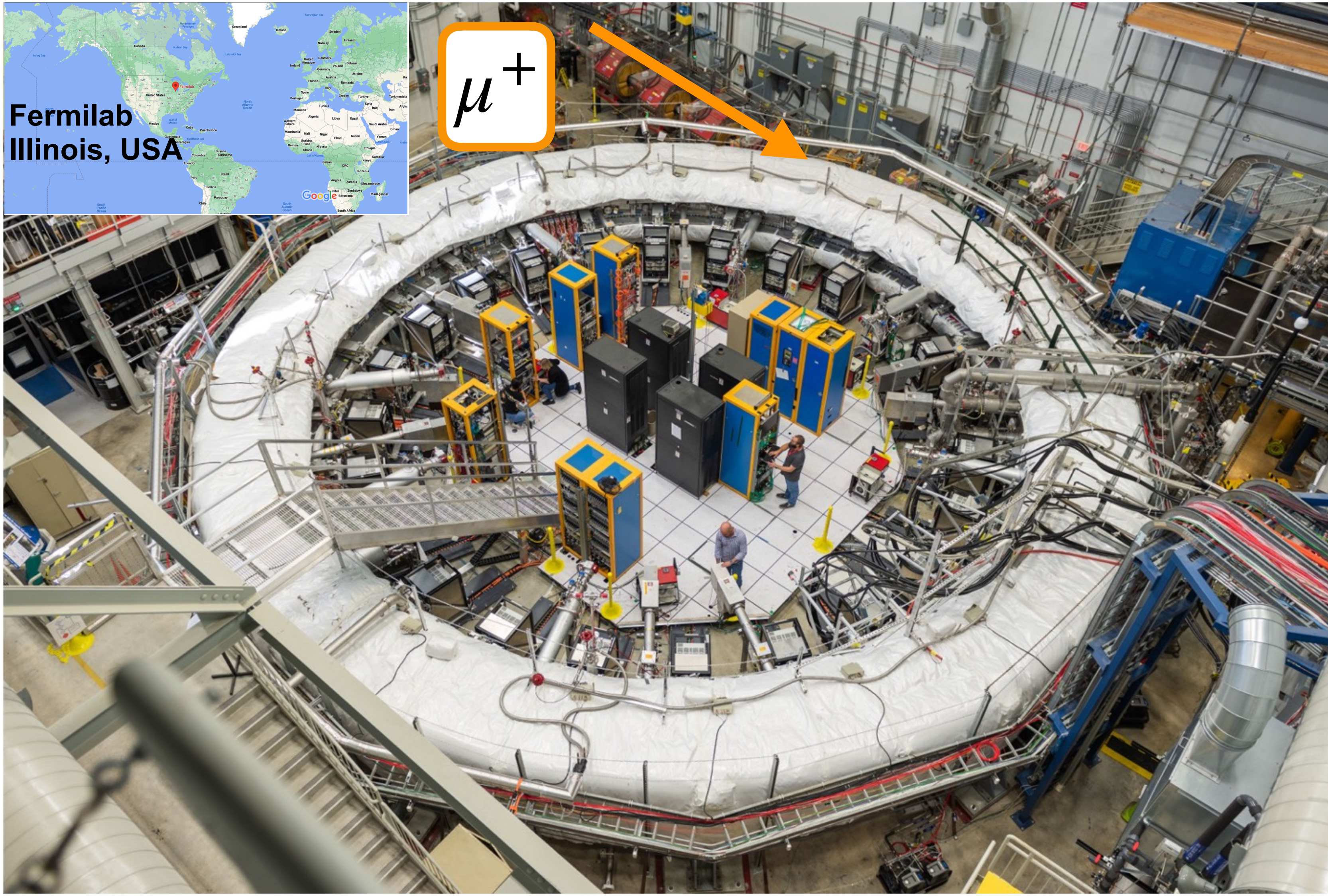
Measurement of the muon anomalous precession frequency ω_a in the Muon $g-2$ Experiment at Fermilab

Sean B. Foster
University of Kentucky
On behalf of the Muon $g-2$ Collaboration

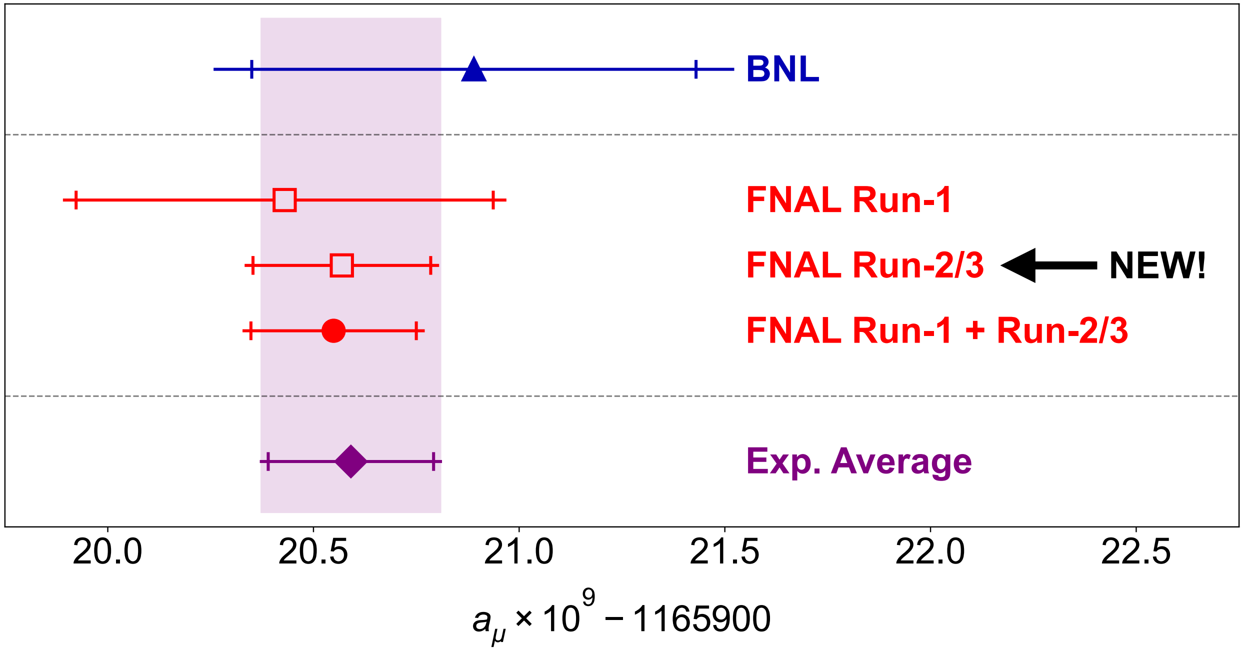
EPS-HEP 2023
August 21, 2023
Hamburg, Germany

Muon g-2 experiment at Fermilab



New measurement of muon magnetic anomaly

- Run-2/3 result **announced at Fermilab** on August 10, 2023



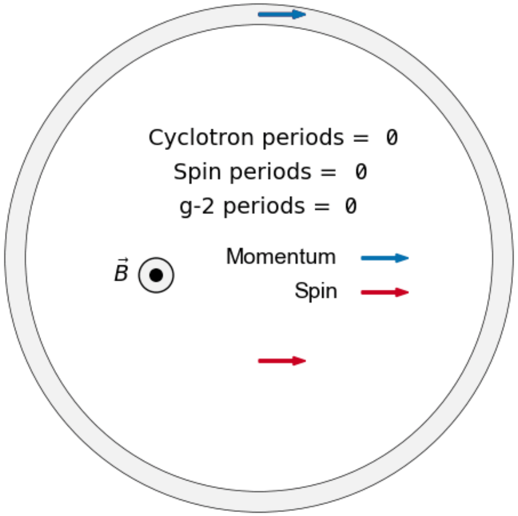
- **Excellent agreement** with Run-1 & BNL
- Uncertainty reduced by **more than x2** compared to Run-1
- a_μ**(Exp; 2023) = 0.00116 592 059(22) [190 ppb]**

Experiment principle

- Store **polarized muons** in a region of **uniform magnetic field**
- Muon's **spin precesses** (ω_s) and its **momentum rotates** (ω_c)
- **Difference frequency** is proportional to **magnetic anomaly** (a_μ)

$$\omega_a = \omega_s - \omega_c = \left[\frac{g-2}{2}\right]\frac{eB}{m}$$

$$a_\mu \equiv \frac{g-2}{2}$$



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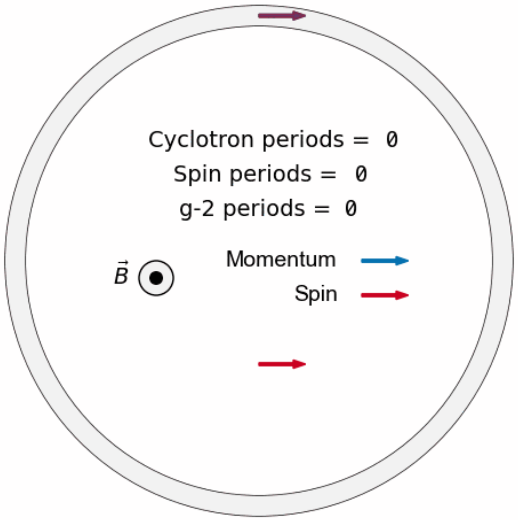


- Measured spin oscillation at fixed location
- Measure a_μ directly, instead of g!

