Taking the Muon for a Spin

The Fermilab “Muon g-2” Experiment

Lawrence Gibbons
Cornell University
The goal:

The muon anomalous magnetic moment ($a_\mu$) to 0.14 ppm via spin precession

$$a_\mu = \frac{g - 2}{2}$$

$$\vec{\mu} = g \frac{q}{2m} \vec{S}$$

Dirac, relativistic QM (ie, tree level): $g = 2$

Loop corrections: $a_\mu > 0$

$a_\mu$ receives contributions
✓ from all SM particles
✓ from Beyond SM particles
The status of $a_\mu$:

\[ a_\mu = 11659208.0(5.4)(3.3) \times 10^{-10} \quad [0.54 \text{ ppm}] \]

Bennet et al, PRD 73072003 (2006)
Why improve $a_{\mu}$

...when $a_e = 1159652180.73(28) \times 10^{-12}$ (0.3 ppb)?

Hanneke, Fogwell, and Gabrielse, PRL 100, 120801 (2008)

Magnetic moment: interaction flips helicity

$\rightarrow a_\ell$ sensitivity scales like $(m_\ell/m_X)^2$

$\rightarrow (m_\mu/m_e)^2 \rightarrow 40,000x$ increase in sensitivity

- must know SM corrections
- Beyond SM sensitivity!
  
  compensates for 1000x reduced precision
The spin on $a_\mu$

Standard Model Evaluation of $a_\mu$

- **QED:** $a_\mu(QED) = 11\,658\,471.8951(80) \times 10^{-10}$
  - $O\left([\alpha/\pi]^5\right)$ Aoyama, Hayakawa, Kinoshita and Nio, PRL 109, 111808
  - 12,000+ diagrams!
  - far better than we need

- **Electroweak:** $a_\mu(EW) = 15.4(2) \times 10^{-10}$
  - probing EW was E821’s goal
  - to 2 loops

and...
...hadronic contributions

Hadronic Vacuum polarization (LO and NLO)

\[ a_\mu (HVP, LO) = \left( \frac{\alpha m_\mu}{3\pi} \right)^2 \int \frac{ds}{m_\pi^2} \frac{R(s) K(s)}{s^2} \]

\[ R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \]

measured (low s) or pQCD (high s)

Slowly varying: 0.63 \rightarrow 1

heavily weights to low \( E_{CM} \)

Jegerlehner, Nyffeler
Phys Rept 477, 1 (2009)
...hadronic contributions

Hadronic Vacuum Polarization (LO and NLO)

many new and anticipated inputs:

Typical result:

\[ a_\mu(HVP,LO) = 685.8(4.6) \times 10^{-10} \]
\[ a_\mu(HVP,NLO) = -9.98(10) \times 10^{-10} \]

Benayouna, Davida, DelBuonoa, Jegerlehner, EPJ C72, 1848 (2012)
...hadronic contributions

Hadronic light by light

• nonperturbative, but higher order
• estimated via modeling + e.g., 2-photon data
• will soon be dominant uncertainty
• KLOE-2 will constrain with new $\gamma^*\gamma^*$ data at low $Q^2$

$a_\mu(\text{HLxL}) = 11.6(4.0) \times 10^{-10}$
Prades, de Rafael, Vainshtein

• size ~ NLO HVP
• lattice calculations under way (10% in ’17 feasible)
Combining it all...

- experiment vs SM

$$\Delta a_\mu \sim (33 - 38) \pm 8.3$$

- deviation remains > 3.5 $\sigma$

- $\Delta a_\mu > 2 \cdot a_\mu^{\text{EW}}$

  - If new physics, why haven’t we seen it?

- $a_\mu$ sensitive to ratio coupling / mass scale

Good agreement among various $a_\mu^{\text{SM}}$ assessments

Benayouna, Davida, DelBuonoa, Jegerlehner, EPJ C72, 1848 (2012)

Outlook $(5.1 \rightarrow 3) \times 10^{-10}$ on prediction circa 2017

- No $\rho$-$\gamma$ mixing correction in $\tau$ data

- Coupling $\ll G_F$

- Masses $\gg M_Z$

(hiddden sectors)
Beyond Standard Model

generally: \[ \delta a_\mu(\text{N.P.}) = \mathcal{O}(C) \left( \frac{m_\mu}{M} \right)^2, \quad C = \frac{\delta m_\mu(\text{N.P.})}{m_\mu} \]

classify new physics: \textit{C} very model-dependent

\[ \mathcal{O}(1) \] radiative muon mass generation \ldots

[Cheung, Keung, Yuan '07]

\[ \mathcal{O}(\frac{\alpha}{4\pi}) \ldots \]

supersymmetry (\text{tan} \beta), unparticles

[Cheung, Keung, Yuan '07]

\[ \mathcal{O}(\frac{\alpha}{4\pi}) \]

extra dim. (ADD/RS) \((n_c)\ldots\)

[Davioudasli, Hewett, Rizzo '00]

