Status of the MUonE experiment

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Abstract

The latest measurement of the muon g-2, recently announced at Fermilab, exhibits a 4.2σ discrepancy from the Standard Model prediction. The hadronic contribution a_μ^{HLO} represents the main source of uncertainty on the theoretical prediction. The MUonE experiment proposes a novel approach to determine a_μ^{HLO} by measuring the effective electromagnetic coupling in the space-like region, via $\mu - e$ elastic scattering. The measurement is performed by scattering a 160 GeV muon beam, available at CERN, on atomic electrons of a low-Z target. A Test run on a reduced detector is planned in 2022, to validate this proposal. The status of the experiment in view of the Test run is presented.

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1 Introduction

The muon magnetic anomaly is defined as $a_\mu = (g_\mu - 2)/2$, where g_μ is the gyromagnetic ratio. It is a low energy observable which can be both computed and measured with very high precision, and can be used as a stringent test of the Standard Model. Recently, the E989 Muon g-2 collaboration at Fermilab announced its first result for a_μ [1], which is in excellent agreement with the previous measurement performed by the BNL E821 experiment [2]. The combination of the two experimental values leads to a 4.2σ discrepancy with the Standard Model prediction currently recommended by the Muon g-2 Theory Initiative [3]. Figure 1 represents the current scenario.

In the next years, the accuracy on a_μ will be improved by a factor of 4 by the E989 experiment, reaching the remarkable accuracy of 0.14 ppm [4]. Moreover, a new technique will be exploited at J-PARC to measure a_μ in an independent way [5]. Therefore, an improvement is also required on the theoretical prediction, as its uncertainty can become the main limitation for a test of the Standard Model.

The accuracy on the Standard Model calculation is limited by the evaluation of the leading order hadronic contribution a_μ^{HLO}, which cannot be computed perturbatively at low energies.

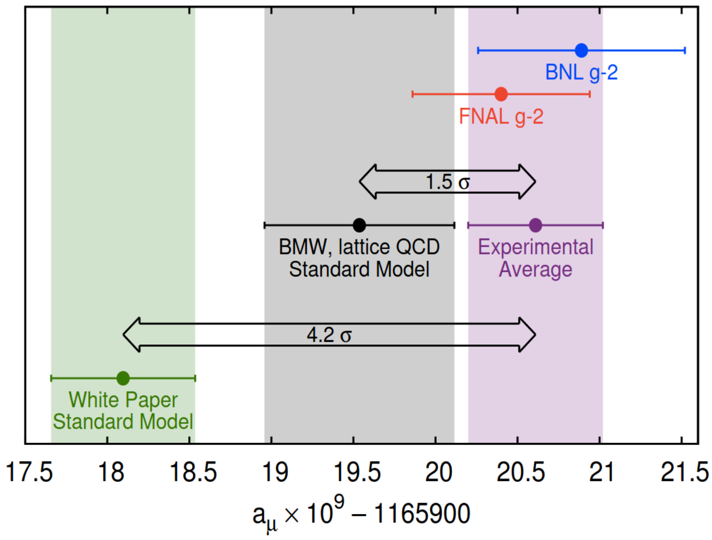

Figure 1: From the top to the bottom: experimental values of a_μ measured by BNL E821 [2], Fermilab E989 [1] and their combined average. Standard Model evaluation of BMW collaboration using lattice QCD [6] is also shown, as well as the value recommended by the Muon g-2 Theory Initiative [3].

For this reason, a_μ^{HLO} is traditionally determined by means of a dispersion integral on the annihilation cross section $e^+e^- \to$ hadrons, which is densely populated by resonances and influenced by flavour threshold effects. These aspects limit the final precision achievable by this method. Despite these difficulties, the calculation of a_μ^{HLO} reached an accuracy of $\sim 0.6\%$ [3].

In addition to this, a recent evaluation of a_μ^{HLO} based on lattice QCD calculation reached for the first time an accuracy comparable to the dispersive approach [6]. However, there is a tension between these two theoretical evaluations. The lattice QCD value weakens the discrepancy between theory and experiment to 1.5σ, as shown in Figure 1. An independent crosscheck of a_μ^{HLO} is then required to solve this tension and consolidate the theoretical prediction.

