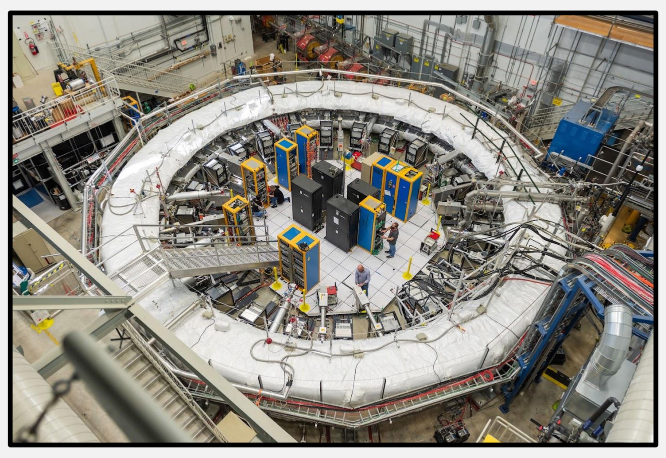

Anomalous precession frequency analysis with a focus on the beam dynamics modeling in the Fermilab Muon g-2 Experiment

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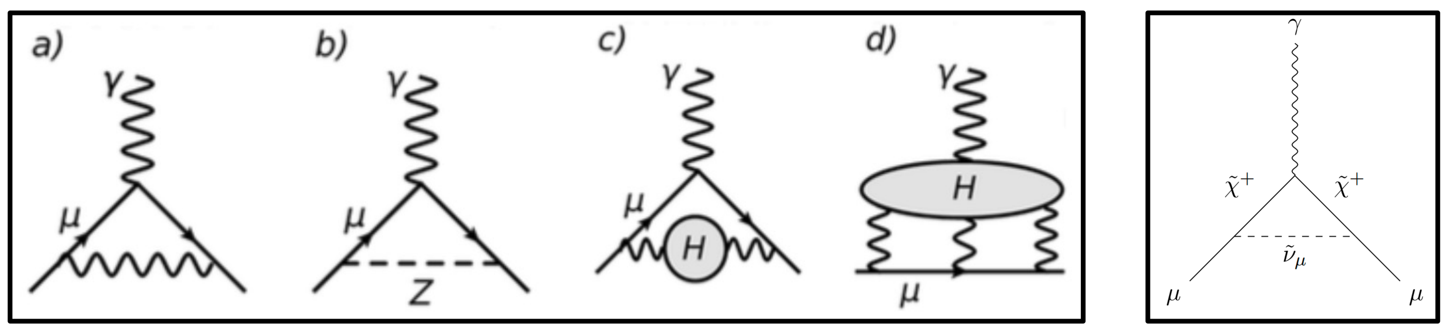
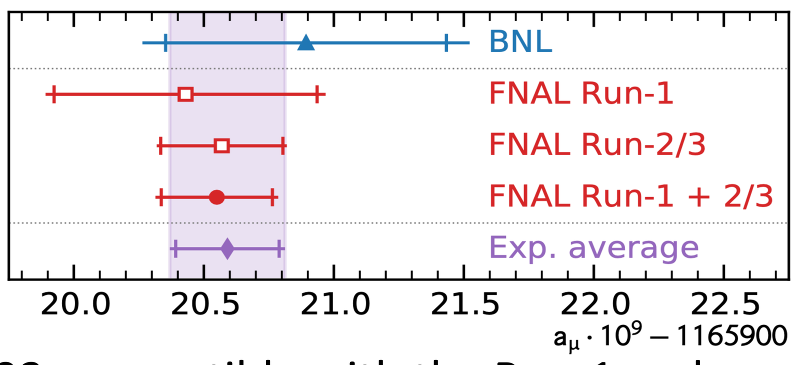
Physics and Measurements of Muon g-2

- A Dirac particle has a magnetic dipole moment of $\vec{\mu} = g\frac{q}{2m}\vec{s}$, with $g = 2$.
- In addition to the effects from QED, electroweak and hadronic effects move the g-factor away from 2. It has become customary to measure the discrepancy, $g - 2$.
- If the discrepancy is not found as the prediction from SM value, beyond SM contributions to $g - 2$ could come from SUSY, dark sector or other new physics.



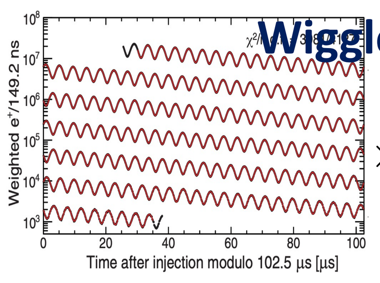
- We will measure the anomalous magnetic moment of muon, $a_\mu \equiv (g-2)/2$, to an unprecedented precision of **140 ppb**.