Measurement recipe

Measure

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{m}$$

Extract

1. Measure ω_a: modulation of decay positron time spectrum
2. Measure B: proton nuclear magnetic resonance
3. Extract a_μ

Muon g-2 talks at EPS-HEP 2023

$$\omega_a = a_\mu \frac{eB}{m} \qquad \frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \frac{1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml}}{1 + B_k + B_q}$$

599. Measurement of the muon anomalous precession frequency ω_a in the Fermilab $g-2$ experiment
Sean Foster
8/21/23, 4:45 PM
Flavour Physics and CP... | Parallel session talk | T08 Flavour Physics an...

Sean Foster: Anomalous precession frequency

601. Measurement of the precision magnetic field in the Fermilab Muon g−2 experiment
Saskia Charity (FNAL)
8/21/23, 5:02 PM
Flavour Physics and CP... | Parallel session talk | T08 Flavour Physics an...

Saskia Charity: Magnetic field

603. Beam dynamics corrections to measurements of the muon anomalous magnetic moment
On Kim
8/21/23, 5:19 PM
Flavour Physics and CP... | Parallel session talk | T08 Flavour Physics an...

On Kim: Beam dynamics corrections

837. News on muon g-2
Graziano Venanzoni (INFN-Pisa)
8/22/23, 3:15 PM
Plenary session talk | Plenary

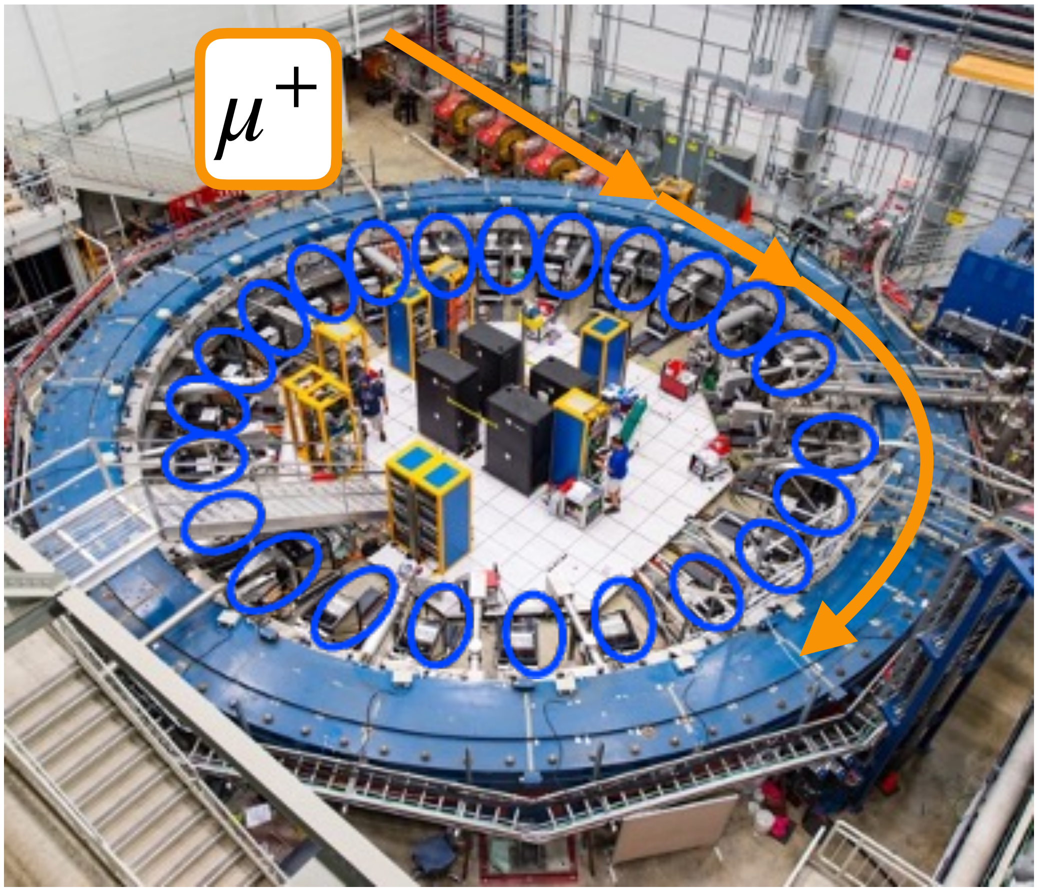
Graziano Venanzoni: Run 2/3 result overview

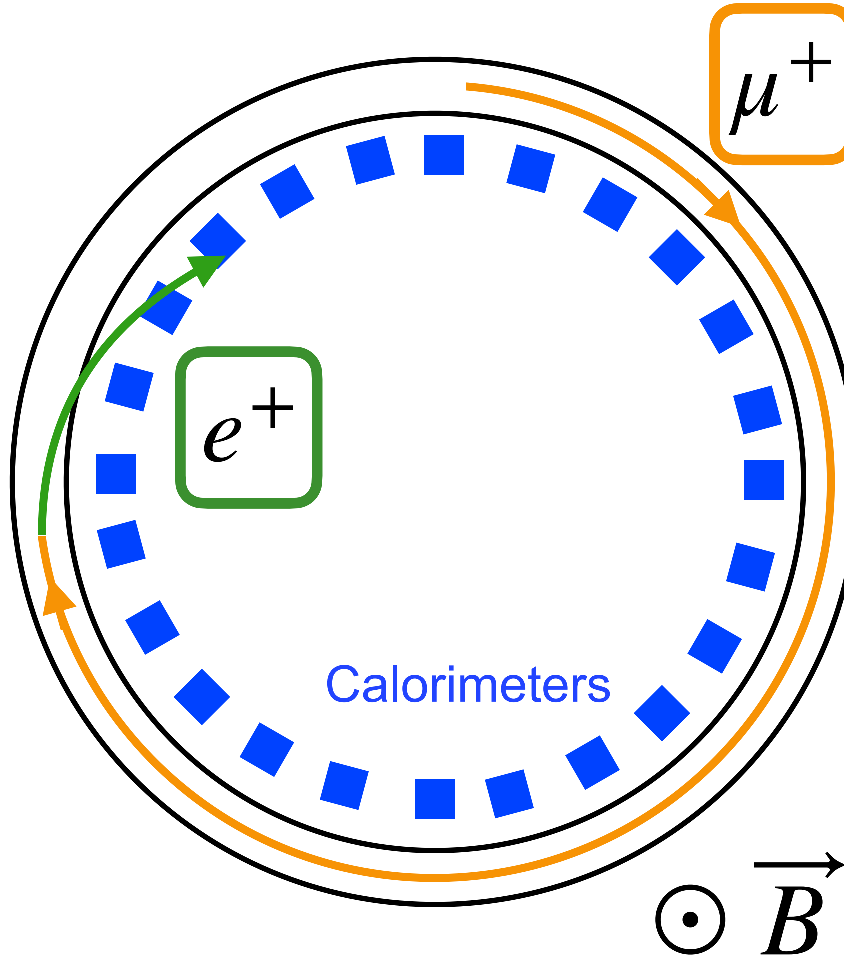
ω_a^m: measured anomalous precession frequency

$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \frac{1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml}}{1 + B_k + B_q}$$

Electromagnetic calorimeters

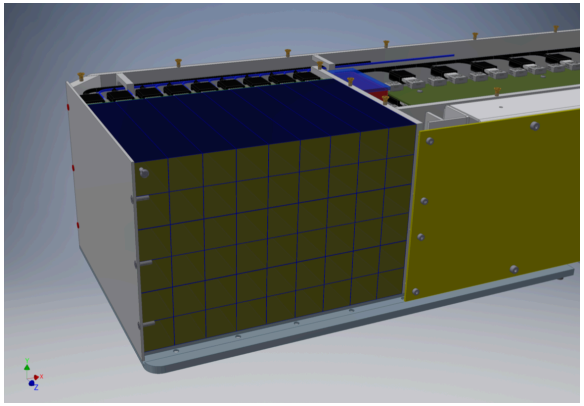
- Suite of 24 **calorimeters** to detect **decay positron** time & energy

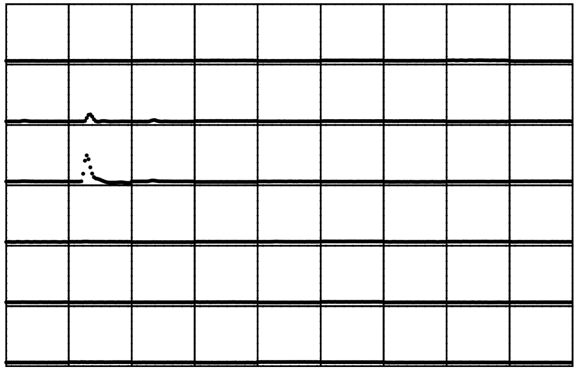


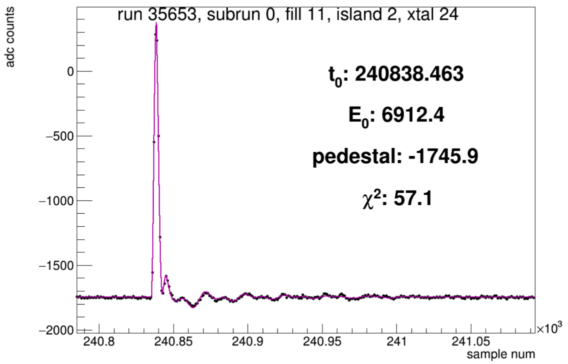


Decay positron reconstruction

- Each calorimeter is composed of a **6x9 grid** of **PbF_2 crystals**
- Decay positrons produces **Cherenkov light**
- Light collected by **silicon photomultipliers**
- Signal is **digitized** and fit with empirical **template functions**
- Extract **time** and **energy** from fit

