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Muon g-2 experiment and future muon experiments

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The Muon g-2 experiment at Fermilab aims to measure the muon anomalous magnetic moment, a_μ, with a final precision of 140 part per billions (ppb). The first results from the Run-1 dataset were released on April 7, 2021, showing a very good agreement with the previous experimental result at Brookhaven National Laboratory (BNL) [1]. In light of the new theoretical calculation of the hadron vacuum polarization contribution of a_μ by the BMW group using the Lattice QCD, a strong tension arose within the theoretical side. Here we discuss this high precision measurement and the current work towards a new result, Run-2/3 analysis, on the muon anomaly that aims to reach a statistical uncertainty of 200 ppb and a systematic uncertainty of 70 ppb. Furthermore, a brief overview of other muon experiments will be given.

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1. Introduction

The magnetic moment of a lepton (l) with spin s, charge q, mass m and gyromagnetic ratio g is defined as:

$$\vec{\mu}_l = g_l \left(\frac{q}{2m_l} \right) \vec{s}. \tag{1}$$

Dirac predicted $g_e = 2$ for the electron (and, consequently, any spin $\frac{1}{2}$ elementary particle) [2]. Schwinger proposed an additional contribution to the electron magnetic moment from a radiative correction, predicting the magnetic anomaly $a_e = \frac{g_e - 2}{2} = \alpha/2\pi \simeq 0.00116$ in agreement with experiment [3]. In the following years the theoretical calculation showed how each sector of the Standard Model contributes, through the vacuum polarization, to the estimate of a_μ.
At the Muon $g-2$ Experiment at Fermilab, polarized muons, with a momentum of 3.1 Gev/c, are injected into a superconducting storage ring of 15 meters in diameter. While muons are collected in the storage ring and orbit with a frequency defined by the cyclotron frequency: $\vec{\omega}_C = \frac{e\vec{B}}{m\gamma}$ their spin rotates with a frequency proportional to the g-factor according to the Larmor precession formula: $\vec{\omega}_S = g\frac{e}{2m}\vec{B}$.
By computing the difference between $\vec{\omega}_C$ and $\vec{\omega}_S$ in the lab frame, we obtain the rotation frequency of the muon spin relative to its momentum, called the anomalous precession frequency $\vec{\omega}_a$. This frequency is determined by "$g-2$ frequency" and, together with the measurement of the storage ring magnetic field, forms the most important observable of the $g-2$ experiment. The most general expression of $\vec{\omega}_a$ is:

$$\vec{\omega}_a \approx \vec{\omega}_S - \vec{\omega}_C = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right)(\vec{\beta} \times \vec{E}) - a_\mu \left(\frac{\gamma}{\gamma + 1} \right)(\vec{\beta} \cdot \vec{B})\vec{\beta} \right]. \tag{2}$$

We can simplify this expression and cancel the effect of the E-field by producing muon at the "magic momentum" of $p_\mu = 3.094$ GeV/c which corresponds to $\gamma = \sqrt{1 + \frac{1}{a_\mu}} \approx 29.3$. This way a_μ can be written as: $a_\mu = \frac{m}{e}\frac{\vec{\omega}_a}{\vec{B}}$, from which we measure $\vec{\omega}_a$ and the B-field, the latter as precession frequency of a proton shielded in a spherical sample of water.

2. ω_a measurement

In the Muon $g-2$ Experiment at Fermilab, polarized muons are injected in the storage ring. Due to the parity violation in the weak muon decay, produced high-energy positrons are emitted preferably along the muon's spin direction. The emitted positrons are detected by 24 electromagnetic calorimeters, which measure the energies and arrival times of the positrons. Each of the calorimeters is made up of 54 crystals of lead fluoride (PbF_2) read by silicon photomultipliers (SiPM). The anomalous precession frequency can be measured by reconstructing the time distribution of high-energy positrons. The simplest description of the positron time dependence is:

$$N(t) = N_0 \cdot e^{-t/\tau} \cdot (1 + Acos(\omega_a \cdot t + \varphi_a)). \tag{3}$$

Due to the motion of the beam about the central orbit, a multiparameter fit function is needed to account for vertical (f_y, f_{VW}) and radial beam (f_{CBO}) oscillations and muon losses that affect the determination of a_μ. Such frequencies can be seen by the Fast Fourier Trasform (FFT) of the fit function residuals as shown in Figure 1, where the FFTs of the fit functions are shown.

