News from Fermilab: 50+ years; g-2; Planck scale

Chris Stoughton
"It only has to do with the respect with which we regard one another, the dignity of men, our love of culture. It has to do with those things. It has to do with, are we good painters, good sculptors, great poets? I mean all the things that we really venerate and honor in our country and are patriotic about. It has nothing to do directly with defending our country except to help make it worth defending." — Robert R. Wilson, answering Congress' question on how the new accelerator will affect the nation's security.
A brief history of Fermilab: $b, t, \nu_\tau, \text{Higgs}$

The comprehensive version:
http://50.fnal.gov/
Theoretical Astrophysics Group (Schramm, Turner, Kolb)
Sloan Digital Sky Survey
Dark Energy Camera
South Pole Telescope 3G
Future: DESI, LSST, CMB-S4
The next 50+

- PIP-II: 1 MW@120 GeV
- Direct Detection of Dark Matter:
  - ADMX
  - SuperCDMS
  - LUX-ZEPLIN
  - SENSEI
Muon Campus – Fermilab’s Back yard
Spin and Magnetic Moment

"g" is the Gyromagnetic Ratio:

Classical: \( g = 1 \)  
[Stern-Gerlach (1922)]

Pauli: \( g = 2 \) for (isolated) point particle (1928)

Otto Stern: \( g = 5.6 \) for proton (1933)

Rabi, and Stern \( g = -3.8 \) for neutron (1934+)

Kusch & Foley \( e = 2.00238 \) for electron (1948)

Schwinger \( 2(1 + \alpha/\pi) \) (1948)

Garwing, Lederman, Weinrich \( 2.01 \pm 0.4\% \) (1957)

Cern I 4300 ppm (1965)

Cern II 270 ppm (1968)

Cern III 7 ppm (1979)

BNL 0.54 ppm (1999)

FNAL Goal: 0.140 ppm
Measure $g$ directly

Muon spin rotation ($\mu$SR)

$N(t) = N_0 e^{-t/\tau} [1 + A_\mu \cos (\omega t + \phi)]$

(Rest frame) Parity violation prefers positron emitted in the muon spin direction

$g = 2m\omega/eB$
So, why bother?

Convenient to deal with the “anomalous magnetic moment”

$$a = \frac{g - 2}{2}$$

Muon g-2: Theory (2018)

<table>
<thead>
<tr>
<th>Contribution</th>
<th>$a_\mu$ Value (x 10^{-11})</th>
</tr>
</thead>
<tbody>
<tr>
<td>QED (Tenth-order)</td>
<td>116 584 718.95 ± 0.08</td>
</tr>
<tr>
<td>Hadronic VP (lo) [DHMZ-17]</td>
<td>6 931 ± 34</td>
</tr>
<tr>
<td>Hadronic VP (lo) [KNT-18]</td>
<td>6 933 ± 25</td>
</tr>
<tr>
<td>Hadronic VP (nlo) [DHMZ-17]</td>
<td>-98.7 ± 0.7</td>
</tr>
<tr>
<td>Hadronic VP (nlo) [KNT-18]</td>
<td>-98.2 ± 0.4</td>
</tr>
<tr>
<td>Hadronic VP (nnlo)</td>
<td>12.4 ± 0.1</td>
</tr>
<tr>
<td>Hadronic LbL (lo + nlo)</td>
<td>101 ± 26</td>
</tr>
<tr>
<td>Electroweak</td>
<td>153.6 ± 1.0</td>
</tr>
<tr>
<td>Total SM [DHMZ-17]</td>
<td>116 591 818 ± 43</td>
</tr>
<tr>
<td>Total SM [KNT-18]</td>
<td>116 591 821 ± 36</td>
</tr>
</tbody>
</table>


Courtesy of Kim Siang Khaw
Use a muon storage ring

Principle of Muon g-2 experiment

In π center of mass reference frame, the ν and μ spins are aligned with their momentum vectors.

