MUonE EXPERIMENT AT SPS*

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The MUonE experiment is dedicated to the precise measurement of the hadronic contribution to the anomalous magnetic moment of the muon, a_μ, which may lead to the observation of a significant discrepancy with respect to the Standard Model predictions. It is planned to be operating at SPS and will allow for a precise determination of hadronic contribution to a_μ employing the measurement of shape of differential cross section for the $\mu e \to \mu e$ elastic process, reaching a competitive precision below 0.5% on the leading hadronic contribution, under the condition that systematic uncertainties are well controlled. The Test Run detector geometry with a reduced setup is being prepared, following a successful test beam in 2018, aimed mainly at checking the ability to select a clean sample of elastic scattering events in view of designing the final experiment.

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1. Introduction

The values of the magnetic moments of the elementary particles have been permanently under experimental and theoretical investigation for almost a century. This started in the sixties and seventies at CERN, concerning among others the measurement of the muon anomaly with a series of experiments. The efforts to increase the precision of the measured anomalous magnetic moment of the muon, defined in terms of the gyromagnetic proportionality factor g as $a_\mu = (g-2)/2$, have been continuously trailed until today. The recent most precise measurements of the anomalous magnetic moment of the muon come from the BNL-E821 [1] and Fermilab-E989 [2] experiments. After combination of these two measurements, a remarkable discrepancy of 4.2σ with respect to the Standard Model predictions can be observed [2], opening a way to the interpretation that it may be a signal

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of new physics. There are several potentially interesting theoretical scenarios [3] to interpret this remarkable difference, such as dark photons or extra dimensions models. There are actually two experiments strictly dedicated to the precision measurement of the muon $g-2$, which is the E989/Muon $g-2$ experiment presently running at Fermilab [2] and the low-energy approach-based E34 experiment planned at J-PARC [4]. Both of them have a goal to measure the muon's anomalous magnetic moment with the precision of 0.14 ppm. However, the main limitation of the potential discovery of new physics phenomena within the a_μ sector comes from the uncertainty of theoretical prediction, where the main theoretical uncertainty is related to the hadronic loops contributions to the Standard Model a_μ that cannot be calculated using pQCD methods. Thus, the idea is to use the process of elastic muon scattering on electrons for the precise estimation of the hadronic contribution to a_μ. The experiment dedicated to measure precisely such a hadronic contribution is the MUonE project [5], designed to determine the hadronic part of the running of the electromagnetic coupling constant in the space-like region by the scattering of high-energy muons on atomic electrons in a low-Z target through the elastic process $\mu e \to \mu e$. By using the muon beam of 150-160 GeV, with an average rate of 5×10^7 μ/s, a result with significantly suppressed statistical uncertainty can be achieved on the hadronic contribution to a_μ after about 3 years of data taking.

2. Proposal of the MUonE experiment

Currently, the leading order contribution from hadronic vacuum polarization $a_\mu^{\mathrm{HVP,LO}}$ is calculated via a data-driven dispersive approach, using the low-energy measurements of hadronic production in e^+e^- annihilation [6], which is however difficult due to resonances and threshold effects in the functional form of the s-channel cross section of $e^+e^- \to$ hadrons, which makes it challenging. The method proposed to be used in the MUonE experiment, however, is based on the measurement of the effective electromagnetic coupling in the space-like region, where the vacuum polarization is a smooth function [7]. As the angles of scattered particles are related to the differential cross section, one can determine the cross sections in the elastic scattering signal region, and also in the reference region dominated by the multiple scattering background far from the signal peak, where the angular correlation is minor. The ratio of these two allows to significantly reduce the systematic uncertainty. The precise knowledge of the cross section allows then to determine the hadronic contribution to a_μ with very high accuracy.

