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Status of the MUonE experiment

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The latest measurement of the muon g-2 announced at Fermilab exhibits a 4.2σ discrepancy from the currently accepted Standard Model prediction. The main source of uncertainty on the theoretical value is represented by the leading order hadronic contribution a_μ^{HLO}, which is traditionally determined through a data-driven dispersive approach. A recent calculation of a_μ^{HLO} based on lattice QCD is in tension with the dispersive evaluation, and weakens the discrepancy between theory and experiment to 1.5σ. An independent crosscheck of a_μ^{HLO} is thus required to solve this tension and consolidate the theoretical prediction.
The MUonE experiment proposes a novel approach to determine a_μ^{HLO} by measuring the running of the electromagnetic coupling constant in the space-like region, via $\mu - e$ elastic scattering. The measurement will be performed by scattering a 160 GeV muon beam, currently available at CERN's North Area, on the atomic electrons of a low-Z target. A Test Run on a reduced detector is planned to validate this proposal. The status of the experiment in view of the Test Run will be presented.

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1. Introduction

The latest measurement of the muon magnetic anomaly, $a_\mu = (g-2)/2$, was announced by the E989 Muon g-2 Collaboration at Fermilab in 2021 [1], confirming the previous result achieved by the E821 experiment at BNL [2]. Their combination results in a 4.2σ discrepancy with the Standard Model prediction recommended by the Muon g-2 Theory Initiative [3].
The accuracy on the theoretical prediction is limited by the evaluation of the leading order hadronic contribution a_μ^{HLO}, which cannot be computed perturbatively at low energies. For this reason, a_μ^{HLO} is traditionally determined by means of a dispersion integral on the annihilation cross section $e^+e^- \to$ hadrons. This approach allowed to achieve an accuracy of 0.6% on a_μ^{HLO} [3]. Furthermore, a recent evaluation based on lattice QCD techniques reached for the first time an accuracy comparable to the dispersive approach [4]. Nevertheless, such a calculation weakens the discrepancy between theory and experiment to 1.5σ, and shows a 2.2σ tension with the dispersive method.
In the next years, further results are expected by the E989 experiment, aimed at improving by more than a factor of 2 the current accuracy on a_μ [5]. Furthermore, a new technique will be exploited at J-PARC to measure a_μ in an independent way [6]. It follows that an improvement is also required on the theoretical side. For this purpose, a fervent research program is ongoing to clarify the current tension on the evaluation of a_μ^{HLO} [7]. MUonE proposes to determine a_μ^{HLO} using a novel approach [8], independent from the existing ones. It is based on the direct measurement of the hadronic contribution to the running of the electromagnetic coupling constant ($\Delta\alpha_{\mathrm{had}}$) in the space-like region, namely for negative momentum transfer t. The following equation will be used to calculate a_μ^{HLO} [8, 9]:

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

where α is the fine structure constant and m_μ is the muon mass. The main advantage of this method is that $\Delta\alpha_{\mathrm{had}}$ is a smooth function for $t < 0$, in contrast with the dispersive approach, which must deal with the presence of resonances and flavour threshold effects in the time-like e^+e^- data.

2. The MUonE experimental proposal

The MUonE experiment aims at extracting $\Delta\alpha_{\mathrm{had}}$ from a precise measurement of the shape of the differential cross section of the $\mu^+e^- \to \mu^+e^-$ elastic scattering [10]. The measurement is performed by scattering a high energy muon beam on the atomic electrons of a light beryllium or carbon target. A 160 GeV muon beam, available at CERN M2 beamline, allows to cover the momentum transfer region $-0.153\,\mathrm{GeV}^2 < t < 0\,\mathrm{GeV}^2$, which is equivalent to $0 < x < 0.936$. This corresponds to $\sim 88\%$ of the master integral in Eq. 1. The remaining fraction can be computed by extrapolating $\Delta\alpha_{\mathrm{had}}$ with an appropriate parameterization [11, 12].
The experimental apparatus consists of a repetition of 40 identical stations, which act as independent units. The layout of a single station is shown in Fig. 1. It is composed of a 1.5 cm thick target, followed by a tracking system with a lever arm of ~ 1 m, which consists of 3 pairs of silicon strip detectors and is used to measure the scattering angles with high precision. The detectors in each pair are rotated by 90° with respect to each other, in order to measure both the transverse directions. An electromagnetic calorimeter is placed downstream of all the stations, to provide particle

