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Status of the Muon $g-2$ experiment at Fermilab

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Abstract

The aim of the Muon $g-2$ Experiment at Fermilab (E989) is to measure the muon anomalous magnetic moment (a_μ) with a relative precision of 140 parts-per-billion (ppb). This precision, which is a factor of four improvement from the current experimental result, will allow for a much more stringent test of the Standard Model. This paper present the current status of the experimental measurement of a_μ after the first physics run.

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1 Introduction

The muon anomaly is defined as the relative deviation of the muon g-factor from 2, $a_\mu = (g_\mu - 2)/2$. The g-factor is the ratio between the particle magnetic moment and the spin of a particle. In the framework of the Standard Model (SM) of particle physics, for the spin-1/2 particles like the muon, g is expected to be 2 at first order, and the higher order contributions from QED, electroweak, hadronic vacuum polarization, and hadronic light-by-light virtual loops lead to $g > 2$. In particular the most recent SM theoretical prediction is $a_\mu^{\mathrm{SM}} = (11659182.04 \pm 3.56) \times 10^{-10}$ [1], and the contributions of each of the four main components are summarized in table 1.

Table 1: Current predictions for the Standard Model contributions to a_μ.

$a\mu$ Contribution	From	Value ($\times 10^{-10}$)
QED	[2,3]	11658471.8971 ± 0.007
Electroweak	[4]	15.36 ± 0.10
Hadronic Vacuum Polarization	[1]	684.68 ± 2.42
Hadronic light by light	[5]	9.8 ± 2.6
Total SM (a_μ^{SM})		11659182.04 ± 3.56

Since the muon anomaly arises from higher-order contributions from virtual loops, the comparison between theoretical and experimental a_μ values is a test of the SM: a possible discrepancy could be a hint of new physics.

Experimentally, $a_\mu^{\mathrm{E821}} = 11659209.1(5.4)(3.3) \times 10^{-10}$ [6] was measured in 2006 by the E821 collaboration at the Brookhaven National Laboratory (BNL), and is about 3.7 standard deviation (σ) higher than the most recent theoretical prediction a_μ^{SM}. The ability to measure a_μ with a relative uncertainty $\delta a_\mu / a_\mu$ of 140 ppb, as aimed at the Fermilab Muon $g-2$ experiment, has the potential to confirm the discrepancy with a 7 σ significance.

2 Experimental Technique

The Muon $g-2$ experiment at Fermilab (E989) [7] is an improved version of the previous E821 experiment performed at BNL. A longitudinally-polarized muon beam is injected into a storage ring with a uniform magnetic field, $\vec{B}$ and electric field $\vec{E}$ for vertical confinement. The storage ring used by the E821 collaboration was moved from Brookhaven (New York) to Fermilab (Chicago) in the summer 2013. Inside the ring the muons are subject to both the spin precession frequency ω_s and the cyclotron frequency ω_c: the difference between them is called anomalous precession frequency ω_a. Under the approximation that the muon velocity is perpendicular to the magnetic field ($\vec{\beta} \cdot \vec{B} = 0$), the magnetic field is perfectly uniform and, betatron oscillations of the beam are neglected ω_a that can be expressed as

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right], \tag{1}$$

where $\vec{\beta}$ the velocity of the muons in units of c, and $\gamma = 1/\sqrt{1-\beta^2}$ is the Lorentz factor. The muon beam enters the storage ring with a forward momentum of $\simeq 3.094$ GeV/c, *i.e*, $\gamma \simeq 29.4$, hence $a_\mu - 1/(\gamma^2 - 1) \simeq 0$ and Eq. 1 simplifies to:

$$\omega_a = -\frac{e}{m_\mu} a_\mu B. \tag{2}$$

Therefore the muon anomaly can be then be extracted by measuring ω_a and B precisely.

The anomalous precession frequency, ω_a, is not directly extracted from the muons but from their decayed high-energy positrons. In fact, because of the parity-violating nature of the $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ decay, the high-energy positrons are preferentially emitted in the muon-spin direction. The spin directions of the muons can then be inferred from the decay time and the energy of the positrons, which are reconstructed using the information recorded by the calorimeter system.

The magnetic field is mapped using proton nuclear magnetic resonance (NMR) probes. These NMR probes return the magnetic field strength in terms of precession angular frequency of the free proton, ω_p. Then the average magnetic field experienced by the muons, $\bar{\omega}_p$, is measured by integrating all the ω_p values over the muon storage region.