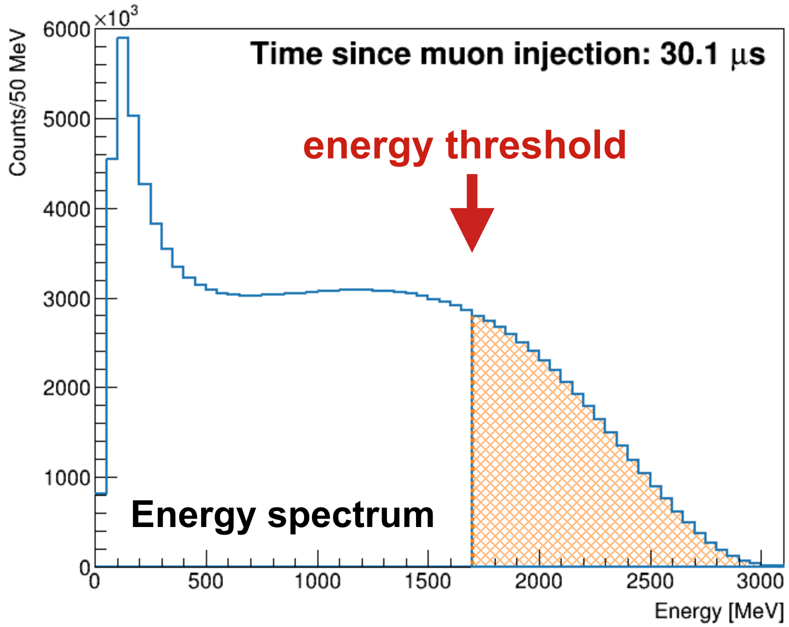




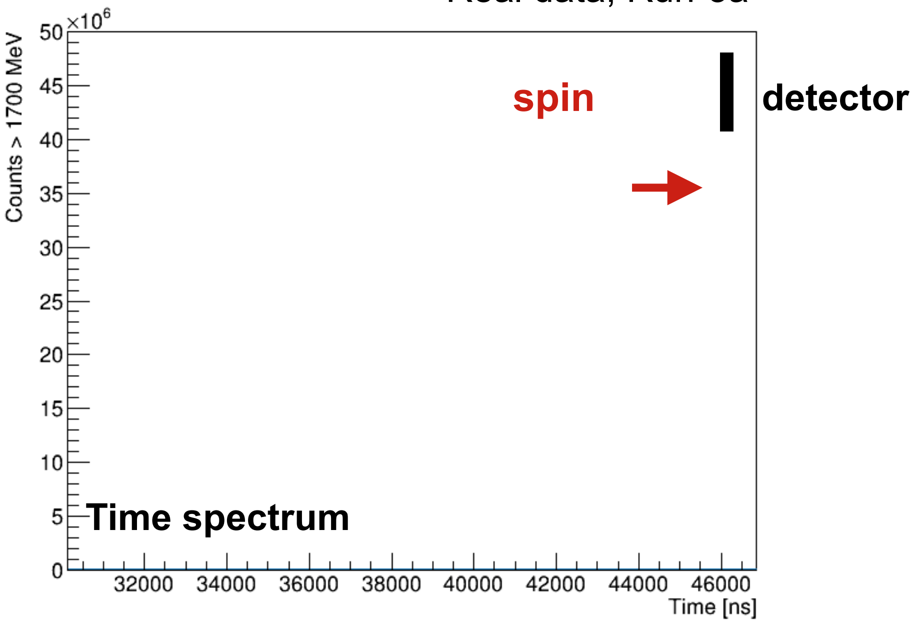


Measure spin precession using muon decay

- Due to **parity violation** in muon decay, number of detected **high energy positrons** oscillates as muon **spin** points towards/away from detector

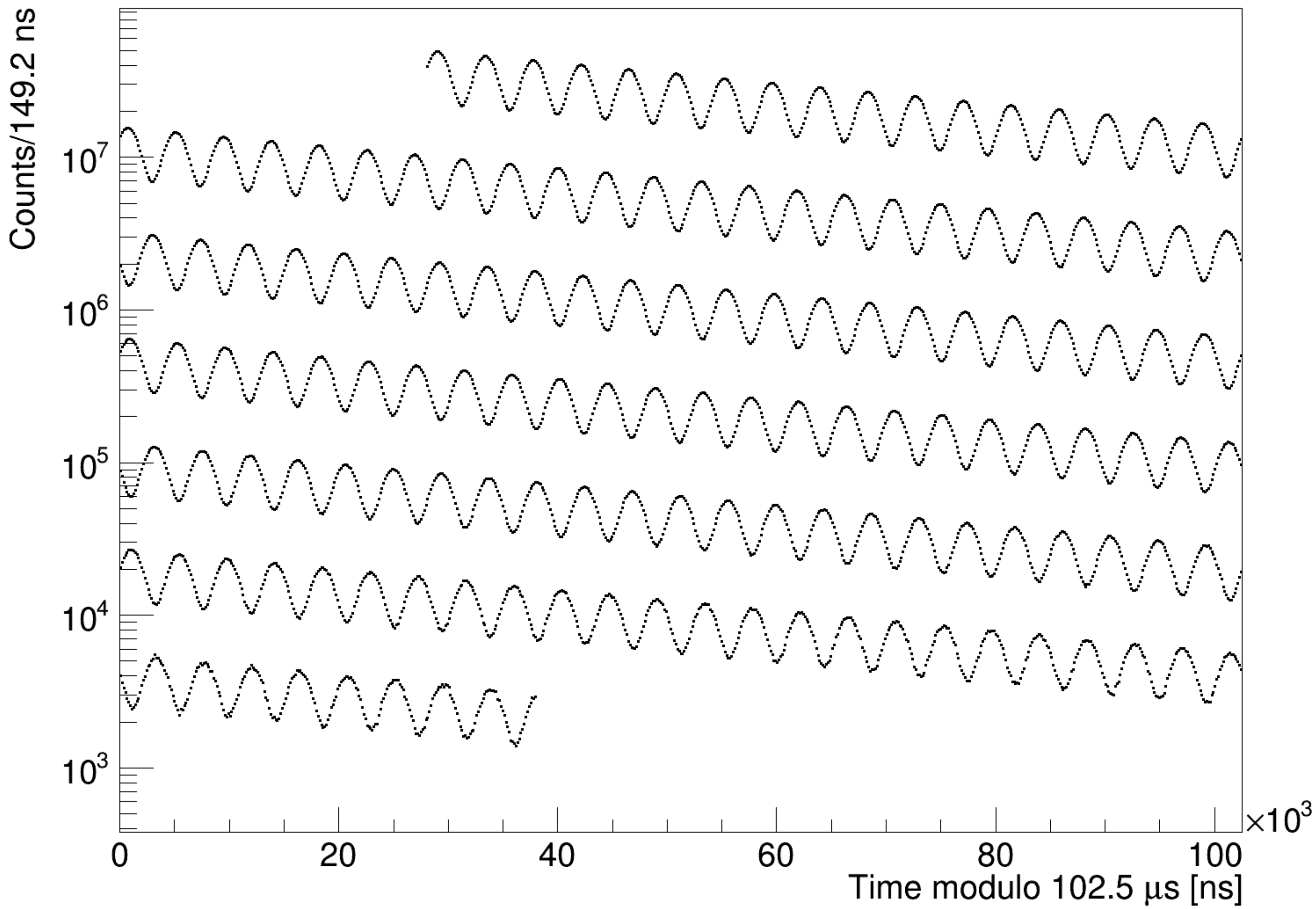


Real data, Run-3a



- **Count positrons** above an energy threshold
- Counts **oscillate** at ω_a; extract frequency from time spectrum

The "wiggle plot"



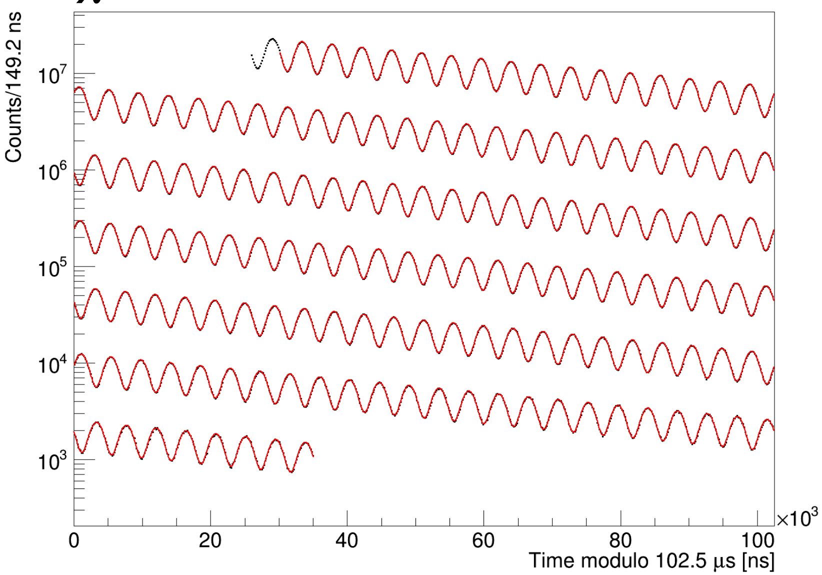
Fit time spectrum to **extract** ω_a!

