The g-2 Experiment at Fermilab

Magnetic dipole moments lead to spin precession.

**Classical Picture**

**Quantum Picture**

Dirac Equation for EM potential:

\[ i \left( -i \gamma^\mu \frac{e}{2m_\mu c} \right) \gamma^\mu = 0 \]

- Spin-1/2 point particles
- Leads to Pauli Theory
- Predicts \( g = 2 \)

Larmor Precession (particle rest frame):

\[ \frac{d \vec{s}}{dt} = \vec{\tau} = g \left( \frac{q}{2m} \right) \vec{s} \times \vec{B} \]

**Quantum Field Theory Picture**

**Vacuum Effects Matter:**

Anomaly:

\[ a \left( \frac{g}{2} \right)^2 \]

- Predicts \( g \neq 2 \)
The Standard Model determination of $a_\mu$

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{had, VP}} + a_\mu^{\text{had, LbL}} + a_\mu^{\text{BSM??}}$$

**QED**

1-loop + 2-loop + ... Known to five-loop (12,672 diagrams)

99.99% of $a_\mu^{\text{SM}} \sim 0.001\%$ of $\delta a_\mu^{\text{SM}}$

**EW**

$\gamma^a)$ + $W^b)$ + $Z^c)$ Known to two-loop (with $m_H$ known)

0.0001% of $a_\mu^{\text{SM}} \sim 0.2\%$ of $\delta a_\mu^{\text{SM}}$

**HVP**

Non-perturbative (data input + lattice)

0.006% of $a_\mu^{\text{SM}} \sim 47\%$ of $\delta a_\mu^{\text{SM}}$

**HLbL**

Non-perturbative (data input + model/lattice)

0.0001% of $a_\mu^{\text{SM}} \sim 53\%$ of $\delta a_\mu^{\text{SM}}$

**BSM**

?? ?? ?? ?? ?? ??

Sensitivity of muons to new physics is $\sim \frac{m_\mu^2}{m_e^2} \sim 40,000$ greater than electrons.
The discrepancy between the latest SM prediction and the result from the Brookhaven experiment (E821) is greater than $3\sigma$.

The discrepancy can be expressed as:

$$\alpha^\text{exp}_\mu - \alpha^\text{SM}_\mu = 26.85 (7.26) \times 10^{-10} > 3\sigma$$

The new result from E989 is 140 ppb, while E821 has an error of 540 ppb.

If central value persists, achieving the Fermilab design error will give a $7\sigma$ difference.
1) Inject polarized muon source

The muons circulate with an angular frequency:

$$\omega_c = \frac{eB}{\gamma m}$$
Muon Spin Dynamics in a Storage Ring.

Muon spin precesses in the vertical external magnetic field of $B = 1.45$ Tesla (Larmor Precession).

$$\omega_a = \frac{d\theta}{dt}$$

Muon spin precession relative to momentum in cyclotron is directly proportional to $a_\mu$

$$\omega_a = \omega_s - \omega_c = \left(\frac{g}{2} - 1\right) \frac{eB}{m} = a_\mu \frac{eB}{m}$$

Measure two quantities in $g$-2
We would like to use electrostatic quadrupoles for vertical focussing of the muon beam.

This introduces an extra term into the formula for $\omega_a$:

$$\omega_a = \frac{e}{m} \left\{ a_\mu B - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\beta \times E}{c} \right\} \sim 0$$

Use muons of specific momentum such that $\gamma = \gamma_{magic} = \sqrt{1 + \frac{1}{a_\mu}} = 29.3$

Muon momentum = 3.094 GeV. Lifetime dilated to $\sim 64.4$ µsecs.
Decay positron distribution in the muon rest frame

\[
\frac{d^2N}{dE \, d \cos(\theta)} \propto N(E)[1 + A(E) \cos(\theta)]
\]

The highest energy positrons are emitted in the direction of the muon spin.
Decay positron distribution in the lab frame

As the spin vector rotates relative to the momentum vector the decay positron energy distribution alters:

Can use the observed number of decay positrons above some energy threshold to measure $\omega_a$:
Spin Precession in g-2 Ring

- Higher energy positrons emitted preferentially in direction of muon spin
- Threshold Energy Cut in calorimeters
- Results in sinusoidally oscillating energy deposition

**Fraction of e\(^+\) above Threshold**

Result from E821 Brookhaven experiment.
What g-2 actually measures.

