The Fermilab Muon g-2 Experiment

Mark Lancaster

UCL
Aim of Experiment

Make a 0.14 ppm measurement

- Electron (g-2)
- Muon (g-2) [FNAL] 0.14 ppm
- Muon (g-2) [BNL] 0.54 ppm
- $G_F (\tau_\mu)$
- $M_Z$
- $M_W$
- $M_{TOP}$

Precision (in PPM)
Motivation

Comparison of SM & BNL Measurement

Present measurement is at odds with SM at 3.5\(\sigma\) level.

A 0.14 ppm measurement moves this to more than 5\(\sigma\)

\[ a_\mu (\text{SM}) - a_\mu (\text{BNL}) \]

Fermilab Muon g-2 Experiment
Interest in this result

3rd most cited paper in experimental particle physics

BNL E821: 2757 total citations

# Citations per year

Fermilab Muon g-2 Experiment

Mark Lancaster : Discrete 2014 : p3
New physics as: \[ \left( \frac{m_\ell}{M_{\text{NEW}}} \right)^2 \]

Muon sensitivity to BSM in 20 MeV (e.g. dark photons) to TeV region

Electron presently limited to BSM contributions from \( m < 100 \text{ MeV} \)
Measurement probes much of the same TeV-scale BSM landscape as LHC.

- **Large +ve anomaly wrt SM**
  - Extended technicolor (fermion masses)
  - SUSY (natural, gauge-mediated, compressed), RS ED
  - $Z'$, $W'$, Little Higgs, Universal ED

Value consistent with SM
BNL anomaly (if real) would be expected to produce a direct observable in 14 TeV LHC data in most TeV-scale models.

In this case the g-2 measurement can resolve degeneracy in model parameters & improve their determination e.g. tanβ.
pMSSM Models

Mastercode collaboration arXiv:1410.6755

Fermilab Muon g-2 Experiment
pMSSM Models

Sampling of pMSSM phase space

Dark photons

Dark photon contribution of $280\pm80 \times 10^{-11}$ to $a_\mu$. 
New results from NA48
How to achieve 0.1 ppm

“Never measure anything but frequency”

I. Rabi
Spin Equation

Measure rate at which muon spin turns relative to momentum vector

\[ \omega_a = \omega_s - \omega_c \]

This is determined by \((g-2)\) and the EM fields and energy of the muon

\[ a_\mu = \frac{1}{2} (g - 2) \]

FNAL/BNL approach: effect of focusing E-field cancelled by using “magic” 3.09 GeV momenta muons.

J-PARC approach: 300 MeV beam with very low transverse momenta requiring no E-field to focus.
Two measured quantities: $\omega_a$ and $B$

$B$ is measured using NMR in terms of the proton Larmor frequency: $\omega_p$

$$a_\mu = \frac{\omega_a / \omega_p}{\lambda_+ - \omega_a / \omega_p} ; \quad \lambda_+ = \frac{\mu_{\mu^+}}{\mu_p}$$

$\lambda_+$ measured from muonium hyperfine structure

Uncertainty in $a_\mu$ determined by precision of $\omega_p$ and $\omega_a$ measurements
Inject 3.09 GeV muons into a storage ring (B = 1.45 T)

Exploit property that direction of $e^+$ from $\mu^+$ decay is strongly correlated with $\mu^+$ spin for highest energy $e^+$

In g-2 experiment: cyclotron period is 149 ns

Spin precesses around momentum direction once every 30 turns (4.3 us)
The Small Move
The Big Move

Travel by barge:
- South along East Coast
- Around tip of Florida
- Northwest through Gulf of Mexico
- North through Mississippi River
- North through Illinois waterways

Atlantic Tropical Cyclone Activity

No tropical cyclones at this time

48-hour formation potential: Low <30%, Medium 30-50%, High >50%

Fermilab Muon g-2 Experiment

Mark Lancaster: Discrete 2014: p17
The Big Move
Long Live The Risk Register
Lower Yoke installed
BNL → FNAL

\[54 \text{ (stat.)} \oplus 33 \text{ (syst.)} → 11 \text{ (stat.)} \oplus 11 \text{ (syst.)} \] \times 10^{-11}