- We released our second result in August 2023, compatible with the Run-1 and BNL E821 result, **reaching the 5σ level**.

Fermilab E989 Measurement Principle

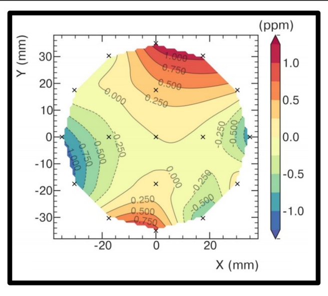
ω_a analysis

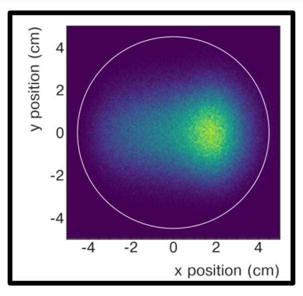


Corrections

$$a_\mu \propto \frac{\omega_a \times (1 + C_e + C_p + C_{pa} + C_{ml} + C_{dd})}{\text{B-field} \otimes \text{Beam motion}}$$

B-filed map measurement

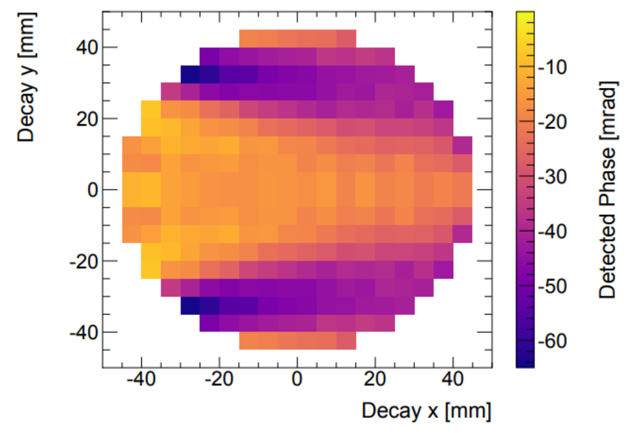




Beam motion measurement

Beam Dynamics and Systematics

- The stored muons do not move in a perfect circle due to the quadruples in the storage ring.
- The betatron oscillations enter the data through **coupling between detector acceptance and the muon decay position**.



- The uncertainty of ω_a is still **statistics dominated** in Run-2/3.

Quantity	Correction (ppb)	Uncertainty (ppb)
ω_a^m statistical	-	201
ω_a^m systematic	-	25

- **The systematics is only 25 ppb**, in which the uncertainty from **coherent betatron oscillation (CBO)** individually contributed to **21 ppb**.

Systematic uncertainty	Run-2 (ppb)	Run-3a (ppb)	Run-3b (ppb)	Run-2/3 (ppb)
CBO handling	22	18	28	21
Pileup corrections	9	6	7	7
Gain corrections	5	4	5	5
Residual slow effect	5	14	10	10
Other systematics	2	5	3	4
Total	25	24	31	25

- **Modeling CBO in a better way will reduce the uncertainty.**

Fitting Wiggle Plots

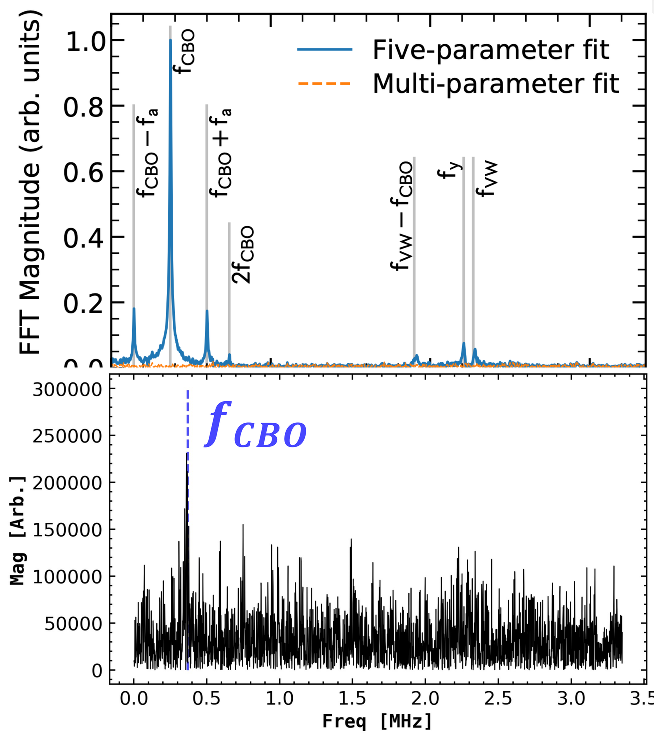
- The fit function for wiggle plot is no longer simple 5 parameters:

