The Muon g-2 Experiment at Fermilab

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Outline

Introduction
  • The Magnetic Moment and the g-factor
  • The Anomalous Magnetic Moment
  • Current Status: Theory and Experiment

Experiment Overview
  • Moving the ring
  • Storing Muons
  • Measuring the Anomaly

The Magnetic Field
  • Magnet Geometry
  • Shimming the Magnet
  • Absolute Calibration

Summary
  • Outlook: Where Are We and What’s to Come?
The Magnetic Moment

\[ \vec{\mu} = g \frac{q}{2m} \vec{s} \]

- Magnetic moment connected to spin via dimensionless g-factor
- Dirac: \( g = 2 \) for \( s = 1/2 \) particles (1928)
- \( g \) for electron found to differ from 2 in hyperfine structure experiments on hydrogen (Kusch, Foley 1948)
  - Anomalous contribution \( a_e \)
  - Interpretation: Schwinger’s QED calculation of \( a_e = \alpha/2\pi \) (1948)
  - Radiative corrections from virtual particles in loops

Dirac

Schwinger \( O(\alpha) \)

Vacuum polarization \( O(\alpha^2) \)
SM Contributions to $a_\mu$

$g_\mu \equiv 2 \left( 1 + a_\mu \right)$

Contributions from quantum electrodynamics, electroweak, and quantum chromodynamics
## SM Contributions to $a_\mu$

<table>
<thead>
<tr>
<th>Source</th>
<th>Value ($\times 10^{-11}$)</th>
<th>Uncertainty ($\times 10^{-11}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>QED</td>
<td>116584718.951</td>
<td>0.080</td>
<td>Kinoshita et al., 2012</td>
</tr>
<tr>
<td>EW (1 loop)</td>
<td>194.8</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>EW (2 loop)</td>
<td>-41.2</td>
<td>1</td>
<td>Czarnecki, Marciano, Stöckinger et al., 2013</td>
</tr>
<tr>
<td>HVP (LO)</td>
<td>6923</td>
<td>42</td>
<td>Davier et al., 2011</td>
</tr>
<tr>
<td>HVP (LO)</td>
<td>6949</td>
<td>43</td>
<td>Hagiwara et al., 2011</td>
</tr>
<tr>
<td>HVP (HO)</td>
<td>-98.4</td>
<td>0.7</td>
<td>Hagiwara et al., 2011</td>
</tr>
<tr>
<td>HLbL</td>
<td>105</td>
<td>26</td>
<td>Prades et al., 2010</td>
</tr>
<tr>
<td>Total</td>
<td>116591802</td>
<td>49 (420 ppb)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>116591828</td>
<td>50 (430 ppb)</td>
<td></td>
</tr>
</tbody>
</table>

### HVP (LO): Lowest-Order Hadronic Vacuum Polarization
- **Critical input** from $e^+e^-$ colliders (data from SND, CMD3, BaBar, KLOE, Belle, BESIII), $\delta a_\mu^{\text{HVP}} \sim 0.7\%$; extensive physics program in place to reduce $\delta a_\mu^{\text{HVP}}$ to $\sim 0.3\%$ in coming years
- **Progress on the lattice**: Calculations at physical $\pi$ mass; goal: $\delta a_\mu^{\text{HVP}} \sim 1—2\%$ in a few years (cross-check with $e^+e^-$ data)

### HLbL: Hadronic Light-by-Light
- Model dependent: based on $\chi$PT + short-distance constraints (operator product expansion)
- Difficult to relate to data like HVP (LO); $\gamma^*$ physics, $\pi^0$ data (BESIII, KLOE) important for constraining models
- **Theory Progress**: New dispersive calculation approach; extend the lattice (finite volume, disconnected diagrams); Blum et al. optimistic (see his talk, Plenary VI)
Current Status

\[ a_\mu (\text{Exp}) - a_\mu (\text{SM}) = 287 \pm 80 \ (3.6\sigma) \]

\[ a_\mu (\text{Exp}) - a_\mu (\text{SM}) = 261 \pm 80 \ (3.3\sigma) \]

- **Disagreement** between experiment and theory
  - Deviation is large compared to EW contribution, uncertainty on hadronic terms
  - Not at discovery threshold (5\(\sigma\))
  - Due to new physics?
    - SUSY, TeV-scale models, dark photon...
- **Improvements** on both theory and experiment sides
  - **Experiment**: more statistics, reduce systematics
  - **Theory**: reduce uncertainties (HVP, HLbL)

