EVENT RECONSTRUCTION IN MUonE EXPERIMENT AT THE SPS ACCELERATOR*

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The MUonE experiment planned to be operating at the SPS accelerator in 2021–2022 (pilot run) and 2023–2026 provides a great potential to search for new physics in the sector of the anomalous muon magnetic moment a_μ. The discrepancy between the most accurate determination of a_μ and the Standard Model predictions is about 4 standard deviations. Since the new experiments dedicated to highly precise measurements of the anomalous magnetic moment of the muon will allow for the measurement with an accuracy of about 0.05%, a serious limitation in increasing the significance of a possible discovery will be the theoretical error, dominated by uncertainties from hadronic contributions. The MUonE experiment will allow for a precise measurement of hadronic contribution to a_μ employing the measurement of the differential cross section for the $\mu e \to \mu e$ elastic process. This would help to increase the significance of the observed discrepancy to the level of 7 standard deviations. The crucial issue in this kind of study is the development of the event reconstruction procedures, allowing to control the systematic effects and, at the same time, to achieve high angular resolution.

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1. Introduction

According to the Standard Model of particle physics (SM), which is supported by a great deal of experimental evidence, one can predict various observables to a very high precision. However, despite the undeniable success of SM, there are strong suggestions that it is incomplete. There are

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some theoretical problems and, what is more, some experiments are showing discrepancies from its prediction. Anomalous magnetic moment of the muon a_μ is one of these issues, as many studies suggest that there may be a discrepancy between its measurements and theoretical predictions [1].

2. Muon $g - 2$

A muon is not only subject to electromagnetic, but also strong and weak interactions, which gives a great potential to search for physics beyond the Standard Model. Anomalous magnetic moment of a muon was precisely measured in a series of experiments, which have begun in 1958 at CERN [2] and continue until today. Combining two most precise measurements, that is, the first results from the Fermilab E989/Muon $g - 2$ experiment [3] and from the Brookhaven National Laboratory (BNL) E821 measurement [4] gives 4.2σ discrepancy according to theoretical predictions.

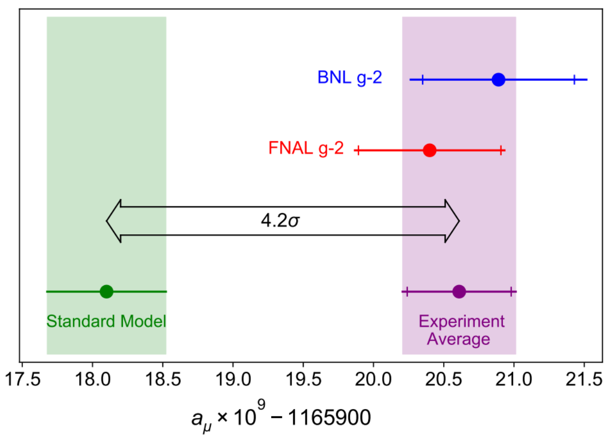


Fig. 1. (Colour on-line) Experimental results on muon anomalous magnetic moment (from BNL E821 in blue and from Fermi National Accelerator Laboratory (FNAL) E989 in red) compared to the theoretical Standard Model predictions (in green). The average of experimental results (in purple) differs from the SM predictions by 4.2 standard deviations. Figure taken from [3].

This is still not enough to claim a discovery. A theoretical value of anomalous magnetic moment of a muon comes from the following factors:

$$a_\mu = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{QCD}} + a_\mu^{\mathrm{NP}} \,, \tag{1}$$

where the first three contributions come from electromagnetic, weak and strong interactions, and the last one corresponds to the effects beyond the

Standard Model. Theoretical error is dominated by uncertainties from hadronic contributions, which cannot be determined using perturbative QCD methods.

3. Hadronic contribution to a_μ

As already mentioned, the main source of uncertainty lays in the hadronic single-loop vacuum polarisation (Hadronic Leading Order — HLO) processes, which are a part of the QCD contribution [5]. This term is non-perturbative and cannot be calculated in QCD directly. There are several strategies that can provide the value of this term, such as the lattice calculations or data-driven dispersion relation employing experimental data from e^+e^- annihilation to hadrons. Nevertheless, these approaches still face some problems and do not provide enough accuracy. Recently, the MUonE experiment proposed a novel method to get the a_μ^{HLO} term [6]. It assumes to measure the shape of differential cross section of high-energy muons elastic scattering on atomic electrons in a low-Z target as a function of the space-like momentum transfer.

4. MUonE experiment

As already stated, the aim of the MUonE experiment is to directly measure the hadronic contribution to running fine structure constant, which enables precise determination of the a_μ^{HLO} contribution to anomalous magnetic moment of a muon. The crucial goal is to ensure effective control of systematic effects, the reduction of which is critical to the success of accurate measurement. Combining expected results from MUonE with the results from Muon $g-2$ experiments may increase the significance of a possible discovery to around 7σ.