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

With $N_{CBO}(t)$ modeled by

$$N_{CBO}(t) = 1 + Ae^{-t/\tau_{CBO}}\cos(\omega_{CBO}t + \varphi_{CBO})$$

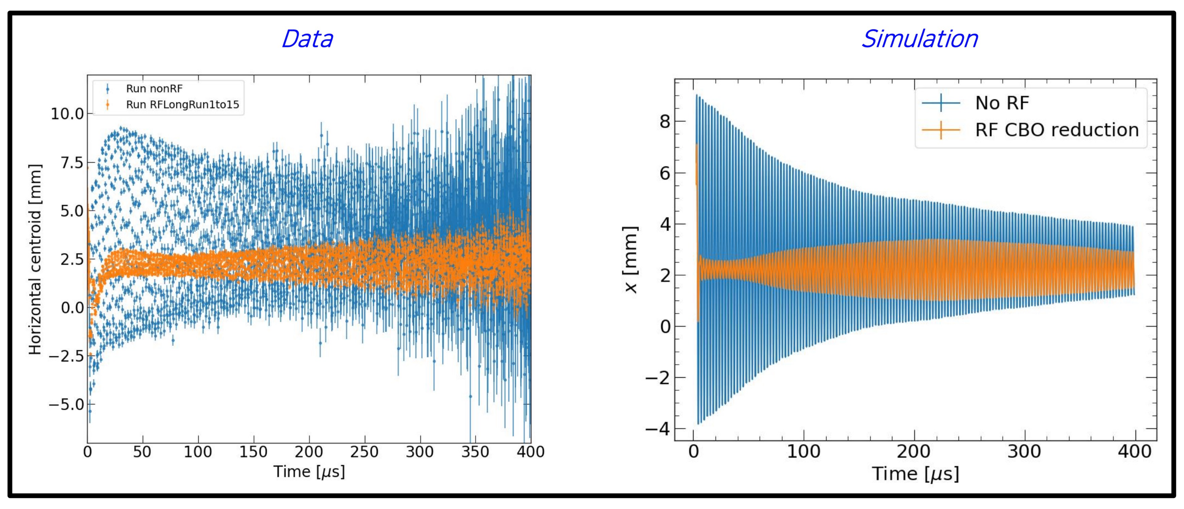
- But the exponential shape is **not applicable** for individual calorimeter data.



CBO modeling in Run-4/5/6 Data Analysis

CBO Amplitudes Suppressed in Run-5/6

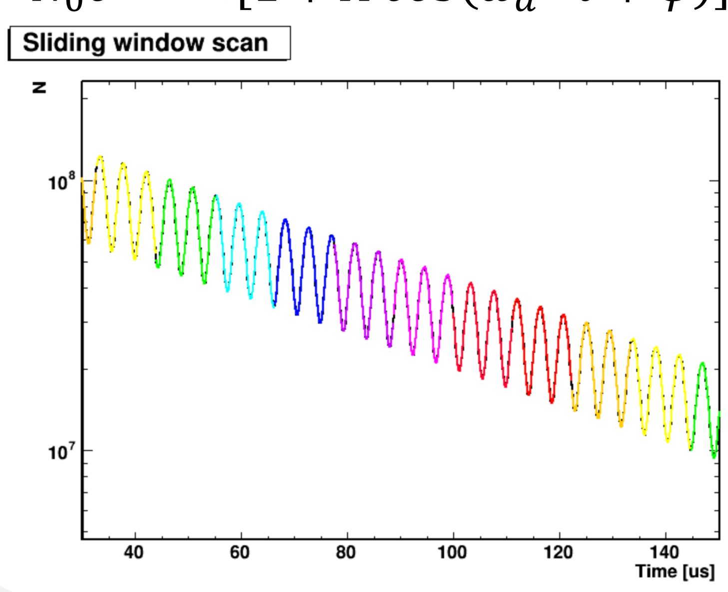
- We applied a **radio-frequency (RF)** electric field to the quadrupole plates to further suppress the CBO amplitude during Run-5/6 data-taking, which makes modeling CBO behaviour more difficult.