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>(\delta a_\mu)</th>
<th>Status 2016 (ppb)</th>
<th>Projected after E989 (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVP</td>
<td>360</td>
<td></td>
<td>215</td>
</tr>
<tr>
<td>HLbL</td>
<td>225</td>
<td></td>
<td>225</td>
</tr>
<tr>
<td><strong>Total Theory</strong></td>
<td>420</td>
<td></td>
<td>310</td>
</tr>
<tr>
<td><strong>Total Experiment</strong></td>
<td>540</td>
<td></td>
<td>140</td>
</tr>
</tbody>
</table>

Blum et al., arXiv:1311.2198
Experiment Overview

The Muon g-2 Collaboration
33 institutions, 150 members

Domestic Universities
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- York College

National Labs
- Argonne
- Brookhaven
- Fermilab

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

England
- University College London
- Liverpool
- Oxford
- KAIST

Korea
- KAIST

China
- Shanghai

The Netherlands
- Groningen

Germany
- Dresden

Russia
- Dubna
- Novosibirsk

D. W. Hertzog, Co-Spokesperson
B. L. Roberts, Co-Spokesperson
C. Polly, Project Manager
The Big Move
Relocating the Ring from BNL to FNAL

Ring successfully cooled and powered to 1.45 T in September 2015 — remarkable achievement!

June 2013—June 2015

- Ring deconstructed at BNL, transported by barge/flatbed trailer
- Reassembled at FNAL
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
Muon Storage Technique

**Inflector: Getting muons into ring**
- Outside ring: $B = 0$ T, inside: $B = 1.45$ T
- Need to cancel field in order to get muons in (strong deflection otherwise)
- No perturbation to field outside shield
- Double-cos $\theta$ superconducting inflector from BNL E821
- New inflector design with higher transmission under development

**Energizing coils cancels the field in the beam channel**

**Kicker: Moving muons onto closed orbit**
- After inflector, muons enter storage region at $r = 77$ mm outside central closed orbit
- Muons cross ideal orbit 90 deg. later in azimuth, angle is off by 10.8 mrad
- Need 14 mrad kick (includes effects from multiple scattering, momentum spread)
- Temporarily reduce field by 280 G over 5.1 m
- Operating time: < 149 ns at $f = 100$ Hz
- Characteristics: 3 x 1.7 m stripline kickers, Blumlein PFN

**Eddy currents in passive superconducting shield prevents flux leakage**
Measuring $a_\mu$

- Inject polarized muon beam (from pion decay) into ring

- Measure **difference** between spin precession and cyclotron frequencies

\[
\begin{align*}
\vec{\omega}_C &= -\frac{e}{\gamma m} \vec{B} \\
\vec{\omega}_S &= -\frac{e}{\gamma m} \vec{B}
\end{align*}
\]

- If $g = 2$, difference of spin precession and cyclotron frequencies is zero

\[g = 2\]
Measuring $a_\mu$

- Inject polarized muon beam (from pion decay) into ring
- Measure **difference** between spin precession and cyclotron frequencies

$$\vec{\omega}_C = -\frac{e}{\gamma m} \vec{B}$$

$$\vec{\omega}_S = -\frac{e}{\gamma m} \vec{B} \left(1 + \gamma a_\mu\right)$$

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

0 for $\gamma = 29.3$ ($p = 3.1$ GeV)

E-field vertical focusing allowed at $p = 3.1$ GeV (higher-order $a_\mu$ contribution cancelled)
Measuring $a_\mu$

Re-write B-field in terms of free-proton precession frequency $\omega_p$:

$$a_\mu = \frac{\omega_a / \omega_p}{\mu_\mu / \mu_p - \omega_a / \omega_p}$$

Muonium hyperfine experiments
25 ppb contribution to $a_\mu$
(see Yasuhiro Ueno’s talk, Beyond SM Parallel VI)

Measure muon decay to positrons

NMR measurements on proton samples
Measuring $\omega_a$

- Self-analyzing decay: $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$
- $e^+$ emitted preferentially along muon spin
- Results in sinusoidally-oscillating energy deposition in calorimeters

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

- Correct for muon losses, pileup, coherent betatron oscillations

3 tracker systems
- 1500-channel straw trackers
- Reconstruct muon distribution from $e^+$ trajectories

