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THE MUON g-2 EXPERIMENT AT FERMILAB

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Abstract

The muon anomaly, $a_\mu = \frac{g-2}{2}$, is a low energy observable that can be both measured and computed with high precision. Therefore it provides an important test of the Standard Model (SM) and it is a sensitive probe for new physics. The a_μ value has been measured to a precision of 0.54 ppm by the E821 experiment at the Brookhaven National Laboratory (BNL). This result shows a difference greater than $3\,\sigma$ compared to the SM prediction. In an effort to clarify this discrepancy between experimental measurement and theoretical calculation, the Muon g-2 (E989) experiment at Fermilab aims to reduce the experimental error on a_μ by a factor of four. E989 collected a dataset with the same statistical power of the BNL experiment during the Run 1 data taking (2018). The analysis of data is ongoing and the first result should become available in early 2020. In this paper, I will discuss the experimental setup and report on the status of the Run 1 analysis.

1 Introduction

The muon anomaly $a_\mu = (g-2)_\mu/2$ can be computed and measured with high precision. Therefore it can provide a test for the SM and, any deviation from the predicted value can be hint of new physics. From the theoretical point of view, there is a great effort to reduce the uncertainty in the hadronic contribution (this contribution has the major uncertainty). The latest theoretical value for the anomaly is [1]:

$$a_\mu^{SM} = (11\ 659\ 182.04 \pm 3.56) \times 10^{-10}\ . \tag{1}$$

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From the experimental point of view, the world average of a_μ^{exp} is dominated by the measurement at BNL. The current average is [2]

$$a_\mu^{exp} = (11\ 695\ 208.0 \pm 5.4_{stat} \pm 3.3_{syst}) \times 10^{-10} \ . \tag{2}$$

The measured value has a total uncertainty (statistics dominated) of 0.54 *ppm*. The difference with the most recent prediction is:

$$a_\mu^{exp} - a_\mu^{SM} = (25.96 \pm 7.26) \times 10^{-10} \ . \tag{3}$$

This difference corresponds to a 3.7 σ discrepancy from the Standard Model's prediction. If the discrepancy is confirmed, it could be the evidence of new physics processes contributing to the g-2 value. Great effort is coming from the new Muon $g-2$ experiment at Fermilab (E989) to achieve 21 times the statistics of BNL experiment and to reduce the uncertainty by a factor 4 (to 0.14 *ppm*).

1.1 The Measurement

The a_μ measurement is based on the extraction of two frequencies: the anomalous precession frequency of the muon's spin in a magnetic field (ω_a) and the free proton precession frequency (ω_p) related to the magnetic field magnitude. We can define the anomalous precession frequency as the difference between the spin precession frequency and the cyclotron frequency. For relativistic muons, assuming that the magnetic field $\vec{B}$ is uniform and the betatron oscillations of the beam are negligible, the $\vec{\omega}_a$ can be written as:

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right] \tag{4}$$

where $\vec{\beta}$ is the particle speed in units of c, and γ is the Lorentz factor. The term $\vec{\beta} \times \vec{E}$ represents the contribution of the electric field. For the specific value of $\gamma = 29.3$ (i.e. $p_\mu = 3.094\ Gev$), called the *magic momentum*, the electric field term in equation 4 vanishes (corrections due to the momentum spread are considered during data analysis), leaving just the B field term. Precision measurement of ω_a and of the magnetic field leads then to a measure of a_μ:

$$a_\mu = \frac{g_e}{2}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}\frac{\omega_a}{\omega_p} \ , \tag{5}$$

where g_e is the electron's gyromagnetic ratio, m_μ/m_e is the ratio between muon's and electron's masses and μ_e/μ_p is the ratio of proton's and electron's magnetic moment.

2 E989 experiment at FNAL

2.1 The storage ring

The main component of the experiment is a 14 *m* diameter superconducting storage ring producing a 1.45 *T* uniform magnetic field recommissioned from the E821 experiment. A highly pure beam of polarized (96%) positive muons produced by FNAL's accelerator chain is injected into the ring via a superconducting inflector magnet. Three fast kicker magnets put the injected muons onto the closed orbit needed for the storage. Electrostatic quadrupoles provide vertical focussing of the beam. The beam is collimated to remove the off-momentum muons.