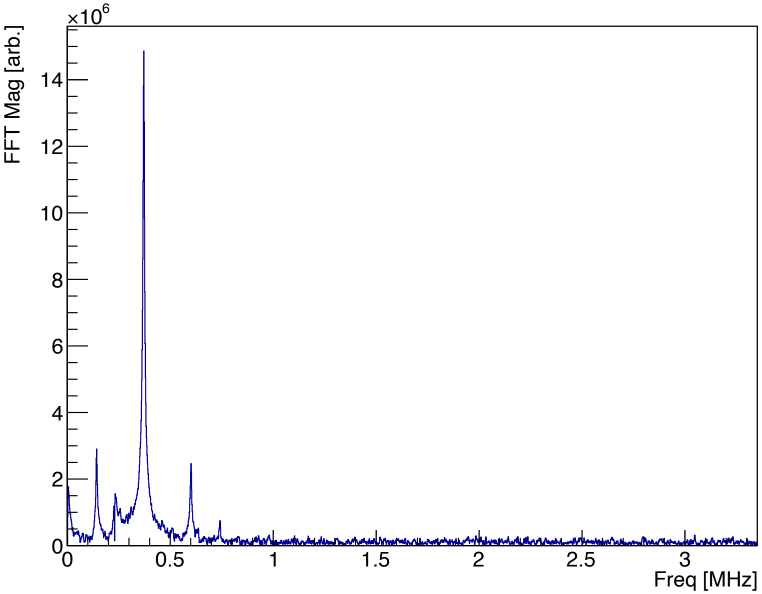
Simple model is not sufficient

- Simplest model captures **exponential decay & g-2 oscillation**

$$N(t) = N_0 e^{-t/\tau}\left[1 + A\cos(\omega_a t - \phi)\right]$$

χ^2/ndf = 51530/4150





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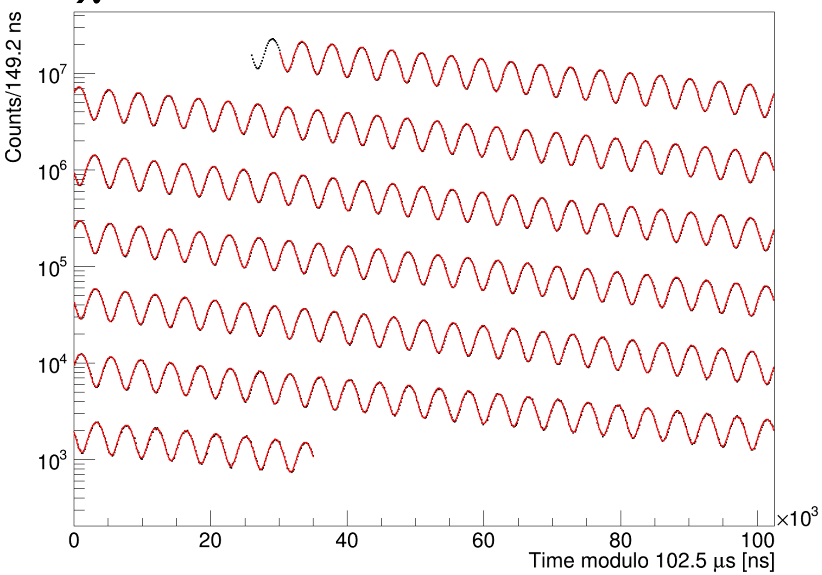
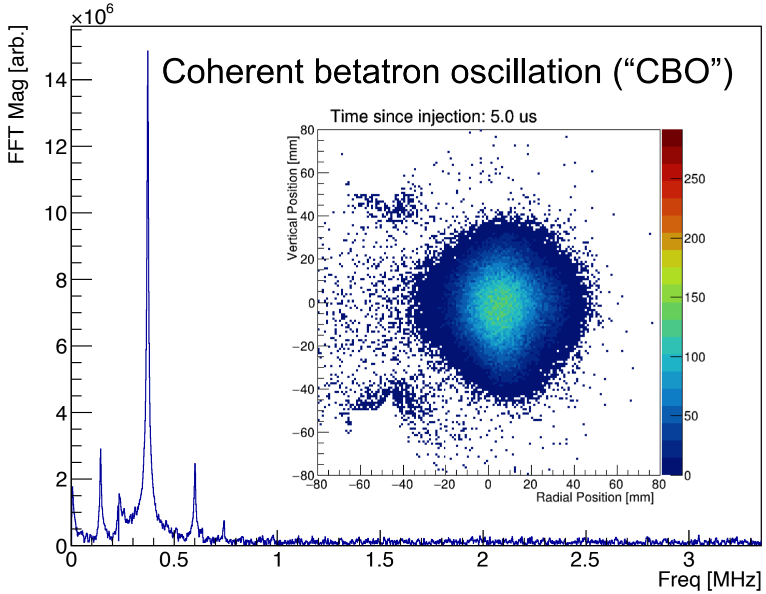
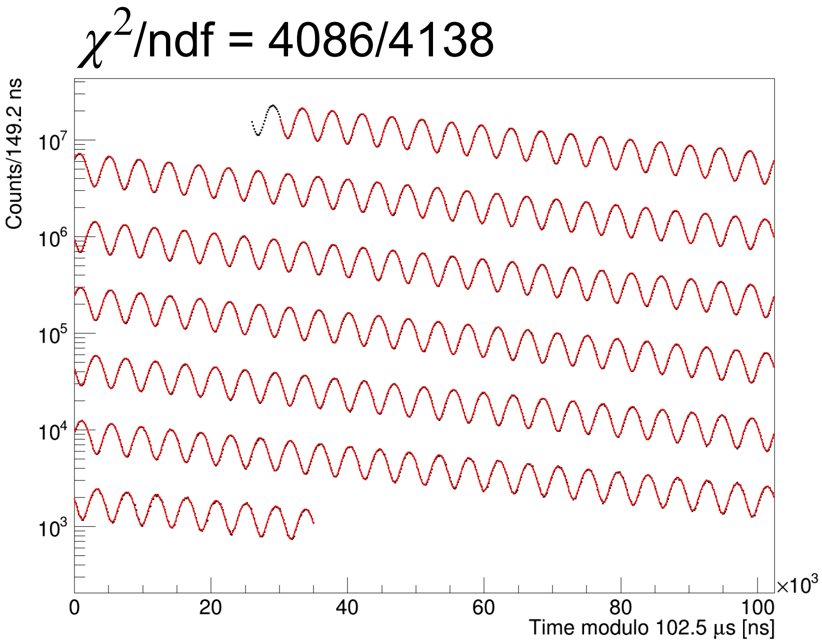


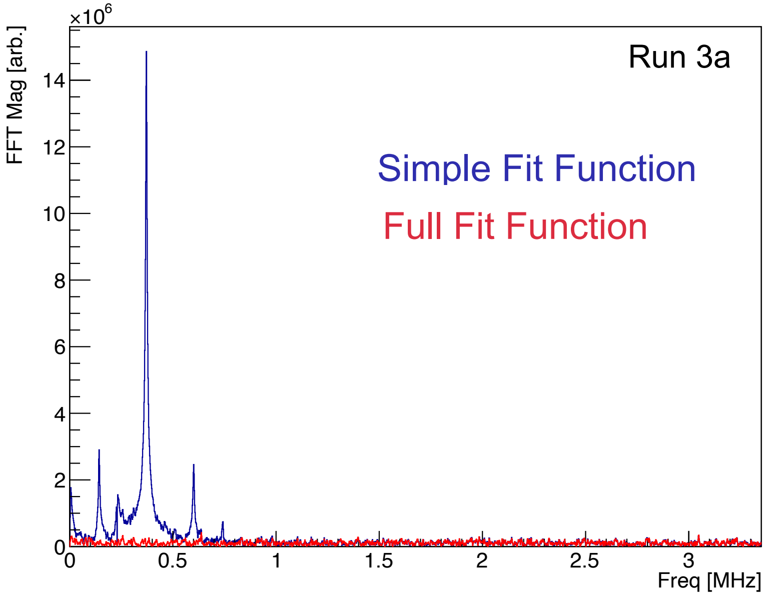


- Need to do better: must account for **beam oscillations** that couple to acceptance, **muons lost** before decay that disrupt pure exponential, and **detector effects (pileup, gain)**

Full model gives good fit quality

- Correcting detector effects & modifying fit function for beam dynamics effects gives good fit quality





- Important to account for these effects: ω_a shifts by 1.6 ppm (!)
- Good fit is only a start; must still check for systematic effects…

