FERMILAB-SLIDES-20-010

Measuring the anomalous precession frequency ω_a for the Muon $g-2$ Experiment

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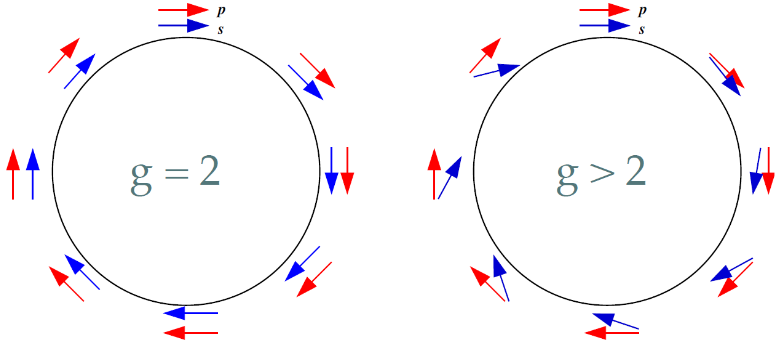
APS April Meeting 2020

20 April 2020

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

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

- Spin precesses relative to momentum in magnetic field



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

≈ 0 for motion transverse to magnetic field

≈ 0 for muons at “magic” momentum 3.1 GeV / c or $\gamma = 29.3$

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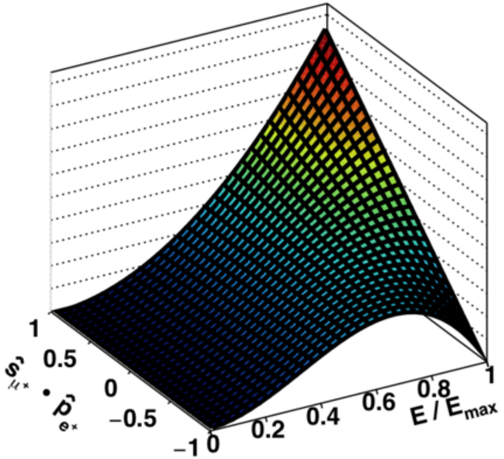
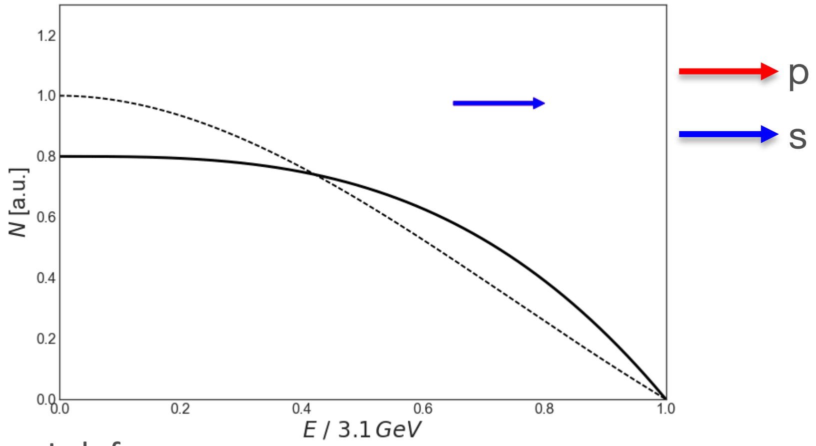
Decay energy as a proxy for spin direction

