Muon *g* - 2 and EDM at FNAL

ZENG Yonghao, on behalf of the Muon *g* - 2 collaboration

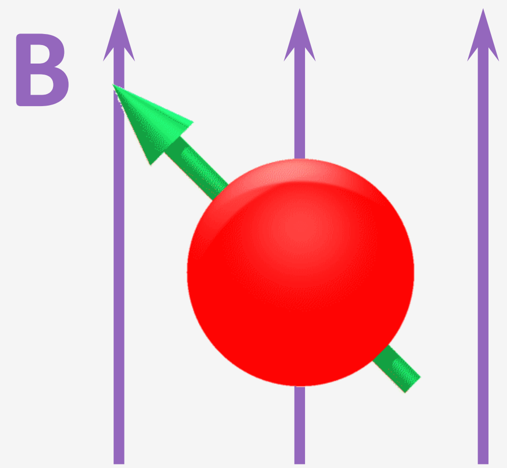
MIP 2026

Huizhou, Guangdong

2026.04.25

李政道研究所
TSUNG-DAO LEE INSTITUTE

Magnetic Moments



Charged spinning particle with angular momentum $\vec{\boldsymbol{S}}$, has a magnetic moment $\vec{\boldsymbol{\mu}}$

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

***g*-factor** connects the spin to its magnetic moment

Classical object: $g = 1$ Fundamental fermion: $g \approx 2$

Spin precesses in an external magnetic field $\boldsymbol{\omega_s} = \frac{g}{2} \frac{e}{m} \boldsymbol{B}$

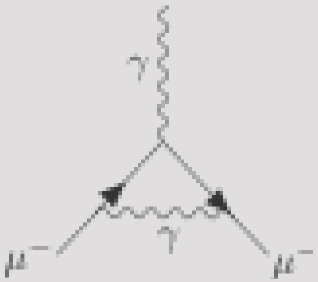
Experimental goal

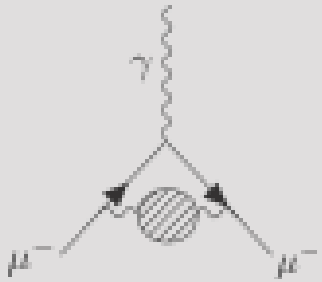
Measure $g - 2$ for muon by observing its spin precession with $\frac{\sigma((g-2)/2)}{(g-2)/2} < \mathbf{140 \times 10^{-9}}$ **(parts per billion, ppb)** precision

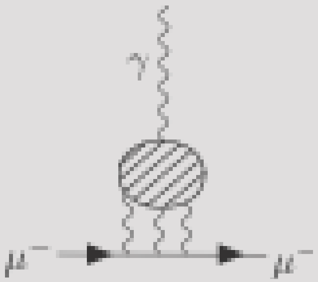
Magnetic Anomaly in the Standard Model

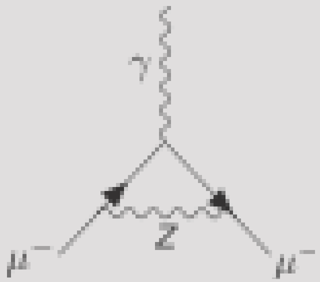
Quantum fluctuations dress the particle, producing **anomalous magnetic moment a**

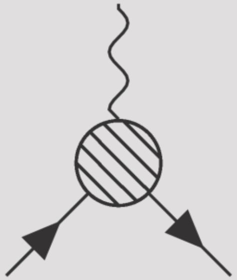
$$a = \frac{g-2}{2} \approx 0.00116$$





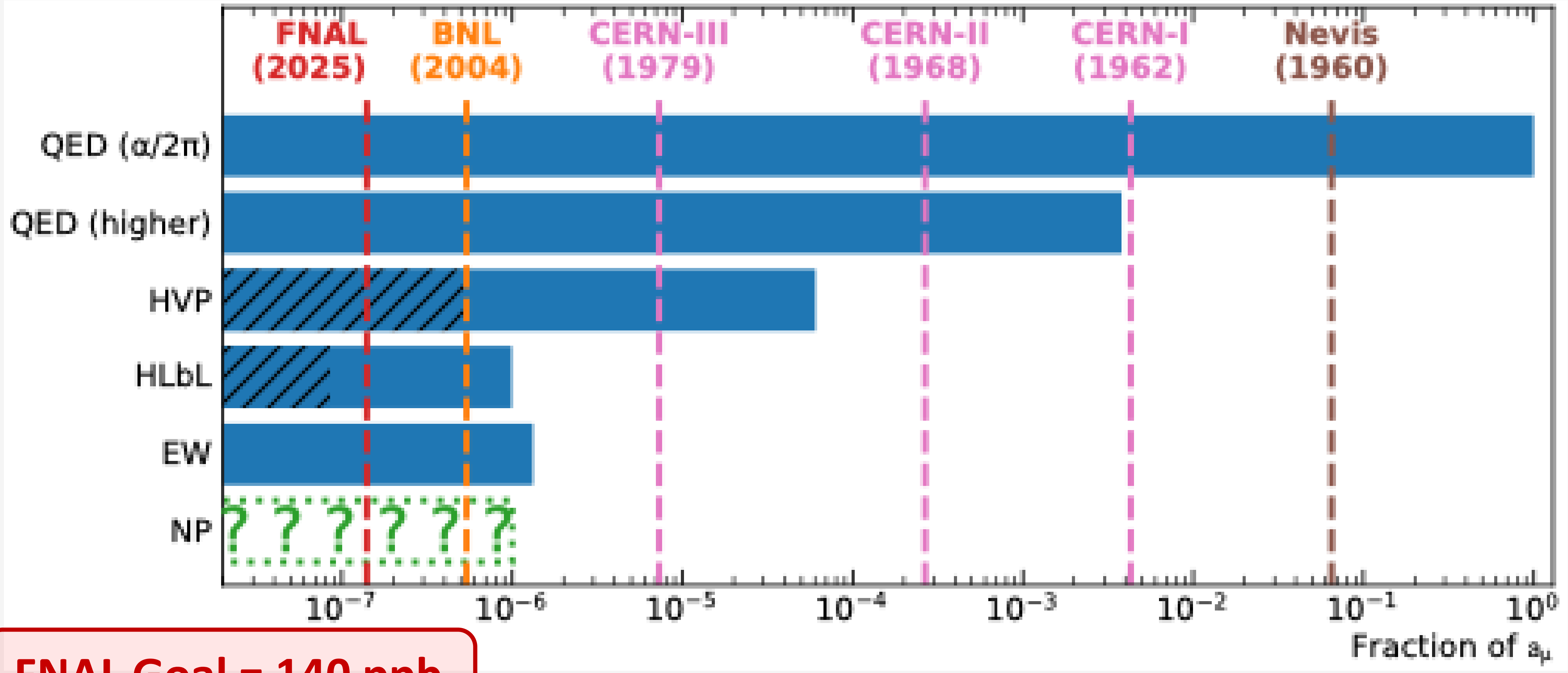






	Quantum Electrodynamics	Hadronic Vacuum Polarization	Hadronic Light-by-light	Electroweak	BSM?
Contribution	99.994%	60.4 ppm	0.99 ppm	1.324 ppm	?
Uncertainty	2 ppb	**523 ppb**	**80 ppb**	3 ppb	?

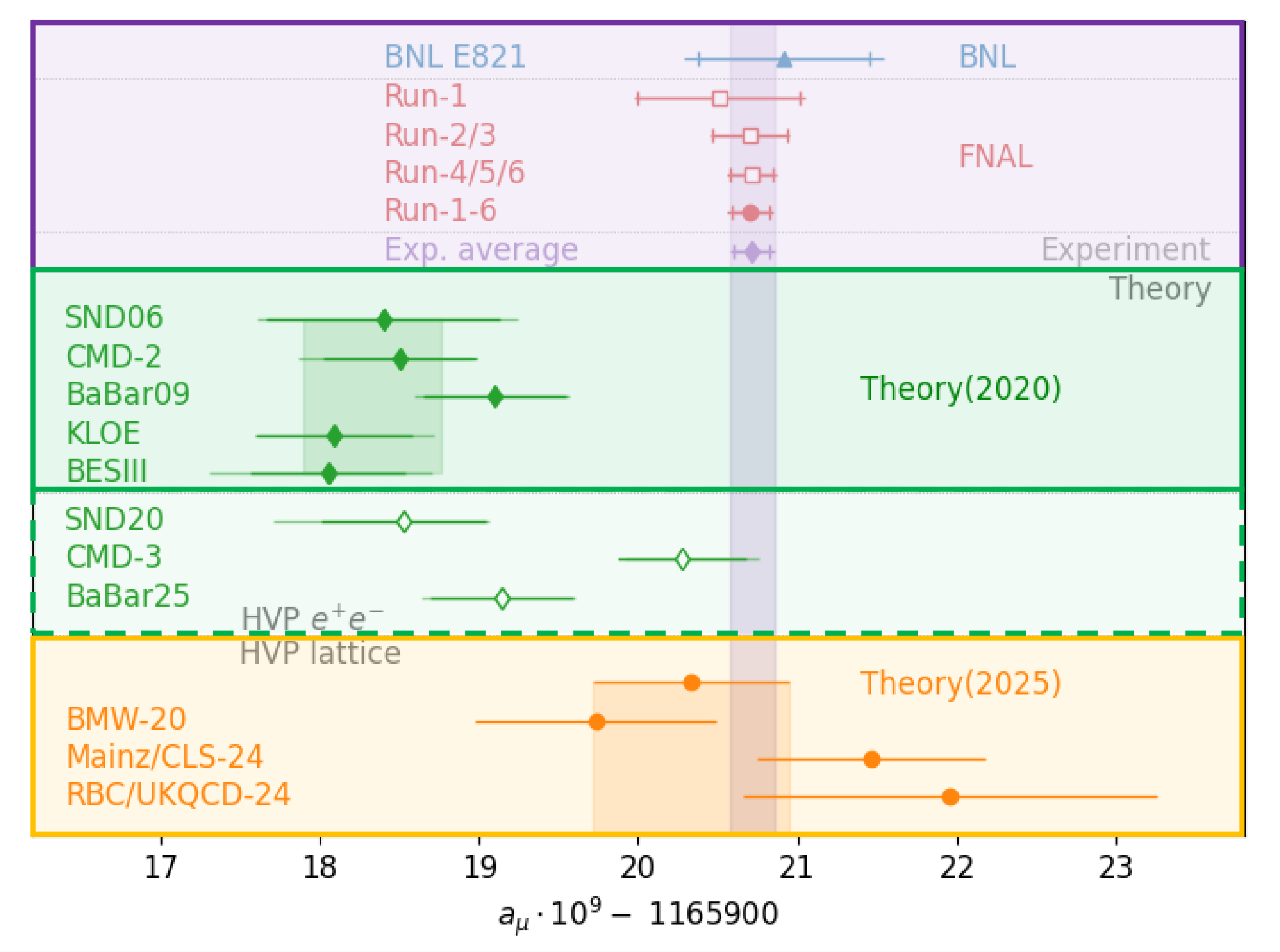
Probing New Physics with Muon $g-2$



FNAL Goal = 140 ppb

The increasing precision of exerpiemts allows more **stringent tests** of the theory.

