes composite operators and improves the continuum limit. Because of these properties, gradient flow is increasingly more often used in lattice QCD calculations. The study of [Brambilla:2022xbd] provides the one loop renormalization in gradient flow of lattice QCD operators appearing in the heavy quark effective theory and non relativistic QCD. There has also been a significant progress in the understanding of quarkonium hybrids, tetraquarks, baryons and pentaquark in the systematic framework of the Born-Oppenheimer effective field theory ([Brambilla:2022hhi] and [Berwein:2024ztx]).

Next, we mention the result of Ref. [Colangelo:2022lzg], which provides an improved analysis of $e^+e^- \to \pi^+\pi^-$, including radiative corrections. There, the cancellation of infrared singularities is discussed in detail. This work provides an important step towards reducing further the theoretical uncertainties of the hadronic vacuum polarisation contribution to the muon $(g-2)$.

The LHCb collaboration has recently reported the largest CP violation effect from a single amplitude in several $B-$meson decays into three charmless light mesons. In Ref. [Garrote:2022uub], a model-independent dispersive analysis of $\pi\pi \longrightarrow K\bar{K}$ data was used, and it allowed to achieve a reasonable description of the asymmetry while being consistent with the measured scattering amplitude and confirming the prominent role of hadronic final state interactions.

In [Du:2023hlu], we investigated the DD^* system at unphysical quark masses in the context of LQCD studies of the exotic $T_{cc}(3875)^+$. We showed that at slightly higher than physical pion mass, the D^* gets stable and the system develops a left-hand cut that calls for significant modifications to be applied to the methods used to analyze lattice spectra.

In Ref. [Ortega:2023pmr], the LHCb $T_{\psi\psi}$ tetraquark candidate was studied in a quark model framework as a possible molecule of two hidden charm mesons. Also in this work, candidates for the experimentally seen $T_{\psi\psi}(6200)$, $T_{\psi\psi}(6600)$, $T_{\psi\psi}(6700)$, $T_{\psi\psi}(6900)$ and $T_{\psi\psi}(7200)$ were also predicted.

The LQCD works of Refs. [Amarasinghe:2021lqa, Tews:2022yfb, Detmold:2024iwz] explored a wide range of interpolating operators: dibaryon operators built from products of plane-wave nucleons, hexaquark operators built from six localized quarks, and quasi-local operators inspired by two-nucleon bound-state wavefunctions in low-energy effective theories and provided for the first-time upper bounds on two-nucleon energy levels, though for a quite heavier pion mass. The NPLQCD collaboration is currently working to obtain results closer to the chiral limit.

In this third period, we should also highlight the great activity of theory groups in the study of two-hadron correlation functions from high multiplicity collisions, measured in experiments like ALICE at LHC. The number of experiments that can be done in accelerators employing a certain beam and target is very limited. This imposes important constraints on which information can be obtained about the interaction of mesons with mesons or baryons. An interesting new line of research, somewhat unexpected, is that the study of high-energy collisions between protons with protons, protons with nuclei, and nuclei with nuclei can provide information on hadron interactions. Femtoscopy techniques were developed as a tool to study the possible creation and properties of the quark-gluon plasma in relativistic heavy-ion collisions. Experiments are designed to be sensitive to correlations in momentum space for any hadron-hadron pair, and in particular, to measure two-particle correlation functions (CFs). These latter observables are obtained as the quotient of the number of pairs of combined particles with the same relative momentum produced in the same collision event over the reference distribution of pairs from mixed events. In high-multiplicity events of pp, pA, AA collisions, the hadron production yields are well described by statistical models, which makes clearer the connection between CFs and two-hadron interactions and scattering parameters. Indeed, CFs are calculated in terms of the spatial overlap between a source function and the square of the absolute value of the wave function of the considered hadron-pair, determined from the half-off-shell $T-$scattering matrix. Thus, CFs provide valuable and complementary access to hadron-hadron dynamics, which should shed light on the intriguing nature of some of the numerous light and heavy resonances, difficult to accommodate within simple quark models, that have recently been discovered in several experimental facilities around the world. In the report above, we have explicitly mentioned three works [Albaladejo:2023pzq], [Torres-Rincon:2023qll], and [Sarti:2023wlg], but additional works have been done and this is an extremely promising line of research.

The experimental component of HaSp kept working on data collection and data and data analysis. LHCb, experiment at CERN, GlueX, CLAS12 at Jefferson Lab, BES-III in China, A2-Mami in Mainz, and CB-Elsa and BGOOD in Bonn, collected hadron (standard and exotics) production and decay data that will be used to extend the existing statistics and cover new territories (e.g. using polarized nuclear targets such as the HD). Studies also focused on the future with predictions for spectroscopy at the EIC. Gray areas, such as scalar resonance, where a clear theoretical understanding is still missing, were covered, publishing new results on light quark systems (sigma, f0(980)) and observation of heavier partners f0(1370), f0(1500) and f0(1710)) using both dispersive and multi-channel analysis approach. A combination of these techniques led to a more precise determination of the resonance pole position. A similar multi-channel approach used in the baryon sector (SAID) led to an improved determination of resonance parameters. New photo and electro-production data were used to refine models and extended to heavy quark systems.

It is worth mentioning that the current effort by experimental groups focuses on data collection and analysis of exotic configurations such as di-baryon, tetraquarks, and pentaquarks. The experimental activity produced interest in the theory community in a virtuous spiral of defining new observables and subsequent interpretations. Pentaquarks, in particular, were studied in different ways (decay and production) trying to set a common interpretation of the rich phenomenology studied at hadron colliders (e.g. LHCb), e+e- colliders (e.g. BES-III) and high-intensity lepton beam experiments (e.g. GlueX). Finally, we had a significant improvement in our understanding of dibaryonic degrees of freedom in neutron stars, EoS and neutron stars dynamics [*Phys.Rev.D* 109 (2024) 2, 023004]. A further work on dibaryon-facilitated hadron-quark phase transition is on the way.

Workshops organized by HaSp collaborators (e.g. NSTAR series) gathered together experimentalists and theorists, in the spirit of the STRONG-2020 initiative.

Members of the Strong 2020 working group participated in a comprehensive review of both the theory and experimental successes of Quantum Chromodynamics [50 Years of Quantum Chromodynamics. Introduction and Review, F. Gross et al., Eur. Phys. J. C83 (12), 1125 (2023)]. This review included a presentation of the present situation regarding determinations of the fundamental constants of QCD, as well as an introductory discussion of lattice QCD and effective field theories among other topics.

Deliverables due in RP3.

D25.3 HaSP white paper – Achieved

HaSP white paper can be consulted in the web portal of the WP: http://web.ge.infn.it/jstrong2020/

Milestones due in the RP3.

MS54 General Workshop on Hadron Spectroscopy and Phenomenology (TUM) Tasks 1, 2, 3 and 4 – Achieved

MS55 School on Hadron Spectroscopy and Phenomenology – Achieved

1.2.17 Work Package 26

Activity Type	Joint Research Activity
Work package title	Advanced ultra-fast solid STate detectors for high precision RAdiation spectroscopy (JRA8-ASTRA)
Lead beneficiaries	2 – OEAW, 26 – UNIZG, 28 – CNR, 30 – INFN, 31 – POLIMI, 38 – UJ

Project objectives

ASTRA will develop a versatile advanced detector system, from sensors and read-out electronics and DAQ, namely compact large-area low-energy detectors using CdZnTe (better performance as CdTe also at lower energies) for high precision photon energy measurements from 10-100 keV. For the high-energy range from 100-1000 keV, also CdZnTe will be used. In addition, it will be possible to design pixelated detectors for imaging measurements.

Progress made during the reporting period towards objectives

Task 1: Development of CdTe detectors for an energy range from about 10 – 100 keV
As underlined in the first reporting period, CNR-IMEM performed several simulations in order to identify the best detector shape and electrodes configuration, and commercial available CdTe material, with characteristics matching the simulations' outcomes has been purchased. The preliminary tests carried out at CNR-IMEM on these detectors revealed that 1 mm custom CZT detectors realized in Redlen material show the same or even better performance than CdTe. So, for all the future activities CZT (or CdZnTe) detectors have been developed and used.
Task 2: Development of CdZnTe detectors for an energy range from a few 10 keV to MeV
After the tests and characterization performed in laboratory, several crucial tests have been carried on testing the performances of the developed devices in an accelerator environment. In June 2022, the first ever measurement of the energy resolution and timing performances of a CdZnTe device in a collider were performed at the DAFNE accelerating complex of the INFN Laboratories of Frascati. In this first test, one 1x1x0,5 mm3 CZT detector developed at IMEM-CNR was employed. Then, based on the very promising results, several additional tests have been carried on with a 4-channel system, first, and with an 8-channel one in the latest phase. These measurements have proven the great capabilities of such devices when operated in a high background environment such as an e+e- collider; in particular, the background rejection capabilities, the linearity and stabilization of the system, the possible arising of radiation damage, the timing and energy resolutions as well as the possibility to operate the detectors with an external trigger have been extensively studied. Finally, thanks to the good performances reached, the first ever spectra of kaonic atoms measured with CdZnTe detectors have been obtained.

The tests and characterization of the CdZnTe detectors at DAFNE already produced 4 publications in peer-reviewed journals:

L. Abbene et al., *Eur. Phys. J. ST* 232 (2023) 10, 1487-1492
A. Scordo et al., *Nucl.Instrum.Meth.A* 1060 (2024) 169060
L. Abbene et al., *Sensors* 23 (2023) 17, 7328
C. Curceanu et al., *Front. Phys*. 11 (2023), 1240250.

Highlights of significant results

As a summary, the WP members report the list of the positive outcomes of the preliminary tests on the CZT detectors:

1) Good energy resolution, in the range of a few percent, have been obtained in the first laboratory tests with typical Cs, Am, and Co sources.

2) The good energy resolutions, as well as a linearity below a few permille, have been also confirmed in the DAFNE accelerator environment.

3) Tests performed in the laboratory, after the first data taking in DAFNE, confirmed that no radiation damage was observed.

4) Two electronics modules, a Time to Analog Converter and a Mean Timer, have been implemented in the CdZnTe DAQ chain to detect Kaons and MIPs, exploiting the Luminosity Monitor system of the SIDDHARTA-2 experiment hosting the CdZnTe tests in parasitic mode. This test allowed to assess the background rejection factor to be of the order of 10^{5-6}, depending on the timing performances of the detectors, matching that of the SIDDHARTA-2 experiment.

5) The energy calibration fitting function has been optimized, resulting in residuals (deviation of the nominal value of a calibration peak with respect to the one obtained from the calibration function) below 0,4 %.

6) "In-situ" detector calibration procedure has been successfully established, allowing for an efficient alternative calibration method with respect to the employment of radioactive sources.

7) Thanks to the fast readout of the CdZnTe detectors, a timing coincidence of a few tens of ns between the external trigger and the detectors have been optimized.

8) This coincidence window has been then used in a data taking run with a Cu target, from which the first ever signals of kaonic atoms measured with such devices were obtained.

Deliverables due in RP3.

D26.2 Report on the characterization of the final CdTe detector device – Achieved

The deliverable D26.2 contains and describes all the results obtained with the characterization of the CdTe crystals. This characterization consisted in performing the following measurements:

- Evaluation of Te-inclusion density and sizes

- Electric Characterization
- Spectroscopic characterization

The first test already revealed how the CdTe crystals include more large inclusions with respect to the CdZnTe ones, resulting in a degradation of the spectroscopic performances. From the second test, on the contrary, a smaller leakage current of CdTe devices has been observed. Finally, spectroscopic characterization, the most important test, revealed how CdZnTe crystals produced by Redlen show superior performances to CdTe, even in the low-energy range.

The outcome of this characterization funneled all the next phases of the project to be focused on the development of CdZnTe based detectors.

In the following, the figures included in the D26.2 are reported.

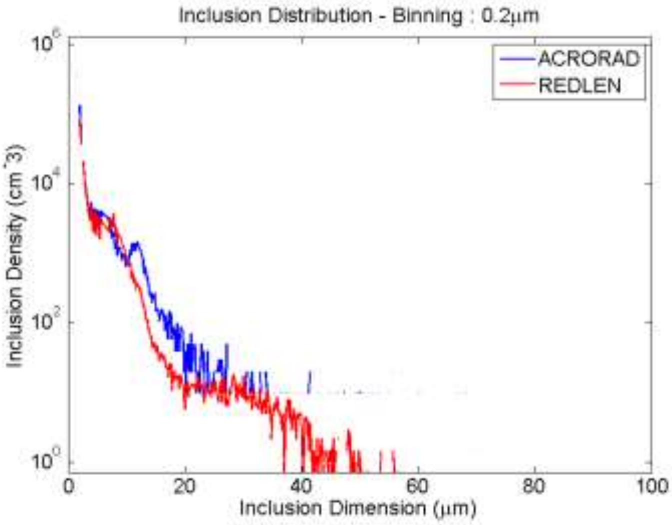


Fig. 1: Compared inclusion distribution of the CdTe (Acrorad) and CZT (Redlen) detectors.

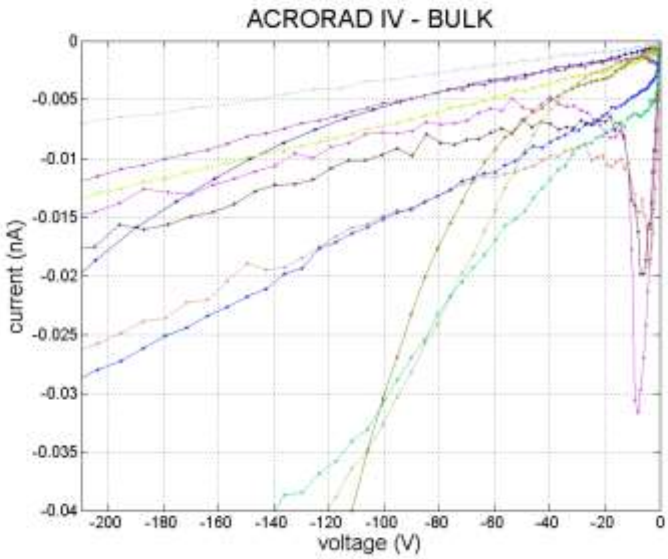


Fig.2: I-V characteristics of the functioning pixels of the CdTe samples.

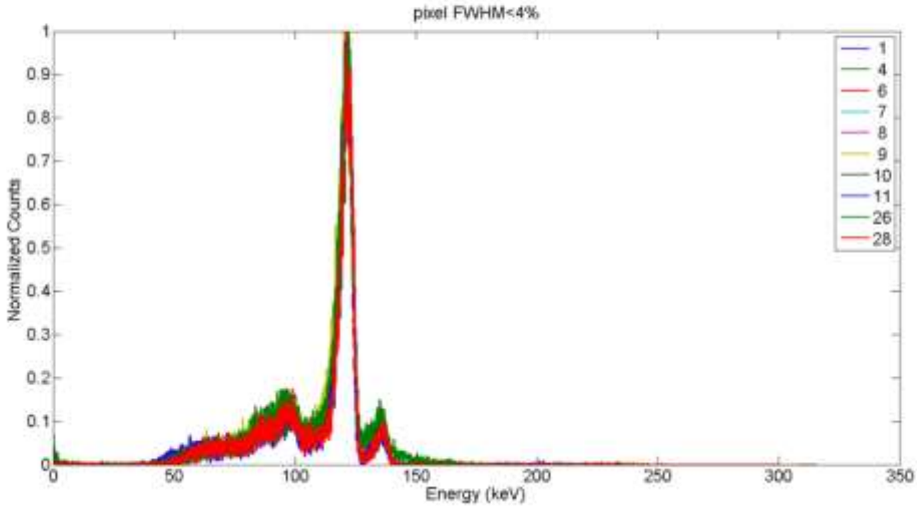


Fig. 3: Spectrum from the best-performing pixel of the CdTe detector

D26.4 Report on the characterization of the final CdZnTe detector – Achieved

The deliverable D26.4 contains and describes all the positive results summarized in the 1.3 section of this document. In the following, the figures included in the D26.4, as well as the three published papers used as references are reported. For the clarity and the completeness of the deliverable, also a paper on the Luminosity Monitor of the SIDDHARTA-2 experiment has been included.

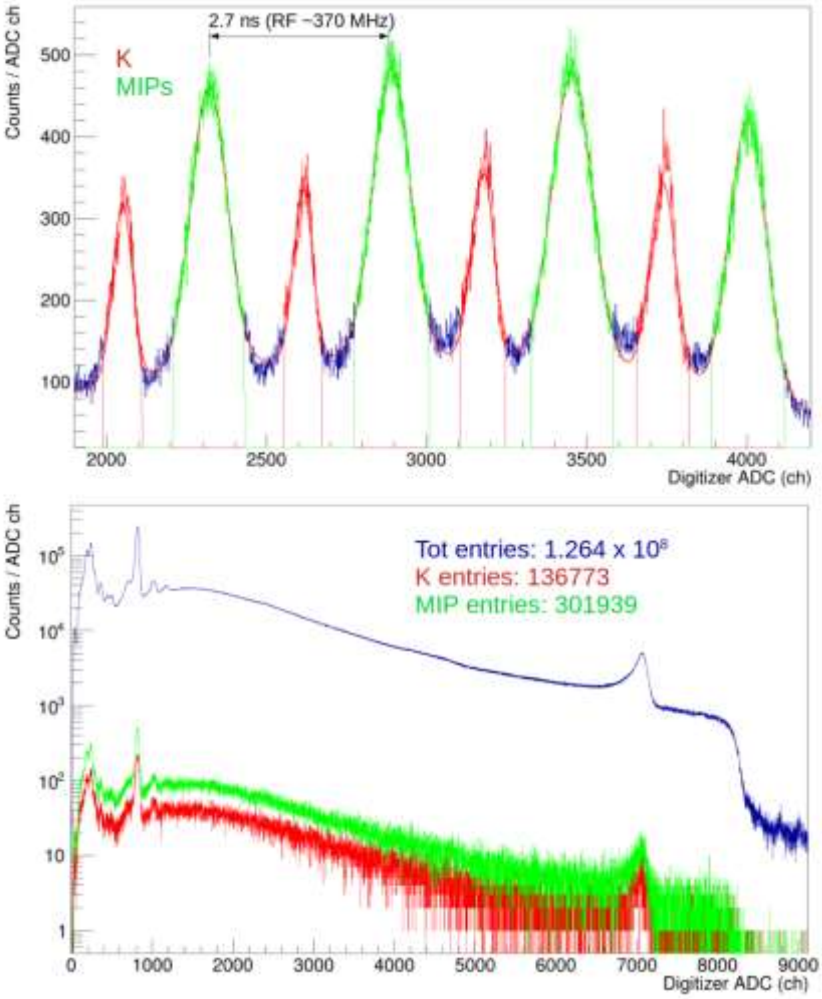
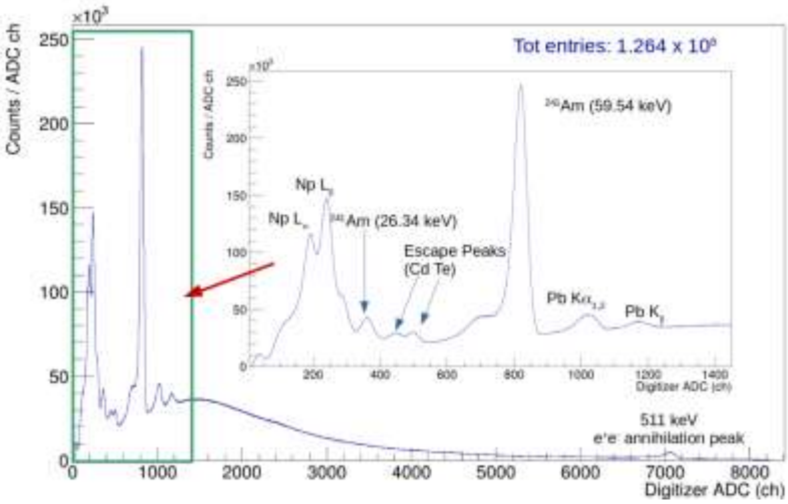


Fig. 1. Top: TAC spectrum from the SIDDHARTA-2 LM; red and green peaks correspond to kaons and MIPs, respectively. Bottom: CZT spectrum with no time selection from the TAC (blue) over imposed on the spectra obtained in coincidence with kaons (red) or MIPs (green) events [2].



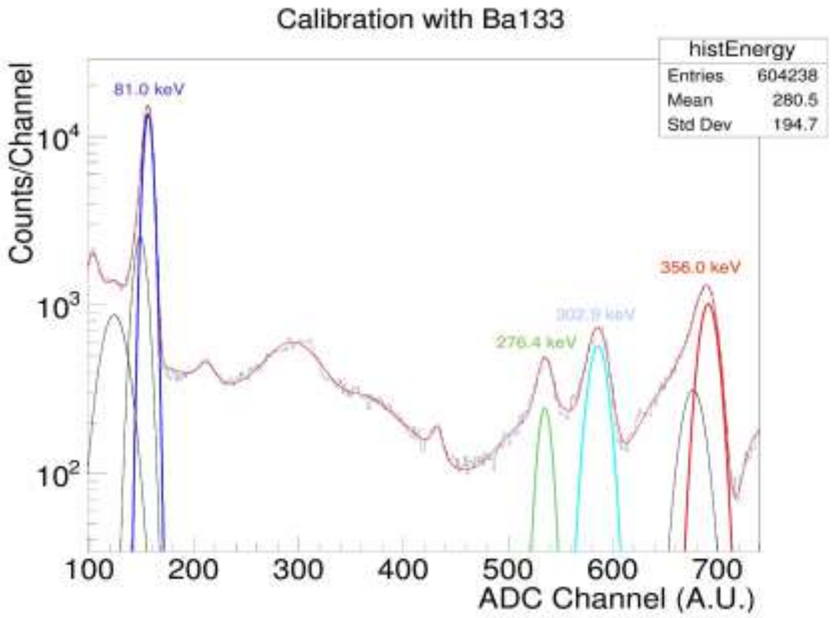


Fig. 2: CZT spectra obtained with the ^{241}Am and ^{133}Ba sources in DAFNE [2-3].

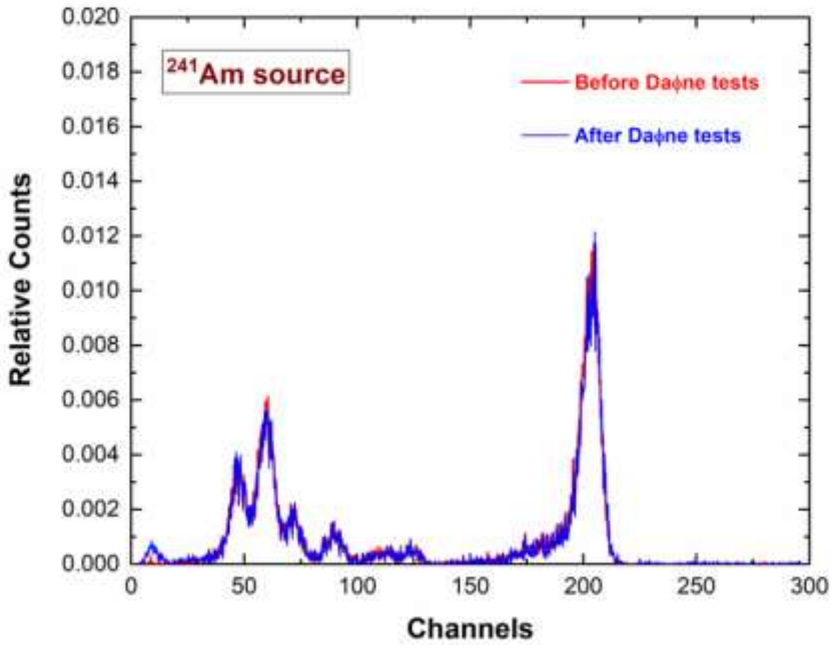


Fig. 3: ^{241}Am energy spectrum measured before (red line) and after (blue line) the tests at the DAFNE collider [4].

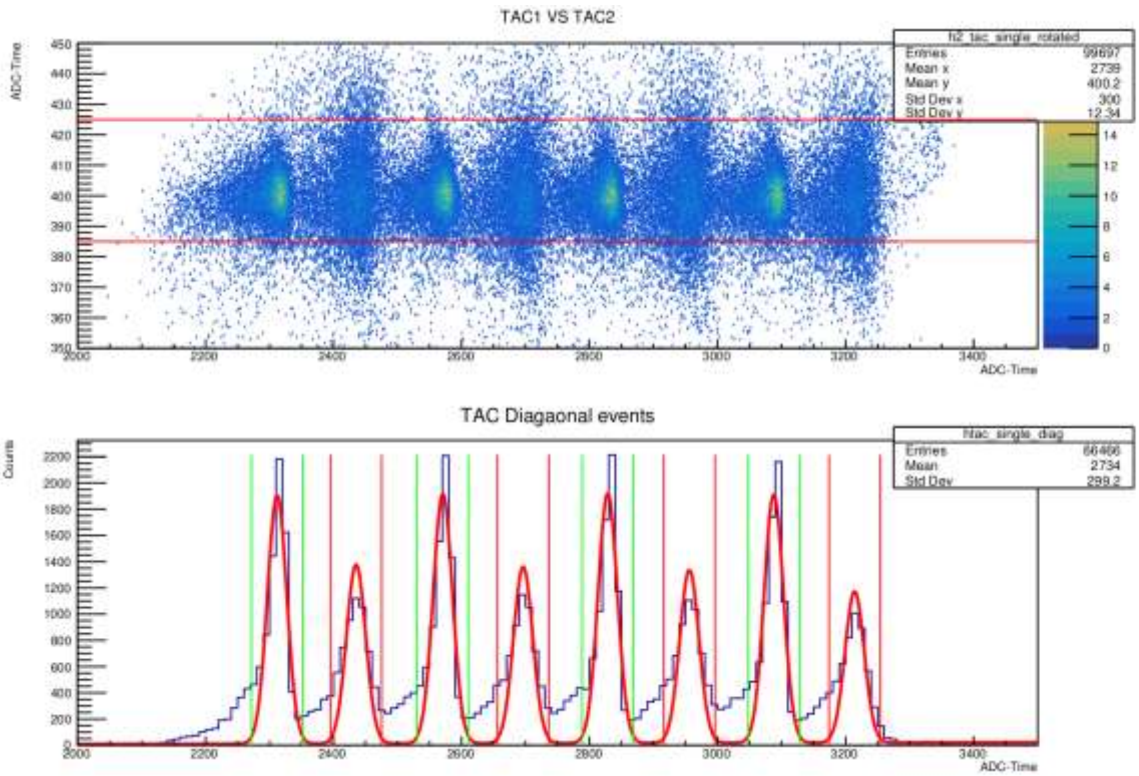


Fig. 4: new K/MIP selection based on the two dimensional (45° rotated) selection of the two TAC modules (up) and the resulting projection on the diagonal

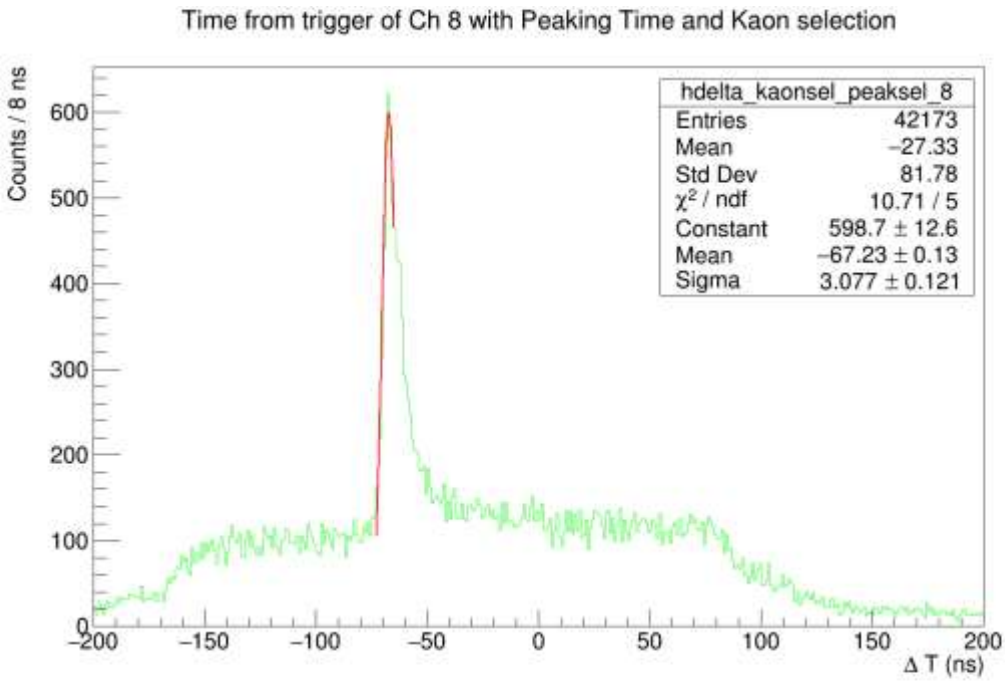


Fig. 5: Triple coincidence timing spectrum between the two SIDDHARTA-2 LM scintillators and one of the CZT detectors; a FWHM < 10 ns is found.

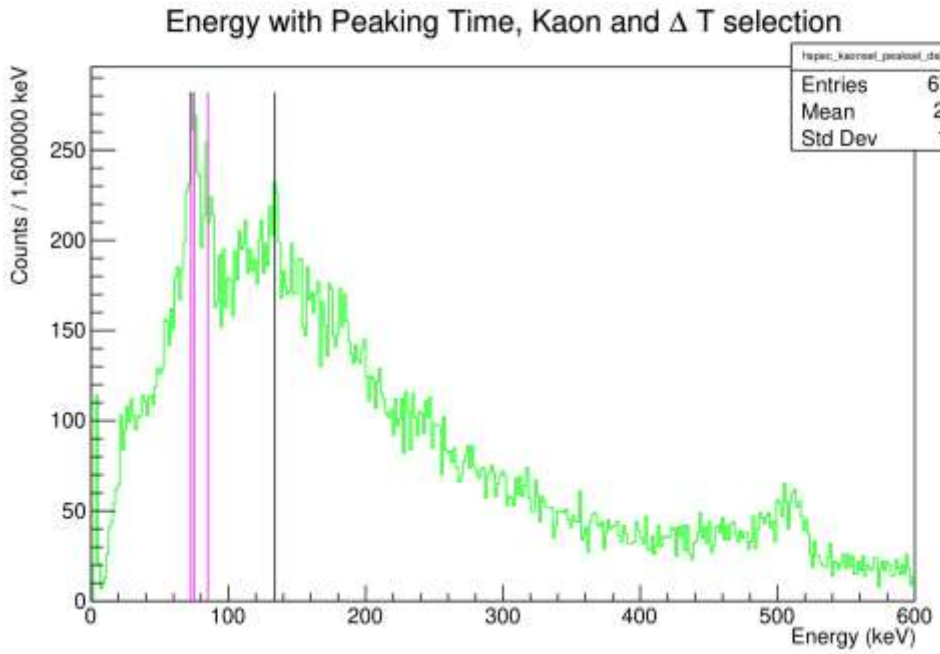


Fig.6: First KCu(6→5) transition spectrum obtained with the CZT detectors; the black line shows the position of the expected peak, while the two pink ones show the positions of the Pb fluorescence peaks due to the shielding activation by the MIPs. The 511 keV e+e- annihilation peak is also clearly visible.

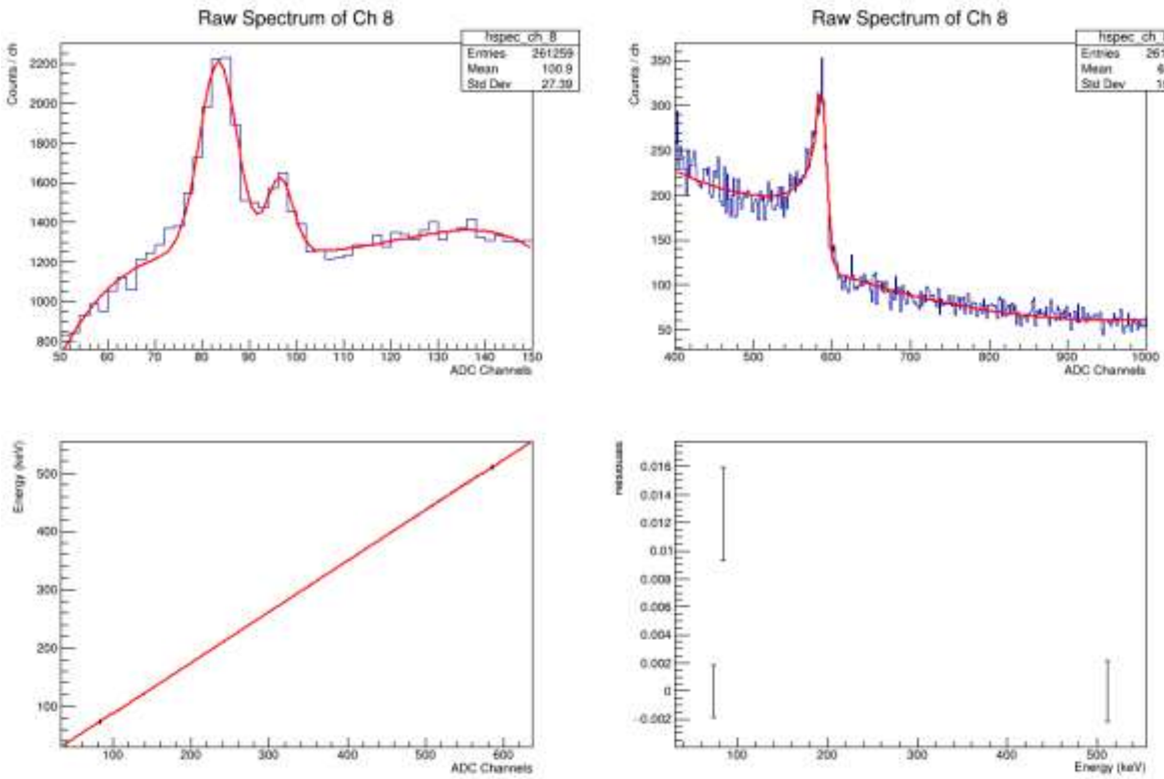


Fig. 7: "in-situ" calibration procedure; the raw spectrum, with no Kaon/MIPs selection cut, has been used for the in-beam calibration with the Pb Kα and Kβ fluorescence lines (up left) and the 511 keV peak (up right). Very good linearity (down left) and residuals below 1% (down right) have been obtained.

