The Fermilab Muon g-2 straw tracking detectors and the muon EDM measurement

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The muon has an intrinsic magnetic moment, $\vec{\mu}$, that is coupled to its spin, $\vec{s}$, by the gyromagnetic ratio $g_\mu$

$$\vec{\mu} = g_\mu \left( \frac{e}{2m_\mu} \right) \vec{s}$$

Interactions between the muon and virtual particles alter this ratio
Physics Motivation

- The current discrepancy is at 3.7σ: $\delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 269(72) \times 10^{-11}$, with $a_\mu = \frac{g_\mu - 2}{2}$.

- Assuming the central values of $a_\mu$ do not change, a 140 ppb measurement at Fermilab will yield a 7σ discrepancy. This will be achieved via reduction in:
  - statistical error via:
    - Improved beam duty cycle (12 Hz vs 1 Hz at BNL)
  - systematic error via:
    - in-vacuum tracking system, segmented calorimeters, field uniformity, laser calibration…

- Additionally, the Muon $g-2$ Theory Initiative will aim to reduce the uncertainty from hadronic contributions to $a_\mu$

See Jason Crnkovic’s plenary talk on Monday for more information
Methodology

• The two frequencies that are measured in the experiment are

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

\[ \omega_p \propto |B| \]

• The anomalous magnetic moment is then determined from the ratio

\[ a_\mu = \frac{\omega_a g_e}{\omega_p} \frac{m_\mu}{2 m_e} \frac{\mu_p}{\mu_e} \]

- The decay positron curls inwards, and is measured by one of the 24 calorimeters

- Histogram high energy positron events over time to extract \( \omega_a \) from a fit
- CERN III precision (10 ppm) per hour

\[ B=1.45 \text{ T} \]

\[ R=7.112 \text{ m} \]
Tracker Overview

- Reduce the systematic uncertainty on the $\omega_a$ via measurements of
  - the muon beam profile
  - positron pile-up in calorimeters
  - independent gain cross-check

- Convolute the stored muon beam with the magnetic field, to determine $\tilde{\omega}_p$

- Access the beam dynamics via measurements of the betatron oscillations

- Improve on the sensitivity to the muon Electric Dipole Moment (EDM)
Tracker Overview

- 8 tracker modules per station
- 4 layers of 32 straws
- An angle of 15° between UV layers
- A straw is filled with 50:50 Ar:Ethane
- Central wire at +1.6 kV
- Module inside vacuum of $10^{-9}$ atm
- Straw is held at 1 atm
- Hit resolution of 100 µm
• Track reconstruction is implemented with GEANE framework, which incorporates geometry, material, and field, utilising transport and error matrices for particle propagation.

• Two tracks close in time as seen by the online event display.
Track Extrapolation

- Fitted tracks are extrapolated back to the decay point using a *Runge-Kutta* algorithm that propagates the tracks through the varying magnetic field.
- Only tracks that are not to passing through material (e.g. vacuum chamber) are used in extrapolation.

- Reconstructed beam position from tracks that have been extrapolated back to their decay position.

- Reconstructed decay arc length as a function of track momentum back to the decay position.

![Diagram of track extrapolation](image)
• Extrapolated tracks to the front face of the calorimeter. Tracker provides trajectory information at the face of the calorimeter, which is used to inform the clustering algorithms.

• Tracks and calorimeter clusters are matched up based on time proximity (10 ns)
• Reconstructed **radial position** of the decay point plotted against time. The oscillations are the radial betatron oscillations.
Pitch Correction

- Muons are going up-and-down in the ring (focused by electrostatic quadruples), reducing the effective field, as the momentum vector now has a (vertical) component along the field

\[ B_{\text{vertical}} = 1.45 \, \text{T} \]

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

- Need to correct for vertical \( \mu^+ \) angle but we measure an ensemble of decay e^+

\[ \frac{\Delta \omega_a}{\omega_a} \propto \sigma_{\text{vertical}}^2 \]

- Trackers measure the **vertical width** of the beam precisely. Uncertainty on the correction is < 30 ppb, in line with the designed expectation
Field Convolution

- Trackers measure the beam profile as a function of time
- Storage region field is measured by a trolley (when muons are not present)
- This is cross-calibrated by the fixed probes outside the storage region
- Convolution finds shapes common in beam and field profiles and projects these shapes to estimate the field experienced by the muons

- The storage region near the tracker station
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- **Field measurement by the trolley**
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Beam profile from the trackers
Motivation for Tracker Alignment

- The reconstructed beam distribution is affected by the internal alignment of individual modules.

- The alignment was implemented using the *Millepede II* framework, minimising

\[ \chi^2(a, b) = \sum_{j} \sum_{i} \frac{(r_{i,j}(a, b_j))^2}{(\sigma_{\text{det}})^2} \]

- Alignment convergence in simulation was reached within 2 µm and 10 µm radially and vertically, respectively. Simulation results were obtained with O(10^5 tracks) with 3 iterations.
Alignment Results

• With data, the number of reconstructed tracks has increased by 6% due to the position calibration from the alignment.
• Extrapolated tracks have a radial shift towards the centre of the ring of 0.50 mm and a vertical shift of 0.14 mm.

• The uncertainty contribution from the tracker misalignment to the pitch correction is now negligible.

• Alignment monitoring results (single iteration) are stable throughout the entire Run-1.
Electric Dipole Moment (EDM)

- A measurement of the muon EDM \(d_\mu\) would provide clear evidence of CP violation.
- The tracker will realise an EDM measurement through the direct detection of oscillation in the average **vertical angle** of the decay \(e^+\) 

- Simulation results with large EDM signal

\[
\omega_{\eta} = \sqrt{\omega_a^2 + \omega_\eta^2}
\]

- SM limit of \(d_\mu \sim 10^{-25} \text{ e} \cdot \text{cm}\) (mass-scaling the measured electron EDM)
- Some SM extensions predict a limit of \(\sim 10^{-23} \text{ e} \cdot \text{cm}\)
- Current experimental limit is \(< 1.8 \times 10^{-19} \text{ e} \cdot \text{cm}\) \textit{Phys. Rev. D} 80, 052008 (2009)
- **Goal**: Measure \(\delta\) to within 0.4 \(\mu\)Rad to place a new limit on the muon EDM, with a sensitivity of \(10^{-21} \text{ e} \cdot \text{cm}\), a 100 fold improvement on the Brookhaven result.
• This figure has 1 billion positrons. The number of wiggles is similar to the one achieved by BNL in 1999

• Run-1 (2018): analysing collected data
• Run-2 (2019): just finished production
• Analysis of Run1 data is nearing completion
• First publication at the end of 2019
• Expecting to accumulate another x17 BNL in the next two years
<table>
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<tr>
<th>Category</th>
<th>E821 [ppb]</th>
<th>E989 Improvement Plans</th>
<th>Goal [ppb]</th>
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<td>Better laser calibration low-energy threshold</td>
<td>20</td>
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<tr>
<td>Pileup</td>
<td>80</td>
<td>Low-energy samples recorded calorimeter segmentation</td>
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<td>Lost muons</td>
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<td>Better collimation in ring</td>
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<td>CBO</td>
<td>70</td>
<td>Higher $n$ value (frequency)</td>
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<td>$E$ and pitch</td>
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<td>Improved tracker</td>
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<td>Precise storage ring simulations</td>
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<td>Total</td>
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<td>Quadrature sum</td>
<td>70</td>
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- Total systematic uncertainty on $\omega_p$: 70 ppb
- Total statistical uncertainty: 100 ppb