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Status of the MUonE experiment(*)

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Summary. — The MUonE experiment wants to measure with an innovative method the vacuum polarization term of the muon magnetic moment. Its theoretical uncertainty represents the major one in the $g-2$ prediction. In 2021 and 2022 some tests have been carried out to study the performances of the MUonE detectors. In 2023 a test run has been performed to validate the methodology and finalize the experimental proposal. The status of the experiment will be presented.

1. – Introduction

Nowadays, one of the most puzzling questions dealing with particles physics concerns the anomalous magnetic moment of the muon $a_\mu = g-2/2$. In 2006, the BNL's E821 experiment [1] measured this quantity and the result deviated 3.7σ from the reference theoretical estimate. After 15 years, in 2021 [2] and again in 2023 [3], the $g-2$ experiment at Fermilab confirmed this result, bringing the discrepancy first to 4.2σ and then to 5.0σ. However, the theoretical landscape changed.

The dominant uncertainty of the prediction is given by the leading order hadronic vacuum polarization term a^{HVP}, which is not calculable in perturbation theory. The reference value reported in the 2020 White Paper [4] was evaluated through a data-driven method based on the measurement of the $e^+e^- \to had$ cross section. In 2020, the BMW Collaboration [6] published a new result for a^{HVP} based on Lattice QCD, that, together with the new 2023 CMD-3 experimentn [5] of the $e^+e^- \to had$ cross section, weakens the $a_\mu^{th} - a_\mu^{exp}$ discrepancy, bringing it to $\Delta\alpha_\mu < 3\sigma$.

Considered this intriguing situation, it is of paramount importance to improve the theory calculation and clarify the status of the available estimates. MUonE aims to provide an independent and innovative method to evaluate a^{HVP} [7] , based on the evaluation of the master equation:

$$a^{HVP} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)], \tag{1}$$

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which depends on the hadronic contribution to the running of the electromagnetic coupling in the space-like region of momenta $\Delta\alpha_{had}(t)$. The main difficulty of the method is to reach the required precision in order to be competitive: $< 0.5\%\, a^{HVP}$. The process used for the measurement is the $\mu - e$ elastic scattering on light target. The CERN M2 muon beam line at $E_\mu = 160$ GeV will be used for the purpose. The project has been submitted to the CERN SPS Committee with a Letter of Intent in 2019 [9] and the next step will be to write a technical proposal in 2024.

2. – MUonE analysis technique

The $\Delta\alpha_{had}(t)$ contribution is most easily displayed considering the ratio:

$$R_{had} = \frac{d\sigma(\Delta\alpha_{had} \neq 0)}{d\sigma(\Delta\alpha_{had} = 0)} \tag{2}$$

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:

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

This 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.

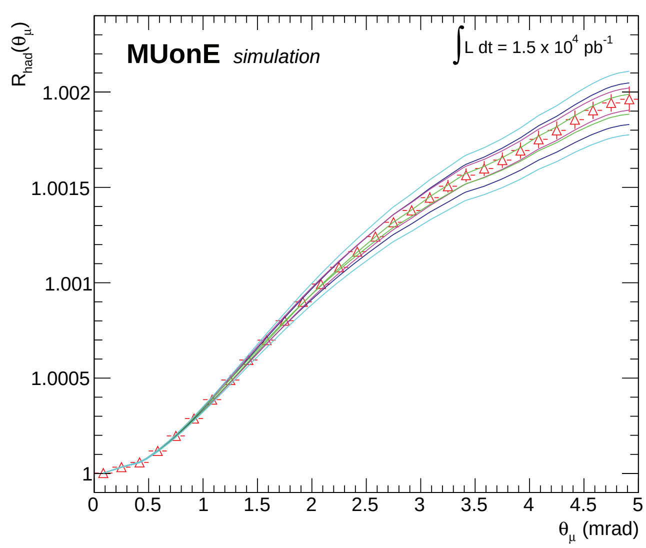

Fig. 1. – Central value of $R_{had}(\theta_\mu)$, the curves represent the representative MC templates [8].

