

Latest results of the Muon $g-2$ experiment at Fermilab

Matteo Sorbara^{1,2,*} on behalf of the Muon $g-2$ Collaboration

¹Università degli Studi di Roma “Tor Vergata”, Via della Ricerca Scientifica 1, 00133, Rome (Italy)

²Istituto Nazionale di Fisica Nucleare Sezione di “Tor Vergata”, Via della Ricerca Scientifica 1, 00133, Rome (Italy)

Abstract. The muon magnetic anomaly, $a_\mu = \frac{g-2}{2}$, is a low-energy observable which can be both measured and computed to high precision, making it a sensitive test of the Standard Model and a probe for new physics. The Muon $g-2$ experiment at Fermilab aims to measure a_μ with a final accuracy of 140 parts per billion (ppb). The experiment is based on the measurement of the muon spin anomalous precession frequency, ω_a , in a magnetic field. The first result of the experiment, based on the 2018 data-taking campaign, was published in 2021 and it confirmed the previous result obtained at Brookhaven National Laboratory with a similar sensitivity of 460 ppb. In this proceeding, the result based on the 2019 and 2020 datasets is presented and the improvement in the accuracy with respect to the 2018 dataset are discussed.

1 Introduction

When a charged particle travels in a region with a magnetic field, due to the interaction between the magnetic moment and the field itself, the particle experiences a torque, and the spin starts a precession motion around the direction of the magnetic field. The frequency of the spin precession is given by $\omega_s = g \frac{e}{2m} B$, where g is the gyromagnetic ratio. For a muon (and in general for an elementary lepton) the value of g can be derived from Dirac equation to be equal to 2 at the tree level. Higher order corrections can be computed in the Standard Model framework. It is useful to define the muon magnetic anomaly as the fractional difference of g from 2, hence $a_\mu = \frac{g-2}{2}$. The corrections shift the a_μ value by a factor $\sim \frac{\alpha}{2\pi} \sim 0.0012$ at first order.

The theoretical calculation of the muon magnetic anomaly includes contributions from the QED, weak interaction and two QCD-related terms: the Hadronic Vacuum Polarization (HVP) and the Hadronic Light by Light (HLbL). The HVP brings the highest uncertainty to the a_μ corrections since it cannot be computed perturbatively in the low energy region. Its calculation is based on two approaches, one uses a dispersion integral and one uses lattice QCD. The full calculation of a_μ has been published in 2021 from the *Muon $g-2$ Theory Initiative* in a white paper [1]. The group provided an estimate for the muon magnetic anomaly using the dispersive approach to compute the hadronic vacuum polarization contribution to the corrections. In 2021, the BMW collaboration presented the first result of a_μ from lattice QCD calculations with a similar uncertainty [2]. This result shows a discrepancy with the dispersive approach a_μ calculation, and a much better agreement with the experimental result.

*e-mail: matteo.sorbara@roma2.infn.it

Moreover, in 2024, the CMD-3 collaboration published a result [3] of the $e^+e^+ \rightarrow \pi^+\pi^+$ cross section that, if included in the dispersive approach calculation, brings the a_μ value closer to the experimental value and to the lattice QCD estimate.

On the experimental side, a_μ was measured in 1999-2001 by the E821 Muon $g-2$ experiment at Brookhaven National Laboratory [4] and, 20 years later by the E989 experiment at Fermilab. First result was published in 2021 using the data from the 2018 data-taking campaign (Run 1), with a precision similar to the one of the BNL experiment [5], while in 2023 results from the 2019 and 2020 (Run 2 and Run 3) campaign were published [6]. Besides the higher statistical power of the Run 2-3 dataset, improvements to the experimental setup and the analysis techniques brought the overall uncertainty of the a_μ value at around 200 parts per billion (ppb).