The muon anomalous magnetic moment can be then obtained from the measurement of ω_a and $\bar{\omega}_p$ using:

$$a_\mu = \frac{g_e}{2} \frac{m_\mu}{m_e} \frac{\mu_p}{\mu_e} \frac{\omega_a}{\bar{\omega}_p}, \tag{3}$$

where g_e is the electron g-factor, m_μ / m_e and μ_p / μ_e are the ratios between respectively, the muon and electron masses and the proton and electron magnetic moments. The value of these three factors are known with a precision of 22 ppb from other independent measurements [8].

3 Overview of the E989 Experiment

The E989 experiment is planning to reduce the uncertainty on the most recent experimental measurement of a_μ by reducing both the statistical and systematic uncertainty as shown in Table 2.

Table 2: Summary of the reported and expected relative uncertainties on the muon anomaly measurements.

$\delta a_\mu / a_\mu$	E821 (BNL) [ppb]	E989 (FNAL) [ppb]
ω_a statistic	480	140
ω_a systematic	180	70
$\tilde{\omega}_p$ systematic	170	70
Total	**540**	**140**

The main limitation of the BNL experiment was the statistical uncertainty. The Fermilab experiment is planning to acquire approximately 20 times the BNL statistics, so that the statistical uncertainty will be reduced to 100 ppb. This can be achieved thanks to the accelerator complex at Fermilab, which provides about 10^5 ($> 90\%$ polarized) positive-muons per second, with very low contamination of pions ($\sim 10^{-5}$) and no protons. These muons are generated from a 8 GeV beam consisting of 10^{12} protons hitting a target with a rate of 12 bunches/second to produce pions. For each bunch, about 1.2×10^8 3.11 GeV monoenergetic π^+ are produced and stored in a 500 m circumference ring called delivery ring. In the delivery ring the pions decay into muons ($\pi^+ \rightarrow \mu^+ \nu_\mu$) [7]. The 3.094 Gev/$c$ beam of polarized-μ^+ is then injected into the 15-ton and 14-m diameter superferric storage ring through a field-cancelling inflector magnet. The ring is made up of rectangular vacuum chambers surrounded by a cryosystem and C-shaped dipole magnets and it is kept mechanically and thermally stable. After injection the muons are moved onto the center of the storage ring's orbit, where the field is more uniform, by a kicker system. The beam is vertically contained in the center region by 4 sets of electrostatic quadrupoles plates placed around the ring, and off-momentum muons are removed using collimators.

The magnetic field inside the storage ring has 1.45 T of magnitude and is as uniform as possible with a target of azimuthal variations not exceeding ±50 ppm point-to-point, and < 1 ppm when considering the transverse variations across the storage aperture after averaging around the azimuth. Uniformity of the field is achieved using various magnetic components placed around the muon region to locally affect $\vec{B}$. In particular, the higher average field magnetic moments along the ring are removed using active surface coils, the dipole field is coarse tuned using iron pole pieces and iron top hats, while localized nonuniformities are cured by gluing iron foils on the pole pieces surface, and quadrupole and sextuple asymmetries are reduced with iron wedges and edge shims. The position of these calibration tools is shown in Figure 1.

The E989 systematic uncertainty budget for the $\tilde{\omega}_p$ measurement is 70 ppb. During data-taking fixed NMR probes located above and below the muon region as shown in Figure 1 are used to determine ω_p. Periodically, the field between the fixed probes is mapped using a trolley with 17 NMR probes that travels like the muons, around ring. To obtain a precise map of the magnetic field, three tracker stations (each made of ~ 3000 straws divided into 8 modules) are used to extrapolate from the decayed positrons trajectory the beam profile of the stored muons. In addition, the x and y profiles of the beam are periodically monitored using a set of scintillating fiber hodoscopes.