References

[1] M. Skurzok et al., *JINST* 15 (2020) 10, P10010
[2] L. Abbene et al., *Eur. Phys. J. ST* 232 (2023) 10, 1487-1492
[3] A. Scordo et al., *Nucl.Instrum.Meth.A* 1060 (2024) 169060
[4] L. Abbene et al., *Sensors* 23 (2023) 17, 7328

Milestones due in the RP3.

No Milestones in the RP3.

1.2.18 Work Package 27

Activity Type	Joint Research Activity
Work package title	Tracking and Ions Identifications with Minimal Material budget (JRA9-TIIMM)
Lead beneficiaries	1 – CNRS, 5 – DKFZ, 8 – GSI, 30 - INFN

Project objectives

This JRA focuses on MAPS technological innovation in the field of tracking detectors for a broad range of experiments primarily in the hadron physics area. Such innovation and corresponding developments are instrumental for the ALICE experiment, and in the more general area of LHC particle physics experiments at CERN, but also in the low energy range ion tracking and identification, as needed in the patient particle treatment in medical physics for instance. A common need to those applications is to combine a precision tracking with energy loss measurement to be used for particle identification (PID), and very low level of crossed material to minimize multiple scattering.

Progress made during the reporting period towards objectives

The final goal of demonstrating particle identification capability of a precise tracking device with low crossed material will be evaluated with the final sensor test. ***The work breakdown structure of the TIIMM WP is structured in five tasks. They are:*** ***Task 1: Definition of the needed sensor characteristics***
The task was completed with the interim report MS60 in 2020. On the one side, the simulation studies defined the specifications for the prototypes, which can be summarized briefly by the need of a large dynamic for the input ionizing signal (10^3 to 10^6 primary electrons) and a digitization over 8 bits. On the other side, the comparison of the potential digitization methods lead to choose the time over threshold technique, which is a good compromise between performance and compactness.An early sensor prototype design (TIIMM-0) allowed to have a first investigation of the implementation of the requirements.
Task 2 and 3: Design of the sensors themselves

Following lessons from the TIIMM-0 prototype, the design of the mais prototype sensors (TIMM-1A/B) was achieved in 2021 and reported with MS61. The sensors were fabricated in 2021. From simulations of the architecture, the specifications reached a dynamic up to $8x10^5$ electrons and allow digitization over 6 bits using time over threshold information. The pixel size was maintained to 40 µm.
Task 4 and 5: Testing of the performances
The sensors have been under test since late 2021. The latest results are highlighted in section 1.3 and reported in further details in section 4. From the positive outcome of these measurements, the plans for a large sensor suitable for applications (outside the deliverable scope of the present project) were drawn.

Highlights of significant results

The TIIMM-1 prototypes were calibrated in the laboratory using radioactive sources and laser beams. Beyond the good operation of the sensors, the key point was the demonstration that the front-end electronics could actually handle the expected dynamic range from 10^3 to $8x10^5$ primary electrons. Output linearity with the ionizing signal was also shown to follow the expectation from the Time of Threshold technique, i.e. a non-linear but calibrated behavior at low signal followed by a good linearity from 10^4 to $8x10^5$.

Further characterization were achieved using proton beams of various energies allowing to cover about a quarter of the dynamic range of interest. There results are detailed in section 4, the main findings are listed below.

- The sensor output follows closely the generated signal as observed with the laser source.
- As expected, the good linearity of the front-end is not entirely reproduced with real detection due to the fact that several pixels are fired at once by a single particle. A careful calibration of each pixel should allow to recover the full linearity.
- The possibility to estimate the ionizing energy deposited in the sensor is demonstrated, which validate the principle of identification of ion species with TIIMM. Still, further tests with different ion species are needed to quantify the performance of the identification.

While the TIIMM participants still plan for the tests with ion species, the positive conclusions of our tests lead us to draw the blueprint of a large sensor exploiting the sensing and signal-treatment elements developed in TIIMM-1. This future sensor will include a digital architecture allowing to read a large pixel matrix, which was not the goal for TIIMM-1 focused on the detection performance.The large area will open the possibility for real applications of ion identification with a pixel matrix.

Deliverables due in RP3.

D27.2 Report on PID performances of final device

Milestones due in the RP3.

MS62 Final device working and characterized – Achieved

1.2.19 Work Package 28

Activity Type	Joint Research Activity
Work package title	Cryogenic Polarized Target Applications (JRA10 – CryPTA)
Lead beneficiaries	9 – JGU MAINZ, 10 – UBO, 25 – RBI

Project objectives

An ambitious spin program is underway at the infrastructures ELSA (Bonn) and MAMI (Mainz), with double polarization experiments with polarized beams on polarized targets. Technically, the polarized nucleons for double polarization experiments are provided by polarized solid-state targets using the method of Dynamic Nuclear Polarization (DNP). To improve this class of experiments and to overcome the drawbacks of the frozen-spin polarized targets: intensity, time loss for re-polarization, external DNP magnet, the objective of this WP is to optimize the small low mass internal LTS (low temperature superconducting) coils to strengthen the magnetic field for permanent DNP ("4-DNP continuous mode" target). Since the PANDA detector will operate with a strong longitudinal magnetic field to provide the measurement of charged particle trajectories with high resolution, it is necessary to shield the polarized gas target from the magnetic field of the spectrometer coil.

The development of a low mass HTS (high temperature superconducting) active or passive shielding is the first step towards a transverse polarized gas target in PANDA. The third task of the JRA is the development of active polarized targets at cryogenic temperatures and the further implementation of this technology with new, improved prototypes. The overall objective of the JRA is hence to develop future key technologies for new and innovative polarization experiments using polarized targets in Europe.

Progress made during the reporting period towards objectives

Task 1: Development of low mass superconducting high field magnets
In the last two years of the funding period (2022-24), we further deepened and concretized the development of the combined coil concept according to the work plan with the support of an experienced postdoc (Victoria Lagerquist) funded by the project. As mentioned in the last report, in Subtask 3 we developed a concept for a holding coil in which a solenoid is coupled to a dipole coil. We call this magnet a "combined longitudinal and transverse holding coil", it is designed for the frozen spin mode of the polarized target and allows variable adjustment of the polarization direction in the plane spanned by the superposition of the two magnetic fields. Both magnets, the solenoid and the "racetrack" dipole, generate a maximum field of 0.5 Tesla.

This idea could be ideally combined with the intention to measure double polarization observables with elliptically polarized photons in the future. Since an elliptically polarized photon beam results from photons with linear rather than circular components, it is possible to simultaneously measure polarization observables associated with these polarization states. Since these polarization observables require different field orientations, it would be useful to change the field/polarization direction of the target nucleons during the scattering experiment.

To that end, a combined holding coil is being developed which pairs longitudinal and transverse coil functionalities within a single configuration. The most straightforward arrangement for such a pairing is to simply concentrically nest the solenoid and racetrack geometries. The primary concern for this configuration is maintaining sufficient field strength without excessively increasing the radiation length material budget. The current single-purpose coils available for use at ELSA (which serve as an initial basis for this design) each have four layers of windings. An ideal combined coil would achieve the dual-purpose without greatly exceeding that number across both coils.

The initial step in attaining that is generating an optimizable model. The basis coils were originally developed using finite element analysis which models blocks of current densities. For the purpose of fine optimization, though, we elected to model our coils computationally using MatLab. Using the Biot-Savart law

$$B(r) = \frac{\mu_0}{4\pi} \int_C \frac{Idl \times r'}{|r'|^3}$$

we calculate each individual winding. The element of interest in this equation is the current path *l*. The *x* and *y* components of *l* are trivially selected by their theta dependence ($R\cos(\theta)$ and $R\sin(\theta)$). The *z* component, however, defines the coil shape.
For a solenoid, the *z* component can either be modeled as a series of discrete circular loops ($z = z_0$) or as a continuous spiral

$$z = \theta \frac{D}{2\pi} + z_0.$$

Checking the result between the two techniques found them to be negligibly different within the target region. With this, we found we can reduce the solenoid by 2 layers while still (barely) meeting the minimum field requirement.

The racetrack coil, however, presents a more interesting geometry. Ideally, it would be composed of straight lines (down the length of the mandrel) connected by semicircular connections (around the mandrel perimeter). However, the superconducting magnet wire has physical limitations in its bending radius, which necessitates a gentler transition between straight sections and connecting arcs. The original transverse coil layers were wound flat then bent over the mandrel generating a smooth curve. We chose to emulate this by modeling the connecting arcs as ellipses wrapped around the polar axis

$$z = a\sqrt{1 - \left(\frac{\theta - k}{b}\right)^2} + h$$

(with appropriate handling of the various quadrants). The result of this parameterization was checked against a standard 3d modeler (Opera3D) and found commensurate. Additionally, like the solenoid, we also tested its sensitivity to single loops and continuous winding calculations.

Optimizing the racetrack geometry presents several options. Analyzing the central field contribution of each winding based on its angular position and layer number allows us to clearly understand the relationship between coil geometry and field strength. From there, decisions can be made regarding the relative importance of material budget, material uniformity, field uniformity, and absolute field strength. The current transverse coil traded maximum field strength and material uniformity for field uniformity and material budget. Choosing differently, we can reduce the layer number to 3 by extending the upper layers to match the angular coverage of the lowest one (increasing the material uniformity) and still reach the required field strength - albeit less uniformly.

Altogether, we anticipate being able to produce a combined holding coil with only 1 additional layer compared to current coils. The next steps are to manufacture and test a prototype coil using the impressive winding facilities at the University of Bonn. Additionally, we can consider the opportunity of arbitrary angle polarization using this configuration. For this, however, the question of relative component uniformities becomes more relevant. Efforts are currently underway to generate a coil configuration, which meets those requirements.

Task 2: Development of low mass HTS active or passive shielding

As already reported in RP2, the periodic report of 30.04.2022, the consortium member "HIM JGU Mainz" has left the joint research activity CryPTA. As a consequence, the task 2 "Development of low mass HTS active or passive shielding" could not be continued.

Task 3: Detection of recoil particles in active polarized targets at cryogenic temperatures

In the reporting period (06/2022 – 07/2024), the Mainz group has continued to work on the realization of new prototypes for an active polarized target. Originally it was planned to test new versions of the active target for the Mainz/Dubna dilution refrigerator in cooperation with the colleagues from the Joint Institute for Nuclear Research in Dubna, Russia. Since this was not possible due to the actual political situation, the necessary steps were realized in Mainz by strengthening the local group. Two student assistants were hired in Mainz and worked with the supervision of the Mainz staff (A.Thomas, M.Biroth, P.Drexler). They have setup a test box to test the new scintillators with fiber readout and SiPM electronic readout, first in lab with a radioactive probe and finally in the MAMI photon beam. The corresponding parts (specifically shaped scintillators, electronic boards, optical fiber connectors) were produced within the local workshops in Mainz.

Finally, a light tight cryogenic test box has been constructed, which was used in 07/2024 in beam. The materials could be tested successfully with liquid nitrogen cooling at 77K and the result were reported (see attached deliverable report).

Highlights of significant results

CryPTA 2022, annual meeting

One of the highlights of the reporting period was the annual meeting (CryPTA2022) of the CryPTA consortium in September 2022. It was the first annual meeting where the participants were able to meet again in person for scientific exchange. The meeting took place from 20.09. to 22.09.2022 in Boppard am Rhein. 20 participants from 10 institutions in the USA, Japan and

Europe took the opportunity to present the latest developments in polarized targets and to enjoy the direct scientific exchange after the corona crisis.

The meeting was thematically oriented towards the three tasks of the CryPTA project: CryPTA:ScM, CryPTA:ScS and CryPTA:APT. The invited presentations were all related to these subprojects.

Detailed information about the program and all presentations of the annual meeting can be found on the workshop web page [1] and in the proceedings of the PSTP2022 workshop [2]. In the following, the most important results and ideas of the CryPTA annual meeting are briefly summarized and reviewed.

1. Superconducting magnet systems using LTSC materials: CryPTA:ScM

1.1 Thin superconducting magnets for DNP

In the double polarization experiments at the large acceptance detector systems Crystal Barrel at ELSA and Crystal Ball at Mami, the target technology of the horizontal frozen spin target with an internal holding coil developed in Bonn [3] has been used very successfully for many years. To improve the figure of merit for future polarization experiments, the thin internal holding coil of the frozen spin target should be replaced by a coil of the same geometry but with a stronger magnetic field. Ideally, the magnet should provide the field of the external polarization magnet, typically 2.5 Tesla. The advantages of this scheme of an internal polarization magnet are obvious: the target polarization can be kept at a high level even during data acquisition by DNP, there is no more loss of time due to the otherwise usual post-polarization phases. We call this scheme '4π-continuous polarized target' [4].

However, the DNP process requires a high field homogeneity over the target volume and since the magnetic field volume of the planned internal polarization magnet is of the same order of magnitude, appropriate correction windings have to be placed on the solenoid. All this requires precise winding of thin superconducting wires on a thin-walled copper substrate using wet winding techniques [5].

In the target laboratory of the Physics Institute of the University of Bonn, a small superconducting solenoid with a nominal field of B_P = 2.5 T was successfully wound on the specially developed winding machine. The coil can be installed in the existing or in the future horizontal dilution cryostat. The coil was tested in a 1K ^{4}He evaporation refrigerator. We demonstrated that both PE and ^{6}LiD can be dynamically polarized [6]. The next step is to install the coil in the new dilution refrigerator and use it in the Crystal Barrel experiment at ELSA.

In order to measure as many polarization observables as possible with one setting of detector system and polarized target, we are currently developing a coil system in which a solenoid is combined with a race-track coil pair in a cylinder carrier [6].

1.2 Superconducting correction coils for DNP in a spectrometer magnet

At JLab, the technique of internal superconducting coils is used at the CLAS12 experiment to correct for an external strong magnetic field. There, the 5 Tesla magnetic field of the large acceptance detector system is used to dynamically polarize the target material in a continuously operated horizontal 1 K evaporation refrigerator. In contrast to the frozen spin operation, the target material is also permanently dynamically polarized during data taking. In this sense, this is also a '4π continuous polarized target' [7]. However, since the homogeneity requirements for the DNP process must also be met here, superconducting correction coils were installed in the cryostat in the target area after prior precise measurement of the spectrometer magnetic field. The coil system was designed to not only correct the external field, but also to provide a significant field shift to reverse the polarization direction in the individual target cells and measurements for NMR calibration. Overall, then, a very elegant solution and use of internal coil technology [8].

2. Superconducting magnet systems using HTSC materials: CryPTA:ScS

In recent years, the development of high-temperature superconductors has progressed to such an extent that these materials are also suitable for special magnet applications. The special geometrical requirements of the thin magnet systems used in the polarized target suggest the use of tubes made of solid high-temperature superconductor material. In addition, tubes made of high-temperature superconductor open the possibility to induce and practically store or completely shield the magnetic field of an external magnet when passing through the critical parameters of the material.

2.1 Bi-2212 shielding tube

Within the framework of CryPTA:ScS, the working group from HIM (UMainz) has investigated the shielding properties of HTSC tubes consisting of bulk Bi-2212 (Bi2Sr2CaCu2O8). Background of this measurement is the planned use of this shielding in the Panda magnetic field to create a field-free space for a polarized target at the interaction point. The measurements on the shielding behavior of the Bi-2212 tube have shown that at a temperature of $T_{Bi\text{-}2212}$ = 4.2 K a longitudinal external magnetic field of B_{ext} = 1.4 T can be almost completely shielded with a shielding factor of SF = B_{ext}/B_{res} = $3*10^5$ (B_{res}: field inside the cylinder) [9]. Further measurements on shielding behavior at higher temperatures and magnetic fields are planned for the future. It is also planned to systematically investigate the high-temperature superconductor YBCO under the same conditions and to test its suitability as a shielding material [9].

2.2 Bulk MgB_2 holding magnet

A really promising concept for field generation or field storage using a high-temperature superconductor as a holding coil for a polarized target was presented by G. Ciullo from INFN Ferrara [10]. There, one uses a tube of magnesium diboride (MgB_2) sintered in one's own laboratory. The tube is produced by the so-called magnesium 'reactive liquid infiltration' process. MgB_2 is an intermetallic compound that currently has the highest transition temperature (39.5 K) among metallic superconductors and is characterized by a high critical current density. To measure the properties of the MgB_2 tubes, the cylinder was cooled to T_{MgB2} = 13 K via a cold head and subjected to an external axial and longitudinal magnetic field of B_{ext} = 980 mT. Depending on the condition under which the temperature fell below the critical temperature, the external magnetic field could be trapped or shielded. This showed that the external magnetic field was almost completely trapped (B_{res} = 943 mT). The shielding behavior of MgB_2 is less pronounced than Bi-2212 at T_{MgB2} = 13 K, but a clear temperature dependence is evident. Thereafter, a much higher shielding factor can be expected at 4.2 K for MgB_2. The long-term stability measurements show a stable shielding behavior and a high stability of the trapped field. In further measurements in the near future, the temperature of the cylinder will be lowered further and exposed to higher external magnetic fields, thus testing its suitability for use in the polarized target. But already now it can be said that the concept of cylindrical high-temperature superconductors is a good alternative to the classical superconducting coils based on low-temperature superconductors. Thus, the high-temperature superconductors significantly expand the application and experimental range of the polarized solid-state targets in polarization experiments. Thus, the use of the concept is envisaged in the future at the CLAS12 experiment.

3. Low temperature detection techniques: CryPTA:APT

Naturally, the polarized solid-state target reaches its limits with respect to the detection probability of the reaction products when measuring threshold reactions or at generally low beam energies. The density of the target material and the large radiation length of the structural materials surrounding the target, and here in particular the internal holding coil, shadow the target material and shift the detection threshold for particle detection by about 100 MeV. Thus, among other things, the measurement of the 'Proton Spin Polarizabilities with Double-Polarized Compton Scattering' is planned at MAMI. Due to the reaction kinematics and the competing processes, the detection of the recoil proton is essential for the process. From this constraint for the experiment, the idea of the active polarized target has been developed in the working group at MAMI [11].

Typically, doped alcohols are used in polarization experiments with real photons because of their high content of polarizable nucleons. Since polystyrene also has this property and at the same time functions as a classical scintillation material, the obvious conclusion is to dope polystyrene, polarize it dynamically and read out the light from the recoil protons. However, all components, scintillator, light guide and first readout electronics are located in the dilution cryostat and are thus partially exposed to temperatures in the millikelvin range. This places high demands on the coupling of the light guide to the scintillator and the quality of the light guide itself. In the meantime, the concept has been used in a first scattering experiment and first data have been taken. The polystyrene used could be polarized to just under $P_p \sim 50\%$. The relaxation times reached $\tau \sim 80$h in the frozen spin mode of the target. The low relaxation times were due to the high thermal conductivity of the optical fiber and are not unusual for now. What was important was the successful detection of recoil protons, which were detected in the analysis process. The tests confirmed the concept, but a modified version of the active target will be used in the future. The idea of a semi-active target is being discussed. It is planned to embed a small classical alcohol target material (high polarization, significantly improved relaxation times) a cage of strongly segmented scintillators and to guide the light via thin fiber elements from the low temperature range to the medium temperature range of the cryostat. This significantly reduces the thermal load on the mixing chamber and improves the performance of the refrigerator [12].

Regardless of the difficulties, the concept has proven that the active target opens a new class of polarization experiments with the polarized solid-state target, offering a significant expansion of experimental possibilities in hadron physics.

In summary, the meeting once again brought together all those involved in the development and operation of solid-state polarized targets worldwide. The polarized target is a well established and reliable experimental device in scattering experiments. For almost 60 years it has been the instrument of choice for studying spin-dependent quantities in hadron and particle physics. But the meeting also showed that in the future only a few laboratories will be able or willing to afford this complicated infrastructure and that further development will shift to the USA (Jlab) due to a lack of young talent here in Europe. In this respect, it was probably the last meeting of its kind in Europe dealing with the topic of polarized targets.

[1] H. Dutz and A. Thomas, *CryPTA2022, Annual meeting of the STRONG2020 Joint Research Activity 'Cryogenic Polarized Target Applications'* (WP28), [Online]. Available: https://indico.hiskp.uni-bonn.de/event/84/.

[2] H. Dutz, *CryPTA2022, Status Report from this year's annual Meeting*, PoS(PSTP2022)021, p. 21, 2022.

[3] Ch. Bradtke et al, *A new frozen-spin target for 4pi particle detection*, Nucl.Instr. and Meth.A 436 (1999) 430-442, p. 13.

[4] H. Dutz, *Summary of the 9th International Workshop on polarized solid-state targets and techniques*, Proceedings of the 16th International Spin Physics Symposium, pp. 221–225, WORLD SCIENTIFIC, 2005.

[5] M. Bornstein, *Development of a thin, internal superconducting polarisation magnet for the Polarised Target*, PoS(PSTP2015)006, p. 6, 2015.

[6] H. Dutz, *Status of CryPTA:ScM*, CryPTA2022, 2022. [Online]. Available: https://indico.hiskp.uni-bonn.de/event/84/contributions/896/.

[7] C. Keith, *Activities of the Jefferson Lab Target Group*, CryPTA2022, 2022. [Online]. Available: https://indico.hiskp.uni-bonn.de/event/84/contributions/887/.

[8] V. Lagerquist, *Optimization and Implementation of Magnet Correction Coils for the Jefferson Lab Polarized Target*, CryPTA2022, 2022. [Online]. Available: https://indico.hiskp.uni-bonn.de/event/84/contributions/892/.

[9] F. Maas, *Experimental tests of the shielding tube BSCCO-2212*, CryPTA2022, 2022. [Online]. Available: https://indico.hiskp.uni-bonn.de/event/84/contributions/899/.

[10] G. Ciullo, *A versatile bulk superconducting MgB2 cylinder for the production of holding magnetic field for polarized targets and nuclear fusion fuels*, CryPTA2022, 2022. [Online]. Available: https://indico.hiskp.uni-bonn.de/event/84/contributions/893/.

[11] A. Thomas, *Status of the polarized target at MAMI*, CryPTA2022, 2022. [Online]. Available: https://indico.hiskp.uni-bonn.de/event/84/contributions/883/.

[12] M. Biroth, *The Mainz Active Polarized Proton Target - Review and Perspectives*, CryPTA2022, 2022. [Online]. Available: https://indico.hiskp.uni-bonn.de/event/84/contributions/895/.

Task 3:

The results of the first active polarized runs with MAMI beam have been reported in the framework of a PhD thesis. New ideas and concepts for an improved version of the polarized active target insert have been developed and reported. The light transport system of the next generation active target insert was replaced by optical fibers with a SiPM readout electronics. Tests with scintillators operating at cryogenic temperatures have been performed in a real photon beam.

Deliverables due in RP3.

D28.1 Prototype of a low mass, internal horizontal polarizing solenoid – Achieved

Deliverable D28.1: Prototype of a low mass, internal horizontal polarizing solenoid, 29 pages, Bonn (2024) was submitted in the Portal.

D28.2 Prototype of a HTSC shield for a large acceptance magnetic detector – Achieved

The document corresponding to the D28.2 Prototype of a HTSC shield for a large acceptance magnetic detector was submitted in the Portal.

D28.3 Prototype of a cryogenic insert with active target material – Achieved

Deliverable D28.3: Detection of recoil particles in active polarized targets at cryogenic temperatures, 5 pages, Mainz (2024) is submitted.

Milestones due in the RP3.

No Milestones in the RP3.

1.2.20 Work Package 29

Activity Type	Joint Research Activity
Work package title	Cryogenically cooled particle streams from nano- to micrometer size for internal targets at accelerators (JRA11-CRYOJET)
Lead beneficiaries	8 – GSI, 16 – WWU, 41 – UU

Project objectives

The objective of this JRA is to significantly develop the science and technology of cryogenically cooled target beam sources for applications in present and planned complex internal-target experiments, which require target beams of highest quality, such as PANDA@FAIR. In addition to hadron physics experiments, cryogenically cooled cluster/pellet/microjet beams have recently been discovered to be perfectly suited as targets for laser-particle interaction.

The comparably small cluster sizes of, e.g., 1-100 nm, of cluster beams make them ideally suited for internal storage ring experiments, targets at electron accelerators, or laser-driven hadron accelerators. Nozzle production techniques will be improved and extended with the aim to achieve higher target beam thicknesses and higher nozzle production yield. Key issue for laser-induced particle acceleration to multi-MeV kinetic energies is to build targets that can make use of the high laser repetition rate (up to kHz), targets that contain only those elements to be accelerated (e.g. hydrogen), and that have a limited density (to assure a high acceleration efficiency. An additional goal of this JRA is to develop cryogenic droplet beam sources, both for hadron physics experiments at storage rings, electron accelerators, and the exciting novel possibility to use them for intense laser-driven proton acceleration. Within this JRA it is planned to prepare a prototype for a real-time pellet tracking system which can predict the time dependent position of an individual pellet in the target region.

Progress made during the reporting period towards objectives

Task 1: Cluster-jet beams
Based on the former results on the production of high-quality cluster-jet beams, a significantly improved cluster generator has been built and installed at the prototype target in Münster. This device allows for a much easier exchange of cluster nozzles, better vacuum sealing between different vacuum stages, and a temperature readout at the warm stage of the coldhead. The latter improvement is especially important for the target operation with gases heavier than hydrogen. Further studies on diagnostic tools for cluster-jets using MCP detection systems were performed. Since commonly used phosphor screens were found to be very sensitive to ionized hydrogen clusters, a more robust YAG:Ce screen is now in use. This chemically more robust device provides also sufficiently good images of ionized cluster jets. Improved cluster nozzle productions techniques were developed which lead to a more reliable production of nozzles with minimum inner diameters down to 30 µm.
Task 2: Cryogenic droplet beam target
A new droplet generator has been set into operation and allows for the generation of hydrogen droplets and 10 µm thick frozen hydrogen filaments. Especially the frozen hydrogen filaments with their high local areal target thickness might be of high interest for new hadron physics experiments, such as MAGIX at MESA. The long-term stability of the apparatus was demonstrated in a hundred-hour long-term measurement. A new method to align the cryogenic target particles in vacuum by using deflection jet beams could be shown.
Task 3: Real-time pellet tracking system
The pellet tracking system has been re-deployed from the The Svedberg Laboratory to the Ångström laboratory. Individual components have been thoroughly tested and refurbished as needed. The detection modules have been assembled. The readout system is in operation and provides trigger outputs on detected pellets for testing purposes. New components, e.g. lasers, have been tuned for the setup. Furthermore, the alignment of the reassembled modules is nearly complete and a comprehensive documentation of the procedure is in preparation.
Task 4: Pellet beams
New droplet/pellet nozzle production techniques have been established. Precise nozzle openings of, e.g., 10 µm diameter are routinely available. In addition, a system to influence the droplet production using a laser has been developed.

Highlights of significant results

Numerical simulations on the evaporation of microspheres, i.e. clusters, droplets and pellets, in vacuum have been further developed and compared with data from experiment. These studies led to a good understanding of the vacuum situation for experiments using hydrogen cluster beams. Moreover, these calculations give important information about the freeze-out time of the droplets in vacuum and by this with the known particle velocity about the freeze-out position in the target device. The obtained results could be compared to measurements using droplets produced in a 10 µm droplet nozzle.

Diagnostic tools to investigate the properties and quality of cluster-jet beams have been improved significantly. In detail, a new MCP detection system with a phosphor screen has been tested at COSY. It was found that ionized hydrogen clusters can lead to long-term damage of the phosphor layer. According to this, a chemically more robust scintillating YAG:Ce screen has been used instead.

A new droplet generator has been built and set into operation. The properties of the produced droplet streams were studied by using a new laser diagnostic system. It could be shown that by switching off the piezo transducer a stable frozen hydrogen filament can be produced. Such filaments are of high interest for future hadron physics experiments, such as MAGIX at MESA. A long-term measurement showed that such filaments can be produced for more than 100 hours without interruption.

An implementation and proof of concept of a real-time pellet tracking system have been done. A pellet tracking section with four detection modules has been completely equipped with line scan cameras and lasers. The fine adjustment and alignment are almost finished. A collimator system with 0.16 mm hole diameter is being prepared. The system allows the prediction of when a pellet will be present in the nominal interaction region with high accuracy. This information can be provided to a pulsed laser as a trigger signal.

Furthermore, a system to study the influence of laser light pulses on the droplet production has been prepared and tested at the pellet generator at Uppsala University. The system consists of a point focused, pulsed laser, a CCD camera monitoring the droplet formation chamber, and a line scan camera monitoring the pellet stream after vacuum injection. The studies included different droplet production frequencies and laser power setting. During these runs, no significant effects from applying the laser pulses could be observed in the droplet formation chamber. The offline analysis of the data from the line scan cameras confirmed these results. To achieve an effect a further increase in laser power or additional laser is required.

Deliverables due in RP3.

D29.1 Report on new nozzle and beam production techniques for high performance cluster-jet, droplet, and pellet targets – Achieved

From left to right: newly, totally in-house produced de Laval nozzle "2202", glass nozzle produced according to our CAD drawings, and newly produced droplet nozzle

For cluster-jet, droplet, and pellet targets the same basic principle holds: cryogenic fluids, in many cases hydrogen is pressed through a dedicated nozzle (system) expanding into vacuum to form ultra-pure targets for a variety of experiments. Due to different requirements on the operation parameters (temperature and pressure) and on the sphere size, different nozzles are necessary. In the report, the production of cluster-jet and droplet/pellet nozzles are presented with their resulting impact on the target performance.

Important for the operation principle of cluster-jet targets is a special nozzle geometry. A convergent inlet leads to the narrowest diameter of 30µm. Afterwards a divergent outlet follows, leading to the total nozzle length of 18mm. The extreme difference between narrowest inner diameter and nozzle length raises the challenge in producing such fine nozzles. As production methods for these nozzles two possibilities are tested.

An external company can produce nozzles according to our CAD drawings out of glass. For gaseous hydrogen being upstream to the nozzle the resulting cluster-jet is similar to cluster-jets emerging from the well-established copper nozzles, but as soon as the vapor pressure curve is crossed the resulting cluster-jet breaks down and ice fragments form inside the nozzle which are then chaotically ejected into the skimmer chamber. Two possible remedies have been tested but were not found to be working. This leads to the omission of these glass nozzles for cluster-jet targets operating with fluids.

As a second production method galvanization in a sulfuric acid copper bath is performed whereas for the first time the production is achieved totally within the Institute of Nuclear Physics of the University of Münster and its mechanical workshop. In total, from nine galvanized workpieces, eight resulted in nozzles from which five have a diameter close to the desired one. Compared to the rejection rate of 60% to 80% of previous (not totally in-house) batches, a huge step forward was taken. The three most promising nozzles were chosen to be inserted in the cluster-jet target. Resulting cluster-jets show similar behavior in density and velocity as well-established nozzles.

Additionally, for the operation with argon a larger nozzle with a narrowest inner diameter of 120µm was galvanized which is significantly easier than the galvanization of 30µm nozzles. The resulting argon cluster-jet was used for experiments in Mainz.

Also, for droplet/pellet nozzles a new production method was established. A platinum iridium orifice with a pinhole of 10µm is welded onto a copper tube with the desired outer geometry. Furthermore, new analysis methods on nozzle clogging were conducted. Raman spectroscopy and electron microscopy can be used to determine the material causing the clogging where insights were gained. As soon as a droplet nozzle functions properly and without clogging, investigations on the jet stability of the droplet target can be performed. It was possible to operate the droplet target stably for 100 hours. During the measurement, the beam position deviations are in the order of tens of microns indicating a stable beam behavior.

D29.2 Report on measurements of ion acceleration using laser-induced production – Achieved

Owing to their extreme field strengths of over 100 GeV/m, plasmas are of high interest for use as compact particle accelerators. In our work, we irradiate a cryogenic hydrogen cluster-jet beam with a high-powered laser beam, thereby accelerating protons to multi-MeV energies.

The cluster-jet beam was generated by the MCT-D (Münster cluster-jet target Düsseldorf). It injects cryogenic hydrogen (e.g. 28 K) through a de Laval nozzle (e.g. 42 µm smallest inner diameter) into vacuum, thus producing an atomized jet of clusters up to around 5 µm in diameter. The laser beam was provided by the Arcturus laser of the HHU Düsseldorf, capable of delivering pulses with energies of up to 7 J at a pulse length of 30 fs, reaching intensities up to 1 x 10^{20} W/cm^2.

For the experiments, the Arcturus laser beam was focused perpendicularly onto the cluster-jet beam, generating accelerated protons via a Coulomb explosion-like mechanism. Two Thomson parabolas were used to record them and determine their energies, one under 0° respective to the laser propagation direction and one under 135°.

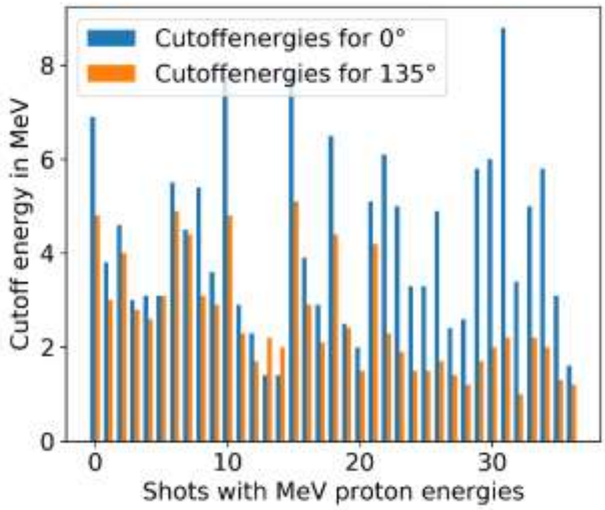


Figure 1: Maximum energies under 0° and 135° grouped per shot.