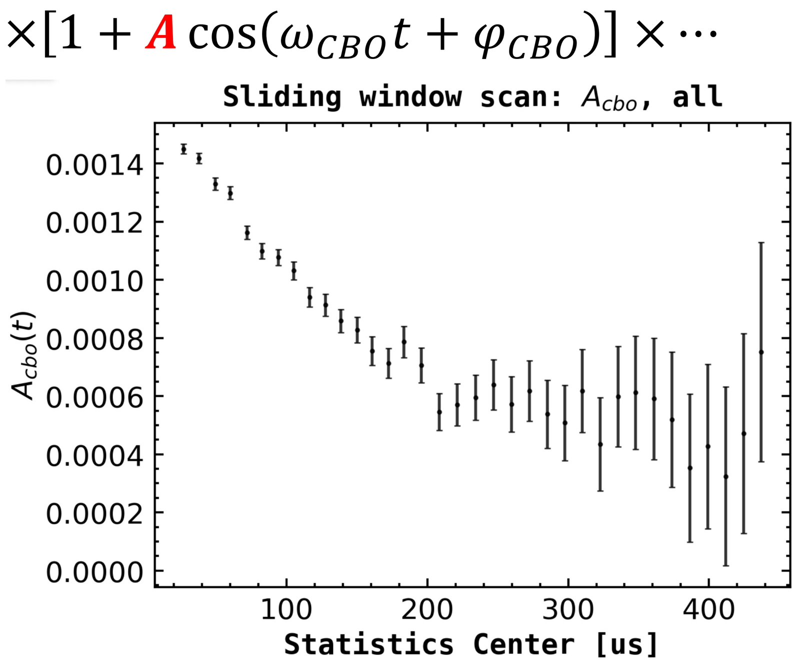


Extracting CBO Amplitude Over Time Using Calorimeter Data

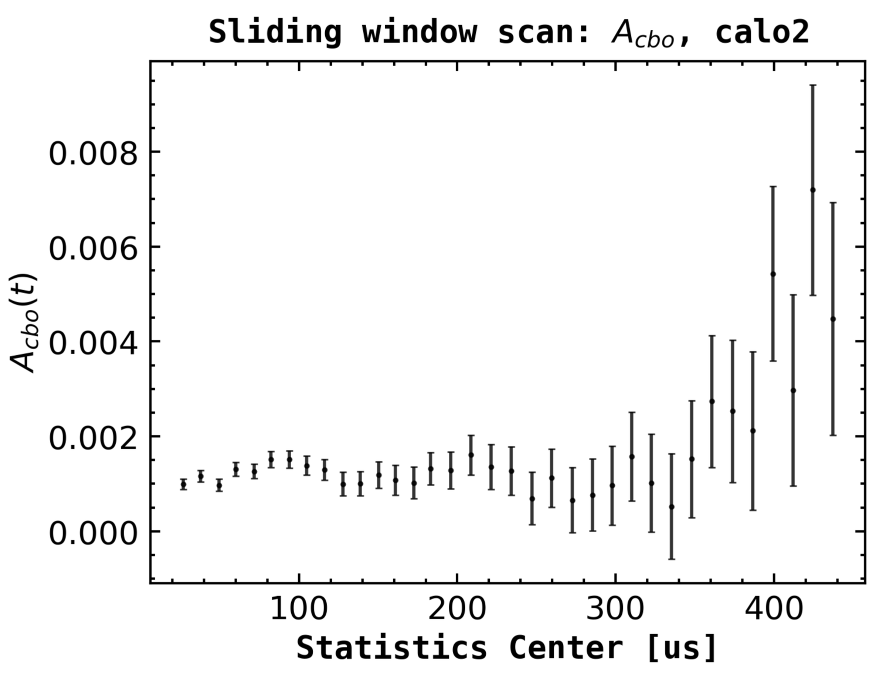
- We slice our wiggle plot into small time windows, such that the CBO amplitude could be sufficiently **regarded as constant**, namely using a **sliding window approach**.
- Fit the time window with:

