Run-2/3 measurement of the muon anomalous magnetic moment by the Muon g-2 experiment at Fermilab

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for Fermilab Muon g-2 collaboration

ICHEP 2024 @ Prague

2024.07.18

Muon g-2 collaboration @ Liverpool

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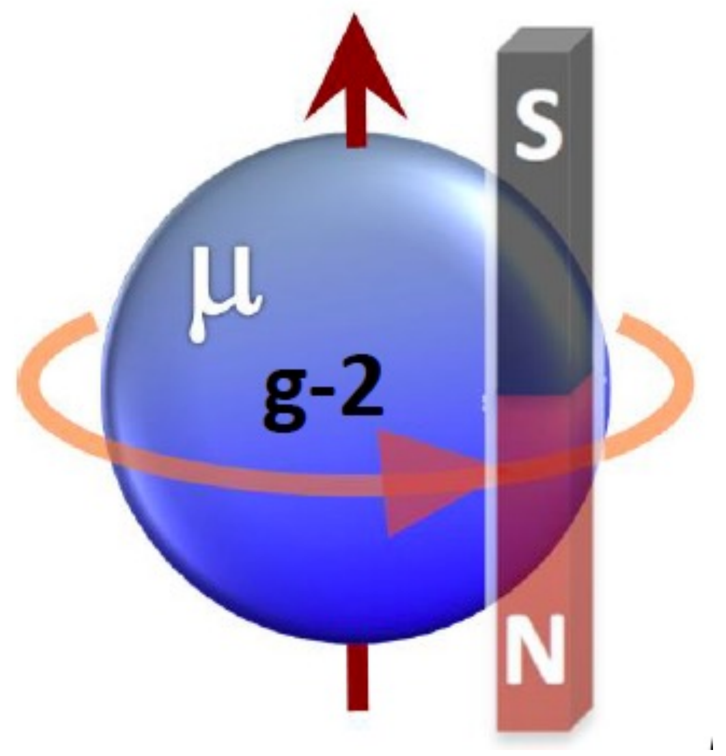
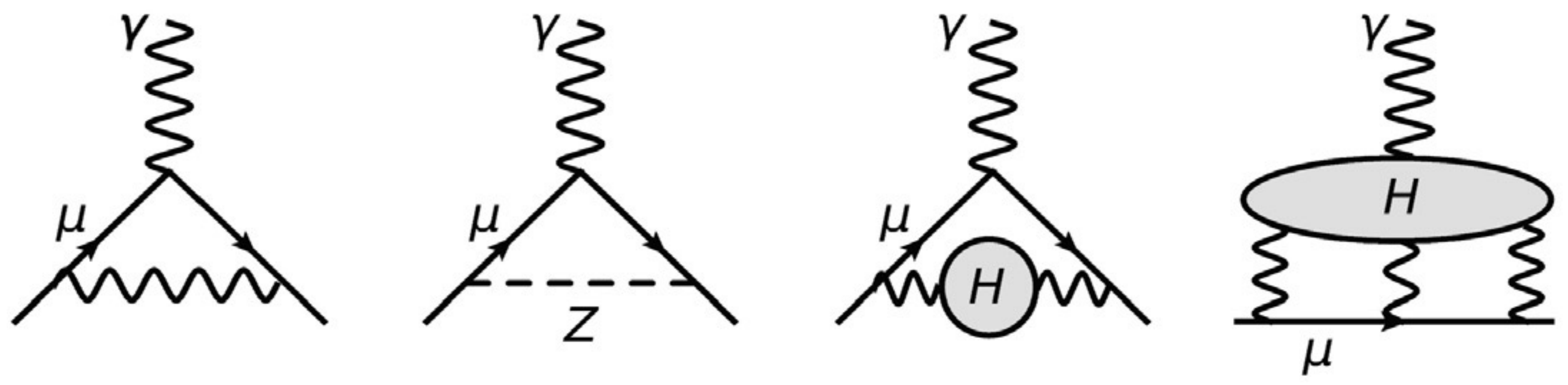
Why the Muon g-2?

$a_\mu = \frac{g-2}{2}$, g = 2 at the tree level

magnetic moment and spin



$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$

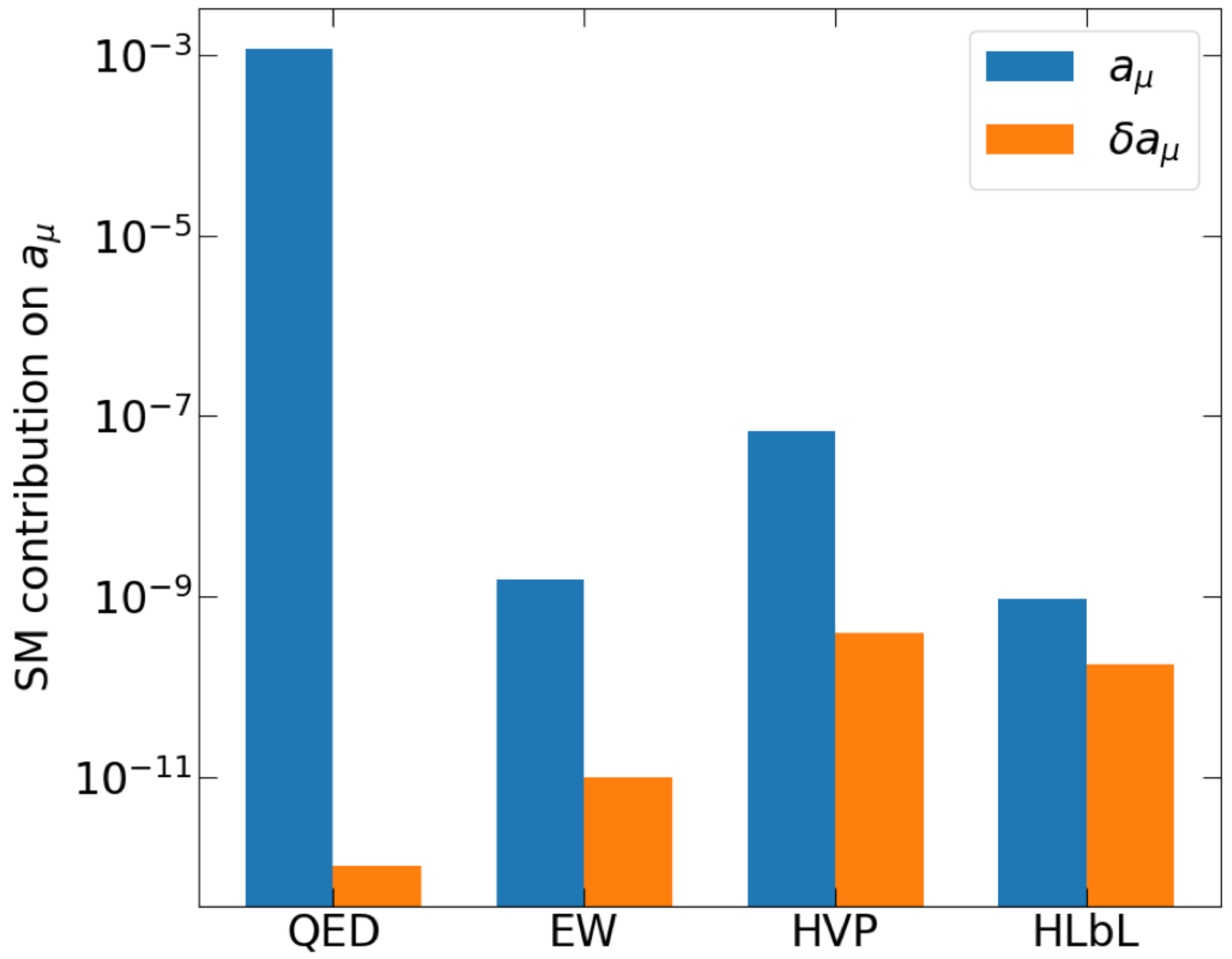


QED | Electroweak | Hadronic Vacuum Polarization | Hadronic Light-by-light

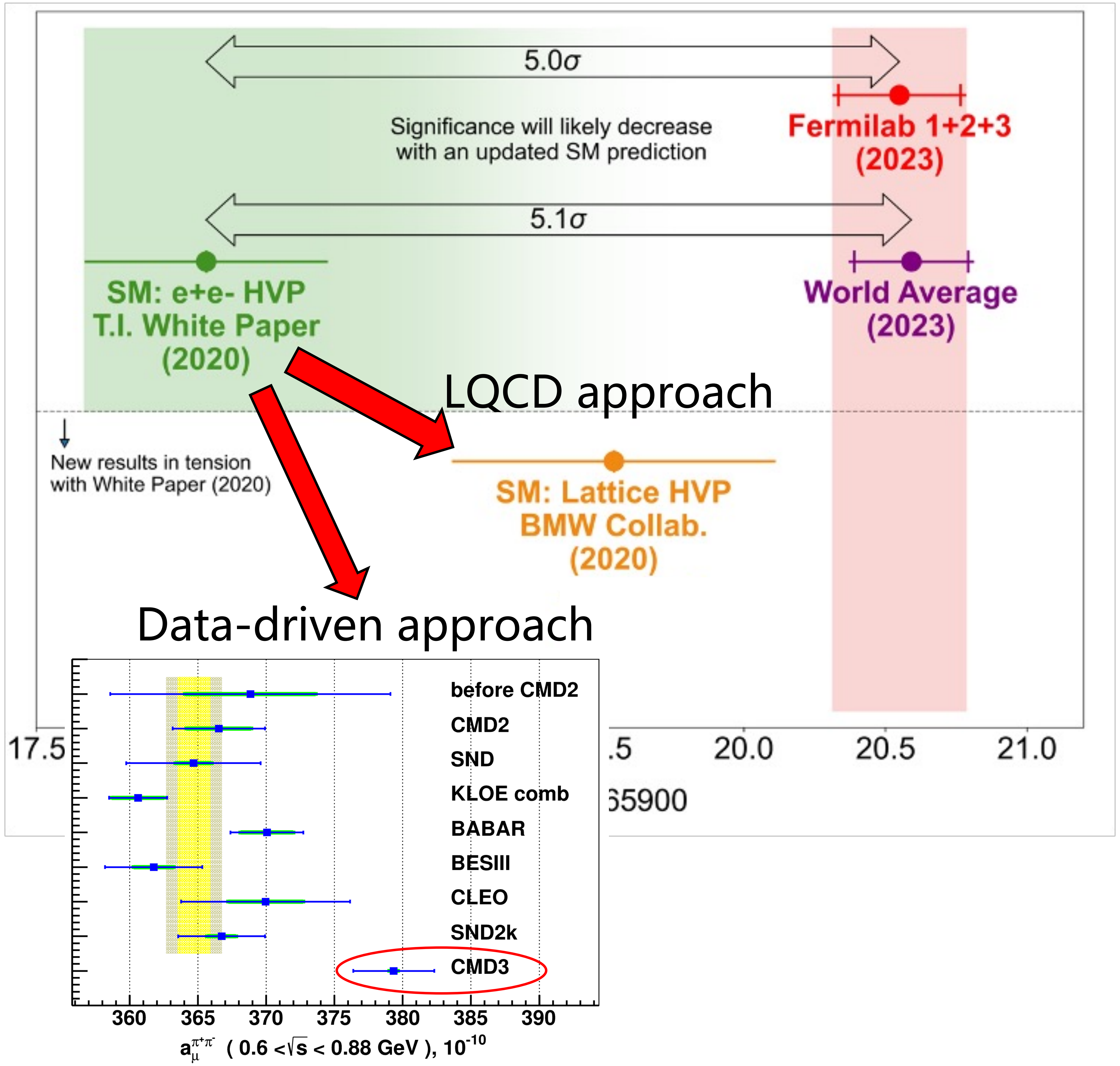
- Can be calculated and measured to high precision (sub-ppm)
- Precision test of SM calculations (at 4-loop QED, EW, and QCD)
- Powerful discriminant for BSM physics models

$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm HVP,\ LO} + a_\mu^{\rm HVP,\ NLO} + a_\mu^{\rm HVP,\ NNLO} + a_\mu^{\rm HLbL} + a_\mu^{\rm HLbL,\ NLO}$$
$$= 116\,591\,810(43) \times 10^{-11}\,.$$

Theory Initiative White Paper
T. Aoyama et al. Phys. Rept. **887** (2020)



Theory vs Experiment for g-2



- Large discrepancy between experiment and WP (2020)
- New results since WP 2020
  - **BMW** (swapping HVP from WP with their value) falls **in between** WP (2020) and experiment **New BMW result, see Z. Fodor's talk on Fri 6:15 pm (Sec 06)**
  - **CMD-3** in tension with other e^+e^- machine data (data-driven approach)
- Many **parallel efforts are underway** to resolve the theoretical ambiguity

