PROCEEDINGS OF SCIENCE

Tackling the muon g-2 anomaly with the MUonE experiment at CERN

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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 method relies on the measurement of the hadronic contribution to the running of the QED coupling, $\Delta\alpha_{had}(t)$, which can be extracted from a precise measurement of the shape of the differential cross section of the elastic process. 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 first preliminary results from the test runs, and discuss the future plans.

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1. Status of the experiment

The leading order (LO) hadronic vacuum polarization term a_μ^{HLO} is currently the dominant source of uncertainty in the theoretical prediction of the muon anomalous magnetic moment (g-2). In 2006, the BNL's E821 experiment [1] provided a measurement of this quantity which deviated 3.7σ from the reference theoretical estimate reported in [2]. In 2025, the final result of the $g-2$ experiment at Fermilab was presented [3], bringing the discrepancy to $> 5\sigma$. However, the theoretical landscape changed along the years. As a_μ^{HLO} is not calculable by perturbative Quantum Chromo Dynamic (QCD), it needs different methods to be evaluated. Until 2021, the theoretical way to estimate it with competitive precision was a data-driven method based on calculation of the e^+e^- hadronic cross section. Lattice QCD (LQCD) estimations have become more precise after 2021, starting from the publication of the BMW collaboration's result [4]. Those calculations, together with the new 2023 CMD-3 experiment [5] measurements on the $e^+e^- \to hadronic$ cross section, result to be compatible with the experimental measurement, weakening the $a_\mu^{th} - a_\mu^{exp}$ discrepancy. The new white paper from the $g-2$ theory initiative has been published this year and only LQCD results have been considered to evaluate the theoretical estimate. With just this contribution, the discrepancy is $< 1\sigma$ [6]. However, as shown in Fig. 1, the landscape keeps on being intriguing and new methods to confirm LQCD are needed.

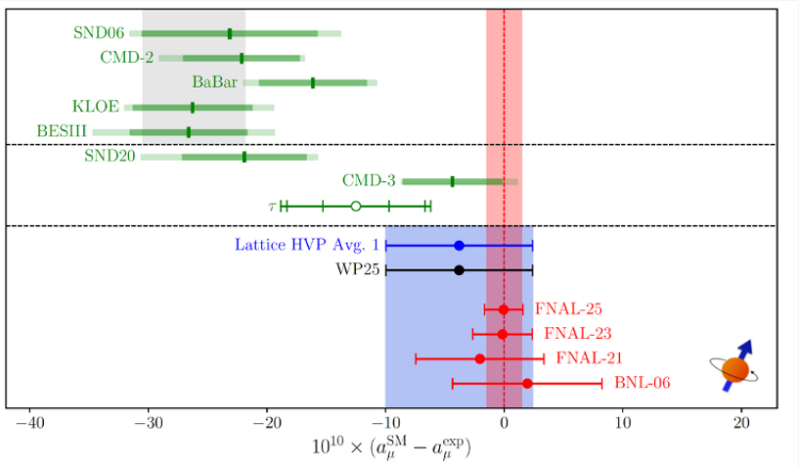

Figure 1: Comparison of SM predictions of the a_μ with its measured value. World-average measurement (red band) compared with the SM prediction from the 2025 white paper (WP) [6] (blue band). The green points represent the dispersive method approach which has not been included in the 2025 WP result.

The goal of the MUonE experiment is to provide a novel and independent way to access this quantity directly through the measurement of the hadronic contribution to the running of the electromagnetic coupling constant in the space-like region of momenta $\Delta\alpha_{had}(t)$ [7]. The proposed process is elastic scattering between high-energy muons from the CERN M2 beam and electrons at rest in low-Z targets. The M2 line is a unique facility worldwide, delivering 160 GeV muons at a high rate exceeding 40 MHz.

