PROCEEDINGS OF SCIENCE

Status of the MUonE experiment

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The MUonE experiment aims to measure with extremely high precision the leading-order hadronic contribution to the muon anomalous magnetic moment $g-2$. This currently represents the largest uncertainty in the theoretical prediction. A first test has been performed in 2021, with prototypes of the silicon sensors and related electronics, the fundamental components of the detector. The detector assembly and the tests have been carried on during 2022. The collected data are under analysis. In 2023 a test run is foreseen to validate the proposed methods and technologies, which will lead to the final proposal of the experiment. The current status and prospects of MUonE will be discussed.

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1. Introduction

One of the unsolved questions that nowadays puzzles the particle physicists concerns the anomalous magnetic moment of the muon $a_\mu = g - 2/2$. In 2006, the E821 experiment at BNL [1] published a new measurement for this quantity, which resulted to deviate from the theoretical calculation of 3.7σ. On April 2021, the E989 experiment at Fermilab confirmed with a new measurement the previous result [2], bringing the discrepancy to 4.2σ. In order to understand whether the theoretical calculation or the experimental measurement is incorrect, two paths may be simultaneously followed:

1. Increase the precision on the measurement;

2. Decrease the uncertainty on the hadronic vacuum polarization term at leading order a_μ^{HLO} in a_μ, which dominates the theoretical uncertainty.

The contributions from the Standard Model to a_μ are [3]:

$$a_\mu = a_{QED} + a_{EW} + a_{had} \tag{1}$$

where the QED and electroweak terms are precisely evaluated with perturbation theory. The main contribution to the hadronic part is given by the LO vacuum polarization term a_μ^{HLO} which dominates the uncertainty and is not calculable by perturbation theory. Until some years ago, the only existing method was a data-driven one based on the low-energy measurement of the $e^+ - e^-$ annihilation cross-section. It is now thought that this method has reached its precision limit so other approaches are needed. In the last few years, some Lattice QCD calculations [4] started to be competitive in terms of precision, reducing the discrepancy with the measurement and consequently introducing some tension with the previous data-driven estimates.
Therefore, a novel independent approach is needed in order to reduce the theoretical uncertainty and clarify this inconsistency between different results. This is the aim of the MUonE collaboration, which proposes an independent way for determining a_μ^{HLO} from the measurement of the hadronic contribution to the running of the electromagnetic coupling in the space-like region of momenta $\Delta\alpha_{had}[t(x)]$ [5]:

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

with

$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0. \tag{3}$$

The main advantage of this method is the smoothness of the integrand, in contrast with the data-driven method where the $e^+ - e^-$ cross-section, at low energies, is very fluctuating.
The MUonE experiment [6] aims to measure the hadronic contribution to the running via $\mu - e$ elastic scattering at low energy. The main difficulty of the method is to reach the needed precision in order to be competitive: $< 0.5\%$ on a_μ^{HLO}. The project has been submitted to the CERN SPS Committee with a Letter of Intent in 2019 [7] and a Test Run of three weeks has been approved for the validation of the experimental method.

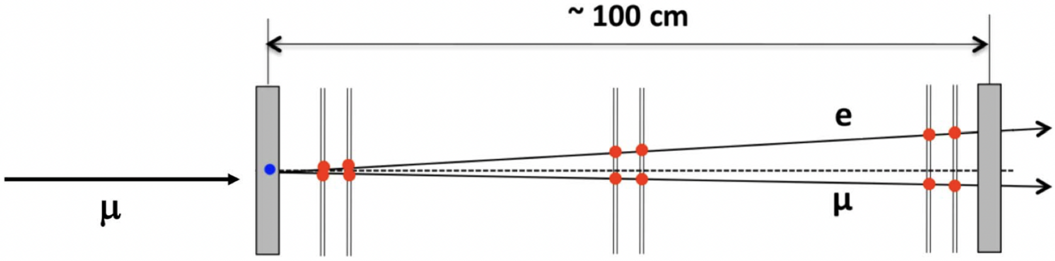

Figure 1: Single MUonE elastic event.

