Letter of Intent for VA *RadioMonteCarLow2++* (RMCL2++)

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Research objectives

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, $(g-2)_\mu$, which can provide stringent limits on physics beyond the Standard Model, but whose theoretical calculation is very difficult. The most recent White Paper of the "Muon $g-2$ 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., $ee \to \pi\pi$, 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 $ep \to ep$ 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 into whether two-photon-exchange (TPE) radiative corrections could be responsible.

Measurements of $ee \to \pi\pi$ 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, e.g. MAGIX and P2 (Mainz), PRad (JLab) and AMBER (CERN). A related process is $e\mu \to e\mu$ 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 $ee \to \pi\pi$ (energy scan) but in $ee \to \pi\pi\gamma$ (radiative-return) measurements. While this method allows one to measure at many different values of $m^2_{\pi\pi}$ 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 $ee \to \pi\pi$ and $ee \to \pi\pi\gamma$ (and similarly $ee \to \mu\mu$ and $ee \to \mu\mu\gamma$ which are used as normalisation processes) are therefore vital. This proposal will build on, continue, and extend the work of the RadioMonteCarLow2 (RMCL2) effort 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 RMCL2.

For $ep \to ep$, 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. 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 foresees several new measurements (e.g., PR12+23-008 and PR12+23-012), and TPEX 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 $e\mu \to e\mu$ by the MUonE experiment (CERN) for HVP extraction is of course a major example. Other examples are $ee \to ee$ and $ee \to \gamma\gamma$ 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.).

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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 $ee \to \pi\pi$ and related processes, this is already well underway as part of RMCL2, 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 RMCL2, we have begun to store the codes used in the comparison in a publicly accessible website. As part of this VA project, we will ensure this is kept complete and up-to-date and that new benchmarks, especially for ℓ-p 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` 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).

Connection to Transnational Access infrastructures and Virtual Access projects

As discussed above, our project will be used by experimentalists working on hadron-physics experiments in Mainz, INFN-LNF, CERN, and JLab. The goal of this VA project is to provide them with cutting-edge MCs from a centralised repository that model radiative corrections for their signals and backgrounds, in addition to the tools & training needed to integrate MCs into their analysis. In turn, this VA can benefit from a number of other projects presented during the Town Hall, such as `VIPER` (which provides an online training platform we could contribute to), `NLOAccess` and `gammaUPC4LHC` (both provide hard matrix element though for different physics scenarios). Further, input could be provided through this VA for `LEARN` (AI learning of EM nuclear structure from data will require MC input at some stage) and `FITTED` (fitting of electroweak and nuclear precision data; radiative corrections could be tailored through our MCs).

Estimated budget request

We plan to hire a postdoc with significant software development experience to carry out Deliverables II and III for one year FTE, ideally spread across two calendar years at 50%. This person would be hosted at the University of Liverpool at approximately 85k€. We aim to either extend an existing contract and/or provide third-party funding to cover their remaining 50% during which they would work on related projects, depending on availability and the exact timeline. For the scientific exchange (Deliverable I), we request an additional 15k€ in travel funding over the duration of the project. Most of this will be used to provide internship opportunities for early-career researchers from different sub-groups to visit and learn from other groups (both experimental and theoretical). We also plan to organise two workshops annually, one small satellite conference and one larger multi-day event. We expect most participants to have their own travel funding but will still apply to workshop centres across Europe (such as ECT*, Miapbp, or MITP) for additional support.

Participating and partner institutions

The project will be lead by three theorists (CMCC, FH, YU) and three experimentalists (AD, AK, GV) in Liverpool, Mainz, Pavia, and Uppsala. On the theory side, we have expertise in the development of MC codes, higher-order corrections, and hadronic (esp. TPE) effects. YU will take particular charge of the repository part of the project and host the postdoc in Liverpool. On the experimental side, we have members of many hadron-physics experiments incl. those listed above. RMCL2 has members at 22 institutes across the EU, UK, and Switzerland. By the time of submission, members from HZDR, NSC KIPT Kharkov, Pavia (INFN & U), INFN Perugia, Pisa (INFN, U & SNS), PSI, Turin (INFN & U), U Bern, U Bonn, U Liverpool, U Mainz, U Uppsala, U Zurich have explicitly confirmed their support for this project though we expect more groups to join in the future.