[Cheung, Keung, Yuan '07][Park et al '01][Kim et al '01]

\[ \mathcal{O}(\frac{\alpha}{4\pi}) \]

\(Z', W', \text{UED, Littlest Higgs (LHT)}\ldots\)
implies the bound on the parameter itself, cannot lead to any instability. The instability for large $	an\beta$ is expected for the supersymmetric part of the potential. The points are obtained through the analysis described in Refs. [30–33].

\[ \Delta a_{\mu} \approx 150 \times 10^{-10} \left( \frac{\tan\beta}{10} \right) \left( \frac{(100 \text{GeV})^2}{\mu M_{\text{wino}}} \right) \]

\[ \Delta a_{\mu} \approx 15 \times 10^{-10} \left( \frac{\tan\beta}{10} \right) \left( \frac{(100 \text{GeV})^2}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2 / \mu M_{\text{bino}}} \right) \]

Giudice, Paradisi, Strumia 2012
(SUSY w/ light staus)

Contributions affect both $a_{\mu}$ and $h \rightarrow \gamma\gamma$

Split spectra, large Higgsino Mass, …

\[ \rightarrow \text{consistent w/ LHC, large } a_{\mu} \text{ contrib's} \]
Taking the muon for a spin

Fermilab E989 “Muon g - 2”

Goal:
\[ a_\mu \text{ to } < 0.14 \text{ ppm} \]

BNL E821 stat’s limited
bring collaboration
+ its experience
+ its ring to FNAL

Deliver 21x the \( \mu \)'s
Taking the muon for a spin

Fermilab E989 “Muon g - 2”

Goal:

$\alpha_\mu$ to < 0.14 ppm

BNL E821 stat’s limited
bring collaboration
+ its experience
+ its ring to FNAL

Deliver 21x the $\mu$’s

150 Members
34 Institutions
7 Countries
Taking the muon for a spin

The principles: motion in B field, V-A

- cyclotron: \[ \omega_C = B \frac{e}{m_\mu c \gamma} \]
- spin precession: \[ \omega_s = B \frac{g_\mu}{2} \frac{e}{m_\mu c} + B \frac{e}{m_\mu c} \left( \frac{1}{\gamma} - 1 \right) \]

Thomas Larmor

\( g = 2 \)

\( g \neq 2 \)
Taking the muon for a spin

The principles: motion in B field, V-A

- cyclotron: \[ \omega_C = B \frac{e}{m_\mu c \gamma} \]
- spin precession: \[ \omega_s = B \frac{g_\mu}{2} \frac{e}{m_\mu c} + B \frac{e}{m_\mu c} \left( \frac{1}{\gamma} - 1 \right) \]

\[ g = 2 \]
\[ g \neq 2 \]
Taking the muon for a spin

The principles: motion in B field, V-A

- **cyclotron:** \[ \omega_C = B \frac{e}{m_\mu c} \frac{1}{\gamma} \]
- **spin precession:** \[ \omega_s = B g_\mu \left( \frac{e}{2 m_\mu c} + B \frac{e}{m_\mu c} \left( \frac{1}{\gamma} - 1 \right) \right) \]
- **relative precession:** \[ \omega_s - \omega_C = B \frac{e}{m_\mu c} \left( \frac{g_\mu}{2} - 1 \right) \]

\( g = 2 \quad g \neq 2 \)

\( a_\mu! \)

\( E_e \longrightarrow E_{\text{th}} \)
Taking the muon for a spin

The principles: motion in B field, V-A

- **cyclotron:** \( \omega_C = B \frac{e}{m_\mu c} \frac{1}{\gamma} \)

- **spin precession:** \( \omega_s = B \frac{g_\mu}{2} \frac{e}{m_\mu c} + B \frac{e}{m_\mu c} \left( \frac{1}{\gamma} - 1 \right) \)

- **relative precession:** \( \omega_a = B \frac{e}{m_\mu c} \left( \frac{g_\mu}{2} - 1 \right) \)

\( g = 2 \) vs \( g \neq 2 \)

Million events per 149.2 ns

<table>
<thead>
<tr>
<th>Time modulo 100 µs</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Million events</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

TABLE II. Running periods, total number of electrons recorded

<table>
<thead>
<tr>
<th>Run</th>
<th>Period (µs)</th>
<th>Total Electrons</th>
<th>Electrons per 149.2 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>R00</td>
<td>1000</td>
<td>100 Million</td>
<td>100 Million per 149.2 ns</td>
</tr>
<tr>
<td>R01</td>
<td>1000</td>
<td>1 Million</td>
<td>1 Million per 149.2 ns</td>
</tr>
<tr>
<td>R02</td>
<td>1000</td>
<td>1 Million</td>
<td>1 Million per 149.2 ns</td>
</tr>
<tr>
<td>R03</td>
<td>1000</td>
<td>1 Million</td>
<td>1 Million per 149.2 ns</td>
</tr>
</tbody>
</table>

FIG. 2. Distribution of electron counts versus time for the FIG. 2. Distribution of electron counts versus time for the...
Taking the muon for a spin

