PROCEEDINGS OF SCIENCE

Status of the MUonE experiment

E. Spedicato for the MUonE collaboration[a,b,*]

[a] *INFN, Sezione di Bologna,*
Viale Berti-Pichat 6/2, 40127 Bologna, Italy
[b] *Department of physics and astronomy, University of Bologna,*
Via Irnerio 46, 40126 Bologna, Italy

E-mail: espedica@cern.ch

The MUonE experiment aims to measure the hadronic vacuum polarization contribution to the muon anomaly a_μ^{HLO} better than 1%. An innovative approach is proposed, using elastic scattering of 160 GeV muons on atomic electrons in a low-Z target. A precision of 10 ppm on the distribution of the angle between the muon and the electron outgoing of elastic-scattering process is required. The M2 beamline at CERN provides the necessary intensity to reach the statistical goal in few years of data taking. In summer 2024 a Proposal has been sent to the CERN SPSC asking for the Phase 1 of MUonE to be performed with a small scale experiment in 2025. This is expected to obtain a first measurement of the hadronic contribution to the running QED coupling, $\Delta\alpha_{had}$, with a 20% statistical uncertainty. We will present the progress achieved in the last years, the current status, and the future plans of the experiment.

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*Speaker

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1. Introduction

The anomalous magnetic moment of the muon $a_\mu = (g-2)/2$ is one of the most intriguing topics in current particle physics. In 2006, the BNL's E821 experiment [1] provided a measurement which deviated 3.7σ from the reference theoretical estimate. In 2021 and again in 2023 [2], the result was confirmed by the $g-2$ experiment at Fermilab, bringing the discrepancy to 5.2σ. However, the theoretical landscape changed along the years. The largest contribution to the theoretical uncertainty of a_μ comes from the hadronic vacuum polarization term at leading order (LO) a_μ^{HLO}, which is not calculable by perturbative Quantum Chromo Dynamic (QCD). Thus other methods need to be used. 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. This theoretical estimate is reported in the 2020 White Paper from the g-2 Theory initiative [3]. 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.

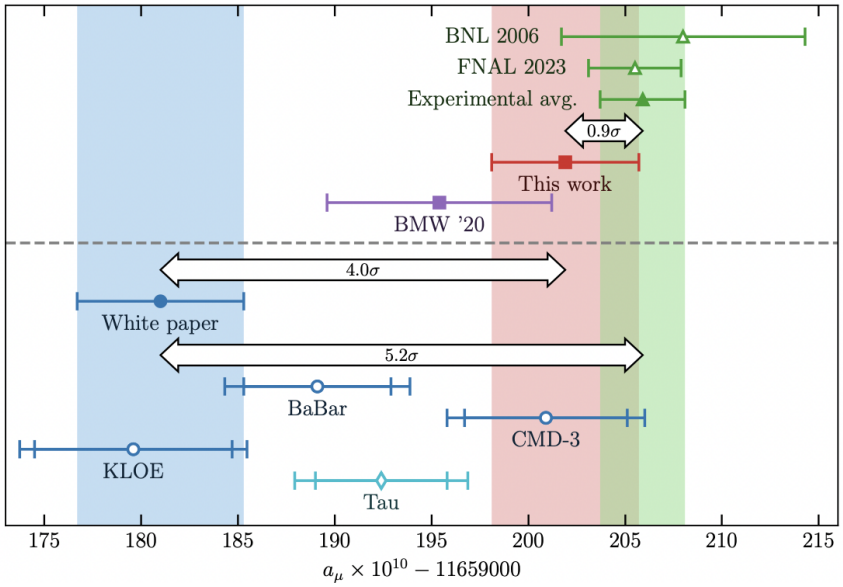

Figure 1: Comparison of SM predictions of the a_μ with its measured value. World-average measurement (green band) compared with the SM prediction [3] (blue band) and with the new BMW result [6] (red point). The panel below the line shows the predictions for a_μ obtained by the data-driven [6].

