First Results From the Fermilab Muon $g-2$ Experiment

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On behalf of the Muon $g-2$ Collaboration
Muon Anomalous Magnetic Dipole Moment \((a_\mu)\)

Magnetic moment \(\mu = g \frac{e}{2m}s\)

Classical: \(g = 1\)

Dirac equation: \(g = 2\)

\[i \left( \partial_\mu - ieA_\mu(x) \right) \gamma^\mu \psi(x) = m\psi(x)\]

Interactions with quantum foam: \(g > 2\)

\[a_\mu = \frac{g-2}{2}\]
Contributions to $a_\mu$ in the Standard Model

QED incl. 4-loops + 5-loops

\[ a_\mu = 116\,584\,718.86 \times 10^{-11} \]
\[ \delta a_\mu = 0.03 \times 10^{-11} \]

Weak to 2-loops

\[ a_\mu = 153.6 \times 10^{-11} \]
\[ \delta a_\mu = 1.1 \times 10^{-11} \]

Hadronic LO VP

\[ a_\mu = 6\,894.6 \times 10^{-11} \]
\[ \delta a_\mu = 32.5 \times 10^{-11} \]

Hadronic LbL

\[ a_\mu = 103.4 \times 10^{-11} \]
\[ \delta a_\mu = 28.8 \times 10^{-11} \]

Theory: \((11\,659\,1783 \pm 43) \times 10^{-11}\)

Experiment (2021): \((11\,659\,2061 \pm 41) \times 10^{-11}\)

Recent Advances in the Theory

Improvements in $a_{\mu}^{\text{Had, LO VP}}$ (KNT18)

Direct energy scan: CMD-3, SND, KEDR
Radiative return: BABAR, KLOE/KLOE-2, BESIII

$\alpha_{\mu}^{\text{had, LO VP}} = (693.26 \pm 2.46) \times 10^{-10}$

Calculation of $a_{\mu}^{\text{Had, VP}}$ and $a_{\mu}^{\text{Had, LbL}}$
using Lattice QCD

- From first principles
- Can be used to improve R-ratio results
- Several collaborations working on this
  - including RBC/UKQCD and Mainz
- Precision needs improvement; calculations ongoing


In case of a Beyond-SM $a_\mu$, some of the possible contributors to the respective discrepancy would be:

- Dark matter
- Supersymmetry (SUSY)
- Extra dimensions
- Additional Higgs Bosons

[S. Iguro et al., arXiv:1907.09845 [hep-ph]]

Muon g-2 window in the search for inelastic dark matter (iDM):

NA62 Experiment at CERN is ongoing and may yield iDM results.

Improvements over the Muon g-2 Experiment at BNL (E821):
- More muons, delivered more often to the storage ring
- Improved muon storage function
- Better beam dynamics modeling
- Higher field uniformity and better field monitoring
- Reduced spin precession frequency systematics
From BNL to FNAL: the Great Move

2013

Tennessee-Tombigbee Waterway / Mississippi, Illinois and Des Plaines rivers
Technical design projection:
- ~20x more data
- ~3x reduction of systematic errors
The Muon g-2 Storage Ring

- Storage ring: 7 m radius toroidal C-magnet with 1.45 T magnetic field
- Inflector: cancels the 1.45 T main magnetic field for muons at injection
- Kickers deflect the injected muons onto the centerline orbit
- Electrostatic quadrupoles provide vertical beam focusing
If $g = 2$, the angle between the magnetic moment and the momentum does not change. If $g > 2$, the angle between the magnetic moment and the momentum changes linearly.

\[
\omega_a = 0 \\
\omega_a = -a_\mu \frac{qB}{m}
\]
Straw trackers: reconstruct decay $e^+$ trajectories
Calorimeters: detect decay $e^+$ energy and arrival times
The Wiggle Plot

Muon spin and momentum are aligned.

\[ f(t) = N_0 e^{-\lambda t} [1 + A \cos(\omega_a t + \phi)] \]

- \( \lambda \): exponential decay constant
- \( \omega_a \): muon anomalous precession frequency

Muon spin and momentum are anti-aligned.