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2. The MUonE experimental apparatus

The experiment will be placed at CERN North Area where the CERN M2 muon beam ($E_\mu \sim 150 - 160$ GeV) will be used on atomic electrons of a light target, an ideal event is represented in Fig.1. The full experimental apparatus consists of 40 tracking stations, one electromagnetic calorimeter (ECAL) and a muon filter, as it is shown in Fig.2. Each station behaves as an independent

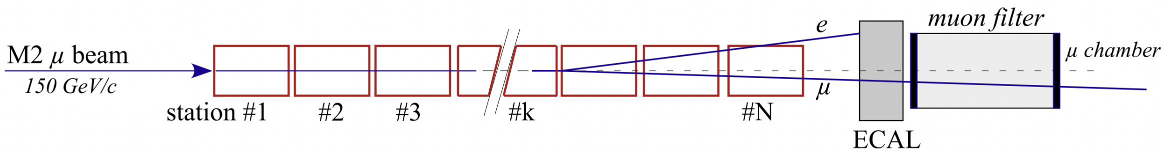

Figure 2: Layout of the MUonE experimental setup.

unit (Fig.3), it is composed of a low-Z target (Beryllium or Carbon) of 1.5 cm and 6 silicon tracking layers. The chosen tracking modules are the 2S modules developed for the CMS outer tracker [8]. This modular layout is essential for reaching the necessary interaction rate minimizing some of

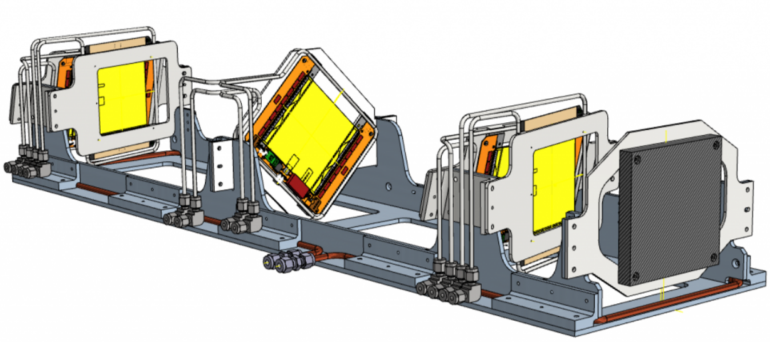

Figure 3: CAD picture of a single tracking station.

the main systematic effects as multiple Coulomb scattering (MCS), as the resolution needed on the angles is of $\sim 10^{-2}$ mrad. With this configuration, in three years of data taking it is possible to reach

the target statistical sensitivity with an integrated luminosity of 1.5×10^{-7} nb^{-1}. The challenge will be to keep at the same level the systematics, as multiple scattering, knowledge of the beam energy (few GeV), alignment and intrinsic angular resolution.
The tracking station is composed of 6 silicon strip modules, where the first two and the last two measure the X and Y coordinates, while the middle ones are rotated in the XY plane of 45° reading the U and V coordinates, to solve tracks ambiguities. The X and Y modules are tilted of 233 mrad around the respective strips' axis. It has been observed from simulations that this tilt improves the single hit resolution of a factor 2, bringing it to 8 mrad. The single hit resolution is important as it strongly influences the capability of selecting pure elastic events, as it is shown in Fig.4. The red line represents the theoretical elastic curve in the $\theta_e - \theta_\mu$ plane, while in blue and green there are respectively the simulated signal events and the main background (pair production). On top the single hit resolution is 8 µm while on bottom 25 µm. It is clear that the better is the resolution, the better is the capability of selecting elastic events.