The results of over 30 individual laser shots are depicted in Figure 1, revealing the production of protons with energies up to the multi-MeV level. However, unlike for a pure Coulomb explosion, the proton acceleration is evidently anisotropic. Additionally, further studies revealed the achieved energies to be laser contrast dependent, with multi-MeV protons only appearing for contrasts better than 10^{-7}. This behaviour can be interpreted together with the anisotropy: The laser's pre-pulse ionises the cluster, which begins to expand before the arrival of the main pulse. At low contrasts, the resulting density is so low that no significant acceleration is achieved. At better contrasts, the cluster remains dense enough to achieve multi-MeV energies, however, the expanded cluster no longer performs a pure, isotropic Coulomb explosion. Instead, the interaction becomes anisotropic, which will necessitate simulations to be understood completely.

Through interaction of a cluster-jet beam and a high powered ultra-short pulse laser, multi-MeV protons could be achieved, albeit with a low shot-to-shot stability. There are two possible approaches to improve it. One could enlarge the size of the laser focus, increasing the number of clusters hit per shot and thus improving the shot-to-shot stability, as well as increasing the probability of hitting larger clusters, potentially increasing maximum energies to the multi-GeV range. The other approach is to use a hydrogen pellet target instead of a cluster-jet target. Such a target delivers individual, well separated frozen pellets with an identical diameter of around 20 µm at a constant rate. Since the laser would be guaranteed to always interact with an identical target, the shot-to-shot stability would greatly improve while the large pellet size would lead to, potentially, maximum energies in the multi-GeV range.

D29.3 Report on a pellet tracking system – Achieved

As outlined in section 4.3.2 using small pellets of frozen gases as targets for pulsed micro-focus lasers is appealing. Given that there is always a certain amount of divergence and velocity spread in a cryogenic pellet stream, its effective use depends on the ability to predict when a pellet will be in the focus of the laser beam.

In this project, the pellets have a diameter of 30-70 µm, velocities around 80 m/s (0.5% spread), and a flux below 3000 pellets/s/mm^2. The pellet stream itself has a diameter of 0.2 mm. The goal is to develop a tracking system that can predict a few milliseconds in advance when a pellet will be inside a nominal target volume of about the same size as the pellets themselves.

The design of the new system is based on adapting a system originally designed for the PANDA experiment at FAIR. Studies have been carried out with Uppsala Pellet Test Station (UPTS). The system is designed to consist of several levels of detector modules, consisting of lasers illuminating the pellets and two synchronized LineScan cameras picking up the reflected light. It was found that pellets passing the narrow line of sight of the cameras can be measured with an accuracy of 20 µm and a time resolution of about 5 µs.

An FPGA processes the data from the multi-camera system in real-time. It contains all the necessary peripheral interfaces and computation resources to realize the trigger function. As part of the processing, the data from the cameras are first de-serialized and parsed, after which the different sensitivity and bias in the pixels is equalized. This is followed by a pellet recognition algorithm and pellet tagging. Having the horizontal pellet coordinates from two levels of detector modules, the trigger output data is prepared, based on which the FPGA can send out timed triggers for the laser.

Most of the components of this real-time pellet tracking system have been successfully tested at the UPTS with pellets. This includes the mechanical components to mount and align cameras and lasers and the electronics to control and read the cameras. A trigger on detected pellets has been implemented in the read-out boards and the performance has been verified using signals from pulsed lasers illuminating a dummy target. A pellet tracking section with four detector modules has been completely assembled.

Milestones due in the RP3.

No Milestones in the RP3.

1.2.21 Work Package 30

Activity Type	Joint Research Activity
Work package title	Spin for FAIR (JRA12-SPINFORFAIR)
Lead beneficiaries	7 – FZJ, 30 - INFN

Project objectives

Objectives: The physics potential for studies with polarized antiprotons is enormous. The flagship experiment, Drell-Yan production, in double polarized proton-antiproton annihilation, will provide direct access to the transverse spin structure of the nucleon. In this perspective the implementation of a double polarized proton-antiproton collider at the coming FAIR facility, as a long-term upgrade, would open new and unique research opportunities for spin-physics with polarized antiprotons. So far, no antiproton beams with sizeable polarization could be produced. It is the aim of the PAX Collaboration to develop an efficient method for polarizing antiproton beams by in-situ build-up in a storage ring. The only viable way to do this effectively is by “spin-filtering” by the repeated interaction of an antiproton beam with a polarized hydrogen gas target in a cooler storage ring, selectively discarding more particles in one of the two spin states. In the framework of the I3HP3 project, the PAX collaboration has successfully performed a spin-filtering measurement with protons at the COSY-ring by using a transverse polarized hydrogen target. The COSY measurement, actually a determination of the transverse spin-dependent polarization build-up cross section, proves that spin-filtering can be considered as a method to polarize a stored beam and that the interpretation of the polarization build-up mechanism in terms of the proton-proton interaction is valid. With the present JRA, PAX intends to make use of the unique environment offered by the COSY ring to transfer this method to longitudinal polarization. This point is motivated by the fact that all the different models for spin-filtering predict a significantly higher degree of polarization for the longitudinal case than for the transverse one. For the optimization of the polarization buildup, it is therefore necessary to study both cases in conjunction. In addition, this approach represents the only way to obtain the relevant spin-dependent cross-sections for producing polarized antiprotons. Afterwards, the PAX collaboration is ready to perform the corresponding experiments with antiprotons.

Progress made during the reporting period towards objectives

Task 1: Siberian snake. Implementation: the natural direction of the polarization in a storage ring is vertical with respect to the beam momentum; longitudinal polarization requires the introduction of a dedicated magnet system: namely a Siberian snake by which the spin-closed orbit at the target installed in the opposite straight section and about which the stored particles precess, is oriented along the longitudinal direction
• The first Siberian Snake commissioning beam time took place in March 2020 at the COSY Storage Ring. The test evidenced that the solenoidal field, acting quadratically on the betatron tunes, introduces a strong phase space coupling creating a tune split around the $\nu_x - \nu_y = 0$ resonance, inhibiting the possibility of operating the ring in this region of the phase space. The $\nu_x = \nu_y$ is essential for the obtainment of the long beam lifetime conditions required for the spin-filtering experiment. • Subsequently, progresses were made in understanding the effect on the beam dynamics caused by the presence of the soleonidal magnetic field. The available way to compensate for the effect of the solenoid in COSY is to modify the quadrupoles strength. This in turn affects the betatron tunes linearly, requiring dedicated simulations with the MAD- X model of COSY. At the time of the first Siberian Snake commissioning test, the model did not include the necessary coupled ion optics yet and the tunes compensation required several iterations, resulting in a time consuming process.

- Dedicated developments have been initiated in view of second commissioning test. The option of installing skewed quadrupole magnets in the COSY beam line, in order to compensate the tune shift caused by the solenoidal field, has also been investigated. - The long shutdown due the COVID pandemic, combined with the budget restrictions causing a reduction of the available beam time at the COSY ring and its premature shutdown at the end of 2023, did not allow the completion of the physics program.
Task 2: Measurements and Data Interpretation: two sets of measurements are foreseen. The first is devoted to the measurement of the target polarization with the twofold goal of commissioning the new detection system and to provide an absolute calibration for the target polarimeter. The second is represented by the longitudinal spin-filtering measurements at COSY
- The detector, with two of the planned four quadrants assembled, has been commissioned with an unpolarized proton beam and a polarized deuterium target demonstrating that it can be used for the low-energy spin-physics experimental program at COSY. - After the first commissioning, the missing two quadrants have also been assembled, while the electronics, the cooling system and the data acquisition have been adapted to the full detector scheme. A test bench has been set up in the IKP-2 Pax laboratory, and an acquisition of cosmic rays data with a fully assembled detector was scheduled before the Covid-19 crisis began. - Operations were resumed in the second half of 2021, when the data taking started and the commissioning of the detector with cosmic rays has been successfully completed. - The final detector commissioning, as well as the beam polarization measurement, was planned together with the final Siberian Snake commissioning, taking into account the beam availability at the COSY facility and the PAX interaction point availability, now occupied by the RF Wien Filter needed for the EDM precursor experiment performed by the JEDI collaboration, whose schedule was heavily affected by the pandemic as well. - As for Task, the long shutdown due the COVID pandemic, combined with the budget restrictions causing a reduction of the available beam time at the COSY ring and its premature shutdown at the end of 2023, did not allow the completion of the physics program.

Highlights of significant results

JRA - SPINFORFAIR has optimized a setup to control the beam polarisation of protons and antiprotons for the GSI/FAIR storage rings. This impacts future possibilities for experiments with polarized beams at GSI/FAIR but also for other upcoming facilities like the Electron Ion Collider in the USA.

Deliverables due in RP3.

No Deliverables in the RP3

Milestones due in the RP3.

MS71 Snake commissioned – Achieved partially

MS72 Measurement of target polarization and beam polarization accomplished – Achieved partially

1.2.22 Work Package 31

Activity Type	Joint Research Activity
Work package title	Polarized Electrons, Positrons and Polarimetry (JRA13-P3E)
Lead beneficiaries	1 – CNRS, 9 - JGU MAINZ, 14 - UHAM

Project objectives

The P3E Joint Research Program aims at pushing further the intensity frontier of polarized electron/positron sources and the precision frontier of electron polarimetry on the basis of novel methods and innovative technologies developed by the P3E partners.

The production of high-quality polarized positron beams is one objective of the P3E project, which will benefit facilities including but not limited to MAMI, MESA, CEBAF, and EIC. It relies on the novel PEPPo method developed by the P3E partners which involves the efficient polarization transfer from a polarized electron beam to the positrons generated by the bremsstrahlung radiation of the primary beam in a high Z target. This asks for high intensity polarized electron sources (Task 1) and specific concepts for the production, collection, and capture of the produced positrons (Task 2).

Precision experiments with polarized electrons and positrons require the best possible measurement of the beam polarization, particularly for experiments searching for deviations with respect to the Standard Model such as the P2 experiment at MESA. The development of high precision polarimetry techniques is the other scientific goal of P3E (Task 3). Specifically, it involves the design and optimization of a Hydro-Møller polarimeter aiming at 0.1% systematics uncertainties on the polarization of the MESA electron beam.

Progress made during the reporting period towards objectives

Task 1: High intensity polarized electron source
The modelling of the quantum efficiency of photocathodes cross-checked by proof-of-concept experiments was successfully completed. It is now serving the development of the high intensity, high polarization and long life-time polarized electron source of the $Ce^{+}BAF$ project at Jefferson Lab (JLab). This source constitutes the first element of the positron injector which was studied as part of the objectives of the JRA13-P3E.
Task 2: High intensity polarized positron source
The design of a novel positron injector to permit the achievement of a unique experimental program at CEBAF was completed, together with the publication of the White Paper of the

Positron Physics Scientific Program of JLab. The three scientific pillars of this program (Two-photon Exchange physics, Generalized Parton Distributions, Tests of the Standard Model) were further validated by the JLab Program Advisory Committee (PAC) in the form of the approval and high rating of experimental proposals.

Following the conceptual evaluation of a high-power target for the production of positrons, experimental tests have been performed at MAMI to study the sensitivity of different materials (W, Ta, Ti alloys) to the effects of high radiation levels produced by an electron beam. These measurements are intending to serve the selection of the most appropriate material for the production of positrons.

Task 3: High precision electron polarimetry: this task consists in the design of the detector system for Hydro-Møller Polarimeter using high-voltage monolithic active pixel sensors (HV-MAPS)

In this task, we developed a Geant4-based simulation package for the Møller polarimeter and the associated magnet and detection systems. The simulation implements both the Hydro-Møller option and the option to use a more conventional iron foil target for Møller scattering. The simulation models for both the signal process and backgrounds from (radiative) Mott scattering were extensively verified and different generators cross checked against each other. The simulation was then used to develop a system of magnets and collimators that lead to high signal-to-background ratios at the detectors. That magnet and collimator system was optimized in an iterative process in order to match the tight space constraints in the MESA/P2 beamline and allow for the use of easy to build magnets without negatively affecting the performance. In parallel, we have developed a series of HV-MAPS silicon pixel sensors which are one potential detector technology. The P2Pix sensors with wide applications in parity violation experiments is currently under production.

Highlights of significant results

Charge lifetime of GaAs photocathodes: The charge lifetimes of a high polarization photocathode were measured over two years, demonstrating an improvement >50% when the photo-gun anode is biased. A new simulation code to model the measurements was created and compared successfully. The results were submitted to Phys. Rev. Accel. And Beams and are in review.

Positron physics program at JLab: The publication of the JLab Positron White Paper as a 2022 topical issue of the European Physics Journal A was a major achievement of a group of physicists including JRA13-P3E partners which goes much beyond the boundaries of the STRONG 2020 program. However, this result was a major step in the scientific motivation of the Ce^{+}BAF positron injector which was further assessed and confirmed by the approval of positron beam experiments by the JLab PAC (PAC51).

Ce^{+}BAF positron injector performance: The full design and evaluation of the new positron injector for CEBAF has also been a significant step not-only with respect to the objectives of the JRA13-P3E but also for the whole Ce^{+}BAF project, particularly showing that an optimized design is capable to achieve high enough performances to efficiently complete the proposed JLab positron experimental program.

Conceptual evaluation of a positron production target: The completion of a finite element modelling of a positron production target has been an essential step into the practical evaluation of a conceptual target, the identification of the different technical/mechanical/thermal issues, and the validation of possible solutions. It was shown that a disk rotating with a moderate speed of 4 turn/s and cooled by water is able to dissipate the 17 kW thermal power deposited by the electron beam in the target. The expected life-time of such a system corresponds to about one year of Ce^+BAF operation.

Positron target irradiation damages: The mechanical and thermal properties of the positron production material are particularly important to optimize the life-time of a target. An electron beam traversing the target produce a high level of radiation and may also activate the target material which result in a progressive destruction of the target. The first experiments to identify the damages to materials resulting from exposure to an electron beam were performed at MAMI and further characterized at PETRA-III. An unexpected signal of the unsensitivity of Tantalum under the Ce^+BAF operating conditions was obtained, opening new prospects for positron target materials.

High precision electron polarimetry: A detailed simulation framework for Møller polarimeters using large solenoidal magnetic fields was created; the physics models used for Møller and Mott scattering were thoroughly validated; a working geometry for collimators and magnets to be used in the polarimeter was developed, delivering excellent signal to noise ratios; HV-MAPS sensors suitable for the detection system were developed and are being produced; the polarimeter design was summarized in a technical design report.

Deliverables due in RP3.

D31.1 Feasibility Report for an Intense Polarized Electron Source - Achieved

Charge lifetime of a highly spin polarized GaAs/GaAsP superlattice photocathode operating in a high voltage dc-photo-gun at the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab was improved by repelling ionized gas from entering the photo-gun accelerating gap. GaAs photocathodes in DC high-voltage photo-guns are highly susceptible to ion back-bombardment (Fig. 1, left), which reduces the photocathode quantum efficiency and limits the useful operating lifetime for producing polarized electron beams. This work demonstrated that applying a small positive bias voltage +1kV to the photo-gun anode can significantly suppress ion back-bombardment and increase charge lifetime. In contrast to a grounded anode (0 V) where positively ionized gas would be accelerated to the photocathode the positively biased anode creates a positive potential of 100’s of Volts in the volume downstream of the anode repelling ionized gas from entering the cathode/anode gap (Fig. 1, right).

This technique was studied extensively using the CEBAF photo-gun while operating at -130kV, where highly polarized electron beams created using a strained-superlattice GaAs/GaAsP photocathode were used and charge lifetimes improved by almost a factor of 2. A new simulation code IONATOR was developed to model ion production and tracking in order to better understand and explain the factors that led to performance improvement.

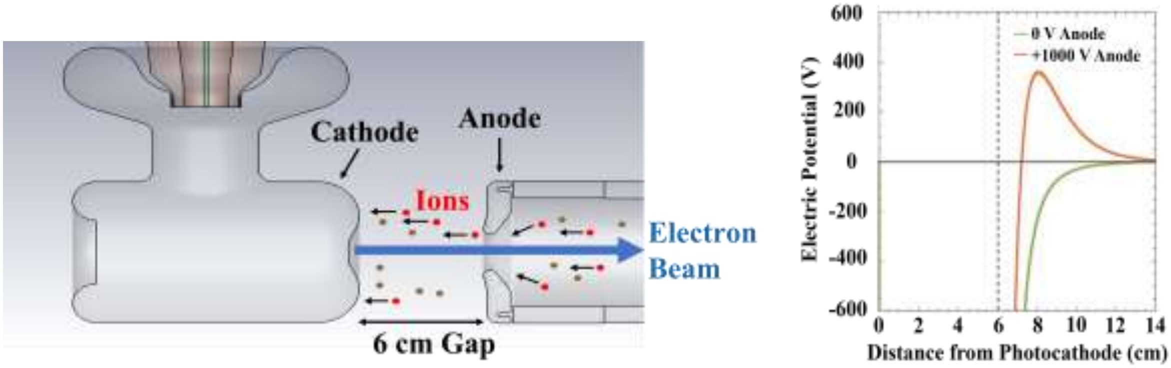


Figure 1: Conceptual schematic of ion-bombardment in a dc high-voltage photocathode with grounded anode (left) and a plot of the electric potential downstream of the anode when the anode is grounded or positively biased for ion repulsion (right).

The document describes the many steps of this research which experimental and simulation results were submitted for publication in June 2024 and are currently undergoing final revisions.

D31.2 Feasibility Report for an Intense Polarized Positron Source - Achieved

This document reports about the design, simulation, and optimization of a new positron injector delivering unpolarized and polarized positron beams to be accelerated by CEBAF. It addresses extensively the optimization of each successive step, which constitutes the full system: the production target, the magnetic collection of positrons, their radio-frequency collection, their momentum selection with an appropriate magnetic chicane, and their matching to the CEBAF acceptance through an accelerating section and a bunch length reduction chicane. The association of these elementary components (Fig. 1) constitutes the full positron injector which optimization showed that an initial Continuous Wave (CW) electron beam of 120 MeV with 1 mA intensity and 90% polarization would provide a CW positron beam with 700 nA intensity and 60% polarization, or an unpolarized positron beam with 3 µA intensity depending on the momentum of collected positrons. Such beams will permit to perform a unique experimental program at CEBAF where the comparison of the response of a nuclear system to the excitation of lepton beams of opposite charges reveals unique features of the nuclear structure and possible deviations from the predictions of the standard model.

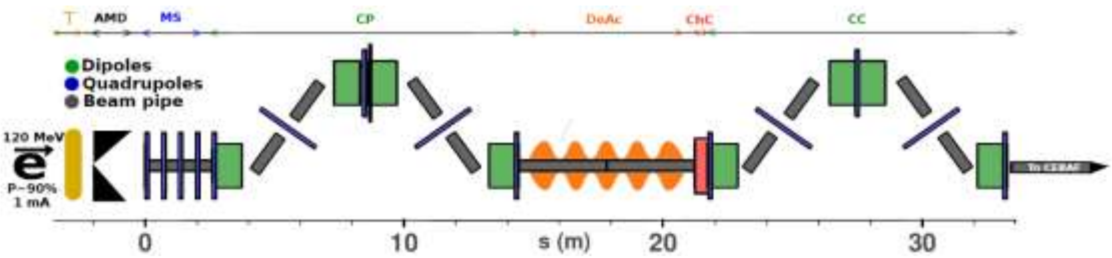


Figure 2: Conceptual layout of the CEBAF positron injector.

This work was presented and discussed at several conferences and led to several publications:

- *Concept of a polarized positron source for CEBAF*, S. Habet et al. JACoW IPAC2022 (2022) MOPOTK012
- *Positron beams at Ce⁺BAF*, J. Grames et al. JACoW IPAC2023 (2023) MOPL152
- *Characterization of polarized and unpolarized positron production*, S. Habet, A. Ushakov, E. Voutier, JLab-ACC-23-3794; arXiv:2401.04484.

D31.3 Technical Design Report for the polarimeter detector - Achieved

The technical design report for the Møller polarimeter detector is available in the participant portal. In it, we discuss the simulation models for Møller scattering and the important background of radiative Mott scattering in detail. Extensive simulation studies have led to the compact geometry and magnetic field set-up described in the report (Fig. 2). An optimized collimator geometry leads to large signal to background ratios on the detectors despite the much larger cross-section for Mott scattering (Fig. 3). By using a coincidence between the two Møller electrons, an almost background-free measurement can be achieved. The design thus fulfills the requirements of the P2 experiment at MESA and will be implemented in the coming years, first using an iron target and eventually using atomic hydrogen in a trap.

Preliminary versions of the design were presented at the spring meetings of the German physical society 2023 and 2024.

The report is being prepared for publication.

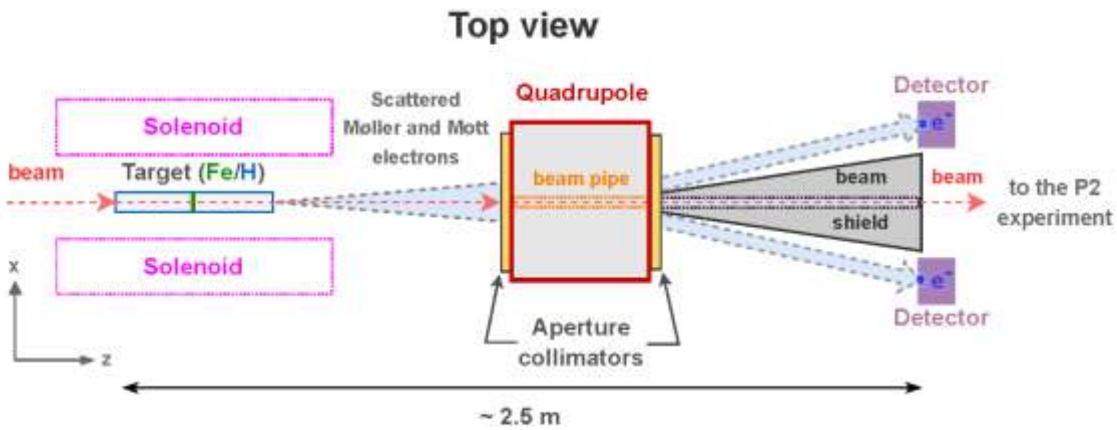


Figure 2: Schematic overview of the Møller polarimeter setup at MESA. The collimator geometry was optimized to produce the best possible signal-to-background ratios in the detector plane.

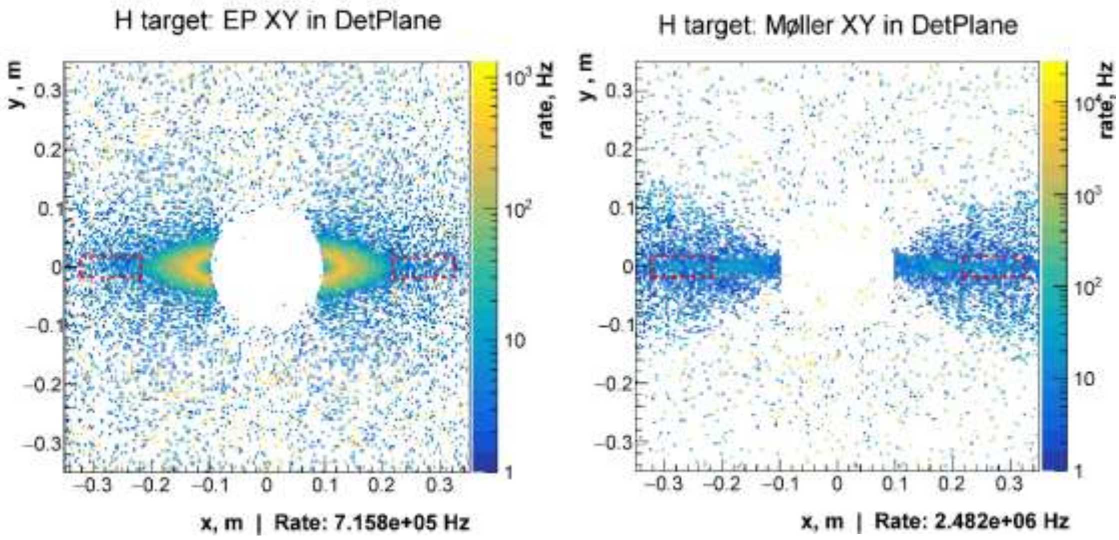


Figure 3: Distribution of electrons in the detector plane for the Mott background (left) and the signal process (right) using the atomic hydrogen target. The proposed active area is shown with a red dashed rectangle.

Milestones due in the RP3.

MS76 Charge lifetime experiments - Achieved

As a result of this work, the CEBAF photo-gun is only operated with a biased anode. The new ion-tracking software IONATOR was created and is used in other projects.

MS77 Simulation package of the positron source - Achieved

The positron injector model was elaborated, implemented within the ELEGANT beam optics platform, and coupled to GEANT4 simulations of the production of positrons. The full package was used to optimize the parameters of the different components of the injector and determine final performances.

MS78 Simulation package of the target stress – Achieved

This implies an appropriate modelling of the positron production target and its operational implementation within the ANSYS finite elements simulation package to allow us to perform systematic studies, performance evaluation, and optimization.

1.2.23 Work Package 32

Activity Type	Joint Research Activity
Work package title	Micropattern Gaseous Detectors for Hadron Physics (JRA14-MPGD_HP)
Lead beneficiaries	2 – OEAW, 8 – GSI, 10 – UBO, 13 – TUM, 24 – CEA, 30 – INFN, 40 – UAVR, 44 - UGLASGOW

Project objectives

There are currently many open fundamental questions and puzzles in physics, which require input or progress in hadron physics. One example is the transverse-momentum dependent inner structure of the proton, which, apart from being a fundamental question of QCD itself, is relevant for many analyses at proton colliders such as the LHC. Another example is the proton radius puzzle, where a very large discrepancy between its determination from elastic electron scattering and a new result from the spectroscopy of muonic hydrogen is yet unexplained. A third example is the question of the existence of exotic bound states of quarks and antiquarks. Progress towards answering these questions requires detectors with improved capabilities in tracking, identification of charged particles, photon detection and timing in the picosecond region. A coherent effort towards these goals by world experts in MPGDs is proposed in this JRA.

Our contribution to the proton radius puzzle, which is also the focus of a networking activity within STRONG-2020, the PREN Work Package will be the simulation and optimization of a TPC for measuring the proton radius via elastic scattering of high-energy muons at CERN.

Progress made during the reporting period towards objectives

The proposed activities are organized in four tasks. ***Task 1: Compact micro-pattern TPC for high-rate experiments. Goal: Prepare foundations for 3D continuous tracking with minimal material budget in environments with extremely high intensities and track densities***
The prototype for the high-rate TPC including a laser calibration system was built and tested successfully (Deliverable D32.3). The TPC is designed for standard-sized 10×10 cm^2 amplification structures employing GEM foils. In the present configuration it uses a hexagonally segmented padplane combined with readout electronics using the AFTER-chip and a DAQ equivalent to the one used by the FOPI-TPC at GSI. With regard to high-rate capabilities of TPCs at collider experiments, a system to calibrate the electric drift field using the photoelectric effect was implemented, with the main goal of measuring static field distortions. To this end, laser light was conditioned and guided through various optical components and a bundle of optical multimode fibers in order to uniformly illuminate the detector cathode. In order to generate artificial field distortions, the field configuration inside the detector was deliberately misadjusted. The resulting deviations could be clearly observed using the known calibration pattern. Moreover, the drift time of photoelectrons was measured varying the detector pressure in order to derive a drift velocity calibration. The concept can easily be extended to future TPCs to be used at high-luminosity fixed-target or collider experiments. One of the future applications of a high-rate TPC is a new detector (multiple time projection chamber, mTPC) that is being designed for upcoming meson structure studies in tagged deep inelastic scattering at Jefferson Lab Hall A. For this detector, GEANT4 and GARFIELD++ simulations were performed and completed to optimize the TPC design. Based on the simulations, a prototype detector was built by colleagues at University of Virginia and the device is currently being tested at JLab.

Task 2: Active target TPC. Goal: Develop TPC which acts as an active target and at the same time performs tracking of low-energy recoil particles from interactions in the active volume
The simulations on energy ranges and resolutions in an active-target TPC were completed (Deliverable D32.4). The layout of the TPC Pad Plane was updated to make use of all 64 available readout channels. An additional pad was added to the second-most outer ring to reduce electronic noise, which depends on the pad area. The rotations of the rings were slightly changed to account for the additional pad. The simulations of the muon reconstruction were extended to study the geometrical acceptance as well as the efficiencies and resolutions over a wide range of the squared four-momentum transfer Q^2. The geometrical acceptance allows us to look into the effects of Q^2-bin migration due to multiple scattering and reconstruction uncertainties. We plan to fill the space between the Unified Tracking Stations with helium instead of air to reduce multiple scattering. There are several options for the material and shape of these so-called Helium Tubes. We started to test the impact of these options using the updated simulation. The TPC trigger threshold from the Pilot Run 2021 was studied and used to update the expected number of events for this measurement. This has also started a separate analysis and tuning of the TPC trigger parameters for the final setup.
Task 3: Photon detectors for PID. Goal: Develop a modular hybrid MPGD (Micromegas + THGEM or GEMs) with high-granularity readout elements for the detection of single photons in harsh environment
The Modular Minipad Photon Detector Demonstrator was built and fully characterized (Deliverable D32.1). The detector consists of a THGEM coated with CsI photoconverter material, a Micromegas and 3×3 mm^2 readout pads. To equip the modular hybrid MPGD with readout electronics suitable for triggerless streaming data taking a second prototype has been built and tested in the laboratory using both APV25-based frontend and VMM3-based frontend. The comparison of performance demonstrated the full compatibility of VMM3-based readout with hybrid MPGD photon detectors. Alternative photocathode materials were investigated. For the first time, the possibility to use hydrogenated nanodiamond-based (H-ND) photocathodes in gaseous detectors was validated. A prototype detector was built and tested with different gas mixtures up to gains of 50×10^3. The systematics of the response of H-ND in different gas mixtures was tested. Aging studies revealed that H-ND is ten times more robust than CsI. The results on the H-ND were published (Deliverable 32.5). A new campaign of H-ND photocathode tests has been performed, with the production of semi-transparent photocathodes deposited on MgF_2 substrates, with different H-ND thickness, to optimize their performance in the context of fast-timing gaseous photon detector development.
Task 4: Very fast timing/tracking by Micromegas-based Cherenkov photons detectors. Goal: establish a new tracking technology based on sub-100 ps timing resolution and high rate capability
A large 10×10 cm^2 prototype of the Picosec detector was built. The detector employs the detection of Cherenkov light produced in a radiator equipped with a transparent photocathode (CsI) to achieve a time resolution of the order of a few 10 ps for charged particles. To realize

this resolution over a larger area requires extremely uniform gaps and a flatness of electrode structures better than 10 μm. For the first prototype, a ceramic board was employed, which, however, is not suitable for applications in hadron physics experiments because of the large material budget. The Picosec FR4 prototype makes use of a printed circuit board made of FR4 material instead. The detectors are built from PCB boards of two thicknesses, 0.8 and 1.6mm, stiffened with a 1-cm thick Rohacell layer. Their active areas are covered with a diamond-like carbon (DLC) layer manufactured at CERN, while the bulk Micromegas structure was added at Saclay. With the stiffener, a very good planarity with a sigma of the Z values at the level of 6.6µm on the 1.6mm thick PCB prototype, and at the level of 7.9µm on the 0.8mm PCB, was achieved. A preliminary value for the time resolution for the DLC layer was measured on a few channels at the level of 44ps. Even though this value is a bit worse than the prototypes with ceramic board and CsI photoconverter, the feasibility of such detector was demonstrated (Deliverable 32.2). Several areas for improvement have been identified, such that an even better time resolution can be expected in the future.

Highlights of significant results

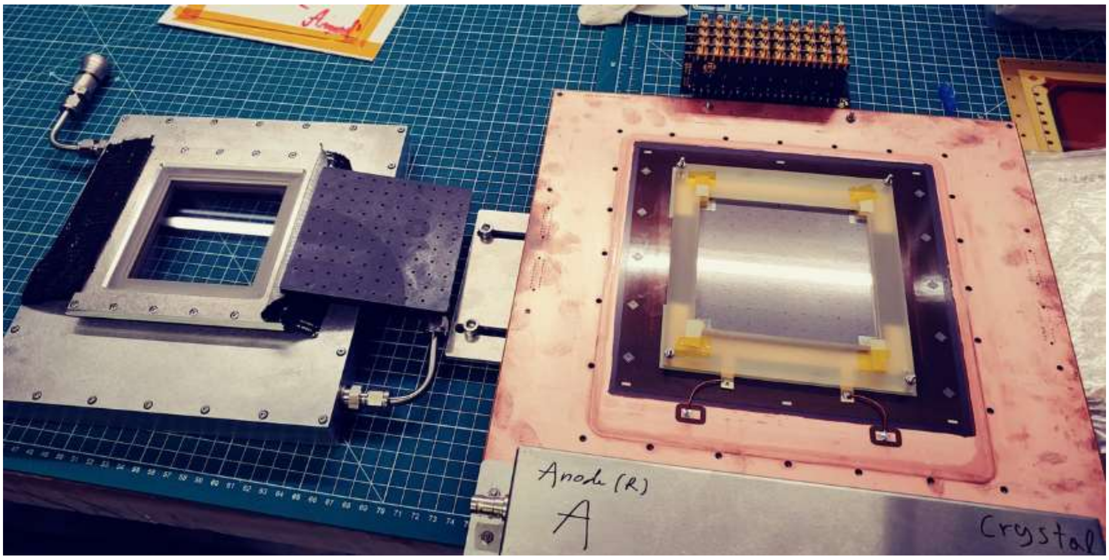
All deliverables were achieved. Parts of the results obtained in this JRA were published in refereed journals.

