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

Riccardo N. Pilato

University of Liverpool, Liverpool, United Kingdom

r.pilato@liverpool.ac.uk

The 17th International Workshop on Tau Lepton Physics (TAU2023)
Louisville, USA, 4-8 December 2023
doi:10.21468/SciPostPhysProc.17

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.

Received 2024-06-28
Accepted 2024-12-18
Published 2025-07-23
doi:10.21468/SciPostPhysProc.17.024

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 [1,2], which is in perfect agreement with their previous result obtained from data collected in 2018 [3]. 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 [4]. 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 [5], 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 [6]. It follows that a clarification of the theoretical prediction is required to maximize the discovery potential of new physics effects from the experimental efforts.

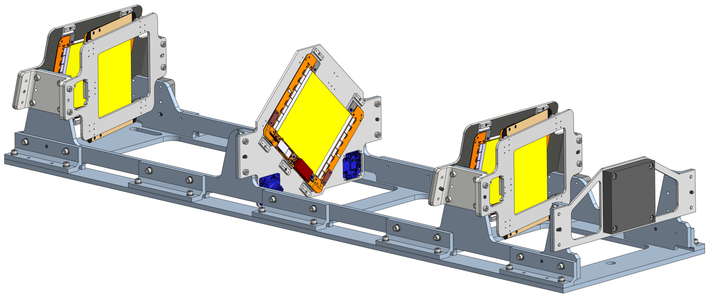

Figure 1: CAD drawing of a MUonE station.

2 The MUonE experimental proposal

MUonE aims to determine a_μ^{HLO} using an independent approach, which is based on the measurement of the hadronic contribution to the running of the electromagnetic coupling constant ($\Delta\alpha_{\mathrm{had}}$) in the space-like region. The following equation will be used to calculate a_μ^{HLO} [7,8]:

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

where α is the fine structure constant and m_μ is the muon mass. Replacing the leading-order kernel $(1-x)$ in Eq. 1 with the higher order ones recently computed in [9], MUonE will also be able to determine the NLO and NNLO hadronic vacuum polarization contributions to a_μ. $\Delta\alpha_{\mathrm{had}}(t)$ will be extracted from the shape of the differential cross section of the $\mu^+e^- \to \mu^+e^-$ elastic scattering [10], which will be observed using a high energy muon beam off a fixed target. The scattering angles of the outgoing particles are correlated by kinematics, and this allows to reject effectively 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 be performed at the CERN SPS M2 beam line, which provides 160 GeV muons with an average in-spill rate of $\sim 50\,\mathrm{MHz}$.

The apparatus consists of a repetition of 40 identical stations, each composed of a beryllium or carbon target $\sim 1.5\,\mathrm{cm}$ thick, followed by a tracking system with a lever arm of 1 m. The tracking system is made up of 6 silicon strip detectors and is used to measure the scattering angles with high precision. Figure 1 shows the layout of a tracking station. 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. The modular structure of MUonE allows to re-use the incoming muon beam for each station, which acts as an independent unit. In this way, $\mu - e$ elastic events will be distributed along the entire apparatus, increasing the collected statistics but minimizing the single target thickness at the same time. This helps to keep under control multiple scattering effects, which break $\mu - e$ angular correlation.
This design is adequate to reach an integrated luminosity of $\sim 15\,\mathrm{fb}^{-1}$ in 3 years of data taking, which corresponds to collect $\sim 4\times 10^{12}$ elastic events with electron energy > 1 GeV. This allows to obtain a statistical error of $\sim 0.3\%$ on a_μ^{HLO}, making the measurement of MUonE competitive with the latest evaluations. The main challenge is to keep the systematic error at the same level, which is equivalent to measure the shape of the differential cross section with a systematic accuracy of 10 ppm at the peak of the integrand function [10]. This requires a significant effort on

the theoretical side, since the higher order corrections to the μ–e differential cross section must be known at least to the NNLO [10]. New results have been obtained to compute the required amplitudes [12, 13], while two independent Monte Carlo codes are under development [14–16]. Furthermore, a dedicated Monte Carlo generator has been developed to simulate the pair production from muon scattering on nuclei [17]. Amongst the main sources of systematic error on the experimental side there are the longitudinal alignment of a station, which must be controlled at $\sim 10\,\mu$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 [11]:

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

which has two free parameters. The extraction of $\Delta\alpha_{\text{had}}$ is carried out through a template fit to the 2D distribution of the muon and electron scattering angles [18]. Different templates are obtained from a unique Monte Carlo sample, whose events are reweighted such that $\Delta\alpha_{\text{had}}$ 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_μ^{HLO} can be computed by substituting the best fit function in Eq. 1. Recently, an alternative method has been proposed to calculate a_μ^{HLO} from MUonE data [19]. Instead of using Eq. 1, the proposed method relies on the knowledge of the derivatives of $\Delta\alpha_{\text{had}}$ at zero momentum transfer, which allow to compute $\sim 99\%$ of a_μ^{HLO} from MUonE data. The remaining 1% can be calculated using perturbative QCD and $e^+e^- \to$ hadrons data. Figure 2 shows values of a_μ^{HLO} obtained from the two methods for different parameterizations of $\Delta\alpha_{\text{had}}$. 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 $\Delta\alpha_{\text{had}}$ 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 $\Delta\alpha_{\text{had}}$ 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.

