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The precession frequency measurement in the Muon $g-2$ experiment at Fermilab

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Summary. — The Muon $g-2$ (E989) experiment aims to reduce the uncertainty on the muon magnetic anomaly value ($a_\mu = \frac{g-2}{2}$) by a factor four (0.14 ppm) compared to the previous experiment at Brookhaven National Laboratory (BNL) in order to clarify the difference (now greater than $3\,\sigma$) between the experimental value and the Standard Model (SM) prediction. 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 approaching the final stage and the first result should become available in 2021. In this paper, I will briefly describe the experimental setup and discuss the measure of the muon's spin anomalous precession frequency.

1. – Introduction

The muon magnetic anomaly $a_\mu = (g-2)_\mu/2$ can be predicted 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, which encapsulates the largest source of systematic errors in the calculation of a_μ. In 2020, the global theory community published a theoretical value for the anomaly [1]. The result still shows a difference between the theoretical and experimental value [2] greater than 3 σ. Great effort is coming from the new Muon $g-2$ experiment at Fermilab (E989) to achieve twenty-one times the statistics of the BNL experiment and to reduce the uncertainty by a factor 4 (from 540 to 140 ppb) in order to clarify this discrepancy.

2. – The measurement

The a_μ measurement is based on the determination of two frequencies: the anomalous precession frequency of the muon's spin in a magnetic field (ω_a) and the free proton

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precession frequency (ω_p) in a magnetic field. We can define the anomalous precession frequency as the difference between the spin precession frequency and the cyclotron frequency of muons in a magnetic field. For relativistic muons, assuming that the magnetic field $\vec{B}$ is uniform, the $\vec{\omega}_a$ can be written as

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

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 eq. (1) vanishes. By using a beam perpendicular to the magnetic field, the term $\vec{\beta}\cdot\vec{B}$ becomes zero. Corrections due to the momentum spread and direction are considered during data analysis. Precision measurements of ω_a and the magnetic field lead to a measurement of a_μ:

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

where $\tilde{\omega}_p$ is the magnetic field intensity convoluted with the muon beam distribution; g_e is the electron's gyromagnetic ratio, m_μ/m_e is the ratio between muon's and electron's masses and μ_p/μ_e is the ratio of proton's and electron's magnetic moments.

3. – E989 Experiment at Fermilab

3·1. *Experimental setup.* – The main component of the experiment is a 14 m diameter superconducting storage ring([1]) that produces a 1.45 T uniform magnetic field. A highly pure beam of polarized (96%) positive muons produced by Fermilab'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 storage. Electrostatic quadrupoles provide vertical focussing of the beam. The beam is collimated and scraped to reduce beam losses during the measurement. For each accelerator cycle, 16 bunches of muons are injected in the storage ring. For each bunch, the measurement window is 700 μs.

The magnetic field is measured during the run by fixed NMR probes placed around the vacuum chamber. Regularly, a trolley equipped with 17 NMR probes is moved through the muon storage region around the ring to measure the field magnitude inside the storage region.

The calorimeter system precisely measures the arrival time and the energy of the decay positrons curling inward 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 that allows positrons to exit the vacuum chamber while minimizing the path in air.

A single calorimeter is made of 54 PbF_2 Čerenkov crystals ($2.5\times2.5\times14$ cm^3) arranged in a 6×9 matrix. Lead fluoride has good features for the $g-2$ measurement: high density

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([1]) Recommissioned from the BNL experiment.

(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, thus improving the time resolution.

The light from each crystal is read out by a Large Area Silicon Photomultiplier (SiPM) working in Geiger mode. Each SiPM has an active area of 1.2×1.2 cm^2 (with 50 μm pixels) that is well-matched with the crystal area [3]. A laser system [4] is used to keep track of and correct for the gain variation of the SiPMs due to multiple positron hits (in-fill gain correction) and long-term temperature variations (out-of-fill gain correction).

