RESULTS FROM THE MUON G-2 EXPERIMENT IN THE LIGHT OF HADRONIC PHYSICS

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SHORT INTRO & MOTIVATION FOR MUON $g-2$
A PRIMER: MAGNETIC MOMENTS

\[ \hat{\mu} = g \frac{q}{2m} \vec{S} \quad a = \frac{g - 2}{2} \]

- Classical current loop in B field: \( g = 1 \)
- Stern-Gerlach and atomic spectroscopy: \( g_e \approx 2 \)
- Dirac theory of elementary spin-1/2 particle: \( g \equiv 2 \)
- Kusch and Foley: \( g_e = 2.00238(6) \neq 2 \)
- Schwinger’s blackboard: \( g_e = 2 + \alpha/\pi = 2.00232 \)
- Garwin (1957): \( g_\mu = 2.00 \pm 0.10 \) (±50,000 ppm)
- CERN I (1965): \( a_\mu = 0.001 \, 162(5) \) (±4,300 ppm)
MUONS IN A STORAGE RING (NO E FIELD YET)

- Cyclotron frequency:
  \[ \omega_c = \frac{e}{m \gamma} B \]

- Spin precession frequency:
  \[ \omega_s = \frac{e}{m \gamma} B \left(1 + \gamma a_\mu \right) \]
  Larmor + Thomas precession

\[ \vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = \frac{e}{m} \left(a_\mu \vec{B} \right) \]
MUONS IN B AND E FIELD

- In presence of additional E-field (neglecting $\beta \cdot B$ and EDM terms):

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

Magic momentum ($\gamma = 29.3$, $p = 3.094$ GeV/c)

E field for vertical focusing
CERN-III, BNL E821, Fermilab E989

No E field: $E = 0$
Weak magnetic focusing
J-PARC E34

- Measuring the anomalous moment $a_\mu$ requires both
  1. the spin precession frequency $\omega_a$
  2. the magnetic field $B$
THE BOTTOM LINE UPFRONT...

\[ a_\mu \times 10^9 = 116592040(54) \times 10^{-11} \quad (0.46 \text{ ppm}) \]

\[ a_\mu (\text{Exp}) = 116592061(41) \times 10^{-11} \quad (0.35 \text{ ppm}) \]
HOW ABOUT THEORY?
A LOT OF PROGRESS OVER THE LAST YEARS...

Second Plenary Workshop of the Muon g-2 Theory Initiative
18 June 2018 - 22 June 2018
In the coming years, experiments at Fermilab and at J-PARC plan to reduce the uncertainties on the already very precisely measured anomalous magnetic moment of the muon by a factor of four. The goal is to resolve the current tantalizing tension between theory and experiment of three to four standard deviations. On the theory side, the hadronic contributions to the anomalous magnetic moment are the dominant sources of uncertainty. They must be determined with better precision in order to unambiguously discover whether or not new physics effects contribute to this quantity.

There are a number of complementary theoretical efforts underway to better understand and quantify the hadronic corrections, including dispersive methods, lattice QCD, effective field theories, and QCD models. The Muon (g-2) Theory Initiative was formed in order to facilitate interactions between the different groups through organizing a series of workshops. The goal of the workshops is to bring together theorists from the different communities to discuss, assess, and compare the status of the various efforts, and to map out strategies for obtaining the best theoretical predictions for these hadronic corrections in advance of the experimental results.

Contact
Date: June 18, 2018 - June 22, 2018
Timezone: GMT+2
Location: Helmholtz-Institut Mainz
Staudingerweg 9, 55099 Mainz, Ground Floor
CURRENT DISCREPANCY BETWEEN
SM PREDICTION AND EXPERIMENT

\[ a_\mu = a_\mu^{\text{SM}} + a_\mu^{\text{QED}} + a_\mu^{\text{QCD}} + a_\mu^{\text{EW}} \]

\[ a_\mu^{\text{SM}} = 0.00116591810 \pm 0.000116592061 \]

Experimental value (FNAL + BNL)

\[ \delta a_\mu = (251 \pm 59) \times 10^{-11} \]

CURRENT RECOMMENDED VALUE FROM THE THEORY INITIATIVE

\[ a_\mu = a_\mu^{\text{QED}} + a_\mu^{\text{QCD}} + a_\mu^{\text{EW}} \]

\[ a_\mu^{\text{SM}} = 0.00116591810 (43) \]