It is possible to rearrange \( a_{\mu} = \frac{\omega_a m_{\mu}}{eB} \) in terms of precisely known ratios:

The g-2 experiment then measures \( \omega_a \)
and \( \omega_p \) (measure the magnetic field via precession of free protons)

\[ a = \frac{2 m_e}{m_e} \frac{g_e}{a} \]

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

Fermilab Experiment \( a_{\mu} \) total error goal is 140 ppb
Increase statistics by a factor of > 20 and reduce systematics by a factor of ~3 w.r.t BNL experiment.

How to obtain a more precise measurement.

- **More beam!!!**
- **Better Uniform Magnetic Field!!!**
- **Better** $\omega_\alpha$ **measurement !!!**
The goal of the Fermilab experiment is to reduce the systematic error on \( \omega_a \) \( 180 \rightarrow 70 \text{ ppb} \)

- Improved Calorimeters
- New Laser control system
- New Tracker to give accurate beam profile and position.

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

**Key element:**
- Laser
- Calo + Laser
- Inflector + Kicker
- Tracker

Largest improvement
<table>
<thead>
<tr>
<th>Category</th>
<th>E821 [ppb]</th>
<th>Main E989 Improvement Plans</th>
<th>Goal [ppb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute field calibration</td>
<td>50</td>
<td>Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics</td>
<td>35</td>
</tr>
<tr>
<td>Trolley probe calibrations</td>
<td>90</td>
<td>Plunging probes that can cross-calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations</td>
<td>30</td>
</tr>
<tr>
<td>Trolley measurements of $B_0$</td>
<td>50</td>
<td>Reduced position uncertainty by factor of 2; improved rail irregularities; stabilized magnet field during measurements*</td>
<td>30</td>
</tr>
<tr>
<td>Fixed probe interpolation</td>
<td>70</td>
<td>Better temperature stability of the magnet; more frequent trolley runs</td>
<td>30</td>
</tr>
<tr>
<td>Muon distribution</td>
<td>30</td>
<td>Additional probes at larger radii; improved field uniformity; improved muon tracking</td>
<td>10</td>
</tr>
<tr>
<td>Time-dependent external magnetic fields</td>
<td>–</td>
<td>Direct measurement of external fields; simulations of impact; active feedback</td>
<td>5</td>
</tr>
<tr>
<td>Others †</td>
<td>100</td>
<td>Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients</td>
<td>30</td>
</tr>
<tr>
<td>Total systematic error on $\omega_p$</td>
<td>170</td>
<td></td>
<td>70</td>
</tr>
</tbody>
</table>
How to obtain a more precise measurement: Summary.

Systematic Uncertainties: Improvements Over E821

Reduce $\omega_a$ systematic uncertainties by a factor of 3

<table>
<thead>
<tr>
<th>E821 Error</th>
<th>Size (ppb)</th>
<th>E809 Improvements</th>
<th>Goal (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain Changes</td>
<td>120</td>
<td>Better laser calibration; low-energy threshold, temperature stability, no hadronic flash</td>
<td>35</td>
</tr>
<tr>
<td>Lost Muons</td>
<td>90</td>
<td>Less scattering due to material at injection; muons reconstructed by calorimeters</td>
<td>30</td>
</tr>
<tr>
<td>Pileup</td>
<td>80</td>
<td>Low-E samples recorded; calor segmentation; trackers cross-calibrate pileup efficiencies</td>
<td>30</td>
</tr>
<tr>
<td>Coherent Betatron Oscillations</td>
<td>70</td>
<td>Higher n-value, straw trackers to determine parameters</td>
<td>10</td>
</tr>
<tr>
<td>E-field/pitch</td>
<td>60</td>
<td>Straw trackers to reconstruct muon distribution, better collimators, better kick</td>
<td>30</td>
</tr>
<tr>
<td>Diff. Decay</td>
<td>50</td>
<td>Better kicker, tracking simulation</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>200</td>
<td></td>
<td>70</td>
</tr>
</tbody>
</table>