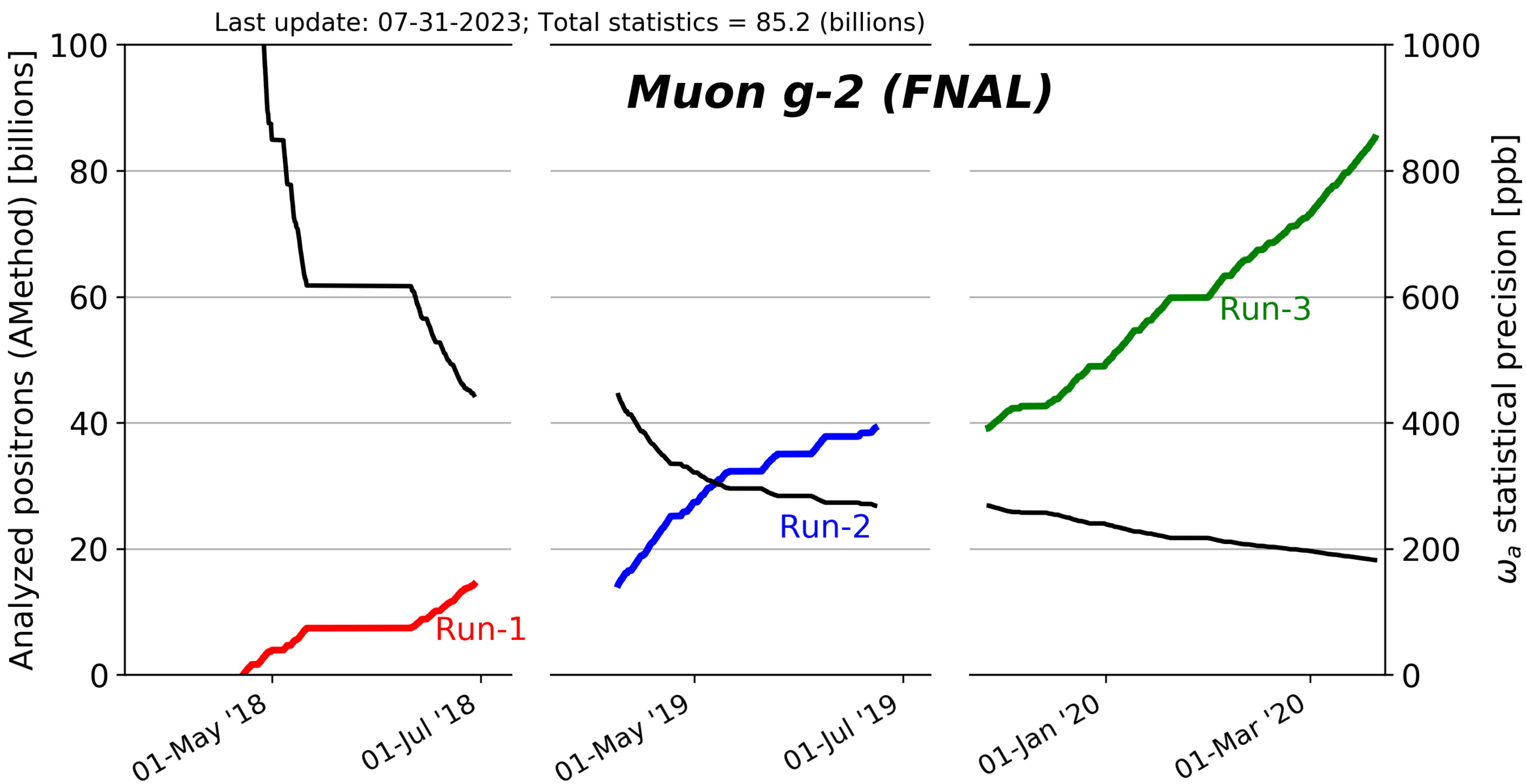
Systematic effects

- Effects that **change early-to-late** over the measurement period can bias the frequency
- **Phase change** early-to-late leads to a bias :

$$\omega_a t + \phi \rightarrow \omega_a t + \phi(t) = \left(\omega_a + \frac{d\phi}{dt}\right) t + \phi_0 + \ldots$$

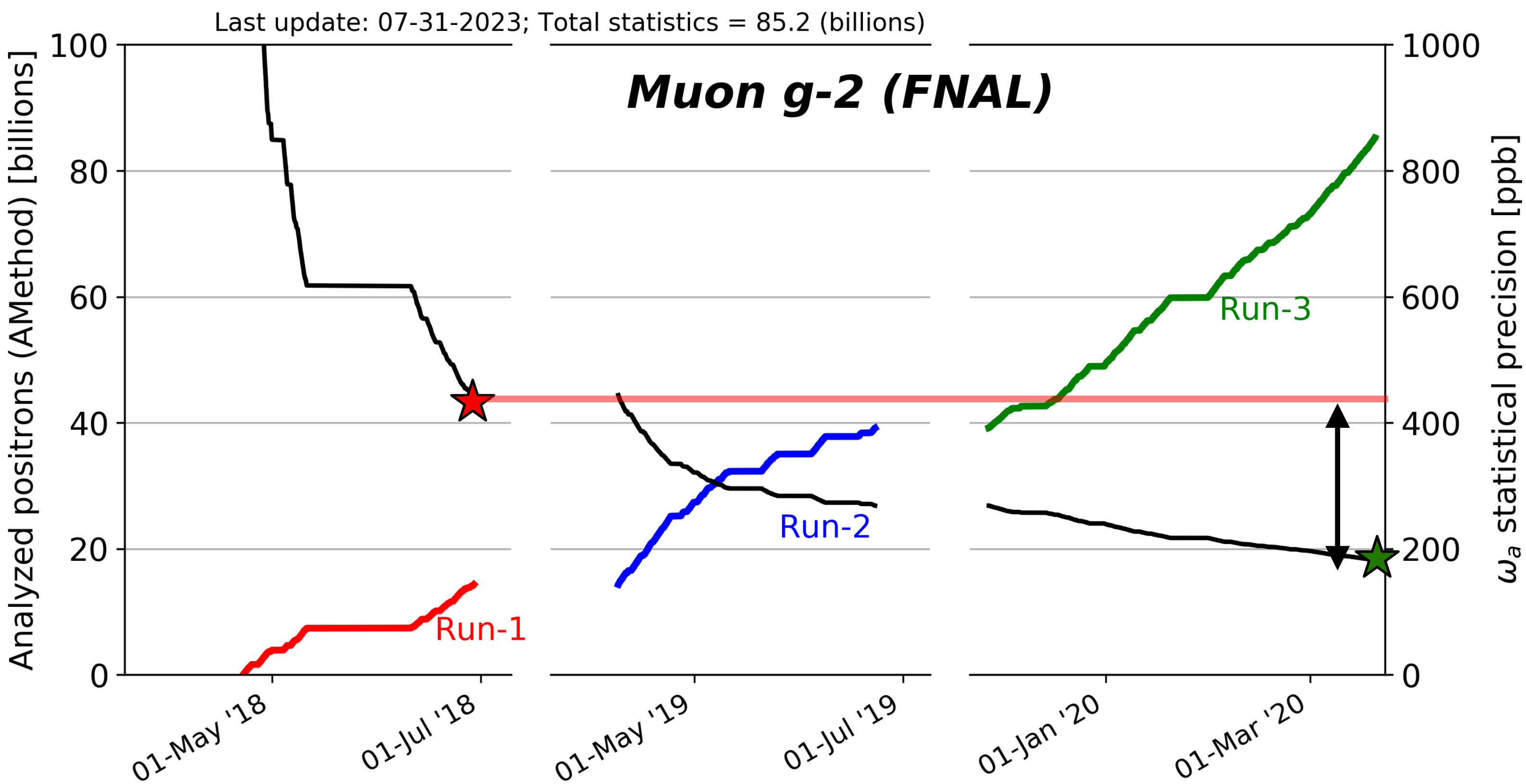
- In our fits, we would measure $\omega_a + d\phi/dt$, rather than ω_a
- Must be careful that we **correct for** any such effects and **evaluate uncertainties**

Run-2/3 uncertainties: statistics



- **4.7 times** more data than Run-1: reduces statistical uncertainty by factor of **2.2**: **434 ppb** → **201 ppb**

Run-2/3 uncertainties: statistics



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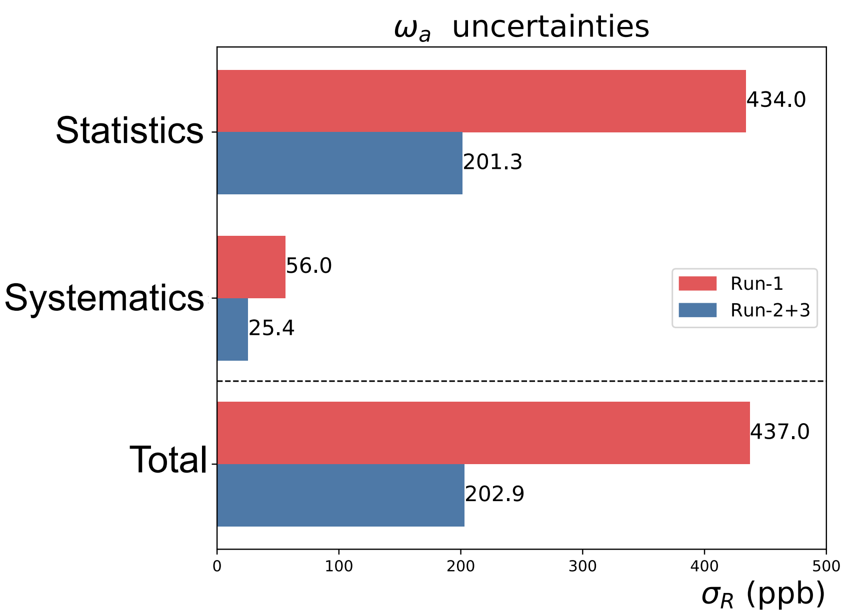
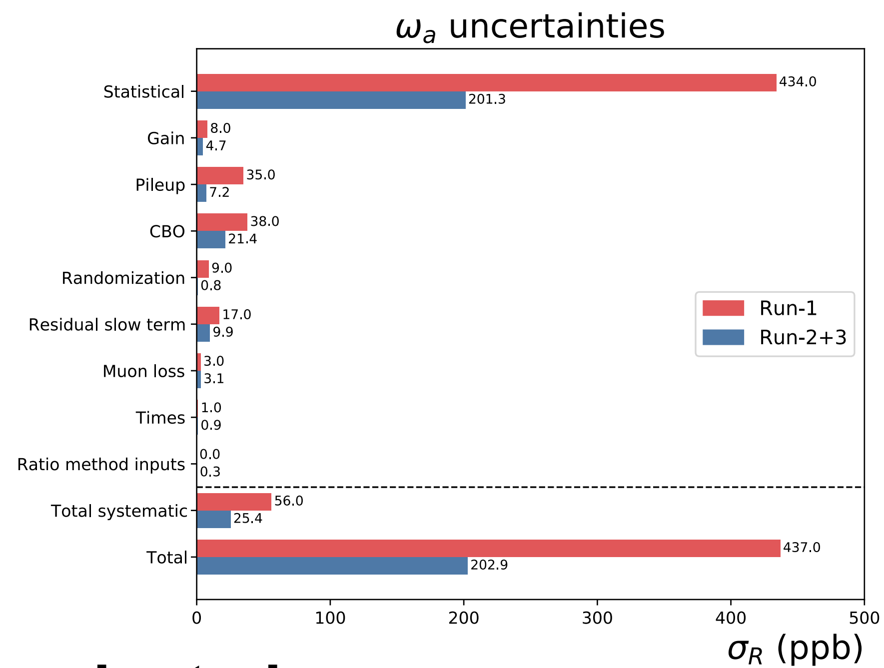
Run-2/3 uncertainties: systematics