In lab frame, select high momentum μ for 90% polarization.
Positron from muon decay aligned with spin

In muon CM, positron direction tends to align with muon spin:  
\[ 1 + A_\mu \cos \theta / 3 \]

Positrons get additional boost if \( P_\mu \) and \( S_\mu \) are aligned

Positrons get less boost if \( P_\mu \) and \( S_\mu \) are not aligned

Calorimeter would see a Time-varying Positron Energy Distribution with frequency \( \omega_a = \omega_s - \omega_c \).
Detect positron from muon decay

Principle of Muon g-2 experiment

The “wiggle” plot

$\omega_a = \alpha_{\mu} \frac{eB}{m}$

- $\sim 0.23$ MHz
- $\sim 4.37$ $\mu$s

measure difference in frequency precisely
Extracting $a_\mu$

CODATA 2017

$\alpha_{\mu}^{\text{Exp}} = \frac{g_e}{2} \frac{\omega_a}{\tilde{\omega}_p} \frac{m_\mu}{m_e} \frac{\mu_p}{\mu_e}$

-0.001 519 270 380(5) [3 ppb]  
Hydrogen Maser

0.0037072064(20) [540 ppb]  
E821

-2.002 319 304 361 82(52) [0.26 ppt]  
Electron g-2 + QED

206.768 2826(46) [22 ppb]  
Muonium Hyperfine Structure

Note: the B field is not here directly. We sample the B field with protons in NMR probes to calibrate.
pNMR probes: trolley, fixed, plunging

\[ \tilde{\omega}_p \]

- **Trolley** runs inside the beam pipe to map periodically the field by a set of pNMR probes: 1 run of ~3h is performed every 3d
- A set of 378 fixed probes are located in 72 locations in azimuth
Track muon locations in storage ring
Convolve B with muon distribution

\[ \tilde{\omega}_p \]

Measure B using pNMR probes
Mechanically adjust steel
Coils adjust dipole
Thermally control steel

**NMR map of field**

Instrument 2 stations with straw tubes
“\(u\),”\(v\)” planes
Trace back to tangent

**Muon distribution**
UCL Team

Gleb

Matt & Erdem

Samer

Mark

Becky
- High-energy positrons tend to follow muon spin direction in rest frame; consider boost to lab frame:

- T method: accept pulses > 1.86 GeV threshold that maximizes $\sqrt{N_A}$
- Q method: total energy vs. time

Positrons detected in 24 calorimeters around inner circumference of ring.
Fermilab Muon g-2 Collaboration
Production Run 1, 22-25 Apr 2018
PRELIMINARY, no quality cut

Spectrum from ~60 hours of stable running over 4 days
Calorimeter gain stability established to ~few x $10^{-4}$

Test Beam Data

$10^{-4}$ / h demonstrated

State-of-the-art Laser-based calibration system also allows for pseudo data runs for DAQ
Calorimeters: pulse separation in space and time

- 24 calorimeters
- Each segmented into 9x6 array of PbF$_2$ Cerenkov crystals.
- Instrumented with silicon photomultiplier (MPPC) arrays.
- Continuously digitized with 800 MSPS sampling.
- Pulses selected and recorded by algorithms in online GPU (graphics processing unit) cluster.

Typical ~3 GeV decay positron event
Overlapping pulses (“pileup”)

Higher energy positrons have longer flight time and therefore different phase.

If two 1.4 GeV positrons add up to one 2.8 GeV count, they have the wrong phase by \(\sim 15\) ns = \(\sim 20\) mrad. The proportion of these events decreases over the fill.

Early-to-late phase shift alters the fitted frequency.
Experiment uses a weak focusing muon storage ring.

\[ \omega_a = \text{anomalous precession frequency} \]
\[ \omega_s = \text{spin precession frequency} \]
\[ \omega_c = \text{cyclotron frequency} \]

\[ \vec{\omega}_a \approx \vec{\omega}_s - \vec{\omega}_c \approx -\frac{q}{m} \left[ a_\mu B - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right] \]

0 when \( \gamma = 29.3 \Rightarrow p_\mu = 3.094 \text{ GeV/c} \)

Horizontal And Vertical Tunes:
\[ v_x \approx \sqrt{1 - n} \]
\[ v_y \approx \sqrt{n} \]

Vertical Focusing Electric Quadrupole Field

Scraping sets bottom, Q2 inner, and Q4 outer plates to ±13.1 kV.

Two corrections to “Wiggle Plot”

\[
\bar{\omega}_a = \frac{e}{mc} \left[ a_\mu \bar{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \bar{\beta} \times \bar{E} - a_\mu \left( \frac{\gamma}{\gamma + 1} \right) \left( \bar{\beta} \cdot \bar{B} \right) \bar{\beta} \right]
\]

1. E-field Correction : 0.25-0.5 ppm (depending on kicker voltage)
   - position uncertainty / misalignment of quad plates
   - deviation of beam from equilibrium radius / magic momentum

2. Pitch Correction : 0.25 ppm
   - due to (small) vertical betatron oscillation

BNL had O(10%) uncertainties on these corrections
Momentum Distribution

Equilibrium radius (mean = 7117.3 mm, peak = 7112.5 mm)

Beam Momentum Distribution is wider than previous experiment.

