The Muon g-2 experiment at Fermilab

Vladimir Tishchenko

Physics Department Summer Lectures, June 28, 2022
Content

- Recap of g-2 lecture W.M. Morse
- Principles of measurements
- Ring reassembly at Fermilab
- Magnetic field shimming
- Upgrades to the experiment
- First result of the Muon g-2 experiment at Fermilab
Recap

Muon

- Elementary particle
- Same electric charge as the electron
- Like the electron, behaves like it is intrinsically spinning
- Approximately 200 times heavier than an electron
- Lives about 2μs

The magnetic moment $\vec{\mu}$ of a muon is a vector along the spin $\vec{s}$: $\vec{\mu} = g \left( \frac{e}{2m} \right) \vec{s}$

where the proportionality constant (known as $g$-factor) relates the observed magnetic moment $\vec{\mu}$ of a particle to its spin $\vec{s}$

Dirac theory predicts $g = 2$: Quantum effects give additional contribution which arise from virtual particles, known and unknown:

$$g = 2(1 + a_\mu)$$

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

$$a_\mu \approx \frac{\alpha}{2\pi} \approx 0.001$$
all Standard Model particles contribute to $\alpha_\mu$

$$g_\mu = 2(1 + \alpha_\mu)$$

$\alpha_\mu$ can be predicted by Standard Model, very precisely.
It can also be measured, also very precisely.
Comparison between theory and experiment provides critical test of theory.
If measurement disagrees with theory …
all Standard Model particles contribute to \( \alpha_\mu \)

\[
g_\mu = 2(1 + \alpha_\mu)
\]

\( \alpha_\mu \) can be predicted by Standard Model, very precisely. It can also be measured, also very precisely. Comparison between theory and experiment provides critical test of theory. If measurement disagrees with theory it may indicate that there exist not yet known particles!

\[ \rightarrow \text{muons are } \left( \frac{m_\mu}{m_e} \right)^2 \sim 40,000 \text{ times more sensitive to New Physics than electrons!} \]
Brookhaven Muon g-2 ring, ca. 1995

\[
\begin{align*}
    a^\text{SM}_\mu &= 0.001 165 918 10 \ (43) \\
    a^\text{exp}_\mu &= 0.001 165 920 89 \ (63) \\
    \Delta a^\mu &= a^\text{SM}_\mu - a^\text{exp}_\mu \approx 3.7 \ \text{Standard Deviations}
\end{align*}
\]

Fermilab goal: improve experimental accuracy by a factor of four


transportation of coils from BNL to Fermilab

more photos and info: http://muon-g-2.fnal.gov/bigmove
muons in the laboratory

8 GeV primary p beam strikes Inconel target
3.1 GeV pions selected with Li lens
8 GeV protons
120-ns-long bunches
$10^{12}$ p/bunch
12 Hz rep. rate
magnet anatomy and $B$-field measurement

Brilliant magnet design by Gordon Danby (BNL)

1.45T superferric magnet

Shimmed to 50 ppm uniformity

$\sim$3x uniformity improvement

Oct 2015 to Aug 2016
Rough Shimming – lamination shims

- Lamination shims: small pieces of iron foil
- Predict foil mass required to make local adjustments of the B-field
- 8500 foils installed in total

laminations affixed to the pole surfaces

foils sorted by mass
spinning toy top wobbles around gravity force

\[ \vec{\omega} \] - angular momentum

\[ \vec{\omega}_s \] - angular momentum

\[ \vec{G} \] - force of gravity
magnetic moment wobbles around magnetic field

- toy top / gyroscope
- muon

- $\vec{G}$ - force of gravity
- $\vec{L}$ - angular momentum
- $\vec{B}$
- $\vec{\mu}$
- $\vec{S}$

torque: $\vec{\tau} = \vec{\mu} \times \vec{B}$

$\omega \sim (1 + a_\mu) B$

Larmor precession
magnetic moment wobbles around magnetic field

\[ \omega \sim (1 + a_\mu)B \]

magnetic moment can be deduced by measuring the wobbling frequency in a known magnetic field
muon – self analyzing polarimeter

decay electrons are highly correlated with muon spin

\[ \omega \sim (1 + a_\mu) B \]

the wobbling of muon spin in a magnetic field can be observed by detecting decay positrons / electrons
measurement of spin precession (wobbling) in a magnetic field

To measure $a_\mu$ to 1% we need to measure the frequency to 0.001%.
\[ g_\mu = 2 \quad \text{and} \quad a_\mu = 0 \]

Spin wobbles at the rate of momentum (velocity) vector rotation.
The spin of a muon orbiting in a magnetic field rotates relative to momentum vector at the frequency of muon magnetic anomaly!

\[ g_\mu = 2(1 + a_\mu) \]

\[ \omega_a \sim a_\mu B \]

\[ \Delta a_\mu \sim \Delta \omega_a \]