Status of a_μ



Experiment

Most precise determination of a_μ

Data-driven HVP, 2020 Theory

Strong tensions with experiment

Data-driven HVP, Since 2020

CMD-3 tensions with others

Lattice HVP, 2025 Theory

Only lattice HVP averaged

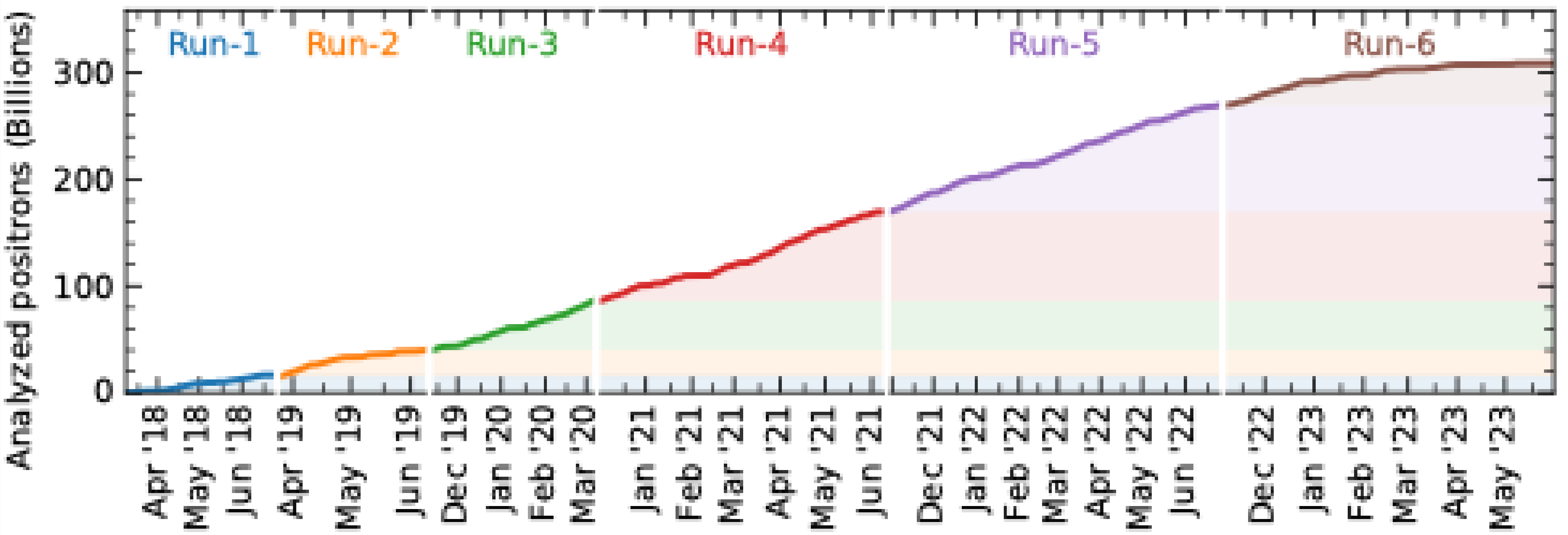
No tension with experiment, but with ~4x larger uncertainty

FNAL Muon g-2 Collaboration

176 collaborators, 34 institutes, 7 countries

Particle-, Nuclear-, Atomic-, Optical-, Accelerator-, and Theoretical-Physicists and Engineers

Data Collection Over 6 Years



April 2020: **Run-1**

August 2023: **Run-2/3**

June 2025: **Run-4/5/6** (this presentation)

Principle of a_μ Measurement

(1) Inject a spin-polarized muon beam into a storage ring

$$\omega_c = \frac{qB}{\gamma m} \qquad \omega_s = \underbrace{\frac{qB}{2m} g}_{\text{Larmor}} + \underbrace{(\gamma - 1)\frac{qB}{\gamma m}}_{\text{Thomas}}$$

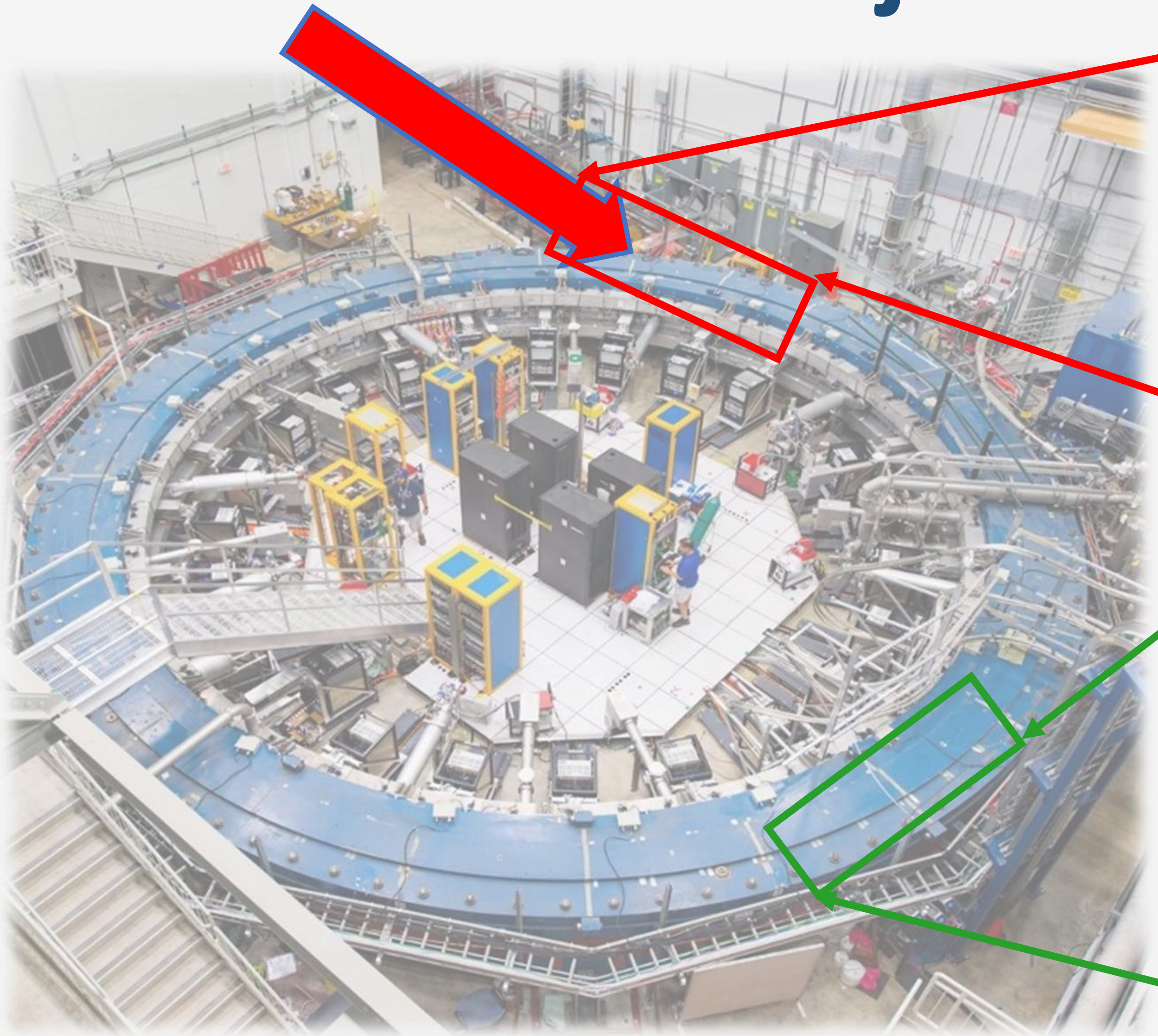
$$\omega_s = \omega_c + \frac{qB}{m}\left(\frac{g-2}{2}\right)$$

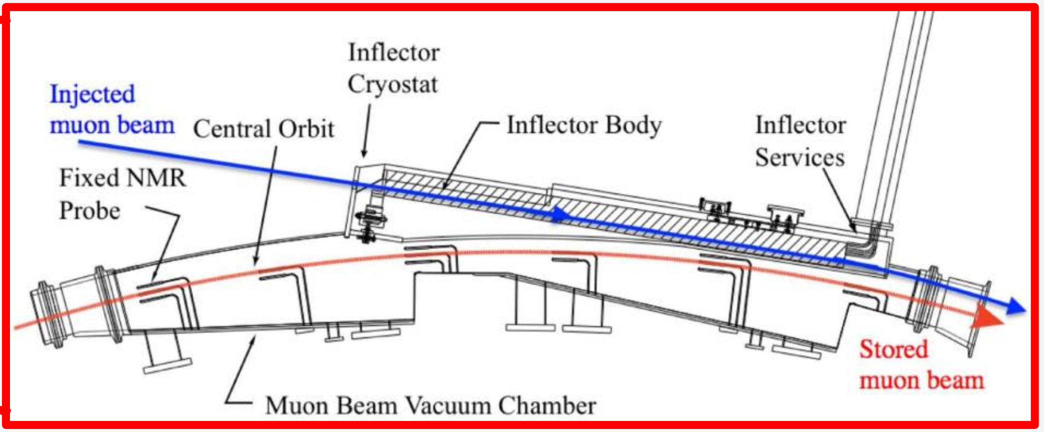
$$\boldsymbol{\omega_a = \omega_s - \omega_c = a_\mu \frac{qB}{m}}$$

