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Muon $g-2$ and EDM at Fermilab

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A precise measurement of the muon magnetic anomaly, a_μ, can be used to test the Standard Model (SM) and search for new physics. An experiment at Fermilab aims to measure a_μ to an unprecedented precision of 0.14 ppm. The experiment's first measurement — based on 2018 data — achieved a precision of 0.46 ppm, confirmed the previous measurement performed at Brookhaven National Laboratory (BNL), and pushed the tension with the SM prediction to 4.2σ, although recent developments have complicated the theory landscape. The analysis of the second and third years of data is nearing completion with an expected uncertainty reduction of more than a factor of two compared to the first result. The experiment is finishing its sixth and final year of data collection, having recently reached its proposal goal of 21 times the number of detected decay positrons as the BNL experiment. In addition to measuring a_μ, the experiment is also sensitive to the electric dipole moment (EDM) of the muon, which, if found, would be a clear sign of new physics. Here, we give a status of the muon g-2 measurement and EDM search being carried out at Fermilab.

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1. Introduction

The muon magnetic anomaly, $a_\mu \equiv (g-2)/2$, can be used to test the Standard Model (SM). The size of the anomaly is determined by interactions with virtual particles, which gives it sensitivity to the particles that comprise our universe. Comparing the measured and SM-predicted value tests whether the SM is complete or is missing so-far undetected particles. A powerful test is possible because a_μ can be both measured and calculated with high precision, at the level of 100s of ppb.

The most precise measurement of a_μ was performed by the Muon $g-2$ experiment at Fermilab in 2021, which achieved a precision of 0.46 ppm [1]. The result, based on the experiment's first year of data, confirmed the previous measurement performed at Brookhaven National Laboratory (BNL) [2]. Combining the two measurements gives the experimental world average [1]:

$$a_\mu(\text{Exp}) \times 10^{11} = 116592061(41). \tag{1}$$

The SM prediction depends on all sectors of the SM: quantum electrodynamics (QED), the electroweak (EW) interaction, and the strong interaction. The strong interaction is parameterized in two pieces: Hadronic Vacuum Polarization (HVP) and Hadronic Light-by-Light (HLbL) interactions. The hadronic contributions are notoriously difficult to calculate and contribute the largest uncertainty to the theoretical prediction. The latest compilation of these inputs was performed by the Muon $g-2$ Theory Initiative (TI) in 2020 [3].

In recent years, the HVP contribution has become more uncertain. It can be calculated in two ways: a dispersive approach reliant on $e^+e^- \rightarrow$ hadrons cross section measurements and lattice QCD; the two method are discrepant at $> 2\sigma$ [3, 4]. If the dispersive method is used, the SM prediction for a_μ is in tension with the measured value at 4.2σ; if the lattice QCD method is used, the tension reduces to 1.5σ. To further complicate the situation, new cross section measurements for the dominant $e^+e^- \rightarrow \pi^+\pi^-$ channel used in the dispersive approach have been reported by SND2k [5] and CMD-3 [6], with the CMD-3 measurement significantly discrepant with all previous measurements. Significant effort is being directed towards identifying the source of these tensions [7], so that a single, reliable, SM prediction for a_μ can be put forward and compared with the measured value.

2. Experiment details

The Muon $g-2$ experiment consists of a 7.112 m radius storage ring magnet, the same magnet used in the BNL experiment, which produces a highly uniform magnetic field. Polarized muons from pion decay are injected into the storage ring, and in the presence of the magnetic field, the muon's spin precesses. The experiment relies on measuring the difference frequency between the muon's spin precession frequency ω_s and its cyclotron frequency ω_c. This difference frequency — also called the anomalous spin precession frequency and denoted ω_a — is given by[1]

$$\omega_a \equiv \omega_s - \omega_c = a_\mu \frac{eB}{m_\mu} \tag{2}$$

[1]Note that the frequencies in Equation 2 are *scalars*.

where e is the elementary charge and m_μ is the muon's mass. Equation 2 gives a "recipe" for extracting the magnetic anomaly: to determine a_μ, measure both the magnetic field seen by the muons B and the anomalous precession frequency ω_a. We describe each of these inputs, in turn.

The anomalous spin precession frequency is measured through the time-modulation of the decay positron energy spectrum, which oscillates at ω_a due to the parity violation of muon decay. The positron's arrival time and energies are extracted from a suite of 24 segmented electromagnetic calorimeters that line the inside of the storage ring [10]. The positron counts are weighted by their energy-dependent oscillation amplitude and a time series is constructed. The frequency is extracted from a χ^2 minimization with a physically motivated model that accounts for muons lost before decay and beam oscillations that couple to calorimeter acceptance.