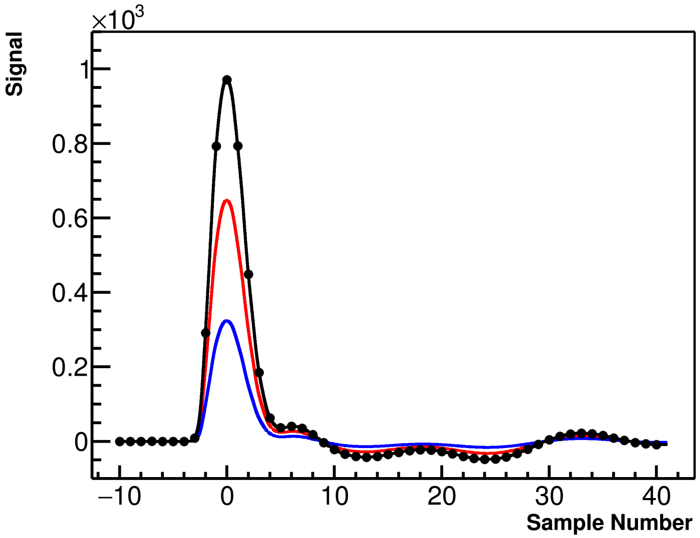


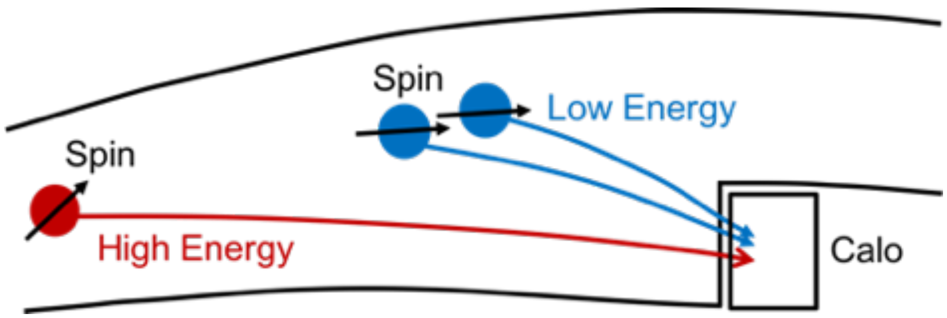


- Measurement is **statistics dominated**
- Improved systematics by factor of **2.2** also
- Uncertainties **reduced across the board** compared to Run-1
  - I'll focus on **pileup** and **CBO**

Pileup

- Pileup occurs when two or more positrons are **misidentified** as a single positron due to arriving too close in time / space



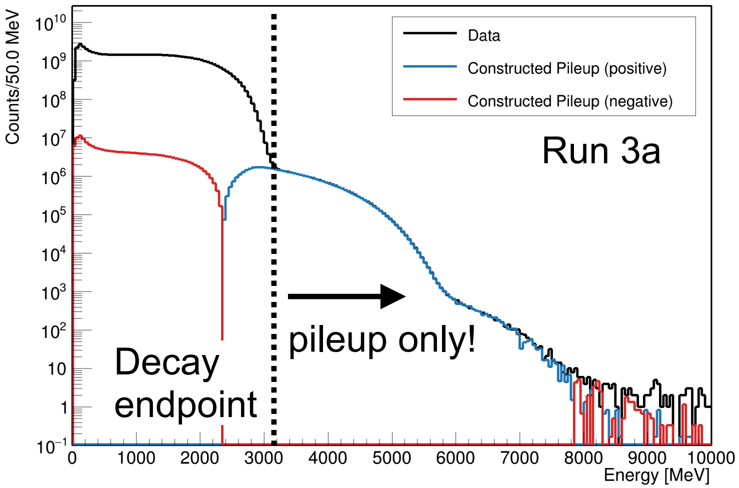


- Phase of two low energy positrons ≠ phase of high energy positron & probability of pileup decreases over measurement period

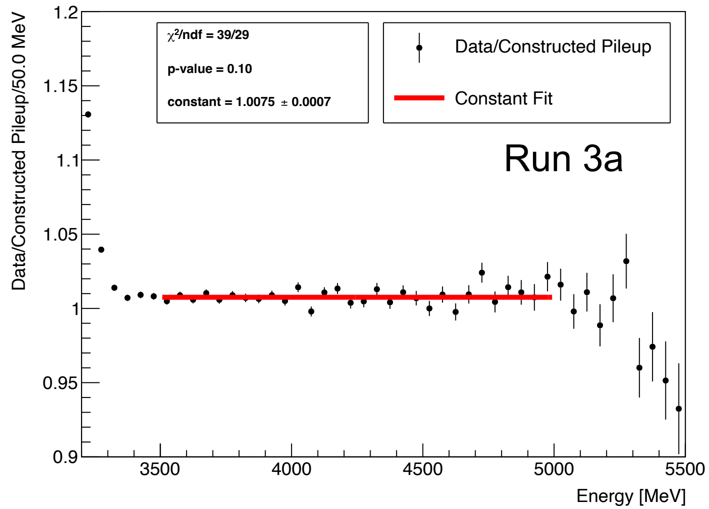
Correct for pileup

- Pileup occurs when two or more positrons are **misidentified** as a single positron due to arriving too close in time / space

Energy spectrum



Data / Pileup Correction Ratio

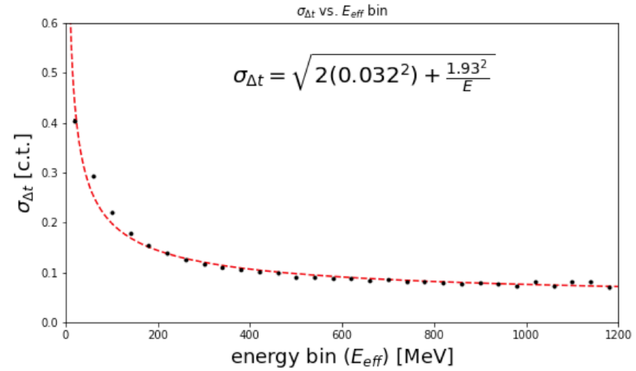


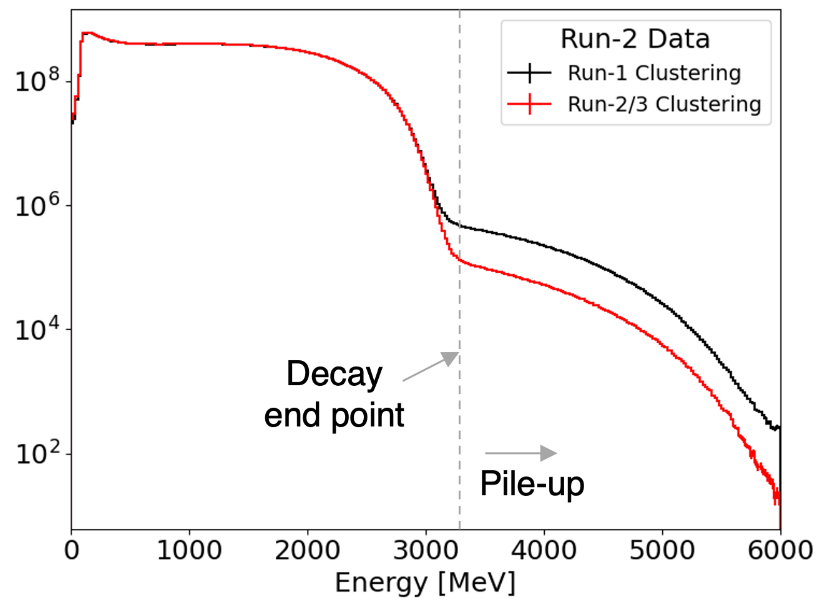
- Phase of two low energy positrons ≠ phase of high energy positron & probability of pileup decreases over measurement period

