**Description of work**

**Task 3.1: RMCL2++ VA: To support the development and usage of Monte Carlo tools in hadron physics experiments**

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*The aim to is develop a common way of using Monte Carlo tools for hadron physics experiments and support their development.*

Overview of the project: Measurements and theoretical predictions of form factors are among the biggest questions in low-energy particle and hadron physics. Prominent among these is the anomalous magnetic moment of the muon, , which can provide stringent limits on physics beyond the Standard Model, but whose theoretical calculation is very difficult. The most recent [White Paper](https://arxiv.org/abs/2505.21476) of the `Muon Theory Initiative' notes significant tensions between different predictions for the hadronic vacuum polarisation (HVP) contribution, which can be evaluated dispersively based on data from electron-positron annihilation, e.g., , or using first-principles lattice QCD calculations. In addition, the proton electromagnetic (em) and weak form factors are another set of theoretically and experimentally relevant quantities. These are measured in scattering for both small and large momentum transfers (where the proton radius or the weak mixing angle can be measured). However, long-standing discrepancies exist between measurements of the em form factor ratio obtained using the Rosenbluth extraction from unpolarised cross sections and those obtained using the polarisation-transfer method. These discrepancies have prompted [investigations](https://arxiv.org/abs/2306.14578) into whether two-photon exchange (TPE) radiative corrections could be responsible.

Measurements of are, or were, carried out at various experiments around the world (e.g. BaBar, Belle, BES-III, CMD-3, KLOE). Tensions persist among existing data sets and analyses are being revisited, especially at KLOE (INFN-LNF), where the data analysis is still ongoing. Measurements of lepton-proton scattering are even more widespread, and are planned, for instance, by e.g. MAGIX and P2 (Mainz), PRad (JLab) and AMBER (CERN). A related process is which is used by the MUonE experiment (CERN) to provide a complementary approach to determine the HVP. All of these experiments share a need for precise radiative corrections. The same is also true for future experiments, which require precise Monte Carlo (MC) tools for feasibility and design studies.

The data underlying the dispersive HVP evaluation are often obtained not in (energy scan) but in (radiative-return) measurements. While this method allows one to measure at many different values of with the same experiment, it increases both the complexity and the size of the corrections significantly. Radiative corrections beyond next-to-leading order (NLO) for and (and similarly and which are used as normalisation processes) are therefore vital. This proposal will build on, continue, and extend the [work of the RadioMonteCarLow2 effort](https://arxiv.org/abs/2410.22882) which has brought together seven independent MC tools (AfkQed, BabaYaga@NLO, KKMC, McMule, MCGPJ, Phokhara, and Sherpa) to compare and contrast approaches. Future improvements to each of these codes --- be it fixed order NNLO, resummation of soft or collinear emission, improved theoretical descriptions of hadronic effects --- are expected as we enter the second phase of RADIOMONTECARLOLOW2.

For , it was recently pointed out that, depending on the kinematic scenario, [NNLO QED effects can be of a similar size as the NLO TPE corrections](https://arxiv.org/abs/2307.16831). An accurate extraction of proton form factors from modern scattering experiments thus requires a better understanding of the QED and TPE radiative corrections. The solution to the aforementioned discrepancy between form factor extractions from different (un)polarised observables depends strongly on the inclusion of TPE corrections. Experiments such as OLYMPUS (DESY), CLAS12 (JLab) and VEPP-3 (Novosibirsk) have determined the TPE experimentally from the cross section ratio of electron- to positron-proton scattering. Efforts to improve our understanding of the TPE corrections continue on both the experimental and the theoretical side. The [JLab Positron Experimental Programme](https://doi.org/10.1140/epja/s10050-022-00699-6) foresees several new measurements (e.g., PR12+23-008 and PR12+23-012), and [TPEX](https://arxiv.org/abs/2301.04708) at DESY has been proposed as a follow-up experiment to cover a wider kinematic range.

There are a number of processes that can be covered without too much additional difficulty. Where feasible, we will try to improve the state of the art of these as well. The measurement of by the MUonE experiment (CERN) for HVP extraction is of course a major example. Other examples are and which are both used for luminosity measurements at e+-e- colliders. Improving radiative corrections is also crucial for New Physics searches in various lepton–lepton and lepton–proton scattering channels studied at MESA (Mainz), JLab, and PADME (INFN-LNF), where the Standard Model background must be understood with high precision to resolve potential New Physics signals (e.g., dark sector particles, X17, etc.).