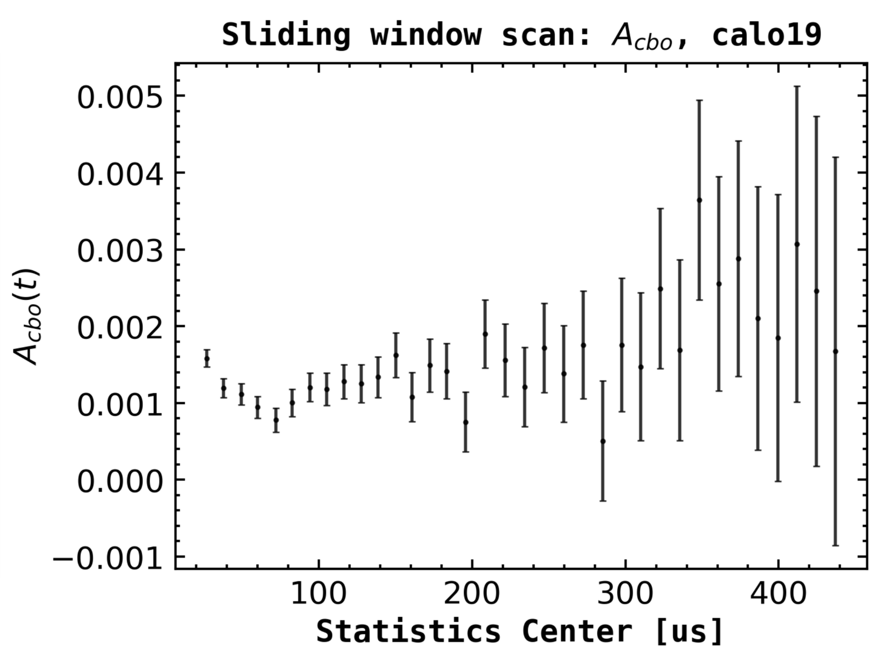
$$N_0 e^{-t/\tau} \times [1 + A\cos(\omega_a \cdot t + \phi)] \times [1 + A\cos(\omega_{CBO}t + \varphi_{CBO})] \times \cdots$$





Unusual CBO Shapes in Some Calorimeters for Run-5/6 Data

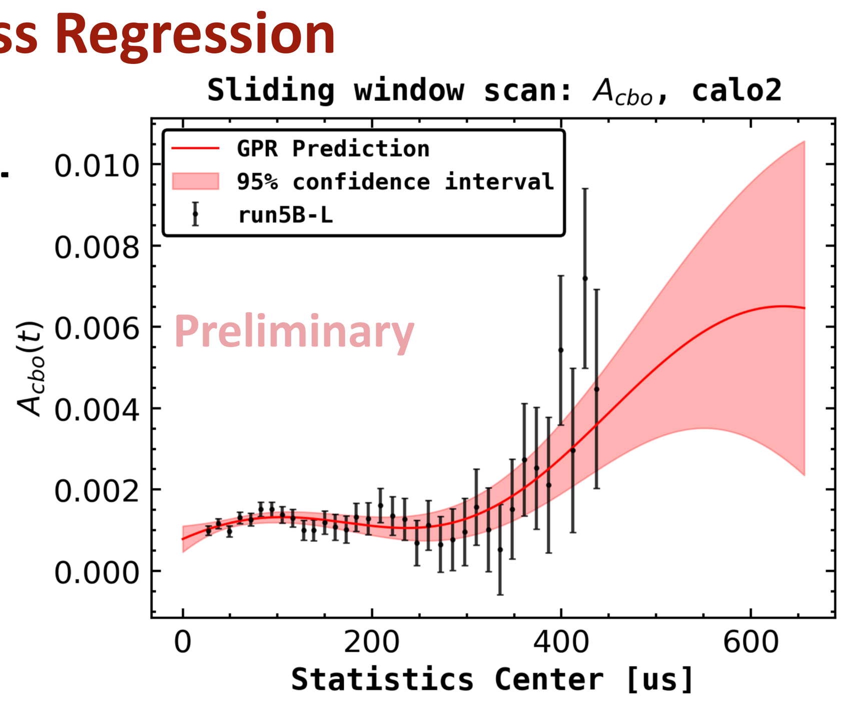




- The shape cannot be described by an exponential function.
- Interpolation methods are limited by the finite data range from the sliding window compared to 700 μs wiggle pot.

Gaussian Process Regression

- Gaussian Process Regression (GPR) is a **non-parametric machine-learning technique**.
- It can be thought of a generalization of the Gaussian probability distribution to infinitely many variables, or as a Gaussian random function.



- We propose using it to model the CBO envelope and make predictions where the sliding window data are not available.

References

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2. G. W. Bennett et al. (The Muon g-2 Collaboration), Phys. Rev. D 73, 072003(2006)
3. D. P. Aguillard et al. (The Muon g−2 Collaboration), Phys. Rev. Lett. 131, 161802(2023)

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