Tracking in the Muon g-2 Experiment

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Motivation

\[ \bar{\mu} = g \frac{e}{2m_\mu c} \bar{S} \]

Tool for probing physics

\[ a_\mu = \frac{g-2}{2} \]

- \( a_\mu \) (theory) = 116 591 802 (49) x 10^{-11} (0.42 ppm)
- \( a_\mu \) (exp) = 116 592 089 (63) x 10^{-11} (0.54 ppm)

The Muon g-2 at Brookhaven measured an ~3.6\( \sigma \) deviation with the Standard Model.

Hints of physics beyond the Standard Model?!

The FNAL Muon g-2 \( \rightarrow \) experimental uncertainty 140 ppb \( \rightarrow >5 \sigma \)
Measuring the muon anomalous magnetic moment:

\[ a_\mu = g-2/2 \]

Inject a polarized \( \mu^+ \) beam in a storage ring with an uniform B-field

B-field = 1.45 Tesla

Need to understand the muon beam!

Time spectrum of high energy decay positrons is used to measure

\[ \omega_a = a_\mu \frac{eB}{mc} \]
Three tracker detectors are placed around the ring to extract the muon beam distribution. The locations are determined by the beam’s view of sight.

The purpose is to reconstruct the trajectories of the decay positrons entering the detector and extrapolate back to the muon decay point.
Trackers live in a vacuum chamber (< 10^-6 Torr) and are placed upstream an electromagnetic calorimeter. Trackers reside in both the uniform and fringe regions of the magnetic field.

Trackers contain 8 modules, where each consists of straw tube chambers (fill with Argon-Ethane gas).

Module consists of:

- 2 planes: U and V (with straws rotated ± 7.5°)
- A plane consists of 2 layers of 32 straws.
- The layers are offset, so the reconstruction can determine if the particle enters the left or right side of the straw.
- A straw tube: ~8 cm long (fiducial region) with a radius of 2.5 mm. ~1.0 mm gap between straw tubes.
Major Challenges

- The muon decay point ranges from 2–3 meters from the front face of trackers.

- Majority of the tracks enter the fringe region of the magnetic field.

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**Table 19.1:** Systematic uncertainty goals for the Muon g-2 experiment. Information from the tracking detectors will be used to constrain these in several ways as indicated in the final column. The first two rows are associated with the tracker’s primary physics goal. The second two are associated with the secondary physics goal of the tracker and the main role played by the tracker will be in validating the reductions in the uncertainties provided by the new calorimeters. The final row is associated with the tertiary physics goal and the improvements are entirely from increased acceptance and statistics in the new experiment.

**Tracker Regions**

- **Vertical Direction (m)**

- **X Direction (m)**

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Plot courtesy of R. Fatemi
Tracking Software and Infrastructure

Consist of developers from international and domestic institutions, along with a national laboratory.

Use the event-processing framework *art*
Fermilab supported, based on CMS, used by many experiments ranging from neutrinos, muons, and dark matter.

The design of the Tracking Infrastructure is modular:

- operation of multiple algorithms at each track stage
- manageable iterations between track stages
- control event model
- developer/user friendly (needed because software frameworks are unfamiliar with a fractional of the collaboration)

**Track Software and Infrastructure**

**Raw/Simulated Data**
- Digitalization
  - StrawDigits (measured hit time, wireID, wire position)
- Calibration
  - StrawDigits (t0, alignment constants, gas response constants, etc)

**Hit Pattern Recognition**
- Time Islands
- Clusters
- Seeds
  (temporal and spatial grouping of digits to give the position)

**Track Finding**
- Track Candidates
  (spatial grouping of seeds to form track candidates having an initial momenta and helical properties)

**Track Fitting**
- Tracks
  (tracks having fitted positions, helix and momentum characterization at each hit, particle type)

**Track Extrapolation**
- Decay Vertices
  (extrapolation of tracks to the decay vertex)
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**Focus on the reconstruction framework**

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Reconstructing Tracks: Hit Pattern Recognition

Hit Pattern Recognition

Time Islands
Clusters
Seeds
(temporal and spatial grouping of digits to give the position)

Step 1:
- Per each station, time-sort the digits into increasing order.

Step 2:
- Check the time gap between the reference and neighboring digit.
- Add the neighboring digit onto the island if the time gap is less than 100 ns.
- Repeat the cycle.

End results: see digits grouped together according to the station and start/stop time.

Singlet cluster
Doublet cluster

Grouping U and V planes
Hit Pattern Recognition

Time Islands
Clustering
Seeds
(temporal and spatial grouping of digits to give the position)

Singlet cluster
doublet cluster

30% inefficiency is due to 1 mm gap between straws
Reconstructing Tracks: Tracking Stages

- **Track Finding**
  - Track Candidates
    - (spatial grouping of seeds to form track candidates having an initial momenta and helical properties)

- **Track Fitting**
  - Tracks
    - (tracks having fitted positions, helix and momentum characterization at each hit, particle type)

- **Track Extrapolation**
  - Decay Vertices
    - (extrapolation of tracks to the decay point)
Reconstructing Tracks

**Track Finding**

**Track Candidates**

(spatial grouping of seeds to form track candidates having an initial momenta and helical properties)

![Graphs showing track finding efficiency and fraction of position's hits on the track vs. number of truth hits on track.](image)
Reconstructing Tracks

Track Fitting

Tracks
(Tracks having fitted positions, helix and momentum characterization at each hit, particle type)

Track Extrapolation

Decay Vertices
(extrapolation of tracks to the decay vertex)

Fitting Algorithms in Progress
- Kalman Filter in uniform B-field
- Kalman Filter in varying B-field
- GEANE
- Karimaki Circle Fitter
- Various Straight Line Fitters

Extrapolation Algorithms in Progress
- Runge Kutta
- GEANE
Event Gallery
using Paraview (www.paraview.org)
Reconstructing Tracks: Digitalized Hits

simulated $\sim10^2$ muons per fill
expected $\sim10^4$ muons per fill (12 Hz)
Reconstructing Tracks : Time Islands

Grouped hits within a time window
• 7 time islands
Clusters share a digitalized hit.
Reconstructing Tracks: Seeding
Reconstructing Tracks: Track Finding
Summary

- It is a very exciting time for the Muon g-2 experiment.