Status of the Muon g-2 experiment

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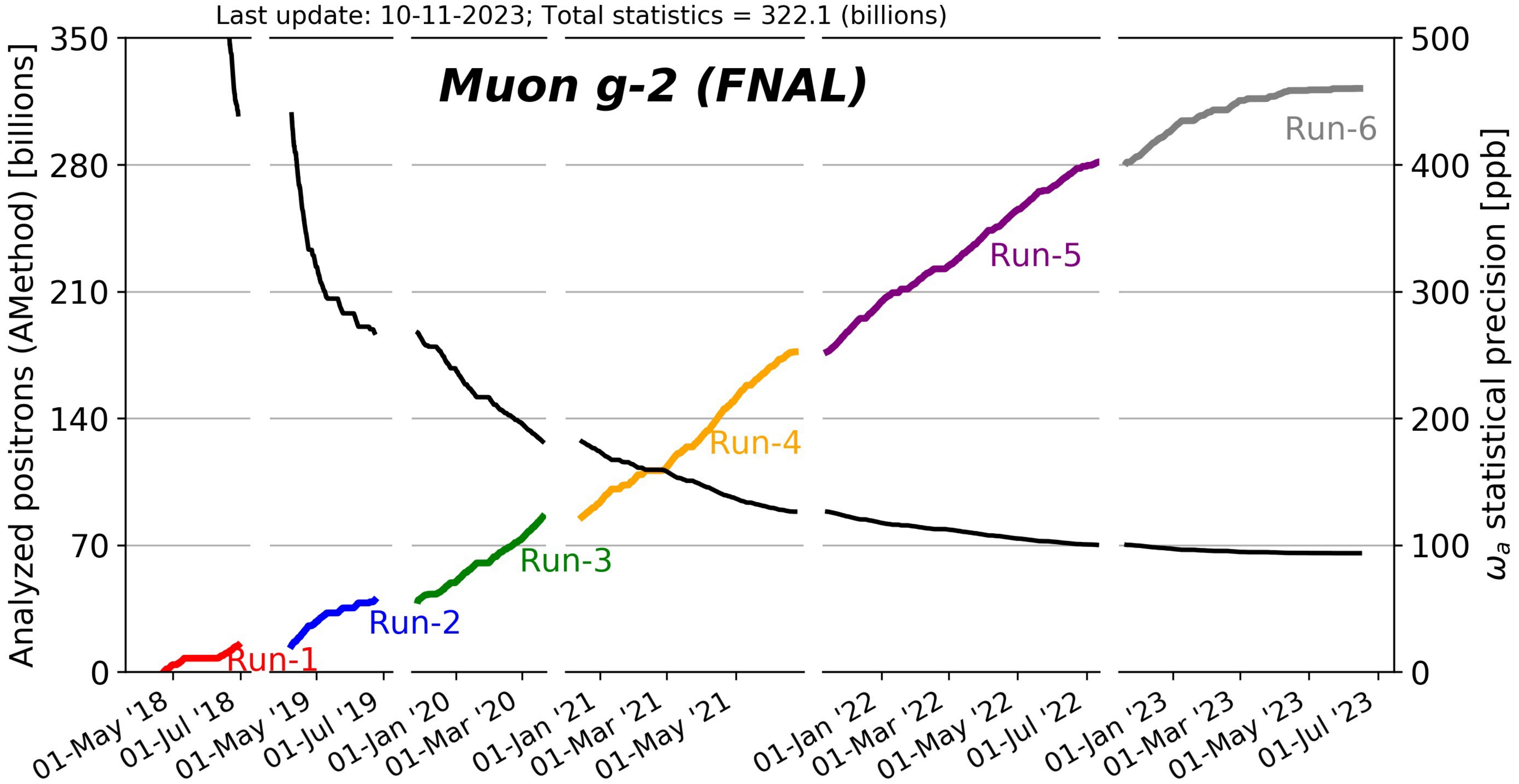
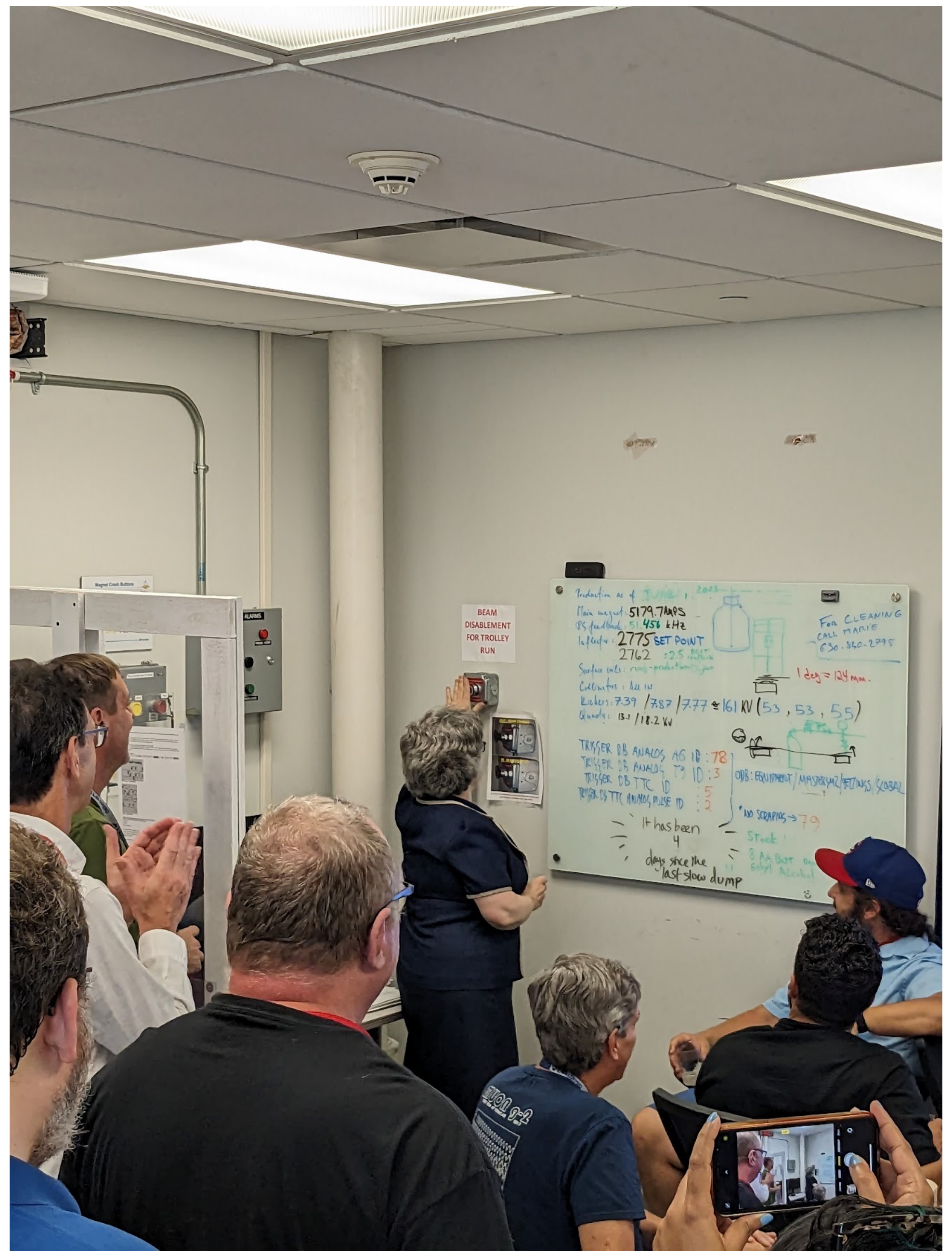
Celebrating first beam at MC1 (Summer 2017)





Fermilab director Lia Merminga pushed the red button to shut the beam down (Jul 10, 2023)

- Apr 2021: **Run-1** Result (2018 data)
- Aug 2023: **Run-2/3** Result (2019-20 data)
- ~2025: **Run-4/5/6** Result (2021-23 data)
- Reached our proposal goal for statistics (~4x Run-1/2/3)

Principle of g-2 measurement

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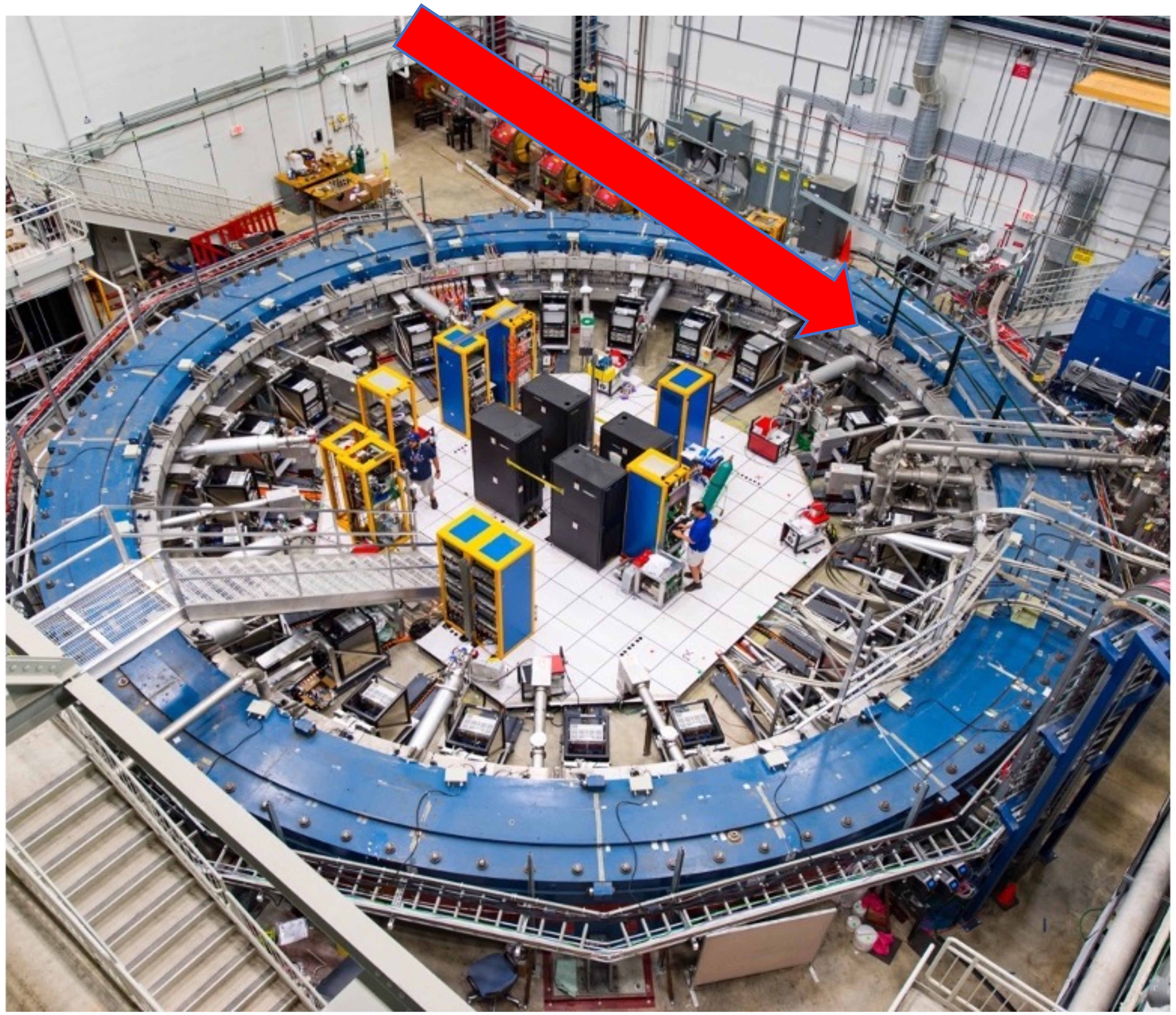
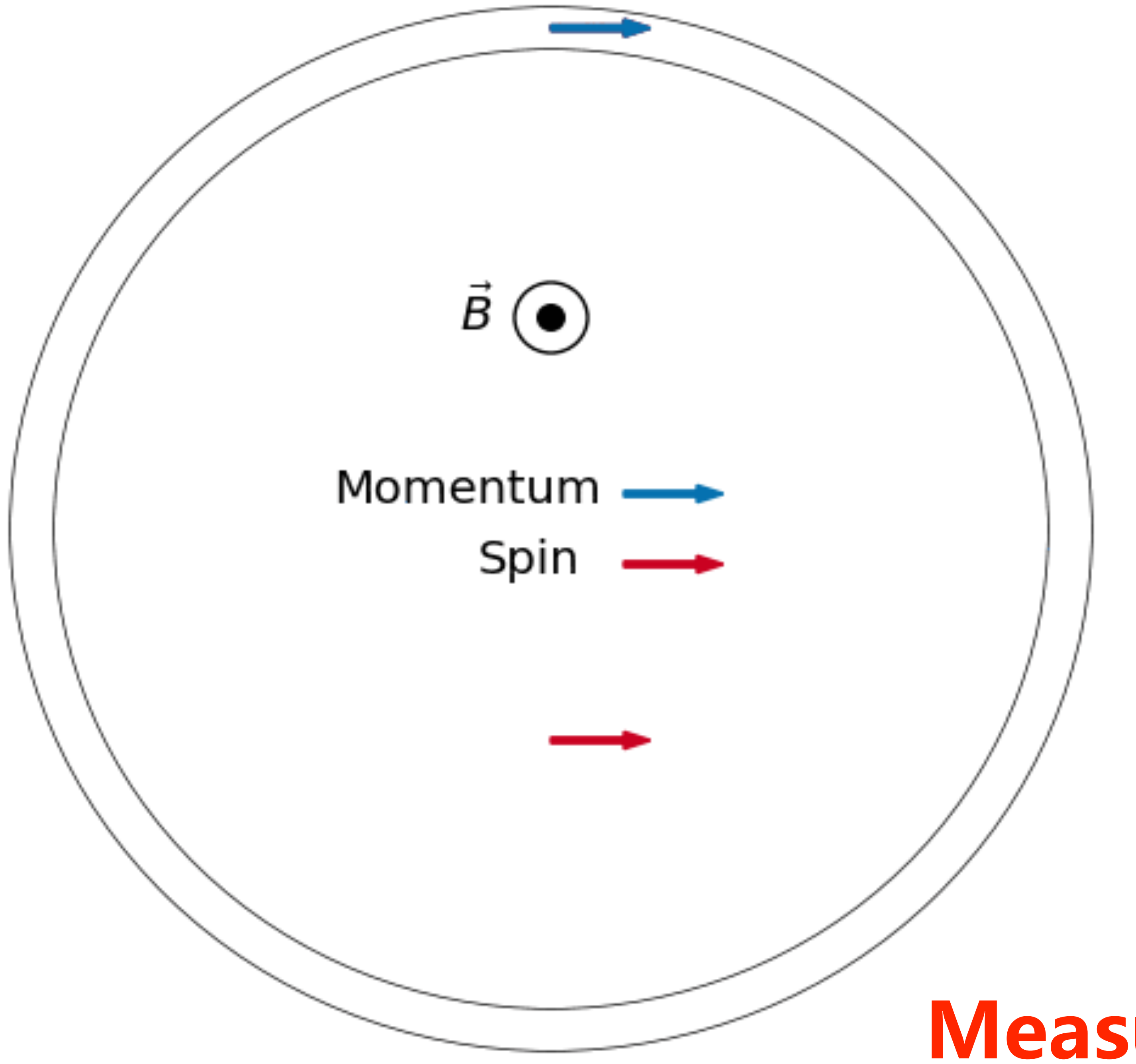
Inject a spin-polarized muon beam into a magnetic storage ring