Reduce $\omega_p$ systematic uncertainties by a factor of 2.5

<table>
<thead>
<tr>
<th>E821 Error</th>
<th>Size (ppb)</th>
<th>E889 Improvements</th>
<th>Goal (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field Calibration</td>
<td>50</td>
<td>Dedicated test solenoid, more probes, better electronics</td>
<td>35</td>
</tr>
<tr>
<td>Trolley Measurements</td>
<td>50</td>
<td>Reduced rail irregularities, field gradients</td>
<td>30</td>
</tr>
<tr>
<td>Fixed Probe Interpolation</td>
<td>70</td>
<td>More trolley runs, fixed probes: better temperature stability of magnet</td>
<td>30</td>
</tr>
<tr>
<td>Muon Convolution</td>
<td>30</td>
<td>Improved field uniformity, muon tracking</td>
<td>10</td>
</tr>
<tr>
<td>Time-Dependent Fields</td>
<td>–</td>
<td>Direct measurements of external fields, active feedback</td>
<td>5</td>
</tr>
<tr>
<td>Others</td>
<td>100</td>
<td>Improved electronics, reduced temperature dependence, kicker transients</td>
<td>50</td>
</tr>
<tr>
<td>Total</td>
<td>170</td>
<td></td>
<td>70</td>
</tr>
</tbody>
</table>
Fermilab is able to produce many more muons than Brookhaven
- ~ 20 times more statistics in the experiment.
Fermilab produces “better” muons
- much less pion contamination.
Coupled with improvements in the experiment design:
  - will measure $a_\mu$ to 0.14 ppm.
If the discrepancy persists should provide an ~ 7σ disagreement with the Standard Model.
Muon delivery to g-2

Muon Beam: From Protons to Muons

Recycler
- Rebunches 8 GeV protons from booster

Target Station
- Protons impinge upon Inconel target
- Focusing lens captures pions

Beam Transfer and Delivery
- Straight section: capture muons from forward-decaying pions (polarized)
- Remove protons by time-of-flight
  - Reduce number of pions and protons in ring

Characteristics
- Fill storage ring 16 times/1.4 sec (2x muons/fill compared to BNL)
- Expect 21x more statistics than BNL
Fermilab beamline decays away most of the pions.

8.89 GeV p beam impacts the target

3.1 GeV secondaries ($\pi$, $\mu$, $p$) travel along M2 & M3, where $\mu^+$ are collected from $\pi^+$ decays

$\mu^+$ are extracted from the ring and transferred into the storage ring via M5

After a few turns remaining $\pi^+$ convert to $\mu^+$

$\mu^+$ enter the g-2 storage ring
A pure muon beam of 3.094 GeV

Short batches of 8 GeV protons into Recycler
Each batch divided into 4 bunches each of $10^{12}$ protons.
Extract each bunch at a time and direct to target
$p/\pi/\mu$ beam enters DR; protons kicked out; pions decay away
$\mu$ enter storage ring (220 muons/fill achieved)
Fermilab Muon g-2 Collaboration ...

**US Universities**
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois
- Regis
- Texas
- Virginia
- Washington

**National Labs**
- Argonne
- Brookhaven
- Fermilab

**Italy**
- INFN
  - LNF Frascati,
  - Naples
  - Pisa
  - Roma 2
  - Trieste
  - Lecce

**England**
- Cockroft Institute
- Lancaster
- Liverpool
- University College London

**Korea**
- KAIST
- CAPP

**Russia**
- Dubna
- Novosibirsk

**China**
- Shanghai

**The Netherlands**
- Groningen

**Germany**
- Dresden (thy)
E989: The Fermilab g-2 Experiment.
IBMS: Beam monitors on entry to g-2 ring.

Just upstream of the inflector:

Scintillators provide map of temporal and transverse beam profile. Gives guidance on muon beam tuning.

Beam X, Y profiles at Inflector Beam Profile Monitor 1
Inflector.

- M5 magnetic quads do final focusing before injection into ring
- Inflector injects muons into ring while minimizing disturbance to B-field

Provides nearly field free region for muons to enter the ring. Muons exiting the inflector take a circle 77mm outward than needed for storage.

B = 1.45 Tesla
R = 7.112 m
τ_c = 149 ns
γτ = 64.4 μs
τ_a = 4.37 μs
New 1.7m long, 3 kicker magnets are used to kick the muons back into ideal orbit. Kickers give a 11 mrad bend to the muon beam. The kicker pulse has to be shorter than the cyclotron frequency, which is ~149ns.
• Muons focused vertically with electrostatic quadrupoles
Calorimeters.