(3) Measure the difference in frequencies

(2) Measure the storage ring magnetic field

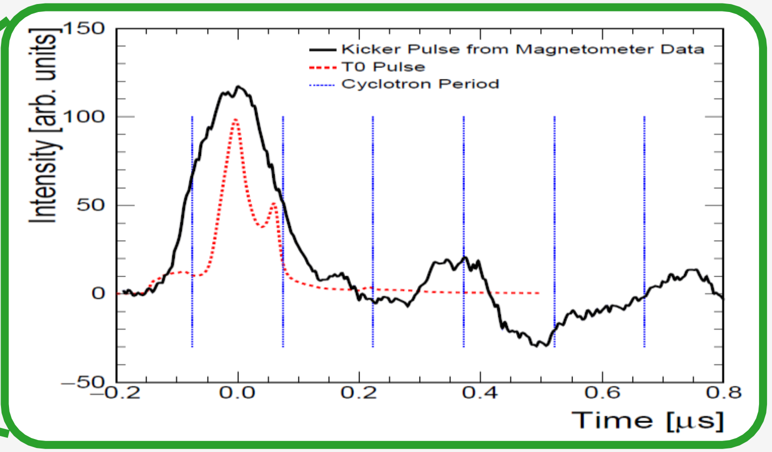
Beam Injection and Storage





Inflector Magnet

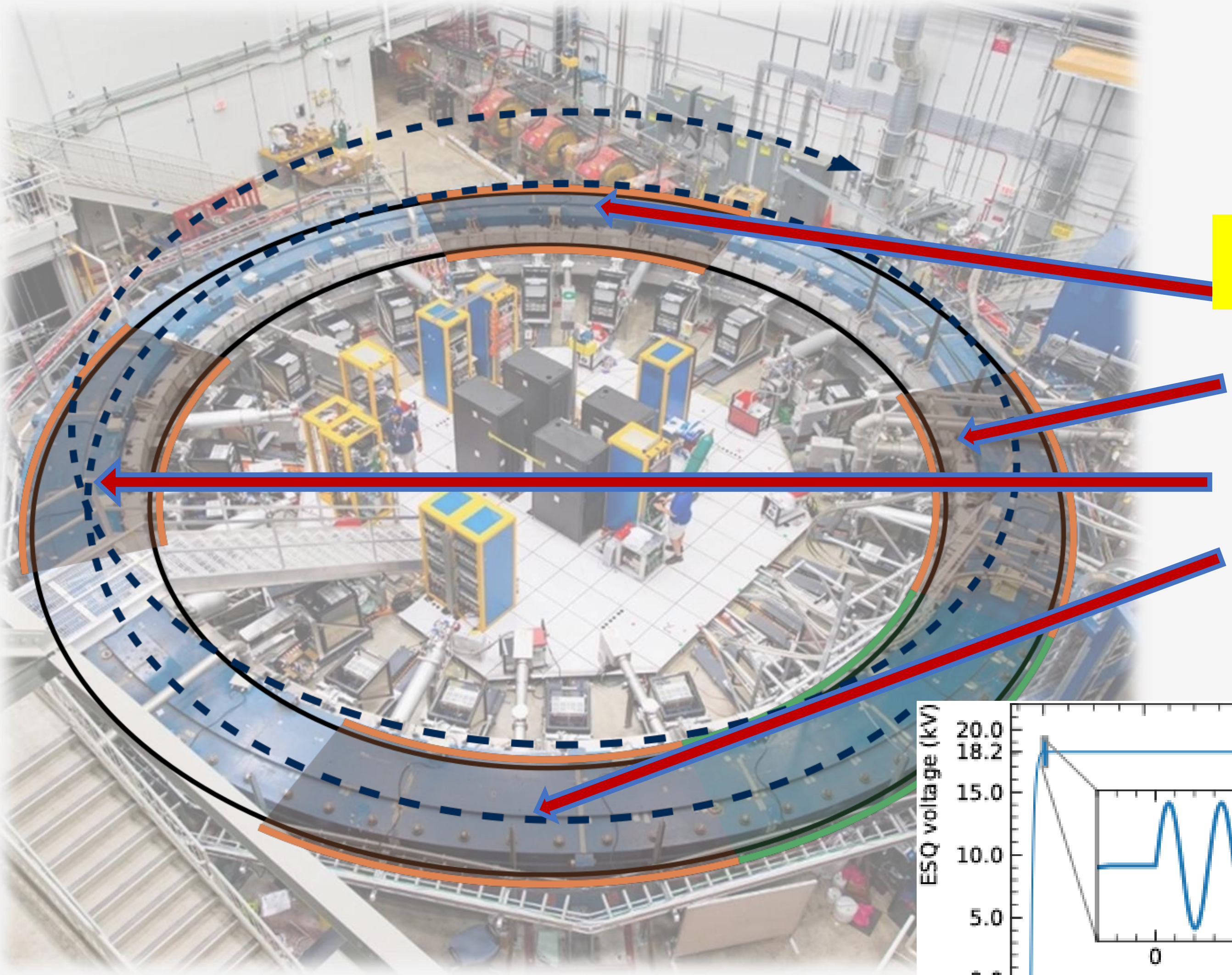
Cancels 1.45 T field while injection

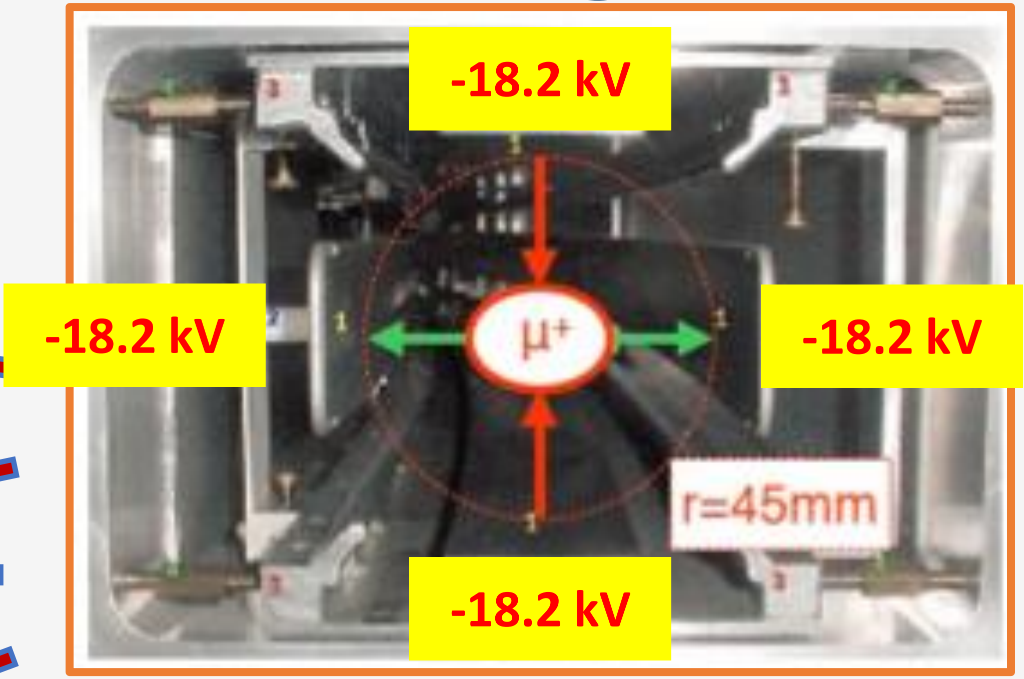


Kicker Magnet

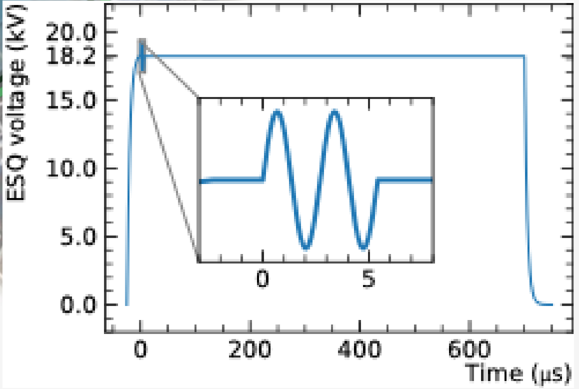
Correct the inflector offset, with ~ 130 ns pulse duration

Beam Injection and Storage





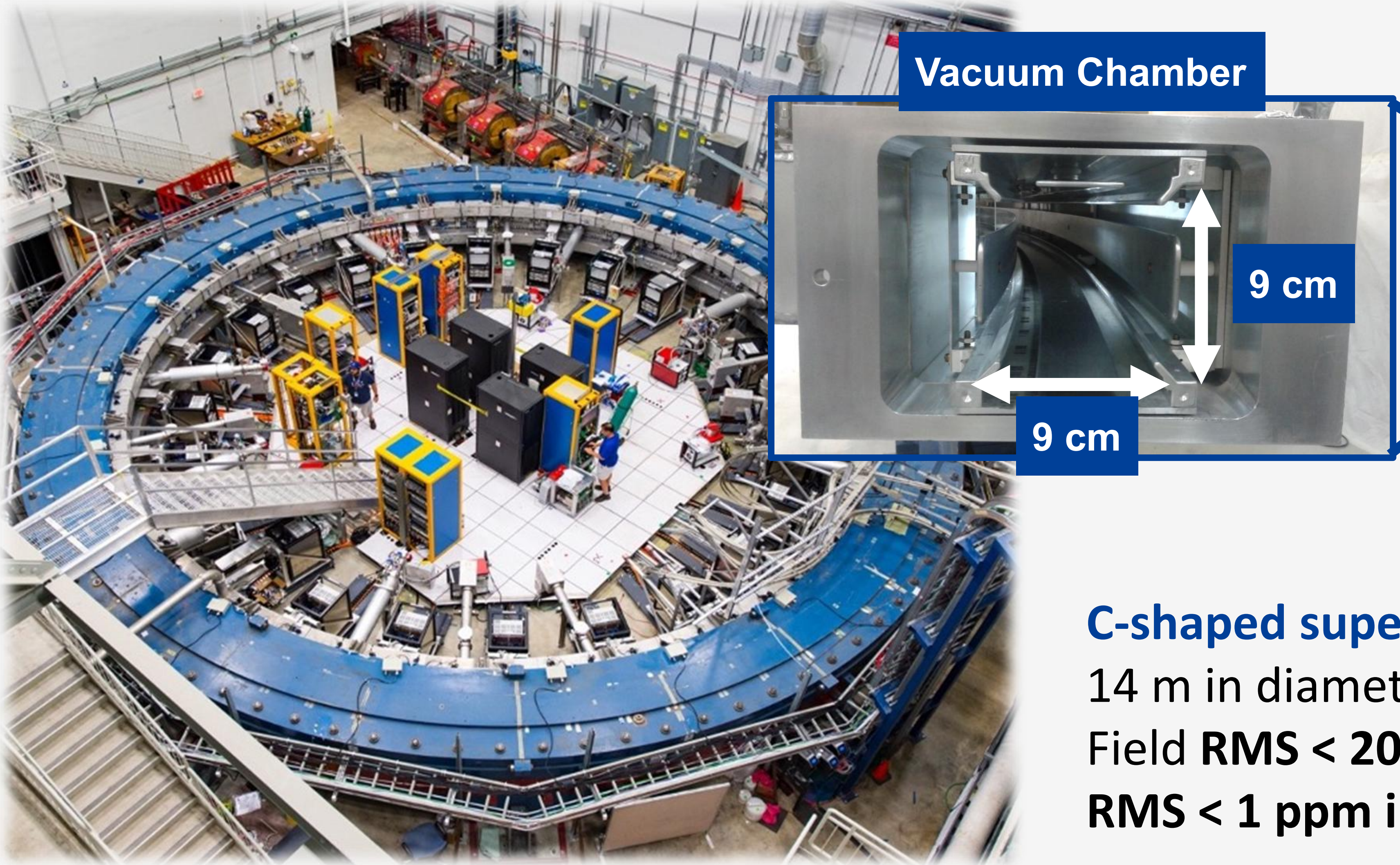
An electrostatic quadrupole system to provide **vertical focusing**

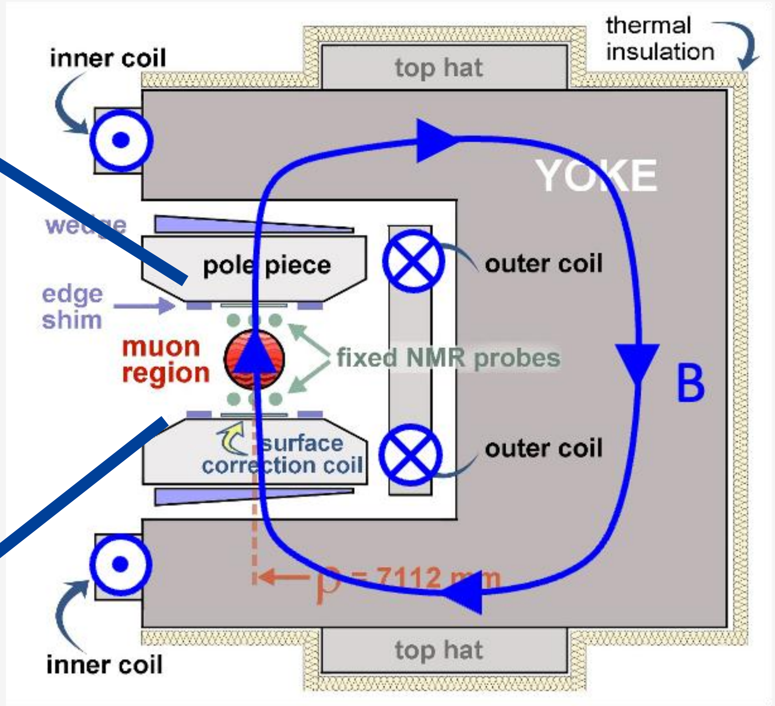


An additional RF modulation
(~1kV at first 6 μs)

New!

Storage Ring Magnet





C-shaped superconducting magnet

14 m in diameter, **1.45 T**

Field **RMS < 20 ppm around azimuth**

RMS < 1 ppm in average cross-section

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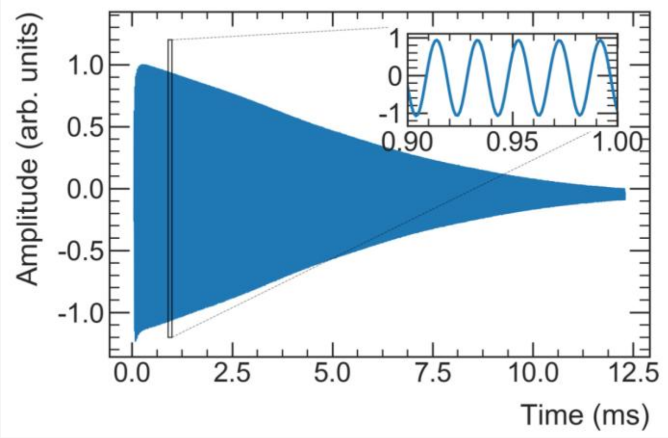
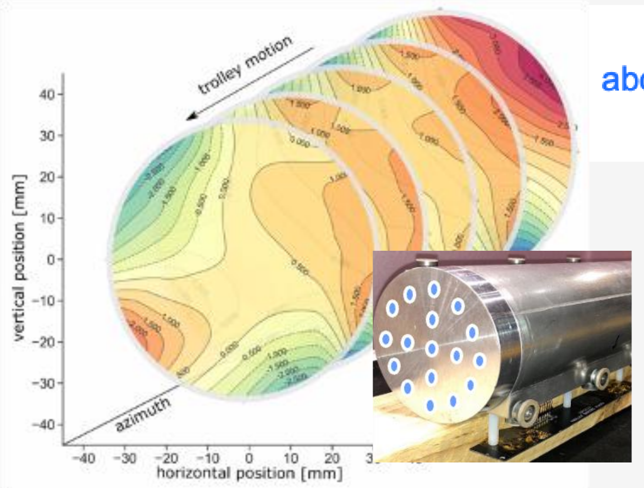
Magnetic Field Measurement



NMR Frequencies

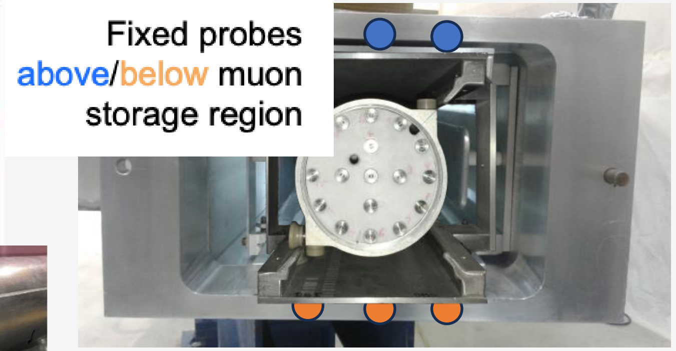
Precession frequency of shielded protons ω_p