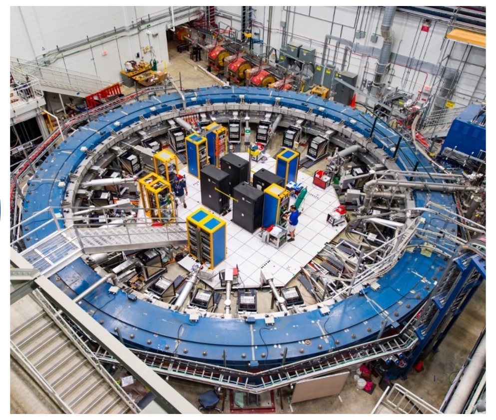
Measure the difference in frequency

Measure the magnetic field of the storage ring

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

Obtain g-2

Muon g-2 superconducting storage ring



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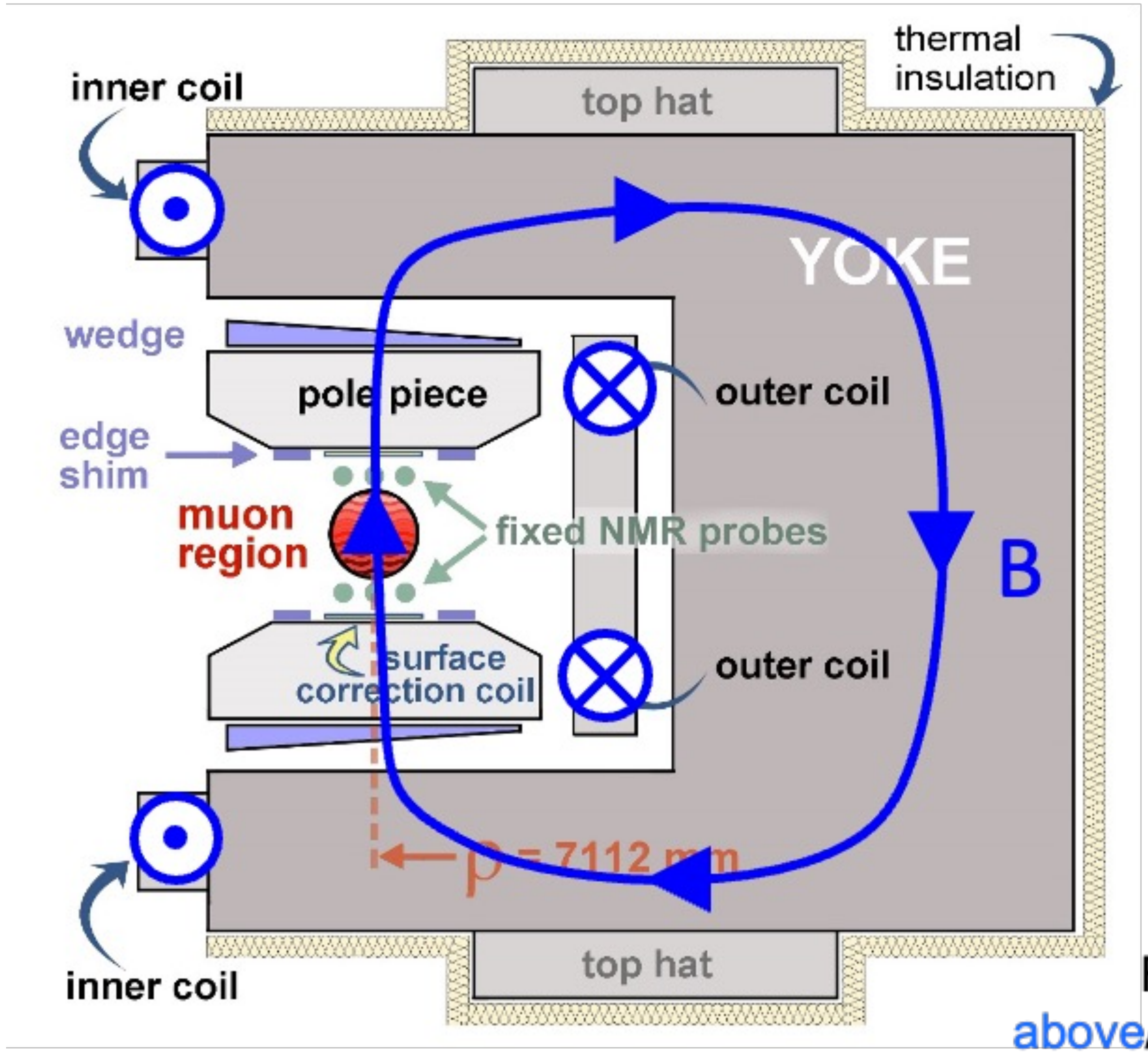
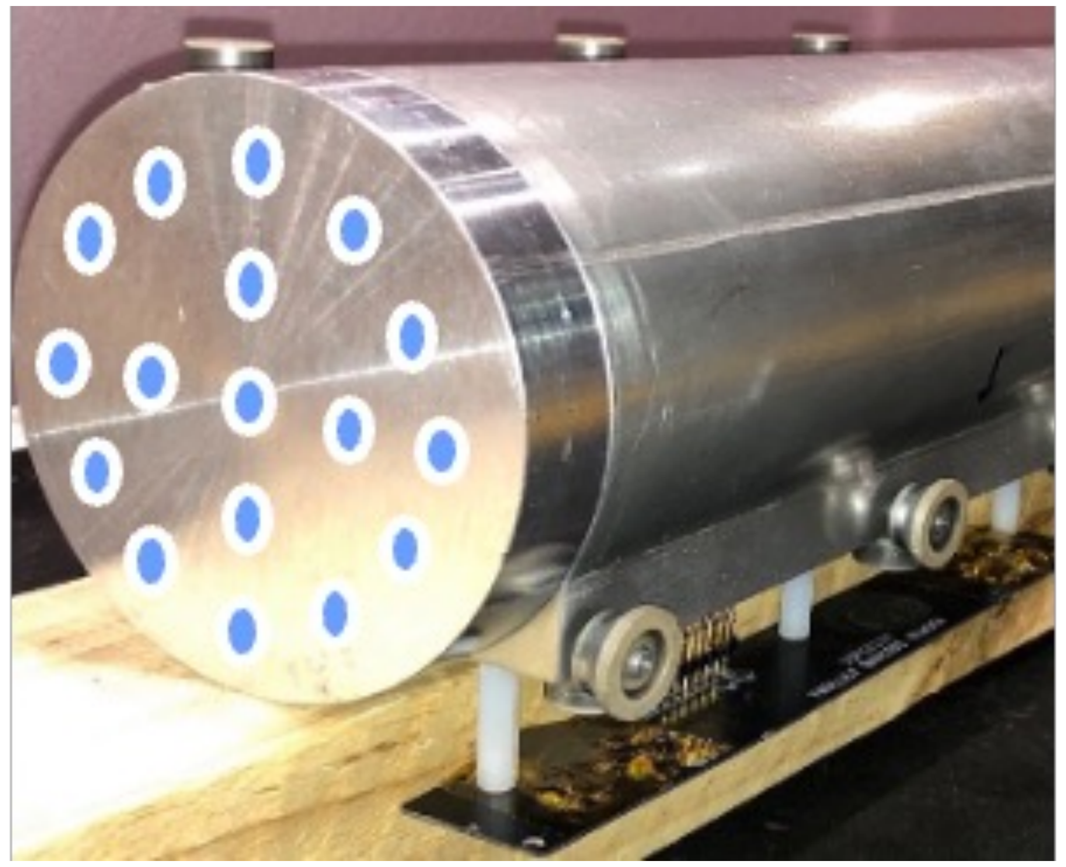
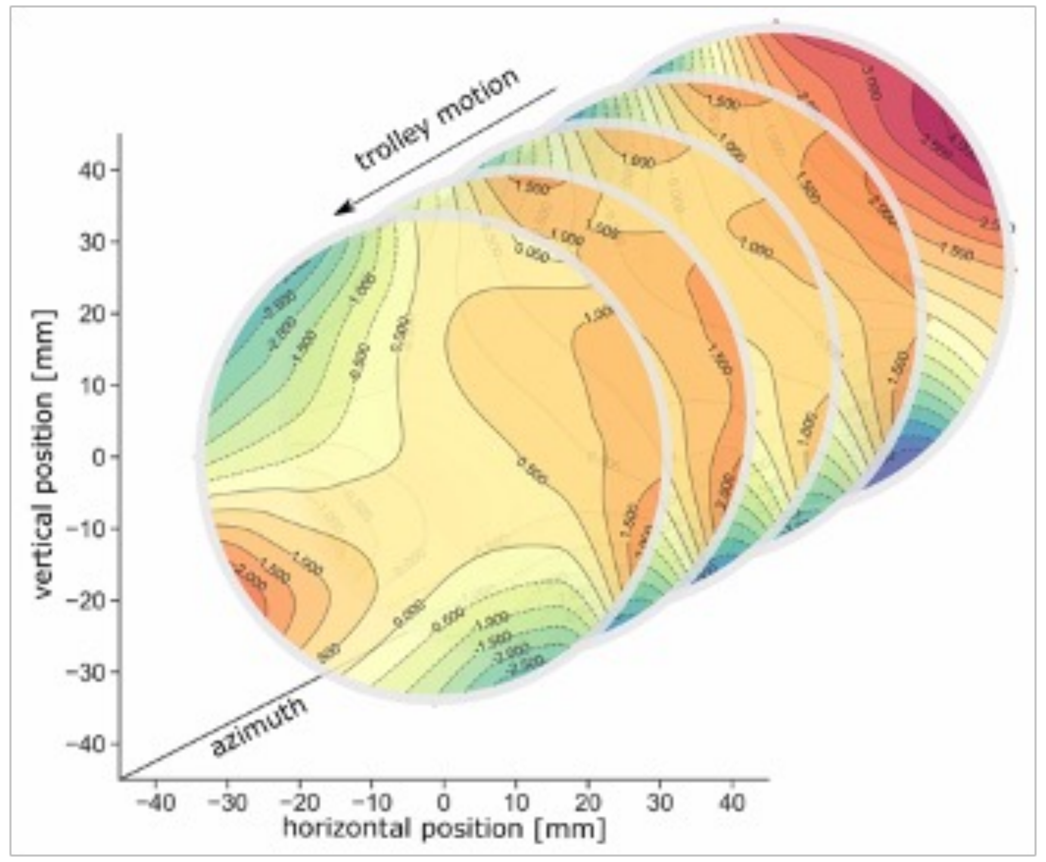
- 14 m diameter, 1.45 T
- C-shaped SC magnet