The magnetic field is measured using the technique of pulsed proton nuclear magnetic resonance (NMR) [11]. There are 378 fixed NMR probes installed above and below the storage region that continuously monitor changes in the magnetic field. The magnetic field where the muons are stored cannot be measured synchronously with muon storage. Rather, every few days, the muon beam is turned off and a trolley equipped with 17 NMR probes circulates the ring. The continuous fixed probe measurements are calibrated with pairs of trolley measurements to obtain the magnetic field at the time and location where the muons are stored.

The muon distribution is measured with two straw tube tracking detectors [12], located 180° and 270° from the muon injection point. The trackers are sensitive to the muon distribution at only two azimuthal locations around the ring. Calculations that use the beam lattice functions determine the muon distribution azimuthally. The magnetic field is weighted by the muon distribution, both spatially and temporally, to obtain the magnetic field "seen" by the muons. Lastly, an absolute magnetic field is obtained by calibrating the probes against a cylindrical sample of water.

In the real experiment, the spin's dynamics are more complicated than Equation 2. The T-BMT equation [8, 9] implies that the difference frequency, in full, is given by[2]

$$\vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - a_\mu \frac{\gamma}{\gamma+1}(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right], \tag{3}$$

where β is the normalized velocity and γ is the Lorentz boost factor. This equation includes two additional terms compared to Equation 2. In the experiment, these terms give nonzero contributions to ω_a due to the vertical pitching motion of the beam and the presence of vertically-focusing electrostatic quadrupole fields $\vec{E}$, respectively. The third term can be set to 0 by choosing a momentum of $p = 3.094$ GeV/c, the so-called magic momentum[3]. A realistic muon beam has a finite momentum spread, which prevents this term from being exactly zero. In addition to these terms, we also account for effects that change the measured $g-2$ phase over the measurement period. There are two pulsed systems: the electrostatic quadruples for vertical focusing [13] and a fast magnetic kicker for pushing the injected muons onto the design orbit [14]; both systems induce transient magnetic fields that are measured and accounted for in the magnetic field determination. All of these "corrections" are small (sub-ppm) compared to the main signal, but must be accounted

[2]This equation is in vector form, as opposed to Equation 2. The difference frequency equals $\vec{\omega}_a$ only if the spin and cyclotron frequency vectors are parallel, which is approximately true. See note [63] in Reference [1].

[3]Given the ring radius of 7.112 m and this momentum, the magnetic field is set to 1.451 T.

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for in the analysis as some are commensurate with our present uncertainty.

3. Muon g-2 measurement status

The first result from the Muon g-2 Experiment was based on just 6% of the total anticipated amount of data. The next result — based on years two and three of operation — will use a dataset 4.7× larger than the Run-1 dataset. The statistical uncertainty will be reduced by 2.2×, which will push the measurement to unprecedented precision. The analysis of this data is nearing completion[4].

In addition to the reduction in the statistical uncertainty, the Run-2/3 analysis benefits from improvements that will reduce the systematic uncertainty. Here, we describe three systematic uncertainties (some of the largest in the Run-1 analysis) that are expected to reduce.

One of the transient magnetic field effects arises from pulsing the electrostatic quadruples, which leads to mechanical vibrations. Neither the fixed probes nor the trolley probes are sensitive to this magnetic field, but the muons do experience it. Dedicated measurements are required to determine its temporal and spatial structure. These measurements were limited in Run-1, leading to the largest systematic uncertainty in the analysis of 95 ppb [16]. An extensive measurement campaign was undertaken to map the transient field with better resolution; this effort will significantly reduce the uncertainty for the Run-2/3 analysis.

The Run-1 data were affected by damaged resistors in the electrostatic quadrupole system, which led to beam instability over the measurement period. An unstable beam led to a large phase acceptance effect — one of the changing $g-2$ phase effects — with a large uncertainty of 75 ppb [17]. The resistors were redesigned and replaced after Run-1, leading to a more stable beam. The better beam stability will reduce the phase acceptance correction and uncertainty.

In Run-1, pileup — in which two or more positrons are identified as a single positron — was one of the dominant systematic uncertainties in the extraction of ω_a at 30-40 ppb [18]. For the Run-2/3 analysis, the treatment of pileup has been improved through a new clustering technique that incorporates the energy dependence of the time resolution, reducing pileup contamination by a factor of four. In addition, many analysis groups have adopted more robust pileup subtraction methods that use the raw traces and reconstruction to build an empirical pileup spectrum.

Looking ahead to the Run-4/5/6 analysis, we expect to surpass our statistical uncertainty goal, having exceeded our target statistics [19] earlier this year. In addition, we have improved the running conditions starting in Run-5 by applying a radio frequency (RF) pulse to the electrostatic quadruple plates [20], which dampens the radial motion of the beam, known as the coherent betatron oscillation (CBO) . Modeling the CBO is the dominant systematic uncertainty in the extraction of ω_a and by dampening the signal, this uncertainty is expected to reduce. In Run-6, the RF pulse was altered to also dampen vertical beam oscillations. Taken all together, the final uncertainty on a_μ using all data is expected to be better than the design goal of 0.14 ppm.