0.54 ppm → 0.14 ppm

**Chart:**

- **BNL wrt SM**
- **FNAL g-2 Uncertainty**
- **HADRONIC**
- **EWK**
- **\(\alpha^5\)**
- **\(\alpha^4\)**
- **\(\alpha^3\)**
- **\(\alpha^2\)**
- **\(\alpha\)**

**Contribution to \(a_\mu\):**

- **QED**
- **\(10^{-12}\)**
- **\(10^{-11}\)**
- **\(10^{-10}\)**
- **\(10^{-9}\)**
- **\(10^{-8}\)**
- **\(10^{-7}\)**
- **\(10^{-6}\)**
- **\(10^{-5}\)**
- **\(10^{-4}\)**
- **\(10^{-3}\)**
- **\(10^{-2}\)**
Seven FNAL g-2 improvements

- More \( \mu \) per proton
- Lower inst. rate
- Fewer pions

Unique capabilities of FNAL accelerators

- Improved detectors
- Improved stored muon beam dynamics
- Improved field uniformity, field measurement & calibration
- Improved modeling of beam & detectors

New / improved technologies
- Additional collaborators
- Building on wealth of experience from BNL E821 & other expts
To provide x20 more muons at lower inst. rate with much reduced pion contamination compared to BNL.

Proton accelerator modifications (Recycler & Booster)

Old Pbar complex being re-configured to provide muons. aka “The Delivery Ring”
Many of these modifications are also required by Mu2e
Accelerator Requirements

- 4 proton pulses of $10^{12}$ @ 8 GeV separated by 10ms (av rate 12 Hz)
- pulse duration to be less than cyclotron period (149ns)

- dispersion in pion momentum < 2%
- long pion decay beamline

Re-uses much of current infrastructure but requires new beamlines, kickers, power supplies, controls etc

Each $10^{12}$ proton pulse results in $\approx 16,000$ stored 3.09 GeV muons in g-2 ring
Accelerator Modifications

Lens tested at required 12 Hz rate
Schedule is funding-constrained.
Beamlines will be ready for operation in April 2017.
Final challenge: reduce systematics by factor of ~3.

B-field systematic ($\omega_p$) from 0.17 ppm -> 0.07 ppm
Precession systematic ($\omega_a$) from 0.2 ppm -> 0.07 ppm

Many aspects to achieving this:

- New, improved detectors, calibration & readout systems
- Improved beam stability/monitoring e.g. new kicker
- Improved calibration/shimming/readout of B-field
- End to end simulation of both accelerator, storage ring and detectors
Improvements to injection system

Baseline: existing BNL inflector but new design under R&D

Inflector Magnet

μ⁺

Q1

Q4

Q3

Q2

7.1 cm

7.1 m

Kicker magnets

New with improved kick

Focussing quads

Collimators

New and with sensors

New with sensors

Fermilab Muon g-2 Experiment
Improvements to injection system

Injection, beam orbit / stability important to:

- minimise muon losses
  - maximise statistics
  - minimise impact of losses that are time dependent

- minimise corrections to the “spin equation”
  - vertical betatron oscillations mean: \( v.B \neq 0 \) (aka “pitch correction”)
  - \( \pm 15 \) MeV variance in beam momentum (aka “E-field correction”)

- ensure beam traverses known/consistent path in B-field
Inflector system
Nulls 1.45 T field at point of injection
Static and non ferromagnetic
Cannot leak flux into storage ring

Both magnet and shield

BNL Inflector

R&D into an open-end design:
- less scattering
- x2 more muons
- better matched
Two double (truncated) $\cos \theta$ magnets that trap their own flux.

New conductor under R&D at FNAL
New Kicker

BNL kicker pulse

Ideal kicker pulse

No (or known) eddy currents during measurement period (30us after injection)

No ferrite materials that can affect the storage ring field
New Kicker Magnet

Blumlein double transmission line to form the pulse into the kicker plate

Stronger field between plates with reduced field at edge of plots
Provide vertical focussing of beam

4 (non-ferrite) metal plates under HV

Influences:

- # lost muons
- E field correction
- $\omega_p$ (orbit distortion)

Dipole B-field & quadrupole E-field means beam undergoes **SHM (betatron) oscillations** in vertical and radial direction.

