SciPost Physics **Submission**

An alternative evaluation of the leading-order hadronic contribution to the muon $g-2$ with MUonE

R. N. Pilato [1⋆],

1 University of Liverpool, Liverpool, United Kingdom
⋆ r.pilato@liverpool.ac.uk

August 2, 2024

The 17th International Workshop on Tau Lepton Physics
Louisville, USA, 4-8 December 2023
doi:10.21468/SciPostPhysProc.?

Abstract

The MUonE experiment proposes a novel approach to determine the hadronic contribution to the muon $g-2$, a_μ^{HLO}, based on the measurement of the hadronic running of the QED coupling through the analysis of $\mu-e$ elastic scattering events. This could clarify the tensions in the current evaluations of a_μ^{HLO}, which are limiting the comparison between theory and experiment for the muon $g-2$. The measurement will be performed at CERN's North Area by scattering a 160 GeV muon beam on the atomic electrons of a low-Z target. The status and future plans of the experiment will be presented. Furthermore, an alternative method to extract a_μ^{HLO} from MUonE data will be discussed.

1 Introduction

The muon magnetic anomaly is defined as $a_\mu = (g_\mu - 2)/2$, where g_μ is the muon gyromagnetic ratio. A long standing discrepancy between theory and experiment persists since more than 20 years, making a_μ one of the most intriguing observables to test the validity of the Standard Model. The Muon $g-2$ Collaboration at Fermilab has recently published a measurement of a_μ based on data collected in 2019 and 2020 [1], which is in perfect agreement with their previous result obtained from data collected in 2018 [2]. The comparison with the Standard Model prediction is currently limited by the evaluation of the leading-order hadronic contribution, a_μ^{HLO}, which cannot be computed by perturbation theory as it involves low energy QCD. a_μ^{HLO} is traditionally determined through a dispersion integral on the annihilation cross section $e^+e^- \to$ hadrons, which allowed to achieve a $\sim 0.6\%$ accuracy [3]. On the other hand, a recent lattice QCD evaluation of a_μ^{HLO} reached an accuracy comparable to the dispersive approach for the first time [4], although showing a 2.1σ tension with the dispersive method. In addition to that, a new experimental measurement of the $e^+e^- \to \pi^+\pi^-$ channel performed by the CMD-3 experiment is in strong disagreement with the previous results [5]. It follows that a clarification of the theoretical prediction is required to maximize the discovery potential of new physics effects from the experimental efforts.

2 The MUonE experimental proposal

MUonE aims to determine a_μ^{HLO} using an independent method, based on the following integral [6,7]:

$$a_\mu^{\text{HLO}} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{\text{had}}[t(x)], \qquad t(x) = \frac{x^2 m_\mu^2}{x-1} < 0 \tag{1}$$

Here, m_μ is the muon mass, α is the fine structure constant, and $\Delta\alpha_{\text{had}}(t)$ is the hadronic contribution to the α-running. The NLO and NNLO kernels in the space-like region have been computed recently [8], meaning that MUonE will also be able to determine the higher order hadronic vacuum polarization contributions to a_μ. The innovative approach proposed by MUonE relies on the extraction of $\Delta\alpha_{\text{had}}(t)$ from the shape of the differential cross section of the $\mu^+e^- \to \mu^+e^-$ elastic scattering [9]. The scattering angles of the outgoing particles are correlated by kinematics, and this allows to reject background events. The main background process is due to e^+e^- pair production by muons interacting with the target nuclei, when one of the three final state particles escapes the detector geometrical acceptance.