In order to be competitive, the precision that needs to be reached is $< 0.5\%\, a_\mu^{HLO}$, so the challenge stands in the precision required. The project was submitted to the CERN SPS Committee with a Letter of Intent in 2019 [9] and a technical proposal was presented at the SPSC in 2024 for the

phase 1 of the experiment [10], which has taken place during summer 2025.
The aim is to measure the electron and the muon scattering angles, which results proportional to $\Delta\alpha_{had}(t)$. To achieve this, we designed the detector as a modular system composed of 40 tracking stations interleaved with thin low-Z targets, as shown in Fig. 2, an electromagnetic calorimeter (ECAL) and a muon filter (MF) at the end. This geometry is essential to reduce multiple scattering

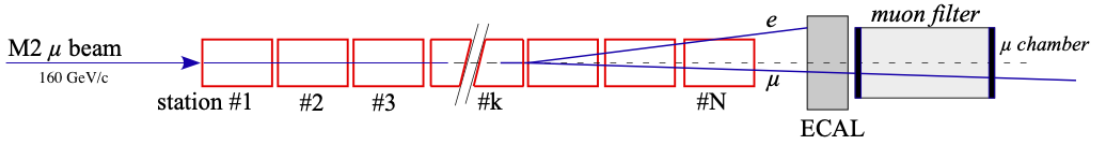

Figure 2: Schematic view of the MUonE apparatus.

effects, thereby preserving the leptons' angular resolution required for precise measurements. Additionally, thin targets minimize muon bremsstrahlung and electron-positron pair production, which are the primary sources of background. When the two leptons interact elastically, their scattering angles are precisely correlated as shown in Fig. 3, and this helps signal selection.

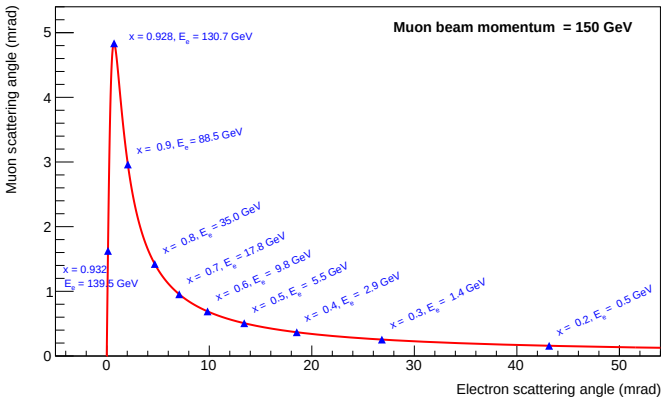

Figure 3: The relation between the muon and electron scattering angles when they interact elastically.

In the current detector design, each tracking station is equipped with six silicon strips tracking modules, the so-called 2S modules, developed by the CMS collaboration for their upcoming detector upgrade. These modules can provide hit information at a rate of 40 MHz, matching the high intensity of the M2 beam line.

The detector prototype under test during Phase I is composed by three tracking stations, a small prototype of the ECAL, the muon filter and an additional beam momentum spectroeter (BMS). The TDR development phase will span three years during the LHC Long Shutdown 3, with the aim of potentially starting the experiment at the end of it, followed by three years of data taking. The detector's modular design allows to scale it up gradually to the 40 tracking stations foreseen for the final experiment.
Several tests have been run over the past years, from 2017-2018 where the multiple scattering effect

and the capability of selecting elastic event were studied [12, 13], to 2023, where the first prototype with two tracking stations, one target and the ECAL was carried out. In 2025 the Phase I of the experiment has taken place, where a more complete setup was tested for the first time.