Calorimeter Improvements:
6 × 9 segmented array of $PbF_2$ crystals (reduces pileup from 2 close low energy positrons).
Laser calibration system to ensure gain stability.
Better time synchronization with beam injection.
Segmented calorimeters provide spatial resolution that can be used to separate positron hits.

6 × 9 segmented array of PbF₂ crystals.

The above June 2017 commissioning data has large proton contamination: 60 p: 4 π: 1 μ.

Calorimeters measure decay positron energy and detector arrival time.

Calorimeter energy distribution: Dec. 2017 data

Crystals are 25×25×140 mm

The above June 2017 commissioning data has large proton contamination: 60 p: 4 π: 1 μ.
Calorimeters well understood both in data and simulations.

Used as online monitors of # of stored muons.

Commissioning data provided opportunity to:
- search for and correct mapping error
- Determine timing offsets between crystals
Calorimeter gain stability established to $\sim$ few $\times 10^{-4}$

Vital to ensure stability of the calorimeter response in order to avoid introducing varying acceptance as a function of time.

Achieved with a state-of-the-art laser-based calibration system.

Test Beam Data

$10^{-4}$ / h demonstrated
Straw Trackers.

- Main tool for beam position measurements:
  - CBO frequency, envelope, amplitude vs muon momentum
  - Pitch correction
  - B-field convolution

- Provides complementary information to calorimeters:
  - Gain, efficiency, pile-up
  - E-field correction (both fast rotation and directly at late times)
  - Lost muon tagging
3 Trackers were built in Liverpool for g-2. Each consists of 8 4-layer Straw Modules. Reconstruct trajectory and momentum of positrons from muon decays. Determine the muon decay point to reduce systematic errors on muon g-2 measurement. Tracker based muon EDM measurement.

Vacuum Tank + HV for Module Testing In Liverpool prior to shipping to FNAL.

4 layers of 32 straws, 7.5° stereo angle
Straw Trackers.

Beam profile is calculated in real time and available during data taking.
Straw Trackers.

- Track finding & fitting work well:

  - Straw Hit Resolution
    - Meas. Resolution = 165 μm
    - 165 μm c.f. req. of 250 μm

  - Tracker Wiggle Plot
    - p > 1.8 GeV
    - 60h Dataset

  - Tracker P vs. Calo E
    - Preliminary Calibration Run

  - Beam Position

  - Radial Mean vs Time (CBO)
    - Average Radial position [mm]

  - Vertical Mean vs Time (BO)
    - Fitted Vertical Mean [mm]
Fibre Harps also measure the beam profile.

Consist of 7 parallel scintillating fibres at 180 and 270 degrees around the ring. Horizontal and vertical detectors to measure radial and vertical beam profile. Retractable since they interfere with the muon beam during normal data taking.
The magnet completed its epic journey from Brookhaven to Fermilab in 2014. It was then reassembled and on initial turn on had a field non-uniformity of $\sim1400$ ppm. Then began a period of magnet shimming that culminated in a uniformity of $\sim25$ ppm by Sept 2016.
First stage of shimming: pole surface adjustments

- Blue was shimmed field at Brookhaven
- Red was starting point at Fermilab
Next: “top hats” and wedge shims

Blue: Brookhaven   Red: Fermilab
leaving azimuthal uniformity comparable to Brookhaven.

Blue: Brookhaven   Red: Fermilab
Final step: iron foil laminations

Blue: Brookhaven   Red: Fermilab

![Graph showing dipole measurements over time with labels for Brookhaven (blue) and Fermilab (red).]
requiring a different scale for the graph.

8000 iron shims inserted to achieve a uniformity of +/- 25ppm. (Sept 2016).

Blue: Brookhaven   Red: Fermilab
Magnetic Field measured with NMR.

Free-proton spin precession frequency $\omega_p$

Trolley can be pulled around storage ring when beam is not being delivered.

- Sample: petroleum jelly
- Deliver $\pi/2$ pulse to probe, induce & record the free-induction decay (FID)
- Extracted frequency precision: 10 ppb/FID

Time

Trolley matrix of 17 NMR probes

- Measure field in storage region during specialized runs when muons are not being stored
- Map the field every 3–4 days

Fixed probes on vacuum chambers

- Measure field while muons are in ring — 378 probes outside storage region
Magnetic Field Determination.