Deliverables due in RP3.

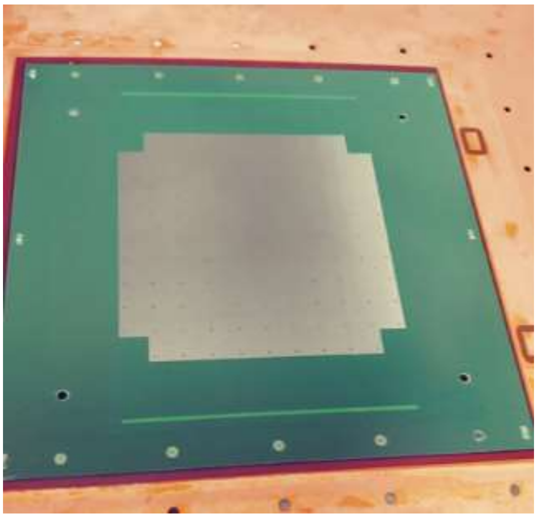
D32.2 Fast Cherenkov Micromegas Detector - Achieved

The 10x10cm² picosec prototypes were finally built and tested ! The last elements were received in June and my colleagues went to CERN for quick beam tests end of June. They plan to do new ones end of September for a longer period, and hopefully less operational troubles.

Concerning the prototypes, they are built from PCB boards of two thickness, 0.8 and 1.6mm, stiffened with a 1-cm thick Rohacell layer. Their active area are covered with a DLC layer done at CERN, and then bulked at Saclay. Two mechanics are available for the moment, allowing to mount two detectors. Here is the picture of one of them:



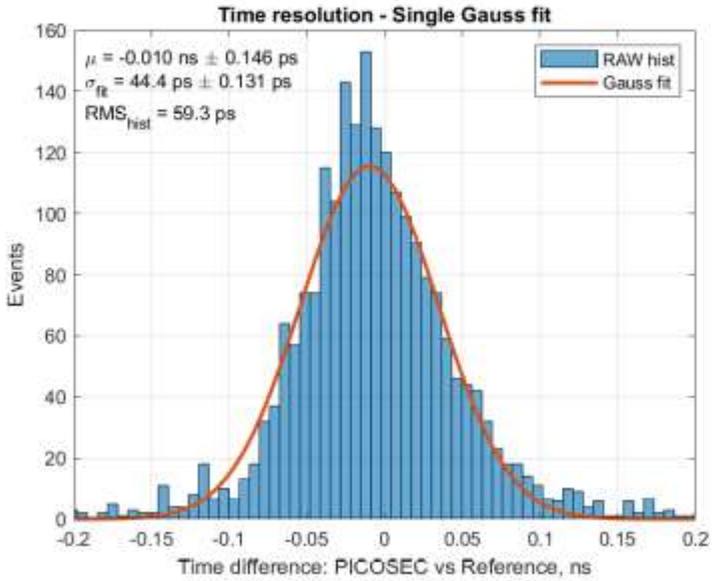
and a view of the bulked active area:



A lot of efforts were done to get a good planarity of the PCB in order to optimize the homogeneity of the time response. With the stiffener, my colleagues got a sigma of the Z values at the level of 6.6µm on the 1.6mm thick PCB prototype, and at the level of 7.9µm on the 0.8mm PCB, which is very good.

Beam tests were done on two prototypes on muon beam at CERN end of June. Only one third of the pads were equipped with electronics, due to the lack of readout cards. They were

equipped with crystals covered with a photoemissive layer. The ones covered with CsI didn't produce results as the CsI layer was destroyed within a very short period of time, most probably due to humidity coming from the resistive layer. Fortunately the prototypes with crystals with DLC worked normally, although such a layer produces less electrons. The time resolution was measured on a few channels at the level of 44ps, not as good as the previous prototypes but this is a very preliminary result with a non-optimized setup. Crystals with B4C were not available yet during the tests, they were just received at the beginning of this week, and they will be tested at the next beam tests. Here a picture of one of the prototype during the beam test, and a plot of the time resolution.



The next beam tests foreseen end of September are planed to last during a longer period, and will include B4C-covered crystals, and hopefully more electronics to connect all the 96 pads. My colleagues expect to get better results with more optimized setup and HV tuning in particular.

D32.3 A small-scale prototype of the high-rate TPC - Achieved

The document corresponding to the deliverable was submitted in the Portal.

D32.4 Simulation results on energy ranges and resolutions in active target TPC - Achieved

The document corresponding to the deliverable was submitted in the Portal.

D32.5 Publication of the diamond-based photoconverter performance in gaseous PDs - Achieved

The publication corresponding to this deliverable os available at https://www.sciencedirect.com/science/article/pii/S0168900223005661

Milestones due in the RP3.

No Milestones in the RP3.

Impact

The research in the field of the strong interaction addresses fundamental questions, such as the nature of confinement, the origin of exotic hadronic states and the properties of hot and dense nuclear matter. Those studies will have a deep impact on the searches beyond the standard model, in astrophysics and strongly coupled systems in particle and condensed matter physics.

STRONG-2020 is leading a coherent effort of theoretical and experimental groups complemented with challenging high-technology developments in instrumentation and industrial applications.

1.3.1 Impact on Low-Energy Frontier

The role of STRONG-2020 together with the European infrastructures is fundamental for tackling the long-standing puzzles in the low-energy frontier of the strong interaction, such as the proton radius puzzle, the neutron star puzzle, and the puzzle of the anomalous moment of the muon $(g\text{-}2)_{\mu}$. The low-energy frontier has a wide and ambitious program involving VA-, JRA- and NA-projects. There has been a strong advancement on the precision computation of hadron spectroscopy and structure, hadrons under extreme conditions, hadrons in the standard model and beyond by embedding ab-initio numerical calculations of QCD on the lattice (LatticeQCD) with the European hadron community via NA-FAIRnet and JRA-HaSP.

Over the whole period of the project, Lattice-QCD simulations have been combined with effective field theories to advance on the knowledge of hadronic observables, allowing precision spectroscopy of exotic and excited states, the treatment of states above thresholds in coupled-channel scattering analyses and the analysis of nuclear systems.

In the low-energy frontier the two main puzzles to be addressed, the proton radius puzzle and the neutron star puzzle, are still very relevant. With more and more precise data from the $(g\text{-}2)_{\mu}$-experiment at BNL, the improvement of the theory prediction for this quantity in JRA_PrecisionSM focuses on the hadronic contributions. In addition, hadronic contributions to observables used for the search for physics beyond the Standard Model have been pushed further in JRA-Precision_SM. This impacts the muon $(g\text{-}2)_{\mu}$, the unitarity of the CKM-matrix as well as the determination of the weak mixing angle at various facilities worldwide like CERN, FERMILAB, MESA, and others.

As for the proton radius puzzle network, NA-PREN has reported important publications, one of them, the PREN white paper, is expected to have a strong impact in the community.

JRA-HaSP has continued the very productive collaboration making a decisive impact by developing and using effective field theories for different hadronic systems (quarkonia, exotics, hadronic transitions and decays, and hadrons in dense matter) with the aim of confronting the precise theoretical calculations with experimental results.

The significant developments in readout, data taking and analysis tools within the NA-FAIRnet set the stage for the future PANDA and CBM experiments at GSI/FAIR. FAIR will start operating in the near future and both PANDA and CBM are essential pieces of the scientific agenda.

Also, other important developments have been done during the last reporting period. Those include theoretical and experimental studies to address the hypertriton puzzle that has turned into a quantitative problem, calling for precision studies. In addition, the first measurement of the kaonic deuterium transitions have been performed at SIDDHARTA-2 at the DAFNE collider at INFN-LNF, with NA-THEIA being an essential partner.

1.3.2 Impact on High-Energy Frontier

STRONG-2020 has had a profound impact on high-energy hadron physics, with a combination of Networks, Virtual Accesses and Joint Research Activities, involving the full community of experimentalists and theorists.

During the third reporting period, the Virtual Accesses kept on making tremendous progress, serving both the heavy-ion and the nucleon structure communities, allowing through their access, to develop programs at the forefront of research. The two platforms developed through STRONG-2020 are unique in the world and years ahead of any other competitors. Our VAs have been at the cornerstone of more than 20 publications during each of the two reporting periods, a number showing maturity of the provided services and an assiduous community of users.

The VA NLOAccess successfully implemented perturbative next-to-leading-order calculations for quarkonia and heavy-ions collisions including MadGraph5aMC@NLO and HELAC-Onia: it allows and widens the usage (thanks to a dedicated online platform) of the cross section computation for heavy-quark bound states. The created and maintained online tools are used by more than 600 registered users. The growing community participates to the training young scientists with providing documentation and organising regular workshops.

The impact of the Virtual Access to 3DPartons can be seen from the software libraries it supplies to the community. These libraries allow to apply theory corrections from the strong force, to extract observables in the field of proton structure observables and to make fits to experimental observables. The release of public codes, in collaboration with JRA-GPD-ACT and JRA-TMD-neXt, is an essential tool for the future progress of the community

Generalized Parton Distributions (GPDs) are important objects to understand the 3D-structure of the hadrons and studied in JRA-GPD-ACT. The new instrumentation built and installed at JLab and the new theoretical developments allow for a much better understanding of this important question.

Transverse Momentum Dependent distributions (TMDs) are the other essential tool encoding a differential structure of the partonic content of the hadrons. A very significant progress has taken place, with several analyses of Drell-Yan data released that help constraining these objects as well as data on semi-inclusive deeply inelastic scattering (SIDS). The results from JRA-TMD-neXt provide significant advances on this topic.

A new facility of special relevance for the hadron community will start operation in the future – the Electron-Ion Collider (EIC) at Brookhaven National Laboratory in the USA – and preparation is needed to fully exploit its potentialities from the beginning. Important progress has been made within the JRA-next-DIS, both in simulation and detector developments that will allow to increase the impact of the future EIC data.

Theoretical developments in the study of parton distribution, both in collinear factorization (usual PDFs), and the small-x region have been performed in NA-Small-x. Exploring the structure of the hadrons with increasing precision is one of the most important scientific goals of collider physics and the progress in the WP is essential to this end.

Research activities within STRONG-2020 have been instrumental in demonstrating the feasibility of a fixed target programme at the LHC, and even started its implementation in LHCb. More generally, on the aspect of R&D, STRONG-2020 has been at the cornerstone of all studies made to design the future detectors for the fixed-target measurements, for both ALICE and LHCb at CERN. In that respect, the timing of STRONG-2020 is perfect and its impact is decisive for all current developments.

The JRA FTE@LHC investigated, developed and implemented gas-target techniques to make available fixed target collisions at the Large Hadron Collider. Whereas the fixed target system at ALICE remained at the level of conceptual design and simulations, the unpolarized target for beam target collisions at LHCb has been designed, installed, and is currently fully operational, with collecting data during simultaneous data-taking with beam-beam collisions.

The JRA LHCCombine definitely improved communication between the four collaborations in the heavy-ion physics field, and the established LHC data-combination working group move to the next step with the creation of an official heavy-ion working group within the LHC Physics Center at CERN (https://lpcc.web.cern.ch).

1.3.3 <u>Impact on Instrumentation</u>

The highlights of JRA-MPGD_HP include the design of prototype high-rate TPC and of a modular hybrid (Micromegas+ THGEM) Photon Detector prototype, a detailed investigation of the beam-induced noise, and the preliminary achievement of a time resolution below 40 ps for Micromegas-based Cherenkov photons detectors.

JRA_TIIMM has fully characterized and tested in beam a prototype thin silicon tracking detector for all kinds of applications. Such innovation and corresponding developments are instrumental for the ALICE experiment, and in the more general area of the LHC particle physics experiments at CERN, but also for the low energy ion tracking and identification, as needed in the patient particle treatment in medical physics for instance.

JRA–ASTRA has developed beyond state-of-art radiation detectors based on CdSnTe-semiconductors to perform high-precision measurements of X-ray and gamma-ray photons in different environments and conditions. This impacts all X-ray spectroscopy experiments and has possible application in medicine.

JRA_CRYPTA designed a combined holding coil; it pairs longitudinal and transverse coil functionalities within a single configuration. This study paves the way towards a combined holding coil with only one additional layer compared to current coils. A prototype will be manufactured and tested at the Bonn University. The work on the realization of new prototypes for an active polarized target was continued, with tests of new scintillators with fiber readout and SiPM readout both in laboratory with a radioactive source and in the MAMI photon beam. A cryogenic test box was constructed and successfully operated cooled at 77K with liquid nitrogen.

JRA–CRYOJET has successfully developed cryogenically-cooled cluster/pellet/microjet sources to be used as targets in a variety of collision setups (storage ring experiments, electron accelerators, or laser-driven hadron accelerators). In addition a laser-based pellet tracking system has been developed. This technique is instrumental for future experiments employing thin targets, like experiments at the storage rings of FAIR as well as for experiments at ERL-electron accelerators like MESA in Mainz. This opens a possibility for internal target experiemtns at LHeC at CERN.

JRA - SPINFORFAIR has optimized a setup to control the beam polarisation of protons and antiprotons for the GSI/FAIR storage rings. This impacts future possibilities for experiments with polarized beams at GSI/FAIR but also for other upcoming facilities like the Electron Ion Collider in the USA.

For the JRA13-P3E - Polarized Electrons, Positrons and Polarimetry (P3E) the publication of the JLab Positron White Paper as a 2022 topical issue of the European Physics Journal A was a major achievement of a group of physicists including JRA13-P3E partners which goes much beyond the boundaries of the STRONG 2020 program. This result was a major step in the scientific motivation of the Ce+BAF positron injector which was further assessed and confirmed by the approval of positron beam experiments by the JLab PAC (PAC51).

1.4 Access provisions to Research Infrastructures

Trans-national Access Activities (TA)

1.4.1 Work Package 3

Activity Type	Transnational Access
Work package title	Transnational Access to COSY (TA1: COSY)
Lead beneficiary	7 - FZJ

1. Publicity concerning the new opportunities for access

Before each CBAC/USP meting a call for proposals is distributed via E-Mail to all actual as well as to potential new users.

The opportunity for support via the transnational access activity at COSY is advertised at workshops and collaboration meetings.

Detailed web-pages are available with information concerning the COSY facility and the experimental installations. A special web-page is available with information about the possibility of support of new users by the EU program:

http://www.ikp.fz-juelich.de/strong2020

2. Selection procedure

2.1 Organization of the Users Selection Panel (USP)

For the selection of experiment proposals the COSY Beamtime Advisory Committee (CBAC) is installed which acts also as USP. The CBAC/USP meets once or twice a year. New proposals or beam time requests have to be sent to the scientific coordinator at COSY four weeks before the CBAC/USP meeting, who will pass them to the CBAC/USP members for evaluation.

2.2 Selection criteria

The proposed measurements are evaluated and selected on the scientific value.

The selection of users for EU support follows the priority rules given by the EU.

2.3 Users Selection Panel members

The USP consists of external international experts in the field of hadron and precision physics, which are all fully independent of the infrastructure. The following list gives the actual USP members with the chairperson Prof. Marc Weber.

Prof. Kurt Aulenbacher University Mainz. Germany

Prof. Oliver Kester TRIUMF, Canada

Prof. Christian Schmidt	GSI Darmstadt, Germany
Prof. Thomas Stöhlker	GSI, HI Jena, Germany
Prof. Marc Weber	KIT Karlsruhe, Germany (Chairperson)

2.4 Users Selection Panel meetings

In the reporting period, only one CBAC/USP meeting took place on February 23rd and 24th, 2023.

Five proposals requesting support via the EU transnational access activity were submitted which are all eligible for support and all proposals were selected for support.

For all submitted projects, a short written report was prepared by the user selection panel (CBAC) which includes also ratings concerning the feasibility, readiness and importance, and these reports with the recommendation for beam time were sent to the users.

3. Transnational Access activity during the reporting period

3.1 Detailed description of the activity

The activities during the reporting period concerns studies in view of an electric dipole measurement in a storage ring and various test measurements of detector components.

In the project DTEST, particle detectors for the R3B and SFRS experiments which are part of the FAIR Phase-0 experimental program have been characterized. These test measurements included Si-strip and pixel detectors and scintillation crystals.

The MVD project studied the performance of micro vertex detectors to be used for the future PANDA experiment including the read out via the new ToAST ASIC under beam conditions.

The project AYPP2 is a continuation of the AYPP activity to test a complex detector system for a measurement of antiproton scattering at CERN. It included tracking detectors, straw tubes and scintillating fibers, scintillators and Cherenkov detectors.

The ITOF project for test measurements of large area scintillators with SiPM read out received beam time in the second reporting period and some travels were accounted for the third reporting period.

With the project D-EDM2, further activities in view of a measurement of the EDM for deuterons have been done. Data have been taken to improve the data statistics and investigations of systematics errors have been performed.

The PSCT project looked for the spin coherence time for protons which is more complicated due to the higher precession speed and higher number of spin resonances. Systematic studies have been done to understand the behavior but a drastic increase comparable to the deuteron case was not achieved.

Table 3.1: Access to the facility during the reporting period supported by the project

Project No.	User-project acronym	Number of users	Number of man/days spent at the infrastructure
1	ITOF	2	21
2	DTEST	13	123
3	D-EDM2	8	96
4	MVD	2	17
5	AYPP2	4	80
6	PSCT	7	120

3.2 Scientific output of the transnational access activity in the reporting period

The following publications were achieved in the reporting period.

First Search for Axionlike Particles in a Storage Ring Using a Polarized Deuteron Beam

S. Karanth et al., Phys. Rev. X 13, 031004

First detection of collective oscillations of a stored deuteron beam with an amplitude close to the quantum limit

J. Slim et al., Phys. Rev. Accelerators and Beams 24, 124601 (2021)

Table 3.2 List of user meetings

User-project acronym	Date	Venue	Number of users	Overall number of attendees
PSCT / D-EDM2	20/21.06.2022	FZJ	15	90
PSCT / D-EDM2	17/18.10.2023	FZJ	20	95

1.4.2 Work Package 4

Activity Type	Transnational Access
Work package title	Transnational Access to MAMI (TA2-MAMI)
Lead beneficiary	9 - JGU MAINZ

1. Publicity concerning the new opportunities for access

A dedicated web site has been set up at the beginning of the STRONG-2020 project at https://www.blogs.uni-mainz.de/fb08-nuclear-physics/tna/ (English), and

http://www.kernphysik.uni-mainz.de/tna/ (German).

These pages can be accessed also through the main home page of the Nuclear Physics Institute of Mainz University and the Mainz Microtron MAMI,
https://www.blogs.uni-mainz.de/fb08-nuclear-physics/

http://www.kernphysik.uni-mainz.de/

by the "STRONG-2020" symbol on the right side followed by using the transnational access item on the right side.

Here, it is described who can apply, how to apply, the coverage of the financial support and the structure and service of the research infrastructure MAMI. An application form is provided, links to the experimental setups including their physics program and contact information are given and calls for proposals are announced. There are also cross-links to the main STRONG 2020 homepage. Next to those web-based efforts, the research possibilities at MAMI, although already widely known in the community, as well as the opportunities for access, are regularly advertised at conferences, workshops and meetings, and at open house events to the interested general public.

Moreover, during the reporting period an outreach program for the national and also international public has been launched during the Covid-19 pandemic. This includes virtual tours of the MAMI facility with prerecorded videos of the experimental halls and the accelerator, which is presented in a videoconference session by at least two scientists. Such a format does allow for a very good communication with the audience and to easily provide answers to specific questions. The virtual MAMI tour has been presented at various occasions and does not only disseminate our work at MAMI, but provides also the opportunity to disseminate the transnational access to MAMI. Given the complementarity between on-site tours of the facility and this virtual format, we have continued with the virtual tours also after the end of the pandemic.

2. Selection procedure

Users of MAMI are admitted on the basis of their participation in scientific proposals which describe the physical goals and the necessary work to be carried out. These proposals are evaluated and recommended by a program advisory committee (PAC). According to the statute of the Institute of Nuclear Physics of Mainz University, all physicists are eligible to become either proponents or join an already existing proposal on the consent of the proposing collaboration.

A proposal has to be submitted in written form to the acting director of the laboratory. The acting director will transmit this proposal to the program advisory committee (PAC) of MAMI, which plays also the role of Users Selection Panel. The user then has, in a regular meeting of the program advisory committee, to present his proposal orally. The program advisory committee will give its recommendation, after negotiation in a closed session, in form of a written statement.

2.1 Organization of the Users Selection Panel (USP)

The role of the Users Selection Panel is played by the Program Advisory Committee (PAC) for MAMI and MESA. The PAC consists of renowned scientists from the international hadron physics community.

2.2 Selection criteria

The Program Advisory Committee bases its selection on scientific merit, following the prescriptions of Chapter 4, Article 16.1 of the HORIZON 2020 Grant Agreement. According to the statute of the Mainz Nuclear Physics Institute/ AMI, all scientists are eligible to become either proponents or join already existing proposals on the consent of the proposing collaboration.

2.3 Users Selection Panel members

Zein-Eddine Meziani, Chair (Argonne National Laboratory, USA) Diego Bettoni (INFN Ferrara, Italy)

William Marciano (BNL, USA) Reinhard Beck (Bonn, Germany)

David Ireland (Glasgow, United Kingdom) Marco Ripani (INFN Genova, Italy)

Nicole d'Hose (CEA Saclay, France)

All the members of the Users Selection Panel are external experts from the field of hadron and particle physics.

2.4 Users Selection Panel meetings

MAMI PAC Meeting, 11. - 13. March 2020, Mainz, Germany

Special Meeting of the Scientific Advisory Committee regarding future directions: 1 December 2021, online.

3. Transnational Access activity during the reporting period

3.1 Detailed description of the activity

The MAMI (Mainz Microtron) research infrastructure delivers a high-current and high-quality electron beam with energies of up to 1.6 GeV and the additional option of beam polarization. The facility currently serves three experimental installations: (1) the A1 experiment with a set of high- resolution magnetic spectrometers for electron scattering experiments; (2) the A2 experiment consisting of the Crystal Ball and TAPS calorimeters, which is located at the tagged photon beam line of MAMI; and (3) the X1 facility for radiation physics experiments as well as detector tests. Beam times are typically shared among the A1, A2, X1, and beam test users. The scientific output in the third reporting period (06/22 – 07/24) is described in detail in the following subchapter.

The STRONG-2020 period has been seriously affected by the Covid-19 pandemic with major shutdowns of the MAMI facility due to the severe restrictions at the Johannes Gutenberg University of Mainz. Furthermore, in the winter of 2022/23, the facility has been closed due to the energy crisis in Germany as a consequence of the war in Ukraine. Luckily, most of the third reporting period of the research infrastructure MAMI of STRONG2020 took place in the post-Covid and post-energy-crisis period and hence the standard operation of MAMI could be reinforced again with regular visits of researchers to the infrastructure. As a consequence, significantly more beam hours could be conducted for external researchers of the transnational access.

Table 3.1 lists the number of users as well as the number of man/days spent at the infrastructure. In total, nine projects have been defined for the MAMI Transnational Access Facility, of which two were conducted at the A1 experiment, three at A2, two both at A1 and A2 and one at the X1 setup. Furthermore, the project dedicated to detector tests took mainly at X1, but some tests had been conducted also at A2 and A1.

At the Institute of Nuclear Physics, currently the new MESA electron accelerator (Mainz Energy- Recovering Superconducting Accelerator) is being installed. The maximum beam energy of MESA is with 155 MeV below the energy range accessible at MAMI, but its beam intensity will be an order of magnitude higher. Furthermore, thanks to the innovative energy-recovering (ERL) concept, a new series of precision experiments will be possible, in which the high-intensity ERL beam is operated in conjunction with a very light internal gas target, which will provide high luminosities at ultra-clean experimental conditions. Three experiments for MESA are being setup: the MAGIX experiment, the P2 detector, and the DarkMESA beam dump experiment. For the design of the detector components of these experiments, the availability of the MAMI beam for detector tests was of utmost importance.

Table 3.1 Access to the facility during the reporting period supported by the project

Project No.	User-project acronym	Number of users	Number of man/days spent at the infrastructure
1	MAMI_A1_SFACT	2	28
2	MAMI_A1A2_FORMFACT	13	340
3	MAMI_A1_NUCLEAR	9	219
4	MAMI_A2_MESON	14	190
5	MAMI_A2_POLAR	5	72
6	MAMI_A2_DECAY	6	69
7	MAMI_A1A2_NSKIN	11	394
8	MAMI_DET_TEST	1	4
9	MAMI_X1_RAD	5	36

3.2 Scientific output of the transnational access activity in the reporting period

In this chapter, we summarize the scientific outcome and highlights of the A1, A2, and X1 collaborations within the reporting period with a reference to the user projects.

A1 Collaboration

The proton's electric form factor is one of its fundamental properties, reflecting the distribution of inside the proton. The proton's size, expressed by the charge radius, is directly related to the form factor slope at zero four-momentum transfer. In a new A1 experiment the elastic electron-proton scattering process has been measured within the four-momentum transfer range of 0.01 ≤ Q2 ≤ 0.045 (GeV/c)2 using the new gas jet target developed for the future MAGIX experiment at MESA. The A1 results are consistent with the two recent measurements of the proton electric form factors at A1 and PRAD. However, one could not discriminate between the two previous measurements due to the limited statistical uncertainty. There is a clear path to improve the precision by optimizing both the jet target itself (subsequent beam times showed more stable operation) and optimization of the collimator-veto system. The A1 results prove the feasibility of the experiment design using high- resolution spectrometers and the gas jet target for future scattering experiments to resolve the discrepancy in form factor measurements, for example, the MAGIX experiment at MESA [MAMI_A1A2_FORMFACT].

Polarization transfer to a bound proton in polarized electron knock-out reactions, $A(\vec{\#}, \vec{\#}\&\vec{p})$, is a powerful tool to look for an in-medium modification of the bound proton. Most properties of the nucleon are modified in the medium due to the off-shell character of the bound nucleon and are no longer directly accessible to experiments. Ratios of polarization variables, however, are less sensitive to bounding effects, but provide still the same sensitivity to nucleon properties like e.g. form factors. With the spectrometer setup of the A1 collaboration an extensive program has been carried out in close cooperation with scientists from Israel. The polarized electron beam of the MAMI accelerator together with the recoil polarimeter of A1 was used for several measurements to extract e.g. the polarization ratio $P\&(x)/P\&(z)$ of a quasi-free knocked out proton for several nuclei in comparison to the same ratio measured on a free proton target. The results are compared to elaborated calculations that consider the many-body effects accompanying the quasi-free process. [MAMI_A1_NUCLEAR]

Beam-normal single spin asymmetries An (or the so-called transverse asymmetries) give direct access to the imaginary part of the two-photon exchange amplitude in the elastic scattering of transversely polarized electrons on unpolarized nuclei. A good knowledge of An is not only essential for a better understanding of box diagrams with excited intermediate states in the electroweak sector, but is also important for any parity-violation electron scattering experiment in order to constrain the systematic error from a possible small normal component of the beam polarization vector. This is especially true for future measurements of the neutron skin of nuclei, e.g at MESA. While the theory describes the available data up to $Z \leq 20$ reasonably well, there is significant disagreement between experiment and theory for 208Pb, which motivates more measurements to study the 34- and Z-dependence.

During the successful campaign at MAMI, using the spectrometer set-up of the A1 Collaboration supplemented by dedicated Cherenkov detectors, the 34 dependence of An for 12C was determined in the range 0.02 $G\#V4/c4$ < 34 < 0.05 $G\#V4/c4$. Follow-up experiments on 28Si and 90Zr were carried out at 34 = 0.04 $G\#V4/c4$ to investigate the charge dependence of the transverse asymmetry. Within the given uncertainties, the experimentally determined values for An are in agreement with the theoretical calculations. To extend our systematic study of the transverse asymmetry to 208Pb, where the rates are significantly lower compared to the lighter nuclei, new data acquisition electronics were developed. The data from the recent experimental campaign on 208Pb will provide important information on the existing discrepancy between experiment and theory and will further enhance our understanding of two-photon exchange processes. [MAMI_A1A2_NSKIN].

Starting in 2025, with the future MESA accelerator at JGU Mainz, precision experiments in electron scattering are foreseen with the MAGIX experiment, which will consist of two identical high- resolution magnetic spectrometers. One of the key experiments to be carried out is the S-factor measurement of the reaction A4$C(\alpha$, ?)ABO, which can be addressed at MAGIX in inverse kinematics. In this case, the alpha particle needs to be detected in coincidence with the scattered MESA electrons producing the quasi-real photon. For the detection of the alpha-particle, a dedicated silicon detector is in preparation, for which dedicated beam time campaigns have been worked out. These beam times allowed for a proof of principle of the overall design and the electronics readout. This project has been carried out in close collaboration with scientists from the University of Kattowice. [MAMI_A1_SFACT]

A2 Collaboration

The extremely high production rate for (pseudoscalar) mesons in photoproduction experiments at A2 opens the avenue for precision form factor measurements by measuring the Dalitz decays: P →??∗ → ?#E#– (P = πH, I, I&) and ω → πH#E#–. There exist already world-class time-like form factor results by the A2 collaboration for the eta meson. In order to achieve world-leading precision measurements also for the pion and omega mesons, large data sets have been collected at A2. These form factor results are fundamental quantities in hadron physics in itself and allow for a comparison with phenomenological calculations. For the omega transition form factor very surprising results have been reported by the NA60-collaboration from CERN, which are difficult to describe in theory. An independent precision measurement from A2/MAMI is therefore desirable. Previous results from MAMI seem to be better in agreement with theory, however the results are not conclusive due to the limited statistics, which will be improved with the new data. Furthermore, these form factor results are of crucial importance for data-driven evaluations of the hadronic light-by-light scattering contribution to the anomalous magnetic moment of the muon, which allows for a unique precision test of the Standard Model of particle physics. [MAMI_A2_MESON]

The electromagnetic response of protons and neutrons at low energy is encoded by the electric and magnetic dipole polarizabilities as well as higher order spin-dependent polarizabilities. As in atomic, molecular and solid state physics, they describe the size of the electric and magnetic dipole moments induced by external electromagnetic fields and represent benchmarks for predictions of lattice QCD and chiral perturbation theory.

At MAMI, the polarizabilities of the proton have been studied extensively in several Compton scattering experiments with a polarized beam and partially with a polarized target. These measurements were performed in strong collaboration with the University of Pavia (Italy), the George Washington University (USA), the University of Regina and the Mount Allison University (Canada).

With new cross section and asymmetry measurements it was possible to determine the proton scalar polarizabilities with unprecedented accuracy resolving ambiguities in the extraction from the previous world data. With polarized target measurements a first experimental extraction of individual spin polarizabilities was achieved.

Similar studies for the neutron are significantly more difficult due to the lack of free neutron targets and a lower sensitivity due to the missing neutron charge. Isospin-weighted nucleon polarizabilities can be obtained from elastic Compton scattering off light nuclei (D, 3He, and 4He). We have performed pilot experiments with a liquid 4He target and have demonstrated that the elastic Compton scattering can be separated from inelastic channels with the existing detector setup. This work resulted in a proposal for an experiment which was highly rated by the MAMI program advisory committee. Furthermore, the CATS NaI(Tl) detector was put into operation and tested during two beamtime periods. CATS stands for Compton And Two photon Spectrometer which refers to a setup which was used in the 1990's to measure Compton scattering at MAMI. The goal of these new measurements is to determine the energy resolution and to investigate if this detector can be used to measure elastic Compton scattering on Carbon. [MAMI_A2_POLAR]

The high-intensity, energy-tagged, polarized photon beam in combination with the hermetic Crystal Ball calorimeter and frozen-spin polarized targets makes MAMI a unique facility to study photo- induced meson production with highest precision. The dynamics of these reactions is dominated by the electromagnetic excitation of nucleon resonances and their strong decay into a variety of meson- baryon final states. The experiments at MAMI are performed for more than a decade in close collaboration with groups from the Universities of Basel (Switzerland), Bonn (Gemany), Glasgow (UK), Pavia (Italy), Washington (USA) and York (UK). In 2017, the cryostat of the Mainz polarized target was transported to the ELSA accelerator in Bonn and integrated into the CBELSA/TAPS experiment. This allows us to extend the measurements to energies above 1.6 GeV, which is the maximum MAMI energy. In parallel, the huge amount of existing MAMI data was fully analyzed and calibration measurements with unpolarized target were performed.

The results published during the last 5 years focus on beam asymmetries and the helicity dependence of single and double pion production from protons and deuterons. Furthermore, the new MAMI data allowed a new evaluation of the $E2/M1$ ration of the $\Delta(1232)$ resonance which provides a benchmark for many nucleon models. Finally, it was demonstrated that reliable measurements with elliptically polarized photon beams are possible. Such beams were produced at MAMI via bremsstrahlung of longitudinally polarized electrons at a diamond crystal. [MAMI_A2_DECAY]

Another experimental campaign in the STONG2020 period at A2 is concerned with investigations of possibly exotic forms of nuclear matter, so-called hexaquarks. Evidence for a new resonance with a mass of $M \approx 2380$ MeV and a width of $\Gamma \approx 70$ MeV was found in proton-neutron fusion reactions and elastic scattering. Speculations about the nature of this d*(2380) resonance range from the existence of a compact exotic 6-quark particle (hexaquark) to deeply bound $\Delta\Delta$ molecules or more complex structures involving excited nucleons and meson clouds.

At the energy-tagged photon facility of MAMI, we started a series of experiments to study this state in the simplest nuclear reaction, deuteron photodisintegration. We have measured the photon beam asymmetry as well as the final state proton and neutron polarizations. The results do not exclude a contribution of the d*(2380), however, a clear and convincing evidence for an electromagnetic excitation is still missing.

Therefore, we proposed in 2021 to study spin-observables with a transversely polarized frozen-spin deuterated butanol target within a dedicated German-Russian initiative. However, after the Russian attack on Ukraine, this project could not be realized. Instead, we decided to increase the statistical accuracy of the recoil polarization and the polarization transfer in deuteron photodisintegration.