To ensure the uniformity of the magnetic field, a shimming process was applied to the storage magnet. Figure 2 shows how this process improved the magnetic field uniformity that is kept under ± 25 *ppm* variation.

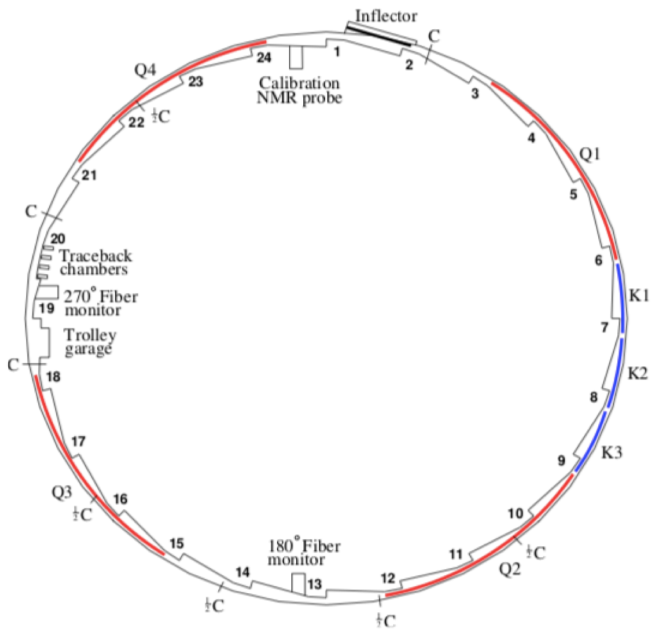


Figure 1: *Schematics of the Muon g-2 storage ring.* Q_{1-4} *represent the electrostatic quadrupoles,* K_{1-3} *are the kickers. Collimators (C), inflector and one tracker station are also shown.*

The field is measured during the run by fixed NMR probes placed around the ring under and over the vacuum chamber. Regular trolley runs are performed: a cylinder equipped with 17 NMR probes is placed inside the vacuum chamber in the muons storing region and moved along all the ring to measure the field magnitude inside the storage region. The total uncertainty related to the field measurement is shown in figure 5b.

The calorimeter system precisely measures the arrival time and the energy of the decay positrons curling into the ring due to the magnetic field. There are 24 calorimeters outside the vacuum chamber along the inner circumference of the ring. Each calorimeter is placed right behind a radial window (figure 3a) that allows positrons to exit the vacuum chamber minimizing the path in air.

A single calorimeter is composed of 54 PbF_2 Čerenkov crystals ($2.5 \times 2.5 \times 14$ cm^3) arranged in

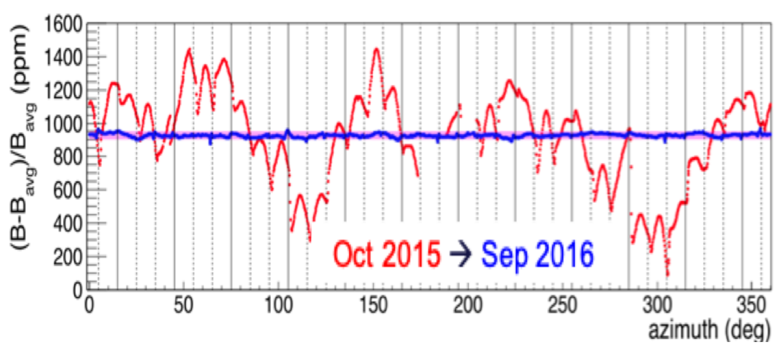
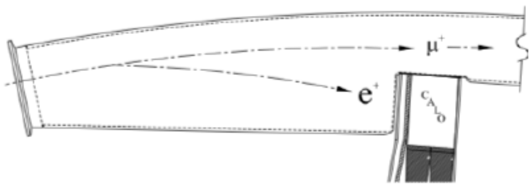
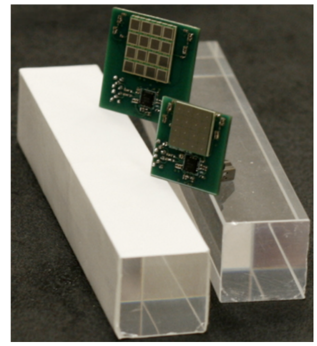