- Hadronic contributions dominate theory uncertainty
- Two main methods for HVP and HLbL:
  - Dispersive, data driven approach using experimental cross-sections
  - Lattice QCD calculations
Dominant contributions (~75% of total) well quantified with ~6% uncertainty
Ongoing work on subleading contributions, which dominate current uncertainty
Lattice QCD and new dispersive approach: <10% uncertainty by 2025 possible
Hadronic light-by-light scattering not expected to solve overall discrepancy
• Theory WP 2020 used conservative merging procedure using data driven approaches only: $a_{\mu}^{hvp,LO} = (693.1 \pm 4.0) \times 10^{-10}$ [0.6%]
• Lattice QCD average: $a_{\mu}^{hvp,LO} = (711.6 \pm 18.5) \times 10^{-10}$ [2.6%]
• Lots of current work ongoing to understand possible discrepancy, comparison of intermediate time regions
• Data-driven approach can reach 0.3% by ~2025 (BaBar, SND, CMD-3, BESIII, …)
• If Lattice results are consistent, then <0.5% possible by 2025
OVERVIEW OF THE E989 MUON g-2 EXPERIMENT AT FERMILAB
FERMILAB ACCELERATOR COMPLEX: 20 TIMES MORE MUONS

Some key ingredients:
- Long beamline to collect muons from pion decay
- Reduced hadronic flash
- 4x higher fill frequency than at BNL
MUON INJECTION & STORAGE: STORAGE RING MAGNET

- Superconducting magnet at 1.45T
- Shim toolkit:
  - 48 top / bottom hats to tune dipole
  - 800 wedge shims to tune dipole
  - edge shims to tune quad and sextupole
  - About 9000 iron foils to fine tune field
- Power supply feedback to stabilize dipole
- 200 tunable coils to shim average multipoles

Achieved ~2.5 better homogeneity than BNL
MUON INJECTION & STORAGE: INFLECTOR MAGNET

- Inflector cancels main field for muon injection through yoke
- Muons injected with 77mm offset from ideal orbit
MUON INJECTION & STORAGE: KICKER MAGNET

- 3 kicker magnets change muons’ trajectories onto stored orbits
- Deliver pulse in <149 ns (muon revolution time)
MUON INJECTION & STORAGE: ELECTROSTATIC QUADRUPOLES

- Main B field provides radial focusing
- Four electrostatic quadrupoles for vertical focusing
- Also used to scrape the beam after injection
- Added a new RF system to reduce coherent betatron oscillation

Quadrupole plates
MEASURING THE MUON SPIN PRECESSION: CALORIMETER & LASER CALIBRATION

- 24 calorimeter stations detect the muon decay positrons:
  - 54 PbF2 crystals per station
  - SiPM readout
  - 800 MSPS digitization

- Laser calibration system:
  - Each crystal receives laser pulse
  - Demonstrated gain corrected to $10^{-4}$/h
MEASURING THE MAGNETIC FIELD: NUCLEAR MAGNETIC RESONANCE PROBES

- 378 NMR probes in 72 stations track the field drift
- One field mapping trolley with 17 NMR probes to map field in storage region
- Water-based calibration probe to provide an absolute reference
MEASURING THE MUON DISTRIBUTION: STRAW TRACKERS

- 2 in-vacuum straw trackers:
  - 8 modules per tracker
  - 4 layers with 32 straws per module
  - 50:50 Ar:Ethane
  - ~100µm resolution

- Measurement of the muon distribution and handle on beam dynamics
A VIEW INSIDE THE VACUUM CHAMBERS

Video editing: Simon Corrodi
MEASURING $\omega_a$ AND $\tilde{\omega}'_p$:

THE BIG PICTURE
MEASURING THE MAGNETIC FIELD USING PROTON NUCLEAR MAGNETIC RESONANCE

\[ \omega_a = \frac{e}{m_\mu} a_\mu B \]

\[ \mu_e = g_e \frac{e \hbar}{4m_e} \]

\[ B = \frac{\hbar \omega_p(T)}{2 \mu_p(T)} \]

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

Determined by the experiment

\( \omega_a \) Anomalous spin precession frequency

\( \tilde{\omega}'_p(T_r) \) Larmor frequency of shielded proton in spherical water sample weighted by the muon distribution