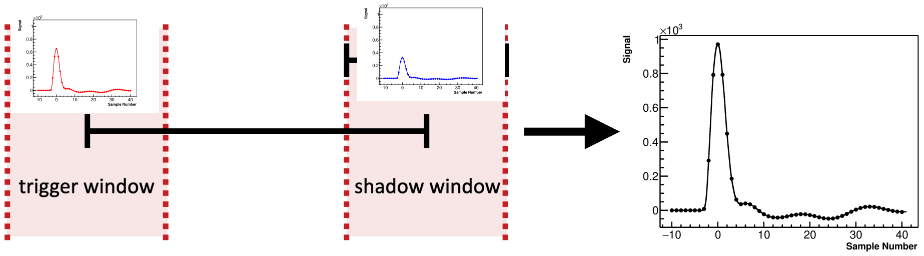
- Correct data with **empirically determined pileup spectrum**

Improving pileup treatment in Run-2/3

- **Improved reconstruction techniques** reduced level of pileup by up to x4
- More **robust pileup subtraction** methods implemented
- Systematic uncertainty reduced from **35 ppb** to **7 ppb**

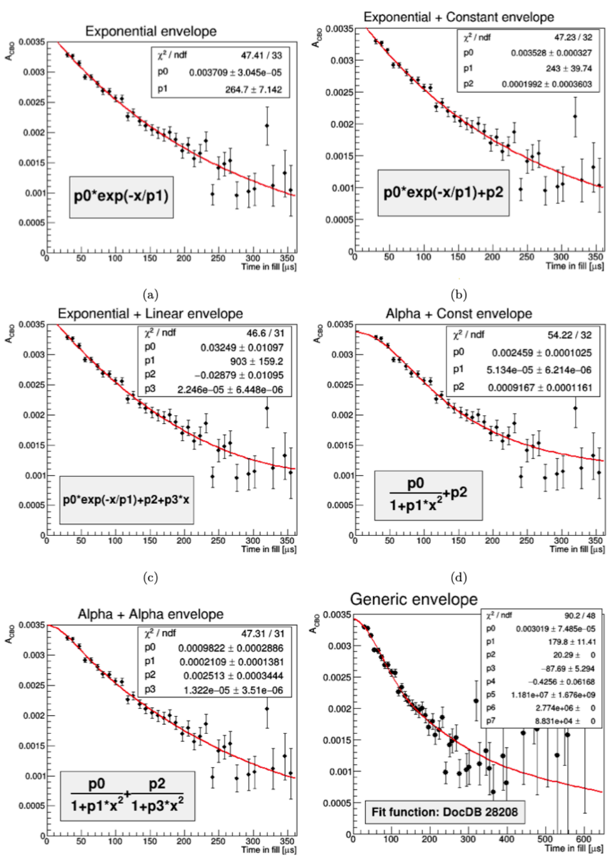


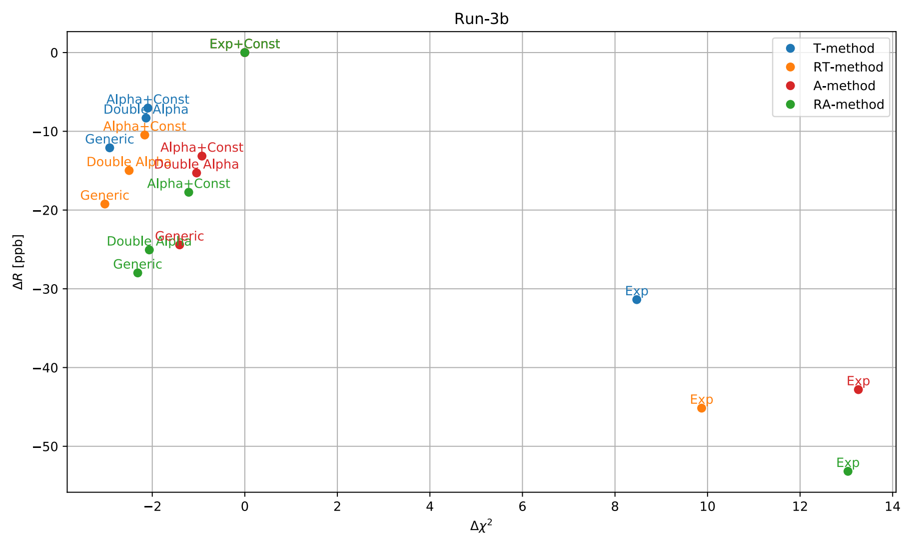




Modeling beam oscillations: CBO

- Must model **decoherence envelope** and **frequency change**
- **More data** in Run-2/3 allowed us to test **more models**



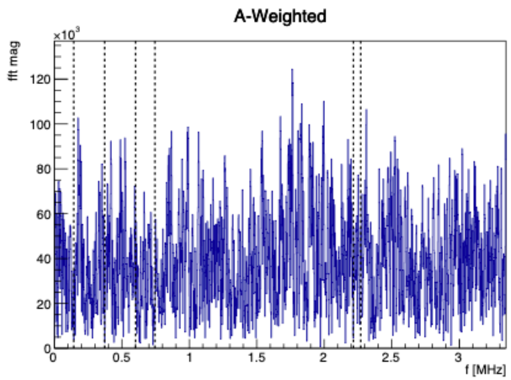


- Reduced systematic uncertainty from **38 ppb** to **21 ppb,** but remains dominant in analysis

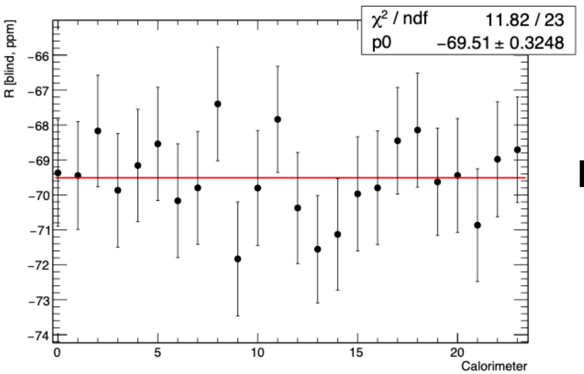
Consistency checks

- We perform many consistency checks: **fit residual FFTs**, **fit start time scans**, **fits by calorimeter**, **fits by positron energy**, etc.