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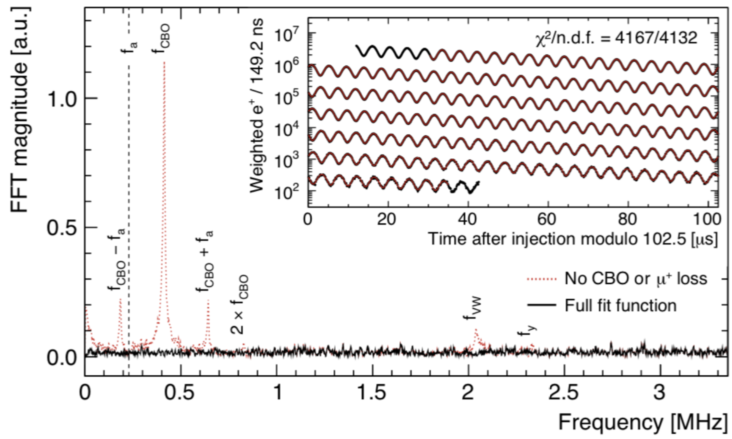

Figure 1: Fourier transform of the residuals from a fit using Eq. 3 (red dashed curve) and using a multiparameter function (black solid line). Inset: asymmetry-weighted e^+ time spectrum (black) with the full fit function (red) overlaid. [1]

Muons motion inside the storage ring is correctly modelled by the multiparameter fit function, however the measured anomalous precession frequency strongly depends on other beam dynamics effects. The measured quantity by the fit, ω_a^m, needs to be corrected by 4 different corrections. While two of them change the precession frequency phase as function of the time, the others introduce an intrinsic bias on the measured frequency. The largest, the electric field correction, C_e, belongs to the second type. It comes from the second term in Eq. 2 and depends on the distribution of equilibrium radii. The Run-1 correction applied to ω_a^m is $C_e = (489 \pm 53)$ ppb.

3. ω_p measurement

The magnetic field is measured by a suite of pulsed-proton NMR probes. Every ~3 days the data taking is stopped and a mobile set of 17-probe NMR probes, carried on a device called the trolley, measures the field at about 9000 locations in azimuth to provide a set of 2D field maps while 378 pulsed NMR probes located outside the beam region continuously monitor the field. To determine the magnetic field weighted by the muon distribution in time and space, the distribution measured by the trackers $M(x, y)$ are used. The interpolated field maps are averaged over periods of roughly 10s and weighted by the number of detected positrons during the same period. We determine the muon-weighted average magnetic field by summing the field moments multiplied by the beam-weighted projections for every three-hour interval. In Figure 2, the superposition of the azimuthally averaged field contours over the muon distribution is shown.

4. Run-1 result

The first result on the Run-1 dataset was published on April 7, 2021, showing a very good agreement with the previous experimental result from BNL, see Figure 3. The total error on the measurement is 462 ppb, given by the statistical error of 434 ppb, and the total systematic error of 157 ppb. While some of the systematic errors from BNL have been largely improved, the total uncertainty

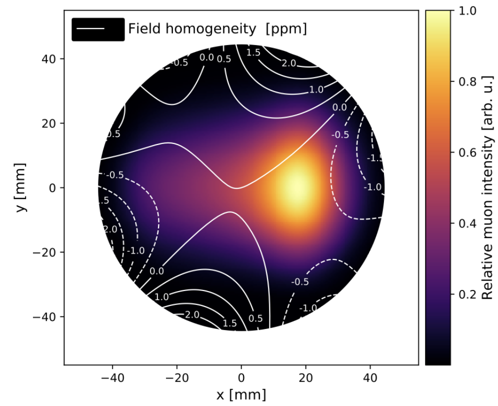

Figure 2: Azimuthally averaged magnetic field contours $\omega_p'(x, y)$ overlaid on the time and azimuthally averaged muon distribution $M(x, y)$ [1].

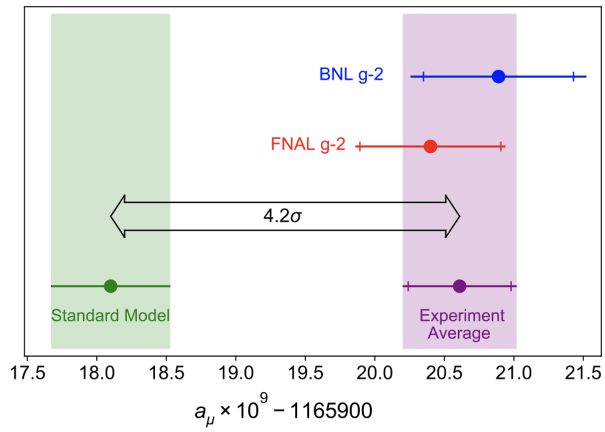

Figure 3: From top to bottom: experimental values of a_μ from BNL E821, this measurement, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g - 2$ Theory Initiative recommended value [4] for the SM is also shown. [1]

has been slightly enlarged by the presence of damaged resistors during Run-1 acquisition. The corresponding experimental average increases the significance of the discrepancy between the measured and Standard Model predicted a_μ to 4.2σ [1]. Furthermore, a recent evaluation of a_μ^{HLO} based on lattice QCD techniques reached for the first time an accuracy comparable to the dispersive approach, which weakens the discrepancy between theory and experiment to 1.5σ and shows a 2.2σ tension with the dispersive method [5].