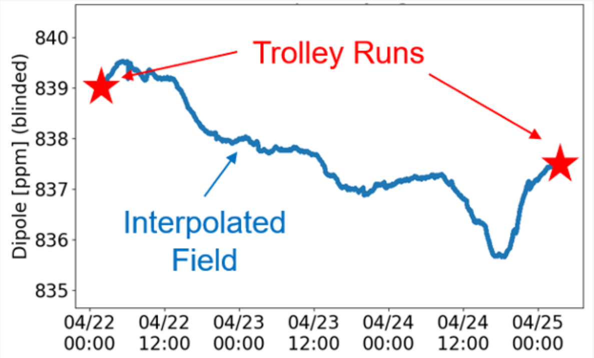


Trolley Runs

17 NMR probes

~ 9000 azimuthal maps

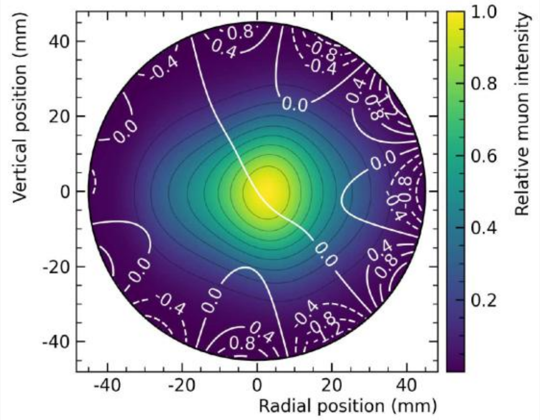




378 Fixed NMR Probes

Monitor the field

Interpolate trolley maps



Muon Weighting

$\langle \omega_p'(\mathbf{r},\mathrm{t}) \cdot M(\mathbf{r},t) \rangle$

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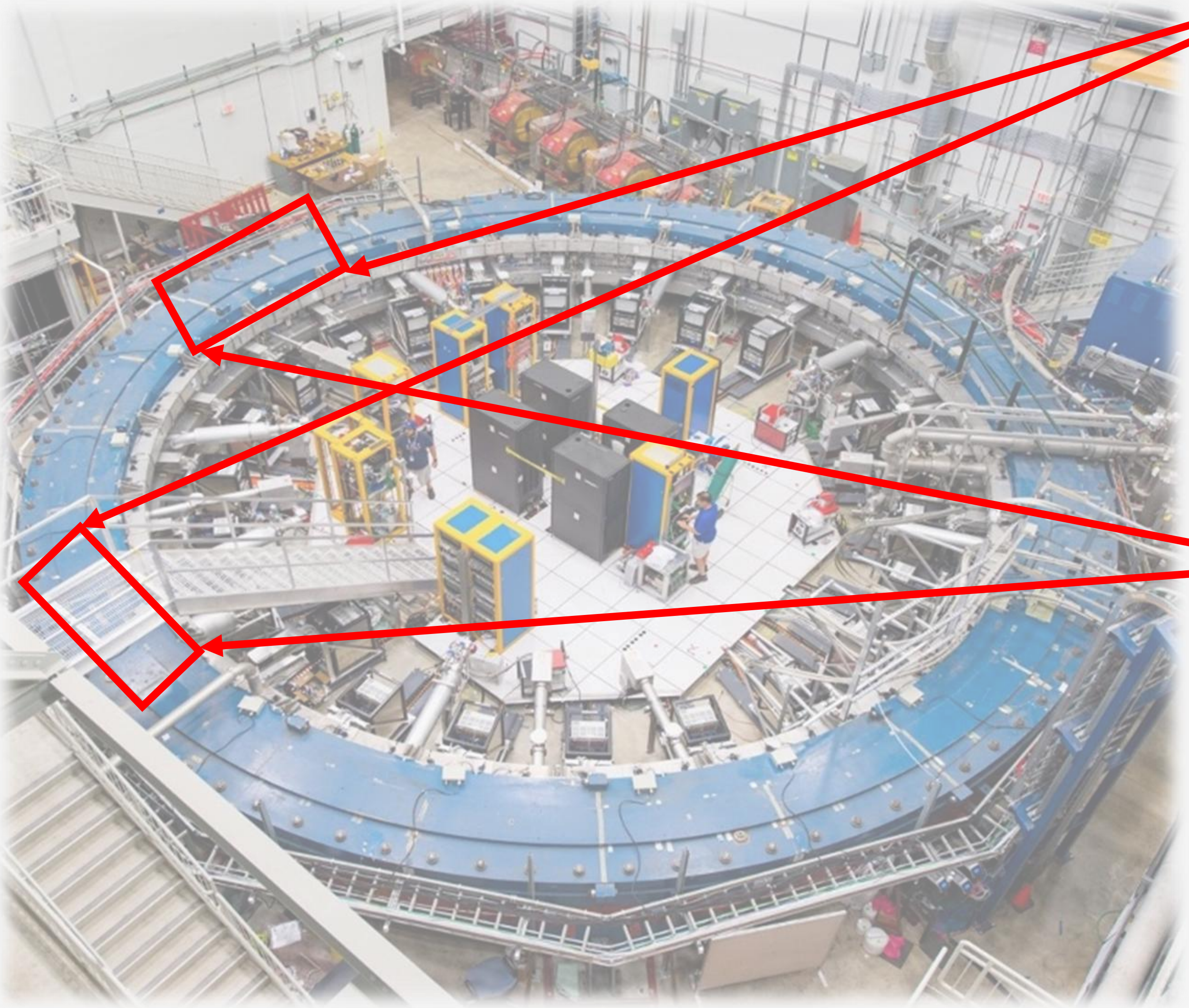
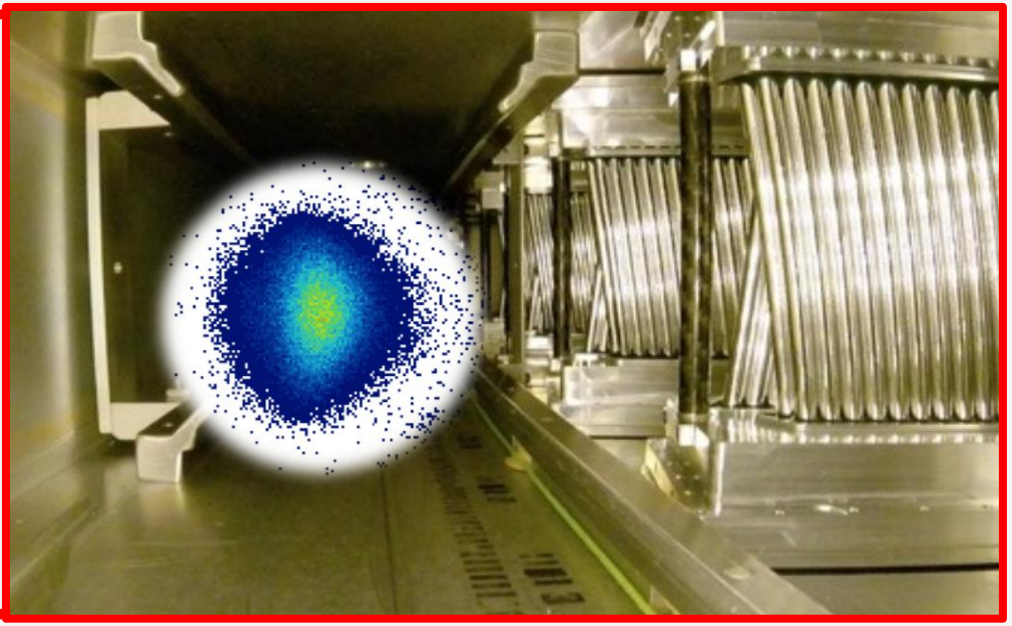
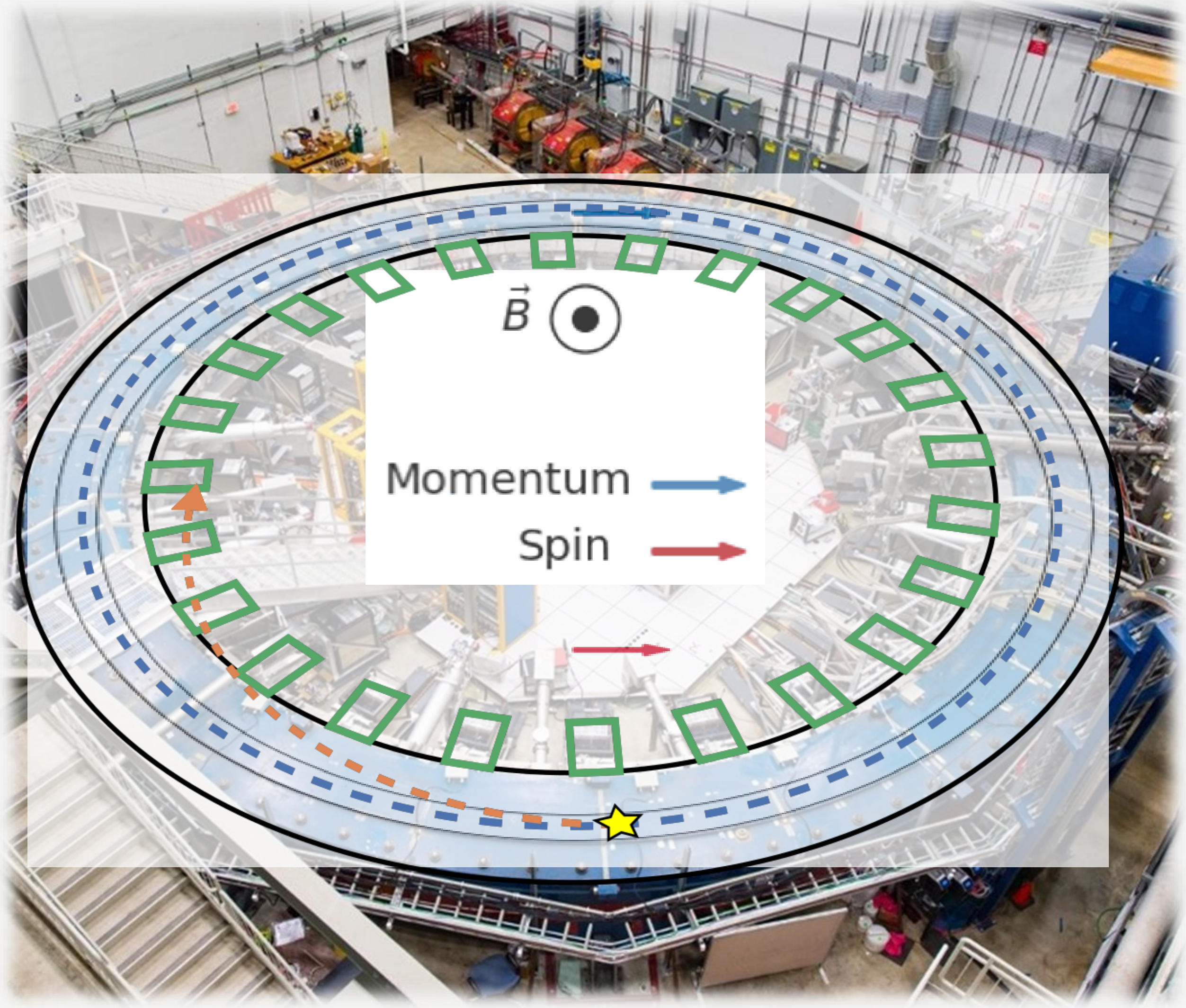
Trackers

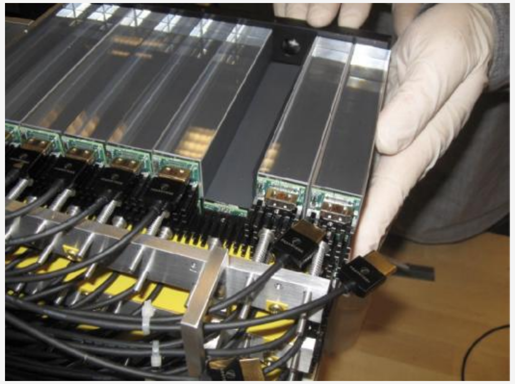


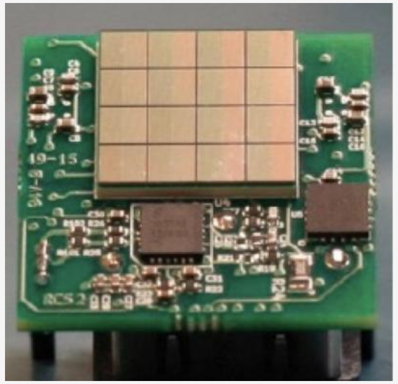


- 2 **straw trackers** provide 3D distribution $(\mathbf{r}, t)$ of stored muon
- Each has 8 modules of straw layers
- **Muon decay position** is extrapolated from straw hits

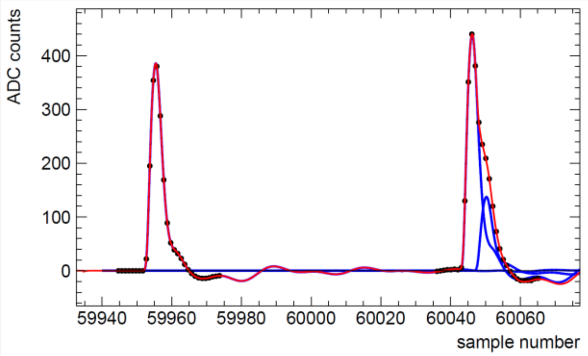
Calorimeters

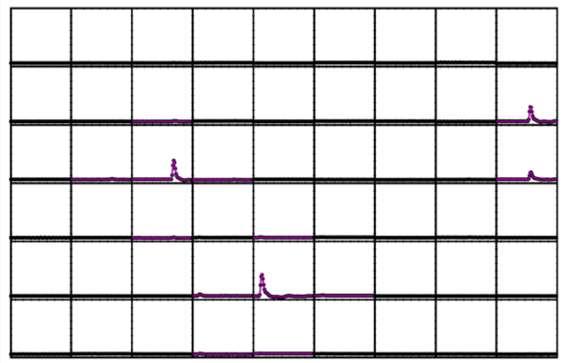






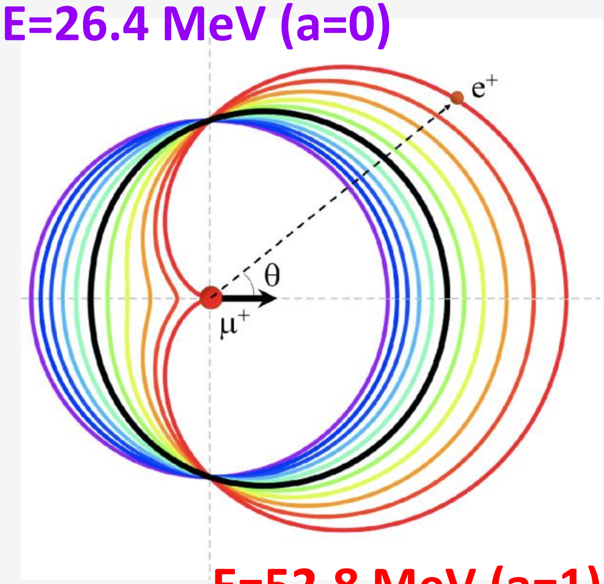
- Measure decay e^+ **time and energy**
- 24 stations around the inner ring
- 6x9 PbF_2 crystals array
- Template fits on the pulse to get (t, E)