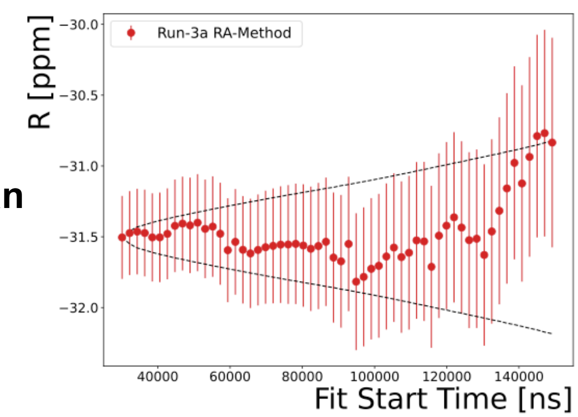
Residuals FFT



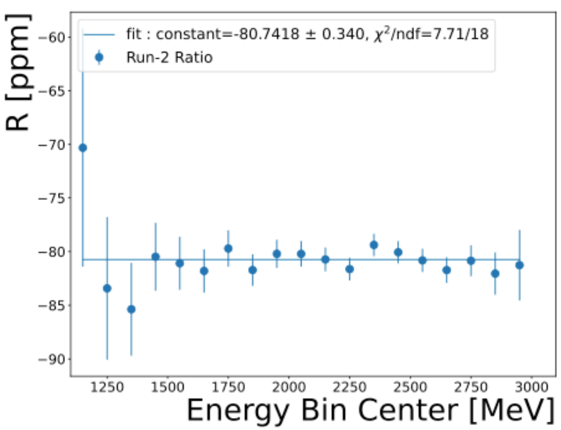
Per-calorimeter fits



Fit start time scan



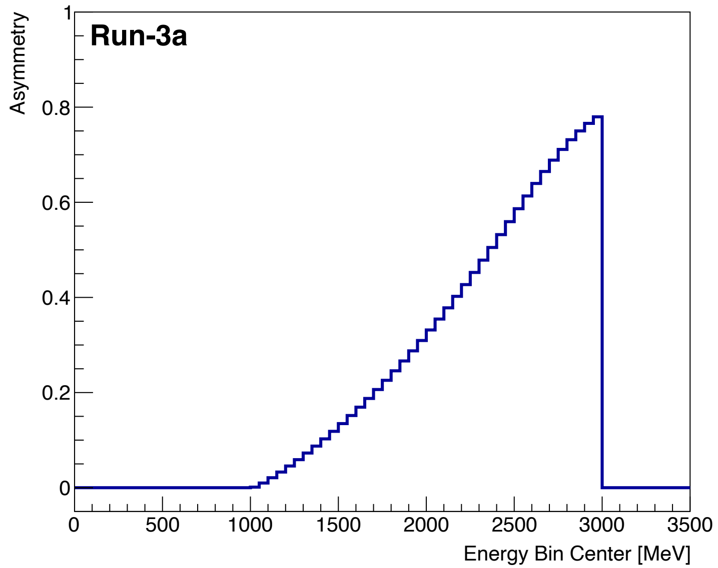
Energy-bin fits



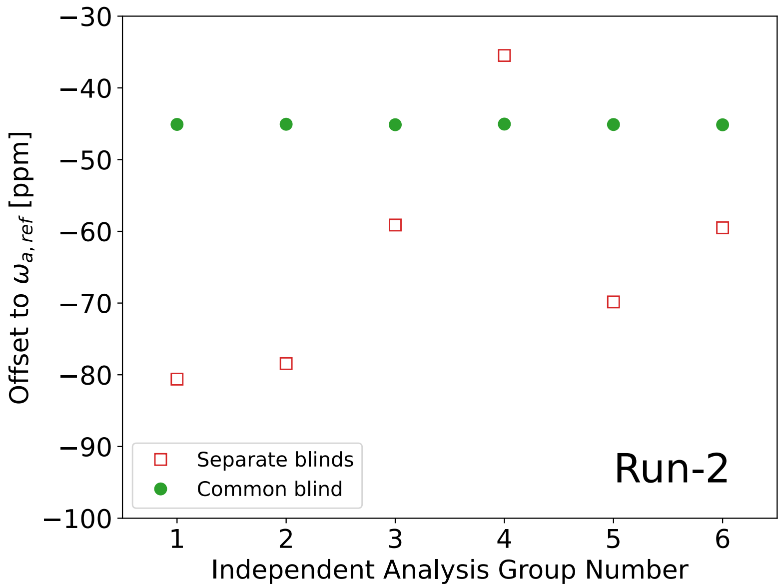
Analysis combination

- Analysis performed by **7 independent groups**
- Analysis is performed with **software & hardware blinding**
- Final number combines the **statistically optimal asymmetry-weighted** analyses (6 groups use this method)

g-2 oscillation amplitude vs. energy



Relative unblinding of Run-2



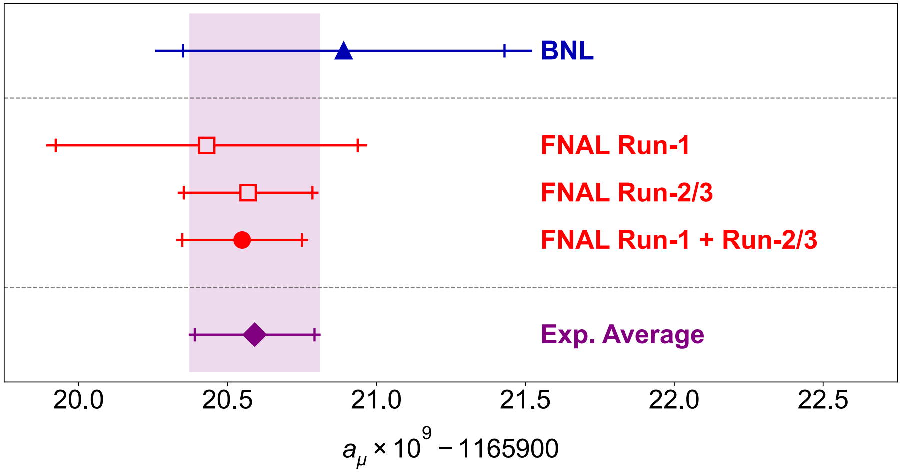
Summary of Run-2/3 result

- I've described the ω_a^m analysis
  - Run-2/3 uncertainty is **2.2 times smaller** than Run-1

Quantity	Correction [ppb]	Uncertainty [ppb]
ω_a^m (statistical)	–	201
ω_a^m (systematic)	–	25
C_e	451	32
C_p	170	10
C_{pa}	-27	13
C_{dd}	-15	17
C_{ml}	0	3
$f_{\text{calib}}\langle\omega'_p(\vec{r}) \times M(\vec{r})\rangle$	–	46
B_k	-21	13
B_q	-21	20
$\mu'_p(34.7°)/\mu_e$	–	11
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	70
Total external parameters	–	25
Totals	622	215

a_μ(FNAL) = 0.00116 592 055(24) [203 ppb]

a_μ(Exp; 2023) = 0.00116 592 059(22) [190 ppb]



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- Next, you will here about the magnetic field and beam dynamics corrections

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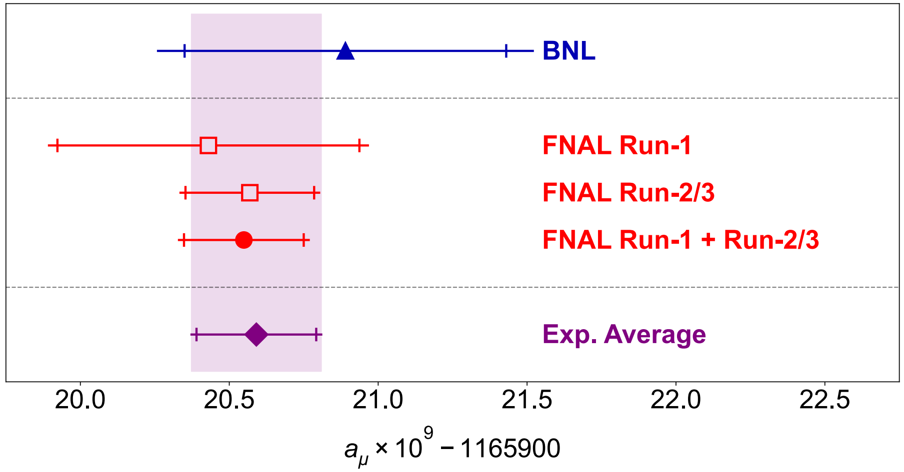
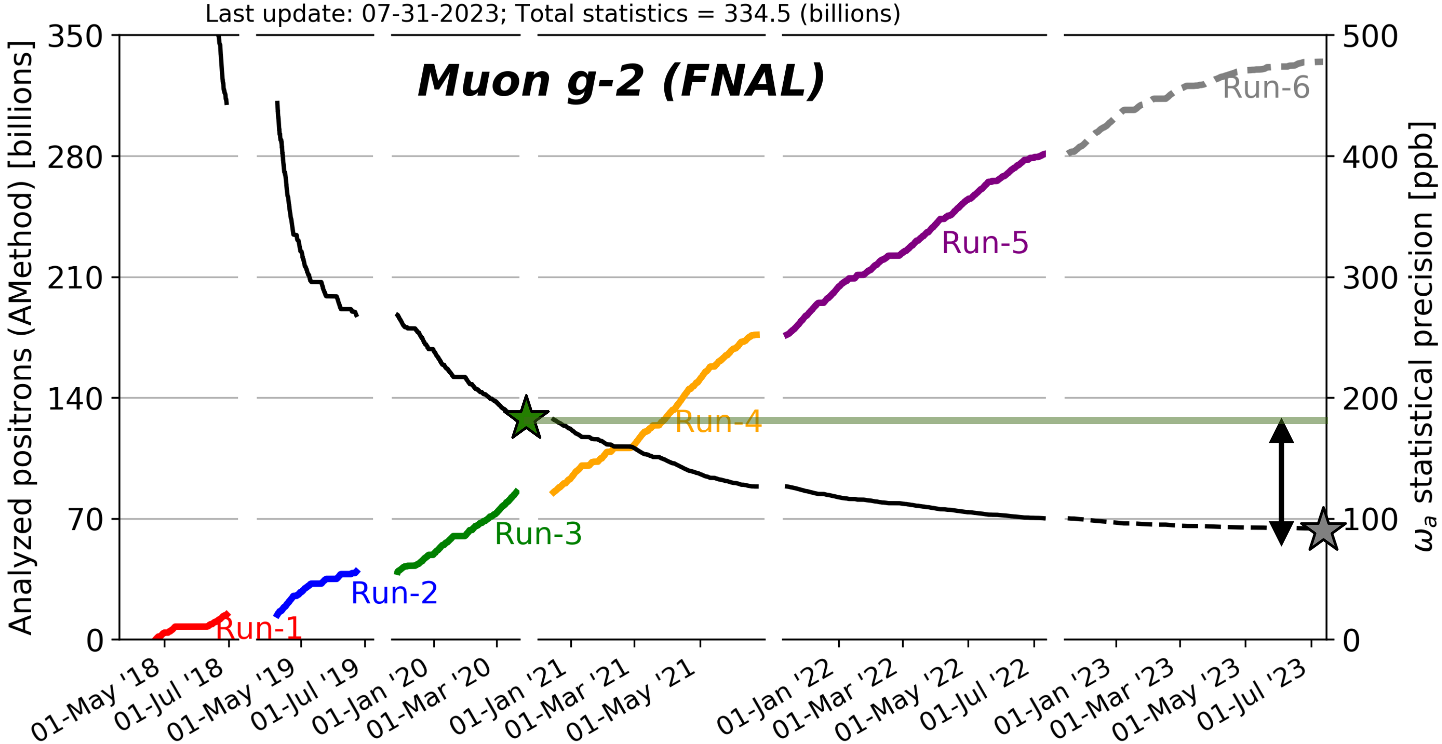


Run-4/5/6 outlook



- Three years of additional data collected; analysis ramping up!
- Statistical uncertainty on ω_a^m to reduce by another factor of two!

Acknowledgments

- Department of Energy (USA)
- National Science Foundation (USA)
- Istituto Nazionale di Fisica Nucleare (Italy)
- Science and Technology Facilities Council (UK)
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- European Union's Horizon 2020
- Strong 2020 (EU)
- German Research Foundation (DFG)
- National Natural Science Foundation of China
- MSIP, NRF, and IBS-R017-D1 (Republic of Korea)

Thank you for listening!

Muon g-2 Collaboration @ Liverpool meeting, July 2023