Current status of the muon $g-2$ measurement at Fermilab

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on behalf of the Muon g–2 Collaboration
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Motivation

Comparison of the measurement to the calculation of $a_\mu = (g_\mu - 2)/2$ allows for a precise test of the Standard Model and to look for new physics.

BNL $g - 2$ experiment (E821) found a discrepancy $> 3\sigma$ w.r.t. theoretical prediction.

Fermilab $g - 2$ experiment (E989) aims for a reduction of the experimental uncertainty by a factor of 4 with respect to BNL result:

$\delta(a_\mu)^{\exp.} : 540 \text{ ppb} \to 140 \text{ ppb}$

If $a_\mu$ value is confirmed (using latest $a_\mu^{SM}$), the new $g - 2$ result has the potential to confirm the discrepancy and claim discovery:

$a_\mu^{FNAL} - a_\mu^{SM} \sim 7\sigma$
1. Muon production

2. Polarized muons are injected into a magnetic storage ring

3. Measure B and the “anomalous precession frequency” i.e., the Spin precession frequency relative to the Cyclotron frequency:

$$\tilde{\omega}_a = \tilde{\omega}_S - \tilde{\omega}_C = -\frac{e}{m} \left[ a_\mu \tilde{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\beta \times \tilde{E}}{c} \right]$$

Choose $\gamma = 29.3$ ($P_\mu = 3.094 \text{ GeV/c}$)
In the final analysis the anomaly is extracted with:

\[
a_\mu = \frac{g_e \frac{m_\mu}{m_e} \omega_a}{2 \frac{\mu_e}{\mu_p}}
\]

- \(\omega_a\): anomalous spin precession frequency is extracted from decay positron time spectra
- \(\bar{\omega}_p\): average magnetic field seen by the muons is measured by NMR
- \(\delta a_\mu\): is determined by precision of \(\omega_a\) and \(\omega_p\) measurements:

<table>
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<tr>
<th>(\delta a_\mu)</th>
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<th>FNAL goal (ppb)</th>
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<td>(\omega_a) statistic</td>
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<td>(\omega_a) systematic</td>
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<td><strong>Total</strong></td>
<td><strong>540</strong></td>
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Get from CODATA\[^3\]:

- \(g_e = -2.002\ 319\ 304\ 361\ 82(52)\ (0.00026 \text{ ppb})\)
- \(m_\mu/m_e = 206.768\ 2826(46)\ (22 \text{ ppb})\)
- \(\mu_e/\mu_p = -658.210\ 6866(20)\ (3.0 \text{ ppb})\)

\[^3\] Rev. Mod. Phys. 88, no. 3, 035009 (2016) [arXiv:1507.07956]
Requirements for a 140 ppb measurement

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- **20 × BNL statistics**
  - more muons/second, higher quality beam, store more muons, ...

- **3 × more uniform magnetic field and improve the $\omega_p$ measurement**
  - optimize shimming procedure, precise pNMR probes, ...

- **Improve the $\omega_a$ measurement**
  - new instrumentation: segmented and fast EM calorimeters, higher bit-depth WFDs, laser calibration system, tracker system, ...
Production of the muon beam

- **Recycler Ring**: 8 GeV protons from Booster are rebunched

- **Target Station**: $p$ are collided with target and $\pi^+$ with $p = 3.1$ GeV/$c$ ($\pm 10\%$) are collected

- **Beam Transfer and Delivery Ring**: in decay line magnetic lenses select $\mu^+$ from $\pi^+ \rightarrow \mu^+\nu_\mu$, while in circular ring the $\mu$ are separated from $p$ and $\pi^+$

- **Muon Campus**: a beam of $\mu^+$ polarize is ready to be injected into the storage ring. We expect 20 times BNL statistics!
Journey of the storage ring: from BNL to FNAL

summer 2013
Injection of the Muons in the ring

$\mu^+$ injected first through a air **tunnel** in the iron yoke and then a field-cancelling **Inflector** magnet

$\mu^+$

$P_0 = 3.094 \text{ GeV/c}$

$R_0 = 7.112 \text{ m}$

$B_0 = 1.4513 \text{ T}$
Muon Storage

3 magnetic kickers to deflect the beam outward by \( \sim 10.8 \text{ mrad} \) at 90\(^\circ\) to put beam onto a centered orbit.

\[
\mu^+ \quad P_0 = 3.094 \text{ GeV/c}
\]

\[
R_0 = 7.112 \text{ m}
\]

\[
T_c = 149.2 \text{ ns}
\]

\[
B_0 = 1.4513 \text{ T}
\]