In the planned experiment, the data samples of $\mu e \to \mu e$ elastic scattering will be used, collected in the MUonE experiment [5] using 150–160 GeV muons impinging on the atomic electrons of beryllium targets. The upgraded

M2 muon beam at the CERN SPS [8] will be used for this purpose, delivering high-energy and high-intensity muon and hadron beams, and also low-intensity electron beams for calibration. The main detectors of the MUonE experiment are specified in Fig. 1. The tracking system will provide the pre-

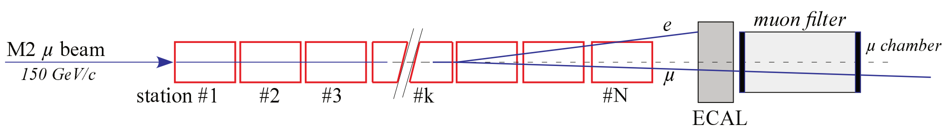

Fig. 1. Schematic veiw of the MUonE detector. Figure adopted from [5].

cise measurement of the scattering angles of the outgoing electron and muon, with respect to the direction of the incoming muon beam. It will contain 40 identical stations, each consisting of a 3 cm thick layer of beryllium coupled to 3 Si layers located at a relative distance of about one meter from each other and spaced by intermediate air gaps (see Fig. 2). Such an arrangement

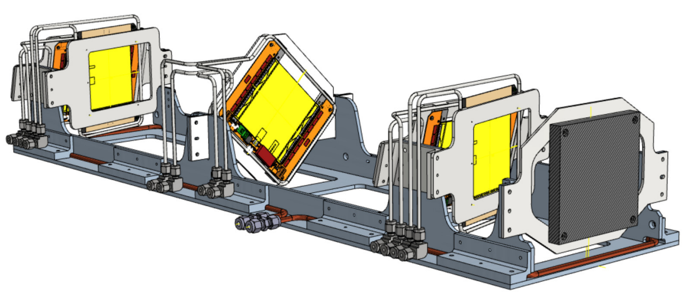

Fig. 2. CAD image of the tracking station. Figure adopted from [11].

provides both a distributed target with low-Z and the tracking system. The state-of-the-art silicon strip sensors for the MUonE project are adopted from the CMS Tracker upgrade, characterized by a large active area sufficient to cover the full MUonE required acceptance, together with appropriate spatial resolution. They can also support the high readout rate of 40 MHz required for MUonE with their accompanying front-end electronics. The silicon sensors are 320 μm thick with n-in-p (n-type readout implant in the p-type bulk), being square sensors with an area of 10 cm $\times$ 10 cm. The strips are capacitively coupled, with a pitch of 90 μm and are segmented into two approximately 5 cm long strips. The DAQ is also adopted from the one developed for CMS sensors for the HL-LHC upgrade. The downstream particle identifiers are planned to be installed, required to solve the muon–electron ambiguity. That will be a calorimeter for the electrons and a muon filter for the muons. A homogeneous electromagnetic calorimeter placed downstream of all the tracker stations will be used, in order to accomplish the physical requirements, *i.e.* particle identification, measurement of the electron energy, and event selection. It will be composed of lead tungstate ($PbWO_4$) crystals, similar to those used by the CMS electromagnetic calorimeter [9]. $PbWO_4$ has a fast light scintillation emission time, a good light yield, and allows for compact dimensions. The crystals consisting of sections of 2.5×2.5 cm^2 are 23 cm long, and the radiation length is $X_0 = 26$ g/cm^2. The readout constitutes solid-state sensors (SiPM or APD). The electromagnetic calorimeter's transverse dimension would be of the order of 1×1 m^2, covering the electrons with energy $E \geq 30$ GeV, while angular acceptance of $\theta_e \leq 5$ mrad is for $E \geq 10$ GeV. Since the muons have a long lifetime and low interaction probability, they fly through the whole detector. Therefore, the muon chamber will be installed at the end of the detector, so all the other possible charged particles should be then filtered. The development of all the chosen MUonE detector systems as well as front-end electronics is well advanced. They have been preliminarily tested with a few detector modules in fall 2021 and will be validated during the MUonE Test Run in 2022–2023.