24 calorimeters
- 6 x 9 PbF$_2$ crystal arrays
  - fine segmentation, good timing resolution; low sensitivity to pileup
  - readout by SiPMs
- New electronics/DAQ, 800 MHz WFDs
- Laser calibration: $10^{-4}$/hr gain stability demonstrated
Measuring $\omega_p$

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

- Measure field while muons are in ring — probes outside storage region

- Measure field in storage region during specialized runs when muons are not being stored

- Fixed & trolley probes calibrated to free proton Larmor frequency
  - Absolute calibration probes using a water sample
  - Measurements in specially-shimmed region of ring
**ωₐ, ωₚ Improvements**

**Reduce ωₐ systematic uncertainties by a factor of 3**

- Tackling major systematic uncertainties with knowledge gained from E821, improved hardware
- Environmental improvements by changing run conditions (e.g., no hadronic flash)

<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>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><strong>Total</strong></td>
<td><strong>0.20</strong></td>
<td></td>
<td><strong>0.07</strong></td>
</tr>
</tbody>
</table>

**Reduce ωₚ systematic uncertainties by a factor of 2.5**

- Better run conditions (e.g., temperature stability, more time to shim magnetic field to high uniformity, smaller muon beam profile)
- Many hardware and software improvements
The Magnetic Field
Magnet Anatomy

B = 1.4513 T (~5200 A)

- Non-persistent current: fine-tuning of field in real time

12 C-shaped yokes

- 3 poles per yoke
- 72 total poles

Shimming knobs

- Poles: shape field
- Top hats (30 deg, dipole)
- Wedges (10 deg, dipole, quadrupole)
- Edge shims (360 deg, quadrupole, sextupole)
- Laminations (360 deg, dipole, quadrupole, sextupole)
- Surface coils (360 deg, quadrupole, sextupole, ...)

\( \rho = 7112 \text{ mm} \)

g-2 Magnet in Cross Section
Measurement Tools

Rough Shimming

**Shimming cart**

- Lattice of 25 NMR probes (field measurements)
- 4 capacitive gap sensors (pole-pole alignment/separation), 70-nm resolution
- 4 corner-cube retroreflectors (position), ~25 µm resolution

**Laser tracker**

- Cart position (r, φ, z)
Pole Moves and Tilts

- Step and tilt discontinuities in pole surfaces yield large variations in the field.

- To reduce/remove such effects, make adjustments to pole feet, which changes the magnet gaps and tilts.
  - Use 0.001—0.010” thick shims
  - Requires removal of poles from the ring
  - Informed by a computer model that optimizes the pole configurations
    - Requires global continuity between pole surfaces
    - Allows only three adjacent poles to be moved at a time (preserves alignment)
Tuning Out Small(er) Variations

Calibrated shimming knobs

- 48 top hats
- 864 wedges
- ~8400 iron foils (on pole surfaces)

**Coarse tuning:** top hat & wedge adjustments

- Least-squares fit to field maps predicts top hat and wedge positions

**Fine tuning:** iron foils

- Modeled as saturated dipoles in 1.45 T field
- Computer code predicts foil width (mass) distribution to fill in the valleys of the field map
- Radially-segmented distribution: control higher-order multipoles (quadrupole, sextupole,…)
Rough Shimming Results

Azimuthally-Averaged Map

Goal
~1400 ppm
50 ppm
~1400 ppm

Oct 2015
Aug 2016

(B-B_{avg})/B_{avg} (ppm)

vertical (cm)

R-R

azimuth (deg)

Oct 2015
Aug 2016

B-field (ppm)

Quad 25.13 -0.53
Sext -1.99 -0.11
Octu -1.16 -0.31
Decu 0.95 -0.07

B-field (ppm)

Quad -0.02 -0.57
Sext -0.70 3.84
Octu -0.76 0.56
Decu 0.44 -1.61

Vertical (cm)

R-R_{0}(cm)

Oct 2015
Aug 2016
Absolute Calibration

- In the experiment, need to extract \( \omega_p \), but we don’t have free protons — need a calibration

- Field at the location of a proton differs from the applied field:

\[
B_{\text{meas}} = (1 - \delta_t)B = [1 - \sigma (\text{H}_2\text{O}, T) - \delta_b - \delta_p - \delta_s] B
\]

