THE MUON G-2 EXPERIMENT AT FERMILAB

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The muon magnetic anomaly, a_μ, is a powerful test of the Standard Model of particle physics. A new experiment at Fermilab has recently measured a_μ with unprecedented precision, confirming the results of the earlier Brookhaven experiment and strengthening the tension with the prediction of the Standard Model as determined by dispersive methods. We here describe the experimental technique, recapitulate the recent result, and discuss some of the improvements made for subsequent analyses.

1 Background

The magnetic moment $\vec{\mu}$ of a fundamental particle with charge q, mass m, and spin $\vec{S}$ is given by

$$\vec{\mu} = g\frac{q}{2m}\vec{S}\,. \tag{1}$$

The dimensionless parameter g, the gyromagnetic ratio, describes the overall strength of the magnetic moment in units of the classical magnetic moment.

Since 1948, it has been understood [1] that the gyromagnetic ratio of electrons (and also muons) differs from the Dirac Model expectation of 2 at the per-mille level due to interactions of the leptons with virtual particles. This additional contribution is called the magnetic anomaly, a, defined $a \equiv \frac{g-2}{2}$. The contributions of the known Standard Model particles to the magnetic anomaly can be calculated very precisely, making this quantity an outstanding test of the Standard Model.

An earlier measurement [2] of the muon magnetic moment, carried out at Brookhaven National Laboratory, was discrepant from the theory prediction by roughly 3σ. This motivated the construction of a new experiment at Fermi National Accelerator Laboratory to repeat the measurement at higher precision. The first result [3] of the new experiment, which agrees with the measurement at Brookhaven, is discussed here together with the improvements expected for future publications. The high precision expected from the new experiment also motivated an extensive effort in the theory community to further improve the understanding of the prediction within the Standard Model. Recently, the Muon $g-2$ Theory Initiative published [4] a determination of this quantity with an uncertainty of 0.37 ppm. An alternative determination [5] based on lattice QCD stands in some tension with the dispersive estimate of the Theory Initiative.

2 Experimental Principle

In the presence of an externally applied magnetic field $\vec{B}$, a charged particle will traverse a circular orbit, and its spin will feel a torque

$$\vec{\tau} = \vec{\mu} \times \vec{B}\,. \tag{2}$$

Assuming the spin axis is not aligned with the magnetic field, this torque will cause the spin axis to precess about the magnetic field direction. By measuring the frequency of this spin precession, ω_s, and the strength of the applied magnetic field, the magnetic moment may be deduced.

In our experiment, the spin precession is determined through the influence of the spin orientation on the kinematics of the muon decay. We observe the Michel decays of an ensemble of spin-polarized muons into positrons (and neutrinos which escape detection). The differential cross section for this decay strongly correlates the momentum of the daughter positrons with the muon spin direction in the muon rest frame. As the muon spin direction precesses in the magnetic field with respect to its momentum (which is also rotating with cyclotron frequency ω_c), the mean boost given to the daughter positrons, and thus their mean energy, also varies harmonically. The anomalous precession frequency ($\omega_a \equiv \omega_c - \omega_s$) can therefore be measured through the rate of variation of the positron energy in the laboratory frame.

The magnetic field strength is measured using a similar spin precession technique, but in this case, the nuclear spin precession of petroleum jelly samples is measured using nuclear magnetic resonance (NMR) techniques. This allows the well-known nuclear magneton to serve as a comagnetometer for the muons experiencing the same field.

The experimental apparatus consists of a 3.56 m radius, 1.45 T superferric magnetic storage ring used to confine the 3.1 GeV muon beam provided by the Fermilab accelerator in 16 bunches that arrive every 1.4 s. Vertical confinement is provided by a set of four electrostatic quadrupoles. The apparatus is instrumented with detectors of three types. First are 24 electromagnetic calorimeters spaced around the interior of the magnetic ring used to measure the positron energies. Each calorimeter consists of a segmented 9×6 array of PbF_2 crystals, each provided with a SiPM digitized at 800 MSPS. Second are two straw tracking stations located within the storage ring vacuum but outside the muon beam path. The straw trackers measure positron momenta from which the muon beam dynamics can be determined. Third are the nuclear magnetic resonance probes used to measure the magnetic field strength.

3 Overview of the Run-1 analysis

The first experimental run of the experiment was conducted between March and June 2018, and results were published in April 2021 [3]. The analysis consists of three parts, discussed in turn below: the measurement of the muon anomalous precession frequency ω_a [6], corrections to the measured anomalous precession frequency due to muon beam dynamics effects [7], and the measurement of the magnetic field strength ω_p [8]. Combining these results with external reference measurements k, a_μ was determined by

$$a_\mu = k \frac{\omega_a}{\omega_p} g_e\,. \tag{3}$$

A blind analysis was conducted by multiple independent analysis groups on each of four subsets of the Run-1 data. After establishing that the independent analyses were consistent, the results were combined and unblinded. We found $a_\mu = 116592040 \pm 54 \times 10^{-11}$. This agreed with the measurement made at Brookhaven at a level of 0.6σ. When combined with the Brookhaven measurement, the world average disagrees with the Standard Model prediction [4] using dispersive techniques at 4.2σ. The agreement with the lattice QCD estimate [5] is significantly better. A summary of the experimental error budget is presented in Table 1.

Table 1: Error budget of the Run-1 analysis of the muon magnetic anomaly.