- In the muon's (μ^+) 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



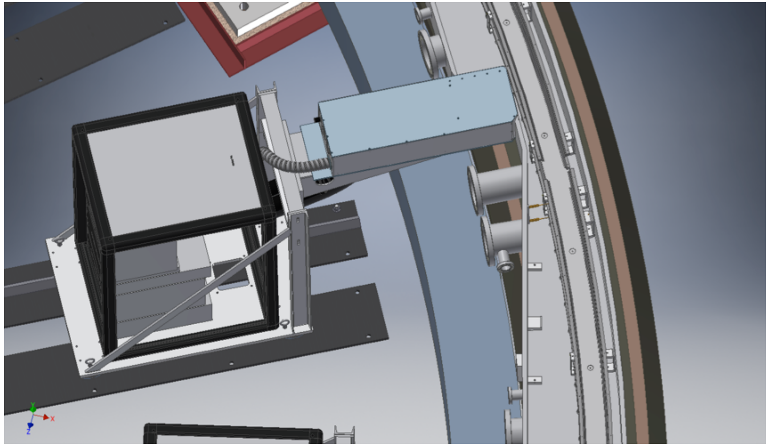
Rest frame



Lab frame

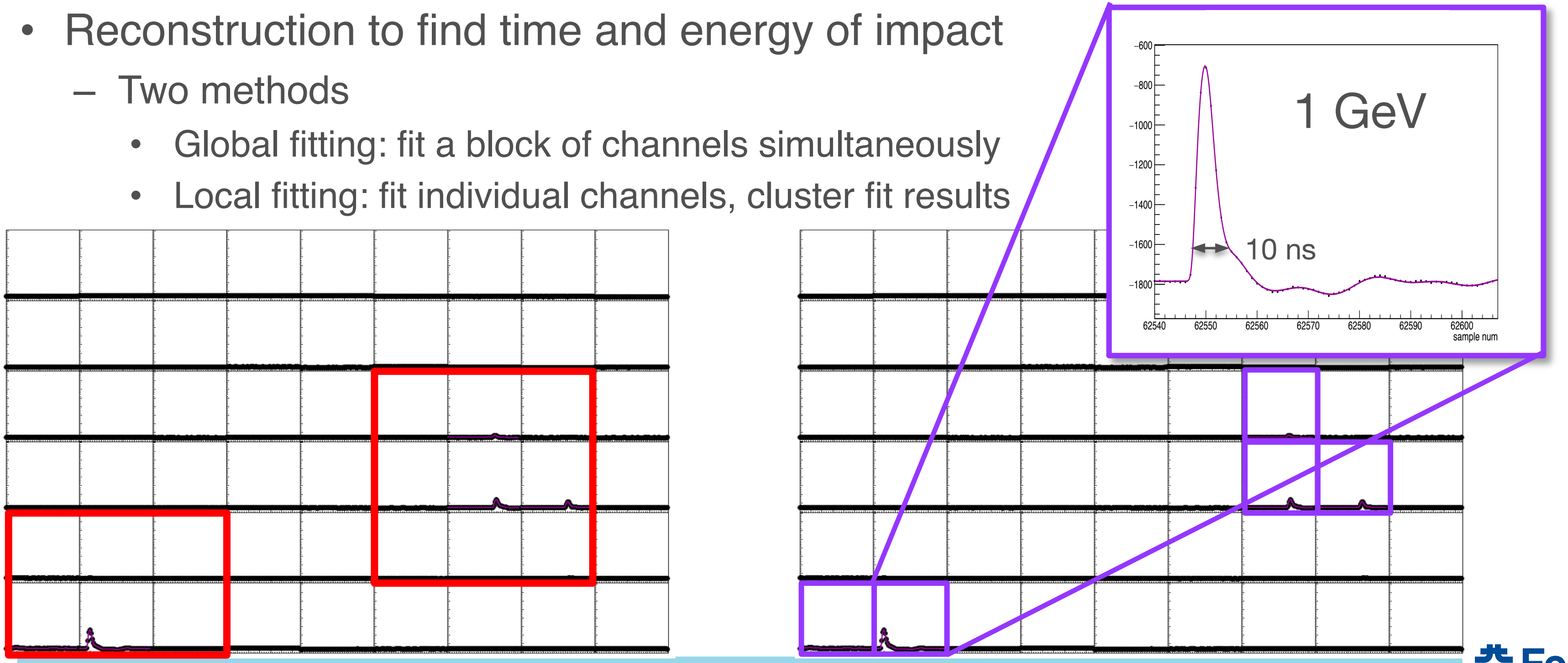
Using calorimeters to measure spin precession

- 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
- ω_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



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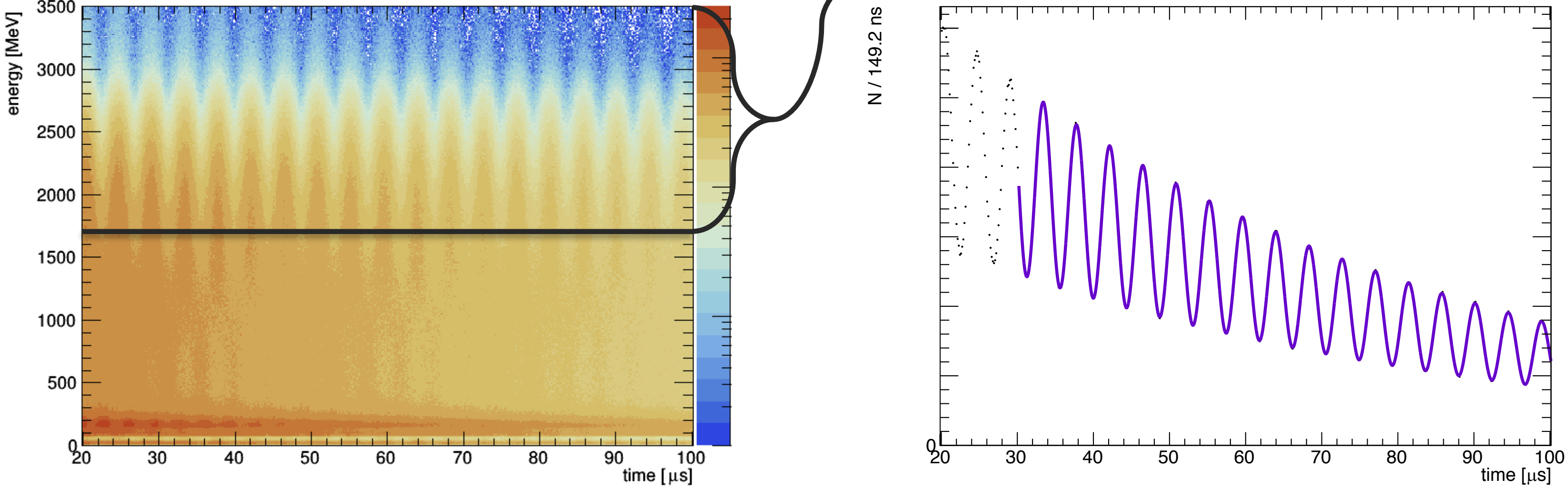
Fit function