There measurements were performed in 2022 and 2023 with a strong participation of the University of York (UK). The data is presently under analysis and will significantly increase the accuracy compared to the previous pilot experiments, which have recently been published. [MAMI_A2_DECAY],

A hardware activity at MAMI is the development of an active polarized target, which was also supported in STRONG-2020 in the JRA10 – Cryogenic Pololarised Target Applications (CryPTA). In the STRONG-2020 period new ideas and concepts for a second improved version of the polarized active target insert have been developed. The light transport system of the next generation active target insert will for instance be replaced by optical fibers. The use of standard target materials like Butanol in a container of scintillating plastic material is foreseen. First tests of such a system have been carried out in dedicated MAMI beam time periods. [MAMI_DET_TEST]

X1 Collaboration

In recent years, a measuring station for detectors, materials and radiation has been established at the X1 beamline at the Mainz Microtron, which is used by a large number of international collaborations. The excellent properties of the MAMI beam allow focusing in the μm range with a small angular divergence. In particular, this has enabled channeling experiments to investigate channeling process of ultra-relativistic electrons for novel radiation sources. Of particular interest is the emission of undulator-like radiation in periodically bent crystals aiming at the construction of compact radiation sources in the MeV range and beyond. In collaboration with the University of Ferrara, the University of Padua, the INFN section of Ferrara and the Department of Physics and Astronomy, Aarhus the radiation spectra of a large number of crystals have been studied using channelled electrons. Beam manipulation assisted by mechanically bent crystals has been demonstrated to steer negatively charged particles using the channeling effect and volume reflection.

Positron sources are the key elements for the future and current lepton collider projects such as ILC, CLIC, SuperKEKB, FCC-ee, Muon Collider/LEMMA. The design and realization of positron sources are essential due to the challenging critical requirements of high-beam intensity and low emittance necessary to achieve high luminosity.

At MAMI in collaboration with Université Paris-Saclay, and INFN section Ferrara test experiments have been performed to measure the thermal stress and stability of crystalline and amorphous thick tungsten targets. For this purpose, a target station was set up in the dump region of the X1 beamline to achieve high electron currents and small beam sizes.

Positrons do undergo channeling between the planes of a crystal. This suppresses multiple scattering and the particles have a considerably longer dechanneling length, which is advantageous for all types of channeling experiments. Due to the lack of high-quality positron beams, a new beam line has been initiated in collaboration with the MBN research center Frankfurt, the University of Ferrara, the University of Padua, the Hellenic Mediterranean University in Crete and the ESRF in Grenoble to produce a low-divergence positron beam. The positrons are created by pair conversion of bremsstrahlung, produced by the focused 855 MeV electron beam of MAMI in a 10 μm thick tungsten converter target, and energy selected by an outside open electron beam-line bending magnet. The magnetic focusing elements in between are designed to prepare in a well shielded chamber located about 6 m away from the converter target a low divergence positron beam. In a preliminary experiment with this newly developed 530 MeV positron beam, the first successful deflection of the beam in a bent silicon crystal was demonstrated with high efficiency.

Meetings related to User-Projects

Table 3.2 List of user meetings

User-project acronym	Date	Venue	Number of users	Overall number of attendees
A1A2-FORMFACT, A1-SFACT, A2-POLAR, A2-MESON, A2-POLAR, A2-DECAY	07-12.08.22	Gordon Conference on Photonuclear Reactions Holderness	18	110
A1A2-FORMFACT A1-SFACT A2-POLAR	17-21.10.22	Santa Margherita NSTAR Conference	8	72
A1A2-FORMFACT, DET_TEST	19-21.03.23	Mainz MAGIX Coll. Meeting	15	34
A1A2-NSKIN A2-MESON, A2-POLAR, A2- DECAY	04.05.23	A2 Coll. Meeting remote	12	21
A1A2-FORMFACT A1A2-NSKIN A1_NUCLEAR	03.07-04.08.23	Mainz Few Body Conference	12	150
A1A2-FORMFACT, A1A2-NSKIN A2-MESON, A2-POLAR, A2-DECAY, A2_NUCLEAR	16-20.10.23	Mainz MENU Conference	43	140
A1A2-FORMFACT, A1A2-NSKIN A2-MESON, A2-POLAR, A2-DECAY, A2_NUCLEAR	31.10.-04.11.23	Paphos EINN Conference	11	63
A1A2-FORMFACT, A1A2-NSKIN A2-MESON, A2-POLAR, A2-DECAY	21.02.24	A2 Coll. Meeting remote	9	22
A1A2-FORMFACT, DET_TEST	26-28.02.24	Mainz MAGIX Coll. Meeting	14	33

A1A2-FORMFACTA1-SFACT A2-POLAR	17-21.06.24	York NSTAR Conference	7	70

1.4.3 Work Package 5

Activity Type	Transnational Access
Work package title	Transnational Access to LNF (TA3-LNF)
Lead beneficiary	30 - INFN

1. Publicity concerning the new opportunities for access

The web page dedicated to the Transnational Access to LNF-INFN has been active.

This page has been widely publicized and spread within the hadron physics community.

The web page address is:

http://www.lnf.infn.it/cee/STRONG2020/

All necessary information could be found in this web page, including the description of the LNF facilities (in particular the DAFNE complex, including the collider, the LINAC and relative Beam Test Facility – BTF), how to apply, the selection procedure, information for users, etc. Moreover, a large scientific community, including both existent users and potential users of the DAFNE complex at Laboratori Nazionali di Frascati dell'INFN, was capillary informed via mail.

2. Selection procedure

2.1 Organization of the Users Selection Panel (USP)

Eligible researchers wishing to have transnational access to LNF (TARI-LNF), taking advantage of the support of the European Grant Agreement 824093 STRONG-2020, were requested to submit to the secretariat of TARI-LNF written proposals.

A User Selection Panel (USP) for the selection of the submitted proposals and the monitoring of the progress of the approved projects was implemented. The USP was formed by 4 members: 3 external members and one internal member, chosen on the basis of their internationally recognized expertise and appointed by the LNF Director. For all selected projects, a short report was prepared by the USP, including the results of the assignement, and sent to the applicants.

2.2 Selection criteria

The USP based its selection criteria on scientific merit and following the statements contained in the Chapter 4 Article 16.1, Section 1, of the Grant Agreement 824093 — STRONG-2020.

2.3 Users Selection Panel members

The USP members were:

Frank Maas (chairperson)	Helmholtz Institute, Mainz (Germany)	external member
Josef Pochodzalla	Johannes Gutenberg University, Mainz (Germany)	external member
Edoardo Milotti	Trieste University (Italy)	external member
Antonella Antonelli	Laboratori Nazionali di Frascati (Italy)	internal member

2.4 Users Selection Panel meetings

A second Call of TARI-LNF within STRONG-2020 was launched on 15/07/2020 and closed on 10/09/2020. Given the impossibility for the users to reach Frascati due to the restrictions for pandemic, the USP decided to postpone the selection of the received proposals.

In the mean time, a relevant number of man*days already assigned in the first Call could not be utilized.

At the light of the fact that the restrictions lasted until fall 2021, it was decided to reset the second Call and to launch a new Call, with dead line 14 November 2021.

The USP met on 7th December 2021, giving a new assignment of days and trips for 2022, to be added to the days/trips already assigned in the first Call and that could not be utilized. Additional to the pandemic, the international crisis added to the difficulty in users travelling, which made so that the use of man*days was less intensive than (initially) planned; The TA providers and USP monitored constantly the situation in 2022 and in the first half 2023; in summer 2023 all projects were still having consistent man*days assigned and not yet used. The USP monitored the situation and discussed it in June 2023 to verify the status of TA, and decided to extend the use of the assigned days to the projects until the end of STRONG-2020; moreover, for the few projects which required more man*days to achieve their goals the USP decided to supplement the requests from the remaining funding.

Note: since not all money could be spent, together with the STRONG-2020 management (EB) it was decided to setup a task force of 2 Postdocs to guarantee the successful completion of the INFN-LNF TNA by 07/24 (included in the amendment and approved).

The goal of the task force, which was fundamental in achieving the full success, was as follows:

1) One post doc who acted as technical support for the INFN-LNF TNA related projects, including the technical support for: a) the High Purity Germanium Detector (HPGe detector system), related to Zagreb University TA project, for measurements of heavy kaonic atoms (kaonic lead), as test measurements for the very important kaon mass measurement and kaon-nuclei potential; b) the veto-2 and the luminosity monitor, related to Vienna University and Jagiellonian University TA projects, aiming to the measurement of kaonic deuterium and light

kaonic atoms measurements during the 2024 run on the DAFNE collider. In particular the post doc assisted in the installation and optimization of the detectors; in the shifts for the run on DAFNE collider and also as a link between experiments/ TA projects and the DAFNE collider. In this last context, the post doc contributed to the information exchange between the projects and the accelerator team for the optimization of machine parameters for the kaonic atoms runs, including: background optimization, luminosity (kaons) optimizations for the better use of the delivered beams and kaons. The post doc was fundamental to fulfil at best all the goals of the project(s), which also contribute towards various publications (which include acknowledgements to the STRONG-2020 project).

2) One post doc who acted as data analyses and Monte Carlo support for the TNA projects which aimed for data taking on kaonic deuterium (Vienna University, Jagiellonian University) and other kaonic atoms (Zagreb University), with SDD also HPGe detector systems, integrating veto-2 system and luminometer. The Monte Carlo and data analyses using advanced statistical methods, is fundamental to achieve the physics outcome aimed by the TNA projects. In particular, the post doc applied newly developed analyses methods implementing Machine Learning algorithms both for the detector calibration as well as for the signal extraction by using the veto systems. Monte Carlo advanced simulations of the various setups and their components, in parallel with the data taking, in the realistic run conditions of the 2024 runs, both for the kaonic deuterium as well as for kaonic lead (this last one with HPGe detector) are fundamental to extract the yields of kaonic atoms transitions, and for a better understanding of the physics processes at the basis of exotic (and kaonic) atoms cascade. The post doc was fundamental in last months of the project to fulfil at best all the goals of the project(s), which also contributed towards various publications (which include acknowledgements to the STRONG-2020 project).

3. Transnational Access activity during the reporting period

3.1 Detailed description of the activity

The following activity was carried on during the reporting period:

Facility PADME:

Project n.2 (Venelin Kozhuharov, Sofia University, Bulgaria): Searching for new light particles with PADME at BTF (Dark And Rare). The aim of this application was: participation in the preparation of the PADME experiment, improved calibration and monitoring of the charged particles veto system, control system preparation.

Project n.9 (Venelin Kozhuharov, Sofia University, Bulgaria): Searching for new light particles with PADME at BTF (Dark And Rare). The aim of this application was: continuation of the search with the PADME experiment of Dark Matter, in particular of the Dark Photon at 17 MeV; the activity was focused on calibration of the detector and data analyses.

Facility SIDDHARTA:

Project n. 3 SIDDHARTA-2 "Studying kaonic deuterium atoms with SIDDHARTA-2" (Johann Zmeskal, SMI, Vienna, Austria), with the following activities:
• Participation in beam time shifts
• Data analysis
• MC simulations
• Calibration of Veto-2 system and its use

Project n. 4 KRAKOW@SIDDHARTA-2 "Investigation of kaonic deuterium atoms with SIDDHARTA-2" (Szymon Niedzwiecki, Jagiellonian University, Cracow, Poland), with the flowing activities:
• Participation in beam time shifts
• Optimization of data analysis for luminosity detector
• Optimization of programs for fast on-line data analysis
• Participation in data analysis
• MC simulations

Project n. 6 EARS-2 "Exotic atoms research with SIDDHARTA-2" (Alexandru Mario Bragadireanu, IFIN-HH, Magurele (Bucharest), Romania) with the following activities:
• Participation in beam time shifts for kaonic atoms measurements
• Data analysis of data collected
• Optimization of the degrader
• Calibration and optimization 1 mm thick SDD
• Development of new interface in LabView software for DCS
• Integration of new DCS in DAQ and Slow Control systems.

Project n. 7 SIDDHARTA-2 & HPGetest "SIDDHARTA-2 data taking and HPGe tests measurements" (Damir Bosnar, University of Zagreb, Zagreb, Croatia), with the following activities:
• Test measurements with HPGe in parallel with SIDDHARTA-2 data taking
• Determination of background level, position and shielding of HPGe, for the precision measurement of the charged kaon mass
• Participation in data taking
• Participation in data analysis and MC simulations.

Project n. 8 IGFAE-Kd “Kaonic Atoms at SIDDHARTA-2” (Antonio Romero Vidal, Santiago di Compostella, Spain), with the following activities:
• Participation in beam time shifts
• Data analysis for kaonic deuterium using Machine Learning

Project n. 10 SIDDHARTA-2 "Studying kaonic deuterium atoms with SIDDHARTA-2" (Johann Zmeskal, SMI, Vienna, Austria), with the following activities:
• Participation in beam time shifts for kaonic deuterium at various densities
• Data analysis
• MC simulations
• Continuous maintenance and calibration of Veto-2 system during run

Project n. 11 Project n. 4 KRAKOW@SIDDHARTA-2 "Investigation of kaonic deuterium atoms with SIDDHARTA-2" (Magdalena Skurzok, Jagiellonian University, Cracow, Poland), with the flowing activities:
• Participation in beam time shifts for Kd
• Continuous data analysis for luminosity detector and extraction of luminosity during runs
• Participation in data analysis
• MC simulations

Project n. 12 Project n. 5 MeKaSD "Measurements of Kaonic atoms with SIDDHARTA-2 at Dafne" (Laura Fabbietti, TUM, Munich, Germany) with the following activities:
• Data analysis of SIDDHARTa-2 Kd run
• Participation in beam time shifts
• SDD calibration in loco during data taking
• Development of advanced data analyses using ML

Project n. 13 SIDDHARTA&HPGetest "SIDDHARTA-2 data taking and HPGe tests measurements" (Damir Bosnar, University of Zagreb, Zagreb, Croatia), with the following activities:
• Continuous optimization of HPGe detector in the DAFNE Hall
• Test measurements with HPGe in parallel with SIDDHARTA-2 data taking continued
• Determination of background level, position and shielding of HPGe, for the precision measurement of the charged kaon mass
• Participation in data taking for Kd
• Participation in data analysis and MC simulations.

Project n. 14 EARS-2 "Exotic atoms research with SIDDHARTA-2" (Alexandru Mario Bragadireanu, IFIN-HH, Magurele (Bucharest), Romania) with the following activities:
• Participation in beam time shifts for SIDDHARTA_2 full setup
• Data analysis of data collected
• Optimization of the degrader for Kd measurements
• Calibration and optimization 1 mm thick SDD
• Optimization of DAQ and Slow Control systems

Project n. 9 and 15 IGFAE-Kd “Kaonic Atoms at SIDDHARTA-2” (Antonio Romero Vidal, Santiago di Compostella, Spain), with the following activities:
• Participation in beam time shifts for final Kd run
• Data analysis for kaonic deuterium using Machine Learning

Table 3.1 Access to the facility during the reporting period supported by the project

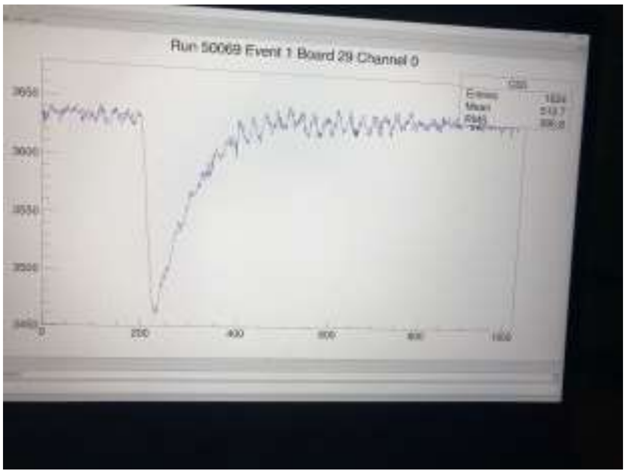
Project No.	User-project acronym	Number of users	Number of days spent at the infrastructure
2	**DarkAndRare**	**4**	**38**
3	**SIDDHARTA-2**	**1**	**24**
4	**KRAKOW@SIDDHARTA-2**	**6**	**16**
6	**EARS-2**	**1**	**10**
7	**SIDDHARTA-2 & HPGe**	**1**	**10**

8	**IGFAE-Kd**	**1**	**10**
9	**DarkAndRare**	**5**	**134**
10	**SIDDHARTA-2**	**4**	**223**
11	**KRAKOW@SIDDHARTA-2**	**10**	**178**
12	**MeKaSD**	**1**	**10**
13	**SIDDHARTA&HPGetest**	**2**	**123**
14	**EARS-2**	**2**	**43**
	TOTAL	**38**	**819**

3.2 Scientific output of the transnational access activity in the reporting period

Follows a description of the scientific outputs followed by articles resulting from TA3-LNF.
Facility PADME: projects 2 and 9.
Data analyses for the X17 run is ongoing, with results expected by autumn 2024. The new eTagger has been installed (2021-2022) and a new gaseous tracking detector is under construction to better measure X17 decay products in a run to take place in 2025. This system was tested and will be used to separate gg from ee clusters; also a new gaseous tracking detector is under construction to better measure X17 decay products.

Gamma-gamma tagger test:



Facility SIDDHARTA

Project n. 4 KRAKOW@SIDDHARTA-2: the activity consisted in the installation of the luminometer and its calibration with the kaon monitor and the DAFNE calculated luminosity; participation in the beam time shifts; data analysis.

Project n. 5 ANTIKD: the activity consisted in the participation in the beam time shifts with SIDDHARTA-2 and in the participation in data analysis for extraction of kaonic helium.

Project n. 6 EARS-2: the activity consisted in the participation in the beam time shifts of SIDDHARTINO and in the development of a new interface in the software LabView for DCS.

Project n. 7 SIDDHARTA-2 & HPGetest: the users installed the HPGe detector in the DAFNE hall, and performed first tests measurements, in parallel with the SIDDHARTA-2 data taking.

Project n. 8 SIDDHARTA-2: the Vienna group participated in the final SIDDHARTA-2 detector assembly; participated in the calibration of the Veto-2 system and in its installation; participated in the beam time shifts and in the data analyses and Monte Carlo simulations.

Project n. 9 AntiKD: the Munich group participated in the beam time shifts for calibration of the SIDDHARTA-2 setup with various kaonic atoms measurements for degrader optimization; in the data analyses and Monte Carlo simulations.

Project n. 10 SIDDHARTA-2: the Vienna group participated in the maintenance and optimization of SIDDHARTA-2 setup, in particular of veto-2 detector, during Kd run; participated in the calibration of the Veto-2 system and extraction of the veto signal; participated in the beam time shifts and in the data analyses and Monte Carlo simulations.

Project n. 11 KRAKOW@SIDDHARTA-2: the activity consisted in monitoring the luminometer and calculating the luminosity during the Kd run; participation in the run shifts and in the data analysis to extract the Kd and other kaonic atoms signals.

Project n. 12 MeKaSD: the Munich group participated in the beam time shifts for kaonic deuterium run to extract shift and width of kaonic deuterium fundamental level; in the data analyses and theoretical interpretations.

Project n. 13 SIDDHARTA-2 & HPGetest: the Zagreb group optimizaed the data taking of the kaonic heavy atoms with the HPGe detector in the DAFNE hall, by performing test measurements for kaonic lead; data were analysed and submitted for publication, in parallel the group took part to the SIDDHARTA-2 data taking.

Project n. 14 EARS-2: the activity consisted in the participation in the beam time shifts of SIDDHARTa-2 for kaonic deuterium and other kaonic atoms and in the optimization of in the software LabView for DCS

Project n. 15 IGFAE-Kd: the Spanish team participated in the shifts for Kd measurement, in data analyses and MCarlo simulations by also applying ML method.

The most precise measurement of the kaonic helium transitions to the 2p level in gas, obtained with the SIDDHARTINO setup (reduced SIDDHARTA-2 setup) in which all Projects were involved; the obtained kaonic helium spectrum is shown in Fig. 1, and published in J. Phys. G: Nucl. Part. Phys. 49 0551.

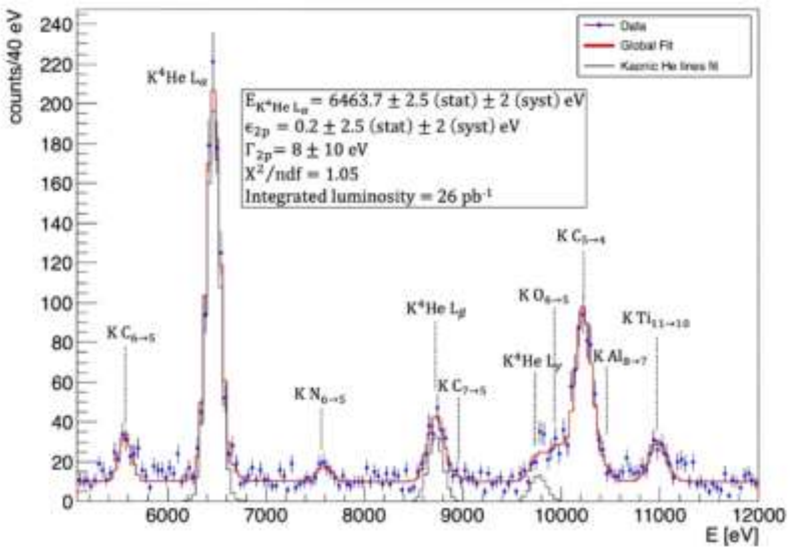


Figure 7. Fit (red line) of the K^{4}He energy spectrum. The Lα peak is seen together with the Lβ and Lγ ones (black lines). The peaks labeled as KN, KC, KAl, KTi (dotted lines) are the kaonic atoms lines produced by the kaons stopped in the Kapton ($C_{22}H_{10}O_5N_2$) walls of the target cell and in other parts of the setup (see text for details).

Figure 1: the kaonic helium spectrum obtained with support of transnational access in SIDDHARTA facility (from paper J. Phys. G: Nucl. Part. Phys. 49 055106)

$$\epsilon_{2p} = E_{exp} - E_{e.m} = 0.2 \pm 2.5(\text{stat}) \pm 2.0(\text{syst})\ \text{eV}$$
$$\Gamma_{2p} = 8 \pm 10\ \text{eV}\,(\text{stat}).$$

- Optimization of the degrader for stopping kaons in a gaseous target – with application to the helium target – Figure 2 (taken from J. Phys. G: Nucl. Part. Phys. 49 055106)

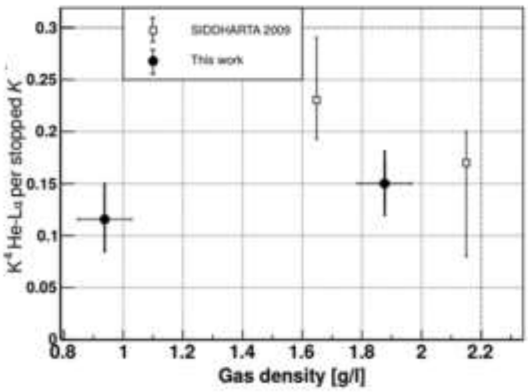


Figure 3. The L_α X-ray yield of K^- ^{4}He as function of the X-rays target density from all gaseous target measurement: this work (filled dots) and SIDDHARTA experiment [13] (hollow dots).

Figure 2: Optimization of the degrader for gaseous helium target with SIDDHARTINO setup

- The yields of kaonic helium transitions on 2p level for 2 different gas target densities (0.7 and 1.5% Liquid density)
- The installation of the final SIDDHARTA-2 setup with all key-elements (SDD, veto1, veto2 , trigger, luminometer, slow control, DAQ…) on the DAFNE Collider, Figure 3 test and debug and first characterization with kaonic helium

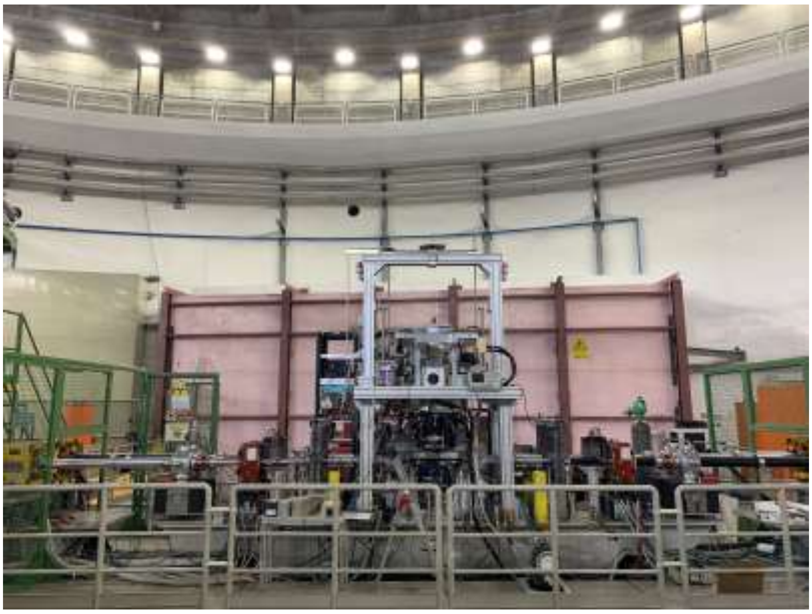
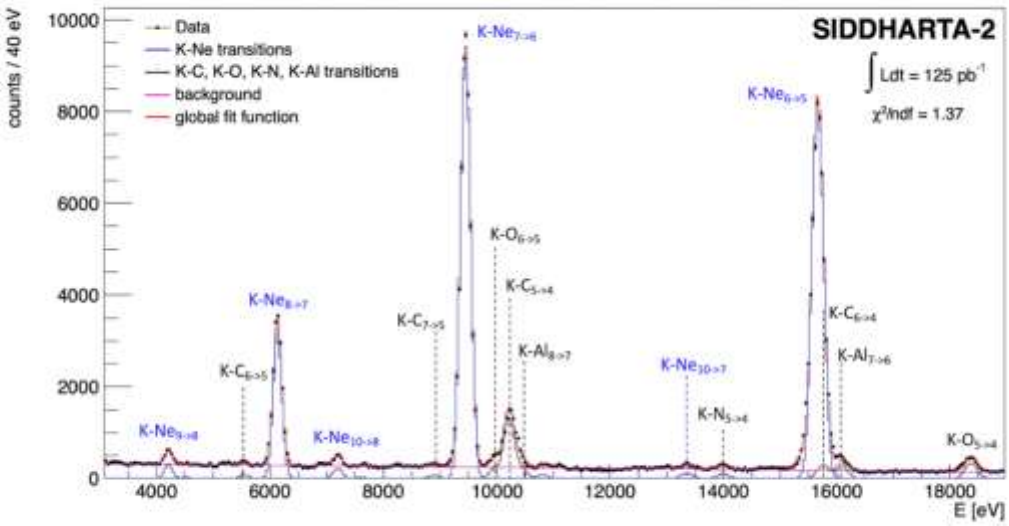


Figure 3: The final SIDDHARTA-2 setup installed on DAFNE Collider

- The first measurement of kaonic neon (data taken for optimization of final SIDDHARTA-2 setup) with measurement precision below 1 eV which proves that this measurement could in the future provide the kaon mass with best precision up to date, Fig. 4



Transition	Yield
K-Ne (10 → 8)	0.010 ± 0.001 (stat) ± 0.001 (sys)
K-Ne (9 → 8)	0.137 ± 0.012 (stat) ± 0.010 (sys)
K-Ne (8 → 7)	0.228 ± 0.004 (stat) ± 0.011 (sys)
K-Ne (7 → 6)	0.277 ± 0.002 (stat) ± 0.014 (sys)
K-Ne (6 → 5)	0.308 ± 0.003 (stat) ± 0.015 (sys)

Figure 4: The kaonic neon spectrum obtained by SIDDHARTA-2 and the precision of the measurement

- The first kaonic deuterium run in April 2022 – June 2024 – data analyses is ongoing and looks very promising
- Installation and characterization of the High Purity Germanium detector on DAFNE in parallel with SIDDHARTA-2 setup, Figure 5; first measurement of kaonic lead with HPGe at DAFNE, Fig 6

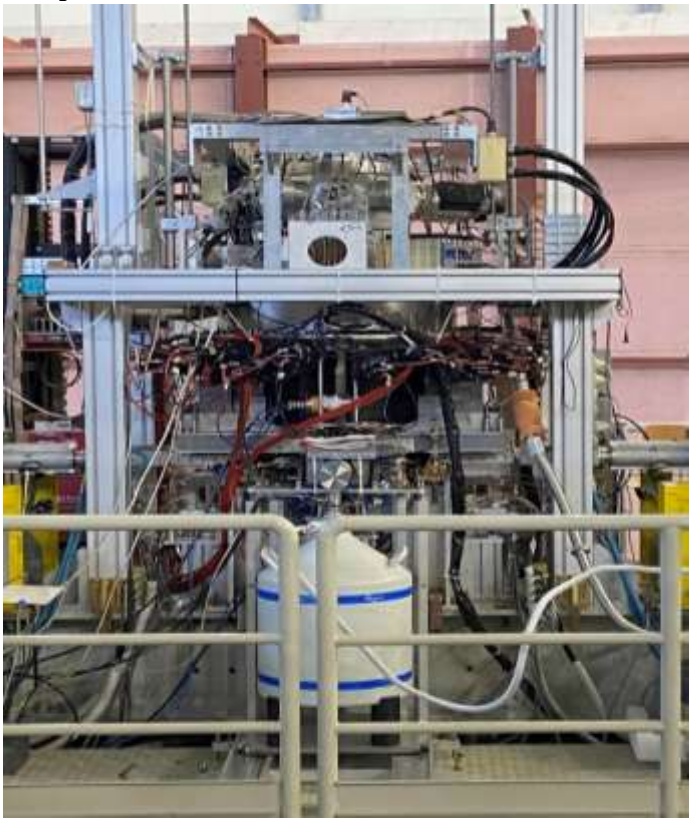


Figure 5: The HPGe detector installed on DAFNE collider

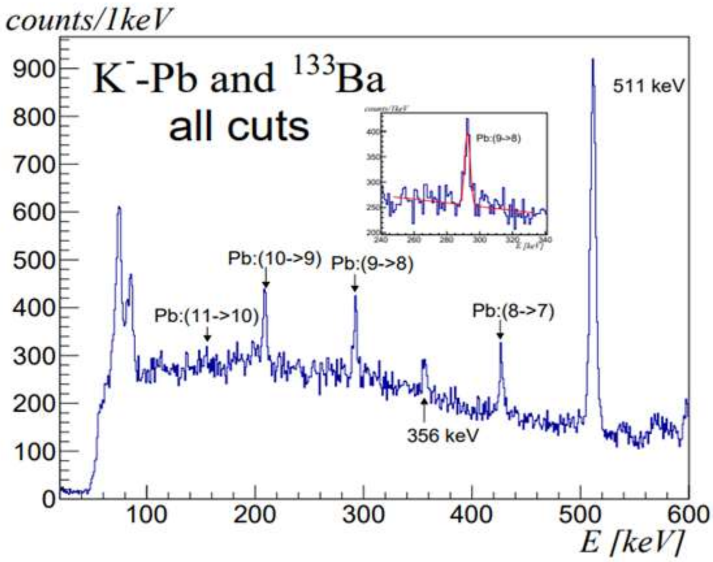


Figure 6: Kaonic Lead spectrum – results submitted for publication

Publications as results of the activities at LNF within TA3-LNF

Facility SIDDHARTA:

Kaonic lead feasibility measurement at DAΦNE to solve the charged kaon mass discrepancy, e-Print: 2405.12942, submitted to NIM

Characterization of the SIDDHARTA-2 Setup via the Kaonic Helium Measurement, Condens.Mat. 9 (2024) 1, 16

Kaonic atoms with SIDDHARTA-2 at the DAϕϕNE collider, EPJ Web Conf. 291 (2024) 01008

Kaonic Helium-4 L-series Yield Measurement at 2.25 g/l Density by SIDDHARTA-2 at DAΦΦNE, Acta Phys.Polon.Supp. 17 (2024) 1, 1-A8

The Odyssey of Kaonic Atoms Studies at the DAΦΦNE Collider: From DEAR to SIDDHARTA-2, Acta Phys.Polon.B 55 (2024) 5, 5-A

The SIDDHARTA-2 Veto-2 system for X-ray spectroscopy of kaonic atoms at DAΦNE, JINST 18 (2023) 11, P11026

First measurement of kaonic helium-4 M-series transitions, J.Phys.G 51 (2024) 5, 055103

Kaonic atoms at the DAϕNE collider: a strangeness adventure, Front.in Phys. 11 (2023) 1240250

Potentialities of CdZnTe Quasi-Hemispherical Detectors for Hard X-ray Spectroscopy of Kaonic Atoms at the DAΦΦNE Collider, Sensors 23 (2023) 17, 7328

Measurements of high-n transitions in intermediate mass kaonic atoms by SIDDHARTA-2 at DAΦNE, Eur.Phys.J.A 59 (2023) 3, 56

New opportunities for kaonic atoms measurements from CdZnTe detectors, Eur.Phys.J.ST 232 (2023) 10, 1487-1492

New measurements of kaonic helium-4 L-series X-rays yields in gas with the SIDDHARTINO setup, Nucl.Phys.A 1029 (2023) 122567

Kaonic atoms measurements with SIDDHARTA-2, J.Phys.Conf.Ser. 2446 (2023) 1, 012023

SIDDHARTA-2 veto system design and performance for kaonic atoms studies at DAΦNE, EPJ Web Conf. 290 (2023) 06005

Towards the first kaonic deuterium measurement with the SIDDHARTA-2 experiment at DAΘNE, Nuovo Cim.C 45 (2022) 6, 205

Studies of the Linearity and Stability of Silicon Drift Detectors for Kaonic Atoms X-ray Spectroscopy, Acta Phys.Polon.Supp. 15 (2022) 4, 1

First Tests of the Full SIDDHARTA-2 Experimental Apparatus with a 4He Gaseous Target, Acta Phys.Polon.A 142 (2022) 3, 373-37

Large area silicon drift detectors system for high precision timed x-ray spectroscopy, Measur.Sci.Tech. 33 (2022) 9, 095502

Status and perspectives for low energy kaon-nucleon interaction studies at DAΦΦNE: from SIDDHARTA to SIDDHARTA-2, PoS PANIC2021 (2022) 200

The SIDDHARTA-2 calibration method for high precision kaonic atoms x-ray spectroscopy measurements, Phys.Scripta 97 (2022) 11, 114002

Kaonic atoms at the DAΦNE collider with the SIDDHARTA-2 experiment, Phys.Scripta 97 (2022) 8, 084006

Facility PADME

Investigating the dark sector with the PADME experiment, Nuovo Cim.C 47 (2024) 4, 241

Characterization of the PADME positron beam for the X17 measurement, JHEP 08 (2024) 121

Design and performance of the front-end electronics of the charged particle detectors of PADME experiment, JINST 19 (2024) 01, C01051

Beam diagnostics with silicon pixel detector array at PADME experiment, JINST 19 (2024) 01, C01016

Dark sector studies with the PADME experiment, PoS ICHEP2022 (2023) 145

The study of the X17 anomaly with the PADME experiment, J.Phys.Conf.Ser. 2586 (2023) 1, 012140

Searching for light dark matter with the PADME experiment, PoS CORFU2021 (2022) 040

Cross-section measurement of two-photon in-flight annihilation of positrons at s=20 MeV with the PADME detector, Phys.Rev.D 107 (2023) 1, 012008

Table 3.2 List of user meetings

No users meetings have been held during the reporting period

1.4.4 Work Package 6

Activity Type	Transnational Access
Work package title	Transnational Access to FTD/ELSA (TA4-ELSA)
Lead beneficiary	10 - UBO

1. Publicity concerning the new opportunities for access

Information can be found here: https://www.pi.uni-bonn.de/projects/elsa-ftd

This includes a description of the infrastructure, application requirements and selection panel. Online forms are provided for grant applications.