2. Test Run 2023

In the 2023 test run we used 160 GeV muons at the CERN M2 beam line with a maximum asynchronous rate of 35 MHz. The setup was composed by the ECAL and 2 full tracking stations. The DAQ operated without any trigger on FPGAs, data were then processed offline using a skimming

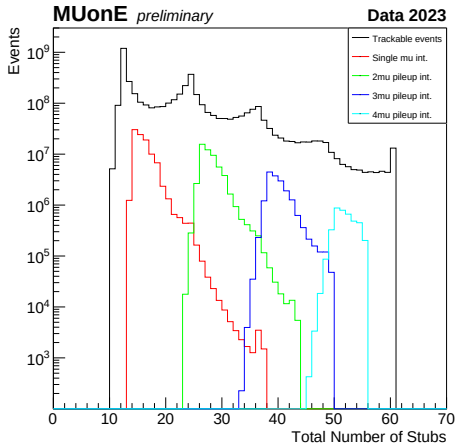

Figure 4: Event classification in terms of incoming muon multiplicity obtained by the filtering algorithm for a high-intensity 2023 run.

algorithm. This algorithm preselected candidate events from target interactions based on the hit pattern in the two stations. The procedure reduced the output rate to just a few percent. Fig. 4 shows the fraction of different event multiplicities, selected by the skimming procedure from an initial sample of about 12B events, recorded during one of the runs of the data taking.
As two full tracking stations were available during the test, we had the opportunity to select elastic events happening in the target within them for the first time. The result of the elastic selection is shown in Fig. 5. The angular distribution and the data over MC ratios are shown in Fig. 6 as a function of the electron scattering angle, where the MC sample is normalized to the data integral after the elastic selection. This allows the differences in the shapes of the distributions to be examined. The ratio between data and MC as a function of the electron scattering angle, shown in the right plot, remains within ±3% across the entire range [14]. This results to be the first preliminary result with a very small statistics of data. However, for the running of $\alpha(t)$ to be observed, the MC description of angular shapes must be accurate to within at least 0.5%. Still, work is in progress to improve MC description of real data and this will help us in getting closer to the needed accuracy.

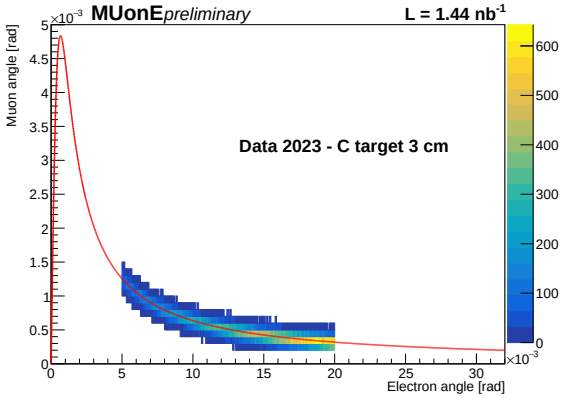

Figure 5: 2D plot of the the muon's scattering angle vs. the electron's one after a basic elastic selection. The red curve represent the elastic function that correlates the angles.

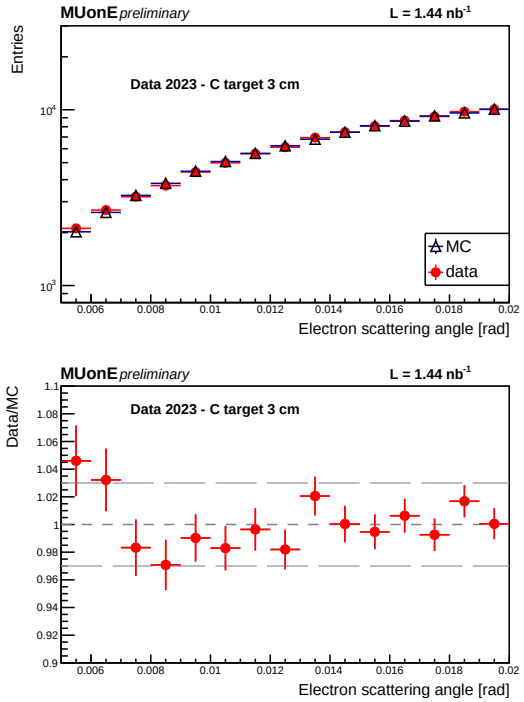

Figure 6: Top plot: distribution of the electron scattering angle for data and MC, normalized to the data. Bottom plot: ratio of data and MC. The grey dashed lines mark the unit ratio and a band of ±3%.