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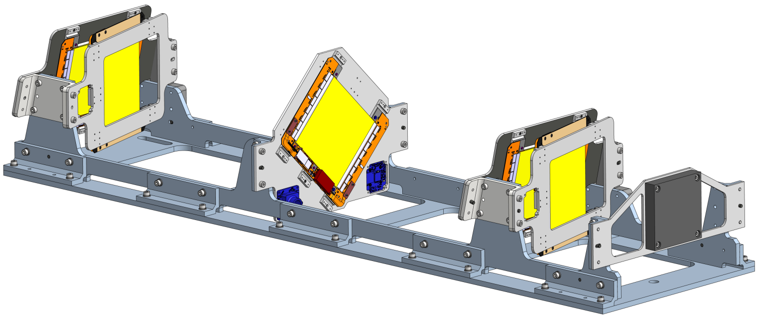

Figure 1: CAD drawing of a MUonE station.

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identification and improve event selection. The apparatus will be also equipped with a muon filter, placed downstream of the calorimeter. This design is adequate to reach an integrated luminosity of $1.5 \times 10^7 \mathrm{nb}^{-1}$ in 3 years of data taking at the M2 beamline, and allows to achieve a statistical error of $\sim 0.3\%$ on a_μ^{HLO}. The main challenge is to keep the systematic error at the same level of the statistical one. This 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, 12]. From the theoretical side, such a goal requires the knowledge of higher order corrections to the elastic scattering differential cross section up to the NNLO. State of art reviews of the theoretical progress are given in [13].

3. Towards the Test Run

The MUonE Collaboration submitted a Letter of Intent to the CERN SPS Committee in 2019 [11], obtaining recommendations for a 3 weeks Test Run to validate the experimental proposal. The Test Run will be mainly aimed at monitoring the mechanical and thermal stability of the apparatus, as well as confirming the validity of the system engineering. It will be also crucial to check the integrity of the DAQ system and test the software alignment procedures. The detector will be composed of two MUonE stations followed by an electromagnetic calorimeter. A further tracking station without target will be placed upstream of the apparatus, to detect the incoming muons. The current status in preparation of the Test Run, to be held in 2023, will be reported in the following.

Tracking system The tracker mechanical structure is made of Invar, a Fe-Ni alloy with a low coefficient of thermal expansion ($\sim 1.2\times10^{-6}\,\mathrm{K}^{-1}$). This is required to keep the longitudinal stability within 10 µm, thereby satisfying the 10 ppm requirement on the systematic uncertainty. For this purpose, a laser holographic system will be used to monitor the longitudinal stability. Moreover, an enclosure and a cooling system have been designed to keep the temperature constant within 1 °C. Two Invar structures are currently assembled, while the third one will be completed soon.
The basic tracking unit has been chosen to be the 2S modules developed for the CMS Outer Tracker Phase-2 upgrade [14]. Each module is composed of 2 close-by silicon strip sensors reading the same coordinate and read-out by the same front-end electronics, with the purpose of finding correlated hits. This feature can be exploited to reject large angle tracks, which are not interesting for the measurement of $\Delta\alpha_{\mathrm{had}}$. The active area of about $10 \times 10\,\mathrm{cm}^2$ allows to use a single module to cover the entire angular acceptance, thus ensuring a uniform response. 2S modules have a resolution of ~ 26 µm, which can be further improved by rotating a module around the strip axis. Simulation

studies performed by MUonE show that a tilt of 233 mrad ($\sim$ 13°) improves the resolution to $\sim$ 10 µm [12]. Accordingly, the first and third pairs of 2S modules in the MUonE station are tilted to exploit such an improvement. In order to enable the tilt around two orthogonal directions, these modules are hosted on different frames. The second pair is instead rotated by 45° around the beam axis to solve reconstruction ambiguities, and the modules are hosted on the same frame. Finally, the 2S modules 40 MHz read-out rate is capable to sustain the M2 beamline in-spill rate of 50 MHz.

The Serenity board [15] developed for the CMS Phase-2 upgrade is used to control and read-out the 2S modules. Since muons from the M2 beamline are asynchronous with respect to the 2S modules clock, the continuous 40 MHz data flow from the 2S modules is captured by the Serenity board. In the Test Run, the entire data stream will be saved to disk, in order to elaborate online selection algorithms that will be implemented in the successive runs with additional stations.