- Carefully-constructed probes
  - Studying build quality and magnetic footprint of materials
  - Pure water sample

- Goal: reduce the uncertainty from 50 ppb (E821) to 35 ppb

<table>
<thead>
<tr>
<th>Source of Error</th>
<th>Uncertainty (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMR detection and measurement</td>
<td>15 → 5</td>
</tr>
<tr>
<td>Field homogeneity</td>
<td>10</td>
</tr>
<tr>
<td>Materials outside the probe</td>
<td>15</td>
</tr>
<tr>
<td>Water/sample holder shape</td>
<td>15 → 10</td>
</tr>
<tr>
<td>Probe materials</td>
<td>10</td>
</tr>
<tr>
<td>Diamagnetic shielding (H(_2)O)</td>
<td>14 → 2.5</td>
</tr>
<tr>
<td>Temperature</td>
<td>10 → 5</td>
</tr>
<tr>
<td>Total</td>
<td>34</td>
</tr>
</tbody>
</table>

*Table: Systematic uncertainties for the E821 absolute calibration probe. Data from Nucl. Instrum. Meth. 394, 349 (1997).*
Probe Design

**Absolute Probe**

- Probe made from macor
- Geometry: spherical sample holder encased in cylindrical tube
- Circuitry: non-magnetic RF coil, capacitors
- Calibrates the **plunging probe**

**Plunging probe**

- **Calibrates** the trolley probes and fixed probes
- Geometry: cylindrical tube
- Operates in vacuum
- Materials: glass, non-magnetic RF coil, capacitors
- Galil controller directs motion (x, y, z), cross-checked by high-res photographs
  - Positional accuracy < 1 mm (inductive linear encoder)

  - **Coverage in ring**: 5 cm azimuthally, 11 cm vertically, 20–25 cm radially
  - **Location in ring**: 6 o’clock position
  - **Vacuum chamber** has been scalloped, rectangular extension welded on and slot cut (BU/FNAL)
Instrumentation at Argonne

**Absolute Calibration DAQ**

**DAQ Characteristics**

- Bandwidth: 61.79 MHz ± 50 kHz (833 ppm)
- Amplitude: ~1 V at t ~ 0
- RMS Noise: ~1 mV
- S/N: ~1000 at t ~ 0
- Resolution: <1 ppb

**Magnet Details**

- **Characteristics:** MRI solenoid, persistent current, 68-cm bore
- **Uniformity:** Shimmed to 13 ppm peak-to-peak over a 50-cm diameter spherical volume (DSV)
- **Stability:** Field drift ~ 9 ppb/hr
## Approximate Project Timeline

<table>
<thead>
<tr>
<th>2015</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep</td>
<td>Oct</td>
<td>Nov</td>
</tr>
<tr>
<td>Prepare vacuum chambers/align cages w/ rails, quad, kicker plates</td>
<td>Field Shimming</td>
<td>Install Chambers</td>
</tr>
<tr>
<td>Prepare old inflector/install infrastructure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construct &amp; install quad pulsed power supplies, feedthroughs, connections</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assemble kicker plates, cages, pulsers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construct and test upgraded NMR trolley &amp; absolute calibration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Receive calo crystals/SiPMs</td>
<td>Construct 1st full calorimeter</td>
<td>SLAC test beam</td>
</tr>
<tr>
<td></td>
<td>Construct M2/M3 beamlines from AP0 to Delivery Ring</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Modify AP0 Li lens and PMAG PS for g-2 rep rate, replace beam dump</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Install Delivery Ring injection, transport, and extraction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Install Blumleins, PS, &amp; kickers</td>
<td></td>
</tr>
<tr>
<td>Install final focus on AP0 target</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*We are here*
Summary

• The experiment will measure the muon’s anomalous magnetic moment to a precision of 140 ppb — a fourfold improvement over BNL E821

• Magnet disassembled at BNL, transported to FNAL and is operational at 1.45 T as of September 2015

• Rough-shimming stage of magnetic field is complete
  • Field variations reduced to 50 ppm peak-to-peak around the ring — factor of 2 better than E821

• Absolute calibration effort well underway: probe design, construction, and material studies all progressing

• Project on pace to take physics data in fall/winter 2017
  • Much to do in the meantime! Calorimeter construction, vacuum chamber installation, simulations, radial & AC magnetic field studies, DAQ stress-testing, ...
Hadronic Vacuum Polarization