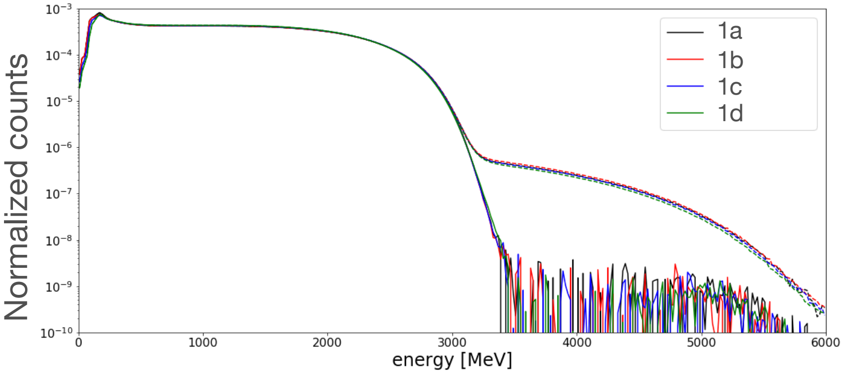
- A typical histogram + fit
  - Cut on positron energy
  - Fit software blinded with offset ΔR
    - Unique to each analyzer

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

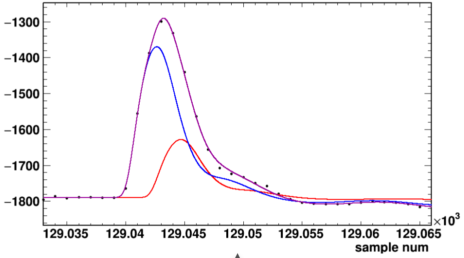


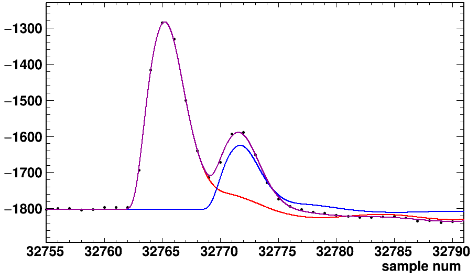
Pileup

- 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

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Extending fit function for other effects

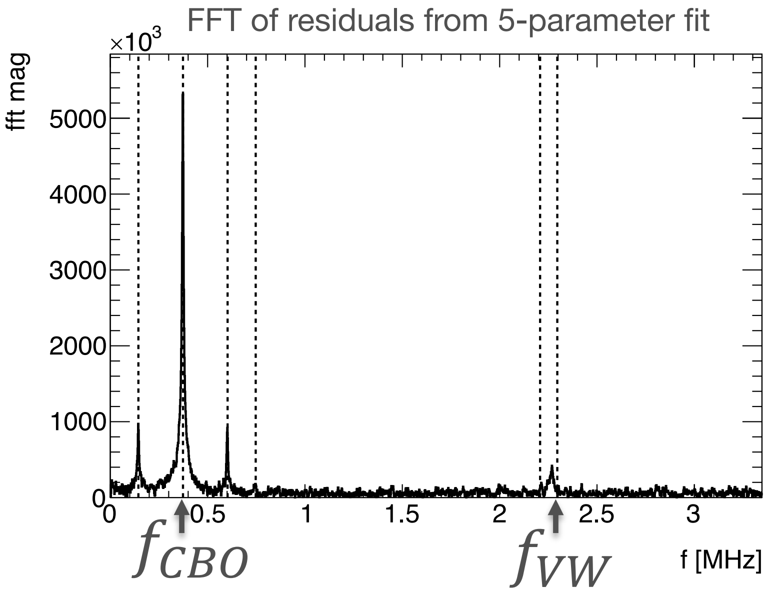
- "Lost muons" change $N \rightarrow N(t)$
  - Muons that escape storage region without decaying
  - See H. Binney's talk in this session
- Beam motion inside storage region
  - Relative acceptance changes
  - N, A, ϕ oscillate at beam frequencies