Preliminary tests of the MUonE DAQ chain occurred at the M2 beamline in a joint effort with the CMS Tracker Group, using an aluminum mockup of a MUonE station partially equipped with 2S modules. In November 2021, the mockup was instrumented with two 2S modules, while two additional ones were hosted in an external box, placed upstream of the station. The apparatus was located at the end of the beamline to take data parasitically during the NA64μ run. During Summer 2022, MUonE exploited the possibility of taking data for intermittent periods thanks to an agreement with COMPASS. The aluminum mockup, instrumented with four 2S modules, was therefore installed upstream of the COMPASS detector, in the final MUonE location. These tests provided a first successful demonstration of the DAQ chain running and of the 2S modules time synchronization. Furthermore, positive indications on the thermal stability of the system were obtained.
A dedicated Beam Test has been held in October, with a fully instrumented tracking station. Data analysis is currently ongoing. The main goals are to characterize the 2S modules response, test track reconstruction algorithms and verify the identification of two tracks events with a common vertex.

Electromagnetic calorimeter The Test Run electromagnetic calorimeter is composed of a matrix of 5×5 $PbWO_4$ crystals. The total area of $14 \times 14\,\text{cm}^2$ allows to cover the full acceptance for the scattering events from the two MUonE stations. Each crystal has a section of $2.85 \times 2.85\,\text{cm}^2$ and a length of 22 cm ($\sim 25X_0$), and will be read-out by APD sensors. A first Beam Test took place at CERN East Area in July 2022, to test the calorimeter DAQ and perform a first calibration using low energy electrons. In October, the calorimeter was installed downstream of the tracking station at the M2 beamline, for a calibration with 40 GeV electrons. Data analysis is currently ongoing.

Test Run analysis strategy Assuming to complete the detector commissioning in the first two weeks of the Test Run, the remaining days could be exploited to collect $\sim 5\,\text{pb}^{-1}$ of good quality data. This will provide an initial sensitivity to $\Delta\alpha_{\text{had}}$, which is $\lesssim 10^{-3}$ in the MUonE kinematic region. Given the limited statistics, the effect of $\Delta\alpha_{\text{had}}$ can be modeled as a linear deviation in t on the shape of the differential cross section. It can be studied considering the ratio R_{had} between the observed differential cross section and the theoretical prediction computed only considering the leptonic running, which is $\lesssim 10^{-2}$. The extraction of $\Delta\alpha_{\text{had}}$ is carried out by means of a template fit method [11, 12]. The Test Run will be also important to assess the strategy to handle systematic effects. One of the main systematics is due to multiple scattering, which breaks the kinematic correlation between muon and electron. Preliminary studies show that this effect can be controlled at the level of ±1% [16]. The effect of a multiple scattering systematic error is shown in Fig. 2. The largest effect is in

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the so-called normalization region, which corresponds to elastic events where the scattered electron is emitted at large angles and low energy, while the muon is scattered at low angle keeping most of its initial energy. Here, $\Delta\alpha_{\text{had}}$ is negligible. Systematic effects are included as nuisance parameters in the template fit, and are identified through vertical interpolation of the template histograms. For this purpose, the `combine` analysis tool is employed [17]. Table 1 shows results of a combined fit to the signal and a nuisance parameter modeling a systematic error in the multiple scattering model. The fit is performed on a pseudo-data sample generated by shifting the multiple scattering model of +0.5% with respect to the expectations. Fit results are in good agreement with the input values. The procedure was succesfully tested including further systematic effects simultaneously.

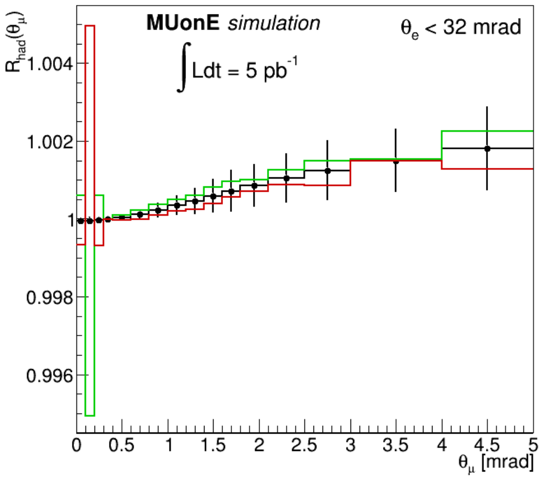

Figure 2: R_{had} as a function of the muon scattering angle. The error bars correspond to the Test Run statistical uncertainty. Effect of a ±1% systematic error on the multiple scattering modelization on R_{had}: red/green lines respectively.