The experimental setup, shown in Fig. 2, has a modular structure made by up to 40 layers of berillium targets interleaved with 6 layers of Si tracking planes. The incoming 160 GeV muon beam is scattered on targets and results in an outcoming electron and muon. All tracks within the detector have to be precisely reconstructed. Systematic effects must be known at least 10 ppm with hit resolution at the level of 10 μm.

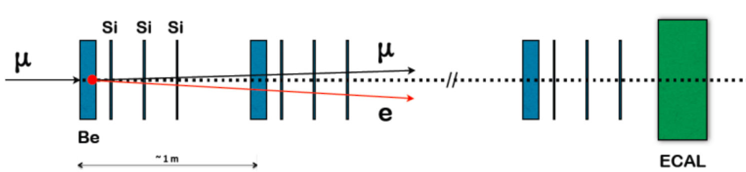


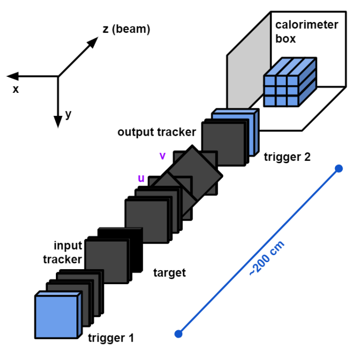
Fig. 2. Scheme of the MUonE experimental apparatus.

4.1. MUonE test beam 2018

The first data was collected during test beam in 2018 and provided very promising results [7]. Its aim was to specify the outlines for the final MUonE experimental setup.

In this case, the experimental setup consisted of 16 tracking stations based on silicon microstrip detectors and a calorimeter within a one-target configuration. The incoming muons were scattered on a 10×10 cm^2, 8 mm thick graphite target. Although the resolution reached in the test beam 2018 setup was far from the one assumed for both the pilot run and final detector, the results turned out to be very optimistic. A good quality, clean sample of elastic scattering events was obtained as it can be seen in Fig. 3 (right).

Recently, in November 2021, a first MUonE pilot run, allowing for tests of the detector itself as well as the data acquisition system, and experiment software on the SPS accelerator took place.



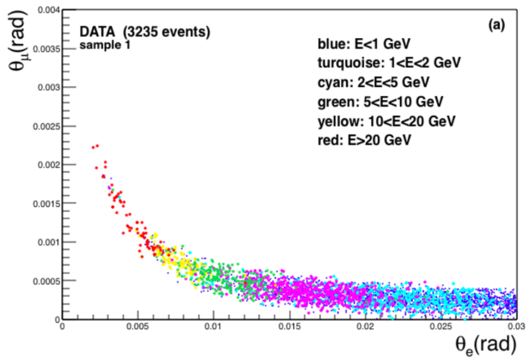


Fig. 3. Scheme of the experimental apparatus used in the MUonE test beam (left). Kinematical correlation of the outgoing electron and muon obtained within the MUonE test beam 2018 (right).

5. Reconstruction process

The MUonE software is being developed within FairRoot framework [8], based on ROOT. The event model consists of generation, simulation, digitalisation, and track reconstruction. The developed experiment software was successfully used for the analysis of 2018 test beam data and is expected to be the software environment for the final experiment.

The topology of muon–electron elastic scattering is relatively simple. There are 3 tracks to be reconstructed — an incoming muon before target and an outgoing electron and muon after the target. The particle tracks are supposed to be approximately straight lines, so the linear fit based on χ^2

minimisation was used for the track reconstruction process for the MUonE test beam data. However, the track reconstruction process must be performed as precisely as possible. And so, the other method of track reconstruction based on the Kalman filter algorithm is being developed for the MUonE purposes. There are several reasons for this solution, but the most important is that it combines knowledge from prediction and measurement, and enables achieving better estimation than prediction and measurement provide separately [9]. What is more, unlike the linear fit, this method can take into account some additional effects which cause that the track is no longer a perfectly straight line. Those effects can occur when a particle goes trough a detector layer, where the most important is multiple scattering.

6. Kalman-filter-based track reconstruction

The Kalman-filter-based track reconstruction algorithm was tested using data from the simulation within the MUonE test beam 2018. The data sample was a set of 150 K elastic scattering events. The simulated apparatus within FairRoot using Geant4 was analogue as used for the MUonE test beam.

The Kalman filter algorithm has been adapted to the detector topology and extended with backward iterations, as shown in Fig. 4.

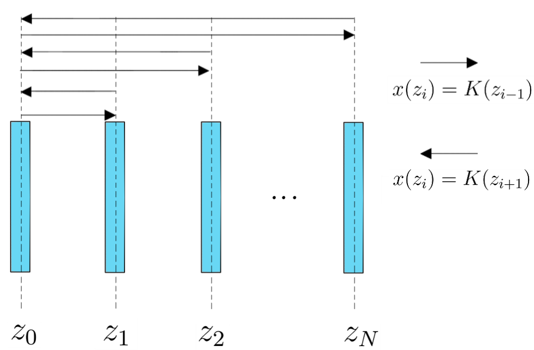


Fig. 4. Scheme of iterations within the Kalman-filter-based algorithm implemented to reconstruct the scattered outgoing particles in the MUonE test beam simulated data.