<p>| | |</p>
<table>
<thead>
<tr>
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<th></th>
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</thead>
<tbody>
<tr>
<td>( \mu'_p(T_r) )</td>
<td>Magnetic moment ratio of proton in spherical water sample at ( T_r = 34.7 \text{C} ) and electron in hydrogen known to ( 10.5 \text{ ppb} ) [Metrologia 13, 179 (1977)]</td>
</tr>
<tr>
<td>( \mu_e(H) )</td>
<td></td>
</tr>
<tr>
<td>( \frac{\mu_e(H)}{\mu_e} )</td>
<td>Bound-state QED correction (exact) [CODATA]</td>
</tr>
<tr>
<td>( \frac{m_\mu}{m_e} )</td>
<td>Mass ratio known from muonium hyperfine splitting experiment and QED to ( 22 \text{ ppb} ) [PRL 82, 711 (1999)]</td>
</tr>
<tr>
<td>( \frac{g_e}{2} )</td>
<td>Electron g-factor known from quantum cyclotron spectroscopy to ( 0.38 \text{ ppt} ) [PRA 83, 052122 (2011)]</td>
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</tbody>
</table>
SO HOW DO WE REALLY MEASURE $\frac{\omega_a}{\tilde{\omega}_p(T_r)}$
SO HOW DO WE REALLY MEASURE $\frac{\omega_a}{\tilde{\omega}_p'(T_r)}$

$$\alpha_\mu = \frac{\omega_a}{\tilde{\omega}_p'(T_r)} \frac{\mu_p'(T_r) \mu_e(H)}{\mu_e} \frac{m_\mu g_e}{m_e 2}$$

Measured g-2 frequency

$$\frac{\omega_a}{\tilde{\omega}_p'(T_r)} \approx \frac{\omega_a^m}{\omega_a^m}$$
SO HOW DO WE REALLY MEASURE $\frac{\omega_a}{\tilde{\omega}_p(T_r)}$

Measured g-2 frequency

$\frac{\omega_a}{\tilde{\omega}_p(T_r)} \approx \frac{\omega_a^m}{\omega_a} \leq \omega_p(x, y, \phi)$

Magnetic field
SO HOW DO WE REALLY MEASURE $\frac{\omega_a}{\tilde{\omega}'_p(T_r)}$

Measured g-2 frequency

$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} \approx \frac{\omega^m_a}{\langle \omega_p(x, y, \phi) \times M(x, y, \phi) \rangle}$

Magnetic field weighted by muon distribution
SO HOW DO WE REALLY MEASURE $\frac{\omega_a}{\tilde{\omega}'_p(T_r)}$ 

Unblinding factor

Measured $g$-2 frequency

$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} \approx f_{\text{clock}} \left( \omega_a^m \right)$

$< \omega_p(x, y, \phi) \times M(x, y, \phi) >$

Magnetic field weighted by muon distribution
SO HOW DO WE REALLY MEASURE \( \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \)

Measured g-2 frequency

Unblinding factor

Beam dynamics related corrections

\[
\omega_a \approx f_{\text{clock}} \frac{\omega^m_a}{\omega_a} \left( 1 + C_e + C_p + C_{ml} + C_{pa} \right) < \omega_p(x, y, \phi) \times M(x, y, \phi) >
\]

Magnetic field weighted by muon distribution
SO HOW DO WE REALLY MEASURE $\frac{\omega_a}{\tilde{\omega}_p'(Tr)}$?

Measured $g$-2 frequency

Unblinding factor

Beam dynamics related corrections

Field calibration

Magnetic field weighted by muon distribution

$\frac{\omega_a}{\tilde{\omega}_p'(Tr)} \approx \frac{f_{clock}}{f_{calib}} \frac{\omega_a^m}{(1 + C_e + C_p + C_{ml} + C_{pa})} < \omega_p(x, y, \phi) \times M(x, y, \phi) >$
SO HOW DO WE REALLY MEASURE \[ \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \]

Measured g-2 frequency

Unblinding factor

\[ \omega_a \approx \frac{f_{\text{clock}}}{f_{\text{calib}}} \omega_a^m < \omega_p(x, y, \phi) \times M(x, y, \phi) > (1 + C_e + C_p + C_{ml} + C_{pa}) \]