Early-to-late phase change:
If, \( \phi = \phi(t) = \phi_0 + \phi_1 t \), then
\[
\cos(\omega_a t + \phi) = \cos(\omega_a t + \phi_0 + \phi_1 t) = \\
= \cos((\omega_a + \phi_1) t + \phi_0)
\]
Calculation of $a_\mu$ from Muon and Proton Spin Precession

\[
\alpha_\mu = \frac{\frac{g_e}{2}}{\frac{m_\mu}{m_e}} \frac{\omega_a}{\left\langle \omega_p \right\rangle}
\]

(140 ppb)

From CODATA [1]:
\[
\begin{align*}
g_e &= -2.002\ 319\ 304\ 361\ 82(52) \ (0.00026 \text{ ppb}) \\
m_\mu/m_e &= 206.768\ 2826(46) \ (22 \text{ ppb}) \\
\mu_e/\mu_p &= -658.210\ 6866(20) \ (3.0 \text{ ppb})
\end{align*}
\]

Passive shimming is performed by inserting tiny metal pieces to increase the field.

Magnetic field was made 3× more uniform than at BNL.

Active shimming is also used.
Fixed and Trolley-Mounted NMR Probes

Fixed probes on vacuum chambers

Trolley with matrix of 17 NMR probes

Electronics, Microcontroller, Communication

Position of NMR probes
<table>
<thead>
<tr>
<th></th>
<th>Correction</th>
<th>Uncertainty</th>
<th>Design goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega^m_a ) (statistical)</td>
<td>–</td>
<td>434</td>
<td>100</td>
</tr>
<tr>
<td>( \omega^m_a ) (systematic)</td>
<td>–</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>base clock</td>
<td>–</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>( C_e )</td>
<td>489</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>( C_p )</td>
<td>180</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>( C_{ml} )</td>
<td>-11</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>( C_{pa} )</td>
<td>-158</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>( \omega_a ) beam dynamics corrections (( C_e + C_p + C_{ml} + C_{pa} ))</td>
<td>499</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>( \omega_a ) total systematic</td>
<td>499</td>
<td>109</td>
<td>70</td>
</tr>
<tr>
<td>( \omega'_p(T)(x, y, \varphi) )</td>
<td>–</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>( M(x, y, \varphi) )</td>
<td>–</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>( \langle \omega'_p(T)(x, y, \varphi) \times M(x, y, \varphi) \rangle )</td>
<td>–</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>( B_q )</td>
<td>-17</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td>( B_k )</td>
<td>-27</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>( \omega'_p(T) ) transient fields corrections (( B_q + B_k ))</td>
<td>-44</td>
<td>99</td>
<td></td>
</tr>
<tr>
<td>( \omega'_p(T) ) total</td>
<td>44</td>
<td>114</td>
<td>70</td>
</tr>
<tr>
<td>( \omega_a/\omega'_p(T) ) total systematic</td>
<td>544</td>
<td>157</td>
<td>100</td>
</tr>
<tr>
<td>external measurements</td>
<td>–</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>total [correction is for ( \omega_a/\omega'_p(T) )]</td>
<td>544</td>
<td>462</td>
<td>140</td>
</tr>
</tbody>
</table>
In the following eight or nine slides, I will talk about some of my recent personal contributions:

- end-to-end simulations
- application of simulation results to muon loss systematics
Need to understand potential sources of early-to-late beam-related systematics.
Muon g-2 Target Station

Inconel target

Copper collimator

Lithium lens

Pulsed magnet (PMAG)

Lithium Lens

Target
Simulations Using High Performance Computing Systems

$2 \times 10^{13}$ protons on target

HPC systems:
- NERSC
  - Cori (2015–): 30 PFLOPS
- Open Science Grid
  - Up to 10000 cores at a time
- FermiGrid

Simulation tools:
- gm2ringsim (Geant4)
- COSY INFINITY
- BMAD
- MARS
- G4Beamline (Geant4)
InitZ: muon creation location. PhiX: muon spin phase at entrance into the ring. dp/p0: momentum deviation. All data within $|\frac{dp}{dp0}| < 0.5\%$, i.e. $3\sigma$ acceptance of the storage ring.
Dependence of Relative Initial Phase on Momentum

Experimental data: Hannah Binney.

