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The MUonE experiment: $\mu\, e$ elastic scattering as a key to understand the muon $g-2$ puzzle

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The MUonE experiment aims to measure the differential cross section of the $\mu\, e$ elastic scattering using the CERN SPS muon beam with mean energy of 160 GeV onto atomic electrons of a low-Z target. Thanks to the intense M2 beam with in-spill intensity of 5×10^7 muons/s, a precise measurement of the scattering angles allows to extract the running QED coupling, and by a novel approach the leading hadronic contribution to the muon anomalous magnetic moment. This determination will be completely independent from the usual data-driven method, based on measurements of the R-ratio in e^+e^- annihilations, and could clarify the discrepancy between these results and the theory-based estimates from recent lattice QCD calculations.

The MUonE challenge resides in the control of theoretical and experimental uncertainties to an unprecedented level of precision for a scattering experiment. A pilot run was held this summer, operating for the first time two tracking stations and a prototype electromagnetic calorimeter connected to a triggerless readout system. The status and plans of the experiment will be presented.

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1. Introduction

The muon magnetic anomaly is defined as $a_\mu = (g_\mu - 2)/2$, where g_μ is the muon gyromagnetic ratio. Currently, a_μ represents one of the most intriguing observables to test the validity of the Standard Model, since a discrepancy between theory and experiment has persisted for more than 20 years. Recently it has received renewed attention following the first measurement of the muon anomaly performed by the Muon $g-2$ Collaboration at Fermilab [1], subsequently confirmed by a new result with a twofold improved precision [2]. The comparison with the theoretical prediction is limited by the evaluation of the leading-order hadronic contribution $a_\mu^{\rm HLO}$, which cannot be computed perturbatively as it involves QCD at low energy. For this reason, $a_\mu^{\rm HLO}$ 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 $a_\mu^{\rm HLO}$ [3]. Furthermore, a recent evaluation based on lattice QCD techniques reached for the first time an accuracy comparable to the dispersive approach [4]. However, such a calculation shows a 2.1σ tension with the dispersive method. Additionally, 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]. New calculations from other lattice QCD groups and new results from other e^+e^- colliders are expected to shed light on these tensions in the next few years [6].

2. The MUonE experimental proposal

MUonE proposes to determine $a_\mu^{\rm HLO}$ using a novel approach [7], independent of the existing ones. It is based on the direct measurement of the hadronic contribution to the running of the electromagnetic coupling constant ($\Delta\alpha_{\rm had}$) in the space-like region, namely for negative momentum transfer t. The following equation will be used to calculate $a_\mu^{\rm HLO}$ [7, 8]:

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

where α is the fine structure constant and m_μ is the muon mass. Furthermore, 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 higher order hadronic vacuum polarization contributions to a_μ up to NNLO. $\Delta\alpha_{\rm had}(t)$ will be determined from a very precise measurement of 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 the atomic electrons of a thin beryllium or carbon target. An attractive feature of the elastic process lies in its simple kinematics, which makes the scattering angles of the outgoing electron and muon correlated. This constraint allows to select the signal events effectively and reject the background, which is expected to be mainly due to e^+e^- pair production by muons interacting with the target nuclei.

The experiment is performed at the M2 beamline at CERN SPS, which provides 160 GeV muons with an average in-spill rate up to 50 MHz. This energy allows to cover the momentum transfer region $-0.153\,\text{GeV}^2 < t < 0\,\text{GeV}^2$, which is equivalent to $0 < x < 0.936$ and corresponds to $\sim 88\%$ of the master integral in Eq. 1. The remaining fraction can be computed by extrapolating $\Delta\alpha_{\rm had}(t)$ with an appropriate parameterization [11, 12]. Moreover, an alternative method has been recently proposed to calculate $a_\mu^{\rm HLO}$ from the derivatives of $\Delta\alpha_{\rm had}(t)$ at zero momentum transfer [13].

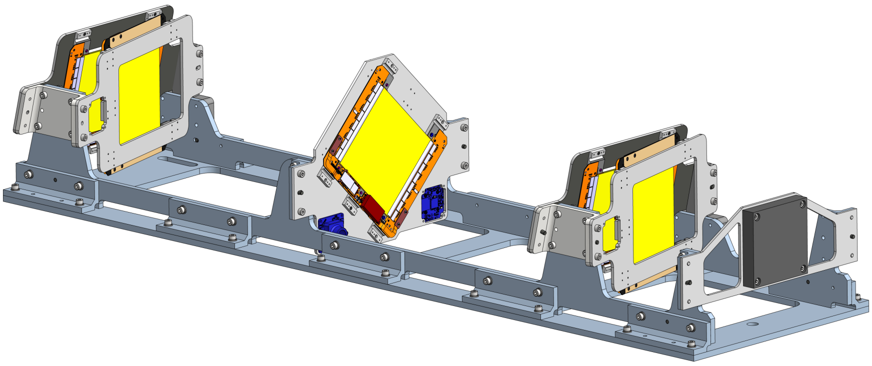

Figure 1: CAD drawing of a MUonE station.