4 Test run 2023

The MUonE Collaboration submitted a Letter of Intent to the CERN SPS Committee in 2019 [11] obtaining recommendations for a 3 weeks Test Run in Summer 2023, to demonstrate the

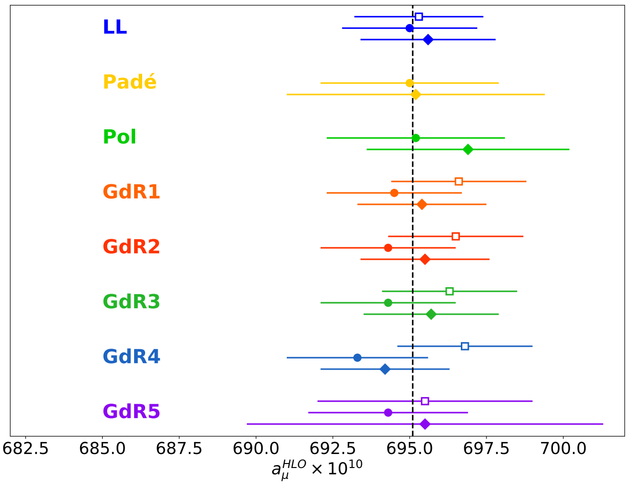

Figure 2: Values of a_μ^{HLO} obtained for different parameterizations of $\Delta\alpha_{\mathrm{had}}$ using Eq. 1 (empty squares), or the alternative method described in [19] (circles and diamonds). The results for the Padé and Pol parameterizations computed using Eq. 1 are outside the plot range. The black dashed line represents the reference value used in the study.

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 2S modules developed for the CMS Outer Tracker Phase-2 upgrade [20] have been chosen as the basic tracking unit. Their 40 MHz read-out is adequate to sustain the M2 beam in-spill rate, and the active area of $\sim 10\times10\,\mathrm{cm}^2$ allows to use a single module to cover the entire angular acceptance. The 2S modules are read-out by the Serenity board [21] developed for the CMS Phase-2 upgrade. Muons from the M2 beam are asynchronous with respect to the 2S modules clock, therefore the continuous 40 MHz data flow from the modules is captured by the Serenity board. The entire 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 a matrix of 5×5 $PbWO_4$ crystals, resulting in a $14\times14\,\mathrm{cm}^2$ active area which allowed to cover the full acceptance of scattering events. Each crystal has a section of $2.85\times2.85\,\mathrm{cm}^2$ and a length of 22 cm ($\sim 25X_0$), and is read-out by a $1\times1\,\mathrm{cm}^2$ APD sensor. The data stream from the calorimeter has been integrated in the main DAQ system 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 3 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.

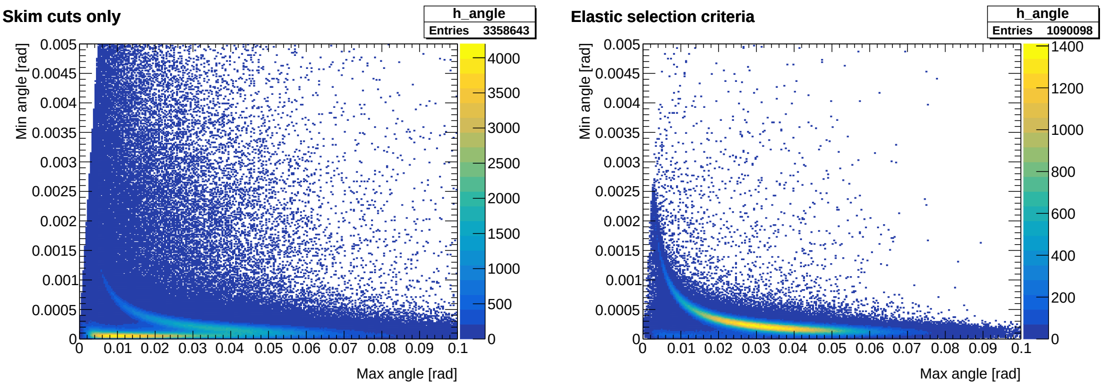

Figure 3: $(\theta_{max}, \theta_{min})$ distribution of elastic scattering candidates before (left) and after (right) the selection cuts as described in the text [22].

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 [22] 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 $\Delta\alpha_{\mathrm{had}}$ with $O(20\%)$ statistical accuracy and comparable systematics. A further proposal is then foreseen to be submitted for the final version of the experiment.

Acknowledgments

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.

Funding information Author's work is supported by the Leverhulme Trust, LIP-2021-01.

References

[1] D. P. Aguillard et al., *Measurement of the positive muon anomalous magnetic moment to 0.20 ppm*, Phys. Rev. Lett. **131**, 161802 (2023), doi:10.1103/PhysRevLett.131.161802.