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

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

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

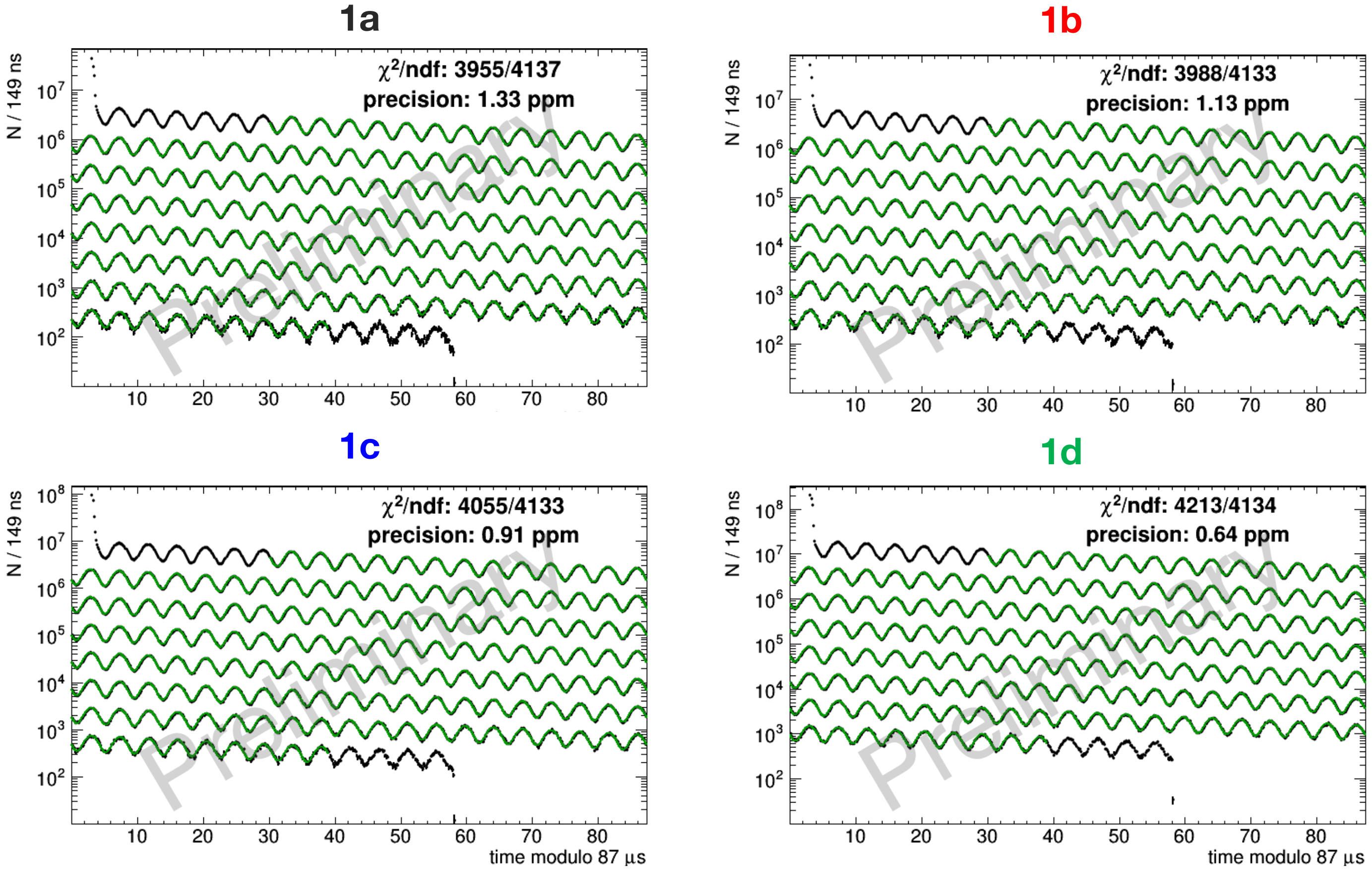
$$A(t) = A_0\left[1 + A_{CBO,A} \cdot e^{-t/\tau_{CBO}} \cos\left(\omega_{CBO} \cdot t - \phi_{CBO,A}\right)\right]$$



Modified fit function:

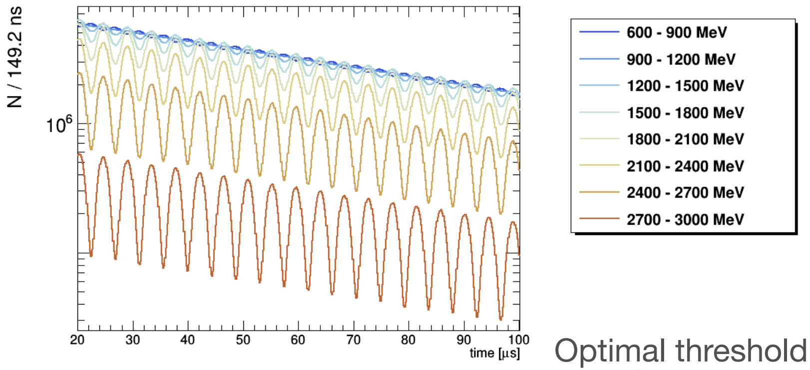
$$N(t) = N_0 \cdot \left(1 - K_{loss} \int_0^t e^{t'/\tau} L(t')\, dt'\right) \cdot N_{CBO}(t) \cdot N_{VW}(t) \cdot e^{-t/\tau} \cdot \left[1 + A(t) \cos\left(\omega_a(R) - \phi(t)\right)\right]$$

Fits for Run 1 (2018) datasets

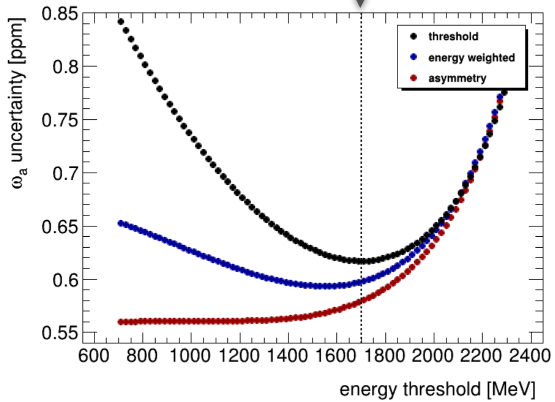


Different histogramming methods

- Threshold (already shown)
  - Optimize energy cut to minimize error on fitted ω_a
- **Asymmetry**
  - Weight each energy bin by the measured asymmetry: $1 + \boldsymbol{A}\cos(\omega_a t)$
  - 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