3. MUonE's Phase 1 (2025)

The phase 1 of MUonE was carried out with the 160 GeV muon M2 beam line at CERN from May to August 2025. This year all detectors foreseen for the final experiment were tested: 3 tracking stations, the ECAL, the MF and the BMS. The main goal was to collect enough data to measure $\Delta\alpha_{had}(t)$ with a $\sim$ 20% statistical uncertainty, providing elements to optimize the full scale experiment. This year, for the first time, an *online* hardware trigger was implemented on

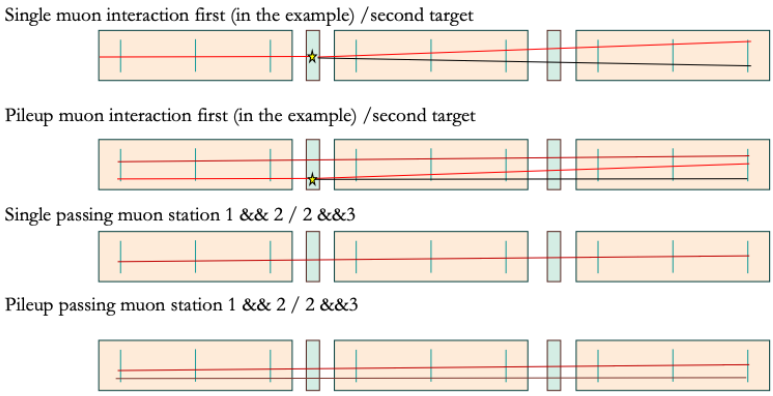

Figure 7: Different classes of triggers implemented on FPGAs based on the hit pattern in the three stations.

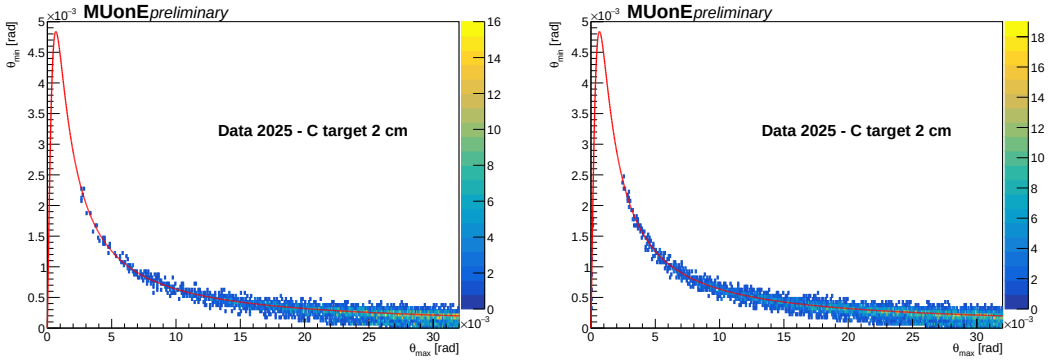

Figure 8: Elastic selection applied on 2025 events passing the *single muon interaction trigger* in the first (left) and in the second (right) target.

FPGAs based on the hits pattern in the three stations, as shown in Fig. 7, where the events were divided in four different classes: single passing muon, pile-up passing muon (more than one beam muon passing straight through the detector), single muon interaction or pile-up muon interaction (more than one beam muon passing through the detector with one of them interacting). The trigger resulted to be efficient. Through an offline analysis, it was possible to see if the machinery was selecting what was expected. In fact, looking at the events passing the *single muon interaction trigger* in the first and in the second target, applying a basic elastic selection, we were able to see and reconstruct elastic events in both targets, as visible in Fig. 8.

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