MUonE proposes an innovative method to measure a_μ^{HLO}. It based on the direct measurement of the hadronic contribution to the running of the electromagnetic coupling constant ($\Delta\alpha_{had}$) in the space-like region [7]. The following equation will be used to calculate a_μ^{HLO}:

$$a_\mu^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)] \,. \tag{1}$$

Here, α_0 is the fine structure constant, and the integration variable x is related to the space-like momentum transfer t through the formula

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

where m_μ is the muon mass.

Figure 2 shows the integrand function of the master integral in Eq. 1. The peak of the integrand occurs at $x_{peak} \simeq 0.914$, which corresponds to a momentum transfer $t_{peak} \simeq -0.108\,\text{GeV}^2$. Here, $\Delta\alpha_{had}(t_{peak}) \simeq 7.86 \times 10^{-4}$.

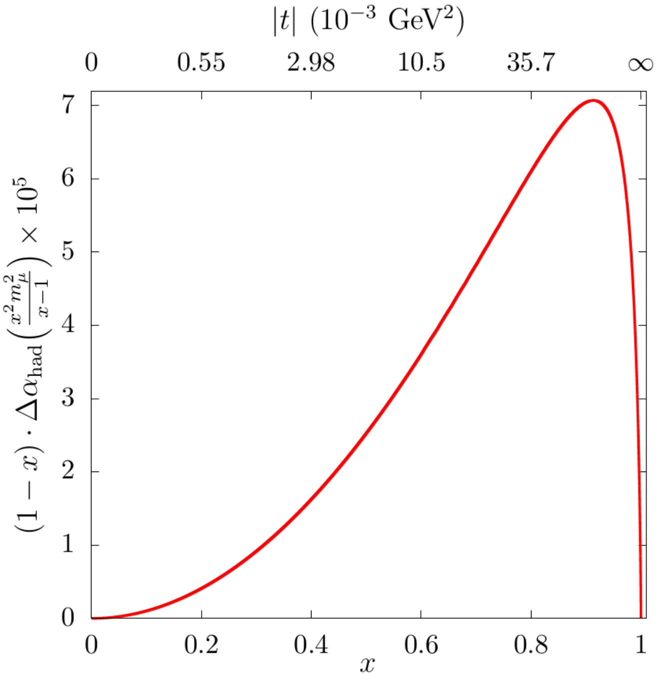

Figure 2: Integrand $(1-x)\Delta\alpha_{had}[t(x)]\times 10^5$ as a function of x and t (upper scale) [8].

The main advantage of this method is that $\Delta\alpha_{had}$ is a smooth function for negative momentum transfer, in contrast with the time-like e^+e^- data used in the traditional dispersive approach. A further advantage is that the electromagnetic running in the region of interest for the evaluation of a_μ^{HLO} can be measured by a single scattering experiment. For this reason, the space-like approach is not affected by the systematic uncertainties due to handling data from different experiments, which instead are relevant for the time-like dispersive method. Therefore, the method proposed by MUonE allows a completely independent estimation of a_μ^{HLO}, which can be compared with time-like and lattice QCD results towards a firmer prediction of a_μ.

2 The MUonE experimental proposal

The MUonE experiment aims to extract $\Delta\alpha_{had}(t)$ from a precise measurement of the shape of the differential cross section of the $\mu^+e^-\to\mu^+e^-$ elastic scattering [8]. It is performed by scattering a high energy muon beam on the atomic electrons of a low-Z target. A 160 GeV muon beam, currently available at CERN M2 beamline, allows to cover the momentum transfer region $-0.153\,\text{GeV}^2 < t < 0\,\text{GeV}^2$, which is equivalent to $0 < x < 0.932$. This corresponds to $\sim 87\%$ of the master integral in Eq. 1. The remaining fraction can be computed by extrapolating $\Delta\alpha_{had}(t)$ with an appropriate parameterization [9]. Furthermore, the simple kinematics of the two-body elastic process makes the scattering angles of the electron and muon correlated. This constraint allows to select elastic events and reject background, which is expected to be mainly due to e^+e^- pair production by muons in the target. The elastic scattering kinematics is highly boosted in the forward direction in the laboratory frame, due to the high energy muon beam employed. This allows to use a single detector to cover the full acceptance, since the elastic events which are interesting for the experiment are contained within ~ 32 mrad for the electron and within ~ 5 mrad for the muon.