[2] D. P. Aguillard et al., *Detailed report on the measurement of the positive muon anomalous magnetic moment to 0.20 ppm*, Phys. Rev. D **110**, 032009 (2024), doi:10.1103/PhysRevD.110.032009.

[3] B. Abi et al., *Measurement of the positive muon anomalous magnetic moment to 0.46 ppm*, Phys. Rev. Lett. **126**, 141801 (2021), doi:10.1103/PhysRevLett.126.141801.

[4] T. Aoyama et al., *The anomalous magnetic moment of the muon in the Standard Model*, Phys. Rep. **887**, 1 (2020), doi:10.1016/j.physrep.2020.07.006.

[5] S. Borsanyi et al., *Leading hadronic contribution to the muon magnetic moment from lattice QCD*, Nature **593**, 51 (2021), doi:10.1038/s41586-021-03418-1.

[6] F. V. Ignatov et al., *Measurement of the $e^+e^- \to \pi^+\pi^-$ cross section from threshold to 1.2 GeV with the CMD-3 detector*, Phys. Rev. D **109**, 112002 (2024), doi:10.1103/physrevd.109.112002.

[7] B. E. Lautrup, A. Peterman and E. de Rafael, *Recent developments in the comparison between theory and experiments in quantum electrodynamics*, Phys. Rep. **3**, 193 (1972), doi:10.1016/0370-1573(72)90011-7.

[8] C. M. Carloni Calame, M. Passera, L. Trentadue and G. Venanzoni, *A new approach to evaluate the leading hadronic corrections to the muon $g-2$*, Phys. Lett. B **746**, 325 (2015), doi:10.1016/j.physletb.2015.05.020.

[9] E. Balzani, S. Laporta and M. Passera, *Hadronic vacuum polarization contributions to the muon $g-2$ in the space-like region*, Phys. Lett. B **834**, 137462 (2022), doi:10.1016/j.physletb.2022.137462.

[10] G. Abbiendi et al., *Measuring the leading hadronic contribution to the muon $g-2$ via μe scattering*, Eur. Phys. J. C **77**, 139 (2017), doi:10.1140/epjc/s10052-017-4633-z.

[11] G. Abbiendi, *Letter of intent: The MUonE project*, Tech. Rep. CERN-SPSC-2019-026, CERN, Geneva, Switzerland (2019), https://cds.cern.ch/record/2677471.

[12] R. Bonciani et al., *Two-loop four-fermion scattering amplitude in QED*, Phys. Rev. Lett. **128**, 022002 (2022), doi:10.1103/PhysRevLett.128.022002.

[13] A. Broggio et al., *Muon-electron scattering at NNLO*, J. High Energy Phys. **01**, 112 (2023), doi:10.1007/JHEP01(2023)112.

[14] C. M. Carloni Calame, M. Chiesa, S. M. Hasan, G. Montagna, O. Nicrosini and F. Piccinini, *Towards muon-electron scattering at NNLO*, J. High Energy Phys. **11**, 028 (2020), doi:10.1007/JHEP11(2020)028.

[15] E. Budassi, C. M. Carloni Calame, M. Chiesa, C. L. Del Pio, S. M. Hasan, G. Montagna, O. Nicrosini and F. Piccinini, *NNLO virtual and real leptonic corrections to muon-electron scattering*, J. High Energy Phys. **11**, 098 (2021), doi:10.1007/JHEP11(2021)098.

[16] P. Banerjee, T. Engel, A. Signer and Y. Ulrich, *QED at NNLO with McMule*, SciPost Phys. **9**, 027 (2020), doi:10.21468/SciPostPhys.9.2.027.

[17] G. Abbiendi, E. Budassi, C. M. Carloni Calame, A. Gurgone and F. Piccinini, *Lepton pair production in muon-nucleus scattering*, Phys. Lett. B **854**, 138720 (2024), doi:10.1016/j.physletb.2024.138720.

[18] G. Abbiendi, *Status of the MUonE experiment*, Phys. Scr. **97**, 054007 (2022), doi:10.1088/1402-4896/ac6297.

[19] F. Ignatov, R. N. Pilato, T. Teubner and G. Venanzoni, *An alternative evaluation of the leading-order hadronic contribution to the muon $g-2$ with MUonE*, Phys. Lett. B **848**, 138344 (2024), doi:10.1016/j.physletb.2023.138344.

[20] CMS collaboration, *The phase-2 upgrade of the CMS tracker*, Tech. Rep. CERN-LHCC-2017-009, CERN, Geneva, Switzerland (2017), https://cds.cern.ch/record/2272264.

[21] A. Rose et al., *Serenity: An ATCA prototyping platform for CMS phase-2*, Proc. Sci. **343**, 115 (2019), doi:10.22323/1.343.0115.

[22] G. Hall, U. Marconi, C. Matteuzzi and D. Pocanic, *Proposal for phase 1 of the MUonE experiment*, Tech. Rep. CERN-SPSC-2024-015, CERN, Geneva, Switzerland (2024), https://cds.cern.ch/record/2896293.