3. Test beam in 2018

In 2018 the test beam has been performed aiming at the investigation of the elastic interactions of muons on atomic electrons, in a setup configuration similar to the final MUonE detector [10]. The experimental setup was placed downstream of COMPASS in EHN2 experimental area, and consisted of 16 tracking layers of silicon strip sensors and an electromagnetic calorimeter with BGO crystal. The 187 GeV positive muon beam was obtained from decays of pions, which were stopped in the beam dump at the end of COMPASS. The tracking system of 16 tracking stations consisted of a $9.293 \times 9.293 \times 0.041$ cm^3 single-side sensor with 384 channels was located behind the target, which was a 10×10 cm^2, 8 mm thick graphite layer. A calorimeter located at the end of the system covered an angular acceptance of about 15 mrad on each side from the center of silicon layers.

The test beam was aimed mainly at checking the ability to select a clean sample of elastic scattering events in view of designing the final experiment, by measuring the correlation between the scattering angles. Even with much worse conditions as compared to the final detector configuration, it was possible to select a relatively clean sample of elastic events, as it may be seen in Fig. 3. The correlation between the muon and electron scattering angles is clearly visible, where the colors denote the total energy deposited in the calorimeter. The analysis of the 2018 test beam data allowed also to identify the necessity of providing a good quality calorimeter, in order to control the systematic effects as well as to better understand the background.

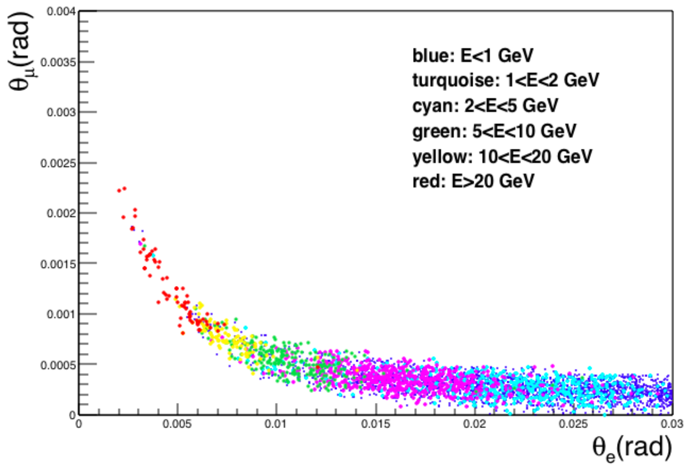

Fig. 3. Kinematical correlations of the outgoing electron and muon. Figure adopted from [10].

4. Test Run in 2022–2023

Thje MUonE experiment requests two weeks of the M2 beam for the Test Run at the end of the running period of 2022, and then three weeks at the beginning of 2023. The detector will be installed in the space available upstream the COMPASS. It is considered a prototype of the final setup, and will consist of two tracking stations, each consisting of a thin berillium target and six tracking layers, with six other tracking layers located upstream of the detector for tracking the incoming muons. The main goal of the Test Run will be to test the validity of the design and detector operation, such as assembly, mounting, and cooling, check the signal integrity in the process of data transfer for DAQ as well as to prove the validity of the triggerless operation mode and evaluate the FPGA real-time processing. In addition, it will be possible to validate the alignment procedure for the sensors and investigate the sources of systematic uncertainty. The physics potential of the Test Run, estimated with the default SPS efficiency for full beam intensity, assumes an integrated luminosity corresponding to about 10^9 scattering events with electron energy greater than 1 GeV. This may provide enough sensitivity to measure the leptonic running of the electromagnetic coupling constant and potentially could provide initial sensitivity to the hadronic running [11].

5. Summary

The MUonE experiment provides a unique analysis of the hadronic part of the running of the electromagnetic coupling constant in the space-like region by the scattering of high-energy muons on atomic electrons through the elastic process $\mu e \to \mu e$. The analysis is expected to significantly reduce the error on $a_\mu^{\mathrm{HVP,LO}}$, being a complementary measurement to the $g-2$ results from BNL-E821 and Fermilab-E989 experiments, providing finally the opportunity to increase strongly the significance of observed discrepancy with respect to the Standard Model predictions, thus increasing the potential for the new physics discovery. The MUonE project is well advanced in view of the Test Run in 2022–2023, which has been approved with a partial apparatus as a validation of the detector design and the overall concept, followed by the main measurement foreseen in 2024–27.

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