After k steps forward, the corresponding calculations were performed backward to the first detector layer. After such an iteration, containing forward and backward performance, the algorithm reaches the next $k + 1$ layer.

The Kalman filter equations [9] had to be adapted to the particles' trajectory inside the MUonE test beam detector. The state vector includes hit coordinates and slopes of the particle. The initial values of those quantities was extrapolated using the hit coordinates. The state transition matrix corresponds to the theoretical evolution of the system and the input-control matrix presence turned out to be redundant. Thus, the state equation has the following form:

$$\begin{bmatrix} x \\ y \\ \tan x \\ \tan y \end{bmatrix}_{k+1} = \begin{pmatrix} 1 & 0 & \mathrm{d}z & 0 \\ 0 & 1 & 0 & \mathrm{d}z \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{bmatrix} x \\ y \\ \tan x \\ \tan y \end{bmatrix}_{k} , \tag{2}$$

where $\tan x$ and $\tan y$ are the slopes in x and y projections, $\mathrm{d}z$ is the distance between k layer and $k+1$ layer. The multiple scattering effects were included within the covariance matrix $\boldsymbol{Q}$, associated with process noise

$$\boldsymbol{Q} = \begin{pmatrix} \mathrm{MS}^2\mathrm{d}z^2 & 0 & \mathrm{MS}^2\mathrm{d}z & 0 \\ 0 & \mathrm{MS}^2\mathrm{d}z^2 & 0 & \mathrm{MS}^2\mathrm{d}z \\ \mathrm{MS}^2\mathrm{d}z & 0 & \mathrm{MS}^2 & 0 \\ 0 & \mathrm{MS}^2\mathrm{d}z & 0 & \mathrm{MS}^2 \end{pmatrix} , \tag{3}$$

where MS denotes the multiple scattering event given by the following formula:

$$\mathrm{MS} = 13.6\sqrt{x_0}\frac{1 + 0.038\log x_0}{1000\,p} , \tag{4}$$

where x_0 is the ratio of the width of the Si layer (0.04 cm) and the radiation length (21.82 cm), and p is the average particle momentum estimated from the observed scattering angle of the electron. The covariance matrix $\boldsymbol{R}$, associated with the noise of the measurement process is

$$\boldsymbol{R} = \begin{pmatrix} 0.009 & 0 \\ 0 & 0.009 \end{pmatrix} . \tag{5}$$

The diagonal elements correspond to the detector resolutions to the power of 2, estimated to be at the level of 30 microns. Equations (2)–(5) and the hits registered by detector layers are the complete input data for the Kalman algorithm and all equations are based on them.

The goal was to compare the linear fit and the Kalman filter performance. To obtain resolutions for both track reconstruction methods, the differences between reconstructed and simulated slopes were calculated. The representative x slope, defined as tangent of an angle between particle trajectory in x projection and the beam axis, was extracted from the reconstructed tracks. Fitting the distributions of those differences with the Gaussian functions allows to obtain the fit resolutions. The obtained resolutions are collected in Table 1.

Table 1. Slope resolutions for electrons and muons determined using the linear fit and the Kalman filter. In the case of electrons, a double Gaussian was used to fit the distributions, while for muons, a single Gaussian function was employed.

	Kalman filter		Linear fit	
Muons	1.515(013)		1.683(017)	
Electrons	σ_1	σ_2	σ_1	σ_2
	4.504(263)	1.678(041)	5.040(260)	1.896(046)

6.1. Conclusions

The slopes obtained with both track reconstruction methods are comparable. The distributions for electrons' slopes are wider than the muon slopes' distributions, as it was expected due to mass distinction between the particles. For both electrons and muons, resolutions for the Kalman-filter-based algorithms are about 10% better. As the Kalman-filter-based algorithm has a significantly better performance than linear fit, it is being implemented into the central software of the MUonE experiment and will be used in the both pilot run as well as final experiment data analyses.

7. Summary

Research on the anomalous magnetic moment of a muon has been ongoing for many years. Today, it seems that the mystery of the discrepancy between theoretical prediction and measurement of a_μ may be solved soon. The MUonE experiment is expected to measure hadronic vacuum-polarisation contribution to muon anomaly with much higher precision than actually provided. Correction to the hadronic part of the theoretical value of a_μ is essential and the method used by MUonE allows to reach the precision below 5 ppm. This, combined with precise measurement of the anomalous magnetic moment of a muon performed by $g-2$ experiments, is expected to reach a 7σ level discrepancy, which surely allows to claim a discovery.

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