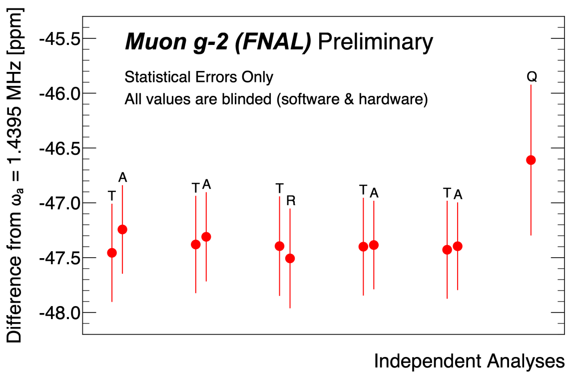


Optimal threshold cut

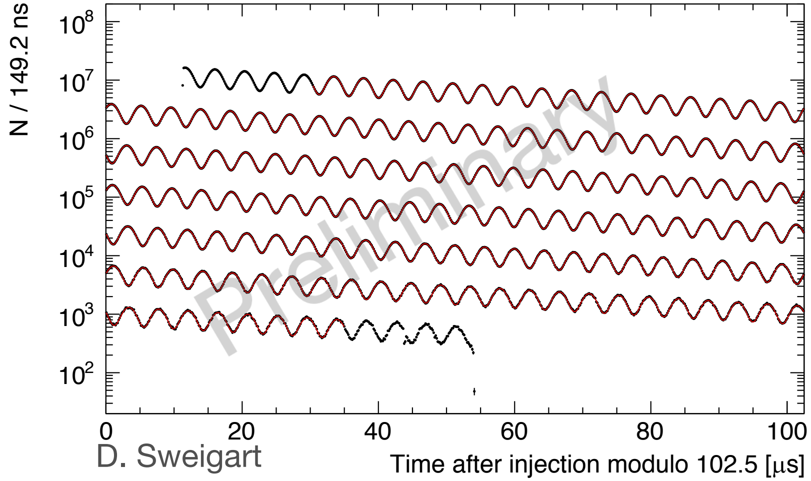


Run 1 (2018)

- 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



Full Run 1 dataset



D. Sweigart

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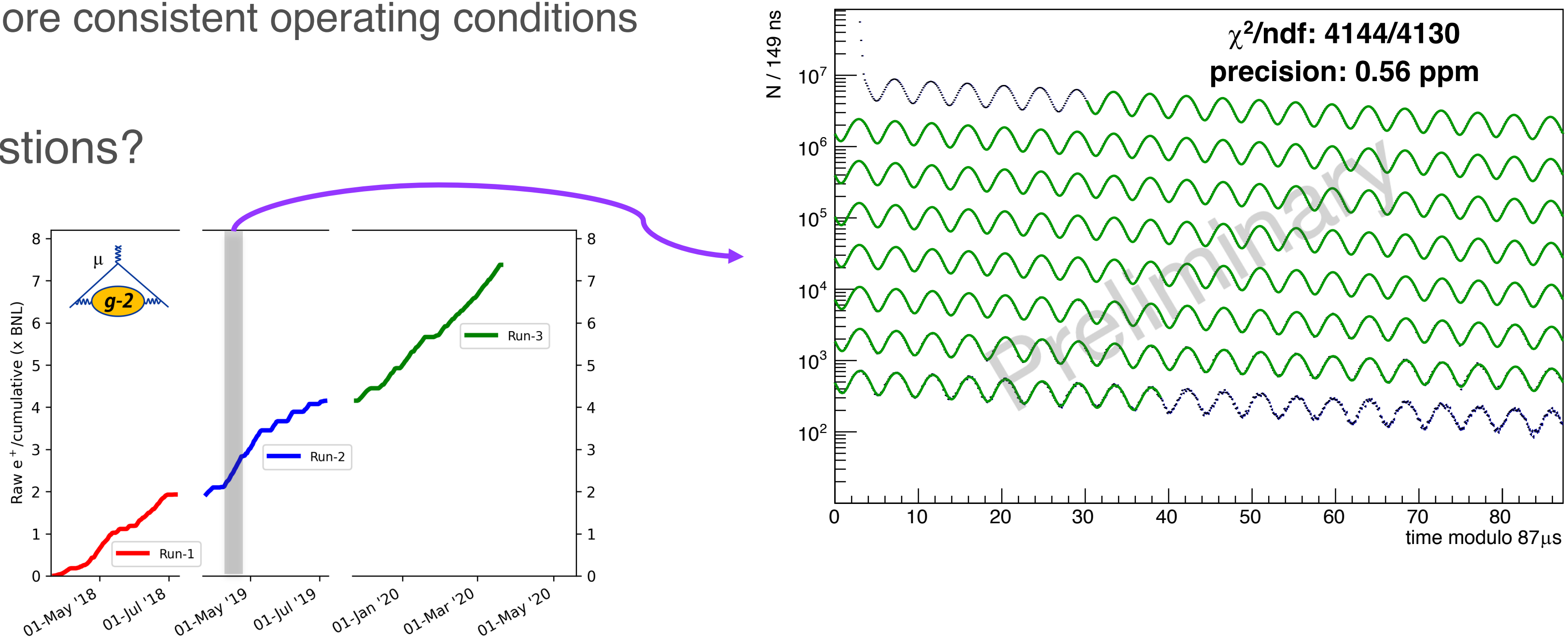
A glimpse at a subset of Run 2 (2019)

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

- Questions?