The experiment will take place at the CERN SPS M2 beam line, which provides muons with 160 GeV energy. The detector will be segmented in 40 identical stations, each consisting of a beryllium or carbon target $\sim 1.5\,\text{cm}$ thick, where the elastic interactions will occur, followed by a 1 m long tracking system. The latter is composed of 6 silicon strip detectors. The stations are followed by an electromagnetic calorimeter and a muon filter, which will be used to improve the event selection and provide particle identification. Moreover, the Beam Momentum Spectrometer (BMS) already present on the beam line will be upgraded to provide a measurement of the beam momentum on an event by event basis. Since each station acts as an independent unit, the same muon beam can be re-used multiple times, thus allowing the elastic scattering events to be evenly distributed over the entire experimental setup. In this way, the number of elastic interactions is maximized, minimizing the single target thickness at the same time. This is crucial to preserve the $\mu - e$ angular correlation, which is instead diluited by multiple scattering effects.

The $\sim 50\,\text{MHz}$ in-spill intensity of the M2 muon beam, combined with the 40 stations layout, allows to collect $\sim 4 \times 10^{12}$ elastic events with electron energy > 1 GeV in 3 years of data taking. This is equivalent to reach an integrated luminosity of $\sim 15\,\text{fb}^{-1}$, and allows to obtain a $\sim 0.3\%$ statistical error on a_μ^{HLO}. The main challenge of the experiment is to keep the systematic error at the same level of precision, in order to make MUonE's evaluation of a_μ^{HLO} competitive with the current results. The shape of the $\mu - e$ differential cross section must be measured with a 10 ppm systematic accuracy in the signal region to pursue such a goal [9]. This requires a twofold effort, both on the theoretical and experimental sides. In particular, the higher order corrections to the $\mu - e$ differential cross section must be known at least to the NNLO [9]. New results have been obtained recently to compute the required amplitudes [11], while two independent Monte Carlo codes are currently under development [12]. Furthermore, a dedicated Monte Carlo generator has been developed to simulate the pair production from muon scattering on nuclei [13]. Amongst the main sources of systematic error on the experimental side there are the longitudinal alignment of a station, which must be controlled at $\sim 10\,\mu\text{m}$, and the knowledge of the average beam energy, which must be known with a few MeV precision. Furthermore, the multiple scattering effects, the angular resolution and the uniformity of the tracking efficiency over the entire angular range must be studied carefully.

3 Determination of a_μ^{HLO}

The 160 GeV muon beam available at the M2 beam line allows to cover directly the momentum transfer range $-0.153\,\text{GeV}^2 < t < -0.001\,\text{GeV}^2$. This corresponds to $\sim 86\%$ of the integral in Eq. 1, while the remaining fraction can be obtained by extrapolating $\Delta\alpha_{\text{had}}$ outside the MUonE range with an appropriate analytical function. In this case, the integral is sensitive to the behaviour of the function used to model $\Delta\alpha_{\text{had}}$ in the asymptotic limit $t \to -\infty$, which could affect the determination of a_μ^{HLO}. A convenient choise is based on the functional form of the pure QED leading order contribution to the running of α in the space-like region [10]:

$$\Delta\alpha_{had}(t;K,M) = KM\left\{-\frac{5}{9}-\frac{4}{3}\frac{M}{t}+\left(\frac{4}{3}\frac{M^2}{t^2}+\frac{M}{3t}-\frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\} \tag{2}$$

which has two free parameters. The extraction of $\Delta\alpha_{\rm had}$ is carried out through a template fit to the 2D distribution of the muon and electron scattering angles [14]. Different templates are obtained from a unique Monte Carlo sample, whose events are reweighted such that $\Delta\alpha_{\rm had}$ is modeled by Eq. 2 for different values of the fit parameters. In this way, each template corresponds to a different pair of parameters. A χ^2 comparison between data and each template is then performed, and the best fit parameters are determined by parabolic interpolation across the grid points. Finally, $a_\mu^{\rm HLO}$ can be computed by substituting the best fit function in Eq. 1. Recently, an alternative method has been proposed to calculate $a_\mu^{\rm HLO}$ from MUonE data [15]. Instead of using Eq. 1, the proposed method relies on the knowledge of the derivatives of $\Delta\alpha_{\rm had}$ at zero momentum transfer, which allow to compute $\sim$ 99% of $a_\mu^{\rm HLO}$ from MUonE data. The remaining 1% can be calculated using perturbative QCD and $e^+e^- \to$ hadrons data. Figure 1 shows values of $a_\mu^{\rm HLO}$ obtained from the two methods for different parameterizations of $\Delta\alpha_{\rm had}$. A simple toy Monte Carlo has been used to simulate the effect of the hadronic running in the MUonE range, including statistical fluctuations according to the final MUonE statistics. Results show that the alternative method based on the derivatives of $\Delta\alpha_{\rm had}$ provides a statistical accuracy which is similar to the integral method. Moreover, results are model independent, meaning that the derivatives method allows to avoid the difficulties in the extrapolation of $\Delta\alpha_{\rm had}$ outside the MUonE range, which are instead present in the integral method. This is particularly evident for a simple third order polynomial function, which makes the integral in Eq. 1 to be divergent, whilst leads to satisfactory results using the derivatives method.

