Status of the MUonE experiment

E. Hess([1])([2])([*]) on belhalf of the MUonE Collaboration

([1]) *INFN and University of Pisa - Pisa, Italy*
([2]) *University of Rijeka - Rijeka, Croatia*

Summary. — The MUonE experiment at CERN aims to determine the leading-order hadronic contribution to the muon $g-2$ by an innovative approach, using elastic scattering of 160 GeV muons on atomic electrons in a low-Z target. The M2 beam line at CERN provides the necessary intensity needed to reach the statistical goal in few years of data taking. The experimental challenge relies in the precise control of the systematic effects. A first run with a minimal prototype setup was carried out in 2023. A pilot run has been approved to be held in 2025 with a reduced setup of the full detector components. We will present the status of the experiment, first preliminary results and the future plans.

1. – Introduction

The muon's anomalous magnetic moment, $a_\mu = (g-2)/2$, provides one of the most sensitive tests of the Standard Model. In the early 2000s, Brookhaven National Laboratory's (BNL) Muon g–2 experiment reported a 3.7σ deviation from theoretical expectations, suggesting potential new physics. In June 2025, the Muon g-2 experiment at Fermilab released its final measurement achieving a 4-fold improvement in precision over the confirmed BNL result [1].

While the experimental precision has significantly improved, the uncertainty of the Standard Model theoretical prediction remains approximately four times larger. The dominant source of uncertainty in the Standard Model prediction comes from hadronic effects, notably the hadronic vacuum polarization (HVP) term. Traditionally, HVP has been estimated via a dispersive, data-driven approach using the $e^+e^- \to$ hadrons cross-sections as an input. However, conflicting results, most notably between CMD-3 and earlier experiments, have undermined the reliability of the dispersive estimate. In parallel, the lattice QCD approach, a purely computational method free from experimental inputs, has recently made significant advances. Its latest calculations raise the Standard Model prediction to align with Fermilab's measurements.

([*]) emma.hess@df.unipi.it

Although experiment and theory are now in agreement, important challenges remain. Discrepancies among e^+e^- cross-section measurements need to be resolved, and lattice-QCD techniques refined to achieve sub-percent precision. One of the experimental efforts aimed at resolving these tensions is the MUonE experiment, which employs a novel method to determine the leading-order HVP contribution via elastic muon–electron scattering, offering an independent cross-check and deeper insight into the remaining uncertainties.

2. – The MUonE experiment

The leading-order hadronic contribution, a_μ^{HLO}, can be determined via an innovative method that exploits the hadronic running of the QED coupling, $\Delta\alpha_{\mathrm{had}}(t)$ [2]. In this approach, $\Delta\alpha_{\mathrm{had}}(t)$ is extracted from the angular distribution of the elastic scattering process $\mu^+e^- \to \mu^+e^-$ by measuring the differential cross section as a function of the momentum transfer t (see fig 1).

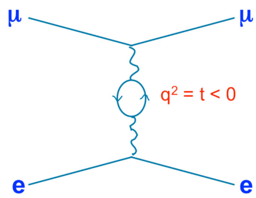

Fig. 1.: Feynman diagram corresponding to the μ^+e^- elastic scattering.

The quantity a_μ^{HLO} is then computed through the dispersion integral

$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)] \tag{1a}$$

with $t(x) = -\frac{x^2}{1-x}m_\mu^2$.

The experiment utilizes a 160 GeV asynchronous muon beam, delivered at a 50 MHz rate by the M2 beam line in CERN's North Area. The high intensity of the M2 beam is essential to reach a target statistical uncertainty of 0.3% on a_μ^{HLO} within a few years of data taking, with systematic uncertainties controlled to a comparable level [3].

