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The precision measurement of the muon $g-2$ at Fermilab(*)

P. Girotti(**)
INFN, Sezione di Pisa - Pisa, Italy

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Summary. — The Muon $g-2$ Experiment at Fermilab aims to measure the magnetic anomaly of the muon with the unprecedented precision of 140 parts per billion. In April 2021, the collaboration published the first measurement based on the first year of data collection, which was found to be consistent with the previous experiment at Brookhaven. The new global average of the experimental measurements strengthens the long-standing tension with the data-driven Standard Model prediction to a combined discrepancy of 4.2σ. On the theory side, however, recent improvements in the theoretical calculation of the hadronic contribution based on Lattice-QCD techniques are introducing new tensions on the value predicted by the theory. The Muon $g-2$ Experiment at Fermilab has now concluded its sixth and final year of data taking and a new result based on the Run-2 and Run-3 data was published in August 2023. This paper briefly describes the precision measurement conducted by the Muon $g-2$ Experiment at Fermilab and its current status.

1. – Introduction

The muon anomaly, or muon $g-2$, is a dimensionless quantity that measures the quantum loop corrections to the interaction between a muon and an external magnetic field:

$$a_\mu \equiv \frac{g-2}{2} = 0.0011659\ldots\ , \tag{1}$$

with its precise value depending on all the possible virtual particles participating in the loop corrections. A comparison between the precise measurement of such quantity and the respective calculation based on the knowledge of particle physics is therefore of great interest. A deviation between the experimental measurement and the theoretical prediction could reveal new physics contributions in the loop corrections. The history of the muon $g-2$ is a 70 years old story of alternating experiments and theoretical calculations with ever-increasing precision on both fronts. By the end of 2020, the best

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(**) On behalf of the Muon $g-2$ Collaboration.

experimental measurement showed an interesting tension of 3.7σ with respect to the theoretical value compiled by the Muon $g-2$ Theory Initiative([1]) (TI) [1, 2]:

$$a_\mu^{Exp}(\text{BNL, 2006}) = 0.00116592089(63) \ \ [540 \text{ ppb}] \ , \tag{2}$$

$$a_\mu^{Th}(\text{TI, 2020}) = 0.00116591810(43) \ \ [368 \text{ ppb}] \ . \tag{3}$$

In this context, the Muon $g-2$ Experiment at Fermilab (E989) was built to increase the precision of the experimental measurement by a factor of four, with the goal accuracy of 140 ppb. On April 7th, 2021, the Muon $g-2$ collaboration announced the first measurement of a_μ based on the first year of data taking, which took place in 2018. The measured value is:

$$a_\mu^{Exp}(\text{FNAL, 2021}) = 0.00116592040(54) \ \ [460 \text{ ppb}] \ , \tag{4}$$

which is perfectly consistent with the BNL value with a slightly improved precision of 460 ppb [3]. Combining the two results, we have the new experimental average of:

$$a_\mu^{Exp}(\text{World, 2021}) = 0.00116592061(41) \ \ [350 \text{ ppb}] \ , \tag{5}$$

and an increased discrepancy with the TI theoretical prediction of 4.2σ [3].

However, in the same period, a new theoretical calculation of the QCD contribution to a_μ based on ab-initio Lattice-QCD techniques, *i.e.*, without any external input from experimental cross-section data, was published [4]. While the hadronic light-by-light a_μ^{HLbL} term is in agreement with the data-driven estimations, the lowest-order hadronic vacuum polarization $a_\mu^{HVP,LO}$ term is creating a tension between the two methods and is moving the theoretical value of a_μ closer to the experimental one. Figure 1 shows the comparison between the experimental values and the two theoretical approaches. In the past few years, other groups provided preliminary results on the same quantity measured in a reduced region of energies which accounts for ∼30% of the total value [5-7], all in agreement with the original value. The tension that is now consolidating between the two theoretical approaches for the estimation of a_μ^{HVP} is being referred as *the new* $g-2$ *puzzle* and remains unexplained as of today.

2. – The experiment

The Muon $g-2$ Experiment (E989) in operation at Fermi National Accelerator Laboratory aims to measure the muon's anomalous magnetic moment with a precision of 0.14 ppm, a factor of four better than the previous BNL E821 Experiment.

The experimental technique consists of producing a polarized beam of muons, sending it to a storage ring with very uniform magnetic field, and observing the decay positrons. The precession frequency of the muon's spin is proportional to the muon $g-2$ and to the magnetic field strength. Three measurements are needed to calculate the muon anomaly a_μ: the muon anomalous precession frequency, the magnetic field intensity, and the beam distribution inside the storage region. The master formula is the following:

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p} \frac{g_e}{2} \frac{m_\mu}{m_e} \frac{\mu_p}{\mu_e} \ , \tag{6}$$

([1]) https://muon-gm2-theory.illinois.edu/.