- In-vacuum NMR trolley maps field every ~3 days



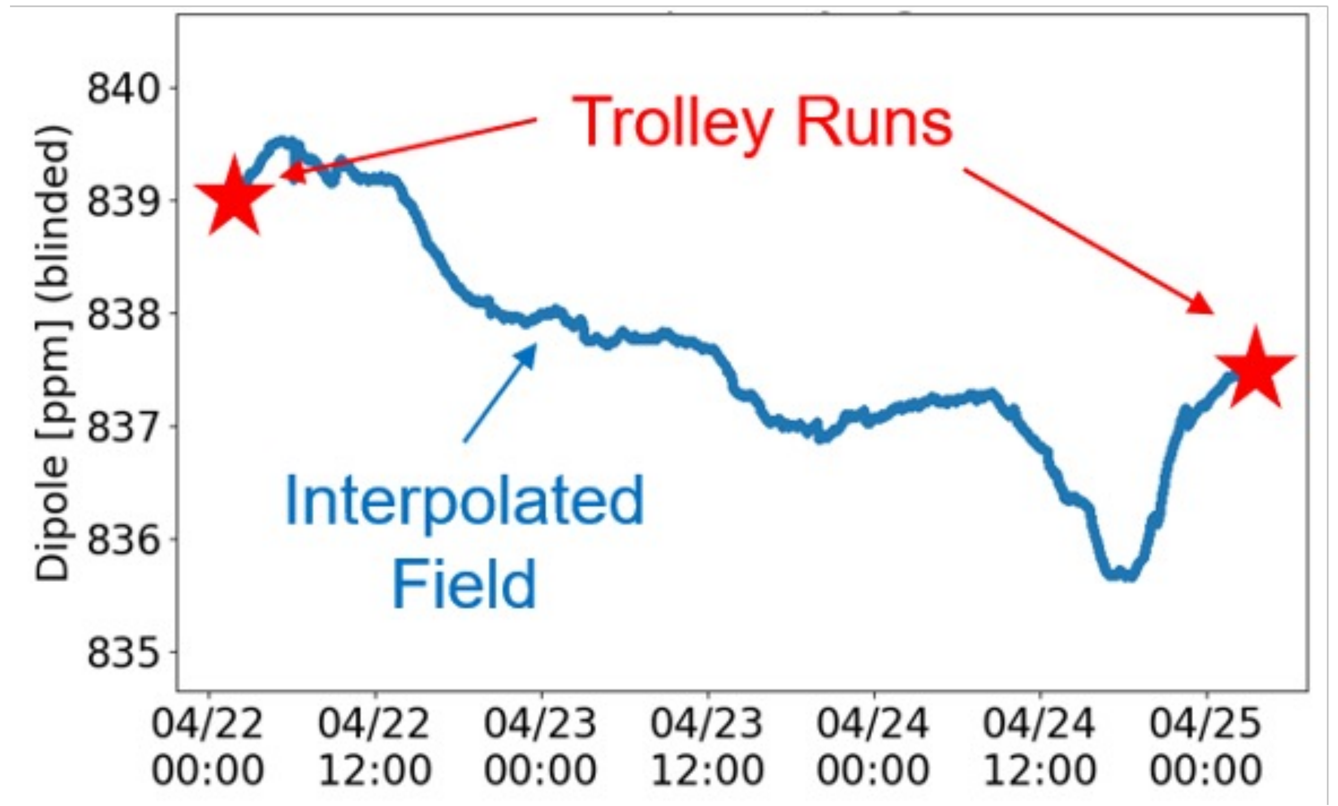
17 petroleum jelly NMR probes



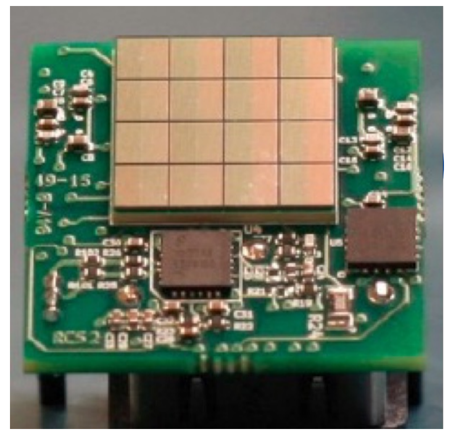
2D field maps (~8000 points)

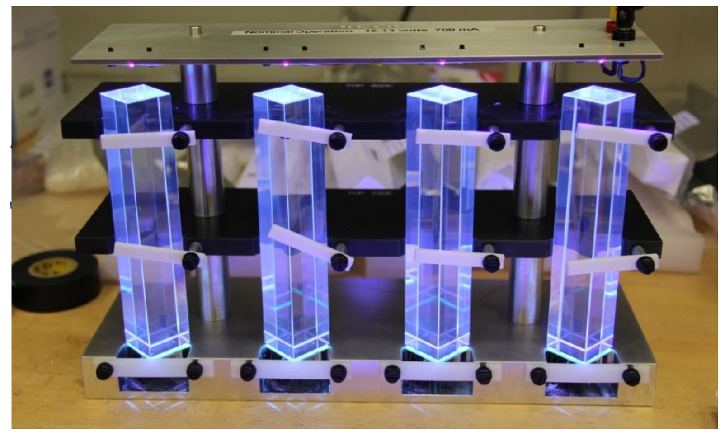
- 378 fixed NMR probes monitor field during muon storage at 72 locations

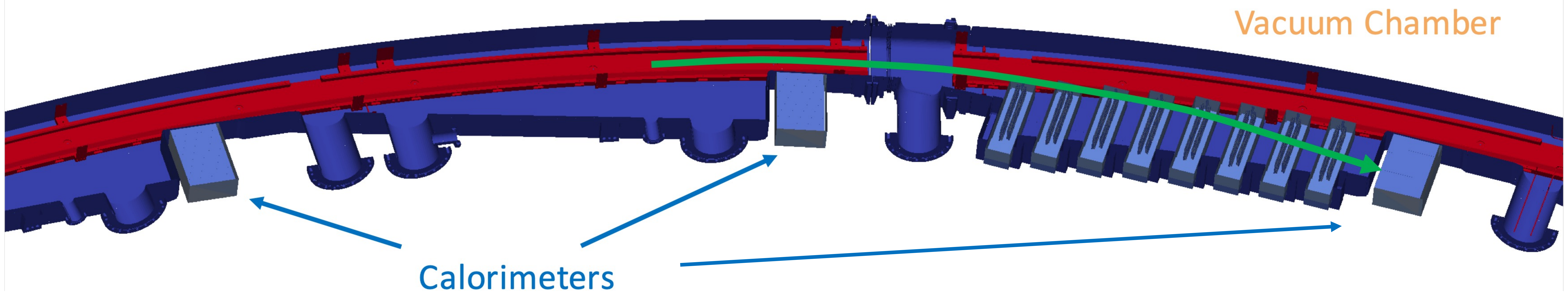
Fixed probes above/below muon storage region