To measure the scattering angles of muons on atomic electrons in low-Z targets with high precision, the final apparatus will comprise:

- Forty identical tracking stations, each equipped with a 2 cm graphite target (except the first station) and six silicon-strip 2S modules (developed for the CMS Phase-2 upgrade [4]) to accurately measure the scattering angles of muons and electrons,
- An incoming-muon spectrometer for beam characterization,
- An electromagnetic calorimeter (ECAL) for energy measurement of scattered electrons and enable particle identification (PID),
- A muon identification system for correct identification of the interacting muons (to distinguish from the pion contamination or pileup muons).

3. – The 2023 Test Run

In 2023, a dedicated Test Run data taking was performed to validate the detector design, data acquisition, and analysis procedures. The experimental apparatus consisted of two tracking stations, with a graphite target of either 2 cm or 3 cm thickness before the second station, and followed by an electromagnetic calorimeter (ECAL) as depicted in fig 2. This configuration allowed precise reconstruction of incoming and scattered particles. Data were acquired using a triggerless readout system operating at 40 MHz, yielding approximately 350 TB of raw data over a one-week period [5].

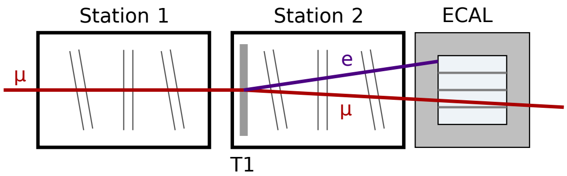

Fig. 2.: Schematic of two tracking stations and a graphite target (not to scale).

3˙1. *Event Preselection.* – Accurate identification of elastic muon–electron scattering events is essential in MUonE, particularly to suppress backgrounds such as electron–positron pair production, bremsstrahlung, and inelastic nuclear interactions. Pair production is one of the main sources of contamination since it can mimic the signal if one of the produced leptons goes undetected.

During the 2023 test run, data were recorded continuously at 40 MHz without any hardware trigger. As a result, non-interacting muons, partial or corrupt readouts, and abundant background events had to be removed offline, in software. An offline skimming algorithm was therefore developed: it examines only the hit patterns in the silicon-strip modules to extract good elastic-scattering candidates. It distinguishes between trackable events (those with hits in both stations), single muon interaction candidates, and pileup muon interaction candidates (see fig 3).

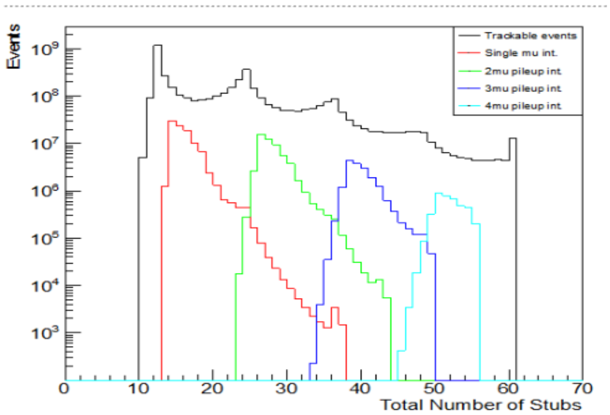

Fig. 3.: Histogram showing data events which passed the skimming selection: trackable events (have hits in both stations), single muon and pileup muon interaction candidates.

This kind of preselection reduces the dataset to high-quality events and was thoroughly studied to be applied as a real-time trigger in the 2025 physics run.

3˙2. *Elastic Selection Cuts*. – After passing the preselection, candidate elastic scattering events undergo the elastic selection to remove events that would affect the precision of the final measurement. The main source of the contamination in this case comes from the various types of background interactions that have similar detector signatures, interactions that happen on the silicon detector instead of target, that are not reconstructed correctly *etc*.