Air tunnel + Inflector

Fast kickers: Off before the beam returns!
Vertical Focusing

4 Sets of Electrostatic Quadrupole plates for vertical focusing

$\mu^+$
$P_0 = 3.094 \text{ GeV/c}$

Quadrupoles

Air tunnel + Inflector

$T_c = 149.2 \text{ ns}$

$B_0 = 1.4513 \text{ T}$

3 Fast magnetic kickers
ring equipped with two in-vacuum straw tracker detectors.

trackers used to extrapolate decay $e^+$ trajectory back to muon decay position $\rightarrow$ they provide an image of the store muon beam profile

final alignment and calibration not yet complete: beam not centred!

tracker detectors essential for $g - 2$ systematics and EDM search
In FY18 collected ~ 2×BNL statistics of raw data (no quality selection):
How we measure $\omega_P$

- $\omega_P$ is proportional to the magnetic field;
- magnetic field is created as uniform as possible (shimming procedure) and kept mechanically and thermally stable;
- during data-taking the field is monitored by fixed NMR probes;
- periodically (∼1 run every days) field is mapped by a trolley that runs around the inside of the ring and calibrates the stationary probes.
**ω_p Measurement**

**March 18**

<table>
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<tr>
<th>Multipole Moments (ppm)</th>
<th>Norm</th>
<th>Skew</th>
</tr>
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<tbody>
<tr>
<td>Quad</td>
<td>-0.19</td>
<td>0.28</td>
</tr>
<tr>
<td>Sext</td>
<td>0.05</td>
<td>0.27</td>
</tr>
<tr>
<td>Octu</td>
<td>-0.07</td>
<td>0.25</td>
</tr>
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**June 25**

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<td>0.87</td>
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<td>-0.46</td>
<td>0.67</td>
</tr>
<tr>
<td>Octu</td>
<td>-0.86</td>
<td>0.36</td>
</tr>
<tr>
<td>Decu</td>
<td>0.24</td>
<td>0.08</td>
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RMS ~ 15 ppm (vs 40 at BNL)

Dipole moment

Averaged around azimuth

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A. Driutti (U. Udine & INFN)  
TAU2018 - Amsterdam, September 27, 2018
How we measure $\omega_a$

Injected polarized muons decay: $\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$:

$\Rightarrow$ high energy $e^+$ are emitted preferentially with electron momentum direction strongly correlated with $\mu^+$ spin (parity violation of the weak decay)

Counting the number of $e^+$ with $E_{e^+} > E_{\text{threshold}}$ as a function of time (wiggle plot) leads to $\omega_a$:

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

$E_{e^+}$ and $t$ are the measured observables.
Detectors for $\omega_\alpha$ Measurement

- The energy and hit time of the $e^+$ from the $\mu$ decay are measured by the 24 calorimeters positioned inside the ring.
Calorimeters

- Each calorimeter is composed of 6×9 PbF$_2$ crystals read out individually by large-area SiPMs.
- Calibration, time alignment, and gain stability for each of 1296 channels is provided by the laser calibration system.

- Custom pulse shapes for all crystals
- Relative time alignment to 5 ps
- > 5 ns beam pileup separation
- 20 ps timing resolution
- 3% resolution at 2.5 GeV
- Laser system provides gain stability to $10^{-4}$

A. Driutti (U. Udine & INFN) TAU2018 - Amsterdam, September 27, 2018
Methods to obtain $\omega_a$

- Multiple analysis techniques
  - Threshold (T) Method
  - Integrated Charge (Q) Method
  - Asymmetry Method
  - Energy-binned Method
  - Ratio (R) Method

- Two independent reconstruction routines to turn raw waveforms into energies and times
- Results hardware and software blinded
Advanced fitting algorithms accounting for systematics

Fit time spectrum of high-energy $e^+$ detected by calorimeters

T-method

Preliminary 5-parameter fit

$N_{\text{ideal}}(t) = N_0 \exp(-t/\gamma \tau_{\mu})[1 - A \cos(\omega_a t + \phi)]$

In-fill energy scale stability

Pileup events

Lost muons

Beam motion (CBO, etc)

T-method: FFT of fit residuals: Big improvements when accounting for CBO, lost muons,...

FNAL 5-parameter fit

14-parameter fit
Summary and Conclusions

- The experiment just finished the 1\textsuperscript{st} physics data taking: $\sim 2\times$BNL statistics (raw data) has already been collected!

- Measurements of $\omega_a$ and $\omega_p$ are becoming more mature: \textbf{goal of publishing in 2019} ($\sim 400$ ppb)!

- The ultimate goal is to measure $a_\mu$ with a precision of 140 ppb ($4\times$BNL precision).