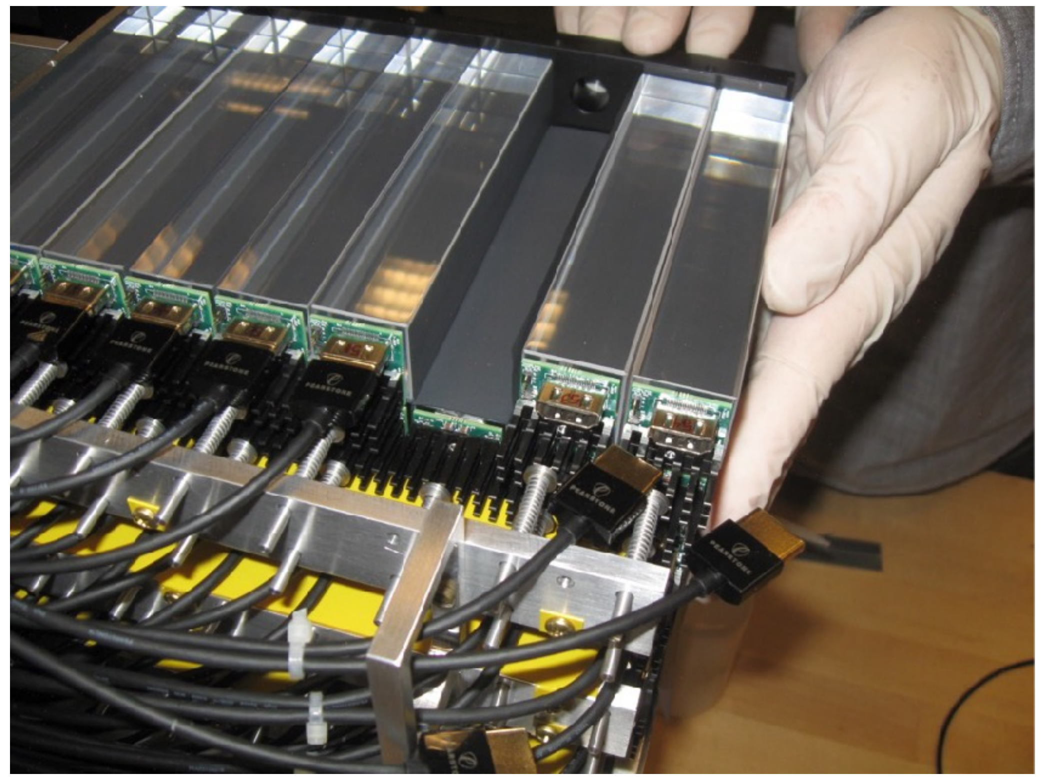


Precession frequency measurement



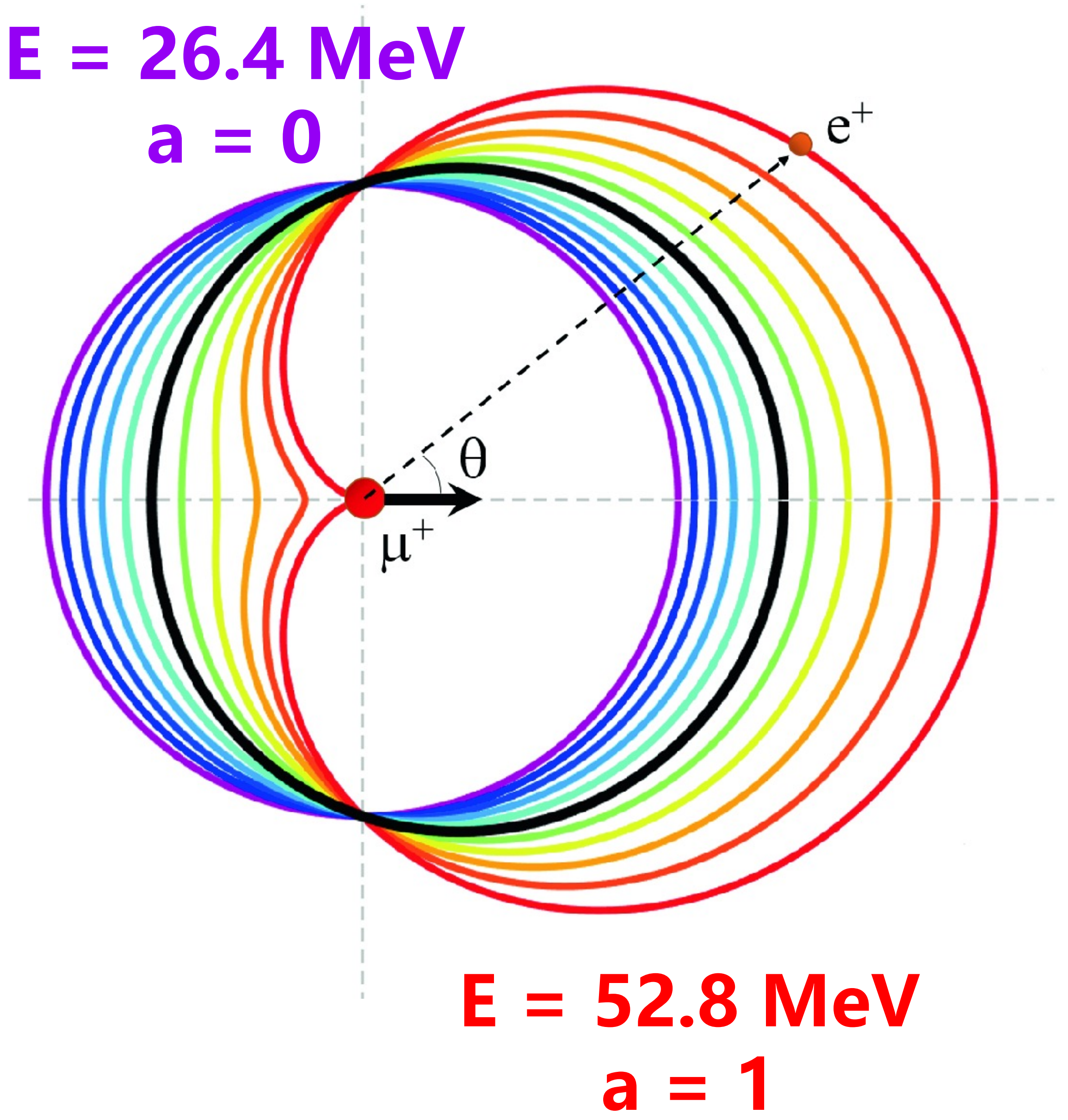


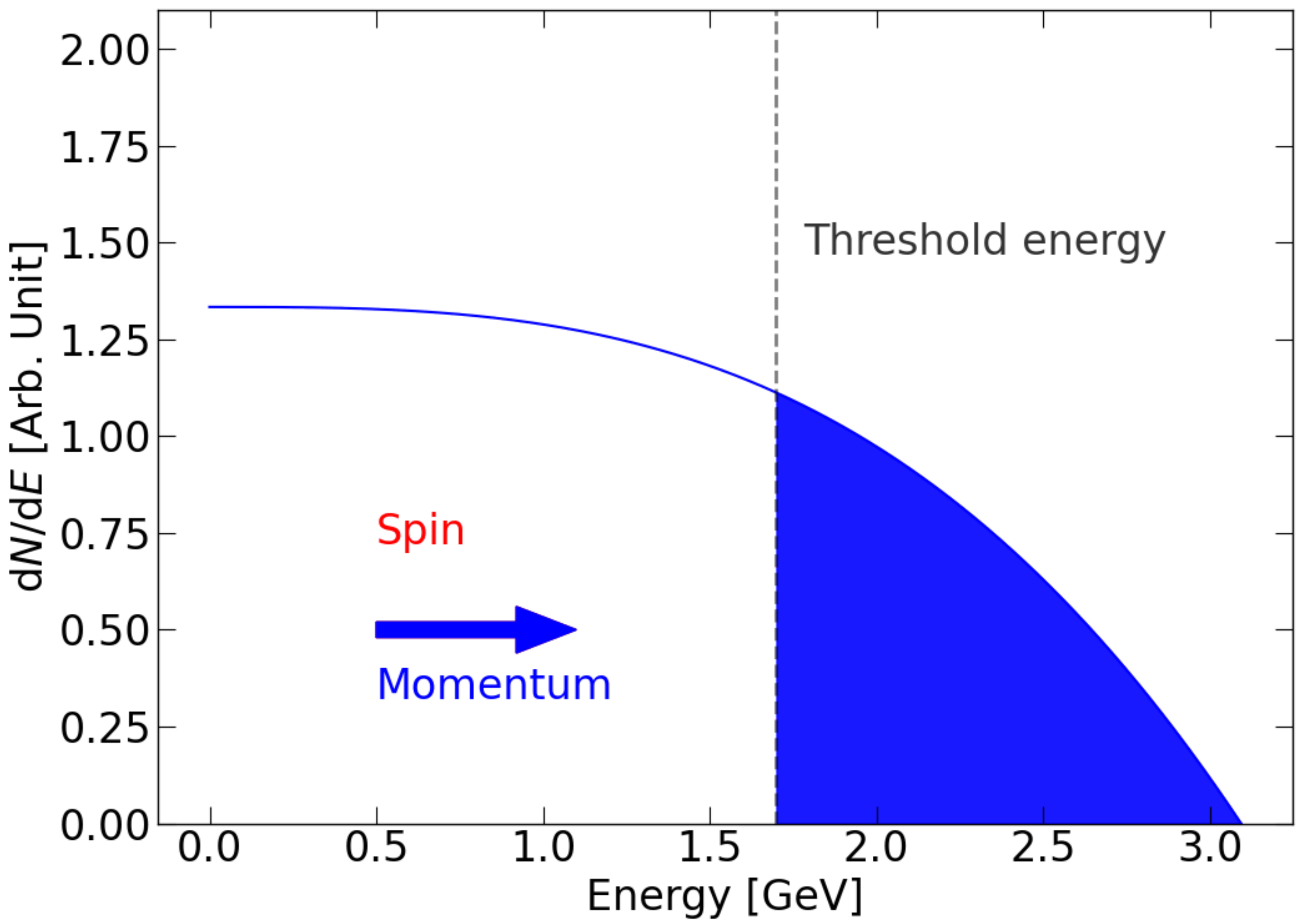




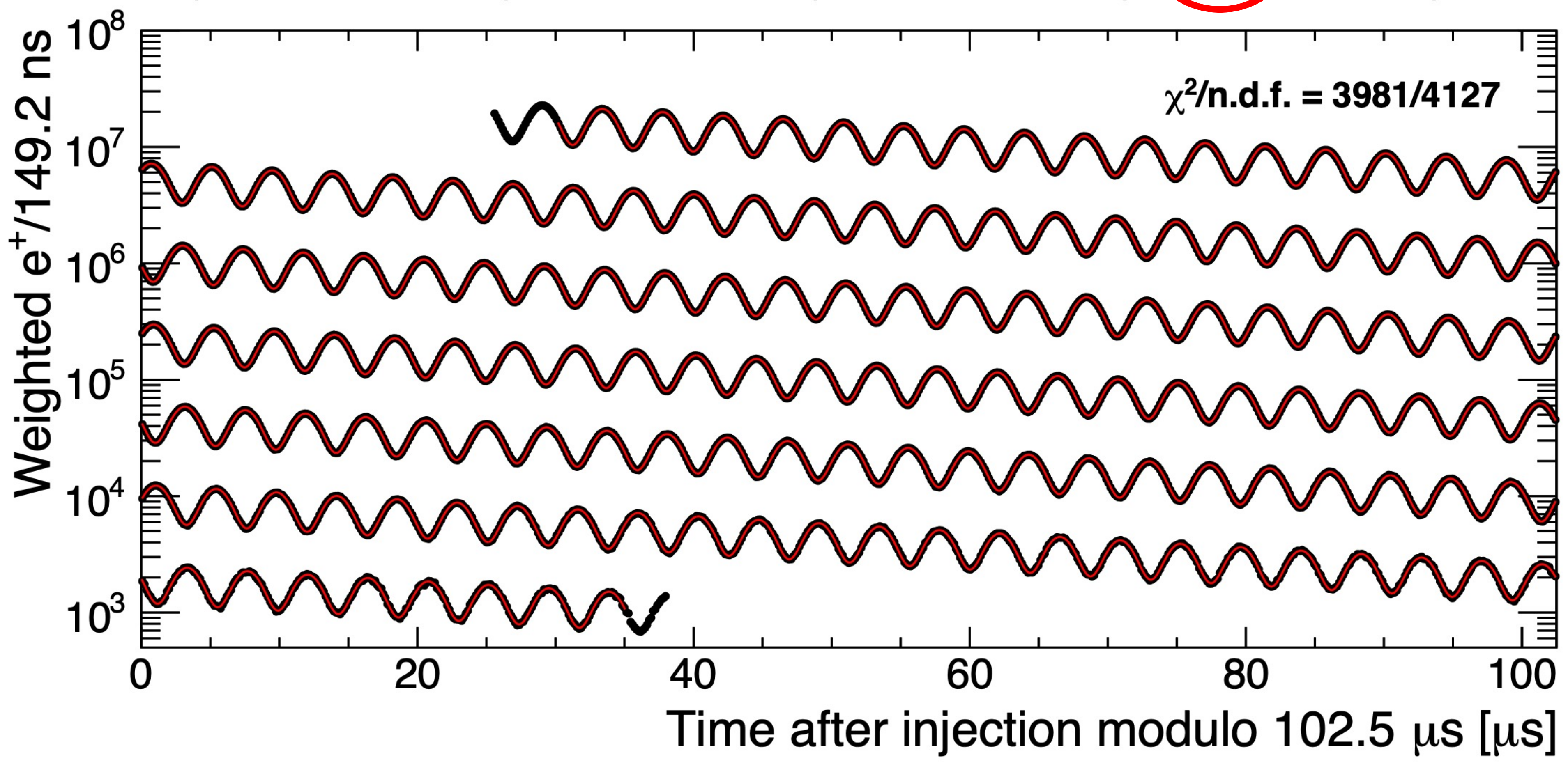
PbF_2 calorimeter

high energy e^+ is emitted preferentially in the muon spin direction due to parity-violating weak decay





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



Additional corrections

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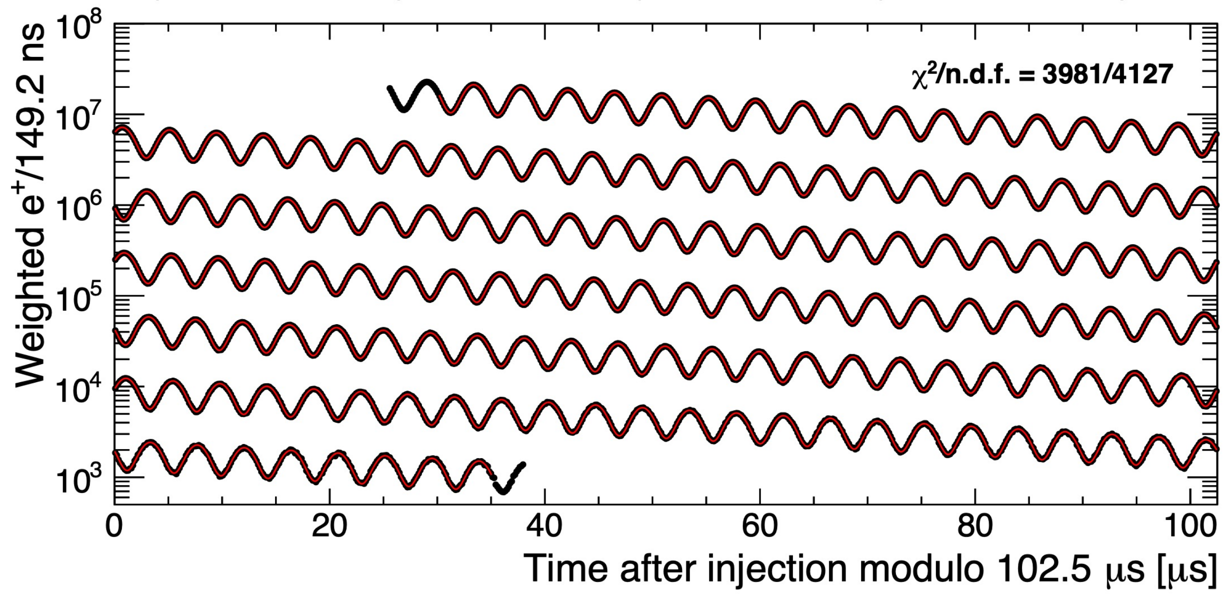


$$N(t) = N_0 e^{-t/\tau}\left[1 + A_\mu \cos(\omega_a t + \phi)\right]$$

see L. Cotrozzi's talk on Thu 11:00 am (Sec 05)

see KSK's poster 225 on Thu 7:00 pm (Sec 05)

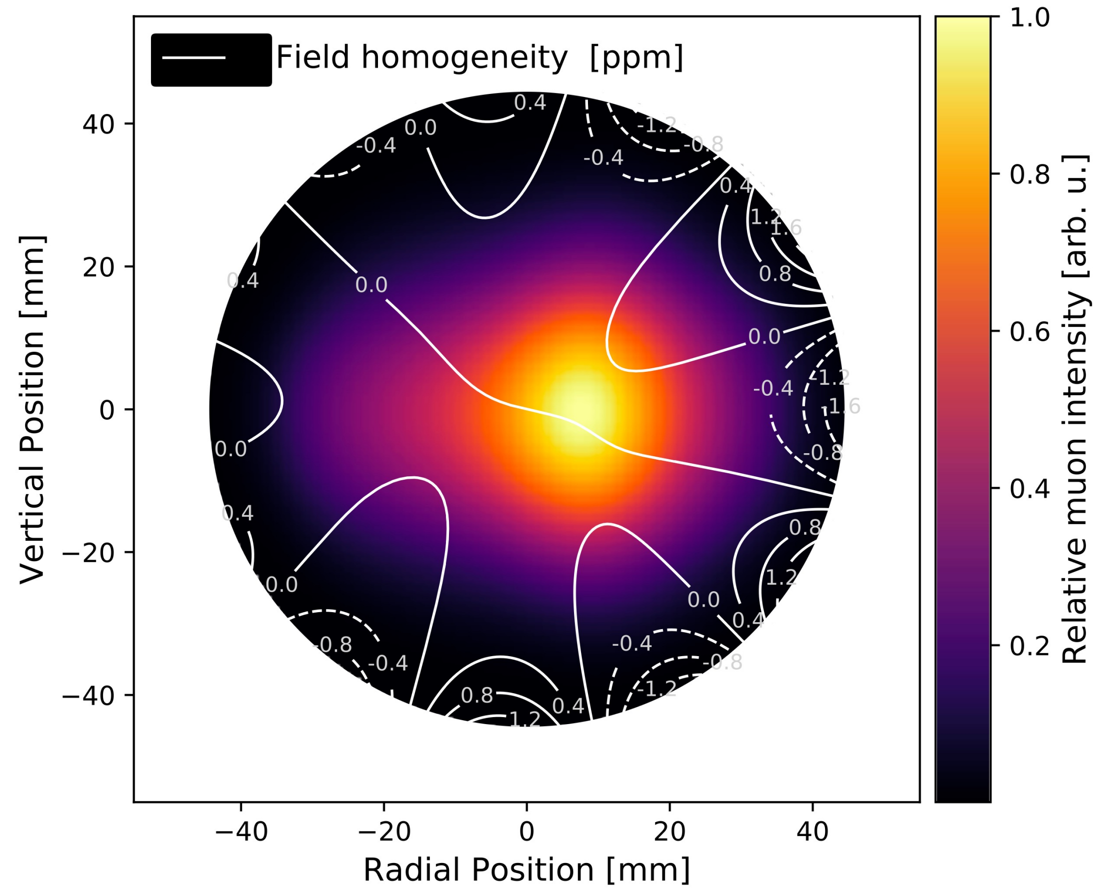
Beam Dynamics Corrections

E-field & vertical motion: Spin precesses slower than in basic equation

Phase changes over each muon fill: Phase acceptance, differential decay, and muon losses