Selection cuts	Fit results
$\theta_e \leq 32$ mrad	$K = 0.136 \pm 0.028$
$\theta_\mu \geq 0.2$ mrad	$\mu_{\text{MS}} = 0.51\% \pm 0.01\%$

Table 1: Template fit results for the Test Run statistics. K is the slope of the hadronic running, μ_{MS} is the nuisance parameter modeling multiple scattering errors. Expected values: $K = 0.137$, $\mu_{\text{MS}} = 0.5\%$.

4. Conclusions and future plans

The MUonE experiment will provide an independent evaluation of a_μ^{HLO}, competitive with the latest evaluations, thus contributing to understand the current muon g-2 puzzle. An intense activity is ongoing for the preparation of the Test Run, which will be a proof of concept of the overall project. If successful, a full proposal will be prepared including support from the Test Run results. The full detector construction will then take place, with the prospect of performing a first measurement of a_μ^{HLO} before the Long Shutdown 3 foreseen in 2026-28.

Acknowledgments

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References

[1] 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) 141801 [hep-ex/2104.03281].

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[2] G. W. Bennett *et al.* (Muon g-2 Collaboration), *Final report of the E821 muon anomalous magnetic moment measurement at BNL*, *Phys. Rev. D* **73** (2006) 072003 [hep-ex/0602035].

[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) 1-166 [hep-ph/2006.04822].

[4] S. Borsanyi *et al.* (BMW Collaboration), *Leading hadronic contribution to the muon magnetic moment from lattice QCD*, *Nature* **593** (2021) 51-55, [hep-lat/2002.12347].

[5] J. Grange *et al.* (Muon g-2 Collaboration), *Muon (g-2) Technical Design Report*, FERMILAB-FN-0992-E (2015), [physics.ins-det/1501.06858].

[6] M. Abe *et al.*, *A new approach for measuring the muon anomalous magnetic moment and electric dipole moment*, PTEP **5** (2019) 053C02, [physics.ins-det/1901.03047].

[7] G. Colangelo *et al.*, *Prospects for precise predictions of a_μ in the Standard Model*, [hep-ph/2203.15810] (2022)

[8] 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) 325-329, [hep-ph/1504.02228].

[9] B. E. Lautrup, A. Peterman, E. de Rafael, *Recent developments in the comparison between theory and experiments in quantum electrodynamics*, Phys. Rept. **3** (1972) 193-259.

[10] G. Abbiendi *et al.*, *Measuring the leading hadronic contribution to the muon g-2 via μe scattering*, Eur. Phys. J. C **77** (2017) 139, [hep-ex/1609.08987].

[11] G. Abbiendi *et al.* (MUonE Collaboration), *Letter of Intent: the MUonE project*, CERN-SPSC-2019-026, SPSC-I-252 (2019).

[12] G. Abbiendi, *Status of the MUonE experiment*, Phys. Scr. **97** 054007 (2022), [physics.ins-det/2201.13177].

[13] P. Banerjee *et al.* (MUonE Theory Initiative), *Theory for muon-electron scattering @ 10 ppm*, Eur. Phys. J. C **80** (2020) 591, [hep-ph/2004.13663]. E. Budassi, *High precision calculations for the MUonE experiment*, *PoS(ICHEP2022)* **414** (2022).

[14] CMS Collaboration, *The Phase-2 Upgrade of the CMS Tracker*, CERN-LHCC-2017-009, CMS-TDR-014 (2017).

[15] A. Rose *et al.*, *Serenity: An ATCA prototyping platform for CMS Phase-2*, PoS(TWEPP2018) **343** (2019) 115.

[16] G. Abbiendi *et al.*, *Results on multiple Coulomb scattering from 12 and 20 GeV electrons on carbon targets*, JINST **15** (2020) P01017, [physics.ins-det/1905.11677].

[17] combine tool: https://cms-analysis.github.io/HiggsAnalysis-CombinedLimit. ATLAS and CMS Collaborations, *Procedure for the LHC Higgs boson search combination in Summer 2011*, CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11 (2011).

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