To reduce the systematic uncertainty on the ω_a measurement to 70 ppb, the E989 exper-

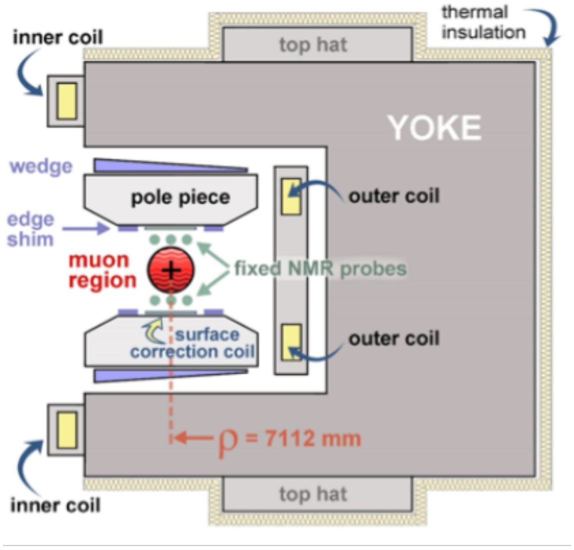


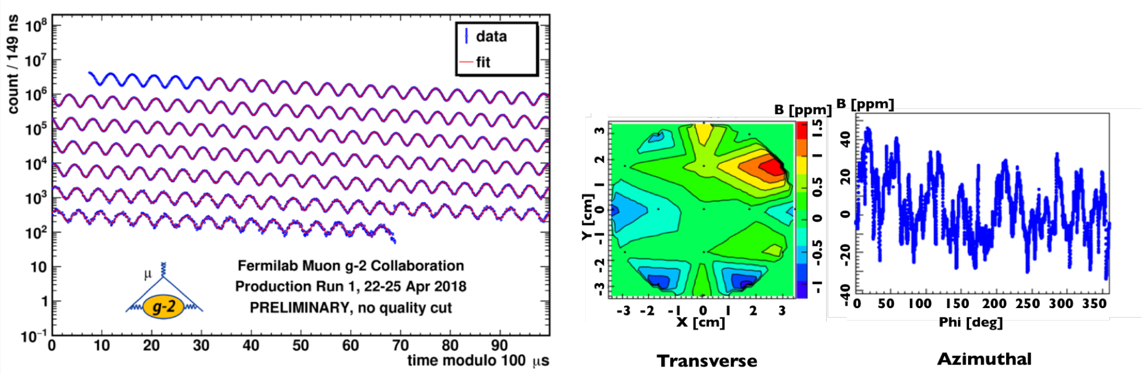
Figure 1: Schematic drawn of the $g-2$ storage ring cross-section. The muon beam is schematically depicted as a circle with a plus (⊕) and travels around the ring towards the reader.

iment has been equipped with 24 new highly segmented electromagnetic calorimeters. Each calorimeter is made of 54 lead fluoride crystals read out by arrays of silicon-photomultiplier (SiPMs). The calorimeters are located around the inner part of the ring to detect the positrons from the decay of the stored muons. In E821, the main sources of the systematic uncertainty for the ω_a measurement were related to the gain stability of the calorimeters and the pile-up identification and correction. In E989, an elaborate laser calibration system is used to monitor and ensure the gain stability at the sub-per-mil level [9]. The systematic uncertainty due to pile-up events, *i.e.* events where multiple positrons hit a calorimeter at the same time and are reconstructed as a higher-energy single positron, is reduced thanks to the better time and spatial separation allowed by the fast response and the finer segmentation of the calorimeters.

4 E989 First Physics Run

The E989 first physics run, Run 1, took place between late March and early July 2018. During Run 1, the storage ring magnet was operational for about 95% of the time and about $\sim 500\ e^+$ per muon bunch were recorded. The final raw dataset (no quality cuts applied) contains about twice the statistics accumulated at BNL and the magnetic field was mapped with more than 30 trolley runs. A blinding factor was applied to the reference clock frequency, and in figures 2a and 2b the preliminary blind measurements of ω_a and ω_p performed with a small part of the Run 1 dataset are shown. Completion of the full Run 1 analysis is expected for the second half of 2019.

The rate of muons stored was about 50% of the TDR design [7]. During the summer shutdown of 2018, upgrades to the accelerator complex and to the experiment muon kicker and electric quadrupole systems are taking place to increase the number of stored muon during Run 2, which will start in late 2018.



(a) (b)

Figure 2. (a) Preliminary positron time spectrum (with no data quality cuts applied). (b) The magnetic field averaged over azimuth and the dipole component as a function of azimuth around the ring.

5 Conclusion

The goal of the muon $g-2$ experiment at Fermilab (E989) is to perform a test of the SM of particle physics measuring the anomalous magnetic moment of the muon with a precision of 140 ppb. The E989 successfully completed its first physics run, during which a dataset exceeding the statistics of the previous experiment was acquired. In 2019, the E989 collaboration expects to complete the analysis of the Run 1 data and to collect a significantly larger data set.

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