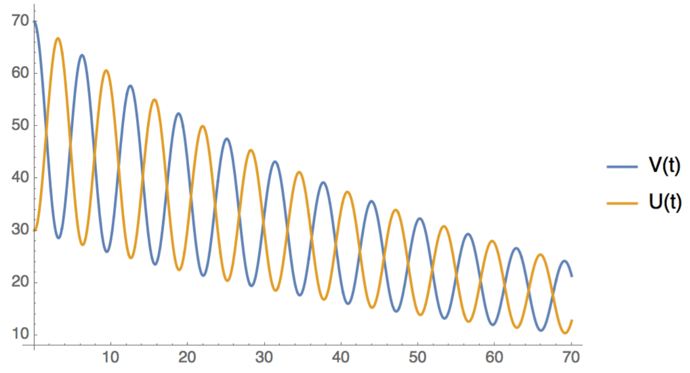


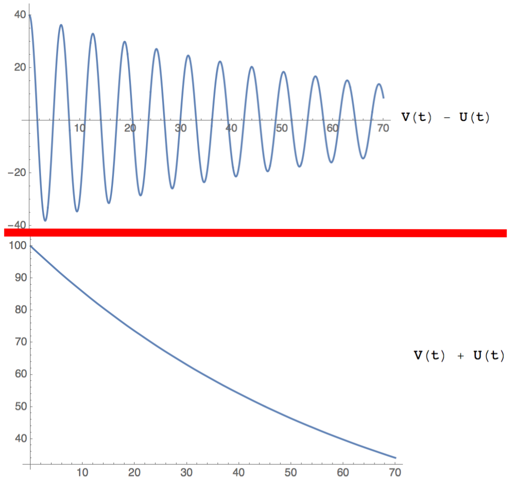
Backup slides

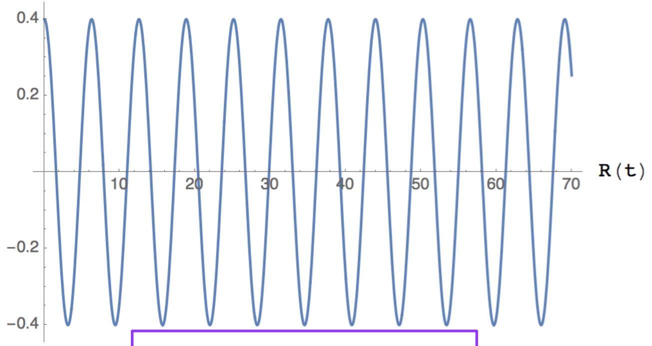
Ratio method

- Split data randomly into 4 subgroups: a_i
  - Shift 2 in time

$$
\begin{aligned}
u_+(t) &= a_1(t + T_a/2) \\
u_-(t) &= a_2(t - T_a/2) \\
v_1(t) &= a_3(t) \\
v_2(t) &= a_4(t)
\end{aligned}
\qquad
\begin{aligned}
U(t) &= u_+(t) + u_-(t) \\
V(t) &= v_1(t) + v_2(t) \\
R(t) &= \frac{V(t) - U(t)}{V(t) + U(t)}
\end{aligned}
$$







$$R(t) \approx A\cos(\omega_a t + \phi)$$

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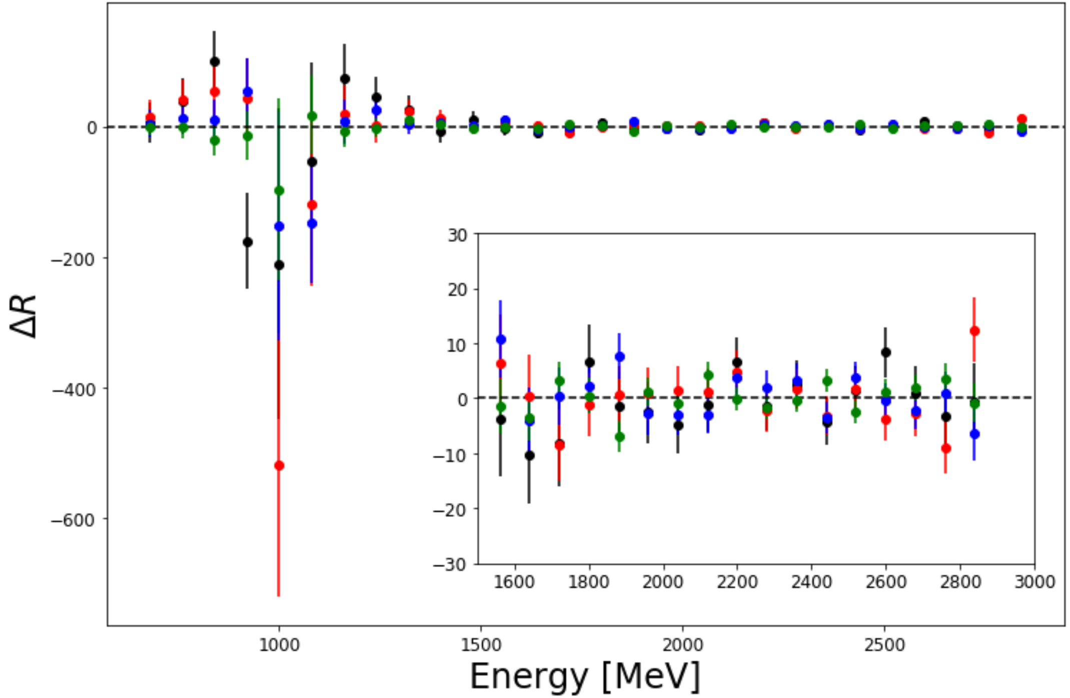
Detector gain