This information was circulated throughout our scientific community numerous times to announce the webpage and any upcoming deadlines. Calls for grant applications with dates for the selection panel were clearly disseminated

2. Selection procedure

2.1 Organization of the Users Selection Panel (USP)

The USP is a board of international physicists for peer reviewed access requests. Members of ongoing hadron physics collaborations and representatives of ELSA are also included

2.2 Selection criteria

- Formal access request via the Access Coordinator
- Formal proposal (including detailed beam/lab-time request with physics/technical justification and required beam/lab parameters)
- Evaluation by the user selection panel
- Upon acceptance of user-proposal, beam/lab-time allocation by the Allocation Committee
- Formal assessment of the offered services for outside users via web-interface.
- Suitable proposals are selected respecting the principles of transparency, fairness and impartiality.

2.3 Users Selection Panel members

- Prof. Dr. Philip Cole (Lamar University, Beamont, Tx, USA)
- Prof. Dr. Jochen Dingfelder (Bonn Internal and chair)
- Prof. Dr. Bernhard Ketzer (Bonn Internal)
- Prof. Dr. Michael Ostrick (Mainz University, Germany)
- Dr. Christoph Rembser (CERN)
- Prof. Dr. Piotr Salabura (Jagiellonian University, Krakow, Poland)
- Prof. Dr. Danial Watts (University of York, York, UK)

2.4 Users Selection Panel meetings

Meetings are held to assess grant applications and the dates for launching new requests for submissions. Current information is given here: https://www.pi.uni-bonn.de/projects/elsa-ftd

A USP meeting was held during the final workshop, Exotic states and baryon spectroscopy in June 2023 to assess the scientific output of the approved projects which was deemed highly successful.

3. Transnational Access activity during the reporting period

3.1 Detailed description of the activity

The following table indicates the man days spent for projects, which successfully used the infrastructure within this funding period.

Projects TA4-6, TA4-1, and TA4-2 (MWPC development, Eta polarised beam asymmetry and Eta prime respectively) were pursued within the BGOOD experiment. Projects TA4-3 used the man days solely during data taking periods. Project TA4-2 used man days for detector development and Project TA4-1 used man/days for both detector development and data taking periods.

If a data taking period can be used for multiple projects, the man days below are shared between projects, to ensure there is no duplication.

Table 3.1 Access to the facility during the reporting period supported by the project

Project No.	**User-project acronym**	**Number of users**	**Number of man/days spent at the infrastructure**
TA4-6	MWPC	1	9
TA4-1	EPBA	8	55
TA4-3	MQS	7	44

3.2 Scientific output of the transnational access activity in the reporting period

Analysis of data taking for both the BGOOD and CBELSA-TAPS experiments has continued and beenpresented at many international conferences and workshops.

During this period, one paper has been published in peer-reviewed journals for BGOOD:

1. *Measurement of the* $\gamma n \rightarrow K^0\Sigma^0$ *differential cross section over the* K^* *threshold*, K. Kohl, T.C.Jude et al., Eur. Phys. J. A 59. 254 (2023)

BGOOD also has two papers submitted for publication, preprints of which can be found on the archive:

1. *Coherent* $\pi^0\eta d$ *photoproduction at forward deuteron angles measured at BGOOD*, A. J. ClaraFigueiredo, T. C. Jude et al., arXiv:2405.09392 (2024), submitted to Phys. Lett. B

2. $K^+\Lambda(1520)$ *photoproduction at forward angles near threshold with the BGOOD experiment*, E. O.Rosanowski, T.C. Jude et al., arXiv:2406.01121 (2024), submitted to Eur. Phys. J. A

BGOOD also published two peer reviewed conference proceedings during this funding period:

1. The BGOOD experiment at ELSA - Exotic structures in the strange quark sector? T.C. Jude etal., MESON 2023, EPJ Web Conf. 291, 01004 (2024)

2. The BGOOD experiment at ELSA, T.C. Jude et al., INPCC2022, J. Phys.: Conf. Ser. 2586 012003 (2023)

The workshop *Exotic multi-quark states and baryon spectroscopy* was held in Bonn in June 2024 todiscuss the scientific output within the context of an international meeting of leading scientists in ourcommunity.

Table 3.2 List of user meetings

With the exception of project TA4-10, all projects are either within the framework of the BGOOD (TA4-1 to TA4-6 and TA4-9) or CBELSA/TAPS (TA4-7 and TA4-8) experiment and collaboration. The work within these projects form the cornerstone of the pursued physics interests of the experiments. User meetings for projects have occurred during, and been a vital input to collaboration meetings held within this period. These are listed below.

User-project acronym	Date	Venue	Number of users	Overall number of attendees
CBELSA/TAPS	August 2023	Online (COVID restrictions)	7	~40
BGOOD	Analysis meeting every2nd week	Online	~25	~15
CBELSA/TAPS	Analysis meeting every2nd week	Online	~3	~14
BGOOD & CBELSA/TAPS	Exotic hadronand baryon spectroscopy workshop, June 2024	Bonn	~32	~50

1.4.5 Work Package 7

Activity Type	Transnational Access
Work package title	Transnational Access to GSI (TA5-GSI)
Lead beneficiary	8 - GSI

1. Publicity concerning the new opportunities for access

The opportunities for support offered to users of the accelerator and experimental facilities, are published on the following website:

https://www.gsi.de/en/work/organisation/scientific_boards/user/funding/strong.htm

Apart from general information about GSI, the website contains information about available research capabilities, access procedures and beam time scheduling. Transnational Access to GSI within the context of STRONG-2020 is introduced and the funding opportunities are described. Additionally, the support for users, which is offered by the Welcome Office of GSI: technical and logistic support such as access to the computing infrastructure and the laboratories of GSI, accommodation, housing, health and liability insurances.

The form to apply for Transnational Access is provided at the STRONG-2020 website as well as the access to the user registration and to the statement of travel costs.

Calls for applications are published on the website, mails have been distributed to the user groups working on Strong-2020 topics and information on the opportunities have been distributed during collaboration meetings. The possibility of direct payment of GSI's guest houses for STRONG-2020 users was introduced in order to facilitate the travel cost reimbursement process.

2. Selection procedure

2.1 Organization of the Users Selection Panel (USP)

GSI is open to national and international user groups. To apply for the access to the accelerator and experimental facilities, a written project proposal has to be submitted to the GSI scientific director. The proposals are reviewed by an international panel of experts, which is the GSI General Program Advisory Committee (G-PAC).

The call for proposals the experimental campaigns in 2023/24 was opened April, 25th, 2022 and the G-PAC meeting took place September 22nd-23rd, 2022. Close to 1,800 participants from 45 countries submitted 124 proposals. Out of the proposals selected by the G-PAC for beam time allocation have been 4 with direct connection to hadron and dense nuclear matter physics.

If a user group in addition applies for EC support under the Integrated Infrastructure Initiative STRONG-2020, a separate funding application has to be submitted to the coordinator of the activity. These applications are evaluated by a User Selection Panel which consists out of members of the G-PAC and selected scientists of the field and – ex officio - the GSI research director. Only applications, which are approved by the G-PAC and are scheduled for experiments will be chosen. Once, the duration and date of the experiments are fixed, applications for access funding are evaluated. The applications are either sent to the Users Selection Panel for evaluation by mail or, as an exception, they are discussed in a face-to-face meeting.

2.2 Selection criteria

GSI is participating in several EC funded projects in which transnational access is offered. Therefore, the first selection criterion is the scientific topic, which is pursued by the user group.

For STRONG-2020 only, user groups planning research on the field of hadron and heavy ion reaction physics are eligible.

If the proposals have been suggested for beam time allocation by the G-PAC, the User Selection Panel decides about the funding of the user group. The groups are evaluated according to different aspects. One aspect is the number of scientist supporting personnel from countries, where funding for fundamental research is limited. Another aspect is whether the group has been newly formed and does experiments at GSI for the first time or members of the user group are coming from institutions, which are taking part in GSI experiments for the first time. During the 3rd reporting period only experienced user group applied for funding.

Most of the collaborations working on STRONG-2020 topics and performing experiments at GSI are rather large. Special emphasis is put on the funding of early career scientists, in order to allow postdocs, master and doctoral students to participate in experiments at GSI. Several early career researchers stayed for rather long times (> 1 month) for the preparation of the beam time, such that they gained valuable experimental experience, and strengthened the position of their group within the collaboration.

2.3 Users Selection Panel members

Since the proposals have been scientifically evaluated by the program advisory committee already, the user selection panel USP only decides on the funding of the user groups. Therefore, the USP is rather small and scientists with experimental experience at GSI or other large facilities have been selected to serve in the USP. Current members of the user selection panel are:

- Prof. Dr. Philippe Crochet, LPC-Clermont Ferrand (expert for heavy ion reactions, member of the ALICE collaboration with no connections to any of the experimental groups, former post doc at GSI and member of the G-PAC)
- Prof. Dr. Jana Bielcikova, Nuclear Physics Institute, Czech Academy of Science (expert for heavy ion reactions, member of G-PAC, member of the STAR collaboration at RHIC, during her doctoral studies she did experiments at GSI)
- Prof. Dr. Kai Brinkmann, University of Giessen, (expert in hadron physics and detector technology, member of the PANDA collaboration; he did experiments at the linear accelerator of GSI)
- Prof. Dr. Karlheinz Langanke, GSI (research director, expert in theoretical nuclear astrophysics; member of the user selection panel by virtue of office, chair)

The USP is constituted out of members, which have done experiments at GSI or are situated at GSI, but are not directly involved in ongoing experiments. Chair of the USP is the research director of GSI, since most of the communication and the decision processes will be realized via mail or video meetings and, therefore, will be organized by GSI. However, due to the envisaged of the project and sufficient budget there was no decision process necessary during this reporting period, and the applications have been granted without essential cuts.

2.4 Users Selection Panel meetings

Only an informal User selection panel meetings took place in July 2023 via E-Mail circulation

3. Transnational Access activity during the reporting period

GSI, together with national and international partner institutions, has started in 2016 the construction of a new large accelerator and research complex: The Facility for Antiproton and Ion Research (FAIR). Those activities require major human and financial resources, what has consequences for the availability of beam time until the start of the commissioning of the FAIR accelerators. In order to enable beam time during the construction of FAIR, GSI launched the FAIR Phase-0 program. The FAIR Phase-0 program started 2018/19 made commissioning and testing of the upgraded GSI accelerators along with early physics experiments using the upgraded GSI accelerators and novel FAIR instrumentation possible. Approximately three months of beam time per year are available to the scientific community until FAIR is operational.

3.1 Detailed description of the activity

In 2022, the beamtime was successfully concluded with an uptime of the accelerator facility of 88 % of the scheduled hours. The availability for the users was 75 % with beam on target. These values are within the typical range of the last years and confirm the stable operation conditions of the GSI facilities Major shutdown activities of the accelerator during 2022 were: Renovation of the ventilation system of the UNILAC RF power stations and the refurbishment of the medium voltage switchgear stations. In order to reach the intensities of highly charged U28+ needed for FAIR operation two major upgrades are underway: a) the replacement of the nitrogen pulsed gas stripper by hydrogen pulsed gas stripper, to enhance the efficiency of production of the 28+ charge state of uranium and b) the replacement of the Alvarez drift tubes. The new drift tubes will be housed in novel tanks of close to 2 m diameter. For the latter the Galvanic workshop of GSI was refurbished. All large components of the novel accelerator will be copper plated in house.

In 2023, only an engineering took place in December. Major achievements relevant for the STRONG-2020 experiments are: The uranium 28+ beam, was set-up and an intensity of up to 42.7 billion ions was measured at the end of the GSI accelerator chain, downstream of the SIS18 ring. New best GSI values were reached for carbon (35 billion ions / cycle) and nitrogen (68 billion ions / cycle) behind SIS18 and for nitrogen up to the pion target. This achievement is important for future pion runs at HADES, in particular. Two different methods for optimization of the micro-spill and macro-spill structures were tested, a spill smoothing cavity in the SIS18 and a feedback system working with KO extraction. Both produced impressive improvements and nearly doubled the duty cycle of the HADES run in 2024.

The next experimental beam time took place in 2024. Three scheduled experiments in the framework of STRONG-2020 were performed. The HADES experiment on heavy-ion collisions could not be completed due to a failure of the cooling-system of the super-conducting magnet.

S522/COR (beam time 2022): Short Range Correlations (SRC) are two-body components of the nuclear wave function with high relative momentum and low center of mass (c.m.) momentum with respect to the Fermi momentum $k_F \sim 250$ MeV/c. The goal of this project is to provide new precise data on the isospin content of SRC as a function of N/Z asymmetry and intrinsic momentum by performing measurements in inverse kinematics, where radioactive carbon ions (up to ^{16}C) can be used as the beam. Hence, the key element of the set-up is a liquid hydrogen target, which has been designed and constructed by members of the user group. This liquid target was integrated into the R3B set-up.

Main achievements: Several issues due to the novelty of this type of measurement were encountered. The beam energy and intensity were higher than for standard R3B experiments, and the FOOT vertex tracking system has been used for the first. Nevertheless, data taking was completed successfully and data analysis has been started with the development of the appropriate analysis tools.

HAD/TLU (beam time 2022): HADES is a set-up to detect lepton pairs originating from decays of mesonic and baryonic resonances produced in heavy ion collisions or elementary reactions. In order to enhance the physics performance for investigation of exclusive decay channels in pp reactions, tracking and time-of-flight detectors have been installed in the forward acceptance region. The user group was responsible for parts of the upgrade of the HADES set-up and for the commissioning of all sub-detectors, in particular, the newly setup, and successful operation of the full system during a full one-month beam time. The scientific goal of this project addresses the following topics (S518): (1) Hyperon electromagnetic decays (2) Hyperon hadronic decays. (3) Production of double strangeness and hidden strangeness. (4) Inclusive hadron and di-electron production as a reference for p+A and heavy-ion data.

Main achievements:

- Forward tracker installation based on PANDA technology: Two new Straw Tracking Stations (STS1, STS2) were installed together with new RPC based time-of-flight detector to detect particles emitted at low polar angles.
- Construction, installation and software development of a novel T0 detector based on LGAD sensors: The experiment required time-of-flight measurement for beam particles with intensities of 108 particles/s. Modern LGAD technology was used, highly segmented strip sensors were produced and a dedicated readout system was designed. The full system has been tested at various facilities. A software package for calibration was developed and applied.
- Upgrade of HADES MDC gas subsystem: The upgrade of current MDC gas subsystem was also accomplished. This involved the optimization of the gas distribution by improving the mixing system with the possibility of adding water individually in each of the 6 sectors. Individually selecting the amount of water vapor enhanced the stability of the wire chambers and increased the efficiency of the entire system.
- DAQ, analysis and database software development, detector control: All mentioned items were updated, and complemented with parts dealing with new sub-detectors.

Highlights: Two new Straw Tracking Stations (STS1, STS2) using the technology of the PANDA-STT/FT detector systems, together with the new forward RPC time-of-flight detector, were installed at HADES in order to extend the single-track acceptance to low polar angles

($\Theta<7°$) and thereby increase the acceptance by a factor two for hyperon reconstruction. In a four-week HADES beam time with 4.5 GeV protons impinging on a proton target, these detectors were operated with highest detection efficiency and high spatial resolution. That beam time produced a rich sample of experimental data for a wide range of reaction channels and the data analyses include studies of the $pn\pi^+$, $pK\Lambda$, $pK^0S\Lambda\pi^+$, and ppK^+K^- final states and also proton-proton elastic scattering for cross section normalization.

A modern T0 detector based on LGAD technology developed and successfully utilized in this experiment has been used also in other fields, beam diagnostics and medical applications. It demonstrates an excellent synergies and very efficient usage of the resources.

MCBM/ZAB: The Compressed Baryonic Matter experiment (CBM) at FAIR is designed to measure nucleus-nucleus collisions at unprecedented interaction rates of up to 10 MHz, which will allow study of extremely rare probes with high precision. To achieve this high rate capability, CBM will be equipped with fast and radiation-tolerant detector systems, readout by a free-streaming data acquisition system, transporting data with a bandwidth of up to 1 TB/s to a large scale computer farm for event reconstruction and first level event selection. mCBM comprises prototypes and pre-series productions of all CBM detector systems with their read-out electronics, transporting synchronized data streams into the Green IT Cube of GSI/FAIR. To further validate CBM's read-out and data processing concept, the production yield of rare Λ baryons is studied in nucleus-nucleus collisions serving as a benchmark observable, which will allow comparison with published data

Main achievements: For the beam campaign 2021, the mCBM DAQ system was upgraded to the final CBM configuration. DAQ hardware as well as firm- and software were continuously tested and optimized since 2021. Detailed high-rate studies were carried out for all detector systems, in particular rate scans and ageing studies under extreme conditions for the Time-Of-Flight (TOF) and the MUon CHamber (MUCH) system, using ^{238}U (March'22) and ^{197}Au beam (June'22 and March'24) beam with collision rates up to 10 MHz (and beyond). And finally, benchmark runs, dedicated for the reconstruction of rare Λ baryons, were taken in Ni+Ni collisions at 1.93 AGeV (May'22) and in Au+Au collisions at 1.23 AGeV (June'22) as well as in Ni+Ni collisions at three kinetic projectile energies of 1.23, 1.58 and 1.93 AGeV in May'24. While the development of the CBM data analysis chain is ongoing, Λ baryons were successfully reconstructed in Ni+Ni collisions at 1.93 AGeV, taken in 2022. An essential step towards the CBM experiment was made by developing a first prototype of the CBM on online reconstruction and selection system, which could be tested within the mCBM 2024 campaign.

Difficulties encountered: Due to pandemic restrictions in the years 2020 and 2021, the DAQ/data transport was upgraded and operated remotely, controlled by VNCs while the communication was granted by permanent Zoom sessions. During preparation (dry) runs or during data taking, the mCBM experiment could thus be operated properly with a small 4 to 6 persons' team on-site and about 20 experts word-wide connected remotely.

Highlights representing essential steps towards the CBM experiment at FAIR:

- Development, test and optimization of a free-streaming DAQ and data transport system for CBM, based on a Common Readout Interface board: a stable synchronization of all individual detector data streams were observed and tested under realistic experiment conditions.

- Successful high-rate and ageing studies of CBM detector systems, up to the highest collision rates.
- Reconstruction of rare Λ baryons with mCBM in Ni+Ni collisions at 1.93 AGeV, involving the complete CBM data chain.
- Development and test of the CBM online system for real-time reconstruction and selection.

G00022/TLU: The project goals are the preparation and realization of the HADES experiment on “Searching for critical behavior and limitations of the universal Freeze-out line” (G-22-00022). A gold beam in the kinetic energy range 0.2-0.8 A GeV is employed to investigate Au+Au collisions with the aim to study baryonic matter in the proximity of the nuclear liquid-gas phase transition.

Main achievements:

- Completion of full electromagnetic calorimeter: In 2022, the last sector was installed, and during 2023 was fully commissioned. The comprehensive maintenance of the entire detector and the precise gain settings of the photomultiplier tubes (PMTs) were achieved using cosmic muon measurements.
- Upgrade of the HADES Forward Wall time-of-flight subsystem: A new HV system, powered by the CAEN A7435N high voltage supply housed in CAEN SY4257 crates, was connected to the photomultiplier tubes (PMTs) using SHV cables and CAEN R647 distribution modules. To set the gain of the PMTs accurately, cosmic muons were used. During beamtime, regular quality assurance (QA) checks were performed to monitor the HV system's performance.

Highlights: During the beamtime in February-March 2024, the fully operational ECAL was employed to study particle production in carbon-carbon (C+C) and gold-gold (Au+Au) collisions at 800 A MeV. The C beam, with an intensity of $1x10^6$/sec, and the Au beam, with an intensity of $2.7x10^6$/sec, were impinging on segmented targets. The quality of measured data was controlled during the beamtime via online analytical plots i.e. time over threshold vs cell number, multiplicity vs sector or event rate monitor. Preliminary results include the successful reconstruction of the π^0 mass peak from its double gamma decay with an expected resolution of 15 MeV/c^2, demonstrating the detector's high performance and accuracy.

G00122/RUS: Objective of the project is to measure the density dependence of the symmetry energy of the nuclear equation of state at densities above the saturation one. This will be achieved by comparing the neutron-to-proton elliptic flow ratio, as experimentally measured in semi peripheral Au+Au collisions at beam energy of 250, 400 and 800 AMeV (S122/ASY-EOS II experiment), to transport model calculations. The obtained results will complete the ones obtained by multi-messenger astronomy studies (binary neutron stars merger and X-ray neutron star satellite-based observations).

Main achievements: During an extended commissioning run in 2024, the detectors that will be used in the main data taking, foreseen in 2025, have been commissioned and successfully tested. In particular the March 2024 test-beam has allowed to commission the new KRAB detector which was constructed for measuring the collision centrality and reaction plane orientation. The DAQ coupling among the different devices needed (CHIMERA from LNS Catania, KRAB from Warsaw, and the R3B detectors, ToFD, LOS, ROLU, and NeuLAND) have been established and verified.

Highlight: Extended data analysis of the previous experiment (S394/ASY-EOS I experiment) has proven the importance and effectiveness of heavy-ion collision to complete/interpret the high-density symmetry energy constraints from multi-messenger astronomy.

Table 3.1 Access to the facility during the reporting period supported by the project

Project No.	User-project acronym	Number of users	Number of man/days spent at the infrastructure
1	S522/COR	13	308
2	HAD/TLU	22	421
3	G00022/TLU	24	541
4	mCBM/ZAB	14	126
5	G0122/RUS	11	127

3.2 Scientific output of the transnational access activity in the reporting period

No user meeting too place.

1.4.6 Work Package 8

Activity Type	Transnational Access
Work package title	Transnational Access to ECT* (TA6-ECT*)
Lead beneficiary	29 - FBK

1. Publicity concerning the new opportunities for access

Projects carried out at ECT* are workshops, collaboration meetings, and the annual Doctoral Training Program (DTP). The role of the projects is to enhance cooperation and discussion among workshop participants in order to foster existing collaborations and stimulate new scientific endeavours and joint research activities. Project proposals can be submitted online through an ECT* web interface.

The selected projects, once approved by the ECT* Scientific Board, are announced on the ECT* website and publicized by email to the ECT* Associates and to research institutions worldwide.

The call to submit workshop and DTP proposals is announced in April of each year, and publicized on the ECT* website and via by email to the ECT* Associates and to research institutions worldwide.

2. Selection procedure

2.1 Organization of the Users Selection Panel (USP)

The selection of projects is decided by the ECT* Scientific Board based on scientific content and timeliness of the proposals. The participants of the proposed activities (users) are selected by the organizers of the activity. The Scientific Board is composed of internationally renowned scientists, thus ensuring scientific excellence in a selection procedure.

The selection procedure is as follows.

The Scientific Board, which acts as Selection panel, has two annual meetings (usually in June and October), during which it carries out the selection of the projects and the nomination of the project group leaders (one of the organizers of the activity) that should benefit from access.

2.2 Selection criteria

- Scientific excellence
- Timeliness of scientific topics
- Balance between theoretical and experimental research
- Interdisciplinarity with other/related fields
- Professional status of the project leader and organisational skills
- Balance between nationalities as well as senior/junior participants.

2.3 Users Selection Panel members

The ECT* Scientific Board acts as the selection panel and consists of (correct July 2024)

- Almudena Arcones | TU Darmstadt (D)
- David Kaplan | INT Seattle (USA)
- Denis Lacroix | CNRS-IN2P3 (F)
- Marek Lewitowicz | NuPECC/GANIL (F)
- Alexandre Obertelli | TU Darmstadt (D)
- Assumpta Parreno Garica | University of Barcelona (E)
- Barbara Pasquini (chair) | University of Pavia (I)
- Vittorio Soma | CEA Saclay (F)
- Urs Wiedemann | CERN-TH (CH)

2.4 Users Selection Panel meetings

- April: call for proposals for workshops, collaboration meetings and the Doctoral Training Program made public
- June meeting: first selection of projects
- October meeting: the Board finalizes the full programme of activities for the next year

3. Transnational Access activity during the reporting period

3.1 Detailed description of the activity

The scientific infrastructure of ECT* and the Fondazione Bruno Kessler (FBK) has provided services for its users throughout most of the whole duration period of the Project. Once accepted through a peer reviewing procedure, the users are given access to ongoing ECT* projects and to the Centre’s computational facilities, library, seminar and discussion rooms.

Services currently offered by the infrastructure: Specific benefits for users result from the unique opportunities provided by the ECT* International Projects series (workshops, collaboration meetings, training programs) to transfer and update information on theoretical and experimental research at the frontiers of the field; its excellent computing facilities and links to European computing networks.

During the third period of reporting of STRONG-2020 activities, that is, from June 2022 to July 2024, 28 workshops and schools were supported with dedicated funds

Table 3.1 Access to the facility during the reporting period supported by the project

Project No.	User-project acronym	Number of users	Number of man/days spent at the infrastructure
1	06MULLIGAN22	10	57
2	07TEWS22	4	24
3	09HUPIN22	8	43
4	10BLUMENFELD22	9	47
5	11CLINE22	8	43
6	13ATHENODOROU22	4	22
7	14CORCELLA22	5	23
8	16BINOSI22	7	35
9	20LITVINOVA22	10	45
10	21FREESE22	9	45
11	22TUMINO22	9	42
12	05Triantafillopoulos23	25	107
13	06Huber23	20	93
14	07Krinitras23	16	50
15	09Shadmand23	28	130
16	14Fomin23	5	24
17	16Diehl23	9	41
18	18O'Connor23	30	141
19	19Ding23	5	23
20	20Varese23	16	70
21	22Kievsky23	17	84
22	01Enterria24	3	12
23	02Sadofyev24	10	39
24	06Schwenk24	12	52
25	08Pochodzalla24	17	73
26	09Jalilan-Marian24	10	47
27	12Royon24	13	60
28	15Celiberto24	10	43

3.2 Scientific output of the transnational access activity in the reporting period

Scientific outputs are not normally linked back to the ECT* activity, although workshop participants are encouraged to acknowledge STRONG-2020 in their papers which were progressed during an ECT* activity.

Table 3.2 List of user meetings

User-project acronym	Date	Venue	Number of users	Overall number of attendees
06MULLIGAN22	13-17 June, 2022	Trento	10	35
07TEWS22	20-24 June, 2022	Trento	4	25
09HUPIN22	4-8 July, 2022	Trento	8	28
10BLUMENFELD22	11-15 July, 2022	Trento	9	17
11CLINE22	18-22 July, 2022	Trento	8	21
13ATHENODOROU22	1-5 August, 2022	Trento	4	18
14CORCELLA22	29 Aug. - 2 Sept, 2022	Trento	5	44
16BINOSI22	12-16 September, 2022	Online	7	41
20LITVINOVA22	24-28 October, 2022	Trento	10	43
21FREESE22	7-11 November, 2022	Online	9	51
22TUMINO22	12-16 December, 2022	Trento	9	32
05Triantafyllopoulos23	15-19 May, 2023	Trento	25	38
06Huber23	22-26 May, 2023	Trento	20	39
07Krinitras23	29 May - 1 June, 2023	Trento	16	36
09Shadmand23	12-16 June, 2023	Trento	28	43
14Fomin23	17-21 July, 2023	Trento	5	31
16Diehl23	21-25 August, 2023	Trento	9	23
18O'Connor23	11-15 September, 2023	Trento	30	66
19Ding23	18-22 September, 2023	Trento	5	16
20Varese23	25-29 September, 2023	Trento	16	39
22Kievsky23	23-27 October, 2023	Trento	19	40
01Enterria24	5-9 February, 2024	Trento	3	47
02Sadofyev24	12-16 February, 2024	Trento	10	46
06Schwenk24	22-26 April, 2024	Trento	12	34
08Pochodzalla24	13-17 May, 2024	Trento	17	51
09Jalilan-Marian24	20-24 May, 2024	Trento	10	25
12Royon24	10-14 June, 2024	Trento	13	30
15Celiberto24	8-12 July, 2024	Trento	10	36

1.4.7 Work Package 9

Activity Type	Transnational Access
Work package title	Transnational Access to CERN (TA7-CERN)
Lead beneficiary	4 - CERN

1. Publicity concerning the new opportunities for access:

During RP3, the CERN Transnational Access (TA) possibilities have been advertised as follows:

1) Presentations in front of all relevant STRONG-2020 working groups in the 2021, 2022 and 2023 annual meetings of the consortium.

2) Emails sent by the Users Selection Panel to all STRONG-2020 working group principal investigators providing all details for CERN TA [emails were sent out December or each year with a request for feedback before February of the year after].

3) The CERN TA access opportunities were also publicized in two public web-pages:

STRONG-2020 web site: http://www.strong-2020.eu/transnational-access/ta7-cern.html,

CERN web site: https://cerneu.web.cern.ch/h2020-european-research-infrastructures

4) Last but not least, the conferences/workshops funded by STRONG-2020, had the logo in their web pages and this further publicized the CERN access possibilities across participants and outside the consortium members.

2. Selection procedure

2.1 Organization of the Users Selection Panel (USP)

The users selection access to CERN was based on the requests made by the different STRONG-2020 Working Packages (WPs), as well as from external requests related to the scientific activities of the consortium, that need to carry out activities (detector work, beam-test activities, experimental runs, meetings, conferences,...) on site. The USP checked that the WPs and external requests were scientifically sound, timely, topical and meaningful in terms of people/activities, and took an overall decision so that the final allocated funding was commensurate with the average resources available per year.

2.2 Selection criteria

The allocated funds for CERN TA activities provided per-diem funding to STRONG-2020 members to access the CERN laboratory for:

a) Beam-tests at SPS/PS beamlines and irradiations at PS/GIF++/IRRAD facilities (this concerned mostly the activities of STRONG-2020 Instrumentation WPs, as well as detector beam-tests of SPS, LHC and EIC experiments).

b) Participation to experimental runs of officially approved experiments at the SPS (this mostly concerned experimental activities of the COMPASS, MuOnE, and AMBER experiments) and at the LHC (ALICE/ATLAS/CMS/LHCb/…, including fixed-target FT @ LHC activities in ALICE/LHCb).

c) Participation to STRONG-2020-related meetings, workshops, conferences (this mostly concerns all instrumentation, experimental and theoretical SPS- and LHC-based activities).

The ~170kEUR budget (administrative overheads discounted) was equivalent to having every year on average ~320 people receiving the flat official per-diem of 138 CHF/day (~125€/day). In order to plan and organize the access of STRONG-2020 members to CERN over each year, the USP sent out an email to all WPs asking them to provide feedback on: (i) the motivation of the request (based on points a), b), or c) above), as well as the indicative needs in terms of (ii) number of days, and (ii) number of people of each WP that may need potential access at CERN. All received requests for each year were basically approved, as they were commensurate with the available budget.

2.3 Users Selection Panel members

David d'Enterria (CERN-TA coordinator),

Eugeni Grauges (Univ. Barcelona, experimentalist),

Tanguy Pierog (KIT, phenomenologist),

Patricia Rebello (Univ. Rio de Janeiro, phenomenologist and experimentalist).

2.4 Users Selection Panel meetings

The USP members exchanged various emails every year to discuss the received TA requests. The yearly requests were all within the available average budget per year, so the selection was simple (we checked that all proposals were well justified scientifically and financially, and inline with the goals of the consortium), and therefore no in-person meeting of all panel members was needed as everything was sorted out through email exchanges and Skype discussions.

