MUonE experiment

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Abstract. The anomalous magnetic moment of the muon has been a long standing issue in the field of particle physics. The recent results by Fermilab have pointed to a possible discrepancy of 4.2σ with respect to the Standard Model prediction. Although the future measurements will undoubtedly strengthen this result, the large uncertainty of the prediction, caused by a non-perturbative hadronic contribution, remains an issue. The MUonE experiment is designed to provide an independent, precise measurement of this contribution by employing a series of tracking stations and low-Z targets, to precisely determine the shape of differential cross-section of an elastic $\mu + e \to \mu + e$ scattering. It is expected to increase the result's significance to at least 7σ, thus solidifying the discovery. The design of the detector allows also for New Physics searches with a signature of displaced vertices.

1 Muon's anomalous magnetic moment

The anomalous magnetic moment of a lepton is defined by the relative deviation of the gyromagnetic constant from its value predicted by Dirac equation:

$$a = \frac{g-2}{2}.$$

In case of electrons, the anomaly has been measured with an incredible precision and remains one of the most important Standard Model (SM) benchmarks. Due to the mass difference, however, muons are much more sensitive to corrections from potential massive loops related to the New Physics phenomena. For this reason, the discrepancies of measured and theoretical values of a_μ, reported over the years by various experiments, have been of great interest. Most recently, the Muon g-2 Collaboration at Fermilab published results suggesting a significance as high as 4.2σ with respect to the SM prediction with the hadronic contribution calculated using a dispersion integral on the experimentally measured hadron production cross-section in e^+e^- annihilation [1]. A summary of new and previous results, together with theoretical predictions is presented in figure 1. It may be observed that the uncertainty of Standard Model prediction is, at best, comparable with that of the measurement. As the hadronic contributions, mainly the leading Hadronic Vaccuum Polarization (HVP) term and the Hadronic Light-by-Light, cannot be calculated perturbatively, they constitute about 99.8% of the total uncertainty. The former can be estimated using either the data-driven approach described above (shown as squares in figure 1) or using lattice-based methods (shown as circles). In general, the lattice results seem to be more compatible with measurements, but the tension of data-driven ones is not yet understood.

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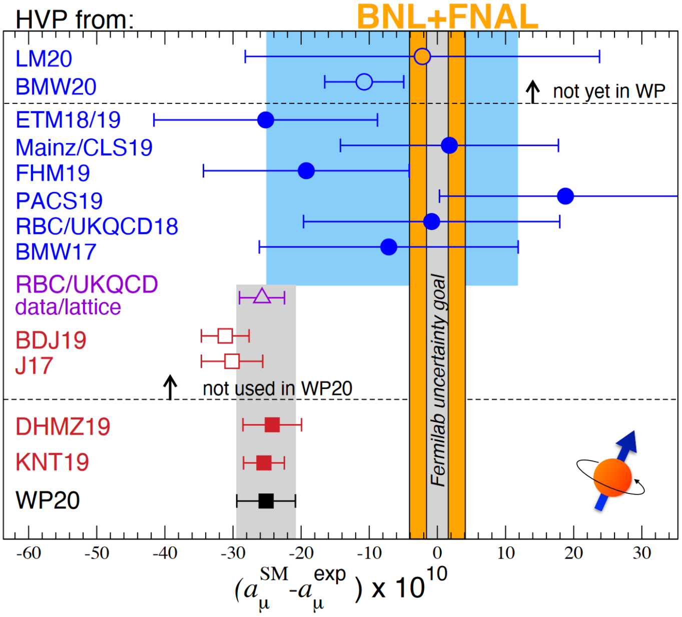

Figure 1. Comparison of measurements of the anomalous muon magnetic moment with theory prediction. Figure taken from [2].

2 MUonE experiment – a space-like approach to HVP

The main challenge of data-driven methods to measure the hadronic contribution to a_μ is the limited precision with which the hadronic cross-sections can be integrated due to the abundance of resonances and thresholds effects. The MUonE collaboration proposes a novel approach, based on the measurement of the effective electromagnetic coupling in the space-like region, where the integral is performed over a smooth function of its hadronic part instead [3]. Experimentally, the problem is reduced to measuring the differential cross-section in the simplest scenario of a single $\mu + e \rightarrow \mu + e$ scattering. Since all other contributions to the running of α are perturbative and known very precisely, the hadronic part can also be extracted with very high accuracy. Additionally, the systematic uncertainty can be reduced significantly by considering the ratio of the cross-section in the elastic signal region and the reference one in which the angular correlation would be insignificant.

3 MUonE detector

The main challenge of the MUonE experiment is to control the systematic effects at the same level as the statistical precision. Therefore, the main goal of the trigger and event reconstruction is to reduce the contribution related to the overall reconstruction efficiency, software alignment and particle identification. The experiment will be located at the upgraded M2 line of the CERN SPS, providing high intensity muons with the required energy of 160 GeV as well as low intensity calibration beams. The elastic $\mu+e \rightarrow \mu+e$ scattering events will be collected using a series of Beryllium targets with thickness optimised for signal-to-background ratio. In order to achieve the required angular resolution, while ensuring redundancy and high data collection rate, a modular approach has been developed. The detector will consist of 40 identical stations (see figure 2), equipped with a target and a set of tracking layers, with a relative distance between consecutive targets of about 1 meter. Each station can thus independently fulfil the role of reconstructing either the beam muon or scattered particles, depending on which target initiated the interaction. The tracking will be performed using the state-of-the-art silicon strip sensors, designed for the upcoming CMS Tracker upgrade [4], which provide the necessary spatial resolution and cover the acceptance required by MUonE. Additionally, an electromagnetic calorimeter and muon chamber will be located at the downstream end of the detector, in order to improve the inelastic background rejection and muon identification.