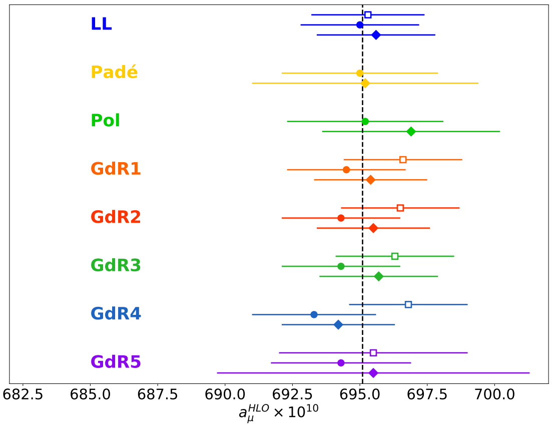

Figure 1: Values of $a_\mu^{\rm HLO}$ obtained for different parameterizations of $\Delta\alpha_{\rm had}$ using Eq. 1 (empty squares), or the alternative method described in [15] (circles and diamonds). The results for the Padé and Pol parameterizations computed using Eq. 1 are outside the plot range. The black dashed line represents the reference value used in the study. Figure adapted from [15].

4 Test Run 2023

The MUonE Collaboration submitted a Letter of Intent to the CERN SPS Committee in 2019 [10] obtaining recommendations for a 3 weeks Test Run in Summer 2023, to demonstrate the ability to identify and reconstruct elastic events. The detector was composed of two tracking stations followed by an electromagnetic calorimeter. The first station was not instrumented with a target, and was used to detect the incoming muons. Graphite targets of 2 cm or 3 cm thickness were alternatively installed on the second station, in order to evaluate the systematic effects and study the background processes taking data in different configurations. The tracking stations have been instrumented with 2S modules, silicon strip detectors developed for the CMS Outer Tracker Phase-2 upgrade [16]. The 2S modules have a $\sim 10 \times 10\,\mathrm{cm}^2$ active area, thus they are capable to cover the full angular acceptance of relevant elastic events. The 40 MHz 2S modules read-out rate is suitable to sustain the M2 beam in-spill rate. The Serenity board [17] developed for the CMS Phase-2 upgrade is used to read-out and control the modules. The continuous data flow of the 2S modules is acquired by the Serenity board, since the M2 beam muons are asynchronous with respect to DAQ clock. The complete data stream was saved to disk during the Test Run, resulting in approximately 350 TB of raw data collected in a week of data taking. The calorimeter is composed of 5×5 $\mathrm{PbWO_4}$ crystals. Each crystal has a $2.85 \times 2.85\,\mathrm{cm}^2$ transverse section and a $22\,\mathrm{cm}$ ($\sim 25X_0$) length, and is read-out by a $1 \times 1\,\mathrm{cm}^2$ APD sensor. The calorimeter data stream has been integrated in the main DAQ only during the last days of the Test Run.