Field map from March 2018 (averaged over azimuth) Good to 1 ppm.
Determination of B field actually seen by the muon beam.

Obtain the muon beam distribution from the Straw Trackers.

Obtain the B field from NMR measurement probes.

Combine to obtain the actual magnetic field experienced by the muons.
Imagine that we could inject all our muons into the ring at $y = 0$ with no vertical momentum at all.

The muon stays perfectly horizontal until it decays:
• If we inject with a non-zero vertical momentum, the particle will oscillate due to the restoring force from the quad field

• Amplitude is related to incoming direction (momentum)
Radial case is a bit more complicated. Start with a horizontal muon pre-kick:
We need to kick the particle to stop it coming back round into the inflector:
Betatron Oscillations: Radial Case

- If kick is perfect, we end up on the magic orbit with no radial motion:
But we have many muon directions/momenta and we can’t kick them all perfectly:

Muons oscillate radially in/out
Betatron Oscillations: Radial Case

- But we have many muon directions/momenta and we can’t kick them all perfectly:

Muons oscillate radially in/out
What is CBO?

- Coherent **Betatron Oscillation** – movement of all muons together
- Muons all started at **similar position** (as they came through inflector)
- They have **same betatron frequency**, so there’s a coherent movement back and forth on average
- **Smeared out** by **different kicks** that each particle gets
- This is **washed out** over time due to the different **cyclotron frequencies** of different momenta (as with fast rotation)
- This is caused by both imperfect kick and because we can’t fill entire phase-space of ring at injection
But does this really happen?

- Yes! Here’s some data showing the radial CBO in a tracker:

**Station 12 - 3.50 us**

- Entries: 61187
- Mean: -4.912
- Std Dev: 24.48
- Underflow: 0
- Overflow: 0
- Integral: 5.119e+04

Why do we care? We will see that the wiggle plot is affected.
The recent physics run ended on July 7th.

The data so far.

The data so far.

Magnet reassembled
Magnet Shimming Complete
Detector Installation
Fix issues during commissioning run
1st Commissioning Run
Begin 2nd Commissioning Phase
Start blinded Production Running

Summer 2015
Summer 2016
May 2017
July 2017
October 2017
March 17th, 2018

Approximately twice the BNL dataset collected.

The data so far.
In principle, we perform a 5 parameter fit to the wiggle plot to extract \( \omega_a \). The analysis is blinded – I don’t know the result!

\[
dN / dt = N_0(t) e^{-\frac{t}{\tau}} [1 + A(t) \cos(\omega_a t + \phi_a(t))]\]

Residuals to the fit highlight the effects of systematics such as the CBO discussed earlier.
Why do we care about CBO and other systematics?

- Fraction of decay $e^+$ at detectors (acceptance) changes with CBO affecting $A(t)$ term. (Instability in the calorimeter gain would as well.)

- This shows up the wiggle plot and pulls our result for $\omega_a$:
  
  \[
  \Delta \omega_a \text{ if CBO uncorrected}
  \]

\[\Delta \omega_a \quad \text{10 ppm}\]
Anything leading to early/late variations in $A(t)$ and $\phi(t)$ have to be kept under control as they lead to a pull on $\omega_a$

$$\cos(\omega_a t - \phi) = \cos \left[ \omega_a t - \phi_0 - \frac{d\phi}{dt} t + O\left(\frac{d^2\phi}{dt^2}\right) \right]$$

$$= \cos \left[ \left(\omega_a - \frac{d\phi}{dt}\right) t - \phi_0 + O\left(\frac{d^2\phi}{dt^2}\right) \right]$$

$$= \cos \left[ \omega'_a t - \phi_0 + O\left(\frac{d^2\phi}{dt^2}\right) \right]$$

**Things that might change f(t):**

- Gain change.
- Pileup contamination (mixture of e+ having different average phases)
- Muon Loss with different average phases
- CBO (radial and vertical)
- Rate dependent energy and time reconstruction
The equation for the time derivative of the population is:

\[ \frac{dN}{dt} = N_0(t) e^{-\frac{t}{\tau}} \left[ 1 + A(t) \cos(\omega_a t + \phi_a(t)) \right] \]

Population at time \( t \):

\[ N_0(t) = N_0 \left[ 1 + A_N e^{-\frac{t}{\tau_{cbo}}} \cos(2\pi f_{cbo} t + \phi_N) \right] \]

Amplitude at time \( t \):

\[ A(t) = A \left[ 1 + A_A e^{-\frac{t}{\tau_{cbo}}} \cos(2\pi f_{cbo} t + \phi_A) \right] \]

Phase at time \( t \):

\[ \phi_a(t) = \phi_a + A_\phi e^{-\frac{t}{\tau_{cbo}}} \cos(2\pi f_{cbo} t + \phi_\phi) \]

FFT of Fit Residuals including BCO in fit.
The analysis is in full flow ..... We are busy analysing \( \sim 9 \times 10^9 \) recorded muon decays.

