Measuring the anomalous precession frequency $\omega_\alpha$ for the Muon $g - 2$ Experiment

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Measuring $a_\mu = g^{-2}/2$

- Spin precesses relative to momentum in magnetic field

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

\[ \approx 0 \] for motion transverse to magnetic field

\[ \approx 0 \] for muons at “magic” momentum 3.1 GeV / c or $\gamma = 29.3$
Decay energy as a proxy for spin direction

- In the muon’s ($\mu^+$) rest frame, higher energy decay positrons were more likely emitted in the direction of the spin.
- Boost to the lab frame, we’ll see an oscillation in number of high-energy positron events as the spin precesses relative to momentum.
Using calorimeters to measure spin precession

• 24 calorimeters equally spaced around the inner radius of the storage region
  – Each is a 6 high by 9 wide array of PbF$_2$ crystals
  – Large-area SiPMs to read out Cherenkov light
• Laser distribution system to track and correct for gain fluctuations
• $\omega_a$ is imprinted on the arrival time and energy of decay positrons
Positrons shower when striking a calorimeter

- Signals are digitized at ~800 mega-samples per second (actual clock frequency is hardware blinded)
- Reconstruction to find time and energy of impact
  - Two methods
    - Global fitting: fit a block of channels simultaneously
    - Local fitting: fit individual channels, cluster fit results

![Sample graph showing time and energy of impact](image)
Fit function

- A typical histogram + fit
  - Cut on positron energy
  - Fit software blinded with offset $\Delta R$
    - Unique to each analyzer

$$N(t) = N_0 \exp\left(-t/\gamma \tau_\mu\right) \left[1 + A \cos \left(\omega_{a,\text{ref}} \left(1 + \Delta R + R \cdot 10^{-6}\right) t - \phi\right)\right]$$
Pileup

- 2 classes of correction methods:
  - Macro
    - Take an \((E, t)\) histogram and determine the probability of multiple hits happening within the detector dead time
  - Micro
    - For each event, determine the chance it could have been involved in a pileup event
    - "Shadow window"

Energy spectra before and after pileup correction

Examples of pileup
Extending fit function for other effects

- “Lost muons” change $N \rightarrow N(t)$
  - Muons that escape storage region without decaying
  - See H. Binney’s talk in this session

- Beam motion inside storage region
  - Relative acceptance changes
  - $N, A, \phi$ oscillate at beam frequencies

\[
N_{CBO}(t) = 1 + A_{CBO,N} \cdot e^{-t/\tau_{CBO}} \cos(\omega_{CBO} \cdot t - \phi_{CBO,N})
\]

\[
N_{VW}(t) = 1 + A_{VW,N} \cdot e^{-t/\tau_{VW}} \cos(\omega_{VW} \cdot t - \phi_{VW,N})
\]

\[
\phi(t) = \phi_0 + A_{CBO,\phi} \cdot e^{-t/\tau_{CBO}} \cos(\omega_{CBO} \cdot t - \phi_{CBO,\phi})
\]

\[
A(t) = A_0 \left[ 1 + A_{CBO,A} \cdot e^{-t/\tau_{CBO}} \cos(\omega_{CBO} \cdot t - \phi_{CBO,A}) \right]
\]

Modified fit function:
Fits for Run 1 (2018) datasets

1a

\[ \chi^2/\text{ndf}: 3955/4137 \]

precision: 1.33 ppm

1b

\[ \chi^2/\text{ndf}: 3988/4133 \]

precision: 1.13 ppm

1c

\[ \chi^2/\text{ndf}: 4055/4133 \]

precision: 0.91 ppm

1d

\[ \chi^2/\text{ndf}: 4213/4134 \]

precision: 0.64 ppm
Different histogramming methods

- **Threshold (already shown)**
  - Optimize energy cut to minimize error on fitted $\omega_a$

- **Asymmetry**
  - Weight each energy bin by the measured asymmetry: $1 + A\cos(\omega_a t)$
  - Improved statistical precision

- **Ratio**
  - Split data into 4 subsets; shift 2 of them by $\pm T_a/2$
    - Combine and take a ratio of subsets in a way that reduces to only sinusoid
  - Less sensitive to slow effects

- **Energy-integrated**
  - See L. Kelton’s talk in this session
Run 1 (2018)

- 6 independent analyses
  - 2 reconstruction methods
  - 3 pileup correction algorithms
  - 4 fitting methods
- Relative unblinding was encouraging
- Total statistical error for Run 1 is ~450 ppb
  - Still working through the systematic error, expected to be below statistical error
- Method paper underway
A glimpse at a subset of Run 2 (2019)

- Total Run 2 is about twice the data as Run 1
  - More consistent operating conditions

- Questions?
Backup slides
Ratio method

• Split data randomly into 4 subgroups: $a_i$
  – Shift 2 in time

\[
\begin{align*}
  u_+ (t) &= a_1 \left(t + T_a/2\right) & U(t) &= u_+ (t) + u_- (t) \\
  u_- (t) &= a_2 \left(t - T_a/2\right) & V(t) &= v_1 (t) + v_2 (t) \\
  v_1 (t) &= a_3 (t) & R(t) &= \frac{V(t) - U(t)}{V(t) + U(t)} \\
  v_2 (t) &= a_4 (t)
\end{align*}
\]

\[R(t) \approx A \cos(\omega_a t + \phi)\]
Detector gain

• Measured by laser system
  – Hours
    • Temperature-based drifts
  – Microseconds
    • Large “splash” of particles at beam injection
    • Capacitance drop causes reduced effective overvoltage
  – Nanoseconds
    • Multiple pulses close together
    • Pixel recovery
Consistency checks: energy bins
Consistency checks: calorimeter

1a
1b
1c
1d
Consistency checks: start time scan

A-Weighted

ΔR

Δt [μs]

start time [μs]

35 40 45 50 55 60 65 70

60-Hour High Kick 9 Day End Game Average

35 40 45 50 55 60 65 70

60-Hour High Kick 9 Day End Game Average
Run 1 fit residuals FFTs

• T-method