3. Transnational Access activity during the reporting period

3.1 Detailed description of the activity

The CERN TA possibilities involved the access of users from 7 STRONG-2020 working groups, plus a few external requests related to the STRONG-2020 activities. Their associated activities on-site are described below:

1. JRA2 FT@LHC:

- Installation, calibration, commissioning and upgrade of the SMOG2 Gas Feed System for the fixed-target system of the LHCb experiment (2022, 2024)

- Coating studies for the polarized H recombination in the storage cell at the TE-VSC-SCC lab for the LHCb fixed-target project (2023)

- Organization & Participation in the "Fixed target experiments at LHC" Workshop (https://indico.cern.ch/event/1143479/, 22–24 Jun 2022)

2. JRA3-WP21 (PrecisionSM):

- MuOnE test runs (2022-2024)

- Participation to Meetings/Workshops on baryon CP tests at LHCb (2023)

3. JRA4-TMD-neXt:

- COMPASS data-taking data-taking runs (2022-2024)

- Participation to COMPASS Collaboration Meetings (2022-2024)

- Beam tests of the AMBER detector (2023)

4. JRA6-next-DIS:

- Beam tests of a new SiPM-based photon detector readout plane and the prototype of the EIC dual radiator Cherenkov detector (2023)

- Workshop participation: «Synergies between the Electron-Ion Collider and the Large Hadron Collider » Kick-off Workshop (https://indico.ph.tum.de/event/7014/, June 2022)

5. JRA7-WP25 (Light-and heavy-quark hadron spectroscopy):

- Beam test (T10 beamline) of a prototype of scintillating tracker of the ePIC (EIC) dRICH detector (2023-2024)
- Beam test of uRWELL prototype for LHCb and JLab (2022-2024)

6. JRA9-TIIMM (Tracking/ID) :

- ALICE ITS3 beam tests (2023)

7. JRA14-WP32 (Micropattern Gaseous Detectors for Hadron Physics):

- Beam tests at SPS M2 beamline of RD51 and nanodiamond-based photocathodes (2023-2024)

- Hardware activities related to the AMBER experiment (2023)

- Workshop participation: «IWHSS-2022 Conference ». (https://indico.cern.ch/event/1121975/, 29-31 Aug., 2022).

8. NA7-Heavy Flavour

- Organization & Participation in internal NA7-HF working meetings at CERN (2022-2024)

9. VA1-NLOAccess

- Support for scientific activities on-site of senior NLOAccess members (2022-2024)

- Support for multiple PhD students on-site for various theoretical activities (2022-2024)

- Organization & Participation in the "Physics with high-luminosity proton-nucleus collisions at the LHC" workshop (https://indico.cern.ch/e/pA_LHC_2024, July 2024)

10. VA2-3D Partons

- Participation in the xFitter workshop https://indico.cern.ch/event/1273738/ (3-5 May 2023)

- Participation in the "Theoretical systematics in LHC precision measurements" workshop, https://indico.cern.ch/event/1368033/ (26–27 Feb 2024)

11. Off-WPs activities

- Support for MSc students on-site carrying out STRONG-2020-related studies (2023-2024)

- Support for senior researchers participating in STRONG-2020-related activities: QCD physics programme of the forward proton spectrometer (PPS) of the CMS experiment (2024), work on particle flow and QCD jet reconstruction within the feasibility studies of the FCC-ee collider project (2024).

- Organization and participation at the "First Lund Jet Plane Institute" Workshop, (https://indico.cern.ch/e/LundJetPlane2023, 3–7 July 2023)

- Support for STRONG-2020 scientific activities to be presented at the “Axion Quest” conference (http://vietnam.in2p3.fr/2024/axions/program.php, summer 2024)

Table 3.1 Access to the facility during the reporting period supported by the project

Project No.	User-project acronym	Number of users	Number of person-days spent at the infrastructure
1	JRA2 FT@LHC	16	84
2	JRA3-WP21 PrecisionSM	11	139
3	JRA4 TMD-Next	9	158
4	JRA6-next-DIS	6	29
5	JRA7-WP25	6	53
6	JRA9-TIIMM	1	15
7	JRA14-WP32	15	115
8	NA7-Heavy Flavour	6	59
9	VA1-NLOAccess	27	249
10	VA2-3D Partons	1	7
11	Off-WPs (external) activities	10	154
	TOTAL	109	1067

3.2 Scientific output of the transnational access activity in the reporting period

The concrete scientific output of the TA activities related to CERN accesses are described in detail in the corresponding reports of each of the 10 working packages listed above. With respect to the off-WP STRONG-2020-related activities, a few scientific papers/conference proceedings were produced involving MSc students, participation with (partial) support from the consortium:

- Nicolas Crepet, David d’Enterria, Hua-Sheng Shao: “Improved modeling of $\gamma\gamma\to\gamma\gamma$ processes in ultraperipheral collisions at hadron colliders”, DIS2024-Grenoble Proceeds., https://arxiv.org/abs/2409.18485

- David d’Enterria and Van Dung Le : « Rare and exclusive few-body decays of the Higgs, Z, W bosons, and the top quark », JPG to appear, https://arxiv.org/abs/2312.11211

- Marina Maneyro and David d’Enterria, « Six-jet production from triple parton scatterings in proton-proton collisions at the LHC », DIS2024-Grenoble Proceeds. to be submitted.

1) «Synergies between the Electron-Ion Collider and the Large Hadron Collider » Kick-off Workshop, June 20-21, 2022, https://indico.ph.tum.de/event/7014/

2) “Fixed target experiments at LHC” Workshop https://indico.cern.ch/event/1143479/ (22–24 Jun 2022)

3) IWHSS-2022 Conference https://indico.cern.ch/event/1121975/ August 29th to 31st, 2022.

4) xFitter workshop https://indico.cern.ch/event/1273738/ (3-5 May 2023)

5) “First Lund Jet Plane Institute” Workshop, (https://indico.cern.ch/e/LundJetPlane2023, 3–7 July 2023)

6) “Theoretical systematics in LHC precision measurements” workshop, https://indico.cern.ch/event/1368033/overview, 26–27 Feb. 2024

7) “Physics with high-luminosity proton-nucleus collisions at the LHC” workshop (https://indico.cern.ch/e/pA_LHC_2024, 4–5 Jul 2024)

8) “Axion Quest” conference (http://vietnam.in2p3.fr/2024/axions/program.php, July-Aug. 2024)

Table 3.2 List of user meetings

User-project acronym	Date	Venue	Number of users	Overall number of attendees
JRA6-NextDIS	20-21 June, 2022	CERN	3	86
JRA2 FT@LHC	22–24 Jun 2022	CERN	14	44
JRA4-TMD-neXt	29-31 Aug, 2022	CERN	9	102
VA2-3D Partons	3-5 May 2023	CERN	1	50
Jet Lund Plane (external)	3–7 July 2023	CERN	4	90
VA2-3D Partons	26–27 Feb 2024	CERN	1	100
VA1-NLOAccess	4–5 Jul 2024	CERN	11	109
Axions’24 (external)	July-Aug. 2024	Quy-Nhon	2	65
TOTAL			45	645

1.4.8 Work Package 10

Activity Type	Virtual Access
Work package title	Automated perturbative NLO calculations for heavy ions and quarkonia (VA1-NLOAccess)
Lead beneficiary	1 - CNRS

1. Description of access facilities

To facilitate the access and create new opportunities for access, several measures have been taken during the reporting period (June 2022 – July 2024).

- We have further mantained the NLOACCESS code, by updating all the major packages used for the platform workflow.
- We have further enriched the NLOACCESS portal website (https://nloaccess.in2p3.fr) with a description of the Access, the list of participating institutions to the project, its objectives, a selection of useful references and the scientific news related to the Access.

2. International Assessment Board

2.1 Organization of International Assessment Board

An International Assessment Board (IAB) of eight researchers has been named. The composition of IAB reflects a balance between experimental and theory communities and EU and non-EU institutions. Indeed, the IAB is composed by:

- four researchers from the experimental community;
- four researchers from the theory community;

- among the eight researchers, five of them are from EU institutions and research centres, while the other three are from non-EU institutions.

The IAB is given all the relevant information about the Access including the detailed statistics. They are invited to send feed back to the

2.2 International Assessment Board Members

1. Prof. Asmita Mukherjee, IIT., Mumbai, India (Theory, Spin physics)
2. Dr. Barbara Trzeciak, CTU Prague, Czech Republic (Experiment, ALICE)
3. Dr. Cynthia Hadjidakis, IJCLab Orsay, France (Experiment, ALICE)
4. Prof. Elena Ferreiro, USC, Spain (Theory, Heavy-Ion Physics)
5. Dr. Emilien Chapon, IRFU-CEA, Paris-Saclay U., France (Experiment, ATLAS)
6. Dr. Nodoka Yamanaka, Nagoya U., Japan (Theory, Nuclear and Hadronic Physics)
7. Dr. Marc Schlegel, Tübingen U., Germany (Theory, Spin physics)
8. Prof. Zhenwei Yang, Tsinghua U., China (Experiment, LHCb)

2.3 International Assessment Board Meetings

The International Assessment Board (IAB) met virtually during the reporting period on July 26, 2024. The IAB has very positively assessed the result of the VA, which outperformed the initial objectives.

3. Virtual Access activity during the reporting period

3.1 Detailed description of the activity

Activities of different kinds have taken place since the beginning of the reporting period. They are connected to different projects stemming from the usage and the developments of different computing codes for various scientific objectives. Let us list them here first by starting with the multi-purpose codes and then we will detail the related activities:

- MADGRAPH5AMC@NLO by the Madgraph team:
- Extention of the automated NLO computations to asymmetric hadronic collisions (proton-nucleus, pion-nucleus, nucleus A-nucleus B).
- Validation of inclusive photoproduction at NLO in perturbative QCD.

Other (single purpose) codes were also considered for integration in NLOACCESS. Let us cite a TMD evolution code at NLL written by J. Bor (Groningen & IJCLab), or a NLO code for inclusive quarkonium photoproduction with high-energy resummation by M. Nefedov (IJCLab) and Y. Yedelkina (IJCLab & UC Dublin). The software framework developed for NLOACCESS is fully general adn can be applied to any code running with inputs transmitted by files and running via command lines on a Linux-based system.

We first report on the actions about the development of the Access *per se*:

1. As explained in section 1, we have further maintained and updated the packages needed for the correct functionning of the web application. In particular, we have updated the

PYTHON OwnCloud client to its latest version. This allows the cloud service to safely work and store the users' results.

2. We have studied with Y. Feng how to integrate the FDC workflow in a web page application similar to that of HELAC-ONIA Web and MADGRAPH5, which could thus be integrated in NLOACCESS. This has not been considered a priority by the IAB and paused by a lack of human resources

As what regards scientific projects using NLOACCESS, here is a summary of our activities:

1. Our 100-page review on the quarkonium-physics case at the High Luminosity (HL) LHC, heavily relying on predictions made with HELAC-ONIA, MADGRAPH5 and FDC, has been published in Progress in Particle and Nuclear Physics.

2. We have written and edited an 80-page review on the physics case for quarkonium related studies at the future US EIC. The review heavily relied on the usage of NLOAccess-related codes (HELAC-ONIA, FDC), and it has been submitted to Progress in Particle and Nuclear Physics.

3. We have used our proposed new method to match fixed-order results from collinear factorisation and resummed higher-order correction and we have applied it to the energy dependence of the total photoproduction cross section of vector quarkonia. A scientific paper have been published.

4. We have computed analytically the NNLO virtual corrections to hadroproduction of pseudoscalar quarkonium production paving the way for quarkonium production studies up to NNLO accuracy. Two scientific papers have been published.

5. We have performed several dedicated studies to quarkonium production at the future US EIC in the realm of transverse momentum dependent distributions (TMDs). The private code used for these works is under consideration for a future possible inclusion in NLOAccess. Similar studies have been performed for the LHC and predictions were used by the LHCb collaboration. Two scientific papers have been published.

6. We have described the structure and the usage of the NLOACCESS platform and published a dedicated scientific paper.

7. We have validated photoproduction in MADGRAPH 5.

8. We have implemented asymmetric collisions in MADGRAPH 5.

As what regards the dissemination and outreach activities, NLOACCESS has been advertised by oral communications at research centres and international workshops, in front of students and researchers.

Here is the list of the **70+ oral communications, tutorials and hands-on given by the NLOACCESS team** on NLOACCESS for the reporting period:

- 2 talks by A. Safronov and D. Kikola at *ICHEP 2022*, Bologna, Italy, 06-13/07/2022 (https://agenda.infn.it/event/28874/)
- Talk by Y. Yedelkina at *EIC User Group Early Career Workshop 2022*, CFNS Stony Brook University (virtual), 24-25/07/2022 (https://indico.jlab.org/event/485/)

- Talk by C. Flore, at *Quarkonium Working Group 2022*, GSI, Darmstadt, Germany, 26-30/09/2022 (https://indico.gsi.de/event/13128/)
- 4 talks by J. Bor, C. Flett and C. Flore (2 x) at *Heavy flavours from small to large systems joint Strong-2020 Meeting 'recent results and perspectives in hadron physics'*, Institute Pascal, Orsay, France, 03-21/10/2022 (https://indico.ijclab.in2p3.fr/event/7656/timetable/?view=standard_numbered_inline_minutes).
- 2 talks by L. Manna and D. Kikola at *QCD@LHC2022*, IJCLab, Orsay, France, 28/11-02/12/2022 (https://indico.cern.ch/event/1150707/)
- 5 talks by A. Colpani Serri, C. Flore, L. Manna, D. Kikola and M. Nefedov at *Quarkonia As Tools 2023*, Aussois, France, 04-14/01/2023 (https://indico.cern.ch/event/1213416/)
- Talk by A. Colpani Serri at *Fixed-target experiments at LHC-Strong2020 workshop*, Aussois, France, 05-07/01/2023 (https://indico.cern.ch/event/1222068/)
- Talk by C. Flett at *QCD challenges from pp to AA collisions*, Padova, Italy, 13-17/02/2023 (https://indico.cern.ch/event/1135616/)
- Talk by C. Flore at *IRN Terascale*, Grenoble, France, 24-26/04/2023 (https://indico.in2p3.fr/event/28562/)
- 5 talks by A. Colpani Serri, C. Flett, L. Manna, D. Kikola and M. Nefedov at *QCD Evolution Workshop 2023*, Orsay, Paris, France, 22-26/05/2023 (https://indico.cern.ch/event/1239374/)
- Talk by J. Bor at *Sardinian Workshop on Spin*, Cagliari, Italy, 05-07/06/2023 (https://agenda.infn.it/event/33895/)
- Talk by M. Nefedov at *QCD23*, University of Montpellier, France, 10-14/07/2023 (https://qcd23.sciencesconf.org/)
- 5 talks by A. Colpani Serri, L. Manna, D. Kikola, M. Nefedov and Y. Yedelkina at *EPS-HEP Conference*, Universität Hamburg, Germany, 20-25/08/2023 (https://indico.desy.de/event/34916/)
- Talk by M. Nefedov at *Low-x 2023*, Leros Island, Greece, 02-08/09/2023 (https://indico.cern.ch/event/1214186/timetable/#all.detailed)
- Talk by C. Flett at *QCD@LHC23*, Durham, U.K., 04-08/09/2023 (https://conference.ippp.dur.ac.uk/event/1128/timetable/?view=standard_numbered)
- Talk by C. Flett at *MadGraph5_aMC@NLO meeting 2023*, 17–20/09/2023, Lake Garda, Italy (https://indico.cern.ch/event/1240244/)
- 3 talks by C. Flett, M. Nefedov and Y. Yedelkina (online) at *Assemblée Générale 2023 du GDR-QCD*, Strasbourg, France, 27-29/09/2023 (https://indico.in2p3.fr/event/30003/)
- Talk by C. Flore at *STRONG-2020 Annual Meeting*, CERN, Geneva, Switzerland, 20-22/11/2023 (https://indico.cern.ch/event/1264833/)
- 4 talks by C. Flett, M. Nefedov , A. Safronov and D. Kikola at *NLOAccess/PrecisOnium Meeting*, CERN, Geneva, Switzerland, 20-24/11/2023 (https://indico.cern.ch/event/1269836/timetable/)
- Talk by J. Bor at *Synergies between the EIC and the LHC*, DESY Hamburg, Germany, 14-15/12/2023 (https://indico.desy.de/event/41404/)
- 5 talks by J. Bor, M. Nefedov, A. Safronov D. Kikola and S. Nabeebaccus at *Quarkonia As Tools 2024*, Aussois, France, 07-13/01/2024 (https://indico.cern.ch/event/1324160/overview)

- Talk by M. Nefedov at *Workshop on overlap between QCD resummations*, Aussois, France, 14-17/01/2024 (https://indico.cern.ch/event/1290502/)
- Talk by J. Bor at *International Workshop on Heavy Quarkonium / Quarkonium Working Group*, IISER Mohali, Chandigarh, India, 26/02-01/03/2024 (https://indico.cern.ch/event/1226860/overview)
- Talk by J. Bor at *SCPP Workshop on Probing the Nucleon structure in Three Dimensions at the Electron-Ion Collider,* IIT Bombay, Mumbai, India, 4/03/2024
- 5 talks by L. Manna, D. Kikola, M. Nefedov and S. Nabeebaccus (2x) at *DIS2024*, Grenoble, France, 08-12/04/2024 (https://lpsc-indico.in2p3.fr/event/3268/)
- 2 talks by C. Flore and S. Nabeebaccus at *QCD Evolution 2024*, Pavia, Italy, 27-31/05/2024 (https://agenda.infn.it/event/38747/)
- Talk by C. Flett at *MC4EIC*, Durham, U.K., 05-07/06/2024 (https://conference.ippp.dur.ac.uk/event/1292/overview)
- 2 talks by L. Manna and D. Kikola at *Present and future perspectives in Hadron Physics workshop,* Laboratori Nazionali di Frascati INFN, Italy, 17-19/06/2024 (https://agenda.infn.it/event/38467/)
- 9 talks by J. Bor, A. Colpani Serri, C. Flore, J.P. Lansberg, K. Lynch, L.Manna, M.Nefedov, A.Safronov and Y.Yedelkina at *Synergies between the LHC and EIC for quarkonium physics LHC*, ECT*, Trento, Italy, 08-13/07/2024 (https://indico.ectstar.eu/event/219/timetable/#20240708)
- Talk by C. Flett at *ICHEP 2024*, 18/07/2024, Prague, Czech Republic (https://indi.to/n9HH6)

Moreover, the platform has been also used for Master classes during lectures delivered by J.P. Lansberg for the PHENIICS Doctoral School of the Paris-Saclay U. in Orsay, in 2023 and 2024, and for tutorials and hands-on sessions during the CERN Summer Student program (July 2022).

NLOACCESS is also ideal for training scholars. Indeed, during the project funding period, one Master student participated the aforementioned research projects while joining IJCLab-Orsay for an internship under the supervision of J.P. Lansberg:

1. Anne Riegler (M1 Göttingen & Paris-Saclay U.) worked on the possibilties to include hard-coded quarkonium processes in another Monte Carlo event generator for high-energy reactions, Sherpa.

Moreover, seven PhD theses are related to NLOACCESS:

1. Jelle Bor (RU Groningen and IJCLab Orsay): QCD Evolution of gluon transverse momentum dependent distribution and phenomenology of quarkonium-pair production at the LHC. This will contribute to the extension of MADGRAPH5 to TMD factorisation at NLO.
2. Kate Lynch (UCD Dublin and IJCLab): feasibility study for inclusive photoproduction of quarkonia in ultra-peripheral collisions at the LHC using HELAC-ONIA and Pythia.
3. Laboni Manna (WUT, Warsaw): inclusion and validation of photoproduction in MADGRAPH5. This addition will be included in the NLOAccess version.
4. Anton Safronov (WUT, Warsaw): inclusion of asymmetric hadron-hadron collision in MADGRAPH5. This addition will be included in the NLOAccess version.

5. Yelyzaveta Yedelkina (IJCLab and UC Dublin): New methodology to compute one-loop corrections to quarkonium photoproduction processes. This will contribute to the extension of MADGRAPH5 to quarkonium production at NLO.
6. Alice Colpani Serri (WUT, Warsaw): Extension of MADGRAPH5 to quarkonium production at LO and to TMD factorisation.
7. Allen Cris John Rubesh Rajan (UCD Dublin and IJCLab): Extension of MADGRAPH5 to massive initial states and to CEM with a specific MC integrator.

Our activities during this funding period resulted in valuable scientific outputs. Eight articles have been published or submitted to international peer-reviewed journals. Additional articles are at the drafting stages. We guide the reader to Section 3.3 for more details.

3.2 Access to the facility during the reporting period supported by the project

As of July 31, 2024, there are 662 registered users to NLOACCESS, coming from different institutions/research centres of five regions:

- Europe: 52.27%
- Asia: 22.21%
- Africa: 1.51%
- North America: 21.14%
- South America: 2.72%
- Oceania: 0.15%

As of July 25, 2024, the users have performed 5042 runs, despite the reduced activity since the outbreak of the COVID-19 pandemic.

The scientific output based on NLOACCESS is listed in section 3.3 as what regards written publications. Oral communications are listed in section 3.1.

3.3 Scientific output of the users at the facility

We only list here the scientific written outputs during the reporting period of the users which are public (excluding internship and internal reports; the oral communications are listed as actions above.).

Published articles:

1. TMD evolution study of the cos 2ϕ azimuthal asymmetry in unpolarized J/ψ production at EIC. By J. Bor and D. Boer [arXiv:2204.01527]. 29/07/2022, *Phys.Rev.D **106** (2022) 1, 014030*, [10.1103/PhysRevD.106.014030].
2. Two-loop master integrals for pseudo-scalar quarkonium and leptonium production and decay. By S. Abreu, M. Becchetti, C. Duhr and M.A. Ozcelik [arXiv:2206.03848]. 22/09/2022, *JHEP **09** (2022), 194*, [10.1007/JHEP09(2022)194].
3. Revisiting NLO QCD corrections to total inclusive J/ψ and Υ photoproduction cross sections in lepton-proton collisions. By A. Colpani Serri, Y. Feng, C. Flore, J-P. Lansberg, M.A. Ozcelik, H.-S. Shao and Y. Yedelkina [arXiv:2112.05060]. 10/12/2022, *Phys.Lett.B **835** (2022), 137556*, [10.1016/j.physletb.2022.137556].

4. Two-loop form factors for pseudo-scalar quarkonium production and decay. By S. Abreu, M. Becchetti, C. Duhr and M.A. Ozcelik [arXiv:2211.08838]. 27/02/2023, *JHEP* ***02*** *(2023), 250*, [10.1007/JHEP02(2023)250].

5. NLOAccess: automated online computations for collider physics. By C. Flore [arXiv:2301.09167]. 16/04/2023, *Eur.Phys.J.A* ***59*** *(2023) 3, 46*, [10.1140/epja/s10050-023-00972-2].

6. Transverse momentum dependent shape function for J/ψ production in SIDIS. By D. Boer, J. Bor, L. Maxia, C. Pisano and F. Yuan [arXiv:2304.09473]. 18/08/2023, *JHEP* ***08*** *(2023), 105*, [10.1007/JHEP08(2023)105].

7. Curing the high-energy perturbative instability of vector-quarkonium-photoproduction cross sections at order $\alpha \alpha_s^3$ with high-energy factorisation. By J.-P. Lansberg, M. Nefedov and M.A. Ozcelik [arXiv:2306.02425]. 03/04/2024, *Eur.Phys.J.C* ***84*** *(2024) 4, 351*, [10.1140/epjc/s10052-024-12588-x].

Non-published articles:

1. Breakdown of collinear factorization in the exclusive photoproduction of a pi0-gamma pair with large invariant mass. By S. Nabeebaccus, J. Schoenleber, L. Szymanowski, and S. Wallon [arXiv:2311.09146].

Peer-review proceedings:

1. NLO inclusive J/ψ photoproduction at large PT at HERA and the EIC. By C. Flore, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina [arXiv:2107.13434]. 11/07/2022, *SciPost Phys.Proc. 8 (2022), 011*, [10.21468/SciPostPhysProc.8.011].

2. Reweighting the quark Sivers function with STAR jet data. By C. Flore, M.E. Boglione, U. D'Alesio, J.O. Gonzalez-Hernandez, F. Murgia, A. Prokudin [arXiv:2107.13311]. 11/07/2022, *SciPost Phys.Proc. 8 (2022), 03*4, [10.21468/SciPostPhysProc.8.034]

Normal proceedings:

1. A tool for automated perturbative cross section computations of asymmetric hadronic collisions at next-to-leading order using the MadGraph5_aMC@NLO framework. By A. Safronov, C. Flore, D. Kikola, A. Kusina, J-P. Lansberg, O. Mattelaer and H.-S. Shao. 28/11/2022, *PoS ICHEP2022 (2022), 494*, [10.22323/1.414.0494].

2. J/ψ-pair production at NLL in TMD factorisation at the LHC. By A. Colpani Serri, J. Bor, D. Boer and J-P. Lansberg [arXiv:2403.00640]. 21/03/2024, *PoS EPS-HEP2023 (2024), 272*, [10.22323/1.449.0272].

3. Asymmetric collisions in MadGraph5_aMC@NLO. By L. Manna, A. Safronov, C. Flore, D. Kikola, J.-P. Lansberg and O. Mattelaer [arXiv:2401.14741]. 21/03/2024, *PoS EPS-HEP2023 (2024), 274*, [10.22323/1.449.0274].

4. Revisiting inclusive production of J/ψ and ϒ in high-energy γγ collisions. By Y. Yedelkina, J.-P. Lansberg and M. Nefedov [arXiv:2312.04389]. 21/03/2024, *PoS EPS-HEP2023 (2024), 271*, [10.22323/1.449.0271].

1.4.9 Work Package 11

Activity Type	Virtual Access
Work package title	Virtual Access to 3DPartons (VA2-3DPartons)
Lead beneficiary	24 - CEA

1. Description of access facilities

The 3DParton main website (http://partons.cea.fr), also referenced to on the STRONG-2020 webpage devoted to this work package (http://www.strong-2020.eu/virtual-access/va2-3dpartons.html), has undergone maintenance and it has been recently updated to advertise the release of version 4 of PARTONS and its dependencies. PARTONS v4, amongst other improvements, provides a wider set of physical observables and models for generalized parton distributions (GPDs). Alongside, a virtual machine Docker image with PARTONS v4 has been released. This virtual machine allows users to run PARTONS out of the box on any machine without the burden of having to compile and install locally the software.

The PARTONS website, not only provides information about this specific code that is mostly devoted to GPDs, but also makes reference to other software of the 3DPartons family, such as APFEL, xFitter, NangaParbat, MontBlanc, TMDlib. These codes are devoted to the study of collinear parton distribution functions (PDFs) and fragmentation functions (FFs) as well as of transverse-momentum-dependent distributions (TMDs) and generalized TMDs (GTMDs).

A link to the webpage of the new multipurpose Monte Carlo generator software EpIC for exclusive process based on PARTONS (https://github.com/pawelsznajder/epic) has been added to the PARTONS webpage.
In view of the constantly growing popularity of the Python, a user friendly language that comes with a very large number of tools for, *e.g.*, statistical analysis and plotting, a wrapper of PARTONS in this language has finally been released. This wrapper allows the user to access most of the main functionalities of PARTONS through a Python interface, giving one the possibility to make it interoperable with other tools such as NumPy, Pandas, and Matplotlib.

Finally, a workshop on the virtual access 3DPartons and related physics projects has been held in October 2022 in the Paris area. The corresponding Indico page can be consulted from here: https://indico.cern.ch/event/1175276/overview.

2. International Assessment Board

2.1 Organization of International Assessment Board

This board consist of eight experts in relevant fields. It is composed of two theoretical physicists and two experimental physicists covering GPD and TMD domains, one physicist experienced in PDF fits and computing codes, and one expert experienced in Monte Carlo event generators. This panel of physicists is completed by two researchers specialized in software development and statistical data analysis.

2.2 International Assessment Board Members

In alphabetical order, the members of the International Assessment Board (IAB) are:

- BOBIN, Jérôme (IRFU, CEA, Université Paris-Saclay)
- BRESSAN, Andrea (INFN, Trieste)
- CHAPON, Damien (IRFU, CEA, Université Paris-Saclay)
- DIEHL, Markus (DESY)
- GLAZOV, Alexander (DESY)
- HAUTMANN, Francesco (Rutherford Appleton Laboratory, University of Oxford and Elementaire Deeltjes Fysica, Universiteit Antwerpen)

- PASQUINI, Barbara (INFN, Università Di Pavia)
- SOKHAN, Daria (IRFU, CEA, Université Paris-Saclay and University of Glasgow)

2.3 International Assessment Board Meetings

One IAB meeting took place in the reference period, specifically on February the 2nd 2023. The spokesperson of VA2 gave a detailed overview of the work package presenting the latest achievements both in terms of physical results and code developments. The experts provided feedback in the form of comments and suggestions that were recorded in a set of minutes. The meeting was also video recoded for future reference.

3. Virtual Access activity during the reporting period

3.1 Detailed description of the activity

In the GPD domain, PARTONS v4 was released on July 2024. It contains new observables and new GPD models. The Monte Carlo general purpose event generator for exclusive processes EpIC was developed in order to be fully compatible with PARTONS: each exclusive channel provided by PARTONS can potentially be used for event generation in EpIC, along with the selection of various computing assumptions (GPD models, higher-order corrections, etc.). EpIC has been publicly released and is available from: https://github.com/pawelsznajder/epic.

In the collinear distribution domain, the Denali code was publicly released (https://github.com/MapCollaboration/Denali). This code is devoted to the extraction of longitudinally polarized PDFs and has been used for a determination of these quantities that was made available through the LHAPDF interface.

The TMD fitting framework NangaParbat was updated to include the possibility of determining the flavor dependence of TMDs. This resulted in a publication and the resulting TMDs are released in the TMDlib2 format.

The family of codes belonging to the 3DPartons family proved its capacity to interoperate in a recent study of GTMDs. Indeed, these objects are generalizations of both GPDs and TMDs, which are in turn generalizations of PDFs. In this context, a first model-independent determination of GTMDs including radiative corrections has been achieved using a compound of codes that includes PARTONS, NangaParbat, APFEL++, and LHAPDF.

As mentioned above, an in-person workshop devoted to 3DPartons has been held in the Paris area in October 2022 (https://indico.cern.ch/event/1175276/overview). This workshop gathered many experts from different fields of QCD and hadronic structure with the purpose of advancing our understanding of the 3D structure of hadrons. The participants shared their knowledge and know-how about scientific and technical problems related to GPDs and TMDs. The 3DPartons framework was central in many discussions but many other implications were also discussed.

Google Analytics has been replaced by the GDPR[2]-compliant alternative Piwik PRO, a web analytics service with a consent manager, a tag manager and analytics. The tool is one of the analysis platforms approved by the French National Commission on Informatics and Liberty (CNIL). It offers a free version, with limited features, suited for sites with relatively low traffic,

[2] General data protection regulation https://gdpr-info.eu.

which should be suitable for a website hosting specialized 3D hadron structure computing software. Piwik Pro has a shared history with Matomo (formerly Piwik) which is the basis of Europa Analytics, the corporate service monitoring the European Commission's websites.

3.2 Access to the facility during the reporting period supported by the project

The transition to Piwik Analytics became effective starting from July 1st 2023. Data prior to this date collected through Google Analytics is thus no longer accessible. This caused a gap of 13 months between the 1st of June 2022, end date of the last report, and 31st of June 2023. To fill this gap, the estimates provided below are obtained through a linear extrapolation based on the period 07/2023-07/2024 (13 months) to the full period 06/2022-07/2024 (26 months). The reliability of these estimates is supported by their similarity with previous estimates given in past reports.

Between June 1st 2022 and July 31st 2023, there have been more than 4000 views of the PARTONS website. These views correspond to around 1400 users worldwide. With a bounce rate of about 64%, the website still engages visitors to go deeper into its structure. It received around 10% returning visitors and 90% new visitors. Interestingly, around 1100 users out of 1400 accessed the website directly without passing through a search engine. This indicates that most of the visitors are assiduous users.

Similarly to what was observed during the first and second periods, visitors connected mostly from: the United States (320), France (240), Russia (210), Poland (85), and China (60). The general interpretation of these numbers is presumably as follows: many of the current and forthcoming experimental facilities conducting GPD programs are located in the United States (*e.g.* the Jefferson Laboratory and the Electron-Ion Collider (EIC)). Moreover, there are many developers and users of PARTONS in France and Poland, which explains the large number of visits from these countries. The future electron-ion collider in China (EIcC) explains why there have been a considerable number of visits from this country. More surprising are instead the large number of accesses from Russia. It is conjectured that NICA (Nuclotron-based Ion Collider fAcility), an accelerator complex designed at the Joint Institute for Nuclear Research (Dubna) to study properties of dense baryonic matter, has catalyzed the number of visits from Russia.

3.3 Scientific output of the users at the facility

A large number of physics and technical results have been achieved during the reference period using the tools provided by the VA2 work package, many of which are still on going. Amongst the main results already published or under review in peer-revied journals, we mention:

- An extraction of unpolarized TMD PDFs of the pion from a fit to experimental data accurate to N^3LL.[3]
- A determination of the GTMDs of the proton exploiting our current knowledge of GPDs and TMDs and including one-loop radiative corrections.[4]
- A phenomenological study of the implication of the perturbative calculation the PDFs of the electron at current and future e^+e^- high-energy colliders.[5]

[3] MAP Collaboration, Phys.Rev.D 107 (2023) 1, 014014.
[4] V. Bertone, Eur.Phys.J.C 82 (2022) 10, 941.
[5] V. Bertone *et al.*, JHEP 10 (2022) 089.

- An extraction of unpolarized TMD PDFs of the proton and of the TMD FFs of pion and kaon from a global fit to experimental data at N^3LL accuracy.[6]
- A method to established a connection between GPDs and PDFs and gauge its accuracy.[7]
- A re-computation and implementation of the one-loop evolution kernels for all of the twist-2 quark and gluon GPDs.[8]
- An extraction of helicity-dependent PDFs at NNLO accuracy from inclusive and semi-inclusive deep-inelastic scattering data.[9]
- A benchmark of deep-inelastic-scattering structure functions at N^3LO accuracy.[10]
- A determination of the flavor dependence of unpolarized quark TMDs PDFs and FFs from a global fit.[11]
- A study of perturbative renormalization-group-equation systematics in precision observables at high-energy colliders.[12]
- A combination of lattice QCD and phenomenological inputs to constrain GPDs at moderate skewness.[13]
- A study of the implications of Lorentz symmetry and partial DGLAP knowledge on our knowledge of GPDs.[14]
- An extraction of the distribution amplitude of the η_c-meson at leading twist from lattice QCD.[15]
- A study of exclusive vector-quarkonium photoproduction at NLO in α_s in collinear factorization including evolution effects of the GPDs and high-energy resummation.[16]
- A systematic description of hadron's response to nonlocal QCD probes by means of Froissart-Gribov projections in an analysis of deeply virtual Compton scattering.[17]
- A phenomenology study of double deeply virtual Compton scattering in the era of new experiments.[18]
- A paper describing the EpIC Monte Carlo generator for exclusive processes.[19]
- A phenomenological study of diphoton photoproduction at NLO accuracy.[20]
- A study of the evolution of PDFs in the short-distance factorization scheme.[21]

Almost all of these publications have been presented at international conferences, workshops, or schools. However, we do not attempt to list all oral contributions here.