Figure 2: *Magnetic field measurements before and after the shimming. This process improved the field uniformity by reducing the fluctuations.*



(a) *Calorimeter positioning outside the vacuum chamber.*



(b) *Lead fluoride crystals with large area SiPMs used to read Čerenkov light.*

Figure 3: *The Muon g-2 calorimeter system.*

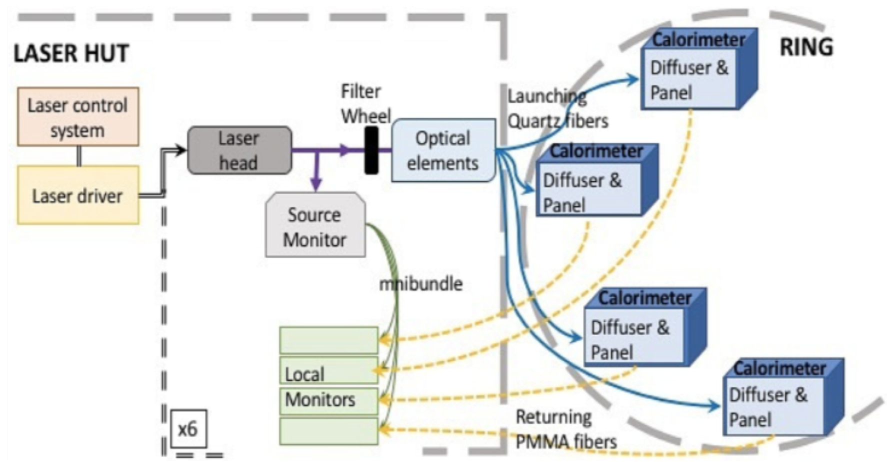


Figure 4: *Laser system scheme. Laser pluses are sent to calorimeters via optical fibers. A source monitor checks the stability of the laser pulse, and a local monitor checks the stability of the distribution system.*

a 9×6 matrix. Lead fluoride has good features for the g-2 measure: high density ($7.77\ g/cm^3$), low Molière radius ($1.8\ cm$ for the Čerenkov light), low radiation length ($X_0 = 0.93\ cm$) and low magnetic susceptibility. Crystals are wrapped in black Tedlar absorbtive wrapping to trasmit only the direct light. The light from each crystal is read by a Large Area Silicon Photomultiplier (SiPM) working in Geiger mode. Each SiPM has an active area of $1.2 \times 1.2\ cm^2$ with $50\ \mu m$ pixels that is well-matched with the crystal area. [3] A laser system, shown in figure 4, is used to keep track of and correct for the gain variation of the SiPMs.

Each laser fires a light pulse with the same wavelength of the Čerenkov radiation emitted by the crystals ($405\ nm$) and the light is evenly distributed to all the crystals. Before the muon injection (fill), on 1 over 10 fills and between fills, laser pulses are sent to the calorimeters and their response is measured. Any variation in the laser intensity is checked with two PIN diodes in the Source Monitor. A third light detector is an 8 mm diameter photomultiplier, used to double check the diodes' stabilities. The PMT stability is checked with a low counts ^{241}Am source. A Local Monitor system measures the light coming back from the calorimeters to correct for variations in the light distribution system. The laser system is measured to be stable at the sub per-mill level in the time period of the measure (700 μs). See ref. [4] and references there in for details. The gain changes in the calorimeter should have a final uncertainty of 20 *ppb*, as shown in figure 5a. [3]

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

(a) ω_a *measure.*

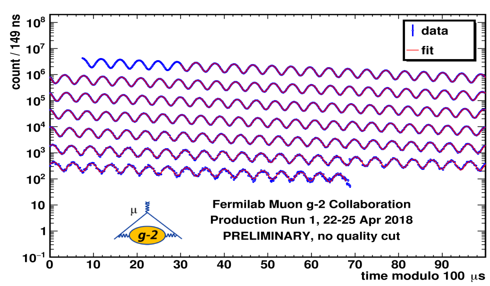
Source of uncertainty	2001	E989
Systematics of calibration probes	50	35
Calibration of trolley probes	90	30
Trolley measurements of B_0	50	30
Interpolation with fixed probes	70	30
Uncertainty from muon distribution	30	10
Inflector fringe field uncertainty	–	–
Time dependent external B fields	–	5
Others †	100	30
Total systematic error on ω_p	170	70