Different estimates of a_μ with the methods discussed are compared in Fig. 1 . The discrepancy $\Delta a_\mu = a_\mu^{th} - a_\mu^{exp}$ varies depending on the method used for the theoretical calculation. Therefore, the different approaches used until now are not enough to draw any solid conclusions on the existing discrepancy between the reference theoretical evaluations and the experimental measurements. The MUonE collaboration proposes an alternative method to shed some light on this intriguing puzzle.

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2. The MUonE experiment

MUonE proposes to provide an independent and innovative method to evaluate a_μ^{HLO} [7], based on the evaluation of the master equation:

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

where α is the fine-structure constant and $t(x)$ is the space-like four-momentum transfer. This depends on the hadronic contribution to the running of the electromagnetic coupling in the space-like region of momenta $\Delta\alpha_{had}(t)$. In order to be competitive, the precision that needs to be reached is $< 0.5\%\, a_\mu^{HLO}$. The selected process for this measurement is the $\mu - e$ elastic scattering on low-Z target, exploiting the CERN M2 muon beam line at $E_\mu = 160\,\text{GeV}$. 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].

The experimental apparatus will be composed by 40 tracking stations, one electromagnetic

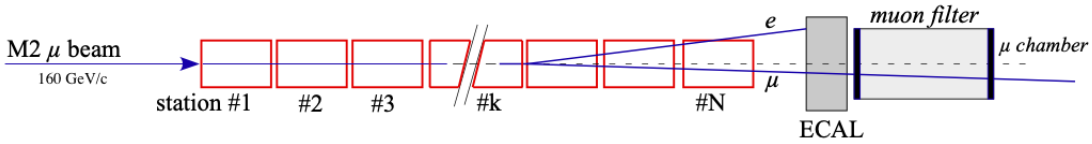

Figure 2: Schematic view of the MUonE apparatus.

calorimeter (ECAL) and a muon filter, as shown in Fig. 2. Each station behaves as an independent detector, with its own target (beryllium or graphite) and six tracking silicon strip modules: two X, two Y and two stereo modules rotated of 45 ° U, V. The chosen modules are the 2S ones foreseen for the CMS Phase-2 upgrade [11]. 25 cells of $PbWO_4$ compose the ECAL, with a total surface of $14 \times 14\text{cm}^2$. Signals arrive to Avalanche PhotoDetectors (APDs) which are read out by two Front-end Boards connected to an FC7 board. A laser pulse system (at 450 nm) is provided to calibrate and control APDs signals [12].

The necessary precision on our measurement requires a Monte Carlo (MC) generator for signal generation at the Next-to-Next Leading Order (NNLO) level. It has been developed [13] and it is currently used by the MUonE Collaboration. Also a MC generator for the main background $\mu^+N \to \mu^+Nl^+l^-$ (l = leptons, mainly e^+e^-) has been developed in the last year [14]. Both for simulated and real data, software has been developed for offline reconstruction and analysis. Fig.3 shows the resulting reconstruction of a real-data events sample, recorded during the 2023 test run. It represents the correlation between the two reconstructed tracks scattering angles, corresponding to the outgoing muon and electron, before and after an elastic selection for signal events.

3. Test runs

Different aspects have been studied in the several test runs carried out since 2017: from the effect of the multiple scattering [15] to the capability of selecting elastic events [16], with a different apparatus with respect the one in use now. Recently from 2022 to 2024 the main goal has been to