Producing 21x the muons:

- ~12x μ / proton yield
- ~3x repetition rate:
  - only ~3-5x BNL instantaneous rate and ~1 year of protons

<table>
<thead>
<tr>
<th>parameter</th>
<th>BNL</th>
<th>FNAL</th>
<th>gain factor FNAL/BNL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y_π pion/p into channel acceptance</td>
<td>≈ 2.7E-5</td>
<td>≈ 1.1E-5</td>
<td>0.4</td>
</tr>
<tr>
<td>L decay channel length</td>
<td>88 m</td>
<td>900 m</td>
<td>2</td>
</tr>
<tr>
<td>decay angle in lab system</td>
<td>3.8 ± 0.5 mr forward</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>δp_π/p_π pion momentum band</td>
<td>±0.5%</td>
<td>±2%</td>
<td>1.33</td>
</tr>
<tr>
<td>FODO lattice spacing</td>
<td>6.2 m</td>
<td>3.25 m</td>
<td>1.8</td>
</tr>
<tr>
<td>inflector</td>
<td>closed end</td>
<td>open end</td>
<td>2</td>
</tr>
<tr>
<td>total</td>
<td>11.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Taking the muon for a spin

Producing 21x the muons:

- ~12x $\mu$ / proton yield
- ~3x repetition rate:
  ⇒ only ~3-5x BNL instantaneous rate and ~1 year of protons

Side benefit:
 reduced hadronic flash = improved systematics!

<table>
<thead>
<tr>
<th>parameter</th>
<th>BNL</th>
<th>FNAL</th>
<th>gain factor FNAL/BNL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_\pi$ pion/p into channel acceptance</td>
<td>$\approx 2.7E-5$</td>
<td>$\approx 1.1E-5$</td>
<td>0.4</td>
</tr>
<tr>
<td>L decay channel length</td>
<td>88 m</td>
<td>900 m</td>
<td></td>
</tr>
<tr>
<td>decay angle in lab system</td>
<td>$3.8 \pm 0.5 \text{ mr}$</td>
<td>forward</td>
<td>2</td>
</tr>
<tr>
<td>$\delta p_\pi/p_\pi$ pion momentum band</td>
<td>$\pm 0.5%$</td>
<td>$\pm 2%$</td>
<td>1.33</td>
</tr>
<tr>
<td>FODO lattice spacing</td>
<td>6.2 m</td>
<td>3.25 m</td>
<td>1.8</td>
</tr>
<tr>
<td>inflector</td>
<td>closed end</td>
<td>open end</td>
<td>2</td>
</tr>
<tr>
<td>total</td>
<td>11.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Taking the ring for a spin

- 6" clearance!
- 15 m diameter
- 1 mm vertical flex tolerance
The precision B field

~1 year to shim, independently,
- dipole
- quadrupole
- sextupole
The precision B field

Measurement + calibration of B:

• Pulsed NMR with free-induction decay yields proton Larmor precession $\omega_p$ in same B field

• Muon hyperfine normalizes (30 ppb)

Improvement highlights

• Extensive Opera modeling of B
• Improved building temp. control ($\pm 1^\circ$C)
• Improved shimming:
  • $\frac{1}{2}$ BNL gradient
  • Improved uniformity
• Improved magnet insulation
• Improved absolute calibration process
• More fixed probes
• Improved trolley position accuracy

0.17 ppm $\rightarrow$ 0.07 ppm uncertainty
Measuring $\omega_a$

24 Calorimetry stations (E and t)
- 9x6 (2.5x2.5) cm PbF$_2$ array ($X_0 = 0.93$ cm)
- Silicon Photomultipliers
- 500 MSPS waveform digitizers

Improvements over E821
- Improved gain control and laser monitoring
- Pileup suppression via segmentation
- entire $\mu$ fill digitized, transferred to DAQ
  - opens new analysis methods
  - better gain systematic control
- reduced pion “flash”

$\omega_a$ systematics: $0.18 \rightarrow 0.07$ ppm
Tracking

Straw tubes in vacuum in front of 2 PbF$_2$ arrays

- stereo angle: ±7.5° from vertical
- Improved diagnostics
  - identify pileup sample
  - identify lost muon sample
  - E/p calibration
- muon EDM measurement (tips precession plane)
  - $d_\mu<1.8\times10^{-19}$ e-cm $\rightarrow$ few $10^{-21}$

N. Pohlman
Summary / Status

Expected beam + incremental measurement improvements:

$\rightarrow a_\mu$ to $\pm 0.1\,(\text{stat}) \pm 0.07\,(\omega_p) \pm 0.07\,(\omega_a)$

Detector funding in hand

- NSF Major Research Instrumentation for calo+daq
- DOE Early Career for straw chambers

Ring has been transferred BNL $\rightarrow$ Fermilab

DOE Critical Decision - 1 review next week

- proceed to technical design
- technically-driven schedule: beam in 2016
- funding-driven schedule: beam in 2017-2018 (?)