**Template JRA**

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| --- | --- | --- | --- |
| **Work package number** | WP21 | **Start date** | 01/06/2022 |
| **Activity Type** | Joint Research Activity | | |
| **Work package acronym** | JRA3-PrecisionSM | | |
| **Work package title** | Precision Tests of the Standard Model | | |

1. Work carried out and overview of progress
   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 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).

* 1. **Progress made during the reporting period towards the objectives**

*[Please describe the progress made during the second 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: Hadronic effects in precision tests of the weak sector of SM*** |
| In the past 2 years we made major contributions in the field of radiative and nuclear corrections to Vud 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 𝛿NS and 𝛿C to superallowed nuclear 𝛽 decays. [1] related 𝛿C 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 𝛿C 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 𝛿NS, applied to an ab-initio calculation for the 10C ￫10B 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 Vud 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 12C 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 Vud. 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 our 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*** |
| Our 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 in the electromagnetic constant, and of the 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 data base 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](https://indico.psi.ch/event/13707/) was organized 5-9 June 2023 at University of Zurich. <https://indico.psi.ch/event/13707/>  The Workstop included STRONG2020 Workshop on “[Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in](https://indico.psi.ch/event/13708/)  e+e- [collisions](https://indico.psi.ch/event/13708/) » 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/)  <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 |

**1.3 Highlights of significant results**

*[Include an overview of the project results towards the objective of the action in line with the structure of the Annex 1 to the Grant Agreement*.*]*

Precision tests in the electroweak sector:

By the end of activities within JRA3 we provided a re-evaluation of the entire body of radiative corrections to Vud and Vus 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-2)𝜇 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−￫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/)

<https://indico.cern.ch/event/1245077/>, 6–7 Mar 2023, Warsaw

[Baryon weak decays - from experiment to lattice QCD](https://indico.cern.ch/event/1361025/)

<https://indico.cern.ch/event/1361025/>, Mar 4-5,2024 Warsaw

[Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in](https://indico.psi.ch/event/13708/)  e+e- [collisions](https://indico.psi.ch/event/13708/)

<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 Vud»*, Phys. Lett. B* 838 (2023) 137654
2. C.Y. Seng, M. Gorchtein, «Dispersive formalism for the nuclear structure correction 𝛿NS to the 𝛽 decay»*, Phys. Rev. C107 (2023) 3, 035503*
3. C.Y. Seng, M. Gorchtein, «Toward ab-initio nuclear theory calculations of 𝛿C»*, 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 Vud : the 10C 🡪 10B 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 12C »  *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
21. 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. Lack of coordination between experimental groups/facilities providing data, and theory groups performing calculations of RC for precision tests of SM (low)

Whether the risk has materialized? (Yes/**No**)

1. A development of partial wave analysis for multimeson production is an ambitious task. Only special cases are considered in a model-dependent way. New data of high precision and detalization exist and wait to be analyzed in a general framework and with the use of dispersive methods (medium)

Whether the risk has materialized? (**Yes**/No) The available person-power at JGU was decimated by early retirements during COVID-19. Additional restrictions caused by the Ukraine war excluded travels to Fermilab for the remaining member of the MAID collaboration.

**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. Three workshops are planned before deadlines for the deliverables. They will allow for coordinating efforts and setting priorities to achieve the goals. The recently signed cooperation agreement between Mainz and Fermilab will permit regular mutual visits between the two institutions at a reduced cost.

Whether the risk-mitigation plan was applied? (**Yes**/No) the workshop planned for this report period was successfully held and the proceedings published on arXiv.

1. New risks (COVID and Russia-Ukraine war) severely affected the cooperation needed for success of MS39

Whether the risk-mitigation plan was applied? (**Yes**/No)

**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.]*

[MS39]: 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 STRONG2020 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.

**3.2 Deviations between actual and planned person months**

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

2 person-months at ½ position were applied to support the work of a new PhD student at JGU, Rolando Ramirez Martinez, who studies 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.

1. 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]](#footnote-1)** | **Delivery month from Annex I** | **Delivered**  **(yes/no)** | **Actual delivery month** | **Comments** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| D21.3 | Report on hadronic  corrections to precision  tests in the weak sector | 9 - JGU MAINZ | Report | PU | 56 | Yes | 42 | Universe 9 (2023) 9, 422;  Ann.Rev.Nucl.Part.Sci.74 (2024) 23 |
| D21.4 | Database on hadronic  processes relevant for  HVP and HLbL | 30 - INFN | ORDP: Open  Research  Data Pilot | PU | 56 | Yes | 42 | <https://precision-sm.github.io/> |

*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*

**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** |
| --- | --- | --- | --- | --- | --- | --- |
| MS39 | New Pi production MC event  generator | 9 - JGU MAINZ | 56 | No |  |  |
| MS40 | Database for hadronic  processes relevant to HVP  and HLbL | 9 - JGU MAINZ | 42 | Yes | 42 | <https://precision-sm.github.io/> |

**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.]*

D21.3: 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: 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− ￫ hadrons data.

The database structure has been reported in several conferences. Few key members involved in this WP has signed the 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>

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). [↑](#footnote-ref-1)