To preserve valuable events, the following cuts were applied:

- Fiducial region requirement for incoming muons, ensuring full geometric acceptance,
- A maximum of 14 hits in each second station,
- Scattering angles constrained to 0.2 mrad $< \theta <$ 32 mrad,
- Acoplanarity cut to suppress multi-particle backgrounds which don't have a planar geometry like a elastic scattering events,
- Quality cut on the event vertex (1 + 2 track χ^2),
- Longitudinal vertex position within one target thickness: $|z_{\mathrm{vertex}} - z_{\mathrm{target}}| \leq$ (target thickness).
- Elasticity cut: $|\theta_\mu^{\mathrm{rec}} - \theta_\mu^{\mathrm{exp}}(\theta_e)| <$ 0.2 mrad.

3˙3. *Simulation of Signal and Background*. – A detailed Monte Carlo (MC) simulation, based on Geant4, was performed using an idealized detector geometry consisting of two silicon-strip tracking stations and a 3 cm graphite target in between. Approximately 3×10^7 single muons were generated on target to model both signal and background processes. After applying the offline preselection algorithm on MC data, roughly 1.2×10^5 events remained with a composition of: 58.3% elastic signal, 41.4% muon-induced pair production, 0.1% photon-conversion pairs and 0.2% nuclear interactions.

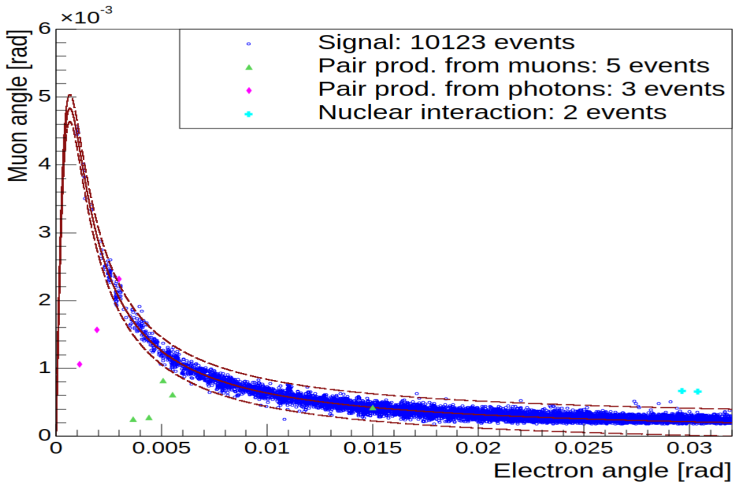

Fig. 4.: Simulated single muon interaction candidates that pass preselection and elastic selection cuts, displayed as correlation between the muon and electron scattering angles.

The key to isolating elastic muon–electron scattering is the correlation between the muon and electron scattering angles, θ_μ and θ_e, which effectively distinguishes signal from background. After the elastic selection, the sample reduces to $\sim 10^4$ candidate events as demonstrated on the fig 4. The remaining background fraction after this loose selection was estimated at $\mathcal{O}(10^{-3})$, improving to $\mathcal{O}(10^{-4})$ once the final elasticity criterion was applied.

3˙4. *Preliminary Analysis*. – The preliminary analysis focused on validating detector performance, reconstruction algorithms, and event selection criteria, as well as studying systematic uncertainties and background processes. The two-dimensional distribution of scattering angles before and after the elastic cuts showed good agreement between data and MC as demonstrated on fig 5.

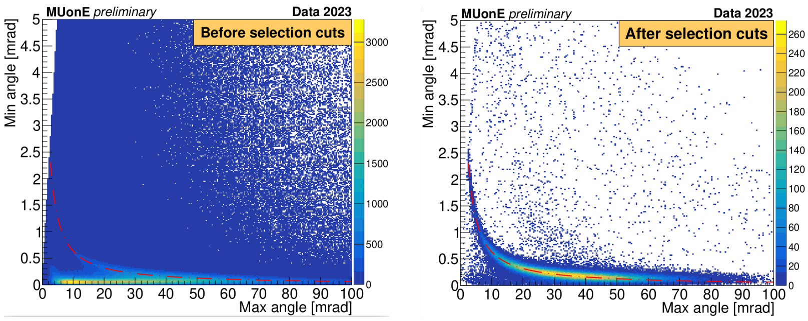

Fig. 5.: All real data single muon interaction candidates that passed preselection (left) and events that passed both preselection and elastic selection cuts (right).