~60 hours of data yielding ~0.95 billion decay positrons

Final E989 goal is \( \sim 2 \times 10^{11} \) is muon decays.
Also important to measure vertical beam oscillations in the straw trackers. They contribute another term to $\omega_a$ if the dot product $(\beta \cdot B)$ is not zero:

$$
\omega_a = \frac{e}{m} \left\{ a_\mu B - a_\mu \left( \frac{\gamma}{\gamma + 1} \right) (\beta \cdot B) \beta \right\}
$$

We will add a small correction for this to the fitted $\omega_a$.

There is a similar small correction for muons that are off the magic momentum and are subject to the electric field from the quadrupoles.

Important to measure the momentum distribution and mean radius of the muon orbits. Again the Trackers are vital for this. Aim to keep uncertainty arising from each of these effects to $< 30$ ppb.
The Ratio Method for $\omega_a$

How the ratio method works:

$$N_5(t) = N_0 e^{-t/\tau} (1 + A \cos(\omega_a t + \phi))$$

$$u_+(t) = \frac{N_5(t + T/2)}{4}$$
$$u_-(t) = \frac{N_5(t - T/2)}{4}$$
$$v_1(t) = v_2(t) = \frac{N_5(t)}{4}$$

Randomly split positron time spectra into 4 sets, two with time spectra shifted up and down by half a g-2 period, and two unchanged. (Equal weighting corresponding to $1/4$ factors.)

$$N_5(t \pm T/2) = N_0 e^{-t/\tau} e^{\mp T/2\tau} (1 + A \cos(\omega_a t \pm \omega_a \frac{T}{2} + \phi))$$

$$T \approx \frac{2\pi}{\omega_a}$$
The Ratio Method for $\omega_\alpha$

Add the datasets separately:

$U(t) = u_+(t) + u_-(t)$

$V(t) = v_1(t) + v_2(t)$

$R(t) = \frac{V(t) - U(t)}{V(t) + U(t)}$

$R(t) = A \cos(\omega_\alpha t + \phi) - \frac{1}{16} \left( \frac{T}{\gamma \tau} \right)^2 + (h.o.)$

Exponential gets divided out – fit is now down to 3 parameters. Less sensitivity to slow effects which divide out.
Publication Plan

Planning on three generations of $a_\mu$ publications

- 1-2 x BNL (~400 ppb) collected in FY18 and aiming for publication by Summer 2019 conferences
- 5-10 x BNL (~200 ppb) collected over FY18+FY19 with publication by end of 2020...caveat that we now enter unknown regime
- 20+ x BNL (~140 ppb) collected by end of FY20 with final publication at end of 2021 or early 2022

Muon EDM and CPT/LV physics results in at least two generations
Several improvements foreseen for this summer, each contributing to increase the stored muons by 10-30%

Accelerator upgrades
- faster switching between MuonCampus-BeamTest
- New target
- Add wedges for beam momentum compaction

Ring upgrades
- Kicker: key upgrade for improving quality of stored beam.
- Quads: fix instabilities which cause Quads to run at HV lower than BNL (20kV vs 25kV)
- Inflector: install new inflector.

Summer Upgrades
Conclusions.

Fermilab experiment finished 1\textsuperscript{st} physics data run July 7\textsuperscript{th}.

Fermilab 1\textsuperscript{st} physics data set is $\sim 2 \times$ BNL data set with a goal of publishing in 2019.

Fermilab experiment has the ultimate goal of measuring muon g-2 $\sim 4$ times more precisely than the BNL experiment. Work is ongoing to drive down the systematics exploiting the improved detector.

Detector improvements taking place over the summer ready for next physics run.

Work continues on improving the precision of the SM muon g-2 prediction.

\begin{itemize}
    \item Needs final set of data quality cuts
\end{itemize}