Tracker data are being analyzed to assess the detector performance and optimize the reconstruction algorithms and event selection. The basic signature of a $\mu - e$ elastic scattering is a pair of tracks reconstructed in the downstream station associated with a common vertex to an incoming muon detected upstream. The vertex should lie inside the target, and the three tracks should be planar. Figure 2 shows the effect of a loose selection, concerning the acoplanarity and the vertex χ^2 and position, starting from events with only one track in the upstream station and two tracks in the downstream one. Due to limited particle identification capabilites, the outgoing tracks are labeled according to the magnitude of their angles, denoted as θ_{max} and θ_{min}. This selection allows to reject a large fraction of background events, which lie at low θ_{min}, making the elastic correlation clearly visible. The residual background is removed by cutting events with $\theta_{min} \leq 0.2\,\mathrm{mrad}$, while events with $\theta_{max} \geq 32\,\mathrm{mrad}$ are rejected to remove the natural cutoff due to the detector angular acceptance. Work is ongoing to provide a preliminary measurement of the leptonic running of α, which is about one order of magnitude larger than $\Delta\alpha_{had}$ in the MUonE range, at $O(5\%)$ statistical accuracy.

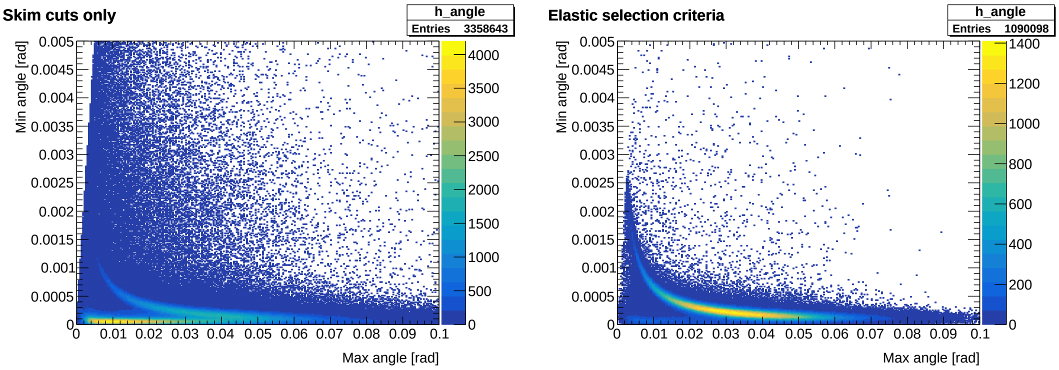

Figure 2: $(\theta_{max}, \theta_{min})$ distribution of elastic scattering candidates before (left) and after (right) the selection cuts as described in the text [18].

5 Conclusions and future plans

The MUonE experiment aims to provide an independent evaluation of a_μ^{HLO}, competitive with the latest results, thus contributing to understand the current muon g-2 puzzle. A Test Run with 2 tracking stations and a calorimeter was held in 2023. Data analysis is currently ongoing. An experiment proposal has been submitted to the CERN SPS Committee in April 2024 [18] to run 4 weeks at the M2 beam line in 2025 with a small scale version of the final apparatus, composed of 3 tracking stations, a calorimeter, a muon filter and the BMS. This would allow to study systematic errors under realistic conditions and to make a preliminary measurement of $\Delta\alpha_{\text{had}}$ with $O(20\%)$ statistical accuracy and comparable systematics. A further proposal is then foreseen to be submitted for the final version of the experiment.

Acknowledgements

The author is grateful to the members of the MUonE Collaboration for their contribution in the studies described in this document, and acknowledges the contributions of the CMS Tracker Group during the Test Run. Author's work is supported by the Leverhulme Trust, LIP-2021-01.

References

[1] D. P. Aguillard, *et al.* (Muon g-2 Collaboration), *Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm*, Phys. Rev. Lett. **131** (2023), doi:10.1103/PhysRevLett.131.161802. D. P. Aguillard, *et al.* (Muon g-2 Collaboration), *Detailed Report on the Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm*, https://arxiv.org/abs/2402.15410.