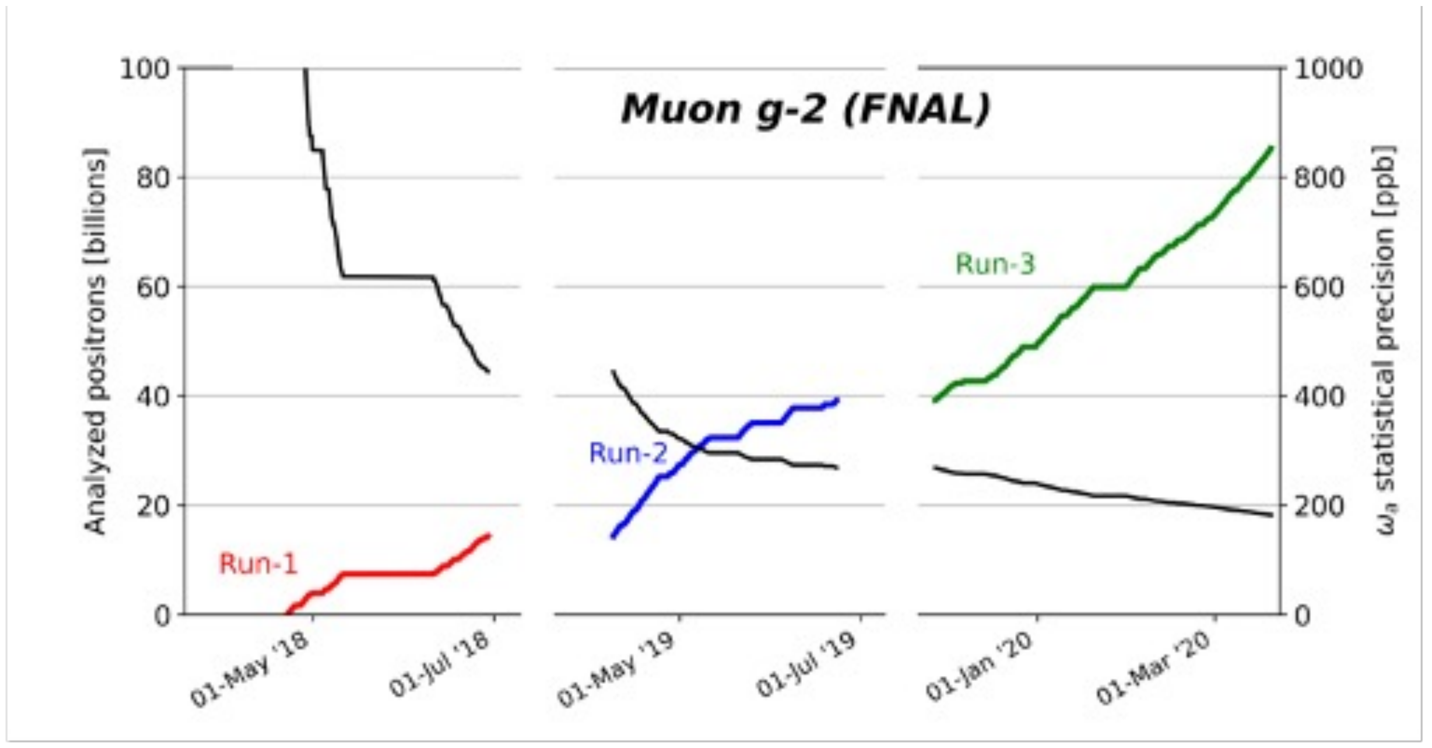
$$a_\mu \sim \frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m}\frac{1+C_e+C_p+C_{pa}+C_{dd}+C_{ml}}{1+B_k+B_q}$$

Transient magnetic fields: Quad vibrations and kicker eddy current

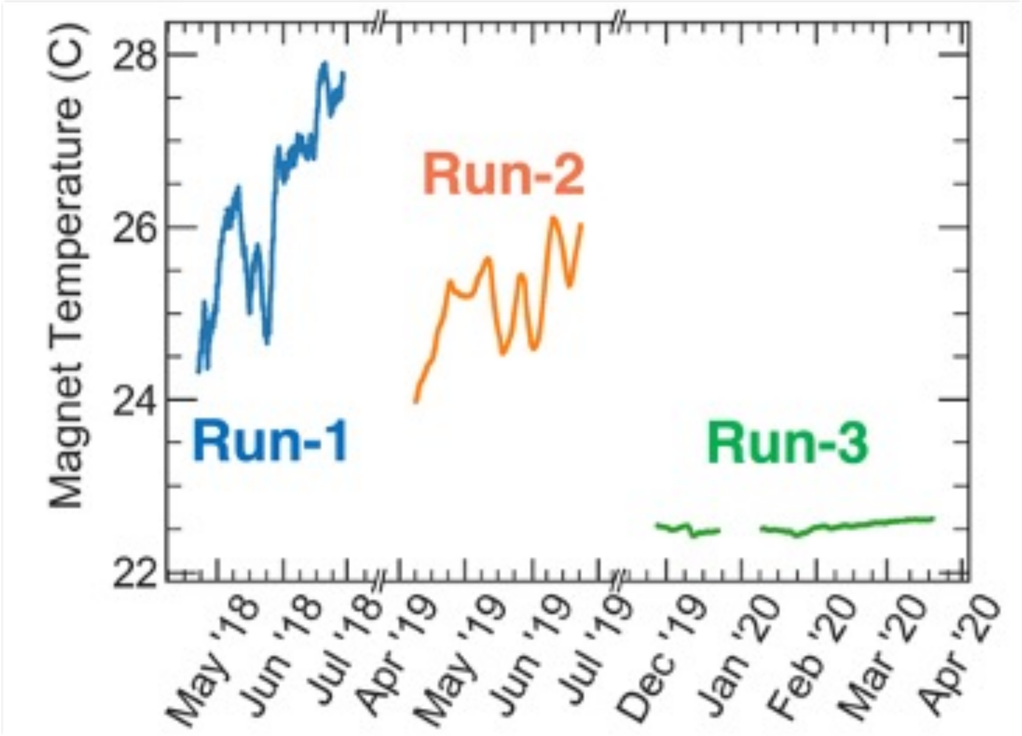


- ω_a corrections dominated Run-1 systematics: 500(93) ppb
- For Run-2/3 they are 580(40) ppb, dominated by C_e and C_p

Run-2/3 uncertainty improvements

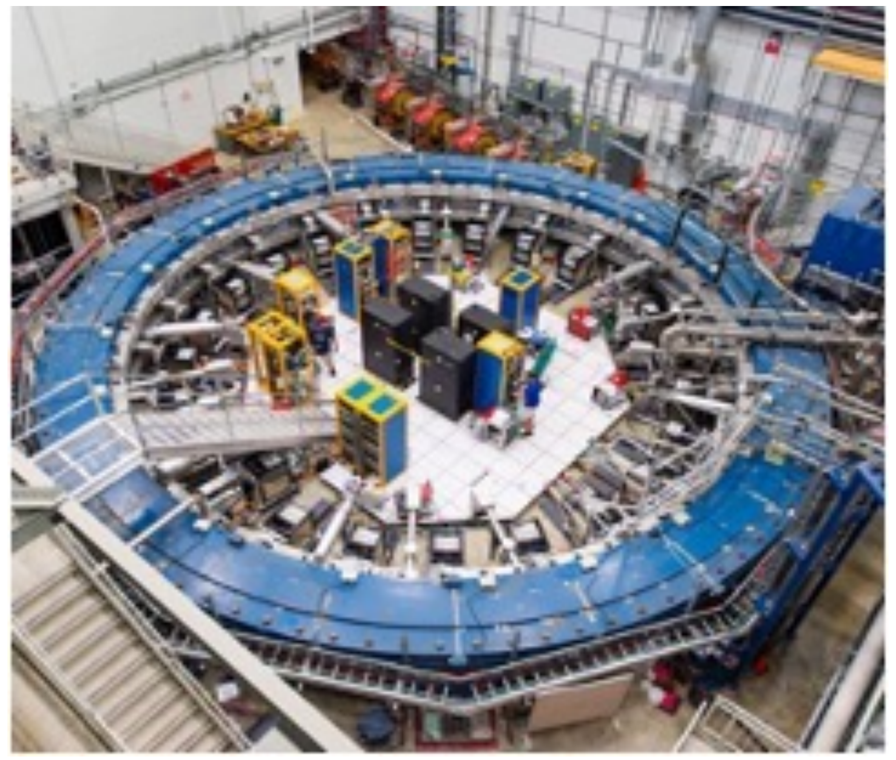


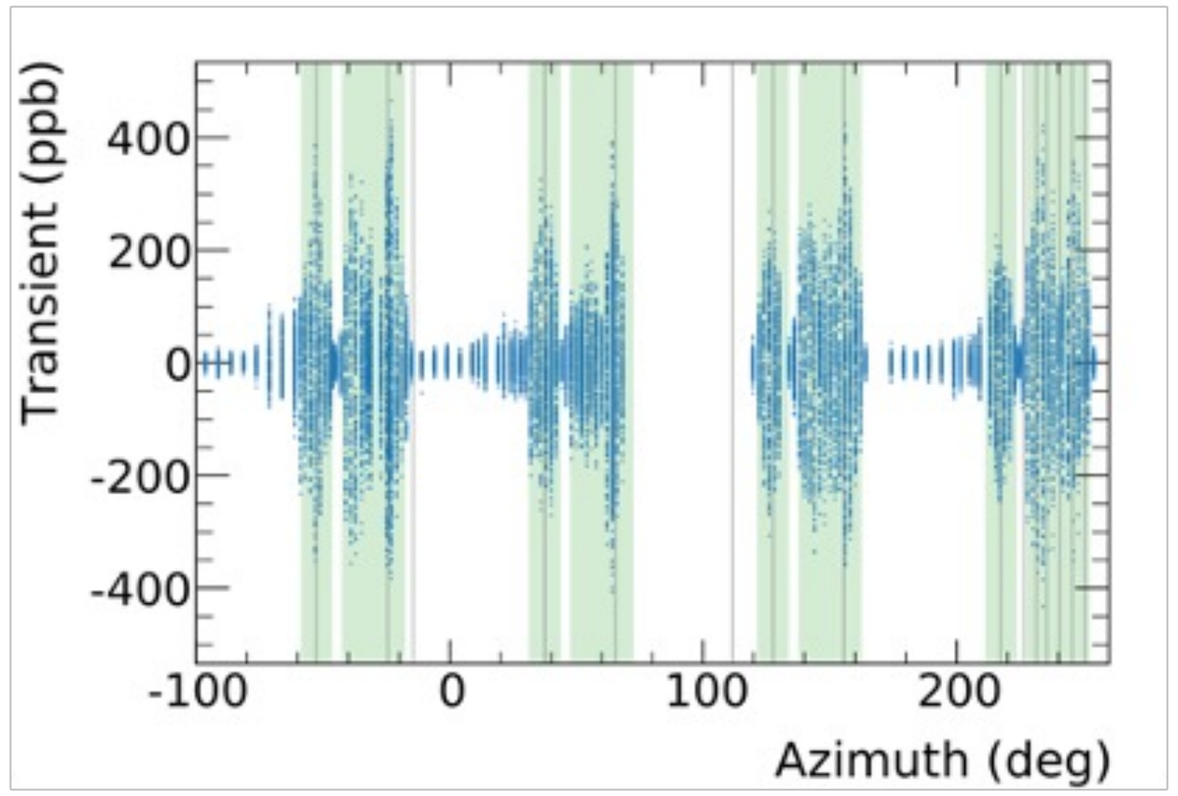
Statistics



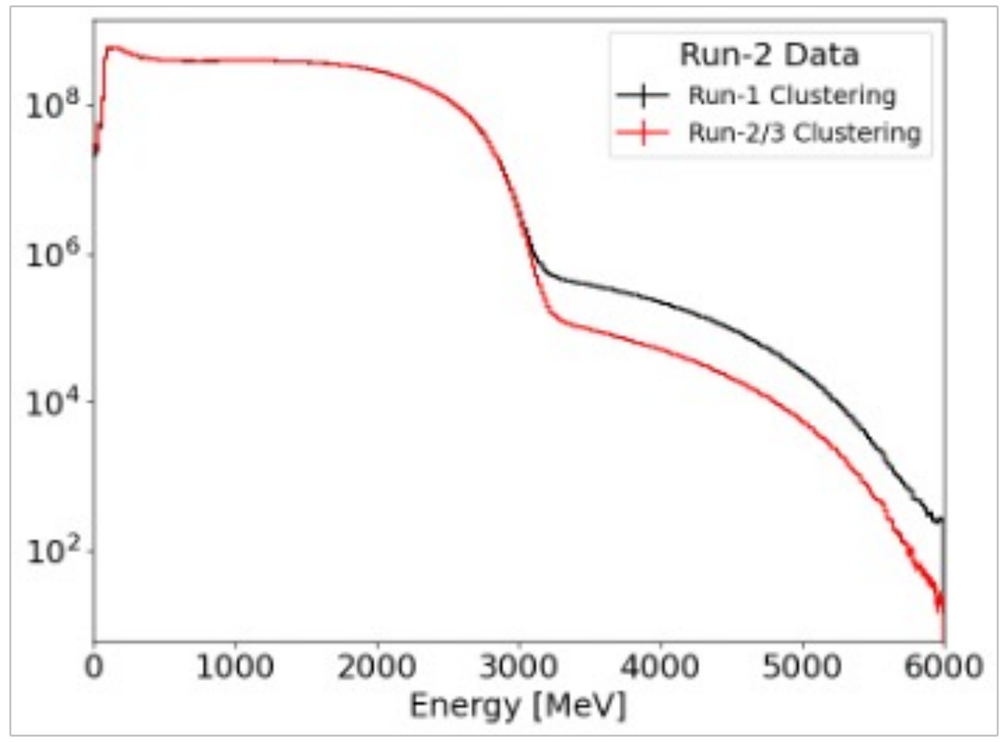
Running Conditions

- Damaged quad resistors fixed
- Hall/Ring temperature stabilized
- Kicker strength improved