5. Run-2/3 improvements

The Muon $g-2$ Collaboration is currently analysing the Run-2/3 data taken between 2018 and 2020. The expected statistical uncertainty is ~200 ppb together with a ~70ppb systematic uncertainty. During these two years of data taking, many hardware improvements were done. In particular, during the summer shutdown between Run-1 and Run-2 the damaged resistors in the Electrostatic

Quadrupole System (ESQ), which affected the beam during Run-1 and caused an increase of the systematic uncertainty on ω_a, have been repaired. In the same period the main magnet temperature has been stabilized through a coating of the magnet. During the shutdown between Run-2 and Run-3 the experimental hall has been thermalized within 1°C through a dedicated cooling system. Figure 4 shows the temperature comparison between the runs. Finally the kickers high voltage has been increased to better center the stored muons [6].

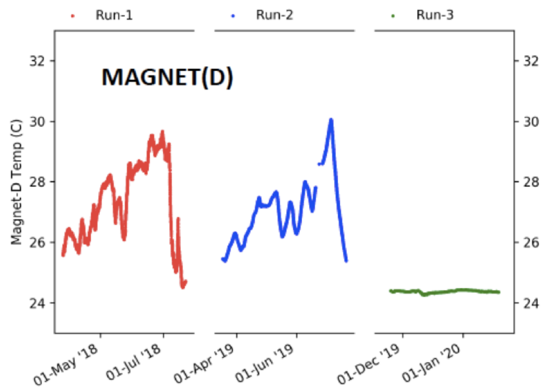

Figure 4: From the left to the right, the magnet temperature in Run1-2-3.

Thanks to these improvements, a large reduction of the total systematic uncertainty was possible, going from 157 ppb to 70 ppb.

6. Future muon experiments

6.1 MUonE experiment

The MUonE experiment aims to extract $\Delta\alpha_{had}$ in the space-like region, namely for negative momentum transfer t by precisely measuring the shape of the differential cross section of the $\mu^+e^+ \to \mu^+e^+$ [7]. From the measured $\Delta\alpha_{had}$ is possible to extract a_μ^{HLO} by using the following equation [8]:

$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)], \qquad t(x) = \frac{x^2 m_\mu^2}{x-1} < 0 \tag{4}$$

Measuring a_μ^{HLO} at the level of precision required by the experiment, (0.3% for both statistical and systematic error), comparable to dispersive approach, will help to clarify the current status of the theoretical prediction discussed in Section 4. The experimental apparatus consists of a repetition of 40 identical stations. Each station is composed of a 1.5 cm thick target, followed by a tracking system with a lever arm of ~1 m, which consists of 3 pairs of silicon strip detectors and is used to measure the scattering angles with high precision.

6.2 Mu2e experiment

The Mu2e experiment at Fermilab [9] aims to search for the charged-lepton flavour violating (CLFV) neutrino-less conversion of a negative muon into an electron in the field of an nucleus: $\mu^- + N \to e^- + N$ improving by four orders of magnirude the best limit on this process measured by Sindrum II experiment. This process is heavily suppressed in the Standard Model ($\sim 10^{-54}$). To obtain such precision muons are stopped in an aluminium target. When stopped muons convert to electrons, the nucleus recoils and the electron is emitted at a specific energy. The signal is a nearly monochromatic electron with energy close to muon mass 104.97 MeV. In case of detection is unambiguous sign of new physics. To reach the required precision 10^{18} stopped muons are needed.

6.3 Mu3e experiment

The Mu3e experiment is designed to search for charged lepton flavour violation in the process $\mu^+ \to e^+e^-e^+$ with a branching ratio sensitivity of 10^{-16} [10]. This process is suppressed by SM at the same level of Mu2e process, however any observation of CLFV would mean new physics Beyond Standard Model. The requirements for such precision are high rate capability 10^9 muon/s, good vertex resolution (<200 μm), good time resolution (<100 ps) and excellent momentum resolution (<0.5 MeV/c). These results can be reached by high performance detectors as ultra-light silicon pixel tracker for vertexing and two timing detectors: scintillating fibres and scintillating tiles for charge reconstruction and background discrimination.

Acknowledgments

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