A real momentum dependence of the initial phase develops because of magnetic dipoles in the Delivery Ring.

Experimental data: based on runs with muon storage with higher or lower momenta.
A $-11(5)$ ppb correction due to muon losses.
Far below the overall 70 ppb systematic error on the spin precession.
Meeting the TDR goal of 20 ppb.
The Decision to Unblind: a Remote Meeting of the Collaboration
Run-1 Result of the Muon g-2 Experiment

The SM value is the Muon g-2 Theory Initiative recommended value.
Publications of the Muon g-2 Experiment

Run-1 papers

- Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm
  https://doi.org/10.1103/PhysRevLett.126.141801

- Measurement of the anomalous precession frequency of the muon in the Fermilab Muon g-2 Experiment
  https://doi.org/10.1103/PhysRevD.103.072002

- Magnetic-Field Measurement and Analysis for the Muon g-2 Experiment at Fermilab
  https://doi.org/10.1103/PhysRevA.103.042208

- Beam dynamics corrections to the Run-1 measurement of the muon anomalous magnetic moment at Fermilab
  https://doi.org/10.1103/PhysRevAccelBeams.24.044002
Projection of Data Acquisition as a Multiple of BNL Data

Currently at \(~12.43 \times \) BNL data
Future EDM or $\mu^-$ anomalous MDM Possibilities

- Currently measuring $\mu^+$ anomalous MDM
- Measure $\mu^+$ EDM using vertical phase asymmetry detection in calorimeters
- Measure $\mu^-$ by reconfiguring the beamlines and storage ring (switching electric field direction)
  - No other proposed experiment can do $\mu^-$ (JPARC $\mu^+$ only)
The first $a_\mu$ result was released (Run-1), with precision 460 ppb
- The combined FNAL+BNL result has a 4.2$\sigma$ tension with the SM prediction
- We already have $\times 10$ more data compared to Run-1
- Run-2 and Run-3 results are expected to be ready for release in ~1 year
- The experiment continues physics runs to accumulate statistics for a total uncertainty of 140 ppb
  - Run-4 is complete, and Run-5 will begin soon
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• 1.45 T bucking field to cancel main field
• Can’t perturb main field by more than ~1 ppm
• Interface optics of storage ring and the M5 beamline
Fitting Function Example: 20 Point

\[ N = N_0 \Lambda N_{\text{cbo}} N_{2\text{cbo}} N_{\text{vw}} e^{-t/\tau} (1 - A A_{\text{cbo}} \cos(\omega_{\text{cbo}} t + \phi_{\text{cbo}})) \]

\[
N_{\text{cbo}} = 1 - A_{1\text{cbo}} e^{-t/\tau_{\text{cbo}}} \cos(\omega_{\text{cbo}} t + \phi_{1\text{cbo}})
\]

\[
N_{2\text{cbo}} = 1 - A_{2\text{cbo}} e^{-t/\tau_{\text{cbo}}} \cos(2 \omega_{\text{cbo}} t + \phi_{2\text{cbo}})
\]

\[
N_{\text{vw}} = 1 - A_{\text{vw}} e^{-t/\tau_{\text{vw}}} \cos(\omega_{\text{vw}} t + \phi_{\text{vw}})
\]

\[
A_{\text{cbo}} = 1 - A_{A\text{cbo}} e^{-t/\tau_{\text{cbo}}} \cos(\omega_{\text{cbo}} t + \phi_{A\text{cbo}})
\]

\[
\phi_{\text{cbo}} = 1 - A_{\phi\text{cbo}} e^{-t/\tau_{\text{cbo}}} \cos(\omega_{\text{cbo}} t + \phi_{\phi\text{cbo}})
\]

\[
\omega_{\text{cbo}} = \omega_0 (1 + 2.875 e^{-t/7.6} / \omega_0 t + 5.47 e^{-t/8.85} / \omega_0 t)
\]

\[
\Lambda = 1 - K_{\text{loss}} \int L(t') e^{t' / 64.4} dt
\]

\[
\chi^2 = \sum_{i=1}^{n_{\text{df}}} \left[ \frac{N_{\text{bin}} - N_{\text{fit}}}{\sigma(N_{\text{bin}})} \right]^2
\]
Straw Tracking Detectors