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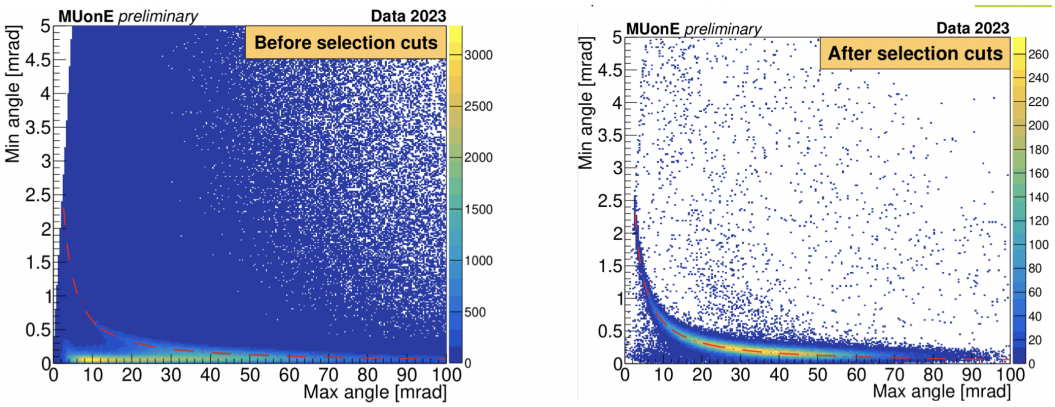

Figure 3: Filtered events of a run from test run 2023 (left), remaining reconstructed events after a basic elastic selection (right). The 2D plot shows the distribution of $(\theta_{max}, \theta_{min})$, while the red curve represents the elastic curve.

test the DAQ and detectors.

The latest test in 2023 used 160 GeV muons in 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. Data

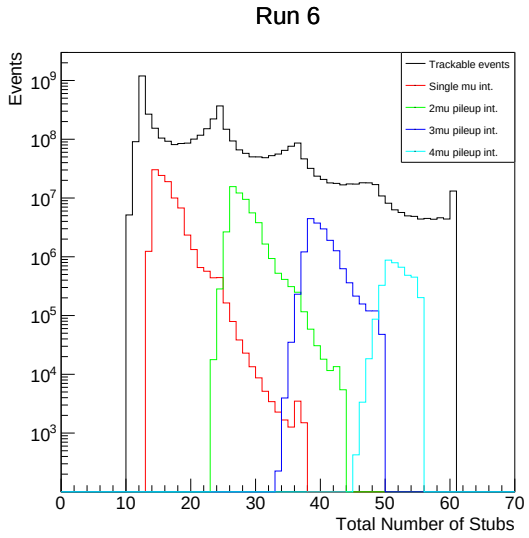

Figure 4: Event classification in terms of incoming muon multiplicity obtained by the filtering algorithm for a high-intensity 2023 run.

were processed offline using a skimming algorithm as the DAQ operated without a trigger. This algorithm preselects candidate events from target interactions based on the hit pattern in the two stations. In the future, the goal is to implement this process online using FPGAs. The skimming 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 a run in 2023 data taking.

Some first results of the 2023 test run data are now presented, although the analysis is still ongoing.

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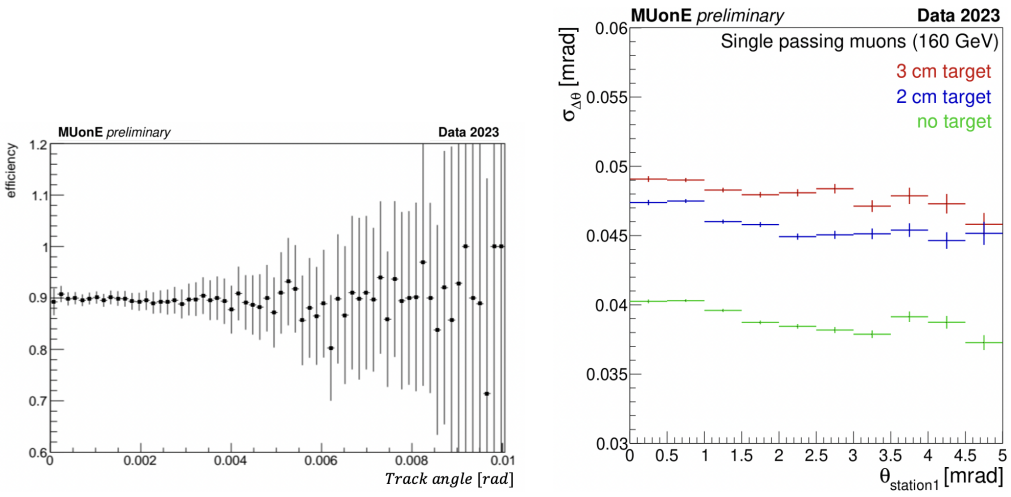