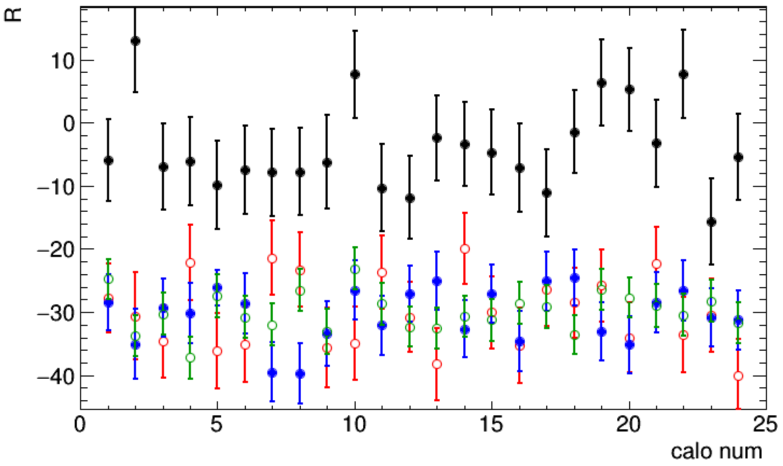
- Measured by laser system
  - Hours
    - Temperature-based drifts
  - Microseconds
    - Large “splash” of particles at beam injection
    - Capacitance drop causes reduced effective overvoltage
  - Nanoseconds
    - Multiple pulses close together
    - Pixel recovery