1% 1%

factor of a 1000 gain in sensitivity!
in one turn around the ring the spin rotates by 12°
decay positrons are detected by 24 calorimeters
New calorimeters

- **Compact** based on fixed space
- **Non-magnetic** to avoid field perturbations

**Resolution** not too critical for $d\omega_a$
- Useful for pileup, gain monitoring, shower partitioning and low thresholds
- **Goal** $<5\%$ DE/E at $2\,\text{GeV}$ (a soft requirement)

**Gain stability** depends on electronics and calibration system
- **Goal**: Short term $<0.1\%$ DG/G in 600 ms
- **Goal**: Longer term $<1\%$ DG/G in 24 h

**Pileup** depends on signal speed and shower separation
- Subdivide calorimeter
- Use Cherenkov light
- **Goal**: 2-pulse separation by space: 2 out of 3
- **Goal**: 2-pulse separation by time: $D_t > 5\,\text{ns}$

1 Moliere R
2 Moliere R

Crystal Calorimeter

Platform for Electronics

No lightguides!

SiPM readout

PbF$_2$ crystals

X$_0=0.93\,\text{cm}$, R$_M=1.8\,\text{cm}$
is derived from a time histogram of high-energy $e^+$ decay events
is derived from a time histogram of high-energy $e^+$ decay events
detector counts undulated at anomalous precession frequency

\[ f_5(t) = N_0 \cdot e^{-t/\tau_\mu} \cdot [1 + A \cdot \cos(\omega_a \cdot t + \varphi_0)] \]
Superconducting Inflector

- creates a field-free channel for muon injection into the g-2 storage ring
superconducting inflector

- creates a field-free channel for muon injection into the g-2 storage ring
fast non-ferrick kickers

- steer the beam onto the design orbit
electrostatic quadrupoles

- contain the beam vertically
Positive and negative voltage potentials applied to the quadrupole plates create vertically focusing electrostatic quadrupole field.
electrostatic quadrupoles

as muons circulate around the storage ring, they slowly oscillate between the plates

one oscillation takes longer than one revolution around the ring
The ESQ system defines the operating point of muon g-2 storage ring, which must be chosen such that it is away from betatron and spin resonances. The theoretical analysis of resonance conditions was performed by BNL.

In 2018 run, the operation point of g-2 storage ring was chosen to minimize muon losses. The measured muon loss vs. ESQ voltage curve agrees well with theory expectation.

\[
\begin{align*}
\nu_x &= \frac{\omega_x}{\omega_c} \approx \sqrt{1 - n} \\
\nu_y &= \frac{\omega_y}{\omega_c} \approx \sqrt{n} \\
\nu_x^2 + \nu_y^2 &\approx 1 \\
n &= \frac{kR_0}{\nu B} \\
L\nu_x \pm M\nu_y \pm N &= 0 \text{ (betatron)} \\
L\nu_x + M\nu_y \pm N &= a_\mu \gamma \text{ (spin)}
\end{align*}
\]

where \(L, M, N\) are integers.

F.J.M. Farley, W.M. Morse, Y.K. Semertzidis E821 notes \# 106, 116, 149
coherent beam oscillations - observed in a fixed location in the storage ring
tracker detectors measure the beam oscillations
**Purpose:** measure the muon beam profile at multiple locations around the ring as a function of time throughout the muon fill. Is needed for quantifying systematic uncertainties associated with with $\omega_a$ measurements. Will also be used to search for a tilt in the muon precession plane away from the vertical orientation (which would be indicative of an EDM of the muon).

**Design:** 5-mm-diameter 10-cm-long straw UV doublets at 7.5°. Straw walls: 6 μm Mylar sense wires: 25 μm gold-plated tungsten at 1500 V gas: 80:20 Argon:CO$_2$ readout: ASDQ chips
beam oscillations lead to systematic effects

\[ f_5(t) = N_0(t) \cdot e^{-t/\tau_\mu} \cdot [1 + A(t) \cdot \cos(\omega_\alpha \cdot t + \varphi_0(t))] \]
Muon g-2 experiment in a nutshell

\[ \frac{d}{dt} (\vec{\beta} \cdot \hat{s}) = -\frac{e}{m} \vec{s}_\perp \cdot \left[ a_\mu \vec{\beta} \times \vec{B} + \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \vec{E} \right] \]

If \( E = 0 \) and \( \vec{\beta} \perp \vec{B} \):

\[ a_\mu = \frac{m}{e} \frac{\omega_\alpha}{B} \]

K1: \( a_\mu \) is determined by measuring the precession rate \( \omega_\alpha \) of spin \( \hat{s} \) relative to momentum \( \hat{p} \) in the magnetic field \( B \) of a storage ring.

Muons spin precession translates into energy oscillation of decay electrons in the laboratory frame.

K2: Muon spin precession signal is observed as a modulation of the time distribution of decay positrons by applying energy cut.

K3: Decay positrons are detected by 24 calorimeter detectors.