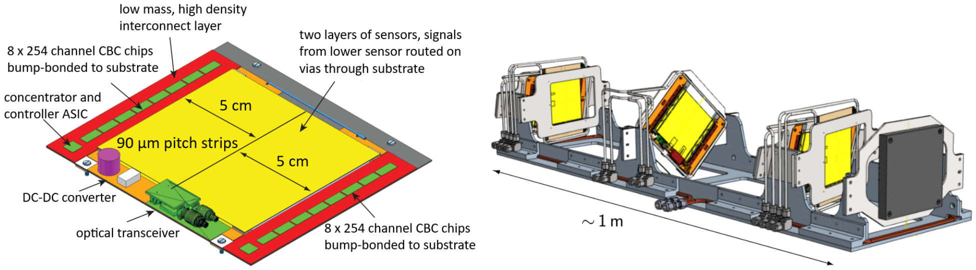

Figure 2. A schematics of a 2S silicon strip sensor (left) and a single MUonE tracking station (right). Figures taken from [3] and [4], respectively.

4 2018 Test Run

The first major test run has been performed in 2018 and involved a setup similar to the final MUonE detector, located downstream of COMPASS [5]. With the goal of studying the potential to extract a clean sample of elastic signal events and aiding in designing the experiment, an assumed performance has been achieved. Most importantly, the scattering angles and the resulting correlation curve have been reconstructed very well (figure 3), despite using tracking modules of much worse quality than ones envisioned for the final detector layout (121 μm pitch with a 242 μm readout pitch compared to 90 μm in the final configuration). The tests also highlighted the need for a high quality calorimeter, in order to properly estimate the systematic effects and study the backgrounds.

5 2022 Test Run and Pilot Run

In 2022, a prototype of a full tracking station in the final detector configuration was tested, together with a calorimeter, managing a successful and stable operation with high intensity beam. The run allowed to collect a large amount of data on the Si tracking layers performance (over 2.5 trillion hits registered) and stress-test the data acquisition system (DAQ) as well as offline processing chain. Finally, a two week long Pilot Run is planned for the end of 2023, using two stations located upstream of COMPASS. The focus will be placed on achieving a full integration of the DAQ from multiple tracking stations and the calorimeter, developing and validating an accurate procedure of their alignment and evaluating various approaches to reducing the data rate (trigger-less, simple trigger and real-time reconstruction). On the physics side, an order of 10^9 elastic scattering events with an electron energy above 1 GeV is expected, allowing to measure the leptonic and potentially providing initial sensitivity to the hadronic running of α. Additionally, the sources of systematic uncertainties will be investigated. The results will be used to prepare the technical proposal of the MUonE experiment.

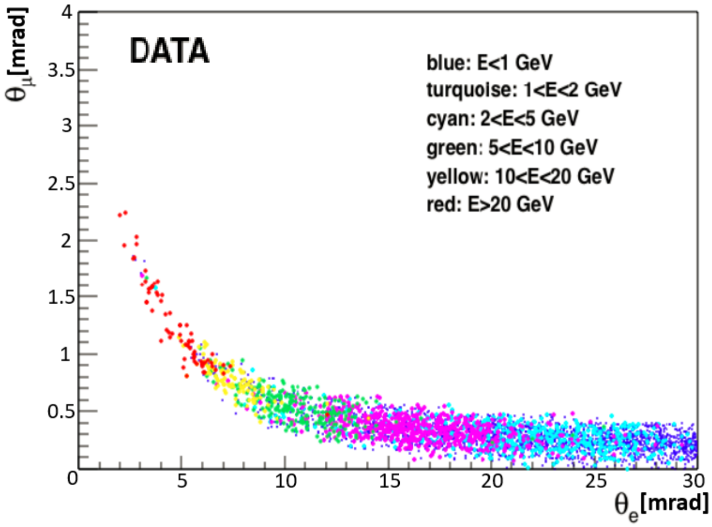

Figure 3. Scattering angles correlation in the elastic signal sample, extracted from data collected during the 2018 test run. The colours indicate the total energy deposit in the calorimeter. The angular resolution in the final detector is significantly better. Figures taken from [5].

6 Summary and plans

The recent Fermilab measurement of α_μ indicates a 4.2σ discrepancy with respect to the Standard Model predictions, where the non-perturbative hadronic contribution is determined using the data-driven approach. One of the main issues is the total SM uncertainty, dominated by the contribution from Hadronic Vaccuum Polarization (α^{HVP}). MUonE aims to provide a complementary measurement of α^{HVP} with a competitive precision of $\sim$ 0.3%. The novel method avoids the necessity of calculating dispersive integrals of experimental hadronic cross-sections, improving the total uncertainty by a factor of 2. With the modular approach to the detector design, the experiment can be scaled up in multiple steps. In the short term, the 2023 pilot run will focus on a measurement of the leptonic running, using two fully instrumented stations. Finally, a 3 year long operation, using 40 stations, will be required to get to the final precision of 0.3%.

7 Acknowledgements

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