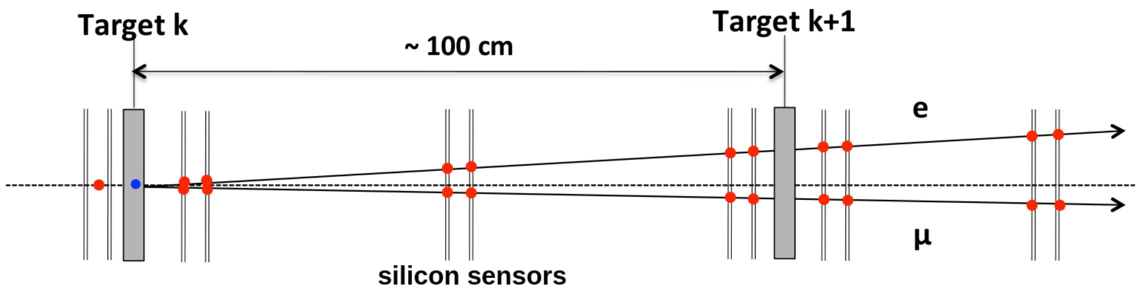

Figure 3: Sketch of a single station (image not to scale).

The experimental apparatus consists of a repetition of 40 identical stations. A sketch of a single station is shown in Figure 3. It is composed of a 15 mm thick Beryllium target followed by a tracking system with a lever arm of ~ 1 m, which is used to measure the scattering angles with high precision. The tracking system is composed of 3 pairs of Silicon strip detectors. Each pair measures both X and Y transverse coordinates, thus strips of the second detector are orthogonal to the first ones. An electromagnetic calorimeter is placed downstream all the stations, in order to provide e/μ particle identification in the low angles region. The apparatus will be also equipped with a muon filter, placed downstream the calorimeter.

The modular structure of MUonE allows to re-use the incoming muon beam for each station, which acts as an independent unit. In this way, $\mu - e$ elastic events will be distributed along the entire apparatus, increasing the collected statistics but minimizing at the same time the thickness of a single Beryllium target. This helps to keep under control multiple scattering effects, which break $\mu - e$ angular correlation.

Given the total target thickness of 60 cm and the average intensity of $\sim 1.3 \times 10^7 \mu/\mathrm{s}$ of the CERN M2 beamline, MUonE can reach an integrated luminosity of about $1.5 \times 10^7 \mathrm{nb}^{-1}$ in 3 years of data taking. This is equivalent to collect $\sim 4 \times 10^{12}$ elastic events with electron energy > 1 GeV, and allows to achieve a statistical error of $\sim 0.3\%$ on a_μ^{HLO}. This makes the measurement of MUonE competitive with the time-like evaluation.

The main challenge of the experiment is to keep the systematic error at the same level of the statistical one. This is equivalent to measure the shape of the differential cross section with a systematic accuracy of $\mathcal{O}(10\text{ ppm})$ at the peak of the integrand function [8]. The most relevant sources of systematic uncertainties are the longitudinal alignment of a station, which must be controlled at the level of 10 µm, the knowledge of the average beam energy, which needs to be determined with a precision of few MeV [9], and multiple scattering effects. Preliminary analyses indicate that these effects can be controlled at the required values. Results from a Test Beam performed at CERN with 12-20 GeV electrons on 8-20 mm C targets show a satisfactory agreement between data and GEANT4 simulation [10].

2.1 Theoretical progress

On the theoretical side, the development of high precision Monte Carlo tools is needed, since the differential cross section must be calculated up to the NNLO to meet the requirement of $\mathcal{O}(10\text{ ppm})$ systematic uncertainty. Presently, the full set of NLO QED and electroweak corrections is completed, and a fully exclusive Monte Carlo generator is available [11]. The NNLO hadronic corrections have been computed in [12, 13]. The full set of QED NNLO corrections is still not yet available, although several important steps have been carried out [14–17]. Two independent Monte Carlo codes with full NNLO corrections are being developed [18, 19]. Reference [20] gives a state of art review of the theoretical progress in MUonE. Possible new physics effects in $\mu - e$ elastic scattering have been investigated in [21, 22], and are expected to lie below MUonE sensitivity.

