Template JRA

Work package number	WP25	**Start date**	01/06/2019
Activity Type	Joint Research Activity		
Work package acronym	JRA7-HaSP		
Work package title	Light-and heavy-quark hadron spectroscopy		

1. Work carried out and overview of progress

1.1 Project objectives

[Please give an overview of the project objectives for the third reporting period (June 2022 – July 2024), with regard to the overall objectives as described in the Annex 1 of the Grant Agreement and summarized below.]

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

1.2 Progress made during the reporting period towards the objectives

[Please describe the progress made during the third reporting period in line with your Gantt chart and the project overall tasks as described in the Annex 1 of the Grant Agreement and summarized below.]

Table 1.2 Progress made during the reporting period for each task

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 $D\overline{D}, D_s\overline{D}_s, D^*\overline{D}^*$ and $D_s^*\overline{D}_s^*$ 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 $\overline{K}K$ spectrum in the decay $J/\psi \to \phi K\overline{K}$ 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 $D\overline{D}^*$ and $D^*\overline{D}^*$, 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 $D\overline{D}$ bound state have been analyzed [Brandao:2023vyg]. The $B^{+} \longrightarrow K^{+}\eta\eta$ goes through a $D_s^{*}\overline{D}^{0}$ pair with the $D_s^{*} \to D^{0}K^{+}$ and a posterior fusion of the $D^{0}\overline{D}^{0}$ 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 $\pi\pi \longrightarrow K\overline{K}$ 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 $K\overline{K}$ 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 $\phi K\overline{K}$ 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]

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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. <u>*Precision QCD parameter determinations*</u>

- 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, (^4He) 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.

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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].

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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→$K\bar{K}$ 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 $K\bar{K}$ channels. Given the reduced model dependence, the tension should be due to inconsistencies between ππ→ππ and ππ→KK data sets.

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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.

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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.

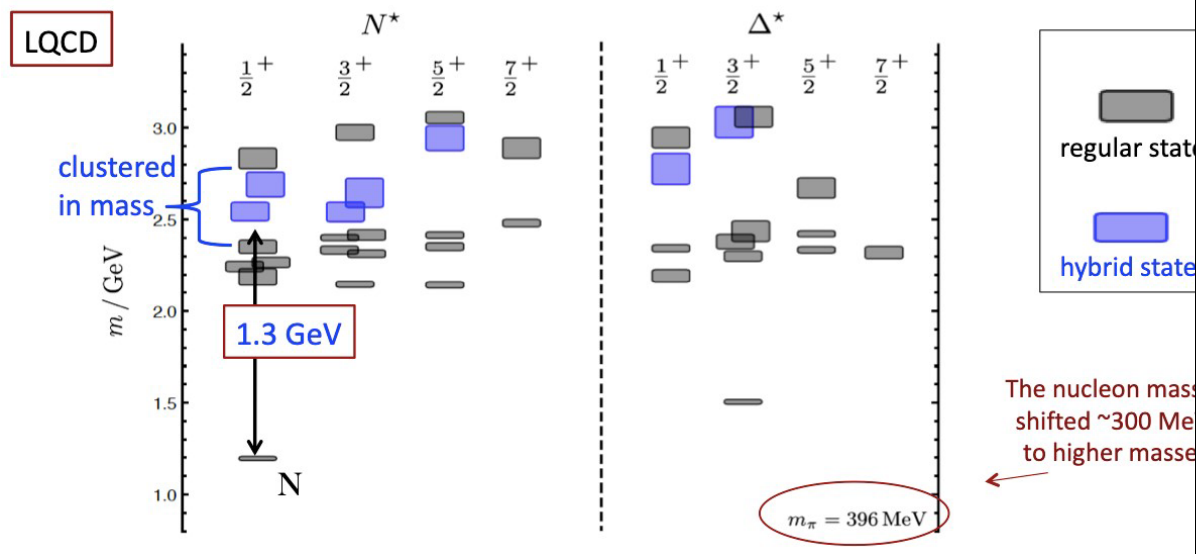

Figure 2. Lattice QCD prediction of light baryons spectrum, including states with dominant gluonic degrees of freedom. [J.J. Dudek and R.G. Edwards, PRD85, 054016 (2012)]

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 $\gamma n \to K^+\Sigma^+$ 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 $\vec{\gamma} + p \to \pi^+ + \pi^- + \pi^0$ 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 $ep \to eK^+Y$ and $ep \to e\pi^+\pi^-$ 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 Σ^+c^-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.