[2] B. Abi *et al.* (Muon g-2 Collaboration), *Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm*, Phys. Rev. Lett. **126** (2021), doi:10.1103/PhysRevLett.126.141801.

[3] T. Aoyama *et al.* (Muon g-2 Theory Initiative), *The anomalous magnetic moment of the muon in the Standard Model*, Phys. Rept. **887** (2020), doi:10.1016/j.physrep.2020.07.006.

[4] S. Borsanyi *et al.* (BMW Collaboration), *Leading hadronic contribution to the muon magnetic moment from lattice QCD*,Nature **593** (2021),doi:10.1038/s41586-021-03418-1.

[5] F. V. Ignatov *et al.* (CMD-3 Collaboration), *Measurement of the $e^+e^- \to \pi^+\pi^-$ cross section from threshold to 1.2 GeV with the CMD-3 detector*, https://arxiv.org/abs/2302.08834.

[6] B. E. Lautrup *et. al*, *Recent developments in the comparison between theory and experiments in quantum electrodynamics*, Phys. Rept.**3**(1972), doi:10.1016/0370-1573(72)90011-7.

[7] C. M. Carloni Calame *et al.*, *A new approach to evaluate the leading hadronic corrections to the muon g-2*, Phys. Lett. B **746** (2015), doi:10.1016/j.physletb.2015.05.020.

[8] E. Balzani *et. al.*, *Hadronic vacuum polarization contributions to the muon g-2 in the space like region*, Phys. Lett. B **834** (2022), doi:10.1016/j.physletb.2022.137462.

[9] G. Abbiendi *et al.*, *Measuring the leading hadronic contribution to the muon g-2 via μe scattering*, Eur. Phys. J. C **77** (2017), doi:10.1140/epjc/s10052-017-4633-z.

[10] G. Abbiendi *et al.* (MUonE Collaboration), *Letter of Intent: the MUonE project*, `CERN-SPSC-2019-026, SPSC-I-252` (2019), https://cds.cern.ch/record/2677471.

[11] R. Bonciani *et al.*, *Two-Loop Four-Fermion Scattering Amplitude in QED*, Phys. Rev. Lett. **128** (2022), doi:10.1103/PhysRevLett.128.022002. A. Broggio *et al.*, *Muon-electron scattering at NNLO*, JHEP **01** (2023), doi:10.1007/JHEP01(2023)112.

[12] C. M. Carloni Calame *et al.*, *Towards muon-electron scattering at NNLO*, JHEP **28** (2020), doi:10.1007/JHEP11(2020)028. E. Budassi *et al.*, *NNLO virtual and real leptonic corrections to muon-electron scattering*, JHEP **98** (2021), doi:10.1007/JHEP11(2021)098. P. Banerjee *et. al.*, *QED at NNLO with McMule*, SciPost Phys. **9** (2020), doi:10.21468/SciPostPhys.9.2.027.

[13] G. Abbiendi *et. al.*, *Lepton pair production in muon-nucleus scattering*, https://arxiv.org/abs/2401.06077.

[14] G. Abbiendi, *Status of the MUonE experiment*, Phys. Scr. **97** (2022) doi:10.1088/1402-4896/ac6297.

[15] F. Ignatov *et. al.*, *An alternative evaluation of the leading-order hadronic contribution to the muon $g-2$ with MUonE*, Phys. Lett. B **848** (2024) doi:10.1016/j.physletb.2023.138344.

[16] CMS Collaboration, *The Phase-2 Upgrade of the CMS Tracker*, CERN-LHCC-2017-009, CMS-TDR-014 (2017), https://cds.cern.ch/record/2272264.

[17] A. Rose *et al.*, *Serenity: An ATCA prototyping platform for CMS Phase-2*, PoS(TWEPP2018) **343** (2019), doi:10.22323/1.343.0115.

[18] G. Abbiendi *et al.* (MUonE Collaboration), *Proposal for phase 1 of the MUonE experiment*, `CERN-SPSC-2024-015, SPSC-P-370` (2024), https://cds.cern.ch/record/2896293/.