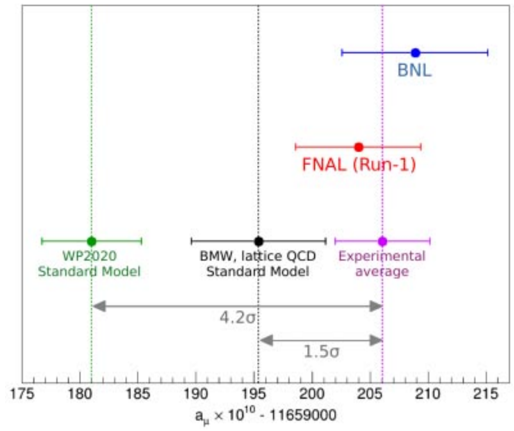

Fig. 1. – Comparison between the experimental measurements of a_μ by the BNL and FNAL experiments and the two theoretical predictions based on the data-driven (WP2020) and lattice-QCD (BMW) approaches as of 2021.

where ω_a is the muon anomalous precession frequency, and $\tilde{\omega}_p$ is the Larmor precession frequency of the proton (ω_p) convoluted with the beam distribution, representing the average field intensity experienced by the muons. The remaining factors are known with sufficient precision from other experiments. Small corrections are applied to the measured quantities of ω_a^m and $\tilde{\omega}_p^m$ due to beam dynamics effects and field transients. Further details can be found in the Run-1 accompanying papers [8, 9].

2˙1. *The muon beam.* – The Fermilab accelerator complex provides an 8 GeV proton beam set to collide on a NiCrFe target, producing pions among the shower of secondary particles. Positive pions with 3.1 GeV momentum are extracted and then allowed to decay into muons while circulating inside a Delivery Ring. Since pions have zero spin, the muons are emitted isotropically in the rest frame of reference, but their helicity is constrained by the weak decay as illustrated in fig. 2. By selecting boosted muons with 3.1 GeV momentum, a highly polarized beam is naturally obtained in the laboratory frame of reference. The 120-ns long muon bunches enter the Muon $g-2$ storage ring at a rate of 11.4 Hz. A superconducting inflector magnet lets the beam pass through the ring yoke into the storage region. Then, after the first quarter of an orbit, a fast pulsed kicker [10] magnet deflects the muon bunch into the final orbit with a radius of 7.112 m and a cyclotron period of 149.2 ns. The ∼5000 muons stored in each bunch circulate inside the ring for up to 700 μs until they decay, while a set of electrostatic quadrupoles provides weak focusing for vertical confinement [11].

Fig. 2. – Decay of the positive pion in the rest frame of reference. The spin of the muon points toward the pion as the neutrino must be left-handed because of parity violation of the weak interaction.

2˙2. *The field measurement*. – The magnet field measurement consists of various components and techniques used to determine the value of ω_p: 378 Nuclear Magnetic Resonance (NMR) fixed probes are placed along the ring under and over the vacuum chamber. The probes keep monitoring the field during the whole data taking. Every three days during data taking, a mobile cylinder equipped with 17 NMR probes traverses the beam storage region to make 9000 measurements along the ring [8]. These measurements produce a three-dimensional (3D) map of the magnetic field inside the storage region. The 3D map is then interpolated over the time between two consecutive trolley runs with the fixed probes data. While the magnetic field is ppm-level uniform along the beam cross section, the muon distribution inside the storage ring has to be precisely determined in order to achieve an uncertainty of 70 ppb on $\tilde{\omega}_p$. For this, a set of two tracker stations observe positron tracks and extrapolate the decay vertex in the storage orbit. The beam distribution is extrapolated over the rest of the ring with data from the calorimeters and multiple dedicated simulations [9].

2˙3. *The muon precession frequency measurement*. – The difference between the spin precession and cyclotron frequencies of a particle with charge and spin placed in a magnetic field is called anomalous precession frequency, ω_a. This quantity is proportional to the particle $g-2$, and is affected by electric fields and non-perpendicular magnetic fields:

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c} - a_\mu\left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\,\vec{\beta}\right]. \tag{7}$$

The Muon $g-2$ Experiment houses several electrostatic quadrupoles for a weak vertical focusing of the beam. This would affect the muon precession frequency, but, for a muon beam with *magic* momentum $p_\mu = 3.094$ GeV/c, corresponding to a value of $\gamma = 29.3$, the second term of eq. (7) cancels out almost perfectly. In addition, the muon beam is not always perfectly parallel to the storage plane, but oscillates vertically and horizontally around the ideal orbit. The remaining effect from the electric fields and the third term of eq. (7) are measured separately and applied as *E-field* and *Pitch* corrections to ω_a [9].