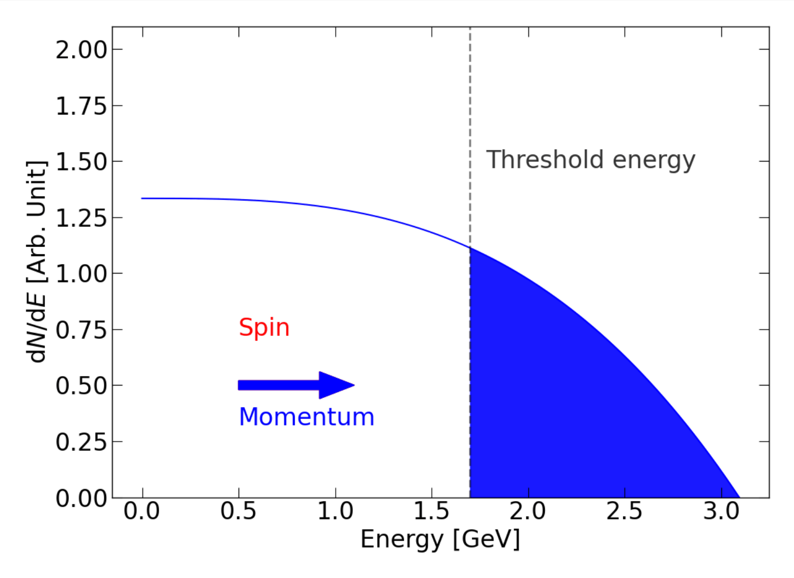


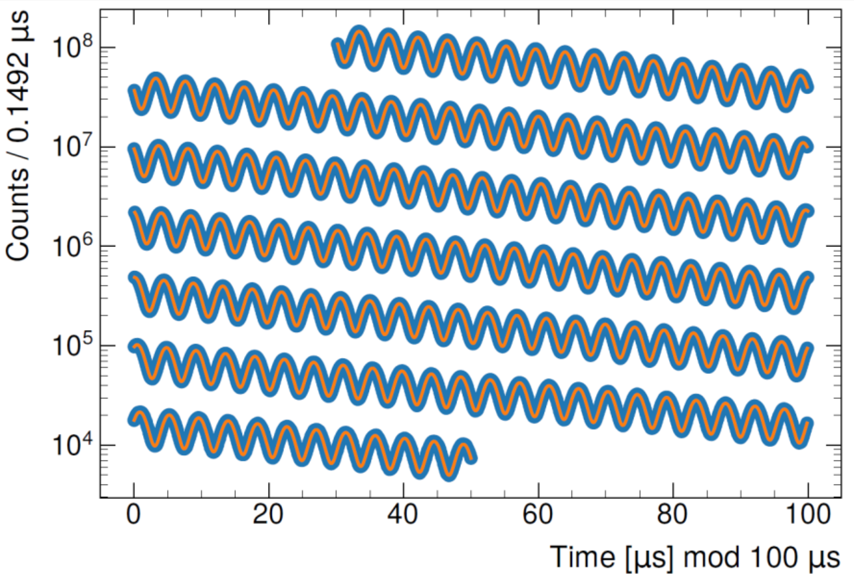
Anomalous Precession Measurement

E=26.4 MeV (a=0)



E=52.8 MeV (a=1)



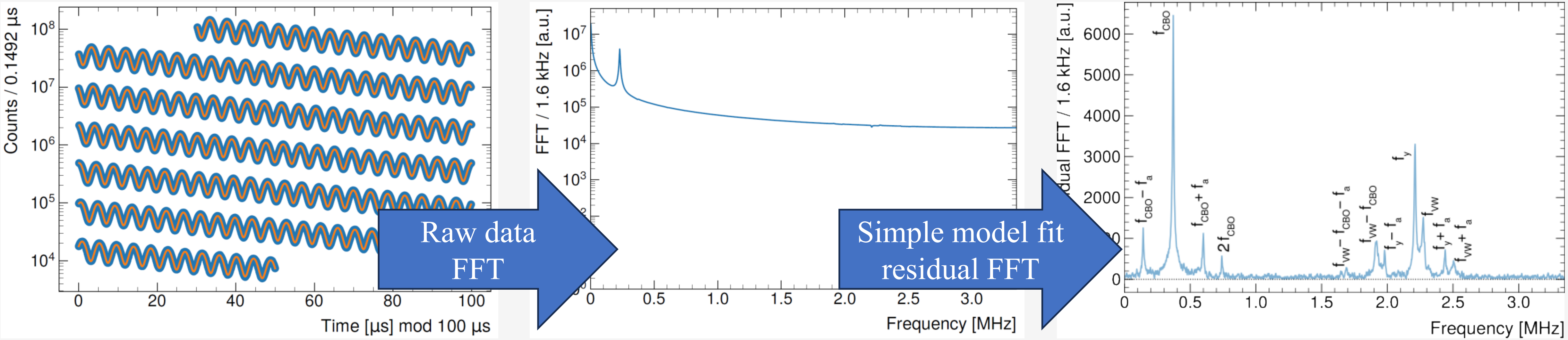


The g-2 wiggle plot!

High energy e^+ tends to be emitted **along the μ^+ spin direction** due to **parity-violation**

Count high-energy decay e^+ over time, resulting a time modulation on ω_a frequency

Precession Analysis

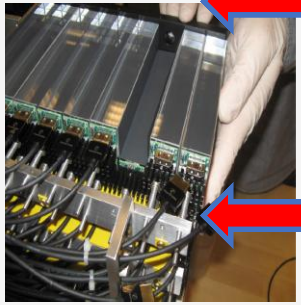


Simplest fit model captures **exponential decay** & *g-2* **oscillation**

$$N(t) = N_0\, e^{-t/\tau}\,[1 + A\cos(\omega_a t\ - \phi_0)]$$

CBO Biases ω_a Measurement

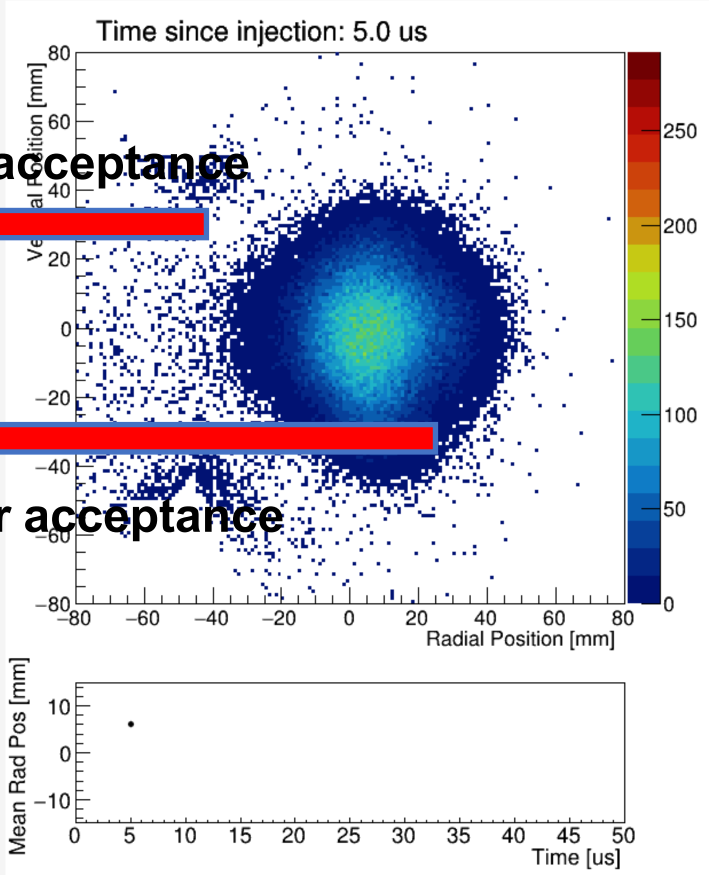
- Stored muon beam exhibits coherent betatron oscillation (CBO)
- Coupled with the calorimeter acceptance, it distorts the time spectrum