Beam dynamics related corrections

Field calibration

 Corrections for transient magnetic fields

Magnetic field weighted by muon distribution
MEASURING $\omega_a$ AND $\bar{\omega}'_p$:
The Run-1 Analysis Details and Results
DETAILS OF THE ANALYSIS

\[
\frac{\omega_a}{\tilde{\omega}_p(T_r)} \approx \frac{f_{\text{clock}}}{f_{\text{calib}}} \omega_{m}^{a} \left( 1 + C_e + C_p + C_{ml} + C_{pa} \right) < \omega_p(x, y, \phi) \times M(x, y, \phi) > (1 + B_k + B_q)
\]

- Measured g-2 frequency
- Unblinding factor
- Magnetic field weighted by muon distribution
- Field calibration
- Beam dynamics related corrections
- Corrections for transient magnetic fields
DETAILS OF THE ANALYSIS

\[
\frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{\mu'_p(34.7°)/\mu_e}{(k + B_q)}
\]

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Correction terms</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega^m_a$ (statistical)</td>
<td>–</td>
<td>434</td>
</tr>
<tr>
<td>$\omega^m_a$ (systematic)</td>
<td>–</td>
<td>56</td>
</tr>
<tr>
<td>$C_e$</td>
<td>489</td>
<td>53</td>
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<tr>
<td>$C_p$</td>
<td>180</td>
<td>13</td>
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<tr>
<td>$C_{ml}$</td>
<td>-11</td>
<td>5</td>
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<tr>
<td>$C_{pa}$</td>
<td>-158</td>
<td>75</td>
</tr>
<tr>
<td>$f_{\text{calib}}(\omega'_p(x, y, \phi) \times M(x, y, \phi))$</td>
<td>–</td>
<td>56</td>
</tr>
<tr>
<td>$B_k$</td>
<td>-27</td>
<td>37</td>
</tr>
<tr>
<td>$B_q$</td>
<td>-17</td>
<td>92</td>
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<tr>
<td>$\mu'_p(34.7°)/\mu_e$</td>
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<td>10</td>
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<tr>
<td>$m_{\mu}/m_e$</td>
<td>–</td>
<td>22</td>
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<tr>
<td>$g_e/2$</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>Total systematic</td>
<td>–</td>
<td>157</td>
</tr>
<tr>
<td>Total fundamental factors</td>
<td>–</td>
<td>25</td>
</tr>
<tr>
<td>Totals</td>
<td>544</td>
<td>462</td>
</tr>
</tbody>
</table>
\[ \frac{\omega_a}{\tilde{\omega}_p(T_r)} \approx \frac{f_{\text{clock}}}{f_{\text{calib}}} \frac{\omega^m_a}{\omega_p(x, y, \phi) \times M(x, y, \phi)} \frac{1 + C_e + C_p + C_ml + C_pa}{(1 + B_k + B_q)} \]
MEASURING $\omega_a$

- Measure time and energy of decay positrons in the 24 calorimeters.

- Due to parity violating weak decay, high energy positrons are emitted more along the direction of the spin.

- Decay positron time distribution above an optimal energy threshold of $E \sim 1.7$ GeV produces “wiggle” plot.

- Main features of the “wiggle” plot from muon lifetime $\tau$ and spin precession $\omega_a$, but actual fit way more complicated:

$$N(t) = N_0 e^{t/\tau} \left[ 1 - A \cos(\omega_a t + \phi) \right]$$

- Statistical uncertainty: $\sigma_{\omega_a} \propto 1/\sqrt{NA^2}$. 
DETAILS OF THE ANALYSIS

\[ \frac{\omega_a}{\tilde{\omega}_p(T_r)} \approx \frac{f_{\text{clock}} \omega_a}{f_{\text{calib}}} \frac{(1 + C_e + C_p + C_{ml} + C_{pa})}{\omega_p(x, y, \phi) \times M(x, y, \phi) > (1 + B_k + B_q)} \]
BEAM DYNAMICS CORRECTIONS

- **Electric field correction** $C_e$:
  - Electric field term cancels for magic momentum but stored muons have momentum spread $\Delta p/p \sim 0.15\%$
  - Correction from measurement of equilibrium radius $\langle x_e^2 \rangle$

- **Pitch correction** $C_p$:
  - Vertical motion due to betatron oscillations reduces $\bar{\omega}_d$
  - Correction from vertical muon distribution $\langle y^2 \rangle$

- **Muon loss correction** $C_{ml}$:
  - Stored muons can be lost and can carry different phase
  - Detect and correct through coincidences in three neighboring calorimeters