- **Critical input to HVP** from $e^+e^-$ colliders (SND, CMD3, BaBar, KLOE, Belle, BESIII)
- **BESIII**: 3x more data available, luminosity measurement improvements
- **VEPP-2000**: Aiming for 0.3% (fractional) uncertainty by 2017; radiative return + energy scan
- **CMD3**: Will measure up to 2 GeV (energy scan, ISR — good cross check)

$$a_\mu^{\text{HVP}} \approx \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} K(s)\sigma(e^+e^- \to \text{hadrons})ds$$

Kernel function $K(s) \sim 1/s^2$

- **Lattice calculations** of $a_\mu^{\text{HVP}}$ to 1% possible, 30% for HLbL in 3—5 years
Theoretical Progress

Lattice Calculations for g-2

**Lattice QCD** has been making **tremendous progress**

- **Initial attempts** to calculate **HLbL** by factorizing QED component

- **HVP (LO)** calculations are converging; expect to be competitive with $e^+e^-$

Lattice results for HVP (LO) and HLbL will have a profound impact
Motivation to Measure $a_\mu$

- **Sensitivity to new physics**
  - SUSY [$\tan \beta$, sgn($\mu$)] — difficult to measure at LHC
  - MSSM, UED (1D), Littlest Higgs: similar signatures at LHC, distinguishable by $\Delta a_\mu$
  - TeV-scale models
  - Dark matter
- Sensitive to flavor- and CP-conserving, chirality-flipping, loop-induced contributions
- **Independent & complementary to LHC physics**
  - Most LHC observables are chirality-conserving; complementary low-energy precision observables are CP-violating (EDMs) or flavor-violating (CLFV)
  - CLFV $\mu \rightarrow e$ process depends upon mass and coupling strength of new physics (many unknowns); $a_\mu$ can determine nature of new physics
  - Sensitive to leptonic couplings; $b$- and $K$-physics sensitive to hadronic couplings
- **Can discern between theories** that predict large/small $\Delta a_\mu$
- Agreement with SM would be interesting too...
Physics Beyond SM?
SUSY, TeV-scale Models

- Higgs measured at the LHC to be \(\sim 125\) GeV
- Theory: Higgs should acquire much heavier mass from loops with heavy SM particles (e.g., top quark)
  - **Supersymmetry**: new class of particles that enters such loops and cancels this contribution
  - Complementary to direct searches at the LHC
    - Sensitivity to \(\text{sgn}(\mu)\), \(\tan(\beta)\)
    - Contributions to \(a_\mu\) arise from charginos, sleptons
    - LHC searches sensitive to squarks, gluinos

Improved precision on \(a_\mu\) will continue to constrain (or validate!) the energy scale of new models
Physics Beyond the SM?

Dark Matter

- **Cosmological observations** (galaxy rotation curves, lensing) point to much more mass in the universe than expected
- Many theories to explain dark matter
- A new U(1)' symmetry: dark photon $A'$

- **Dark photon** could impact the muon’s magnetic moment
- Many direct-detection searches underway

\[ \mu^+ \rightarrow \gamma \rightarrow A' \quad \mu^- \rightarrow \gamma \rightarrow A' \quad \epsilon = \text{mixing strength} \]
Concern for achieving required statistics

- **Need 21x more** statistics than BNL E821
- **Need 85x improvement** in integrated beam coming from many other factors