Radial : affects detector acceptance.
Vertical : lowers $\omega_a$ since $v.B \neq 0$ (pitch correction)
Avoid resonances & minimise CBO impact

Increase “n” by increasing quad field

E989 goal

E989: 32kV

E989: n=0.18

SHM (CBO) frequency
\[
\frac{\Delta \omega_a}{\omega_a} = -2 \frac{\beta E_r}{c B_y} \left( \frac{\Delta p}{p_m} \right) = -2 n (1 - n) \beta^2 \langle x_e^2 \rangle R_o^2
\]

<table>
<thead>
<tr>
<th>( \Delta p/p (%) )</th>
<th>( Q ) position</th>
<th>( E )-field</th>
<th>( B_y ) (ppm)</th>
<th>( C_E ) (ppm)</th>
<th>( \Delta ) (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>perfect</td>
<td>pure quad</td>
<td>0</td>
<td>0</td>
<td>0.01</td>
</tr>
<tr>
<td>0.25</td>
<td>perfect</td>
<td>pure quad</td>
<td>0</td>
<td>2.74</td>
<td>3.0</td>
</tr>
<tr>
<td>0</td>
<td>perfect</td>
<td>m-poles</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>0.25</td>
<td>perfect</td>
<td>m-poles</td>
<td>0</td>
<td>2.74</td>
<td>8.7</td>
</tr>
<tr>
<td>0.25</td>
<td>( Q_{1x} = 0.3 ) mm</td>
<td>pure quad</td>
<td>10 \cos(\phi)</td>
<td>2.74</td>
<td>3.5</td>
</tr>
<tr>
<td>0.25</td>
<td>( Q_{1x} = 0.3 ) mm</td>
<td>pure quad</td>
<td>0</td>
<td>2.74</td>
<td>8.7</td>
</tr>
<tr>
<td>0.25</td>
<td>( Q_{1x} = 0.3 ) mm</td>
<td>m-poles</td>
<td>0</td>
<td>2.74</td>
<td>17.8</td>
</tr>
<tr>
<td>0.25</td>
<td>( Q_{3x} = 0.3 ) mm</td>
<td>m-poles</td>
<td>10 \cos(\phi)</td>
<td>2.74</td>
<td>22.1</td>
</tr>
<tr>
<td>0.25</td>
<td>( Q_{1x} = 0.3 ) mm</td>
<td>m-poles</td>
<td>10 \cos(\phi)</td>
<td>2.74</td>
<td>33.9</td>
</tr>
</tbody>
</table>

0.03 ppm is FNAL aim. BNL achieved 0.065 ppm
Quad affect on “pitch correction”

Smaller than E-field correction but again requires precise alignment of quads
Again it systematically lowers $\omega_a$

<table>
<thead>
<tr>
<th>$A_y$ (mm)</th>
<th>$Q$ position</th>
<th>$E$-field</th>
<th>$B_r$ (ppm)</th>
<th>$C_P$ (ppm)</th>
<th>$\Delta$ (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>perfect</td>
<td>pure quad</td>
<td>0</td>
<td>0</td>
<td>0.006</td>
</tr>
<tr>
<td>41.2</td>
<td>perfect</td>
<td>pure quad</td>
<td>0</td>
<td>1.51</td>
<td>3.5</td>
</tr>
<tr>
<td>40.7</td>
<td>perfect</td>
<td>m-poles</td>
<td>0</td>
<td>1.47</td>
<td>6.5</td>
</tr>
<tr>
<td>41.0</td>
<td>perfect</td>
<td>m-poles</td>
<td>-10</td>
<td>1.50</td>
<td>7.5</td>
</tr>
<tr>
<td>40.7</td>
<td>$Q_{1y} = 0.3$ mm</td>
<td>m-poles</td>
<td>0</td>
<td>1.47</td>
<td>8.0</td>
</tr>
<tr>
<td>41.2</td>
<td>$Q_{1y} = 0.3$ mm</td>
<td>pure quad</td>
<td>0</td>
<td>1.51</td>
<td>6.2</td>
</tr>
<tr>
<td>41.1</td>
<td>$Q_{1y} = 0.3$ mm $Q_{3y} = -0.3$ mm</td>
<td>pure quad</td>
<td>0</td>
<td>1.50</td>
<td>8.8</td>
</tr>
</tbody>
</table>

$A_y$ : Amplitude of vertical betatron oscillation
ω_p systematics need to be reduced by a factor of 2.5

Better run conditions, e.g. temperature stability.