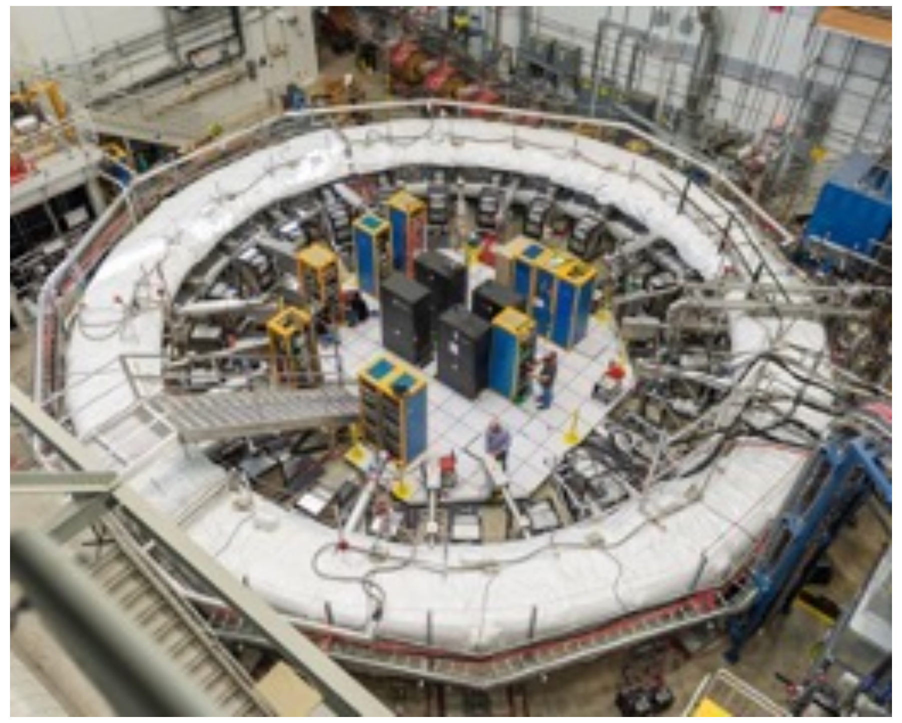




Systematic Measurements & Studies

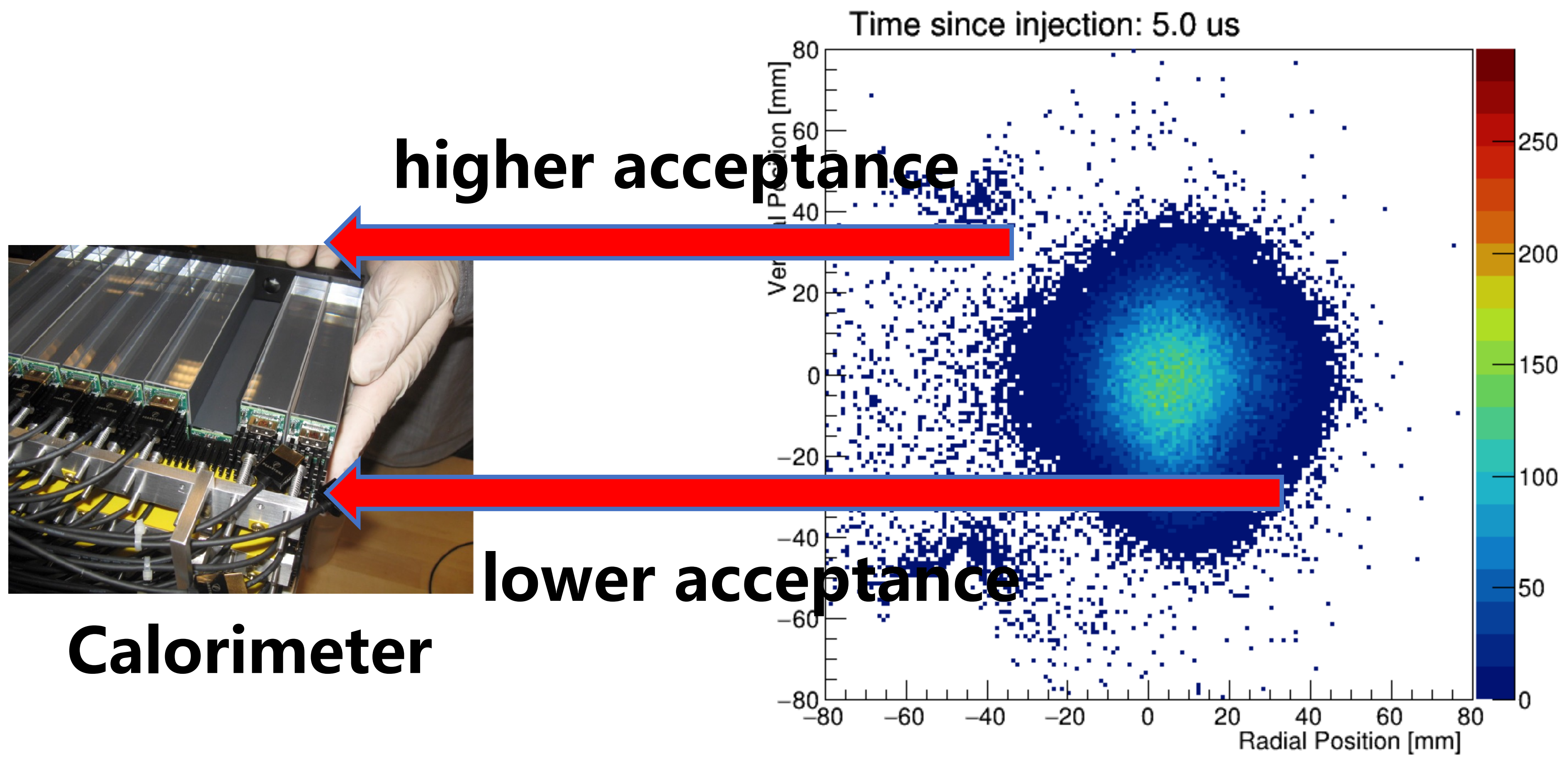


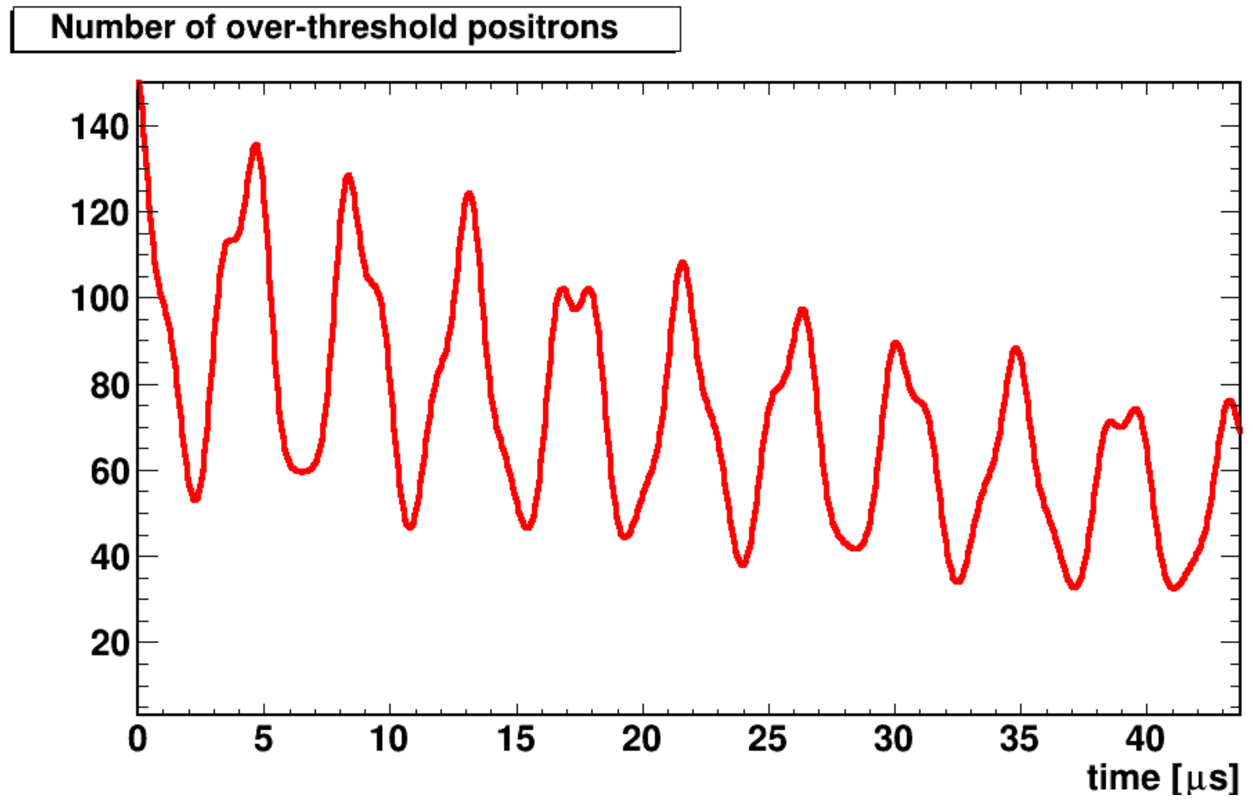
Analysis Improvements



Suppressing CBO with a RF system

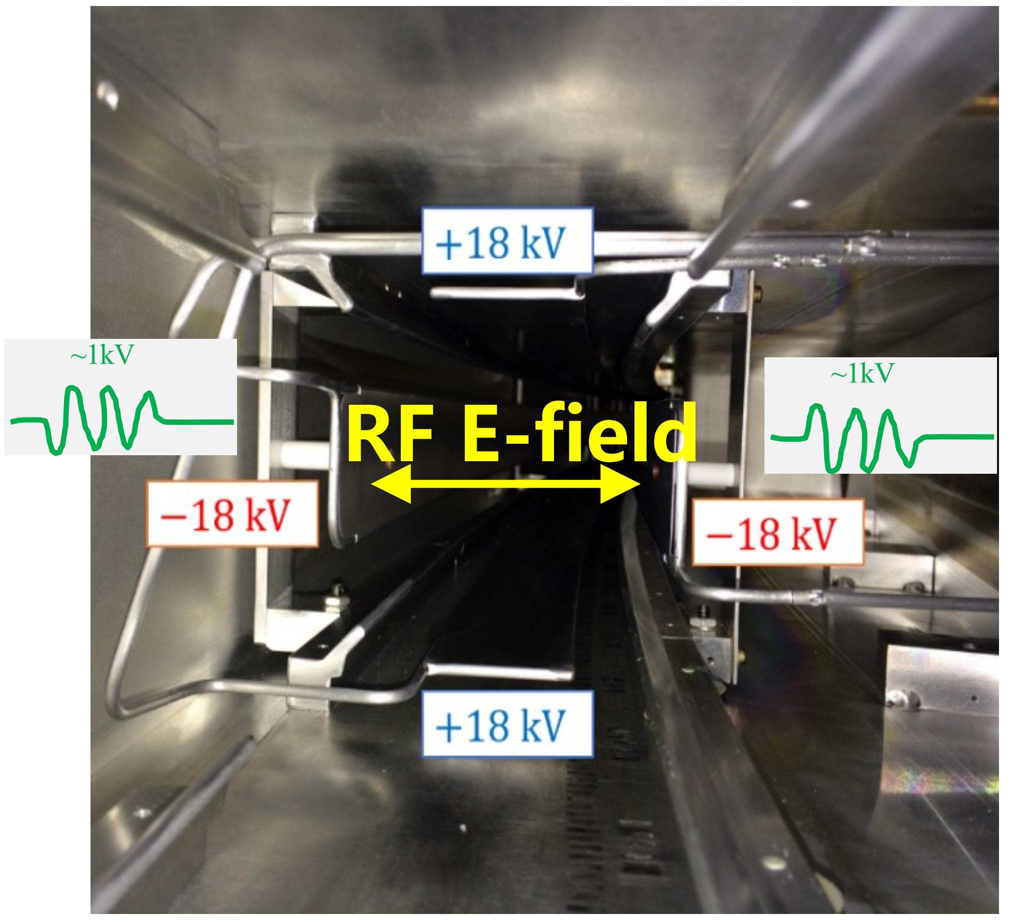
- CBO is the coherent transverse betatron oscillation
- Coupled with the calorimeter acceptance, it distorts the time spectrum