The calorimeter, in Fig.5, is now in a reduced format and it is composed of 25 cells in $PbWO_4$

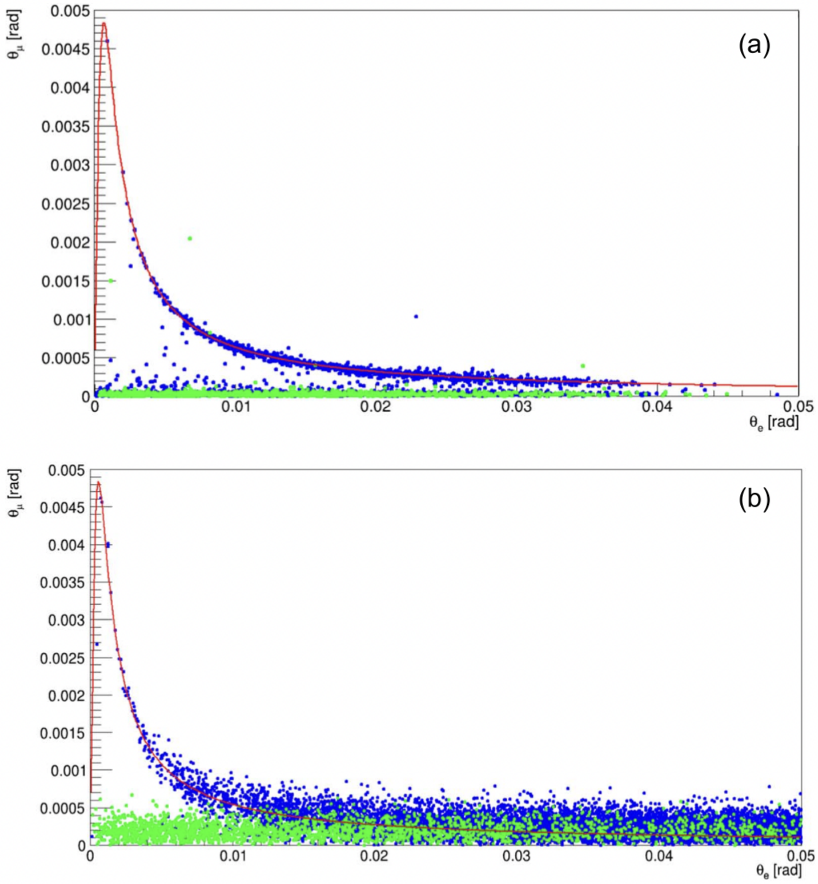

Figure 4: Simulated angular distribution of two-tracks events with two different single hit resolution: 8 µm on top and 25 µm on bottom. In blue elastic events are represented while in green the pair production ones. The red curve is the theoretical elastic curve expected [7].

with a total surface of 14×14 cm^2. Signals arrive to APDs which are read out by two Front-end

Boards connected to an FC7 board. To calibrate and control APDs signals, a laser pulse system (at 450 nm) is provided.

Figure 5: Calorimeter in a reduced format, compesed of 25 $PbWO_4$ cells.

3. Analysis technique

The hadronic contribution to the running is most easily displayed considering the ratio R_{had} defined as:

$$R_{had} = \frac{d\sigma(\Delta\alpha_{had}(t) \neq 0)}{d\sigma(\Delta\alpha_{had}(t) = 0)} \tag{4}$$

where in the denominator the hadronic contribution to the running is switched off in a Monte Carlo simulation. To extract it from data, a template fit method has been chosen where $\Delta\alpha_{had}(t)$ is fitted by a two parameters function:

$$\Delta\alpha_{had}(t) = k\left\{-\frac{5}{9} - \frac{4M}{3t} + \left(\frac{4M^2}{3t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}. \tag{5}$$

That solution was the best found option and it is inspired to the one-loop QED calculation of vacuum polarization induced by a lepton pair in the space-like region. The template fit method consists in generating a grid of points (k, M) in the parameters space covering a region of $\pm 5\sigma$ around the expected values, where σ is the expected uncertainty, as shown in Fig.6.