Goals of the project: For all of these measurements, radiative corrections need to be tightly integrated into the experimental analysis pipelines. Our goal within this project is therefore threefold:

* *support the improvement of MC tools*. For and related processes, this is already well underway as part of RADIOMONTECARLOLOW2, which will be extended to cover also lepton scattering. The actual improvements mostly fall on the MC developers, but we aim to support this through scientific exchange programmes such as workshops and internships (Deliverable I).
* *collate and maintain existing codes in a common repository*. During the first phase of RADIOMONTECARLOLOW2, we have begun to store the codes used in the comparison in a [publicly accessible website](https://radiomontecarlow2.gitlab.io/). As part of this VA project, we will ensure this is kept complete and up-to-date and that new benchmarks, especially for -scattering, are added as they become available (Deliverable II). This repository will help with both theoretical cross-validation of different MCs and experimental usage, by providing starting points for experimentalists to integrate the MCs into their own analysis.
* *support the integration of MC tools into experimental analyses and feasibility studies*. To ensure that the MC tools can be easily used by experimentalists, we will develop a common interface between MC and experimental analysis, similar to the [rivet](https://rivet.hepforge.org/) tool developed for the LHC Community. This interface will be published together with connectors to the MCs, documentation, and examples (Deliverable III). It will avoid duplicating effort and make it easier for users to test different MCs and benefit more directly from theoretical improvements.

Further, we will train experimentalists in using this interface and, time permitting, will actively contribute to including it in experimental analyses (Deliverable IV).

**Table 3.1c: List of Deliverables[[1]](#footnote-1)**

Only include deliverables that you consider essential for effective project monitoring.

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| --- | --- | --- | --- | --- | --- | --- | --- |
| **Number** | **Deliverable name** | **Short description** | **Work package number** | **Short name of lead participant** | **Type** | **Dissemination level** | **Delivery date**  **(in months)** |
| I | Scientific exchange | Support MC development through scientific exchange programmes, most notably internships | RMCL2++, WP1 | leadership | OTHER | PU | Continuous, at least one a year |
| II | benchmarks | Provide repository of benchmark observables for all processes under consideration, incl. lepton-scattering, and ensure list is up to date | RMCL2++, WP2 | YU | DEC | PU | 12 |
| III | interface | Build unified interface between MC and experiment | RMCL2++, WP3 | YU, postdoc | OTHER | PU | Within two years of postdoc start |
| IV | training | Provide training to experimental users | RMCL2++, WP3 | YU, postdoc | R | PU | Continuous, report as part of III |
| V | final report | Report of activities during funding period | RMCL2++ | leadership |  | PU | 60 |

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| **KEY**  Deliverable numbers in order of delivery dates. Please use the numbering convention <WP number>.<number of deliverable within that WP>.  For example, deliverable 4.2 would be the second deliverable from work package 4.  **Type:**  Use one of the following codes:  R: Document, report (excluding the periodic and final reports)  DEM: Demonstrator, pilot, prototype, plan designs  DEC: Websites, patents filing, press & media actions, videos, etc.  DATA: Data sets, microdata, etc.  DMP: Data management plan  ETHICS: Deliverables related to ethics issues.  SECURITY: Deliverables related to security issues  OTHER: Software, technical diagram, algorithms, models, etc.  **Dissemination level:**  Use one of the following codes:  PU – Public, fully open, e.g. web (Deliverables flagged as public will be automatically published in CORDIS project’s page)  SEN – Sensitive, limited under the conditions of the Grant Agreement  Classified R-UE/EU-R – EU RESTRICTED under the Commission Decision No2015/444  Classified C-UE/EU-C – EU CONFIDENTIAL under the Commission Decision No2015/444  Classified S-UE/EU-S – EU SECRET under the Commission Decision No2015/444  **Delivery date**  Measured in months from the project start date (month 1) |

**Table 3.1d:** **List of milestones**

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| **Milestone number** | **Milestone name** | **Related work package(s)** | **Due date (in month)** | **Means of verification** |
| I | Updating repository | RMCL2++, WP2 | 6 | Ensure repository matches public codes |
| II | Including lepton scattering | RMCL2++, WP2 | 24 | Verify with experimentalists that all codes & observables are ready and fit for purpose |
| III.a | Needs analysis of some MCs | RMCL2++, WP3 | by the time postdoc starts | Ensure all MCs have been reached, conclusion presented at Collaboration Meeting |
| III.b | Needs analysis of all MCs | 30 |
| IV | Interface tested against needs | RMCL2++, WP3 | 36 | Number of MCs and number of (pseudo) analysis that interface works with |
| V | Experimental uptake | RMCL2++, WP3 | 60 | Number of experiments using interface & repository |

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| **KEY**  **Due date**  Measured in months from the project start date (month 1)  **Means of verification**  Show how you will confirm that the milestone has been attained. Refer to indicators if appropriate. For example: a laboratory prototype that is ‘up and running’; software released and validated by a user group; field survey complete and data quality validated. |

**Table 3.1e:** **Critical risks for implementation** #@RSK-MGT-RM@#

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| **Description of risk (indicate level of (i) likelihood, and (ii) severity: Low/Medium/High)** | **Work package(s) involved** | **Proposed risk-mitigation measures** |
| Some codes cannot be obtained and/or authors unwilling to collaborate (high, low) | RMCL2++, WP2 | Work with codes that are available and extend later |
| Travel restrictions impacting internships or workshops (medium, medium) | RMCL2++, WP1 | Perform workshops online, postpone internships, encourage remote collaboration between MC groups |
| Codes too heterogenous to allow for common interface (low, high) | RMCL2++, WP3 | Work with largest sensible subset of codes, build specific observable-dependent shims to allow fine-tuning using interface |
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| **Definition critical risk:**  A critical risk is a plausible event or issue that could have a high adverse impact on the ability of the project to achieve its objectives.  **Level of likelihood to occur: Low/medium/high**  The likelihood is the estimated probability that the risk will materialise even after taking account of the mitigating measures put in place.  **Level of severity: Low/medium/high**  The relative seriousness of the risk and the significance of its effect. |

#§RSK-MGT-RM§#

Modality of access: As part of this project, we will have two types of deliverables: the training and exchange programmes (Deliverables I and IV) and the software and data-based projects (Deliverables II and III). We will discuss these in turn.