The measurement principle of ω_a relies on the parity-violating nature of the weak decay. The positive muons decay into a positron and two neutrinos with near 100% probability. In the rest frame of the muon, the highest energy decay positrons come from decays in which the neutrinos are emitted collaterally, as depicted in fig. 3. As the two neutrinos must have opposite spins, conservation of angular momentum forces the decay positron to carry the spin of the parent muon. The $V-A$ nature of the weak decay prefers to couple to a right-handed positron, so the high-energy decay positron depicted in fig. 3 tends to be emitted in the direction of the muon spin. The asymmetry of the decay process, together with the spin precession with respect to the momentum, results in an oscillation of the positron energy spectrum over time as observed in the

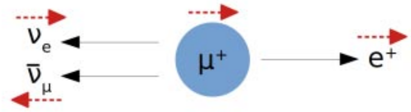

Fig. 3. – Muon decay configuration that maximizes the positron momentum and decay probability. The right-handed positron is emitted in the direction of the muon spin.

laboratory frame. The decay time and energy of the positrons are measured with 24 electromagnetic calorimeters located around the ring. Each calorimeter is a segmented 9x6 matrix of PbF_2 crystals coupled with SiPM detectors, whose gains are calibrated at the $\mathcal{O}(10^{-4})$ level by a Laser-based Calibration System [12, 13].

The number of detected positrons above an energy threshold E_{th} is:

$$N(t) = N_0 e^{-t/\tau}[1 + A\cos(\omega_a t + \phi)] \ , \tag{8}$$

where the normalization N_0, the asymmetry A and the initial phase ϕ are all dependent on E_{th}. τ represents the lifetime of the muon in the laboratory frame of reference, that is $\gamma\tau_\mu \simeq 64.4\ \mu$s. Additional beam-related effects, as coherent betatron oscillations and muon losses, appear as multiplicative terms to N_0, A, and ϕ. Three different reconstruction techniques and several analysis procedures are implemented to obtain the ω_a value [14]. As an example, in the A-Weighted method the positrons counts are weighted by the asymmetry, which depends on the energy, yielding the maximum possible statistical power for a given threshold E_{th}.

3. – Current status

The Muon $g-2$ Experiment at Fermilab just completed its sixth and final year of data taking. During the last year, it achieved and surpassed the statistical goal of 21 times the BNL experiment. In April 2021, the Muon $g-2$ Collaboration released their Run-1 measurement of the muon anomaly with a precision of 460 ppb [3]. In August 2023, few months after the conference this article is about, the collaboration released their second measurement relative to the Run-2 and Run-3 data taking periods, which took place respectively in 2019 and 2020. The new value more than doubled the precision of the Run-1 result and the current FNAL value is reported here [15]:

$$a_\mu^{Exp}(\text{FNAL, 2023}) = 0.00116592055(24) \times 10^{-11} \ \ [200 \text{ ppb}] \ , \tag{9}$$

$$a_\mu^{Exp}(\text{World, 2023}) = 0.00116592059(22) \times 10^{-11} \ \ [190 \text{ ppb}] \ . \tag{10}$$

The new world average is now dominated by the FNAL measurement, and it currently stands at 5.1σ from the TI value of 2020. As anticipated in sect. **1**, however, the tensions between the various theoretical approaches to the QCD calculations have to be resolved before deducing any new physics from this discrepancy.

The Muon $g-2$ collaboration is now actively analyzing the remaining datasets, Run-4, Run-5, and Run-6, which consist of roughly 75% of the total accumulated statistics as shown in fig. 4. A new publication is expected in 2025 with a final error currently on track to beat the original goal of 140 ppb.

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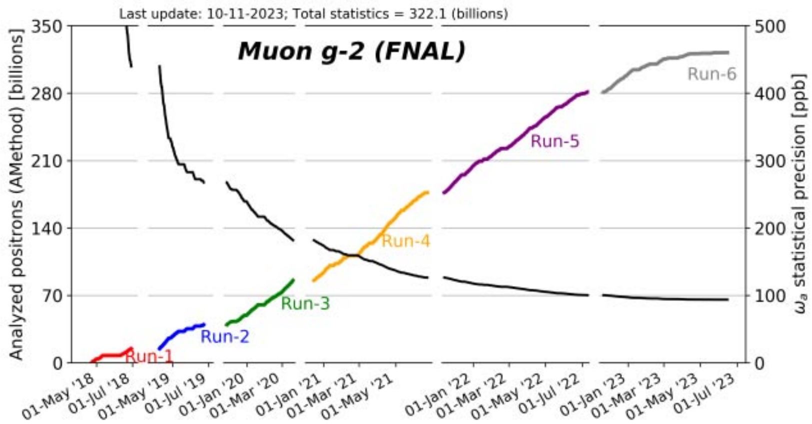

Fig. 4. – Number of positrons above 1 GeV collected and analyzed in the six runs of the Muon $g-2$ Experiment at Fermilab after Data Quality Checks. The black line represents the statistical precision of the anomalous precession frequency measurement according to the cumulative statistics. Run-4/5/6 numbers are not final.

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