Furthermore, the Data/MC ratio as a function of the electron scattering angle remained within $\pm 3\%$ [6] (see fig 6).

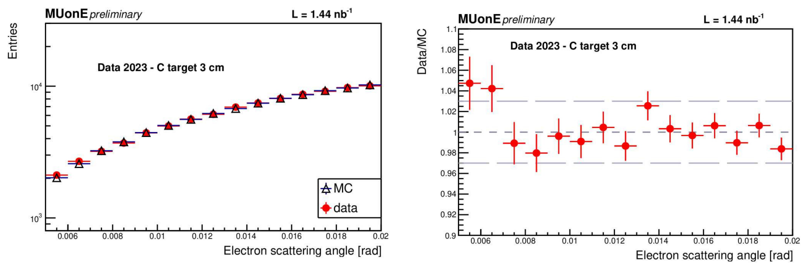

Fig. 6.: Data/MC ratio as a function of the electron scattering angle.

4. – 2025 Run Outlook

The 2025 test run will deploy a scaled-down version of the final MUonE detector, comprising three silicon-strip tracking stations and two 2 cm-thick graphite targets as demonstrated on fig 7. This configuration will exercise all critical subsystems under realistic beam conditions.

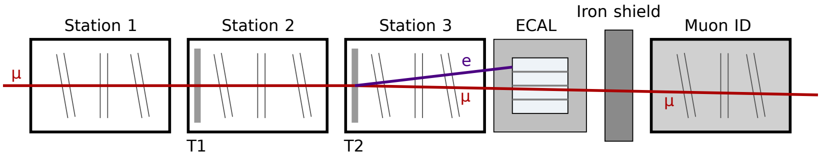

Fig. 7.: Schematic view of tree tracking stations, two graphite targets, ECAL, muon identification system (not to scale) used the 2025 test run.

The primary objectives for the 2025 run are:

1. **Mechanical validation and synchronization:** Verify the tracker alignment, mechanics, and timing synchronization among all detector components.

2. **Beam operation and DAQ performance:** Commission continuous data taking over a four week period in the high intensity 160 GeV muon beam, demonstrating stable and efficient DAQ at 40 MHz.

3. **Real-time processing:** Validate FPGA-based online data reduction algorithms to shrink recorded data volumes without compromising signal efficiency.

4. **Performance studies:** Measure tracking efficiency, particle identification purity, and background rejection in situ, while monitoring beam properties and control systems.

5. **Systematics control:** Demonstrate that systematic uncertainties—arising from alignment, calibration, and background modeling—can be maintained at or below the level dictated by the statistical precision targets.

Successful completion of these goals will confirm the readiness of the full-scale detector for precision measurement of the leading-order hadronic contribution to the muon anomalous magnetic moment.

* * *

This work is supported by the Istituto Nazionale di Fisica Nucleare (Italy), and by the Italian Ministero dell'Università e Ricerca (MUR) and European Union – Next Generation EU through the PRIN research grant number 20225X52RA MUS4GM2.
The MUonE collaboration acknowledges the contribution of the CMS Tracker Group in the 2023 test run.

REFERENCES

[1] The Muon g–2 Collaboration, *Measurement of the Positive Muon Anomalous Magnetic Moment to 127 ppb*, preprint *arXiv*:2506.03069 [hep-ex] (2025).
[2] MUonE Collaboration, *Eur. Phys. J. C*, **77** (2017) 139.
[3] MUonE Collaboration, preprint CERN SPSC-2019-026 / SPSC-I-252.
[4] CMS Collaboration, preprint CMS-TDR-014 (2017).
[5] MUonE Collaboration, preprint CERN-SPSC-2024-015, SPSC-P-370.
[6] Spedicato E., PhD Thesis (2025).