2 The Experiment

The anomalous precession frequency (ω_a), is defined as the difference between the muon's spin and cyclotron precession frequencies:

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

where \vec{E} is the electric field present in the region, $\vec{\beta}$ is the particle speed and γ the Lorentz's factor. For $\gamma = 29.3$ and beam perpendicular to the magnetic field, both the $\vec{\beta} \times \vec{E}$ and $\vec{\beta} \cdot \vec{B}$ terms can be treated as correction terms. Expressing the magnetic field in terms of the Larmor precession frequency of free protons in a nuclear magnetic resonance probe, the formula used for a_μ becomes:

$$a_\mu = \left[\frac{f_{\text{clock}} \cdot \omega_a (1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml})}{f_{\text{calib}} \cdot \langle \omega'_p(\vec{r}) \times M(\vec{r}) \rangle (1 + B_q + B_k)} \right] \times \frac{\mu_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2} \quad (2)$$

where ω_a is the anomalous precession frequency; the factor f_{clock} is the blinding factor, $\omega'_p(\vec{r})$ is the free proton precession frequency averaged over the storage ring azimuth, and $M(\vec{r})$ is the beam distribution inside the storage region. The correction factors C_i and B_i take into account the beam dynamics (altering the measured ω_a) and magnetic transients effects (altering the measured magnetic field) respectively. The last term includes all the external conversion factors, known to a 25 ppb precision.

In the Muon $g-2$ experiment, a beam of positive muons, polarized above the 95% level, is injected into a 14 m diameter superconducting storage ring that produces a vertical 1.45 T magnetic field, uniform at the ppm level. A set of pulsed non-ferric kickers inside the storage region move the muons onto the storage orbit after their injection into the ring. Four electrostatic quadrupoles (ESQ) provide the vertical focussing of the beam.

The muons' anomalous precession frequency measurement is based on the parity-violating decay of the muons in which high energy decay positrons are emitted preferentially in the muon's spin direction. A set of 24 electromagnetic calorimeters, made of lead fluoride (PbF_2) Čerenkov crystals, are placed along the inner circumference of the storage region to measure energy and time of arrival of the decay positrons. The time distribution of the high energy positrons can be fitted to a function, given at leading order by:

$$N(t) = N_0 e^{-t/\gamma\tau} [1 + A \cos(\omega_a t + \varphi)], \quad (3)$$

where N_0 is the normalization factor, τ is the muon lifetime boosted by the Lorentz factor γ , φ is an initial spin phase and A is the decay asymmetry, that quantifies the correlation

between the decay positron momentum and the muon spin directions. The value of ω_a can be extracted from this fit. Additional terms to describe beam dynamics effects are included in the full analysis (see ref. [5] and references therein for details).

The magnetic field intensity in equation 2 is expressed in terms of the free proton precession frequency via the relation $\hbar\omega_p = 2\mu_p|\vec{B}|$. This allows to use nuclear magnetic resonance (NMR) probes to have a precise measurement of the magnetic field. Every 2-3 days, the muons data-taking is interrupted and a special run is performed: a device equipped with 17 NMR probes is moved inside the muons storage region to provide a map of the magnetic field intensity inside the region. During normal data-taking, a set of 378 NMR probes positioned above and below the storage ring vacuum chamber track any change of the magnetic field map during the regular data taking.

The final value of the magnetic field is then used in equation 2, averaged over the azimuth of the storage ring and weighted with the beam distribution term $M(\vec{r})$, measured using two tracking detectors placed in vacuum at 180° and 270° , outside of the storage region. The trackers, made of Argon:Ethane filled straw tubes, measure the trajectory of the decay positrons, reconstructing the position of the muon at the decay time. From this measurement it is possible to reconstruct the beam distribution in a non destructive way.

3 Run 2-3 Improvements

Between Run 1 and Run 2-3, several improvements have been made in order to reduce the systematic effects associated to the experiment's running conditions. The overall data statistics was increased by 4.7 times, reducing the total statistical uncertainty by a factor 2.2.

In Run 1, damage to two ESQ resistors induced a shift in the beam vertical position during the measurement window that affected the fitted value of ω_a . Fixing the resistors greatly improved the beam stability and reduced the related uncertainty. During Run 3, the kicker system was upgraded to increase the kick strength to the optimal beam storage value, also improving the storage conditions and reducing the beam oscillation related systematics. The increase in statistics and the improved storage conditions also allowed to investigate in much more detail some of the C_i correction terms of equation 2, reducing their uncertainty.