The magnetic field is measured by 378 fixed and 17 trolley NMR probes \( \rightarrow \omega_p \).
g-2 storage ring instrumentation

- calorimeter
- beam monitor
- electrostatic focusing quadrupoles
- storage ring instrumentation
- collimator
- Laser gain monitoring system
- Kickers
- Tracker 2
- Fiber Harp 270
- Tracker 1
- Fiber Harp 180
- DAQ
- Slow Control
- Laser control
- Laser Hut
determination

Correction for transient fields from pulsed ESQ and Kicker
Two different analysis methods
Two independent analysis teams
Total uncertainty: 114 ppb
\( a_\mu \) determination from data

\[
a_\mu = \frac{\omega_a}{\tilde{\omega}_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}
\]

22 ppb
hyperfine splitting of muonium CODATA

0.26 ppt
G. Gabrielse

10.5 ppb
\( \mu'_p(T_r) \) proton shielded in a spherical water sample at \( T_r = 34.7^\circ \) C

0.1 ppb
CODATA

\( \mu_e(H) \) electron bound in \( H \)
*Metrologia*, 13(4), 1977
systematic uncertainties in Run-1 at Fermilab

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Correction Terms</th>
<th>Uncertainty (ppb)</th>
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<tbody>
<tr>
<td>$\omega_a^m$ (statistical)</td>
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<td>434</td>
</tr>
<tr>
<td>$\omega_a^m$ (systematic)</td>
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<td>$C_e$</td>
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<td>$C_p$</td>
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<td>$C_{pa}$</td>
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<td>$f_{\text{calib}}(\omega_p(x,y,\phi) \times M(x,y,\phi))$</td>
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<td>56</td>
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<td>$B_k$</td>
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<tr>
<td>Total systematic</td>
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<tr>
<td>Total fundamental factors</td>
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<tr>
<td>Totals</td>
<td>544</td>
<td>462</td>
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</table>
Fermilab run 1 result (2021)

\[
 a_\mu (\text{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46 \text{ ppm}), \\
 a_\mu (\text{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35 \text{ ppm}).
\]

From top to bottom: Experimental values of \( a_\mu \) from BNL E821, FNAL E989 Run-1, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon \( g - 2 \) Theory Initiative recommended value for the Standard Model is also shown.

\[
 a_\mu (\text{FNAL}) - a_\mu (\text{SM}) = (230 \pm 69) \times 10^{-11} \quad (3.3\sigma) \\
 a_\mu (\text{Exp}) - a_\mu (\text{SM}) = (251 \pm 59) \times 10^{-11} \quad (4.2\sigma)
\]
All particles contribute to $\alpha_\mu$

$$g_\mu = 2(1 + \alpha_\mu)$$

$$\alpha_\mu = \alpha_{\mu}^{\text{QED}} + \alpha_{\mu}^{\text{W}} + \alpha_{\mu}^{\text{Had}} + \alpha_{\mu}^{\text{NP}}$$

- Electromagnetic
- Weak
- Hadronic
- + New Physics

<table>
<thead>
<tr>
<th>Source</th>
<th>value ($\alpha_\mu \times 10^{-11}$)</th>
<th>error</th>
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<tbody>
<tr>
<td>QED</td>
<td>116 584 718.93</td>
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<tr>
<td>HLBL</td>
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<td>18</td>
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</table>

Sensitivity to new particles: $\sim m^2$

$\rightarrow$ muons are $\left(\frac{m_\mu}{m_e}\right)^2 \sim 40,000$ times more sensitive to New Physics than electrons!
Muon g-2 Theory Initiative

Moving forward
Other efforts in the world – Muon g-2 at JPARC

- No electrostatic focusing
- Different systematics
  - very weak magnetic focusing, $n \sim 10^{-4}$
  - small emittance beam (0.3π mm-mrad)
  - all-magnetic storage ring, no $\vec{B} \times \vec{E}$ term

\[
\bar{\omega} = -\frac{e}{m} \left[ a_\mu \vec{B} + \frac{\eta}{2} \vec{B} \times \vec{B} \right]
\]

- $\bar{\omega}_\alpha$ and $\bar{\omega}_\eta$ are orthogonal and can be measured simultaneously
- stat. uncertainty goal: 450 ppb
- stage-2 approval: from IPNS – November, 2018 and IMSS – March, 2019
Summary

● Muons are elementary charged particles, similar to electrons but heavier.

● Muon’s charge in combination with muon’s spin generate magnetic moment – important characteristic of a particle.

● Muon’s magnetic moment can be calculated, very precisely, in the frame of Standard Model of Particle Physics.

● Muon’s magnetic moment can be measured, very precisely, by detecting decay electrons (positrons) in a known magnetic field.

● Muon’s magnetic moment is 40,000 times more sensitive to new particles compared to electrons.

● The Run-1 result of new experiment at Fermilab confirmed BNL measurement

● At present, there is a discrepancy between theory prediction and measurement at the level of ~4.2 standard deviations, which may indicate existence of new particles.