For each pair of values, a template for R_{had} is obtained with the Monte Carlo generator. Every template is then compared with data/pseudodata calculating:

$$\chi^2(K, M) = \sum_i \frac{R_i^{data} - R_i^{templ}(K, M)}{\sigma_i^{data}} \tag{6}$$

where $K = \frac{k}{M}$. Fig.7 shows the R_{had} distributions for a pseudoexperiment, obtained as functions of the two leptons angles, with the resulting fits superimposed. In order to validate the method, the template fit was repeated for 1,000 toy experiments, obtaining $a_\mu^{HVP} = (688.8 \pm 2.4) \times 10^{-10}$ which resulted in very good agreement with the value inserted in the generator ($a_\mu^{HVP} = 688.6 \times 10^{-10}$). Thus the method seems to be promising for our aims.

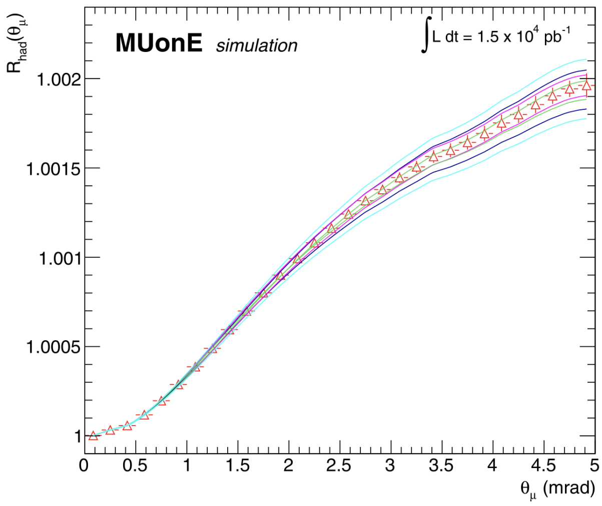

Figure 6: Central value of $R_{had}(\theta_\mu)$, the curves represent the representative MC templates.

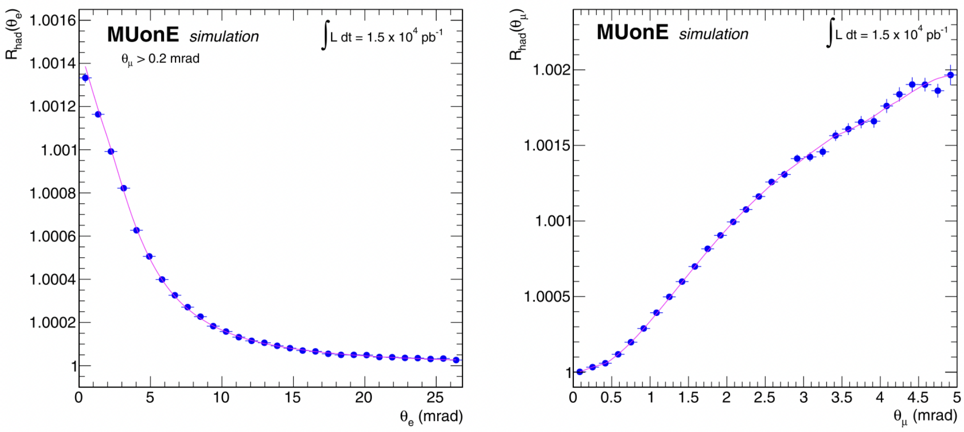

Figure 7: R_{had} resulting from a pseudoexperiment as a function of the electron angle (left) and the muon angle (right).

4. Test Runs

In 2017 a first beam test has been carried out for the study of multiple scattering [9]. The UA9 apparatus was used with the H8 line at CERN with 12 and 20 GeV electrons on a Carbon target. The aim was to compare scattering angles from GEANT4 simulations with real data. It was found an excellent agreement in the core of the angle distributions, leaving some residual disagreement in the tails.

In 2018 a second beam test was set up at the CERN M2 line in order to study the capability of select elastic events [10]. The used detector had a worse resolution and working conditions with respect to the expected final ones, however we succeeded in selecting a first clear sample of elastic events, as it is shown in Fig.8.