- **Phase acceptance correction** $C_{pa}$:
  - In Run-1, damaged high-voltage resistors extended the charging time of the quadrupoles, introducing a time dependency over the fill
  - Correction from tracker data and simulated positron acceptance, asymmetry, and phase maps
DETAILS OF THE ANALYSIS

\[ \frac{\omega_a}{\tilde{\omega}_p(T_r)} \approx \frac{f_{\text{clock}}}{f_{\text{calib}}} \left( \frac{\omega_a^m}{\omega_a} \right) \frac{(1 + C_e + C_p + C_{ml} + C_{pa})}{(1 + B_k + B_q)} \]
MEASURING $\omega_p(x, y, \phi)$

- Measurement of field amplitude via Nuclear Magnetic Resonance:
  - Frequency extracted from Free Induction Decay signal
  - Very good frequency precision (ppb level)
  - Good to track slow field changes

- 378 NMR probes installed in groups of 6 and 4 probes
  - Continuously track slow field drift every ~1 second
  - 72 azimuthal locations around the ring

- In-vacuum trolley maps the field every 3 to 5 days
  - 9000 measurements for each of the 17 probes
  - Detailed frequency maps where the muons are
  - Synchronizes the fixed probes to field maps
MEASURING $\langle \omega_p(x, y, \phi) \times M(x, y, \phi) \rangle$

- The frequency maps $\omega_p(x, y, \phi)$ from trolley and fixed probe data need to be weighted by the muon distribution $M(x, y, \phi)$

\[
\tilde{\omega}_p = \langle \frac{\int \omega_p(x, y, \phi) \, M(x, y, \phi) \, dx \, dy}{\int M(x, y, \phi) \, dx \, dy} \rangle
\]

- The muon distribution $M(x, y, \phi)$ is extracted from the two straw-tracker stations
- $M(x, y, \phi)$ includes beam dynamics information (e.g. beta functions) and detector acceptances (calorimeter)
\[
\frac{\omega_a}{\tilde{\omega}_p(T_r)} \approx \frac{f_{\text{clock}} \omega_a^m}{f_{\text{calib}}} < \omega_p(x, y, \phi) \times M(x, y, \phi) > (1 + B_k + B_q)
\]
QUADRUPOLE TRANSIENT CORRECTION $B_q$

- Electrostatic quadrupoles have fast, pulsed currents
- Fixed probes have low bandwidth and shielded by vacuum chamber
- Built special vacuum compatible probe to measure any fast fields
- Measurement revealed fast magnetic field changes and led to largest systematic uncertainty in Run-1
SUMMARY OF RUN-1 RESULT AND OUTLOOK
SUMMARY OF RUN-1 RESULT

\[ a_\mu \times 10^9 - 1165900 \]

\[ a_\mu(\text{FNAL}) = 116592040(54) \times 10^{-11} \quad (0.46 \text{ ppm}) \]

\[ a_\mu(\text{Exp}) = 116592061(41) \times 10^{-11} \quad (0.35 \text{ ppm}) \]
SUMMARY AND OUTLOOK

- The Muon g-2 experiment measured $\alpha_\mu$ to 460 ppb, consistent with BNL.
- The combined experimental result differs from the SM value by $4.2\sigma$.
- This result is based on ~6% of our total statistical goal.
- Already ~85% of the total statistics on tape (Run-1 to Run-5).
- Several key upgrades since Run-1 will further improve systematics:
  - New quad resistors reduces $C_{pa}$
  - Higher kicker voltage to center beam radially
  - Thermal magnet insulation and better hall cooling stabilize field drift
  - Improved quad transient measurement
  - New RF system to suppress CBO amplitude
- Upcoming final Run-6 should bring us to overall statistics goal.
- ... stay tuned for more results to come (Run2/3 result ~Spring 2023)!
SUMMARY AND OUTLOOK

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**Muon g-2 (FNAL)**

**Much more data to come!**

Run 1 results ~6% of full stats, 434 ppb stat ⊕ 157 ppb syst errors

Run 2/3 analysis in progress, aiming to reduce experimental error by 2 by spring. Systematics on track for < 100 ppb.

Run 4/5, aiming for another factor of ~2 reduction in error

Run-1
Run-2
Run-3
Run-4
Run-5

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*Graph showing cumulative counts from 01-May '18 to 01-Jun '22*