Improved shimming of magnetic field to high uniformity

Smaller stored muon distribution

Hardware and simulation improvements
B-field measurement

300+ NMR probes in vacuum tank walls

17 movable NMR probes on a trolley

Map field at 6,000 locations every 2 hrs (vs 2 days BNL)

Much improved temp. control
B-field measurement

Bar codes every 2.5mm to track location of trolley

Large bore solenoid now at ANL to test all NMR components to better than 20 ppb.
Syst. from lost muons, CBO, E & pitch-corrections : mitigated by quads, ring but detectors provide the input / diagnostics

Detectors also the key in the other $\omega_a$ systematics & provide the “money-plot”

Key systematics to control:
- Gain changes
- Pileup
\( \omega_a \) measurement

- 24 \((\text{PbF}_2 + \text{SiPM})\) calorimeters
- 3 \([9 \text{ (u,v) planes}]\) straw trackers

Fermilab Muon g-2 Experiment
Working prototypes of both detector systems
Final versions of the detectors to be constructed in 2015/16.
We select positrons above $E = 1.86$ GeV: maximises sensitivity.
11% of positrons are above threshold and detected (~ 2k/fill)
The measurement of $\omega_a$ can be simply plotted as the time of positrons above threshold and performed a 5-parameter fit, given by:

$$N(t) = N_0 \exp\left(-\frac{t}{\gamma\tau}\right) \left[1 - A \cos(\omega_a t + \phi)\right]$$

The GEANT-4 RING + DETECTOR SIMULATION results are as follows:

- $N_0 = 1.277 \pm 0.004 \times 10^5$ ppm
- $\tau = 6.424 \pm 0.003 \times 10^4$ s
- $A = 0.4223 \pm 0.0006$
- $R = 10.24 \pm 17.25$
- $\phi = 1.894 \pm 0.002$

The difference $\omega_a(\text{meas}) - \omega_a(\text{MC})$ in ppm is shown.
Calorimeter:
- more segmented.
- x2 sampling (800M/s) vs BNL
- quicker response (5 ns)
- improved energy resolution

Tracker:
- authenticate pileup
- measure muon profile
- measure EDM
Particularly attention is being paid to gain of calorimeter.

Improved wrt to BNL through: better temperature control & much reduced hadronic-flash negating the need for gated operation
<table>
<thead>
<tr>
<th>FY14</th>
<th>FY15</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
<th>FY19</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **g-2 Cryo Plant (AIP)**  
- **Ring Assembly**  
- **Shim Field**  
- **Prep Chambers/Install**  
- **Construct/Install Sub-systems / Detectors**  
- **Accelerator Modifications**  
- **Ring Cold ready for operations**  
- **Experiment ready for operations**  
- **Accelerator ready for operations**  
- **Ring Cold**  
- **Detector/DAQ Commission**  
- **Beam Tune-up**  
- **Physics Production Running**  
- **Analysis Tools Development**  
- **Mock Data**  
- **1st Results**  
- **2nd Results**  
- **1-2 x BNL statistics**  
- **~5-10 x BNL**  
- **Final Results**
“If you enjoy doing difficult experiments, you can do them, but it is a waste of time and effort because the result is already known” : Pauli

"No experiment is so dumb, that it should not be tried” : Gerlach
Muon EDM in two BSM models.

BSM predictions range from: $10^{-21}$ to $10^{-28}$
Essentially zero in SM: any observation is new physics.

Muon is the only 2nd flav. gen. measurement and it’s free of nuclear / molecular effects.

BNL limit is $1.8 \times 10^{-19}$

Can quickly be improved by x10 and ultimately x100 to $10^{-21}$

If there are non mass-scaling BSM effects then $10^{-21}$ becomes competitive.