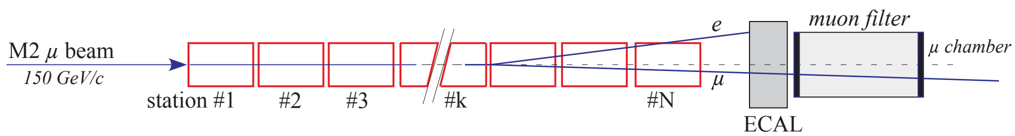

Fig. 2. – Layout of the MUonE experimental setup [9].

For each pair of values, a template for R_{had} is obtained with the Monte Carlo generator (fig. 1), which then is compared with data/pseudodata calculating:

$$\chi^2(K, M) = \sum_i \frac{R_i^{data} - R_i^{templ}(K, M)}{\sigma_i^{data}} \tag{4}$$

where $K = \frac{k}{M}$, and the minimum χ^2 is found by parabolic interpolation across the grid points. The fit can be done on the distribution of the muon or the electron scattering angle, as well as on their two-dimensional distribution, which gives the most accurate result.

3. – MUonE experimental apparatus

The full experimental apparatus is segmented in 40 tracking stations, followed by an electromagnetic calorimeter (ECAL) and a muon filter (fig. 2). Each station behaves as an independent unit and is composed by a 1.5 cm target (Beryllium or Graphite) and 6 silicon strip modules (CMS 2S modules [10]). The electromagnetic calorimeter prototype is composed by 25 cells of $PbWO_4$, 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.

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 average beam energy to few MeV, alignment and intrinsic angular resolution.

4. – Test runs

Several test runs have been carried out between 2017 and 2023, to check the validity of the proposed method and the behavior of the detectors.

In 2017 a first beam test was performed to study multiple scattering [11], while in 2018 a second beam test was set up at the CERN M2 beam line in order to study the capability of selecting elastic events [12], with the proposed method. The used detectors 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. 3.

In August-September 2023, a pilot run was carried out at the CERN M2 muon beam line and it was the first time with 2 fully-equipped tracking station and the ECAL. The main purposes were to scale the DAQ from 1 to 2 station, synchronize it with the ECAL

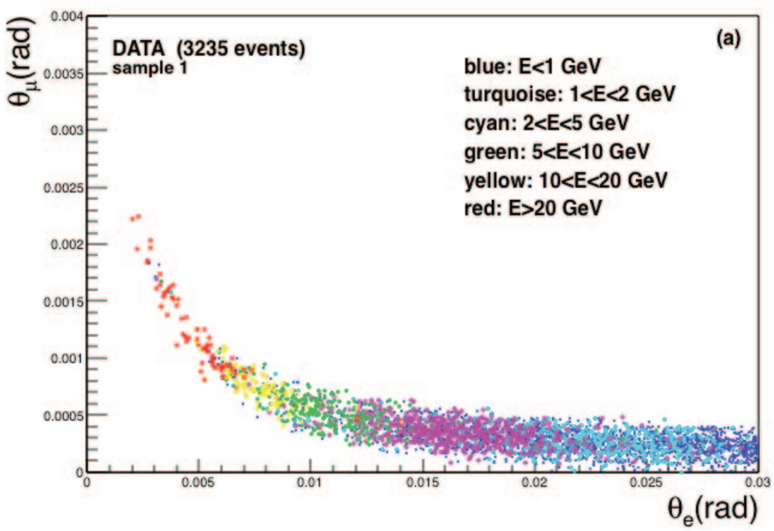

Fig. 3. – Selected sample of elastic events as a result of the 2018 MUonE Test Run [12].

DAQ and test the software and hardware alignment, with the final aim to collect enough statistics for a first measurement of the leptonic running $\Delta\alpha_{lep}$.

The results will be used to write the technical proposal, which is planned to be submitted at the SPSC in 2024.

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