1.3 Highlights of significant results
[Include an overview of the project results towards the objectives in line with the structure of the Annex 1 to the Grant Agreement.]

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 $\pi\pi \longrightarrow K\overline{K}$ 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 STRONG2020 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.

2. Critical Implementation risks and mitigation actions

2.1 Risk materialization
[Provide the information on the project risks described in Annex 1 to the Grant Agreement.]

1) Delay Common Analysis Framework deployment (low)

Whether the risk has materialized? NO

2) Delay in HaSP whitepaper (WP) publication (low)

Whether the risk has materialized? NO

2.2 Risk-mitigation measures applied
[Please indicate whether the risk-mitigation plan described in Annex 1 to the Grant Agreement and corresponding to the risk number was applied in the reporting period.]

1) The HaSP Common Analysis Framework will be developed while theoretical inputs and data from different experiments are collected and filtered in a common format. The framework will be shared using a public repository (e.g. Github) allowing all institutions participating to HaSP to contribute and test it in the very early stage.

Whether the risk-mitigation plan was applied? YES

2) Attendees of HaSP general ws (M3) and school (M4) will be requested to provide a contribution for the WP in advance. The WP will be mainly based on this material, available well in advance.

Whether the risk-mitigation plan was applied? YES

2.3 Comments/new risk-mitigation measures proposed
[Provide any significant comments on the risks encountered and the mitigation plan applied. Give any unforeseen risks encountered during the reporting period and not mentioned above.]

3. Deviations from Annex 1 (Description of Action) and Annex 2 (Estimated budget for Action) (if applicable)

3.1 Deviations from planned objectives and tasks, and their impact on the progress of the work package
[Explain the reasons for deviations, the consequences and the proposed corrective actions.]

No deviation from the planned activity.

3.2 Deviations between actual and planned person months
[Explain deviations between actual and planned person-months. If applicable, propose corrective actions.]

No deviation from the planned person month.

4. Deliverables and milestones tables

4.1 Deliverables

[Please list all the deliverables due in this reporting period, as indicated in Annex I.
Deliverables must also be accompanied by a short report (deliverable description and technical documentation, such as photo, list of publications, etc.), so that the European Commission has a record of their existence.]

Table 4.1 List of deliverables

Deliverable No.	Deliverable name	Lead Beneficiary	Nature	Dissemination level[1]	Delivery month from Annex I	Delivered (yes/no)	Actual delivery month	Comments
D25.3	HaSP white paper	1 - CNRS	Report	PU	62	YES	62	

In case a deliverable has been delivered in the reporting period and a report exists in the Participant Portal, you can indicate "uploaded report" in correspondence of a deliverable

[1] PU = Public
PP = Restricted to other programme participants (including the Commission Services).
RE = Restricted to a group specified by the consortium (including the Commission Services).
CO = Confidential, only for members of the consortium (including the Commission Services).

4.2 Milestones

[Please complete the table if milestones are specified in Annex I.
Milestones will be assessed against specific criteria and performance indicators as defined in Annex I.]

Table 4.2 List of milestones

Milestone number	Milestone name	Lead beneficiary	Delivery month from Annex I	Delivered (yes/no)	Actual delivery month	Comments
MS54	General Workshop on Hadron Spectroscopy and Phenomenology (TUM) Tasks 1, 2, 3 and 4	30 - INFN	40	YES	40	workshop delivered in Sept 22 Proceeding (D25.2) delivered in Oct 23
MS55	School on Hadron Spectroscopy and Phenomenology	30 - INFN	48	YES	52	School delivered in Sept 23 Proceeding delivered in Feb 24

4.3 Deliverable Reports

[Please provide, per each deliverable listed in Table 4.1, a brief description, including if possible some technical documentation (photos, list of publications, etc.). Use as many pages as needed per each report.]

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