Quantity	Uncertainty (ppb)
Precession (stat)	434
Precession (syst)	58
E Field Correction	53
Phase-Acceptance	75
Magnetic Field	56
Kicker Field Transient	37
Quad Field Transient	92
External Factors	25
Total	462

3.1   Anomalous precession analysis and corrections

To determine the anomalous precession frequency, the number of high-energy positrons entering the calorimeters is counted as a function of time in the storage ring. A time series of these high-energy positrons has a characteristic oscillation with the anomalous precession frequency. In practice, a slightly more complex analysis with higher precision is used to obtain the time series by weighting the positrons according to the decay asymmetry associated with their energy.

Besides the anomalous precession oscillation, there are a number of other features present in the time series that must be correctly fit in order to obtain an unbiased frequency estimate. These include the exponential decay of the muon population, acceptance effects due to the coherent betatron oscillations of the muon beam in the storage ring, and the mechanical losses of muons from the storage ring before decay.

Once these effects are included in the analysis, it is possible to achieve an excellent χ^2 to the fitting function describing the data over many muon lifetimes. Many additional checks on the self-consistency of the analysis were performed, including confirming that the fit residuals were without time structure and that the fit results were consistent across calorimeters. Furthermore, six independent analyses using different reconstructions and analysis techniques all yielded consistent results.

The anomalous precession frequency obtained from the time series analysis must be corrected for a small number of effects that bias the measurement. These include an electric field correction needed due to the electrostatic quadrupoles (which appear as a motional magnetic field to the muons), a pitch correction to account for the muons' motion out of the plane due to their vertical oscillations, and phase-acceptance and muon loss corrections that reflect time dependence in the mean accepted spin phase.

3.2   Magnetic field analysis

The magnetic field in the muon storage volume can be measured with exquisite precision with 17 NMR probes mounted in a moveable trolley carriage that can be pulled through the storage ring. These trolley probes can measure many field multipole moments with high azimuthal resolution, and these probes are calibrated against an absolute reference probe. However, the trolley cannot be left in the storage ring during data taking; it is therefore used only two to three times per week during dedicated trolley runs.

In the intervening time, the evolution of the magnetic field multipole moments is tracked with a set of 378 NMR probes located at 72 azimuthal locations just above and below the storage volume. These probes are calibrated against the trolley during the trolley runs and interpolate the field moments between the trolley measurements.

From this set of time-dependent field moments, the average magnetic field strength experienced by the muons in the anomalous precession analysis can be determined by weighting the

field at each time slice according to the number of muons then observed, and by convolving the multipole moments of the field with the multipole moments of the muon beam distribution, as measured with the straw tracker system.

4 Future improvements

The collaboration is currently working on analyzing the data collected in the second and third experimental runs. Improvements to the most significant uncertainties reported in Table 1 are anticipated. In this section, we discuss the reasons for these improvements.

4.1 Statistics

In the first experimental run, only 6% of the final statistical goal was met. The two subsequent experimental runs were longer and together represent about four times the number of muons collected in the first run. We therefore expect the statistical uncertainty, which dominated the Run-1 result, to be reduced by roughly a factor of two.

The experiment is currently collecting its fifth experimental run and is on track to meet its final goal of 100 ppb statistical uncertainty.

4.2 Replaced Quadrupole HV resistors

A significant difficulty in analyzing the Run-1 data was caused by damaged high-voltage resistors used in charging the quadrupole plates. These quadrupole plates are pulsed in time with the muon bunches, and each of the 32 plates is regulated by its own resistor. During the first experimental run, two of these resistors were damaged in such a way as to significantly increase the charging time of the connected plates. This caused an asymmetric time dependence to the vertical focusing that subsequently affected a number of beam characteristics such as its position and width. It also dominated the phase-acceptance effect which contributed a significant systematic uncertainty to the analysis. Following Run-1, the problematic resistors were replaced, which will significantly reduce the uncertainty associated with the phase-acceptance effect.

4.3 Quadrupole Field Transient

Two field transients impact the muon spin evolution but cannot be tracked using the NMR probe system because of the high frequency of the transients and the shielding of the NMR probes. These transients are instead measured with dedicated probes and appropriate corrections applied to the field measurement.

One such transient comes from the pulsing of the quadrupole plates, which induces mechanical vibrations. For the Run-1 analysis, this transient was measured with special NMR probes inserted into the quadrupoles at a limited number of positions. The low granularity of the measurement and uncertainty about the stability of the effect over time limited the precision of the correction. Since that time, an improved set of NMR probes on a trolley frame that can be pulled through the storage ring has been deployed, allowing a highly detailed measurement to be carried out. These data will allow for a significant reduction in the uncertainty on the correction in the future.

4.4 Stronger Kick

A non-ferric kicker magnet is used to place the injected muon bunch onto a stable orbit in the storage ring [9]. For Run-1, this kicker system was unable to operate at a high enough voltage to optimize the storage of muons with the so-called "magic" momentum, at which the electric field correction is minimized. Further upgrades to the kicker circuit and supporting systems enabled the kicker to reach its design targets in Run-3. This improves the number of muons

stored, reduces the size of the electric field correction, and reduces the amplitude of the coherent betatron oscillations, which impact the anomalous precession analysis.

5 Conclusion

The first result of the Muon $g - 2$ experiment at Fermilab [3] has confirmed the tension with the Standard Model prediction calculated using dispersive techniques [4] first established at the Brookhaven experiment [2]. Currently the analysis of the data from the second and third year of the experiment is underway, with significant improvements expected, as described in Section 4. We anticipate the ongoing fifth experimental run will conclude the μ^+ program, with a new measurement of a_μ for the negative muon to commence later this calendar year.

Acknowledgments

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