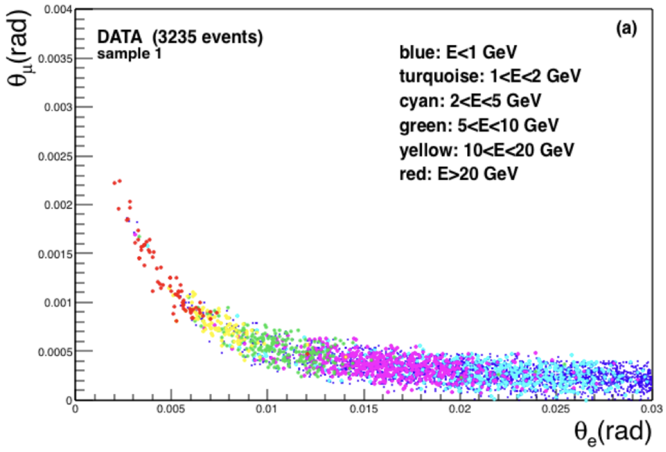

Figure 8: Selected sample of elastic events as a result of the 2018 MUonE Test Run.

In November 2021 we started to test the 2S CMS modules in collaboration with the CMS tracker team. It was a parasitic test with the M2 muon beam at CERN for three weeks. Four 2S modules were provided and the setup used is shown in Fig.9. It was the first time that those modules were tested. A major difference of the MUonE running with respect to the LHC running is that in the fixed target configuration at the M2 beam line the $\mu - e$ interactions are asynchronous. It was demonstrated that the entire DAQ chain works properly with this particular type of beam.

The first calorimeter beam test has been carried out in July 2022. We used the T9 electron beam line

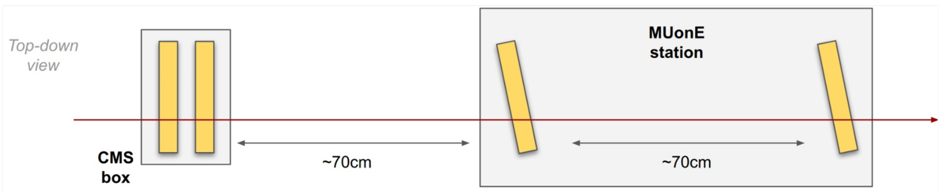

Figure 9: Setup with 4 2S CMS modules for the November 2021 Test Beam.

at CERN, with E_e between 1 and 10 GeV. The signal from the electrons was detected, amplified, read and written out successfully; Fig.10 shows an example signal in one of the calorimeter cells during a spill.

From spring to October 2022 the tracker was under test at CERN North Area with a station equipped of 4 modules. It was an important opportunity to keep on studying the behaviour of those components and their DAQ. In October we had the possibility to test both a complete tracking station with 6 modules and the calorimeter. A first attempt to synchronize the two detectors has been done and for the first time the modules have been used with an high intensity muon beam, as it is needed for the final experiment.

The CERN SPS committee has approved for MUonE a Test Run of three weeks to prove the concept of the experiment and to give some first physical results, with three full tracking stations and the calorimeter. In addition, before the LHC LS3 in 2026 and towards the final configuration, it is

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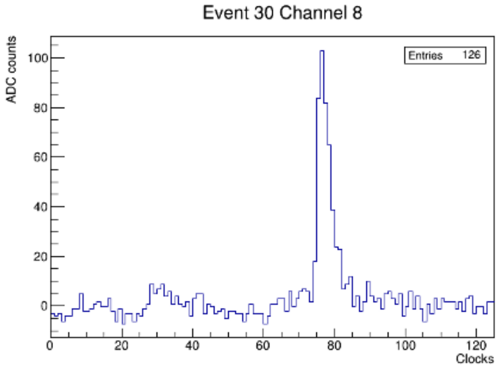

Figure 10: Example of calorimeter signal during July 2022 Test Beam.

planned to have a data taking of 4 months with 10 tracking stations that will allow to reach a statistical error of 2‰.

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