On the ω_a analysis side, new reconstruction algorithm improved the ability to separate pile-up events, in which two or more positrons hit the calorimeters in a 2-3 ns window and are reconstructed as a single higher energy event. The pile-up affects the energy reconstruction, and since it's a time dependent effect, it also affects the ω_a result.

On the magnetic field side, the installation of air conditioning into the storage hall and the application of a thermal blanket over the magnet yoke greatly improved the magnetic field stability over time. The quadrupoles transient effects, B_q in equation 2, was mapped in detail for all the ESQs, while the kickers transient, B_k , was measured improving the sensitivity of the magnetometers used to investigate the effect. Both of this measurements reduced the uncertainty of both the B_i terms.

Figure 1 shows how each of the systematic source of uncertainty changed between the 2021 and the 2023 result. The effect of the improvements reduced the overall systematic uncertainty on the a_μ measurement from 157 ppb in Run 1 to 70 ppb in Run 2-3.

4 Conclusions

The Fermilab Muon $g - 2$ experiment aims to measure the muon magnetic anomaly, a_μ , with a precision of 140 ppb, improving by a factor four the previous measurement at the BNL experiment. With the recently published Run 1, Run 2 and Run 3 results, together

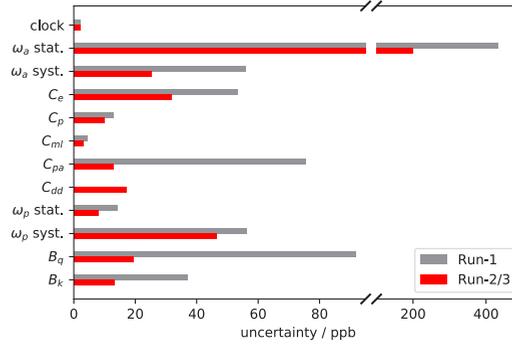


Figure 1. Comparison of the uncertainties in Run 1 [5] and Run 2-3 [6].

with the BNL result, the experimental average for a_μ has reached a precision of 190 ppb. Between Run 1 and Run 2-3 an improvement in the experimental setup and in the analysis techniques brought the systematic uncertainty to a 70 ppb level. The analysis of the last dataset is ongoing and the overall precision of the experiment is expected to reach its goal of 140 ppb uncertainty on a_μ .

Acknowledgements

This work was supported in part by the US DOE, Fermilab, the Istituto Nazionale di Fisica Nucleare and the European Union Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreements No. 101006726, No. 734303.

References

- [1] T. Aoyama *et al.*, The anomalous magnetic moment of the muon in the Standard Model, Phys. Rep. **887**, 1 (2020), <https://doi.org/10.1016/j.physrep.2020.07.006>
- [2] Sz. Borsanyi *et al.* (BMWc collaboration), Leading hadronic contribution to the muon magnetic moment from lattice QCD. Nature **593**, 51 (2021), <https://doi.org/10.1038/s41586-021-03418-1>
- [3] F. V. Ignatov *et al.* (CMD-3 collaboration), Measurement of the $e^+e^- \rightarrow \pi^+\pi^-$ cross section from threshold to 1.2 GeV with the CMD-3 detector. Phys. Rev. D **109** 112002 (2024), <https://doi.org/10.1103/PhysRevD.109.112002>
- [4] G. W. Bennett *et al.* (Muon $g-2$ collaboration), Final report of the E821 muon anomalous magnetic moment measurement at BNL. Phys. Rev. D **73**, 072003 (2006), <https://doi.org/10.1103/PhysRevD.73.072003>
- [5] B. Abi *et al.* (Muon $g-2$ collaboration), Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm. Phys. Rev. Lett. **126**, 141801 (2021), <https://doi.org/10.1103/PhysRevLett.126.141801>
- [6] D. P. Aguillard *et al.* (The Muon $g-2$ collaboration), Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm. Phys. Rev. Lett. **131**, 161802 (2023), <https://doi.org/10.1103/PhysRevLett.131.161802>