While collecting the physics output of VA2 users, we observed that some of them merely cite the original paper describing the PARTONS framework,[22] and do not include in the acknowledgments the sentence: *"The virtual access infrastructure 3DPartons has received*

[6] MAP Collaboration, JHEP 10 (2022) 127.
[7] H. Dutrieux *et al.*, Phys.Rev.D 107.
[8] V. Bertone *et al.*, Phys.Rev.D 109 (2024) 3, 034023.
[9] MAP Collaboration, e-Print: 2404.04712.
[10] V. Bertone, A. Karlberg, Eur.Phys.J.C 84 (2024) 8, 774.
[11] MAP Collaboration, JHEP 08 (2024) 232.
[12] V. Bertone, G. Bozzi, F. Hautmann, e-Print: 2407.20842.
[13] M. Reberdy *et al.*, Eur.Phys.J.C 84 (2024) 2, 201.
[14] P. Dall'Olio *et al.*, Phys.Rev.D 109 (2024) 9, 096013.
[15] B. Blossier *et al.*, JHEP 09 (2024) 079.
[16] C. Flett *et al.*, e-Print: 2409.05738.
[17] K. M. Semenov-Tian-Shansky *et al.*, Phys.Rev.D 109 (2024) 5, 054010.
[18] K. Deja *et al.*, Phys.Rev.D 107 (2023) 9, 094035, Phys.Rev.D 107 (2023) 9.
[19] E.C. Aschenauer *et al.*, Eur.Phys.J.C 82 (2022) 9, 819.
[20] O, Grocholski *et al.*, Phys.Rev.D 105 (2022) 9, 094025.
[21] H. Dutrieux *et al.*, JHEP 04 (2024) 061..
[22] B. Berthou *et al.*, Eur. Phys. J. **C78** (2018) 478.

funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093." To contrast this phenomenon, an explicit statement in the section "License and reference" of the main page of the PARTONS website (http://partons.cea.fr) has been added. In this respect, it is worth stressing that the work carried out within VA2 is likely to have a farther-reaching impact on the hadron structure community than that conveyed by the list of papers given above.

1.5 Resources used to provide access to Research Infrastructures

The two infrastructures that used human resources during the second Reporting Period with the financial support of the project are Virtual Accesses. Taking into account high demand for the Virtual infrastructures and the necessity to maintain user-friendly access, the two VAs have hired full-time employees. These employees continued their activity during the full duration of the second Reporting Period. The actually used person months (p/m) contributions exceed the estimations given in the GA and the necessary adjustments were introduced with the third Amendment.

The number of p/m used and the nature of tasks performed are given in the tables below:

Automated perturbative NLO calculations for heavy ions and quarkonia (VA1-NLOAccess)

1. Resources used to provide access

Beneficiary/Linked Third Party short name	**Installation(s)**	**P/m**	**Explanations of tasks**
CNRS	NLOAccess-IJCLab	12	-Maintenance of databases for the user registration, the jobs managing and the corresponding statistics. - Update of the user guide for HELAC-ONIA - Cure issue of negative NLO cross-section for quarkonium production - Study of gluon PDF behaviours at low x and low scales - eta(Q) production up to NNLO accuracy - Scientific support to users
UCLouvain	NLOAccess-CP3	3	- Progress towards access to a NLO codes of nuclear PDF effects in perturbative QCD in proton-nucleus collision. - Modification of MADGRAPH5 to include asymmetric hadron-hadron and lepton-hadron collisions - Scientific support to users

2. Researchers who have access to research e-infrastructures through Union support

e-infrastructure name	e-infrastructure service	Activity Domain (Discipline)	Maximum possible number of users	Nr of actual users by max possible number in P2 (%)
NLOAccess	Common services: data generation (cross-section computation) & storage of the generated data; Thematic services: access to self-generated codes based on the user request.	Physics	300-450	>100 %

Virtual Access to 3DPartons (VA2-3DPartons)

1. Resources used to provide access

Beneficiary/Linked Third Party short name	Installation(s)	P/m	Explanations of tasks
CEA	VA 3DPartons	18	Aggregation and improvement of existing codes from the GPD and PDF/FF, TMD, and GTMD communities. Integration, maintenance, release, testing, documentation and technical assistance to users.

2. Researchers who have access to research e-infrastructures through Union support

e-infrastructure name	e-infrastructure service	Activity Domain (Discipline)	Maximum possible number of users	Nr of actual users by max possible number in P2 (%)
3DPartons	Collaborative services enabling the sharing of open-source software, applications, and other research objects	Physics	300	470% (709 users in the period 07/2023- 7/2024 extrapolated to ~1400 users in the period 6/2022-07/2024)

Since the 1st July 2023, following a directive from the STRONG-2020 Governing Board, the tracking platform has been changed from Google Analytics to Piwik Analytics (see above). Unfortunately, data prior to this change has been lost. Therefore, there is a gap between June 2022 and June 2023 for which we have no data. In the table above, we provide a linear extrapolation based on the period 07/2023-07/2024 to the entire reference period 06/2022-07/2024.
The counting criteria of Piwik Analytics are such that a user is counted once no matter the number of actual visits of the website.

2. Update of the plan for exploitation and dissemination of results (if applicable)

There were no modifications in the plan for exploitation and dissemination of results since the first Periodic Report. The Management (MAN) and the coordinator of DISCO continue to ensure the diffusion and exploitation of results produced by the project Consortium. The principles of exploitation and dissemination of produced results, as well as the overall communication plan, were detailed in the Consortium Agreement (CA) and did not need to be updated.

3. Update of the data management plan (if applicable)

The Data Management Plan was submitted in the Portal in September 2020 (Version 1). The considerations presented are still relevant and did not require further updating at this stage of the project.

4. Follow-up of recommendations and comments from previous review(s) (if applicable)

Given the fact that the present version is thye first submission of the final report, no recommendations and comments from the Eu Commission were addressed.

5. Deviations from Annex 1 and Annex 2 (if applicable)

The third reporting period was very productive thanks to two extensions of the project. Indeed, for many of the WPs, it was possible to catch up on numerous delays caused on the one hand by the COVID-19 crisis and on the other hand by the war provoked by Russia against Ukraine.

The deviations that were however observed at the level of the WPs' work plans implementation and at the level of their human and financial resource use are described below. Some explanation of the deviations, especially the ones related to the use of financial resources, can be found in the individual Financial Statements of beneficiaries submitted directly in the Portal (in the section 5.2 Use of resources).

5.1 Tasks

5.1.1 Work Package 1 (MAN)

During the last reporting period, there were some minor deviations in the scheduled timetable for the submission of deliverables and validation of milestones.

The first deviation concerns the organization of the second Workshop in June 2024. Indeed, the date was moved to the end of the project (that caused one month of delay for the MS3) to be able to organize two important events, that are the last Workshop and the last Annual Meeting, during the same week. This decision was taken to obtain the most recent results and to discuss the future perspectives. Therefore, it was agreed to organize this Workshop in June, just before the Annual Meeting.

Another deviation, this time the date of submission of the D1.3, is due to the nature of the deliverable itself. Indeed, the objective of D1.3: "Strategic road map" was to give a general overview for future RI developments based on the results of the project. In order to produce a complete and faithful document, it was necessary to have the inputs, in the form of reports, from all the infrastructures. Therefore, MAN decided to wait for the contributions to the final report from the TAs and VAs to complete and integrate the information received during the project (for the first two periodic reports) and the recent information concerning the achievement of the objectives set in the GA. The above-mentioned factors have therefore shifted the submission of the deliverable D1.3 to the month 64.

The last deviation concerns the validation date for the MS6: Preparation of periodical reports. On one hand, in the GA, the Consortium has 60 days to prepare the final report. This delayed the submission of the validation of the related milestone by two months. Then, since this is the last report and no financial adjustments will be possible afterwards, it was essential to present all the complete financial statements, and take into account the adjustments to be made for the first two periodic reports. Finally, the production of the CFS (Certificate on the Financial Statements), mandatory for partners receiving a contribution equal to or greater than 325 000 euros, requires an external audit and study of all expenses incurred since the start of the project. This process in turn required an additional month to allow the partners to complete all the mandatory operations for the production of the CFS. The PO was informed of this delay and the justifications were provided. The one-month postponement of the submission of the final report was approved.

These deviations had no impact on the implementation of other tasks of MAN nor on the implementation of the work programs of other partners.

No significant deviations from the Annex 2 (Estimated budget for action) was reported in the third reporting period. All the budget changes and transfers between cost categories/project partners involving the MAN budget and occurred during the RP3 were introduced with the amendments and therefore are no longer considered as deviations.

5.1.2 Work Package 2 (DISCO)

The Workshop on the topic "Present and future perspectives in Hadron Physics", which was proposed to be held in the third year of the project, needed to be rescheduled for June 2024 due to the COVID-19 pandemic emergency and the international crisis linked to the war in Ukraine. Consequently, the related proceedings were shifted by a similar amount of time.

5.1.3 Work Package 14 (NA3-Jet-QGP)

As mentioned above, due to the COVID-19 pandemic, some of the planned workshops were changed to online meetings. The related part of the budget has been reallocated to WP32 (JRA14-MPGD_HP), as specified in the amendment request (AMD-824093-77).

5.1.4 Work Package 15 (NA4-PREN)

The WP members took advantage of the COVID-19 acute period (2020) to write a report entitled "The proton size" (Jean-Philippe Karr, Dominique Marchand, Eric Voutier. Nature Rev.Phys., 2020, 2 (11), pp.601-614. DOI:10.1038/s42254-020-0229-x, hal-03011020, acting as the PREN White paper deliverable (D15.2)).

The COVID-19 period implied to shift the organization of the planned meetings in person (vital for the WP network gathering 2 physics communities). The two PREN conventions have been held in 2022 and 2023.

5.1.5 Work Package 16 (NA5-THEIA)

This WP has introduced a new deliverable 16.4 not initially foreseen in the GA. Due to the delays of planned experiments caused by the full or at least partial shut downs of experimental facilities like MAMI, we started to setup a hypernuclear database at MAMI. This project was added as a new and additional task: deliverable D16.4 in this WP. It was included in the GA with the third Amendment. The database will provide a complete collection of published hypernuclear results. This interactive database allows the community to quickly evaluate the impact of new data and will thus help in the planning of new experiments. Furthermore, it will provide standardized numbers and plots to the community, which will lay out the basis for all theoretical discussions. An international group of specialists representing the various experimental methods will assist in gathering and coherently treating all existing and future strangeness nuclear data.

The database is hosted by the Mainz University in the meantime on-line, and is available for the scientific community at https://hypernuclei.kph.uni-mainz.de/. It will continuously be updated when new data are published. Also, the necessary structure to add additional information, like e.g. weak decay branching ratios and doubly strange hypernuclei into the system, is being prepared right now.

5.1.6 Work Package 17 (NA6-LatticeHadrons)

The COVID-19 pandemic led to a significant deviation that was hard to overcome. As travel was restarted for a long period, the WP members have endeavoured to rebuild collaboration links that had moved the meeting to the fully online format or some meetings have been cancelled. To make the training of the next generation of lattice experts more effective, online training material has been planned and developed instead.

Deliverable D17.5 "White paper on the near-future challenges in lattice hadron physics and the links to other aspects of phenomenology and large-scale numerical computing" had to be cancelled. The travel and secondments that were to take place over the course of the project were disrupted by the COVID-19 pandemic and could not be restarted. In the end, this was to be the main driver for input into the white paper and so it will not be a valuable document if the WP members proceed. The WP members pivoted to focus on setting up LaVA, an online virtual training platform from the experiences during the lock-down, and this is progressing as a positive output from NA6 that replaced the in-person interactions. This has mitigated the impact of the cancellation on the overall Work Program. The white paper was to be written by senior staff in the network, so no resources were costed to the budget.

5.1.7 Work Package 18 (NA7-Hf-QGP)

Deviations have been registered for two tasks:

- The task 2 (Hidden heavy flavor), which has accumulated a delay of about 9 months mostly due to pandemic crisis. It has not consequence on the other activities. It should be recovered thanks to the extension (6 months) of the duration of the project.
- The deliverable D18.3 “Paper with recommendation for the dedicated heavy-ion periods of LHC after the 2nd Long Shutdown for the different LHC experiments”. At the time of the proposal, the idea was to focus on the LHC run3 and run4. The project has started a bit later than expected at the time of the proposal, and the LHC schedule accumulated one year delay. In the meanwhile, a document was prepared, CERN-LPCC-2018-07 arXiv 1812.06772 “Report from Working Group 5: Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams”, to which most of the participants of the networking participated, but that was not an action driven by the networking. Therefore, it has been decided that the deliverable D18.3 will have a focus mostly on the LHC run5, and the expected new date for this deliverable was moved to month 48.

5.1.8 Work Package 19 (JRA1-LHCCombine)

No significant deviations from the planned objectives and tasks were observed. However, two facts slowed down the progress of this JRA as initially planned: a) the late and conjectural hiring of the post-doctoral researchers working on the project, b) the difficulty to have such large collaborations more involved into common endeavors and global objectives in parallel of aggressive deadlines already dictated by the LHC schedule.

5.1.9 Work Package 21 (JRA3-PrecisionSM)

The MS39 “Monte Carlo generator for pion production in neutrino scattering experiments” within this WP could not be achieved:

During COVID-19, the MAID collaboration consisting mostly of senior researchers effectively dissolved due to unanticipated early retirements. This affected the amount of manpower, which could be dedicated to the work on MC generator for pion production in neutrino experiments. The only active member of MAID collaboration, Mikhail Gorchtein, was unable to travel to Fermilab since the beginning of the Russia-Ukraine war (Mikhail Gorchtein (MG) is a Russian citizen). Extended visits of MG to Fermilab were necessary to kickstart the work on that task, and according to the plan of the project, the JGU-FNAL agreement for mutual visits was favoring these. Since within the framework and timeline of STRONG-2020 neither the composition of the MAID collaboration nor the international situation could be changed, MS39 had to be dropped for now. The work on the MC event generator will be continued in the future.

Nonetheless, the rest of the project objectives was met, and in many aspects, the obtained results exceeded the original plans. The muon g-2 experiment confirmed the previous measurements and improved their precision, while an ongoing progress in reducing the hadronic uncertainties has resulted in one White Paper published in 2020 and the next one is planned in late 2024. Unanticipated fundings from lattice QCD and from the CMD3 experiment sparked a renewed interest of the community, and JRA3 has been pivotal in coordinating this global effort. A complete re-evaluation of the radiative corrections to beta decays of free and bound nucleons and kaons led to improved theoretical uncertainties and resulted in an apparent deficit of CKM unitarity in the first row. Here, new formalisms have been developed, and new connections between various experimental programs established, e.g. to muonic X-ray program at PSI and PVES and neutron skin program at the future MESA facility.

5.1.10 Work Package 22 (JRA4-TMD-neXt)

Overall, the WP has progressed according to plans. The only significant deviation was the failure to complete the task 3 (analysis of e+e− multiplicities). This deviation has not prevented the WP from completing all other tasks on time, thanks to the wealth of data. However, for the future, more precise determination of TMD fragmentation functions (and, indirectly, also TMD distribution functions) data on e+e− multiplicities will be very useful.

5.1.11 Work Package 23 (JRA5-GPD-ACT)

The only deviation from the planned objectives and tasks is that one deliverable (D23.2) was only partially completed. There is some impact on the progress of the WP but nevertheless, the positive aspects are:

1) many measurements that should have been published as a part of this deliverable have already been presented at conferences, so the scientific community can already assess the impact on the GPD physics,
2) most of the other objectives of the WP were not directly dependent on this particular deliverable and their implementation was not affected.

Also, the lack of these publications were compensated by other unforeseen results achieved within this WP, ensuring that overall progress remained in line with the original expectations.

5.1.12 Work Package 24 (JRA6-next-DIS)

As explained in the two previous periodic reports, the objective of task 4, i.e. the development and characterization of a prototype depleted MAPS sensor for the ePIC SVT, was carried out in a different way than originally planned.

Updated EIC machine parameters and evolving physics requirements resulted in more stringent requirements for the EIC vertex and tracking detector that could be met with a MAPS sensor in the originally proposed 180 nm CMOS imaging technology. The EIC project and ePIC SVT collaboration decided to move to a smaller feature size process (65 nm) available at the same foundry, exploiting similar project requirements and timescale with the ALICE ITS3 collaboration.

Delays due to the pandemic and the semiconductor industry crisis meant that the milestone (MS51) and the deliverable (D24.4) associated to task 4 were delayed but have both been successfully achieved during the project period.

The development of a prototype sensor for the ePIC SVT in 65 nm technology was merged with the ITS3 development and proceeded through two prototype submissions to validate the process and learn about stitching methodology for wafer scale sensor design. The University of Birmingham joined the larger ITS3 and ePIC characterization effort of the MLR1 and ER1 prototypes. The results of this effort led to the ongoing design of the full wafer scale, depleted MAPS sensor for the ITS3 and ePIC SVT projects.

5.1.13 Work Package 29 (JRA11-CRYOJET)

Delays due to COVID-19 and a redeployment of the pellet tracking system, especially since further studies at the Uppsala Pellet Test station, are no longer possible. The WP members have continuously adapted the work plan to the given possibilities to achieve the project objectives despite these difficulties. The planned studies on hydrogen fibers, which were part of the task 4, will not be possible at Uppsala University. However, first exciting results with other shapes of solid target beams were achieved at the University of Münster. All other tasks in the WP could catch up with the delays.

5.1.14 Work Package 31 (JRA13-P3E)

While the scientific objectives of the P3E activity are unchanged, the COVID-19 pandemic impacted their acomplishment by delaying access to experimental facilities as well as personnel hiring. These deviations in time with respect to the original schedule will be compensated by the 6 month extension of the STRONG-2020 program.

5.1.15 Work Package 32 (JRA14-MPGD_HP)

The Deliverable 32.3 (Fast Cherenkov Micromegas Detector) was finished 6 months later than the originally foreseen date (delivered in month 48 instead of 42). The reason for the delay was a combination of many factors, in particular lack of manpower who were also busy with other projects, delay induced by the pandemic, and several problems on the design, which took time to be solved. The extension of the STRONG-2020 project allowed to finalize this deliverable within the project duration.

5.2 Use of resources

5.2.1 Work Package 1 (MAN)

The changes in the p/m contribution of MAN have been explained and justified in the last amendment. The increase in the p/m contribution was accepted by the Commission. No further deviations have taken place since the approval of these explained above and introduced in the amendment.

5.2.2 Work Package 2 (DISCO)

The engagement of the personnel for the partner INFN has exceeded the expected p/m contribution given in the GA. Indeed, the activity of DISCO is transversal to all other activities of the project and was logically continued during the extended period of the project. As a consequence, more p/m contribution was necessary to maintain the activities on dissemination and communication as well as the continued updates of the project web site.

5.2.3 Work Package 11 (VA2-3DPartons)

The partner 24-CEA had a higher average p/m cost for the WP11 as compared to the estimation given in the GA. The average monthly Personnel costs are always based on CEA's usual accounting practices. The average p/m cost for Postdocs at the time of the GA preparation was about 4 to 4,5k euro. However, this cost can be higher depending on the diploma and the experience of the Postdoc. In RP2, the Postdoc fully involved in WP11 has an average salary of about 5 to 5,5k euro, which explains the 30% deviation between the planned and reported average p/m cost.

By the way, there was an overspent amount of Direct Personnel costs declared as unit costs. CEA has chosen to declare its permanent staff contribution in Unit costs as it is showing the real staff effort made on the project. Indeed, the CEA researchers ended up spending more time on the STRONG-2020 project than initially planned. However, CEA is perfectly aware that it cannot receive more than the Maximum Grant Amount indicated in the GA and if there is an overspending on the overall budget at the end of the project, CEA will take it on its own resources.

The partner CEA has declared a higher p/m effort than initially foressen in the GA. Regarding the Personnel costs in the period 3, CEA only plans to declare the costs of the staff effort in WP11 (VA2-3DPartons). The possible overspending will be covered by CEA own resources. Indeed, CEA/IRFU is willing to put extra effort on the interesting work performed in STRONG-2020 and will provide in-kind contribution, if necessary.

Furthermore, an underspending is planned on the equipment cost category in WP11 and it is the partner's wish to devote the remaining money to financing a fraction of personal costs. The text below provider the explanation of this underspending:

The Other direct costs anticipated for the Virtual Access were initially planned for yearly workshops organization, to invite experts and users, as well as to animate an international community around the deliverables. The COVID-19 pandemic prevented the partner from organizing these meetings in person and the latter had to opt for an online participation, thereby reducing the spending in this category.

5.2.4 Work Package 12 (NA1-FAIRnet)

The partner 11-RUB had a higher average p/m cost as compared to the cost stated in the GA. The change of the average p/m cost occurred due to the following reasons: first, several years passed between the application for the project and now. During that time, the standard salary increased. Second, the salary of the employed person, Dr. Tobias Holtmann, is paid according to German laws and the rules for the universities in North Rhine Westphalia. According to his experience and age, he is in the level of TV-L E13, step 4. During the application, the person to be hired was not known and thus, an exact amount could not be calculated for the average p/m cost. Consequently, the partner overspent the total budget for Personnel costs foreseen in the GA. For this reason, RUB kindly requests to transfer the amount overspent (8 749 euro) from Other direct costs of RUB in WP12 to Personnel costs in the same WP. Indeed, because of severe travel restrictions linked to COVID-19, the partner could not use its Travel funds as it was expected, and would like to use these funds to cover its Personnel costs.

For the partner 6-FAIR, the average p/m cost declared in the Financial Statement is also higher than the one indicated in the GA. The fulfilment of the project deliverables and tasks has the highest priority. The participating institutions have to staff the work accordingly. Consequently, the personnel effort significantly deviates from the planned p/m cost in the proposal. Thus, the partner FAIR engaged the necessary personnel in the framework of the budget and even beyond.

Indeed, the partner is convinced that the fulfilment of the project deliverables and tasks has the highest priority. This is the reason why the personnel effort claimed in the RP2 for FAIR GmbH in NA1 (WP12) is significantly higher (twice as high) than the available budget in the Grant Agreement. The partner engaged the necessary personnel for performing the work, as defined and reported for this WP in the STRONG-2020 project (one senior scientist) that caused a higher p/m cost than initially foreseen. The partner is aware that any personnel costs that cannot be covered by EU funds at the end of the project will be carried by FAIR GmbH.

As a consequence of a higher p/m cost, FAIR has consumed 220% of the total planned budget for Personnel costs. Since more engagement than foreseen was necessary for this partner, FAIR has already consumed 132.70% of total planned effort (RP1 & RP2). The personnel effort at FAIR GmbH is significantly higher than planned because the preparation of the CBM event reconstruction software chain, with the implemented new CAD and GEANT geometries, and the upgrade of the components of the mCBM DAQ readout chain required more work (explained in the Technical report B). Since the partner is convinced that the fulfilment of the project deliverables and tasks has the highest priority, it tries to staff the work accordingly and had to engage one senior scientist instead of early-stage scientist. As a consequence, the personnel effort claimed in the reporting period 2 for FAIR in NA1 (WP12) is significantly higher (twice as high) than the planned p/m contribution and exceeds the foreseen personnel budget in the GA. In the original planning, 32 172 euro were foreseen for the participation at workshops, conferences and meetings, but due to the COVID-19 pandemics, there were no in-person meetings and workshops. Thus, we ask for permission to use the budget originally foreseen for meetings and travel (which did not take place because of the pandemics) to cover a part of additional Personnel costs (by using unspent Other costs budget). The rest of the declared costs that exceed the foreseen budget in the framework of this project will be carried by FAIR.

The partner 11-RUB has consumed 151% of the total planned budget for Personnel costs. The WP leader asks to transfer the necessary amount (8 749 euro overspent) from Other direct costs of RUB in the WP12 to Personnel costs in the same WP. Because of the COVID-19 travel restrictions, less money than planned was used for travel. Instead, part of the exchange was done through video conferencing. It will be still possible to reach the goals of the project with this transfer between cost categories.

5.2.5 Work Package 13 (NA2-Small-x)

The use of person-months funded by the project has proceeded as planned. Florian Cougoulic was a joint postdoc between JYU and USC, partially funded by STRONG-2020. He has been at JYU until the end of April 2022 (i.e., person-months at JYU are spent), started at USC at the beginning of May 2022 (person-months are spent), to continue at USC until the end of August 2024 supported by other grants.

Víctor Vila was a joint postdoc between CNRS (Polytechnique) and IFJ PAN and has been for 12 months at École Polytechnique (i.e., person-months spent) and afterwards 12 months at IFJ PAN (person-months spent), to later go to IST-Lisbon supported by other funds.

5.2.6 Work Package 14 (NA3-Jet-QGP)

The hiring of postdocs was shifted in time compared to the original planning given in the GA. The planned 12 person/months for the postdocs at Nikhef were fully used with the contract that was later extended by using external funding.

Only 21 person/months for postdoc, out of the planned 24, were used at LIP due to the departure of the postdoc to take an industry job. The 3 person/month effort was carried out by the co-spokesperson of the WP (Guilherme Milhano) and, for some technical work, by PhD students supported by external grants.

5.2.7 Work Package 16 (NA5-THEIA)

During the first funding periods, the administration of NA5 was managed by local personnel. This has changed in 2021. Furthermore, in view of the situation of the travel budget caused by COVID-19 restrictions and the amount of work required to setup the hypernucleus database, the WP leaders requested to transfer 25% of the travel budget to personnel cost. The preparation of the hypernucleus database was indeed ideal to bridge the peak phase of the corona pandemic in 2021/2022 because it could be performed without major person-to-person contacts.

Mainly for setting up the hypernucleus database during the second funding period, the WP leaders actually used 9.75 person-months. To be able to continuously support the database throughout the last funding period, they asked during the second funding period to increase the total person-months of this work package from 10 to 11.5.

In the seconds half of 2022, the transfer of the database to Japan required an additional 1.25 person-month for 2022, totaling 12.75 person-months. As a consequence, the cost for personnel increased from the envisaged 70.000 euro by about 10% to a total of 77.538,61 euro. Since the overall use of the travel budget for THEIA amounts to only 80.472,13 euro, the total budget of the WP still remains slightly below the assigned sum of 160.000 euro.

5.2.8 Work Package 18 (NA7-Hf-QGP)

There was a transfer of 20K euro from Travel costs to Personnel costs that was accepted by the Project Officer without amendment and thus, that is not reflected in the Annex 2 of the GA.

In the context of the NA7 (Quark-Gluon Plasma characterisation with heavy flavour probes – Hf-QGP), a travel budget of 40.000 Euro has been made available at GSI for the project period from June 1, 2019, to May 31, 2023. Due to the COVID-19 pandemic, the project was extended until July 31, 2024.

This budget was originally foreseen for Travel costs in the context of networking activities, mainly to support the experimental community working on heavy flavour probes in Germany. Due to the COVID-19 pandemic, travelling was essentially impossible or at least severely limited for more than two years. A substantial fraction of the travel budget at GSI was planned to be spent for the two network meetings in year 1 and year 3 of the project and, particularly, for an accompanying workshop at ECT*. The two network meetings could not take place in person. The workshop at ECT* was one of the very first meetings that did take place again, still during the ongoing pandemic, from November 15 to 18, 2021. All participants of that workshop received full support from ECT*, which was not expected but became possible because most of the events planned at ECT* in 2021 were cancelled or postponed. Therefore, ECT* was able to fully sponsor those events that actually did take place. In summary, the three main network meetings, for which a large fraction of the travel budget at GSI was foreseen, did either not take place in person (two network meetings) or were financed from other sources (ECT* workshop), such that no cost occurred at GSI. The implementation of the tasks and the work on the deliverables of the NA7 working package were not affected by this.

The current NA7 budget available at GSI is still more than 30.000 Euro even though normal, networking related travel has resumed since the end of 2022. It is expected that until the end of the project in July 2024, a travel budget of approximately 10.000 Euro will still be needed for activities related to the NA7 objectives. The WP members propose not to spend the remaining 20.000 Euro on travel but use in an alternative way, specifically to hire a postdoctoral research associate to work full time on NA7 objectives and deliverables related to open heavy flavour measurements with ALICE during the HI-IL LHC runs, which are about to start. The extension of the project to July 2024 offers a unique opportunity towards the objectives of NA7. One key element of NA7 is the precision measurement of open heavy flavour hadrons at the LHC. Current work is limited to existing data from LHC runs 1 and 2. Adding a postdoctoral researcher to the NA7 project now will allow for a first analysis of the high-statistics data about to be recorded by ALICE in run 3 at the LHC, significantly extending the sensitivity of previous measurements on transport properties and the hadronization mechanism of heavy quarks in the QGP at ultra-relativistic energies. The researcher will work on the measurement of charm baryons, probes of utmost importance for the NA7 objectives, which are accessible with good precision only in high-statistics data samples as they will be recorded by ALICE in the next months. Furthermore, the scientist's work on charm baryons will contribute significantly to the deliverable D18.3, i.e. a paper with recommendations for dedicated heavy-ion running periods after the 2nd Long Shutdown at the LHC. Given that charm-baryon measurements are one of the strongest motivations for heavy-ion running with upgraded or new experiments at the LHC, strengthening the NA7 efforts in this area is a strategic investment into the future.

Hiring of a postdoctoral researcher from the NA7 budget at GSI at this point in time is a win-win situation. Not only will the scientist contribute to the tasks and deliverables initially foreseen in the Grant Agreement, but also the person will take already a first step towards high precision charm-baryon measurements from the high-luminosity running at the LHC, which clearly represents an added value to the goals of the NA7 working package.

This proposal has met unanimous support of the STRONG-2020 and NA7 coordinators, the justifications were communicated and accepted by the PO.

5.2.9 Work Package 19 (JRA1-LHCCombine)

The partner 30-INFN (in the frame of the WP19) has received a transfer from 1-CNRS (in the frame of WP1) to cover one additional month for a PhD student working for STRONG -2020 so that she could complete her work and give a presentation of the results at a major conference. The total amount of transfer was 3.038,00 euro, it was accepted by the PO without an amendment and thus, is not reflected in the Annex 2.

5.2.10 Work Package 21 (JRA3-PrecisionSM)

Two person-months at ½ position were used to support the work of a new PhD student at JGU, Rolando Ramirez Martinez, who studied the effects of hadronic form factors for the interpretation of PVES experiments at the future MESA facility in Mainz. This work includes a feasibility study of the 1.5% measurement of the proton's weak charge, extraction of the axial form factor of the nucleon from a dedicated backward-kinematics measurement on the hydrogen and deuteron target.

5.2.11 Work Package 22 (JRA4-TMD-neXt)

During the project, there have been some delays in the opening and filling of researcher positions, partially due to the COVID-19 emergency. However, by the end of the project, all the planned positions have been filled.

5.2.12 Work Package 29 (JRA11-CRYOJET)

At Uppsala University (UU), the personnel resources were used at a lower level for a long time due to the COVID-19 restrictions, which were lifted in February 2022. Until then, on-site work of expert participants from other divisions at the University has only been possible at a reduced level. The WP members adapted the workflow by prioritizing parts, which did not involve restricted on-site access to minimize the effect on the project. The redeployment of the pellet tracking system has created an additional need for personnel resources. A reallocation of some funds to the staff costs has been necessary to achieve as much of the objectives as possible.

5.2.13 Work Package 31 (JRA13-P3E)

A deviation between the planned (9.6 p.m) and actual (7 p.m) human effort at the University of Hamburg (UHAM) was observed. This deviation can be explained by the increase of personnel costs following the increase of salaries in Germany. The allocated funds for the University of Hamburg allowed to support only 7 p.m instead of the initially planned number. Prof. Gudrid Moortgat-Pick and her team compensated this reduction with an increased involvement such that the goals and contributions of the University of Hamburg have been completely fulfilled.

5.2.14 Work Package 32 (JRA14-MPGD_HP)

There was a budget transfer of 2K euro from Travel costs to Personnel costs that was accepted by the PO without an amendment and thus, this transfer is not reflected in the Annex 2.

In the framework of the WP32, the study of innovative photocathodes based on hydrogenated diamond nanograins is the main activity of a young colleague in Trieste, Dr. Richa Rai. She is working in the INFN Trieste Photon Detector Laboratory, under the supervision of the WP leader (Fulvio TESSAROTTO) and with a contract in association with INFN.

She graduated in India and joined the WP activities thanks to a special fellowship contract, called TRIL (Training in Italian Laboratory), provided by the Abdus Salam ICTP (International Center for Theoretical Physics). Her present TRIL will expire on October 15. An extension of her contract would be very important for the completion of the present work, and ICTP is ready to provide it in a co-financing configuration.

WP 32 has already used all allocated resources for manpower but still has 2.000 Euro allocated to cover travel expenses. Indeed, the original planning included participation to a couple of workshops that were cancelled or took place in remote form only, because of the COVID-19 pandemic.

Furthermore, the specific work performed at CERN has been supported via the STRONG-2020 CERN Transnational Access budget and the work done at Bari by the INFN-Trieste team has been entirely supported by INFN. For these reasons, this WP still has 2.000 Euro available for Travel costs.

In agreement with all colleagues participating in WP32 in Trieste, the WP leaders proposed to move the remaining resources to Personnel costs in order to use them for partially covering the co-financing of Dr. Richa Rai contract extension. This proposition was communicated to and accepted bu the PO.