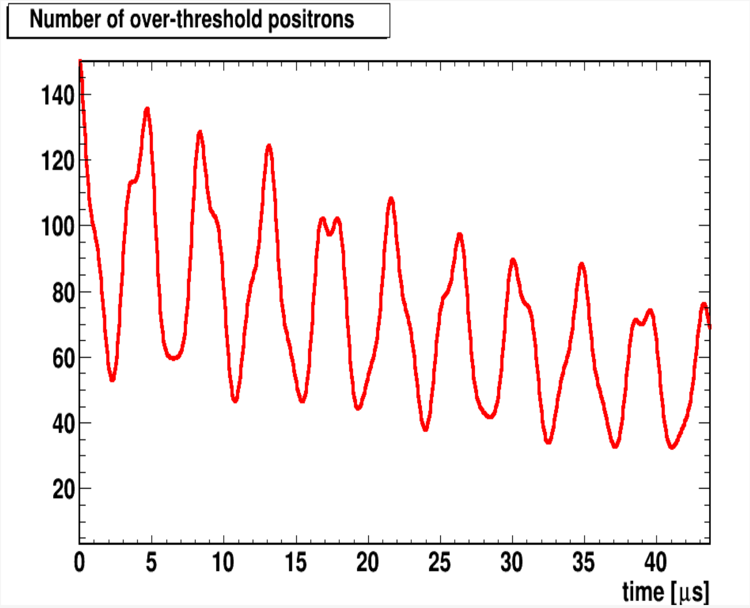


higher acceptance

lower acceptance

Calorimeter



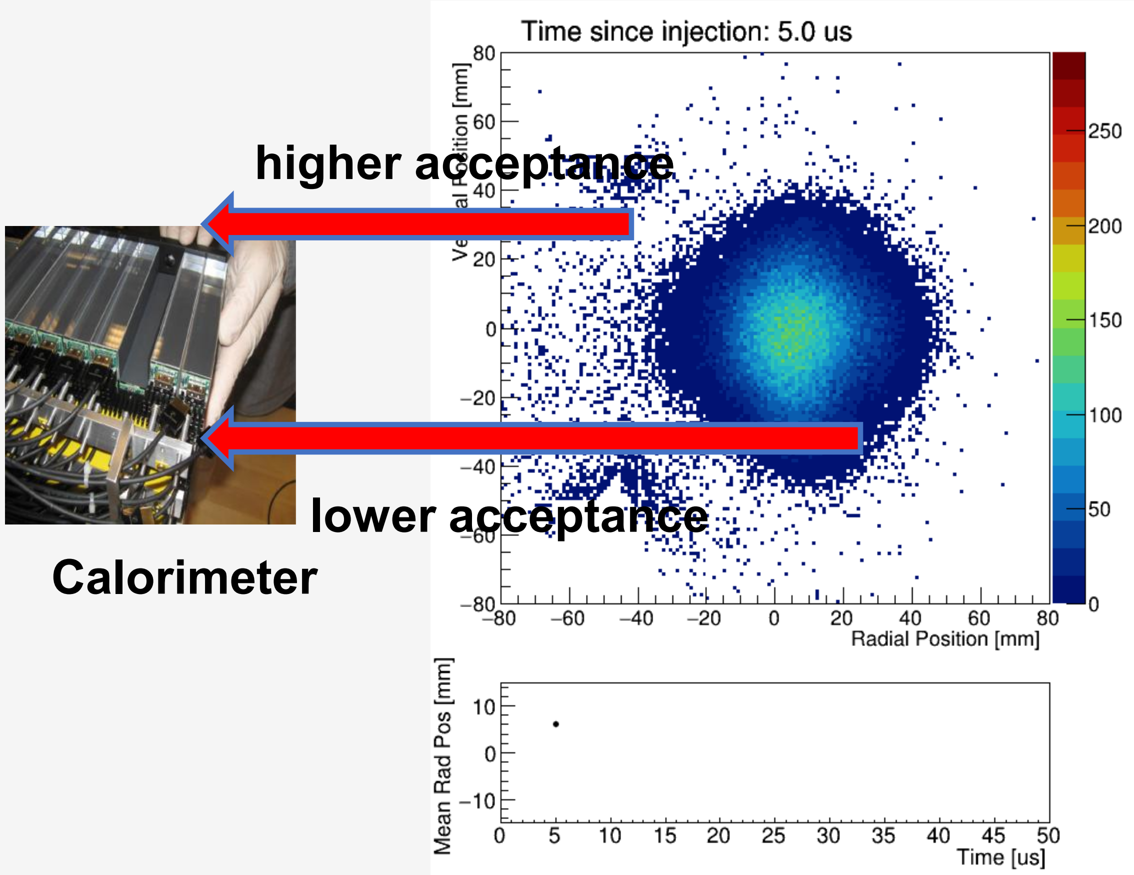


$$N(t) = N_0\, e^{-t/\tau}\,[1 + A\cos(\omega_a t - \phi_0)]$$

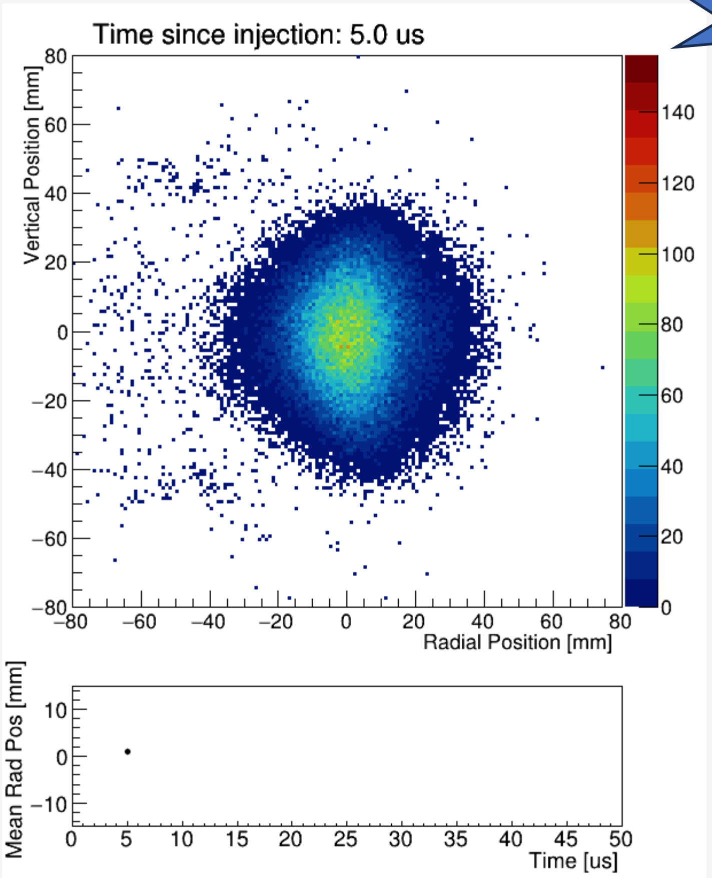
Fitting with this simple function will lead to a wrong ω_a.

CBO Reduced by RF System

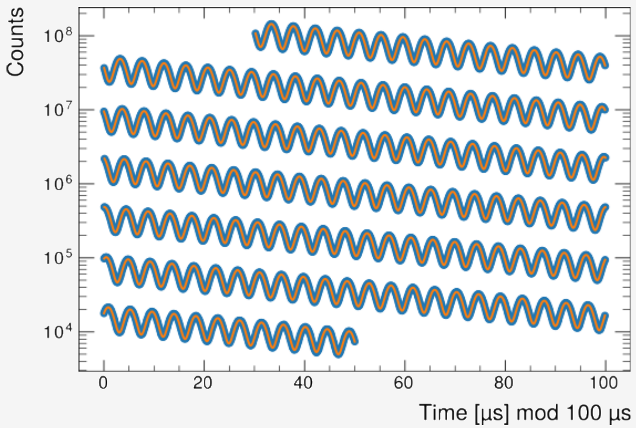
- Stored muon beam exhibits coherent betatron oscillation (CBO)
- Coupled with the calorimeter acceptance, it distorts the time spectrum



New!



Additional Corrections



Beam Dynamics Corrections

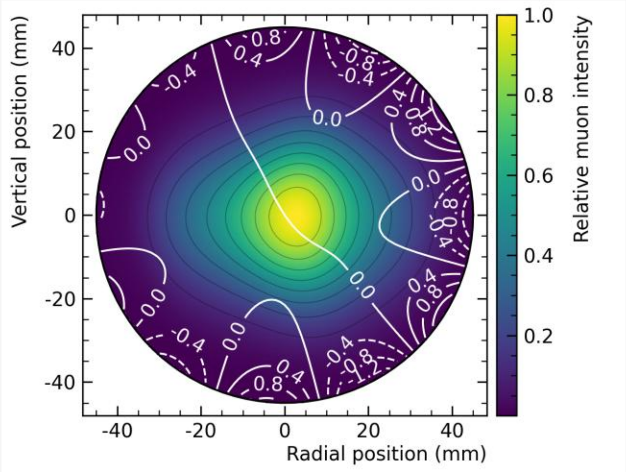
E-field & vertical motion:
Spin precesses slower than in basic equation

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

Transient Field Corrections



Run-4/5/6 Results

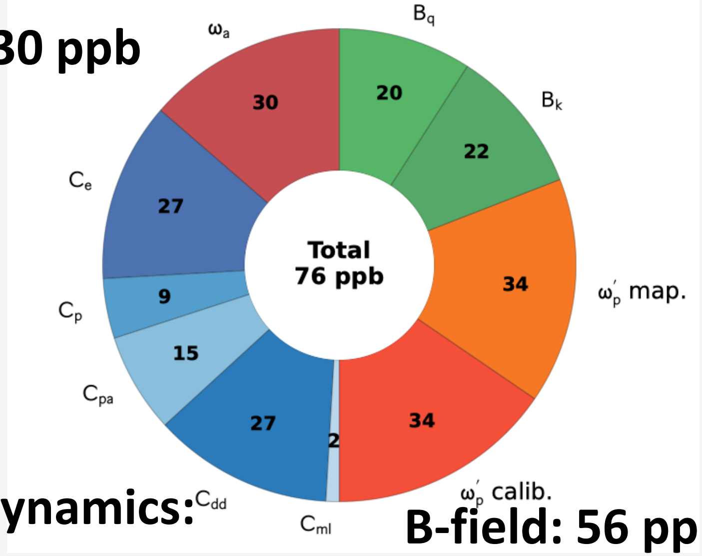
- 76 ppb systematics, 114 ppb statistics
- In **excellent agreement** with Run-1/2/3 and BNL E821
- **New world average** reduces the uncertainty by a **factor of 4.4 (compared to BNL E821)**