- Start data taking in the Summer of 2017.

- Tracking algorithms are under development and making great progress. However, there are many unique challenges for the reconstruction.

- Tracking will constrain and reduce the muon-beam related systematic uncertainties associated with the measured observables, $\omega_a$ and $\omega_p$ (magnetic field).
Thank you
Backup Slides
## Expected Systematic Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>E821 value</th>
<th>E989 goal</th>
<th>Role of tracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field seen by muons</td>
<td>0.03 ppm</td>
<td>0.01 ppm</td>
<td>Measure beam profile on a fill by fill basis ensuring proper muon beam alignment</td>
</tr>
<tr>
<td>Beam dynamics corrections</td>
<td>0.05 ppm</td>
<td>0.03 ppm</td>
<td>Measure beam oscillation parameters as a function of time in the fill</td>
</tr>
<tr>
<td>Pileup correction</td>
<td>0.08 ppm</td>
<td>0.04 ppm</td>
<td>Isolate time windows with more than one positron hitting the calorimeter to verify calorimeter based pileup correction</td>
</tr>
<tr>
<td>Calorimeter gain stability</td>
<td>0.12 ppm</td>
<td>0.02 ppm</td>
<td>Measure positron momentum with better resolution than the calorimeter to verify calorimeter based gain measurement</td>
</tr>
<tr>
<td>Precession plane tilt</td>
<td>4.4 $\mu$Rad</td>
<td>0.4 $\mu$Rad</td>
<td>Measure up-down asymmetry in positron decay angle</td>
</tr>
</tbody>
</table>
### Expected Environment of Tracker Detectors

#### 19.2 Requirements

Requirements for the tracking detectors have been documented elsewhere \[3\] and are summarized here. The DC nature of the muon beam requires that the tracker performs well for all momentum ranges and from the first tracking plane. The arc length between the calorimeter and the muon decay point as a function of positron momentum is shown in Fig. 19.1. The tracker must measure the vertical and radial profile of the muon beam to much better than a centimeter, leading to requirements of order $100 \mu m$ resolution per position measurement in the radial dimension. Since there is no curvature in the vertical dimension, the resolution requirements are significantly relaxed in that dimension. The long extrapolation from the tracking detector to the muon decay point requires that multiple scattering be minimized and that the material associated with each tracking plane be below $0.5\%$ radiation length.

The trackers are required to reside in vacuum chambers in a vacuum of approximately $10^{-6}$ Torr and have either a vacuum load on the system below $5 \times 10^{-5}$ Torr $l/s$ or include a localized increase in pumping speed near the tracker. The tracker must be located as close to the stored muon beam as possible without interfering with the NMR trolley. Any passive material for the tracker should be located outside $\pm 4.5$ cm from the beam center in the vertical dimension to prevent degradation of the positron energy measurement in the downstream calorimeter. Tracking planes should be as close together as possible to maximize acceptance for low momentum positrons while the first and last planes should be as far apart as possible to provide sufficient lever arm for the long extrapolation of high momentum positrons back to the muon decay point.

#### Any Perturbations to the Magnetic Field

Any perturbations to the magnetic field due to material or DC currents must be below $10$ ppm at the center of the storage region over an azimuthal extent of greater than $2\pi$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact parameter resolution</td>
<td>$\ll 1$ cm</td>
<td>Set by RMS of the beam</td>
</tr>
<tr>
<td>Vertical angular resolution</td>
<td>$\ll 10$ mrad</td>
<td>Set by angular spread in the beam</td>
</tr>
<tr>
<td>Momentum resolution</td>
<td>$\ll 3.5%$ at 1 GeV</td>
<td>Set by calorimeter resolution</td>
</tr>
<tr>
<td>Vacuum load</td>
<td>$5 \times 10^{-5}$ Torr $l/s$</td>
<td>assumes $10^{-6}$ Torr vacuum and E821 pumping speed</td>
</tr>
<tr>
<td>Instantaneous rate</td>
<td>$10$ kHz/cm$^2$</td>
<td>Extrapolated from E821</td>
</tr>
<tr>
<td>Ideal coverage</td>
<td>$16 \times 20$ cm</td>
<td>Front face of calorimeter</td>
</tr>
<tr>
<td>Number of stations</td>
<td>$\geq 2$</td>
<td>Required to constrain beam parameters</td>
</tr>
<tr>
<td>Time independent field perturbation</td>
<td>$&lt; 10$ ppm</td>
<td>Extrapolation from E821</td>
</tr>
<tr>
<td>Transient ($&lt; 1$ ms) field perturbation</td>
<td>$&lt; 0.01$ ppm</td>
<td>Invisible to NMR</td>
</tr>
</tbody>
</table>