Figure 5: Results of tracking efficiency (left) and angular resolution (right) for passing golden muons using data from TR 2023. On the right, the different colors corresponds to different target thickness.

The tracking efficiency as a function of the incoming muon angle is shown in Fig.5/left. Reconstructed muons with 6 hits in the first station are selected (golden μ). To evaluate efficiency, the reconstructed muon is searched also in the second station. The average module efficiency is $\sim 98\%$ and the flat efficiency of 90% is consistent with that value. The angular resolution as a function of the golden muon angle is shown in Fig.5/right for different target size. $\Delta\theta = \theta_2 - \theta_1$ is sensitive to intrinsic resolution, residual misalignment and multiple scattering. The estimate of multiple scattering obtained with this method is consistent with the PDG multiple scattering prediction.
A first analysis of the elastic events has been done on a sample passing a fiducial and an elastic selection. The angular distributions 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, as shown in the top plot. The ratio between data and MC as a function of electron angle remains within $\pm 3\%$ across the entire range. For the running of $\alpha(t)$ to be observed, the MC description of angular shapes must be accurate to within at least 0.5%. There is a lot of work in progress to improve the comparison.

The next milestone for MUonE is the test run in October 2024, aimed at validating and expanding the DAQ system and the synchronization of the ECAL and tracker, as well as assessing the reconstruction and analysis tools. Following this, the Phase-1 experiment is scheduled for 2025. A proposal has been presented to the SPSC in June for 4 weeks of running time to study the expected systematic errors and background under realistic conditions. Many technical difficulties have been encountered in recent years (e.g., the use of prototype 2S-modules) and have been successfully overcome, leading to progress toward better results. Therefore, beam time will be crucial for gaining a deeper understanding of the entire system and for obtaining the first results on the running of α.

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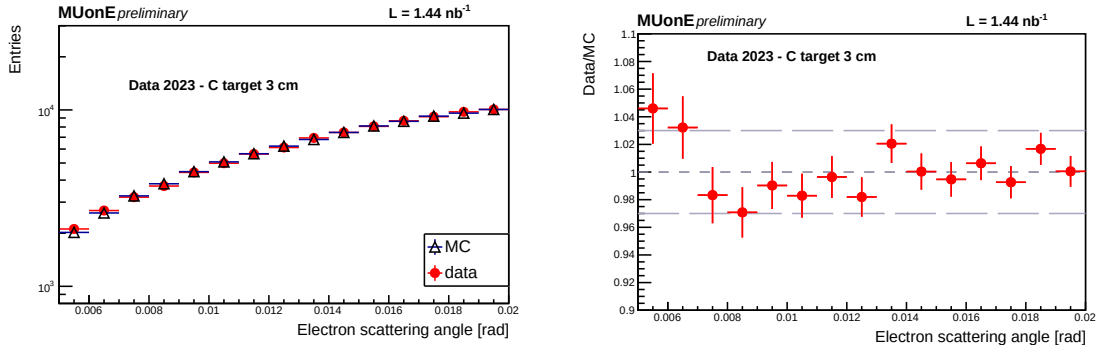

Figure 6: Left plot is the distribution of electron scattering angle for data and MC, normalized to the data. Right plot is ratio of data and MC. The grey dashed lines mark the unit ratio and a band of ±3%.

Scattering for g-2" under the program PRIN 2022.

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