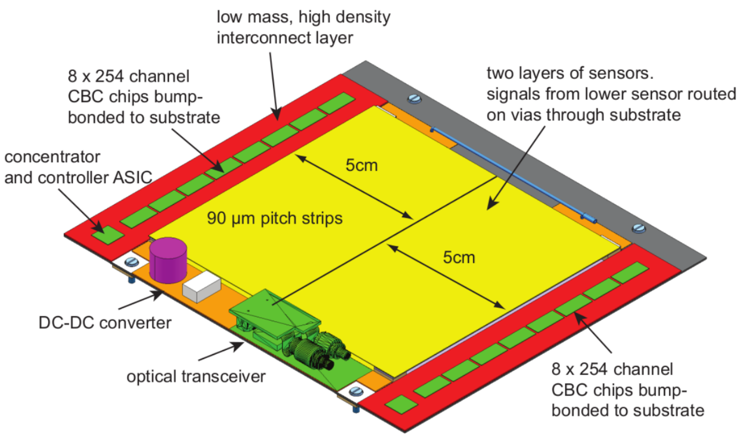

Figure 4: Schematic representation of a 2S module [9].

3 Test run 2021-2022

A Letter of Intent has been submitted to the CERN SPS Committee in 2019 [9], obtaining positive recommendations. A Test run of 3 weeks has been approved to validate the experimental proposal. Due to Covid-19, it has been delayed to 2022. A parasitic run with four Silicon detectors has been performed at the M2 beamline from 25th October to 15th November 2021.

The Test run detector will be composed of two full MUonE stations followed by an electromagnetic calorimeter. A further tracking station without target will be placed upstream the apparatus, to detect the incoming muons.

The basic tracking unit has been chosen to be the 2S modules developed for the CMS Outer Tracker upgrade [23]. Figure 4 shows a schematic view of a 2S module. Each module is composed of 2 close-by Silicon strip sensors with the same dimension and strip orientation, thus reading the same coordinate. Each sensor is 320 μm thick, with an area of approximately $10 \times 10\,\mathrm{cm}^2$. Therefore, a single module allows to cover the full angular acceptance, ensuring a uniform responce over all the scattering angles. The two sensors composing a module are mounted on the same mechanical structure, and are read out by the same front-end electronics, which compares signals from the two sensors to find correlated hits. This feature can be exploited to reject large angle tracks and suppress background from single sensor hits. The read-out rate at 40 MHz is capable to sustain the M2 beamline in-spill rate (50 MHz) minimizing the pileup. 2S modules have a single hit resolution of $\sim 20\,\mu\mathrm{m}$, which can be furhter improved by rotating a module around the strip orientation. Simulation studies show that a tilt of 233 mrad ($\sim 14°$) improves the single hit resolution to $\sim 10\,\mu\mathrm{m}$ keeping a high detection efficiency.

The current setup of a MUonE station is represented in Figure 5. First and third pair of 2S modules are tilted to implement the single hit resolution improvement, while the second pair is rotated by 45° around the beam axis, in order to solve reconstruction ambiguities. The mechanical structure is made of Invar. It is a Fe-Ni alloy which has a low coefficient of thermal expansion ($\sim 1.2 \times 10^{-6}\,\mathrm{K}^{-1}$), in order to meet the stringent request of 10 μm on the stability of the longitudinal size. For this purpose, an enclosure and a cooling system have been also designed to keep the temperature of the station constant within 1 °C.

Presently, an aluminum mockup has been manifactured to test the mechanical structure planarity and the correct integration of the 2S modules. Stepper motors are used to align the station with the muon beam. They have been succesfully tested in the parasitic run of Fall 2021.

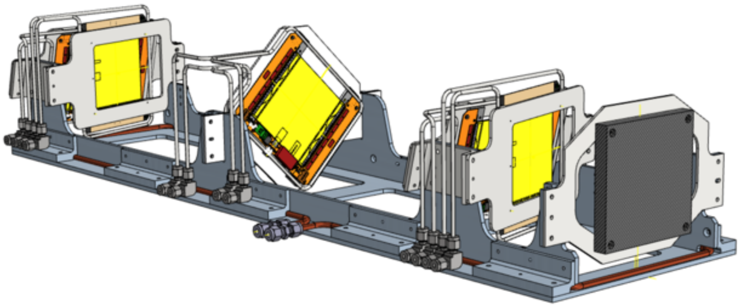

Figure 5: CAD drawing of a MUonE station.