(b) ω_p *measure.*

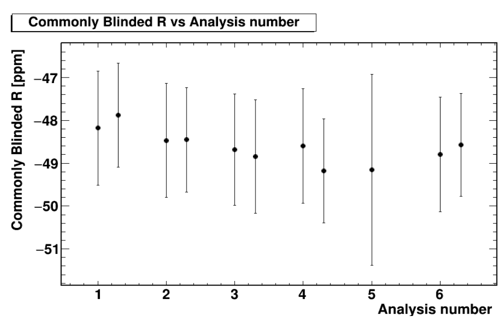
Figure 5: Systematics uncertainty budget for the new E989 experiment. [3]

2.2 ω_a Analysis

The anomalous precession frequency ω_a can be measured due to the parity violating decay of muons. From angular momentum conservation and helicity considerations, there is a strong correlation between the high energy positrons momentum direction and the muon spin. So ω_a can be measured by counting the number of high energy positrons ($E > 1.7\ GeV$) along the muon's momentum axis. The result is the so called "Wiggle Plot" shown in figure 6a): the muon's decay exponential modulated by the anomalous precession frequency.



(a) *PRELIMINARY Wiggle plot of the Muon g-2 experiment (E989) using* ~60 *hour data. The curve is fitted with equation 6.*



(b) *PRELIMINARY Comparison between* ω_a *results from six different working groups. The uncertainty is statistics dominated and it's* $\sim$ 1.33 *ppm. The value is hardware blinded and the points have still a common offset.*

Figure 6: 60h dataset, part of run 1, analysis.

The equation used for the fit, including corrections is:

$$N(t) = N_0 e^{-\frac{t}{\tau}} \left[1 - A\cos(\omega_a t + \phi)\right] \cdot C(t) \cdot V(t) \cdot \Lambda(t) \tag{6}$$

which includes corrections related to the beam dynamics. $C(t)$ accounts for the time dependent radial CBO effect and $V(t)$ for the vertical waist. $\Lambda(t))$ is the muon loss term. CBO terms are evaluated using a tracking detector. Two tracker stations detect positrons in front of two different calorimeters. The track is used to reconstruct the position of the beam during the fills without affecting the beam itself. From the position of the beam, both CBO and vertical oscillation can be parametrized and used as corrections in the fitting function. The lost muon function is evaluated from triple coincidences in consecutive calorimeters and with the application of energy and timing cuts according to MIP behaviour.

The precession frequency value is both hardware and software blinded to avoid biases. The hardware blinding is done by applying an offset in the range ± 25 *ppm* to the 40 MHz clock frequency. The offset is common to all the analyses and unknown by the analyzers. In the fit, ω_a is blinded according to:

$$\omega_a = 2\pi \cdot 0.2291\ MHz \cdot [1 - (R - \Delta R) \cdot 10^{-6}] \tag{7}$$

where ΔR is different for each group.

Six different working groups are performing independent analyses to extract the anomalous precession frequency. The final result will be the combination of each group value. Last February, the 60h dataset was analysed and the results from each group were compared after unblinding the software offset. Results are in good agreement showing consistency of the analyses (see fig. 6b). The total uncertainty is ~ 1.33 *ppm* and it is statistics dominated.

2.3 Conclusions

The new Muon g-2 E989 experiment at Fermilab will provide the measurement of the muon's anomalous magnetic moment with a precision of 0.14 ppm. A precise measurement of the anomalous precession frequency both with a high precision magnetic field measurement will lead to this goal. During Run 1 (2018), the experiment collected almost 1.4 times the positrons collected at the BNL experiment. Recently Run 2 data taking was completed and, after a summer shutdown to improve the system, Run 3 is expected to start in October 2019. A first result with almost the same statistical power as the BNL result is expected in early 2020.

Acknowledgments

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