The experimental setup of MUonE consists of a repetition of 40 identical stations, whose layout is shown in Fig. 1. Each station is composed of a 1.5 cm thick target, followed by a tracking system with a lever arm of $\sim$ 1 m, which consists of 3 pairs of silicon strip detectors and is used to measure the scattering angles with high precision. The second detector of each pair is rotated by 90° with respect to the first one. In this way, each pair is able to measure both the transverse directions. An electromagnetic calorimeter is placed downstream of all the stations, to provide particle identification and improve event selection. A muon filter will be placed downstream of the calorimeter. 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 $1.5 \times 10^7 \mathrm{nb}^{-1}$ in 3 years of data taking at the M2 beamline, which corresponds to $\sim 4 \times 10^{12}$ elastic events with electron energy > 1 GeV. This allows to achieve a statistical error of $\sim$ 0.3% on a_μ^{HLO}, thus making the measurement of MUonE competitive with the latest evaluations. 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]. On the theoretical side, such a goal requires the knowledge of higher order corrections to the elastic scattering differential cross section up to the NNLO [14]. Moreover, dedicated Monte Carlo tools are required to simulate the main background processes. State of art reviews of the theoretical progress are given in [15].

The extraction of $\Delta\alpha_{\mathrm{had}}(t)$ is carried out through a template fit method on the 2D distribution of the two scattering angles [11, 12]. In this procedure, the theoretical prediction is used to generate several Monte Carlo distributions, which differ from each other in the values of the free parameters of the analytical function used to model $\Delta\alpha_{\mathrm{had}}(t)$. A χ^2 comparison of such distributions against the experimental data is then performed, and the best parameters are determined by parabolic interpolation across the grid points.
Systematic effects can be studied in 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. $\Delta\alpha_{\mathrm{had}}(t)$ is negligible in this region, while the main systematic effects will introduce a significant distortion on the shape of the differential

cross section with respect to the expectations. After dedicated studies on the different sources of systematic error in the normalization region, the residual systematic effects are included as nuisance parameters in the template fit. Preliminary studies on a reduced statistics show that this strategy allows identifying correctly the systematic errors with no degradation on the parameters of the $\Delta\alpha_{\mathrm{had}}(t)$ fit function. Work is in progress to adapt the procedure to the full statistics.

3. 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 to validate the experimental proposal. The Test Run was held at the M2 beamline from August 21$^{\mathrm{st}}$ to September 10$^{\mathrm{th}}$ 2023. The detector was composed of one MUonE station followed by an electromagnetic calorimeter. An additional tracking station without target was placed upstream of the apparatus, to detect the incoming muons.

Tracking system One of the main goals of the Test Run is to test the validity of the system engineering, as well as to monitor the mechanical and thermal stability of the apparatus. For this purpose, the tracker mechanical structure is made of Invar, a Fe-Ni alloy with a low coefficient of thermal expansion ($\sim 1.2 \times 10^{-6}$ K^{-1}). This is required to keep the longitudinal stability within 10 µm, thereby satisfying the 10 ppm requirement on the systematic uncertainty. A laser holographic system has been used to monitor the longitudinal stability. Moreover, an enclosure and a cooling system have been designed to keep the temperature constant within 1 °C.
The 2S modules developed for the CMS Outer Tracker Phase-2 upgrade [16] have been chosen as the basic tracking unit. 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. The 40 MHz read-out is adequate to sustain the M2 beamline in-spill rate of 50 MHz, and the active area of about $10 \times 10\,\mathrm{cm}^2$ allows to use a single module to cover the entire angular acceptance. The 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 by almost a factor of 2. 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.
The Serenity board [17] 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. The entire data stream has been saved to disk during the Test Run, in order to elaborate online selection algorithms that will be implemented in the successive runs with additional stations. Further details on the MUonE DAQ are given in [18]. Preliminary tests of the MUonE DAQ chain occurred in a joint effort with the CMS Tracker Group in 2021 and 2022, providing a first successful running of the DAQ chain at the M2 beamline and demonstrating the 2S modules time synchronization. In the Test Run, the scalability of the DAQ system has been tested, and the characteristics of the 2S modules, such as detection efficiency and spatial resolution, are currently being analyzed.

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Electromagnetic calorimeter The Test Run electromagnetic calorimeter is composed of a matrix of 5×5 $PbWO_4$ crystals. The total area of 14×14 cm^2 allows to cover the full acceptance of scattering events from the MUonE station. Each crystal has a section of 2.85×2.85 cm^2 and a length of 22 cm ($\sim 25X_0$), and will be read-out by APD sensors. Preliminary Beam Tests took place at CERN in 2022 and June 2023, to test the calorimeter DAQ, to perform the energy calibration for different electron energies and to evaluate the energy resolution. Further details on the current design of the calorimeter are given in [19]. The calorimeter DAQ system has been integrated with the main DAQ served by the Serenity board during the Test Run, and data analysis is currently ongoing to check the synchronization and assess the energy resolution. The role of the calorimeter in the elastic events selection will be evaluated.

Prospects for the analysis Test Run data will be crucial to test the software alignment procedures and the reconstruction algorithms, as well as to characterize the event selection criteria. The background processes will be studied and compared to the simulations. Moreover, the main sources of systematic error, such as the multiple scattering effects, can be studied. Given the reduced number of stations and limited run time, a first measurement of $\Delta\alpha_{\mathrm{had}}(t)$ will not be possible. Nevertheless, the template fit procedure could be tested to extract the leptonic contribution to the running of α, $\Delta\alpha_{\mathrm{lep}}(t)$, whose effect is 10 times larger than $\Delta\alpha_{\mathrm{had}}(t)$ in the MUonE kinematic region.

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. A Test Run with two tracking stations and a calorimeter was held in August-September 2023. Data analysis is currently ongoing. Results will be included in an experiment proposal which will be submitted to the SPS Committee within June 2024, with the prospect of performing a first measurement of a_μ^{HLO} in 2025 instrumenting more tracking stations. The full detector construction is then expected to take place during the Long Shutdown 3 of 2026-28. The full statistics run is foreseen for the following years.

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