$$a_{\mu}(\mathrm{Run}-4/5/6) = 0.001165920710(162)\ [139\ \mathrm{ppb}]$$

$$a_{\mu}(\mathrm{Exp.}) = 0.001165920715(145)\ [124\ \mathrm{ppb}]$$

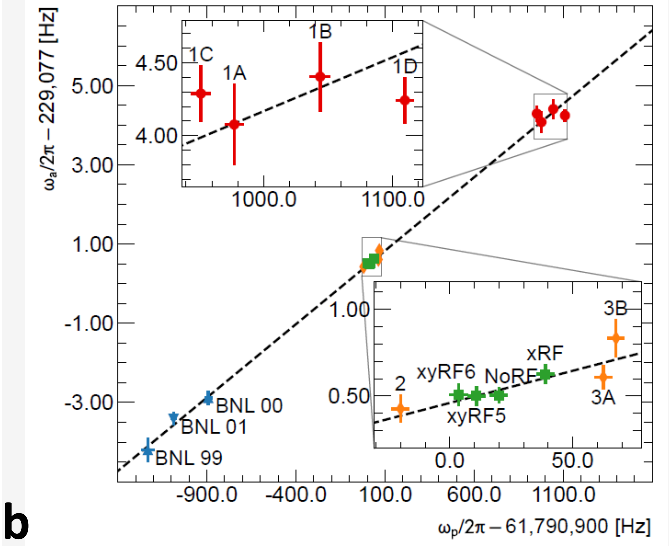
Systematics

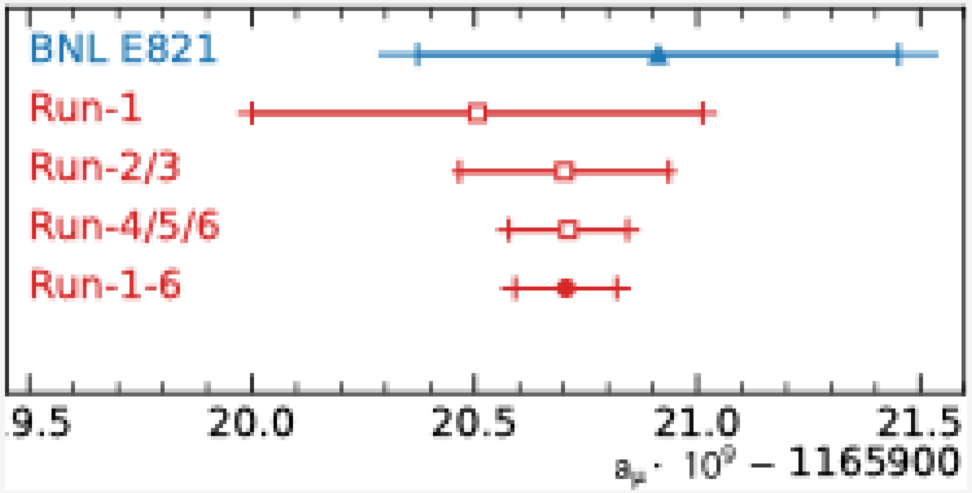
ω_a: 30 ppb



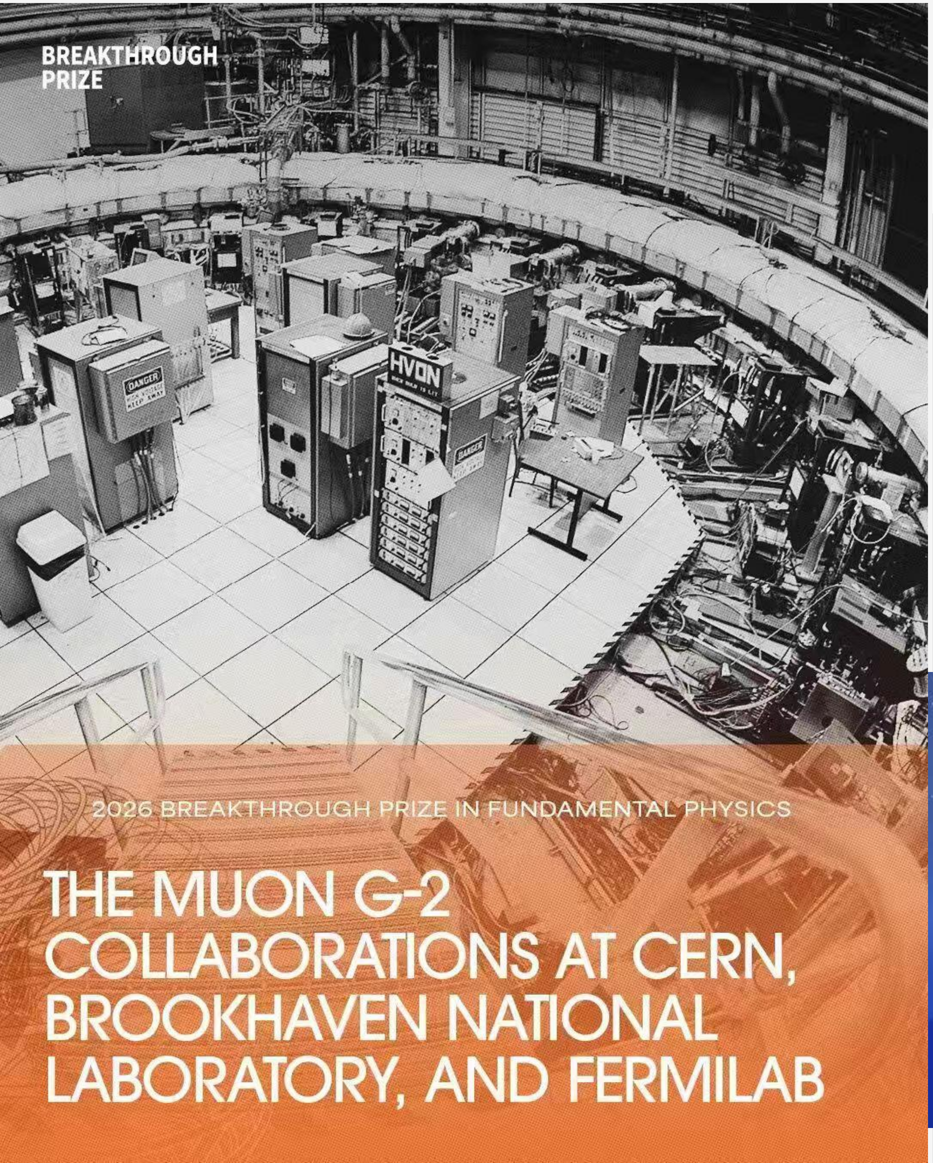
Beam dynamics: 42 ppb

B-field: 56 ppb





2026 Breakthrough Prize in Fundamental Physics



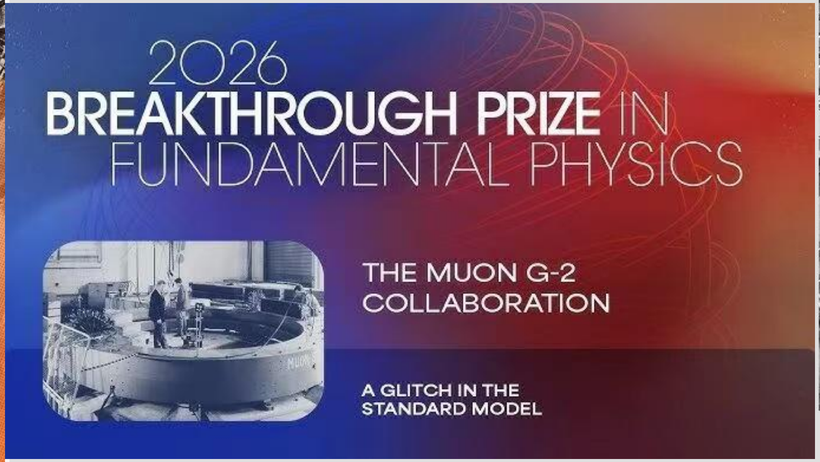
https://breakthroughprize.org/News/98

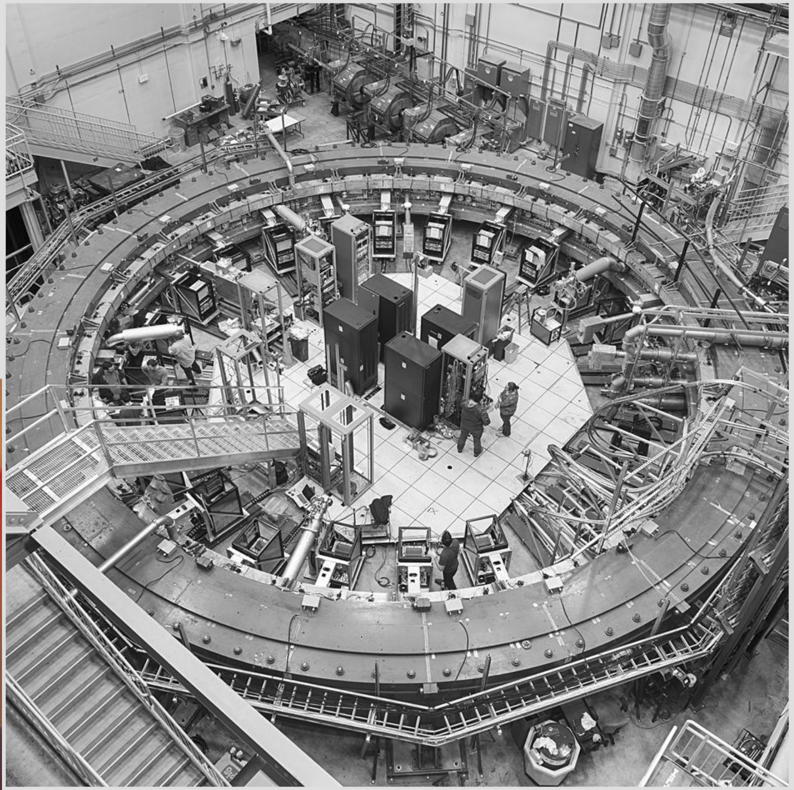
LAUREATES

< Fermilab

2026 Breakthrough Prize in Fundamental Physics

For multi-decade, groundbreaking contributions to the measurement of the muon's anomalous magnetic moment, pushing the boundaries of experimental precision and igniting a new era in the quest for physics beyond the Standard Model.

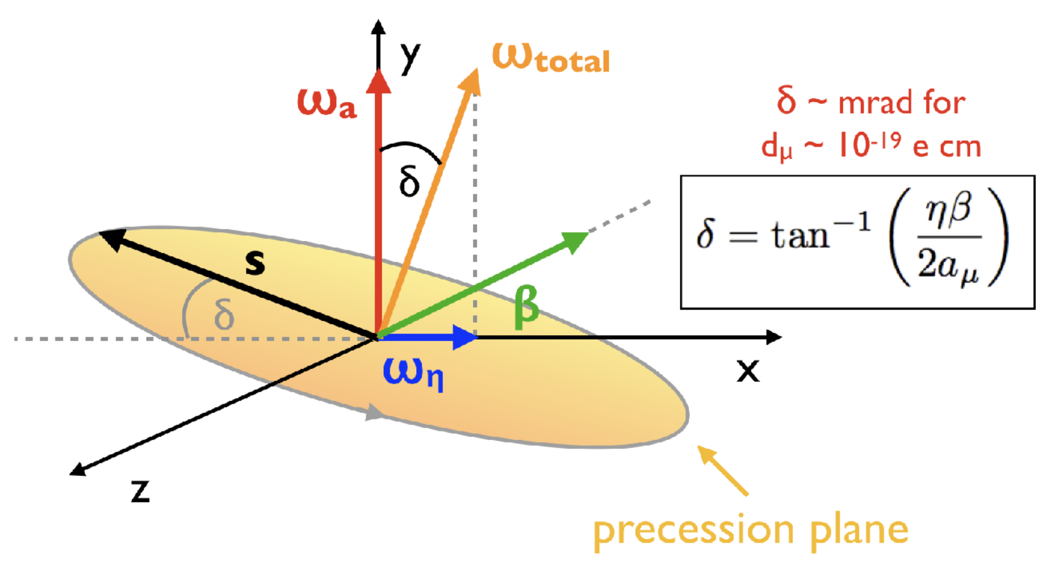




EDM Searches

A non-zero EDM ($\boldsymbol{\eta}$) introduces an extra term into the oscillation of the muons

$$\vec{\omega}_a = a_\mu \frac{e}{m}\vec{B} + \eta \frac{e}{2m}\left[\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B}\right]$$

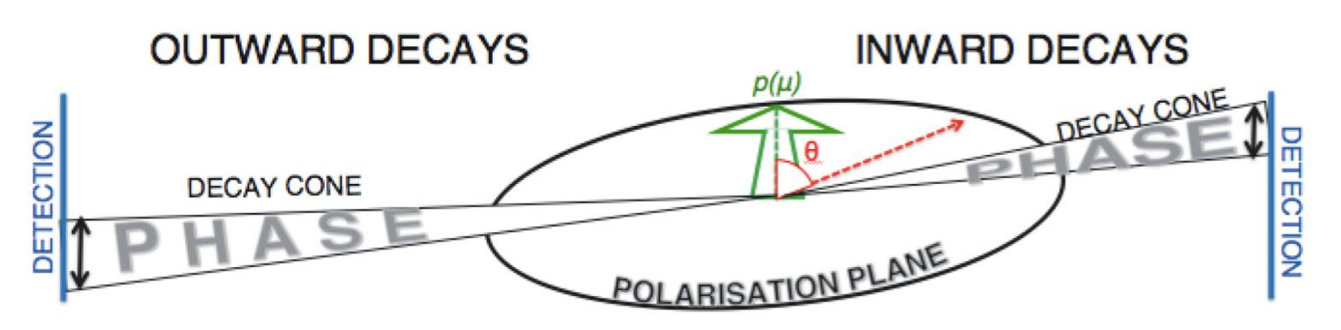


Effects:

- A very small increase in the precession frequency
- A ‘tilt’ precession, $\boldsymbol{\pi/2}$ **out of phase with g-2**

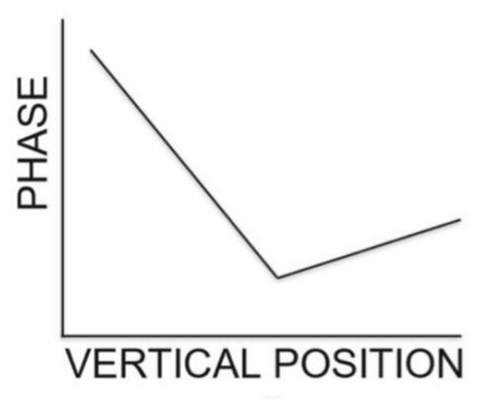
Current limit (BNL): $\mathbf{1.8 \times 10^{-19}}\ \boldsymbol{e} \cdot \mathbf{cm}$

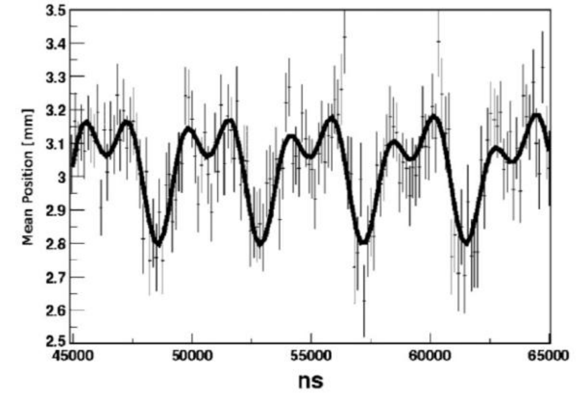
EDM Signal at Fermilab *g*-2

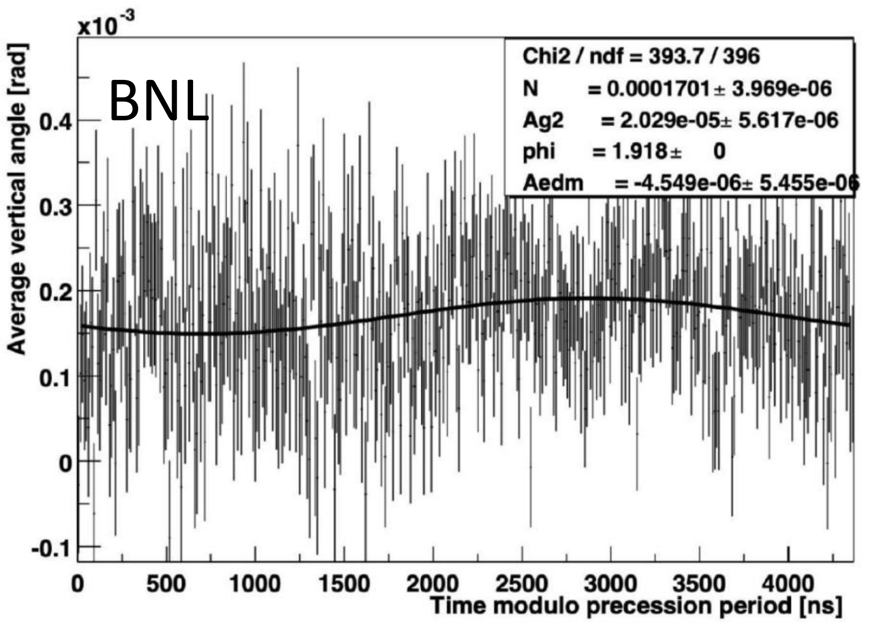


Calorimeter-based

- Phase asymmetry and vertical position oscillation
- Systematically limited





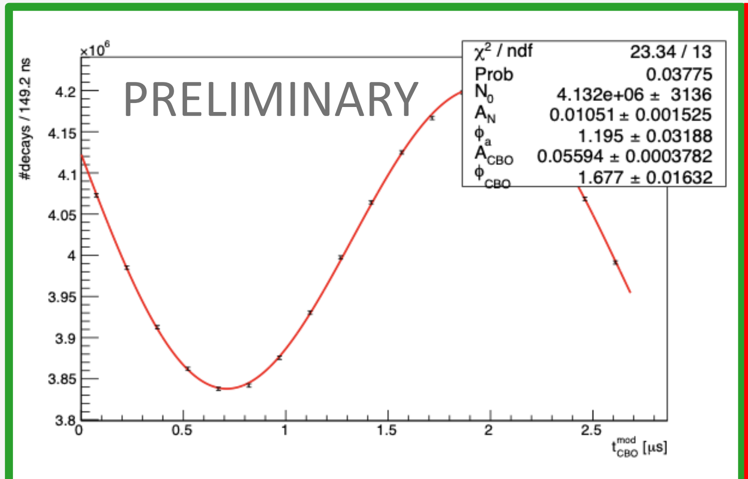


Tracker-based

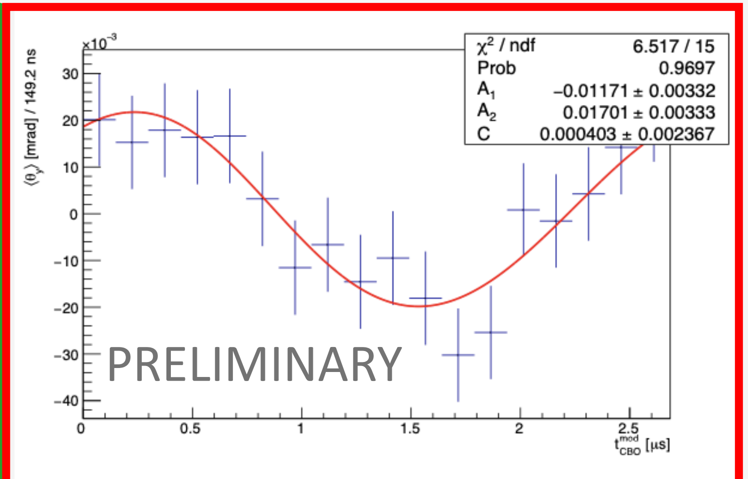
- Vertical angle oscillation measurement
- Statistically limited at BNL