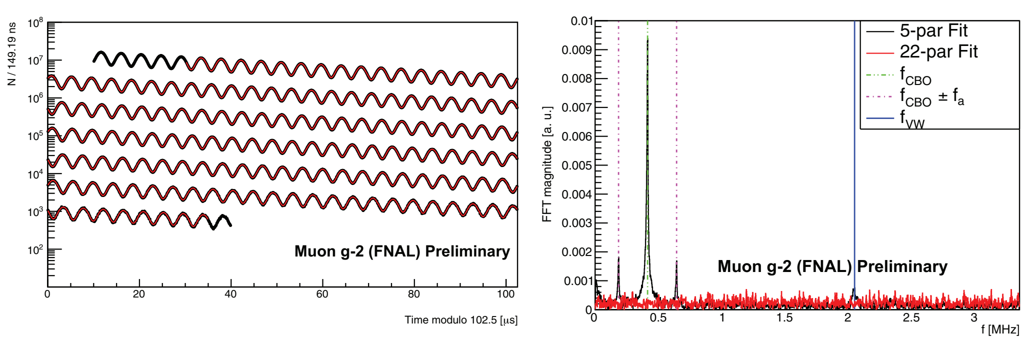
3·2. ω_a *analysis*. – The anomalous precession frequency ω_a can be measured using the parity-violating muon decay. From angular momentum conservation and helicity considerations, there is a strong correlation between the high energy decay positron's momentum direction and the muon's spin. The ω_a frequency can be measured by counting the number of high-energy positrons above an energy threshold (typically $E > 1.7$ GeV) in a fixed direction, as a function of time.

Positron hits in the calorimeters are reconstructed from the raw waveforms using two algorithms called ReconWest [5] and ReconEast [6]. These algorithms give the energy and time of each positron hit in the calorimeter. Then, a pile-up correction procedure is applied before the analysis.

The number of high-energy positrons as a function of time, the "Wiggle Plot", is shown in fig. 1(a). In this figure, the modulation of the exponential muon decay by the anomalous precession frequency is clearly visible.

To extract the anomalous precession frequency value, the Wiggle Plot data are fitted. The equation used for the fit includes the decay exponential and the ω_a modulation term (5-parameter fit). In fig. 1(b), the FFT of the 5-parameter fit residuals is shown in black. The peaks at the main beam frequencies suggest that additional terms related to beam dynamics need to be added to the fitting function. The full equation can be written as the 5-parameter fit times three factors $C(t)$, $V(t)$ and $\Lambda(t)$:

$$N(t) = N_0 e^{-\frac{t}{\tau}} \left[1 - A\cos(\omega_a t + \phi)\right] \cdot C(t) \cdot V(t) \cdot \Lambda(t), \tag{3}$$



(a) Wiggle plot (b) FFT of the fit residuals

Fig. 1. – (a) is the arrival time spectrum of high-energy positrons. (b) shows the FFT of the residuals to a five-parameter fit in black and the residuals to the full 22 parameter fit function, that includes the coherent betatron frequency (CBO), in red. The main peaks identified here are the CBO frequency (f_{CBO}) and the vertical waist (f_{VW}). f_a represents the anomalous precession frequency.

where $C(t)$ accounts for the time-dependent radial CBO, and $V(t)$ accounts for the vertical motion. The $\Lambda(t)$ term accounts for the beam losses during the measurement period. $C(t)$ and $V(t)$ terms are evaluated using a pair of tracker detectors to reconstruct the position of the beam during the measurement. 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 (or higher-order) coincidences in consecutive calorimeters and with energy and timing cuts according to the MIP behaviour. The final fitting function is a 22-parameter function that accounts also for higher-order and varying beam frequencies. The FFT of the fit residuals after all the corrections (red curve in fig. 1(b)) no longer shows beam-related peaks.

Six different working groups performed independent analyses with different procedures (reconstruction algorithm, pile-up subtraction, lost muons identification, analysis method) to extract the anomalous precession frequency and to provide a full systematics evaluation. All values show statistical consistency of the analyses.

The precession frequency value is both hardware and software blinded to avoid biases. The hardware blinding is done by applying an offset, unknown to the collaboration, to the main clock frequency. The offset is common to all the analyses. In the fitting procedure, a software blinding (different for each analyzer) is applied.

4. – Conclusions

After data quality cuts, the number of good positron events in the Run 1 (2018) dataset is approximately 1.2 times the total number of positrons collected by BNL E821. Data have been analyzed by different analysis groups with different procedures, and all the values show statistical consistency. The full Run 1 result is expected to have statistical and systematic uncertainties comparable to the previous BNL result [2]. A first result is expected to be published in 2021.

Run 2 and 3, with qualitatively better stored beam conditions, are now under analysis, while Run 4 data taking is ongoing.

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