Potentially requires larger corrections.

Problem will be fixed by improving the kick strength.
Coherent Betatron Oscillations

- “Swimming” and “breathing” motions caused by focusing a beam that only fills part of the phase space
- Stroboscopic observation at $\omega_{\text{CBO}} = \omega_x - \omega_c$
- Possible interference between $\omega_{\text{CBO}}$ and $2\omega_a$
- Quadrupole voltage now limited (18.3 kV) by vacuum: running at “low-n” solution with $\omega_{\text{CBO}} < 2\omega_a$. (Intend to raise to 32 kV for “high-n” with $\omega_{\text{CBO}} > 2\omega_a$.)
One of the Systematic Errors: Muons Lost from Storage Ring

- Muons that get kicked out by the collimators and punch through calorimeters (MIPs) during measurement

- Need to determine: how many muons are lost, and where they originated

- The loss rate is time dependent and needs to be incorporated in the muon precession frequency fit

How do we detect them?

- Muons can pass through many calorimeters without stopping

3 GeV muons (MIPs) deposit of order 200 MeV as they pass through a calorimeter
One of the Systematic Errors: Muons Lost from Storage Ring

Use energy, position, and time to identify “lost muon” events

Coincidence time window between two consecutive calorimeters

MIPs move radially inward when going from 1st Calorimeter to 2nd Calorimeter
Lost muon signal useful for tuning injection parameters, e.g. inflector, quad scraping, kicker settings and radial field

Fractional Muon Losses as a function of time under different scraping voltages

- Run 8596+8597, 6 kV scraping
- Run 8598+8599, 4.5 kV scraping
- Run 8601+8604, 3 kV scraping

Sudeshna Ganguly
<table>
<thead>
<tr>
<th>Category</th>
<th>E821 [ppb]</th>
<th>E989 Improvement Plans</th>
<th>Goal [ppb]</th>
</tr>
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<tbody>
<tr>
<td>Gain changes</td>
<td>120</td>
<td>Better laser calibration</td>
<td>20</td>
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<tr>
<td></td>
<td></td>
<td>low-energy threshold</td>
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<tr>
<td>Pileup</td>
<td>80</td>
<td>Low-energy samples recorded</td>
<td>40</td>
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<td></td>
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<td>calorimeter segmentation</td>
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<tr>
<td>Lost muons</td>
<td>90</td>
<td>Better collimation in ring</td>
<td>20</td>
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<tr>
<td>CBO</td>
<td>70</td>
<td>Higher $n$ value (frequency)</td>
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<tr>
<td></td>
<td></td>
<td>Better match of beamline to ring</td>
<td>&lt; 30</td>
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<tr>
<td>$E$ and pitch</td>
<td>50</td>
<td>Improved tracker</td>
<td>30</td>
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<tr>
<td></td>
<td></td>
<td>Precise storage ring simulations</td>
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<tr>
<td>Total</td>
<td>180</td>
<td>Quadrature sum</td>
<td>70</td>
</tr>
</tbody>
</table>
Scientific collaboration

US Universities
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois
- North Central
- Regis
- UT Austin
- Virginia
- Washington

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma 2
- Trieste
- Udine

England
- Lancaster
- Liverpool
- University College London

Korea
- CAPP/IBS
- KAIST

China
- Shanghai

Germany
- Dresden

Russia
- JINR/Dubna
- Novosibirsk

7 countries
34 institutions
~185 authors

• National Labs
- Argonne
- Brookhaven
- Fermilab

Financial support
...with substantial contributions from funding agencies in China, Germany, Italy, Russia, South Korea, and the United Kingdom.
8 Countries, 35 Institutions, 190 Collaborators

Fermilab Muon g-2 Collaboration
\[ [X_i, X_j] = iX_k \epsilon_{ijk} \ell'_P \]
See also:

Statistical Model of Exotic Rotational Correlations in Emergent Space-Time arXiv:1607.03048
Inflation with Spooky Correlations arXiv:1811.03283
Quantum-enhanced correlated interferometry for fundamental physics tests arXiv:1810.13386