For the former, we will put out regular calls on the RadioMonteCarLow2 mailing lists and advertise the availability of internships during our biannual meetings. ECRs that are interested in short, funded internships under this programme are invited to submit short, informal applications (incl. a cost estimate), explaining what they aim to achieve during the internship and how it will benefit the development or uptake of Monte Carlo codes, to the leaders of RMCL2++. Once approved, they are invited to make their own arrangements and will be reimbursed through the University of Liverpool which acts as grant manager. Of course, the internships should ideally lead to long-term collaborations beyond the research stay itself. To monitor this, the intern will be asked to provide a short summary of their research stay and follow-up collaboration, incl. results achieved, six months after completion to the RMCL2++ leadership. They will further be asked to acknowledge this EU project in any publication resulting from their stay. This will allow us to track the impact of our internship funding by directly linking Monte Carlo features to funded travels.

For the software projects, we will have a public webpage hosted by GitLab at [https://radiomontecarlow2.gitlab.io](https://radiomontecarlow2.gitlab.io/). Users are already able to browse existing results, as published as [SciPost Phys.Comm.Rep. 9 (2025)](https://doi.org/10.21468/SciPostPhysCommRep.9), on this webpage. We will make this service more accessible and interactive by making it easier to obtain Monte Carlo commented runcards that include explanations on how to tweak those for adaption by experimental users (cf. Deliverable II). For the interface (Deliverable III), we develop the code in public in the same GitLab namespace which allows for early feedback by its experimental and theoretical users. Once initial development is complete, the tool will be hosted and maintained in its GitLab repository indefinitely. Finally, for every data release and version of the interface, we will create a versioned and archived Zenodo record that ensures permanent data retention.

Measurement of access and support provided: To monitor the uptake of both the interface and data repository we will ask users to cite the corresponding Zenodo record and/or journal articles. We opt not to include telemetry in either the website or software tool to preserve our users' privacy. Further, we will remain in constant contact with any experiment and Monte Carlo group that may be interested in using our resources. This complements the bibliometric monitoring and reduces latency.

Of course, such close contact with our users will ensure that they are provided with adequate support and opportunity for feedback. We will measure feedback using GitLab issues that can be created by the users themselves or by RMCL2++ members (should feedback arrive via email). RadioMonteCarLow2 already has systems in place where two volunteer members are responsible for keeping the data repository up-to-date and we will implement a similar system for technical support once the postdoc has completed their contract developing the interface.

Outreach to new users: Through the project leadership and the broader RadioMonteCarLow2 Collaboration we are already in touch with many potential experimental users and Monte Carlo developers. However, we aim to continuously and proactively reach new users and collaborators to use our resources and/or join RMCL2++ directly and therefore become eligible for internships. Since this subproject has connections to many of the TNA facilities covered under this proposal (e.g. Mainz, INFN-LNF, CERN, JLab), we will be well-placed to provide resources for experiments at these facilities. In the case of the e+e- community, RadioMonteCarLow2 already does this for example through a dedicated session in the annual [Plenary Meetings of the muon g-2 Theory Initiative](https://indico.ijclab.in2p3.fr/event) with talks by developers and a discussion chaired by one of us (YU). To ensure awareness within the lepton-scattering community, we will make sure that RMCL2++ is represented at the smaller, more ad-hoc conferences and workshops such as [HADRON PHYSICS 2030](https://indico.ijclab.in2p3.fr/event/10641/), [LEEPP](https://www.jlab.org/conference/LEEPP), [NREC](https://indico.cfnssbu.physics.sunysb.edu/event/253/). Further, we try to organise a small satellite meeting around a larger conference or workshop that we expect RMCL2++ members as well as interested parties to attend. In addition to talks at various international conference, these steps will ensure awareness in the broader community.

Review procedures: Our long-term progress will of course be judged by the RadioMonteCarLow2 Collaboration, our experimental users, and the community at large. However, we, the RMCL2++ leadership, will continuously monitor development and uptake of our software resources and exchange programmes and present this to the Collaboration for review. The discussion after these biannual talks will be minuted. Once the project is complete, we will provide a closing report (Deliverable V). In this, we will include quantitative metrics as discussed above and qualitative reports from interns and users as well as minutes from discussions and reviews.

1. You must include a data management plan (DMP) and a ‘plan for dissemination and exploitation including communication activities as distinct deliverables within the first 6 months of the project. The DMP will evolve during the lifetime of the project in order to present the status of the project's reflections on data management. A template for such a plan is available in the [Online Manual](https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/common/guidance/om_en.pdf) on the Funding & Tenders Portal. [↑](#footnote-ref-1)