Consistency checks: energy bins

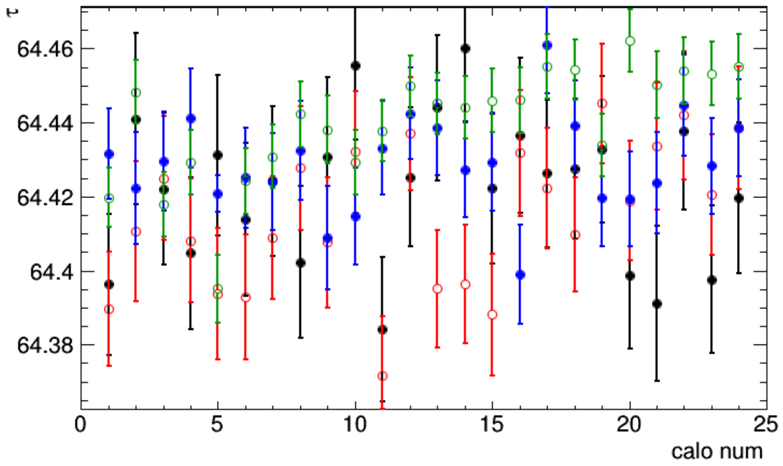


1a
1b
1c
1d

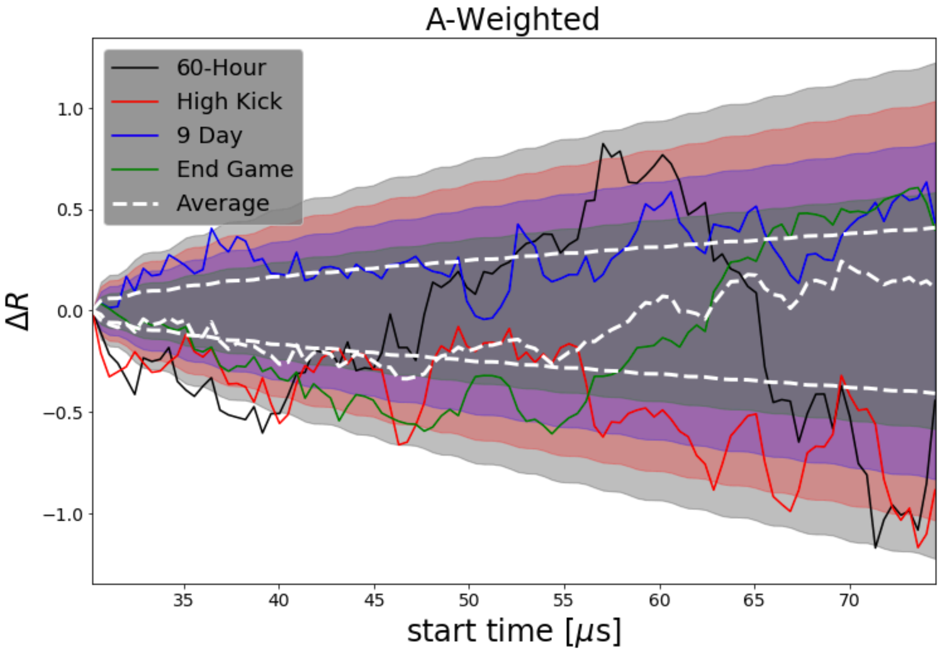
Consistency checks: calorimeter

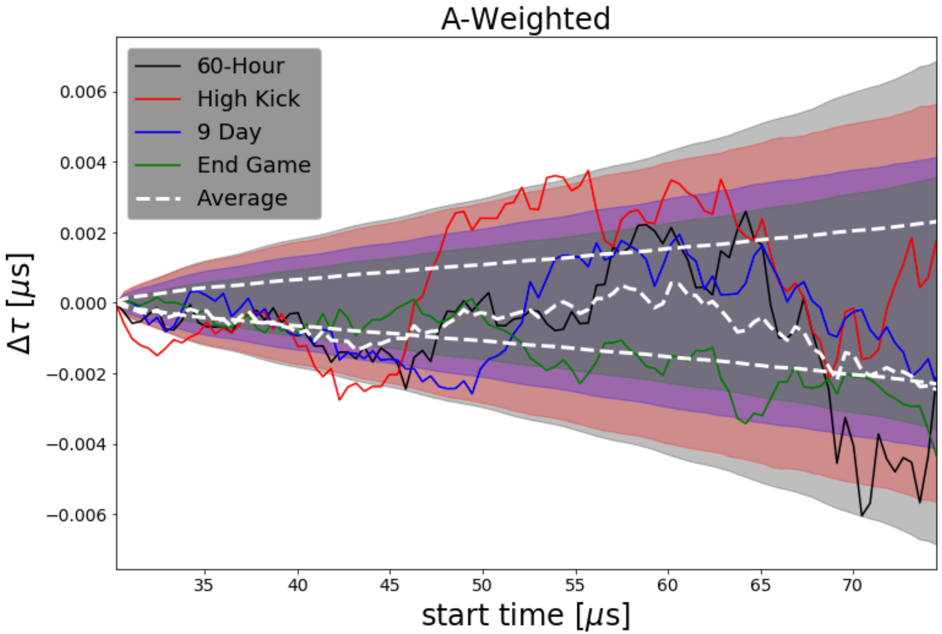


1a
1b
1c
1d



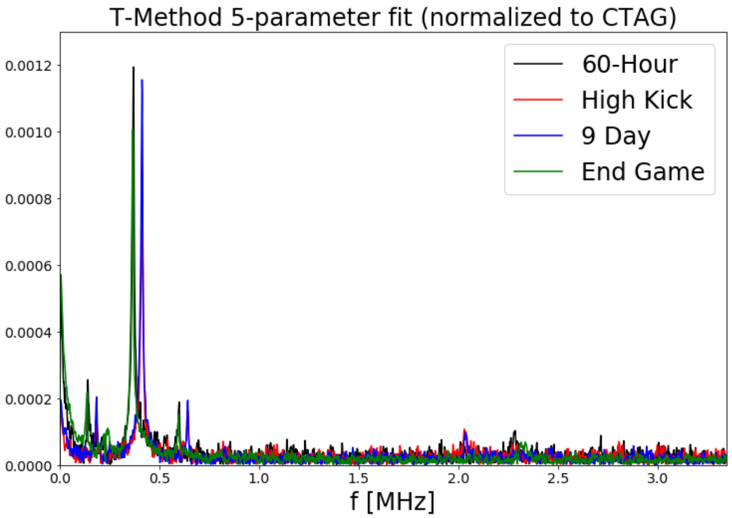
Consistency checks: start time scan

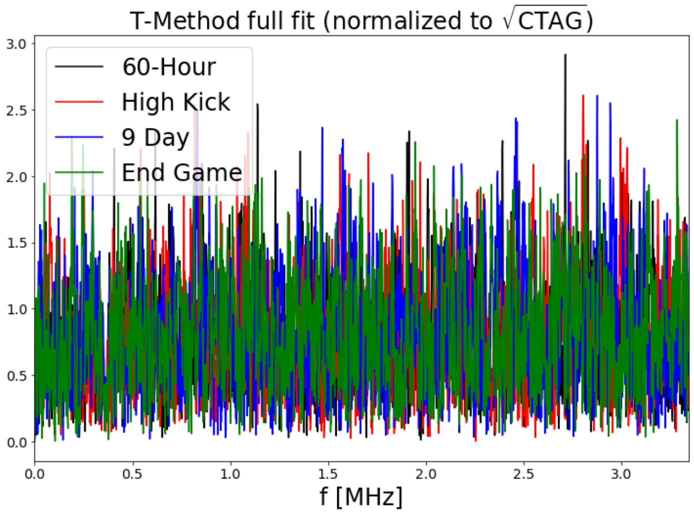




Run 1 fit residuals FFTs

- T-method





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