The electromagnetic calorimeter used in the Test run is composed of a matrix of 5 × 5 $PbWO_4$ crystals. The total area of $14 \times 14\,\mathrm{cm}^2$ allows to cover the full acceptance for the scattering events from the two MUonE stations. Each crystal has a section of $2.85 \times 2.85\,\mathrm{cm}^2$ and a length of 22 cm ($\sim 25X_0$), and will be read-out by APD sensors. Tests on sensors and crystal response are currently ongoing.

The Test run will be mainly aimed at monitoring the mechanical and thermal stability of the apparatus, as well as confirming the validity of the system engineering. It will be crucial to test the alignment procedures and check the front-end electronics and the DAQ system. Data streams from the 2S modules and the calorimeter will be processed by a single Serenity board [24]. No event selection will be applied during the Test run. All the information will be then used to elaborate online selection algorithms to be implemented in the Full run with 40 stations.

Assuming to accomplish these primary goals in the first two weeks of running, the remaining days could be exploited to collect $\sim 5\,\mathrm{pb}^{-1}$ of good quality data, corresponding to $\sim 10^9$ elastic events with electron energy $> 1\,\mathrm{GeV}$. Such a data sample will allow to measure the leptonic contribution to the electromagnetic running, which is $\lesssim 10^{-2}$ in our kinematic range. Moreover, it could be enough to get an initial sensitivity to $\Delta\alpha_{had}(t)$, which is $\lesssim 10^{-3}$ in the MUonE kinematic region. Given the limited statistics which could be collected in the Test run, the effect of $\Delta\alpha_{had}(t)$ can be modeled as a linear deviation in t on the shape of the differential cross section. It can be easily displayed considering the ratio R_{had} between the observed differential cross section and the theoretical prediction computed assuming only the presence of the leptonic running. It turns out to be

$$R_{had} \simeq 1 + 2\Delta\alpha_{had}(t)\,. \tag{3}$$

Figure 6 shows the expectation of R_{had} obtained using the MUonE NLO Monte Carlo generator. The extraction of $\Delta\alpha_{had}(t)$ is carried out by means of a template fit method [9]. The resulting value for the slope of the hadronic running is $K = 0.136 \pm 0.026$.

4 Conclusions and future plans

At present, the MUonE collaboration includes collaborators from institutions in China, Greece, Italy, Poland, Russia, Switzerland, UK, USA and at CERN.

An intense activity is ongoing for the preparation of the Test run, which will be a proof of concept of the overall project. If successful, a full proposal will be prepared including support from the results of the Test run. A first measurement of a_μ^{HLO} could be performed in 2023-24 by adding 10 stations to the existing prototype. Preliminary studies show that a running time of 4 months will allow to achieve a $\sim 2\%$ statistical accuracy. A run with the full detector would be then envisaged in the following years.

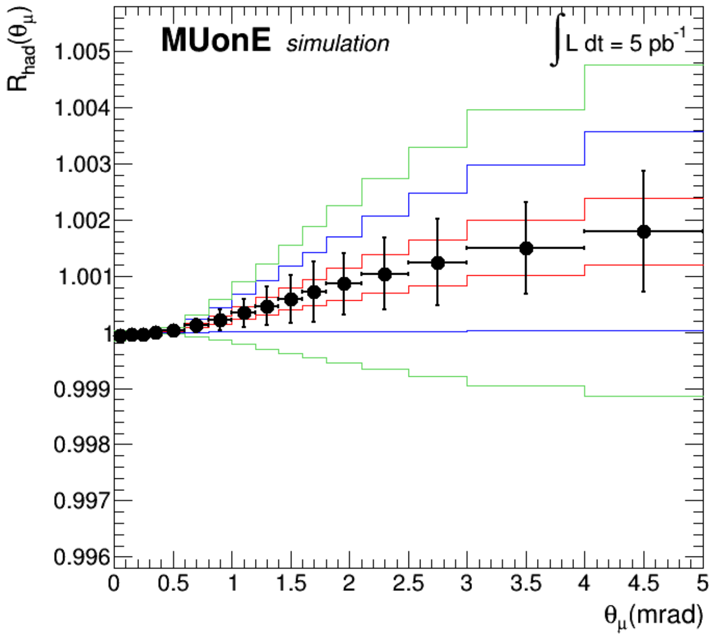

Figure 6: Ratio R_{had} as a function of the muon scattering angle. The error bars correspond to the statistical uncertainties for an integrated luminosity of 5 pb^{-1}. Red, blue and green lines represent templates for different values of the slope of $\Delta\alpha_{had}(t)$.

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