### $\omega_a$ Statistics

<table>
<thead>
<tr>
<th>Item</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons per fill on target</td>
<td>$10^{12}$ p</td>
</tr>
<tr>
<td>Positive-charged secondaries with $dp/p = \pm 2%$</td>
<td>$4.8 \times 10^7$</td>
</tr>
<tr>
<td>$\pi^+$ fraction of secondaries</td>
<td>0.48</td>
</tr>
<tr>
<td>$\pi^+$ flux entering FODO decay line</td>
<td>$&gt; 2 \times 10^7$</td>
</tr>
<tr>
<td>Pion decay to muons in 220 m of M2/M3 line</td>
<td>0.72</td>
</tr>
<tr>
<td>Muon capture fraction with $dp/p &lt; \pm 0.5%$</td>
<td>0.0036</td>
</tr>
<tr>
<td>Muon survive decay 1800 m to storage ring</td>
<td>0.90</td>
</tr>
<tr>
<td>Muons flux at inflector entrance (per fill)</td>
<td>$4.7 \times 10^4$</td>
</tr>
<tr>
<td>Transmission and storage using $(dp/p)_\mu = \pm 0.5%$</td>
<td>$0.10 \pm 0.04$</td>
</tr>
<tr>
<td>Stored muons per fill</td>
<td>$(4.7 \pm 1.9) \times 10^3$</td>
</tr>
<tr>
<td>Positrons accepted per fill (factors 0.15 x 0.63)</td>
<td>$444 \pm 180$</td>
</tr>
<tr>
<td>Number of fills for $1.8 \times 10^{11}$ events</td>
<td>$(4.1 \pm 1.7) \times 10^8$ fills</td>
</tr>
<tr>
<td>Time to collect statistics</td>
<td>(13 ± 5) months</td>
</tr>
<tr>
<td>Beam-on commissioning</td>
<td>2 months</td>
</tr>
<tr>
<td>Dedicated systematic studies periods</td>
<td>2 months</td>
</tr>
<tr>
<td>Net running time required</td>
<td>17 ± 5 months</td>
</tr>
</tbody>
</table>

### Ratio of beam powers BNL/FNAL:

\[
\frac{4 \times 10^{12} \text{ protons/fill} \times (12 \text{ fills/2.7 sec}) \times 24 \text{ GeV}}{1 \times 10^{12} \text{ protons/fill} \times (16 \text{ fills/1.3 sec}) \times 24 \text{ GeV}} = 4.3
\]

Reduced beam power
Measuring the Field

• To measure the field, utilize pulsed **nuclear magnetic resonance** (NMR) on proton sample (petroleum jelly)

• Larmor precession frequency proportional to field magnitude, gyromagnetic ratio

• Record the free-induction decay (FID) signal

• Extracted frequency precision: 10 parts per billion (ppb)/FID

• Deliver $\pi/2$ pulse to probe, induce FID

• Precessing spins induce EMF in RF coil — this signal is amplified, mixed down to kHz and digitized

• Envelope of FID tells us about gradients in the field
Magnetic Field
Multipole Decomposition

\[ B(x, y) = B(r, \theta) = B_0 + \sum_{i=1}^{n} \left( \frac{r}{r_0} \right)^i [a_i \cos (i\theta) + b_i \sin (i\theta)] \]

- Sample at NMR probe locations
- Fit to sum of n-orders of multipoles
- 2D approximation for small \(B_r\), \(B_\theta\)
Magnetic Field Variations

First Magnetic Field Map, Oct 14 2015

- **Gradual drift** from materials, pole gap changes
- **36 pairs of poles** => 10 degree structure
- Pole shape: 

- Pole-to-pole discontinuities
Magnetic Field Comparison
BNL E821 and FNAL E989

Dipole Vs Azimuth

Status:
• Laminations very successful in reducing field variation
• Vacuum chamber installations proceeding

• BNL E821: 39 ppm RMS (dipole), 230 ppm peak-to-peak
• FNAL rough shimming: 10 ppm RMS (dipole), 75 ppm peak-to-peak
Absolute Calibration Procedure

• During the experiment, specialized runs will be taken to transfer the plunging probe measurements to the trolley and fixed probes

1. Move trolley into position, take measurements

2. Pull trolley far away; move plunging probe to a given trolley probe position, take measurements (repeat for each probe)

3. Measurements made in specially-shimmed region in the ring

4. Calibration accounts for probe materials perturbing the field and magnetic images
Absolute Calibration DAQ

System Characteristics

- Bandwidth: 61.79 MHz ± 50 kHz (833 ppm)
- Amplitude: ~ 1 V at t ~ 0
- RMS Noise: ~ 1 mV
- S/N: ~ 1000 at t ~ 0
- Resolution: < 1 ppb
Absolute Calibration

Material Studies

• Need to quantify field perturbations due to materials used in probes

• Measurements for many components have been performed
  
  • zero-\(\chi\) wire: 4 ppb
  
  • capacitors: 3 ppb
  
  • super glue: 1 ppb
  
  • BNL probe: 45 ppb
    
    • Accounts for: aluminum shell, full probe, rotational symmetry

• Will do similar studies for new probes

New translation stage

probe ports

locking ports

BNL calibration probe

water sample

super glue sample