Measurement can only be performed using the tracking detectors.
### B-field / $\omega_p$ systematics

<table>
<thead>
<tr>
<th>E821 Error</th>
<th>Size [ppm]</th>
<th>Plan for the E989 $g - 2$ Experiment</th>
<th>Goal [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute field calibrations</td>
<td>0.05</td>
<td>Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics</td>
<td>0.035</td>
</tr>
<tr>
<td>Trolley probe calibrations</td>
<td>0.09</td>
<td>Absolute cal probes that can calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations</td>
<td>0.03</td>
</tr>
<tr>
<td>Trolley measurements of $B_0$</td>
<td>0.05</td>
<td>Reduced rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients</td>
<td>0.03</td>
</tr>
<tr>
<td>Fixed probe interpolation</td>
<td>0.07</td>
<td>More frequent trolley runs; more fixed probes; better temperature stability of the magnet</td>
<td>0.03</td>
</tr>
<tr>
<td>Muon distribution</td>
<td>0.03</td>
<td>Additional probes at larger radii; improved field uniformity; improved muon tracking</td>
<td>0.01</td>
</tr>
<tr>
<td>Time-dependent external B fields</td>
<td>—</td>
<td>Direct measurement of external fields; simulations of impact; active feedback</td>
<td>0.005</td>
</tr>
<tr>
<td>Others</td>
<td>0.10</td>
<td>Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients</td>
<td>0.05</td>
</tr>
<tr>
<td>Total</td>
<td>0.17</td>
<td></td>
<td>0.07</td>
</tr>
<tr>
<td>E821 Error</td>
<td>Size [ppm]</td>
<td>Plan for the E989 $g - 2$ Experiment</td>
<td>Goal [ppm]</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------</td>
<td>------------------------------------------------------------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>Gain changes</td>
<td>0.12</td>
<td>Better laser calibration; low-energy threshold; temperature stability; segmentation to lower rates; no hadronic flash</td>
<td>0.02</td>
</tr>
<tr>
<td>Lost muons</td>
<td>0.09</td>
<td>Running at higher $n$-value to reduce losses; less scattering due to material at injection; muons reconstructed by calorimeters; tracking simulation</td>
<td>0.02</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.08</td>
<td>Low-energy samples recorded; calorimeter segmentation; Cherenkov; improved analysis techniques; straw trackers cross-calibrate pileup efficiency</td>
<td>0.04</td>
</tr>
<tr>
<td>CBO</td>
<td>0.07</td>
<td>Higher $n$-value; straw trackers determine parameters</td>
<td>0.03</td>
</tr>
<tr>
<td>E-Field/Pitch</td>
<td>0.06</td>
<td>Straw trackers reconstruct muon distribution; better collimator alignment; tracking simulation; better kick</td>
<td>0.03</td>
</tr>
<tr>
<td>Diff. Decay</td>
<td>0.05¹</td>
<td>better kicker; tracking simulation; apply correction</td>
<td>0.02</td>
</tr>
<tr>
<td>Total</td>
<td>0.20</td>
<td></td>
<td>0.07</td>
</tr>
</tbody>
</table>
Fourier Transform of the residuals from a 5-parameter fit (from 1 detector).

CBO means B.β not zero and adds frequency component to $\omega_a$. 
Hadronic Corrections

**Hadronic Vacuum Polarisation (HVP)**

- 0.36 ppm

**Hadronic Light-by-Light (HLBL)**

- 0.22 ppm

Reducing this 0.42 ppm to ensure 0.14 ppm FNAL measurement has maximum impact is a high priority.
Is this hadronic estimate reliable?

97% of the hadronic estimate is **data-driven** and it can now be cross checked by the measured Higgs Mass

\[
a_{HVP}^{(LO)} = \frac{1}{4\pi^3} \int_{4m_Z^2}^{\infty} K(s)\sigma(s) ds
\]

\[
\Delta \alpha^{(5)}_{HAD}(M_Z) = \frac{M_Z^2}{4\alpha\pi^2} P \int_{4m_Z^2}^{\infty} \frac{\sigma(s)}{M_Z^2 - s} ds
\]

This HVP value (+ other EWK data) gives

\[
M_H = 94^{+29}_{-34} \text{ GeV}
\]

Assume HVP is wrong by 6 \(\sigma\) (so BNL = SM)

\[
M_H = 68^{+29}_{-34} \text{ GeV}
\]

Use \(M_H = 125\) GeV for HVP **increases significance** of BNL discrepancy wrt SM