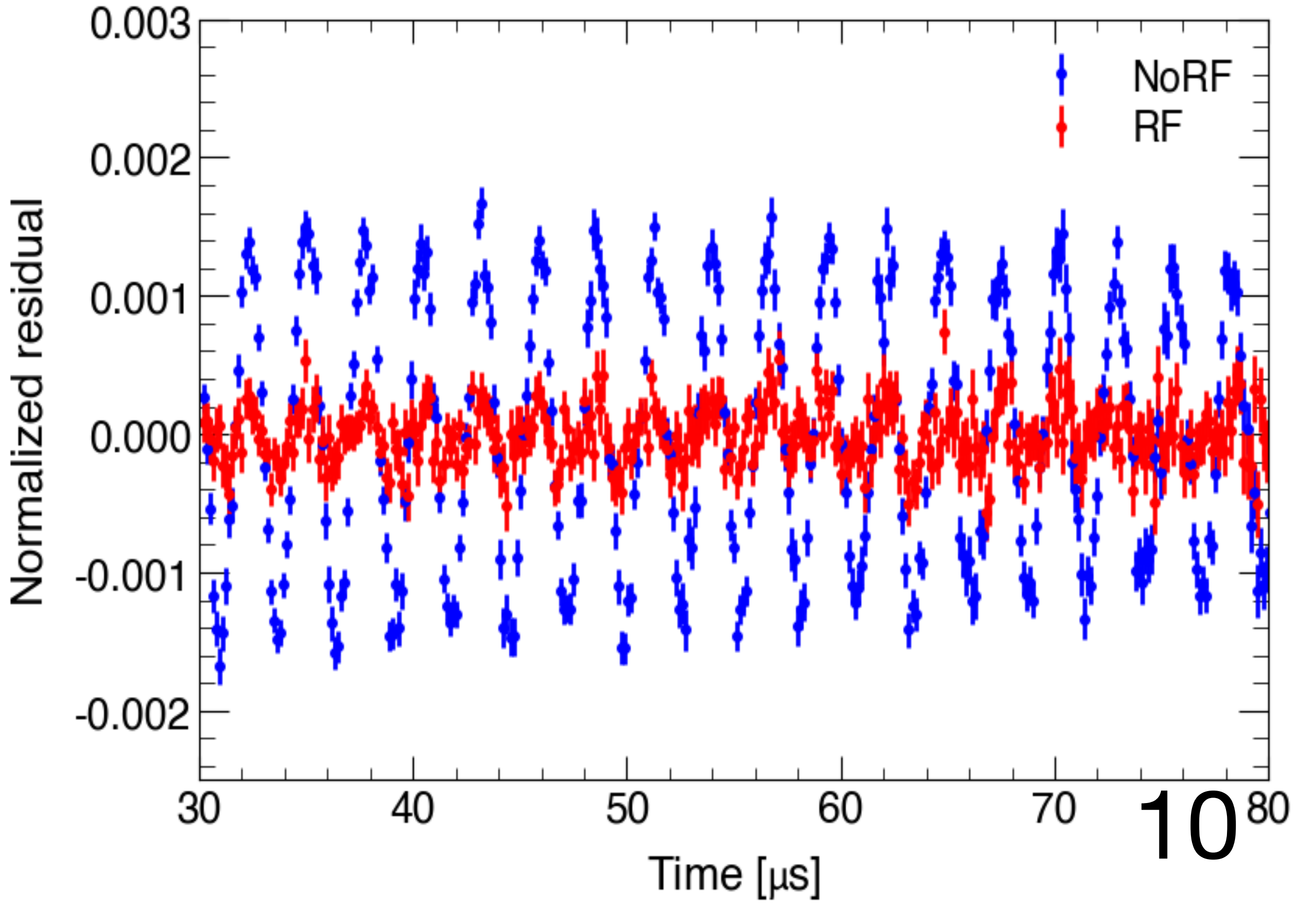


- Implemented a RF system to reduce the CBO significantly.
- Run-5/6 data (almost half of the entire data) was taken with the RF system.

Electrostatic Quadrupole + RF



CBO



Run-4/5/6 expected improvements

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Run-2/3 Result: PRL **131**, 161802 (2023)

TABLE I. Values and uncertainties of the $\mathcal{R}'_\mu$ terms in Eq. (2), and uncertainties due to the external parameters in Eq. (1) for a_μ. Positive C_i increases a_μ; positive B_i decreases a_μ [see Eq. (2)]. The ω_a^m uncertainties are decomposed into statistical and systematic contributions. All values are computed with full precision and then rounded to the reported digits.

	Quantity	Correction (ppb)	Uncertainty (ppb)
ω_a	ω_a^m (statistical)	...	201
	ω_a^m (systematic)	...	25
BD	C_e	451	32
	C_p	170	10
	C_{pa}	−27	13
	C_{dd}	−15	17
	C_{ml}	0	3
ω_p	$f_{\text{calib}} \cdot \langle \omega'_p(\vec{r}) \times M(\vec{r}) \rangle$	...	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 for $\mathcal{R}'_\mu$	...	70
	Total external parameters	...	25
	Total for a_μ	622	215

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\ (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

Expected Run-4/5/6 improvements
(Estimation for systematics on-going)

- ω_a^m (statistical) → ~100 (in total Runs 1-6), ~x4 stats
- ω_a^m (systematic) → ~x10 reduction of CBO with the RF system (Run-5/6)
- C_e → New signal processing algorithm
  New beam-monitoring system (miniSciFi)
- C_{dd} → New tracker-based analysis method
- $f_{\text{calib}} \cdot \langle \omega'_p(\vec{r}) \times M(\vec{r}) \rangle$ → More calibrations + cross-calibrations.
  Better understanding and handling of magnet drift.
- B_k → More and better measurements
- Total systematic for $\mathcal{R}'_\mu$ → Surpassed the TDR systematics goal of 100 ppb.
  And possibly even smaller for Run-4/5/6!

BSM searches (EDM, CPT/LI, DM)

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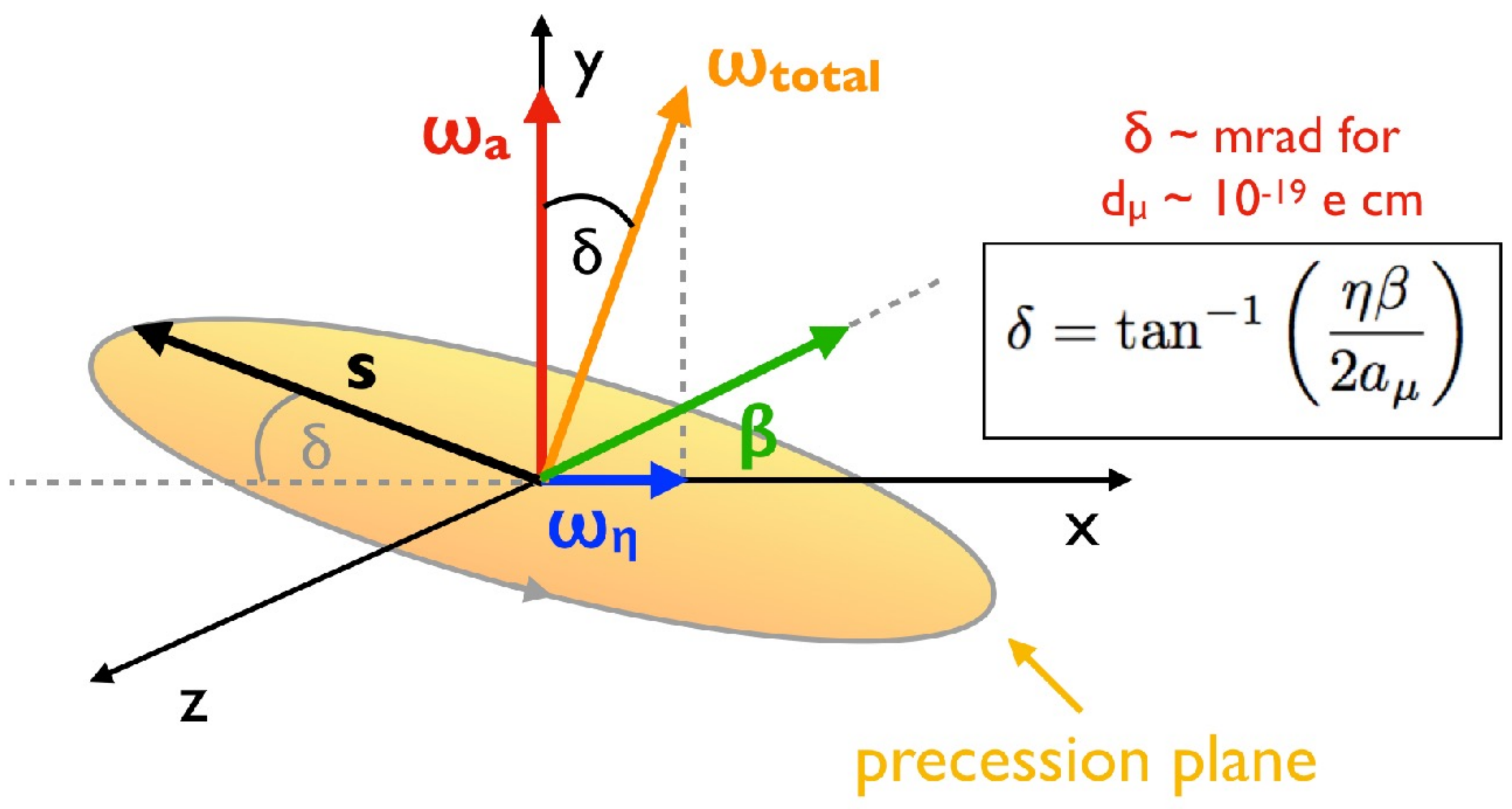
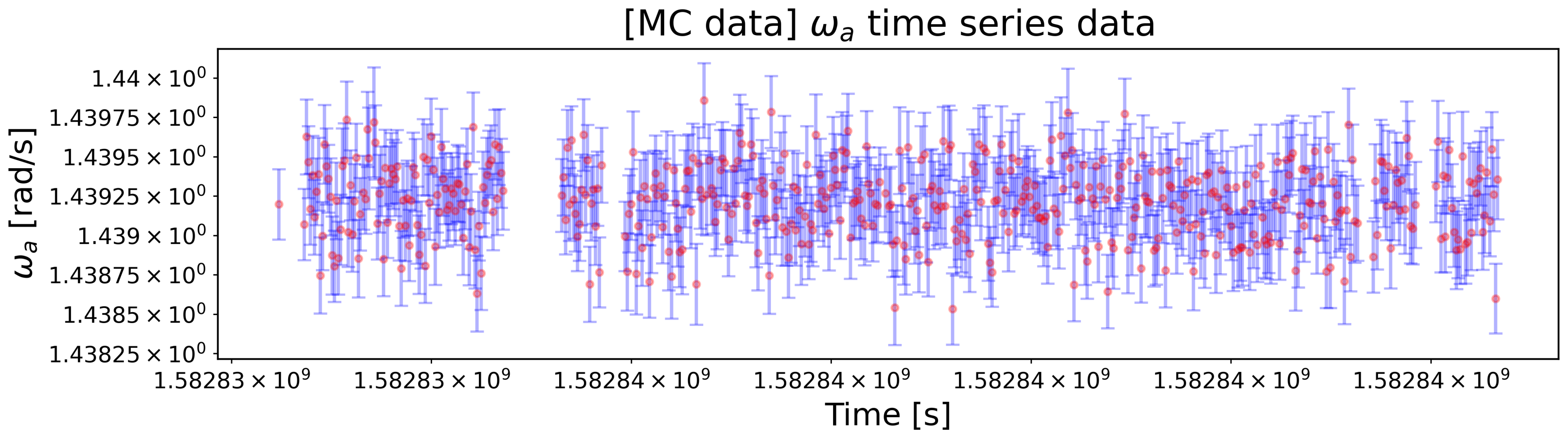
see B. Mitra's talk on Fri 8:47 am (Sec 03)

- **Muon Electric Dipole Moment (EDM)**
  - ➢ The spin precession plane is tilted in the presence of the EDM.
  - ➢ Run-1 analysis in review, Run-2/3 analysis in progress
  - ➢ Current limit (BNL): 1.8×10^{-19} e · cm → Projected limit: $\lesssim 3 \times 10^{-20}$ e · cm



- **CPT and Lorentz Invariance Violation**
  - ➢ ω_a modulated at the sidereal motion freq.
  - ➢ Run-2/3 analysis in review.
  - ➢ Current limit (BNL): 1.4×10^{-24} GeV → Projected limit (FNAL Run-2/3): $\mathcal{O}(10^{-25})$ GeV

- **Ultralight Muonic Dark Matter (scalar)**
  - ➢ ω_a modulated at the DM Compton frequency.
  - ➢ Run-2/3 analysis in progress.



Summary

- Our collaboration has completed the data-taking in Summer 2023
- Run-2/3 results announced last year (PRL **131**, 161802 (2023)), detailed analysis report in arXiv:2402.15410 (accepted by PRD).
- Analysis of the remaining data (Run-4/5/6 taken from 2021-2023) is underway
- A final result with ~140 ppb uncertainty is expected to be published in 2025
  - We met the TDR statistical goal and will likely surpass the systematics goal
  - Many improvements have been made in systematics. For instance, Run-5/6 data was taken with the RF system, and CBO was significantly reduced.
- This result will set the stage for a final showdown between the current theory and experiment in 2025
- BSM searches are also underway – EDM, CPT/LV and DM

Acknowledgement

Tsung-Dao Lee Institute

- Department of Energy (USA)
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- Strong 2020 (EU)
- German Research Foundation (DFG)
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