4. Muon EDM search status

A nonzero electric dipole moment (EDM) breaks CP (charge and parity) symmetry and, therefore, could help explain the matter anti-matter asymmetry of the universe. In the SM, a

[4] The Run-2/3 result was announced on August 10, 2023 [15].

nonzero EDM is expected due to loop processes involving quarks, but the size is both too small to account for the matter anti-matter asymmetry and is experimentally inaccessible. The current best limit on the muon's EDM comes from the BNL experiment, which achieved an upper limit of $|d_\mu| < 1.8 \times 10^{-19} e \cdot \mathrm{cm}$ [21]. Due to the smallness of the SM prediction, an observation of a nonzero EDM would be a discovery of new physics.

An EDM introduces an extra term in the spin precession equation such that Equation 3 becomes

$$\vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - a_\mu \frac{\gamma}{\gamma+1}(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] - \frac{\eta e}{2m_\mu c}\left[\vec{E} + c\vec{\beta}\times\vec{B}\right], \quad (4)$$

where η is a dimensionless quantity that sets the strength of the EDM, analogous to the g-factor setting the strength of the magnetic dipole moment. The dominate signal induced by the EDM comes from the $\vec{\beta}\times\vec{B}$ term, which is orthogonal to the dominant magnetic dipole moment term proportional to $\vec{B}$. This term causes the polarization plane to tilt vertically out of the storage ring plane. An EDM also increases the magnitude of ω_a, but given current limits, the effect is too small to observe directly. The tilted polarization plane is the feature used to search for an EDM.

A search can be performed using both detector systems in the experiment: the calorimeters and the trackers. The calorimeter-based approach looks for an asymmetry in the $g-2$ phase versus the vertical position on the calorimeter. Calorimeter segmentation allows vertical position resolution. The BNL result was systematically limited [21]. The broken quadruple resistors in Run-1, which made the vertical motion of the beam unstable, introduces too large a systematic effect in the calorimeter-based approach, such that it is not performed with the Run-1 data.

The tracker based method measures the vertical decay angle directly and looks for an oscillation at the $g-2$ frequency. The vertical oscillation phase is $\pm 90^\circ$ out of phase with the $g-2$ signal. In this method, the $g-2$ phase is first extracted from the decay positron number oscillation. Then, the average vertical angle versus time — as measured by the trackers — is fit with a sinusoid with the phase fixed to the extracted $g-2$ phase. The amplitude of the sinusoid is the desired signal. The BNL measurement was statistically limited [21].

One potentially problematic systematic effect in the EDM analysis is the presence of a nonzero radial magnetic field. Referring to Equation 4, a radial magnetic field, via the first term, also tilts the polarization plane and therefore mimics an EDM signal. To reduce the systematic uncertainty, the radial field was measured [22]. The measurement was performed by applying a known radial field and scanning the electrostatic quadruple voltages. Using this method, the radial field was measured to a precision of less than 1 ppm, sufficient to make it a sub-dominant effect.

The Run-1 tracker-based analysis is nearing completion, is statistics-limited at ~100 million tracks, and will achieve a limit comparable to the BNL limit. The analysis of the Run-2/3 data is well underway and benefits greatly from $> 4\times$ the number of stored muons. Due to improvements in the tracking efficiency, the number of quality tracks used in the analysis is expected to scale even better then $4\times$. The broken quadruple resistors were fixed following the completion of Run-1, which allows carrying out the calorimeter-based analysis. With the full dataset, including Run-4/5/6, the expected sensitivity from the Fermilab experiment is $|d_\mu| \sim 1 \times 10^{-20} e \cdot \mathrm{cm}$.

5. Conclusions

The Muon $g-2$ Experiment at Fermilab aims to measure the muon magnetic anomaly to 0.14 ppm. The first result, based on the first year of data, reached a precision of 0.46 ppm and confirmed the BNL measurement. The combined experimental value is in tension with the TI's SM value at 4.2σ. Since this result, the theory landscape has become more complicated: lattice QCD calculations of HVP are discrepant with the dispersive method, and a new cross section measurement (which is used in the dispersive approach) is discrepant with previous measurements. Significant effort towards resolving these discrepancies is underway.

Analysis of the Run-2/3 data is nearing completion with the uncertainty expected to reduce $> 2\times$ compared to the first result. The improved precision arises from both $> 4\times$ the data and also significant improvements to our understanding of systematic effects. Currently, the experiment is nearing the end of data collection, having surpassed its proposed statistics goal.

The Fermilab experiment is also sensitive to an EDM through the tilt of the spin polarization plane. The search for an EDM based on the Run-1 data is nearing completion and is expected to have a comparable sensitivity to the BNL result. The analysis of the Run-2/3 data is underway and benefits from both increased stored muons and also improvements to the tracking efficiency. Not mentioned in these proceedings are other efforts searching for CPT and Lorentz violation.

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