Preliminary Results

- **Blind analysis**, with large fake signal
- Fit the *g-2* oscillation
- Fit the average vertical angle oscillation



(a) $750 \leq p < 1000$ MeV



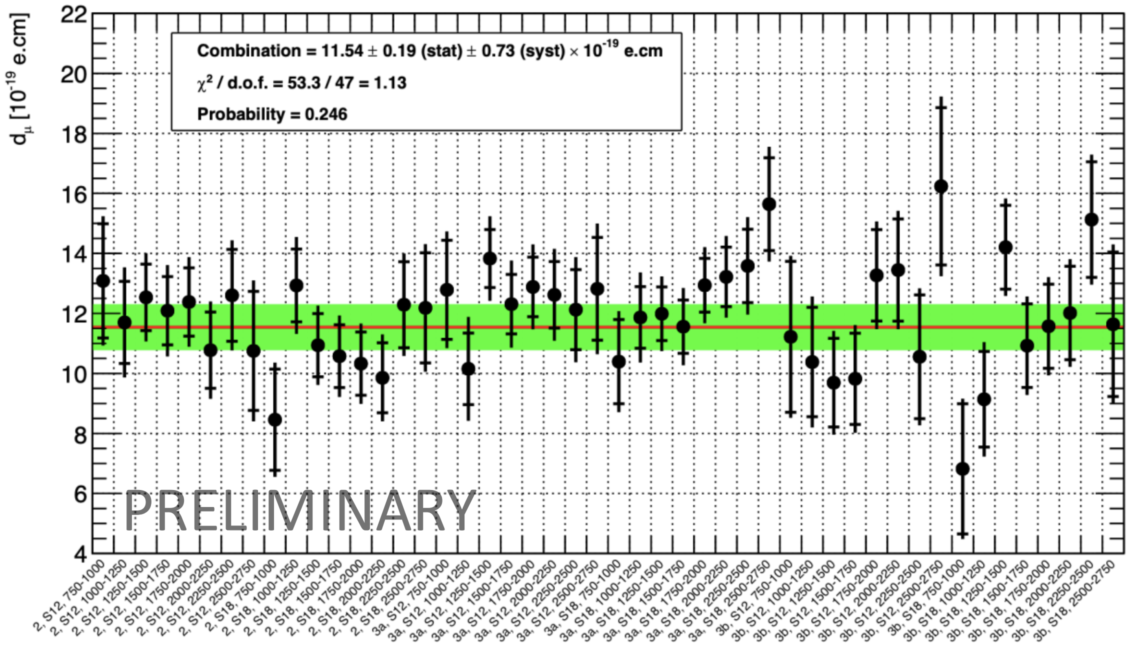
(a) $750 \leq p < 1000$ MeV

EDM Signal

$$\langle\theta_y\rangle(t) = \frac{A_{g-2}\cos(\omega_a t + \phi_a) + A_{\mathrm{EDM}}\sin(\omega_a t + \phi_a)}{(1 + A_N\cos(\omega_a t + \phi_a^p))\,(1 + A_{\mathrm{CBO}}\cos(\omega_{\mathrm{CBO}} t + \phi_{\mathrm{CBO}}))} + C$$

Fixed

- Assuming a central value at 0 after unblinding, gives a limit of 9.2×10^{-20} e $\cdot$ cm, **2x improvement** compared to BNL, using only Run-2/3 data



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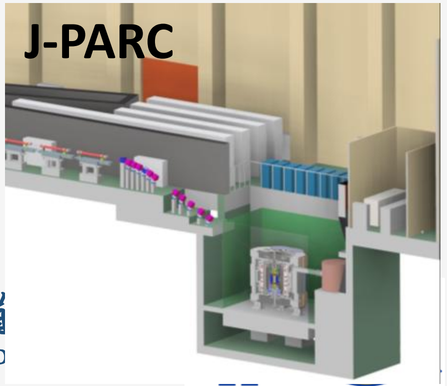
Outlook

More from Muon *g-2* Collaboration

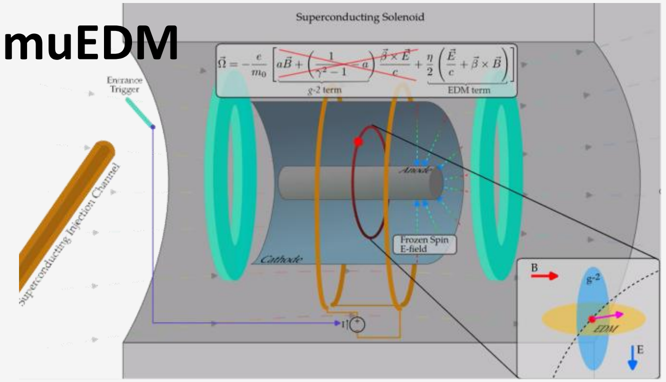
- Publish on details of Run-4/5/6, will appear soon on the PRD!
- New limit on muon EDM, expect results this year!
- BSM studies: dark matter, CPT/LV

Related Experiments

- Independent muon g-2/EDM measurement at J-PARC (see Tsutomu Mibe's talk)
- Frozen-spin method measuring muon EDM at PSI (muEDM, see Philipp's talk)
- Measurement of HVP contribution to muon-electron scattering at CERN (MUonE, see Riccardo's talk)



muEDM



MUonE

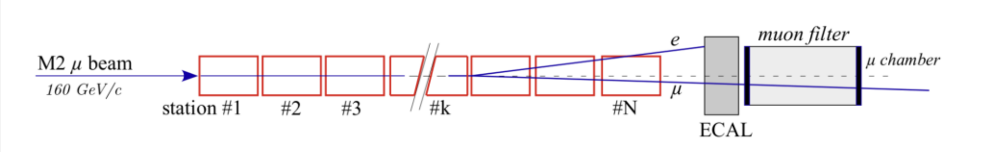
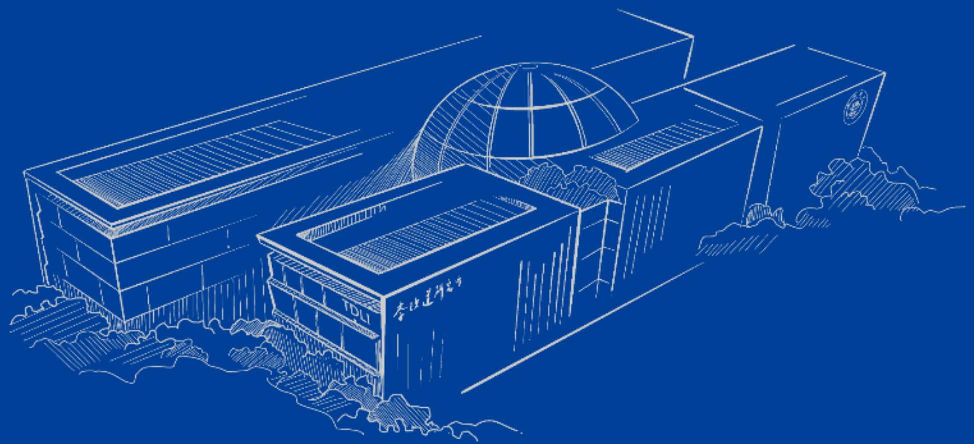


Figure 24: Schematic view of the MUonE experimental apparatus (not to scale).

谢 谢！



PART

Backup

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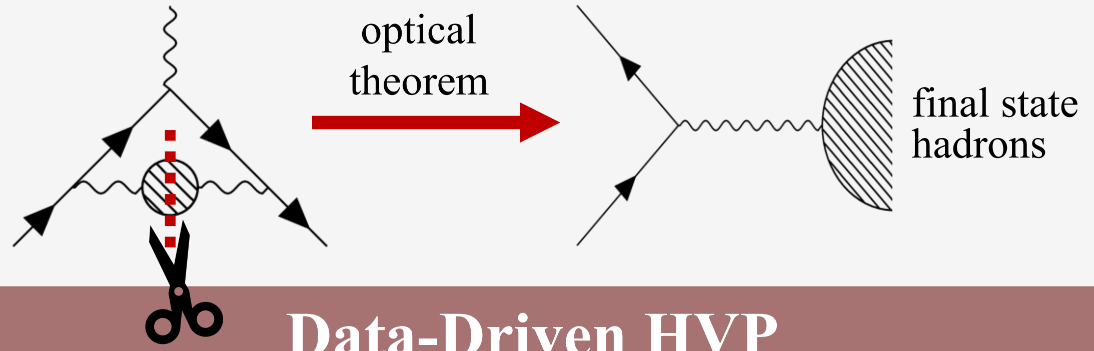
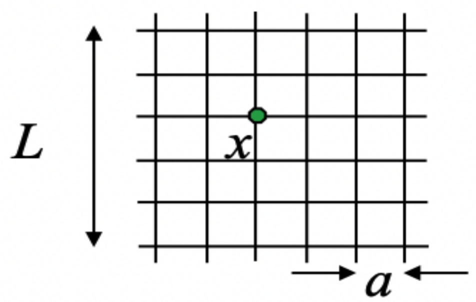
Hadronic Contributions



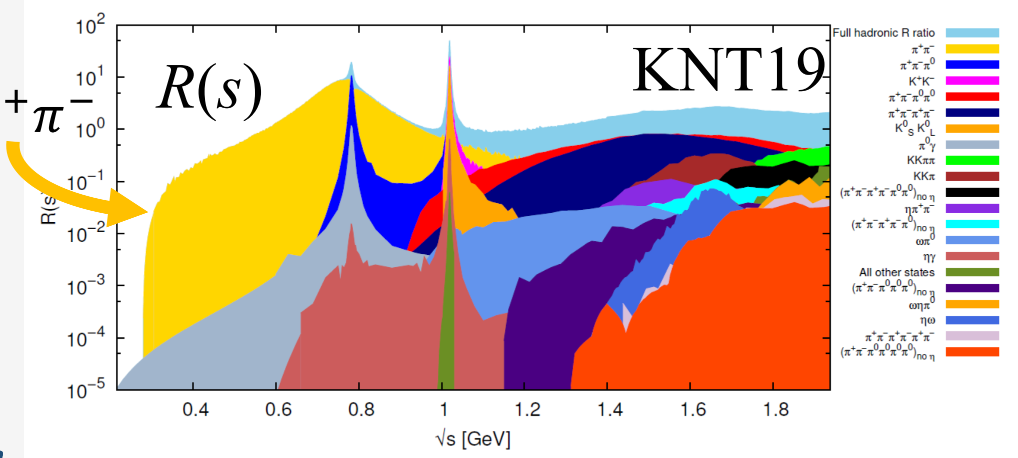


Data-Driven HVP

HVP related to **hadron production** by e^+e^-:

$$a_\mu^{\text{HVP(LO)}} = \frac{\alpha^2}{3\pi^2} \int_{m_\pi^2}^{\infty} \underbrace{\frac{\sigma_0(e^+e^- \to \text{hadrons})}{4\pi\alpha^2/(3s)}}_{R(s)\ \text{ratio}} \underbrace{\frac{K(s)}{s}}_{\text{kernel}} ds$$

$e^+e^- \to \pi^+\pi^-$ weighted strongly by kernel



HVP from Lattice QCD

HVP written as multi-dimensional integral over objects **directly from SM Lagrangian**:

$$a_\mu^{\text{HVP(LO)}} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty f(Q^2)\, \hat{\Pi}(Q^2)\, d(Q^2)$$

$$\Pi_{\mu\nu}(Q) = \int \left\langle j_\mu(x) j_\nu(0) \right\rangle e^{iQ\cdot x}\, d^4x$$

- numerical integration discretized into finite spacetime lattice
- extrapolated to infinite continuum limit

Transient Magnetic Field

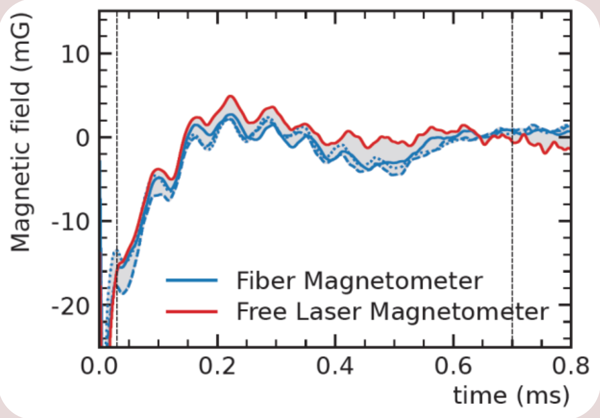
- need B field **experienced by the stored muons**
- **kickers & quadrupoles** turned off during trolley maps
- check for field perturbations with insulating detectors

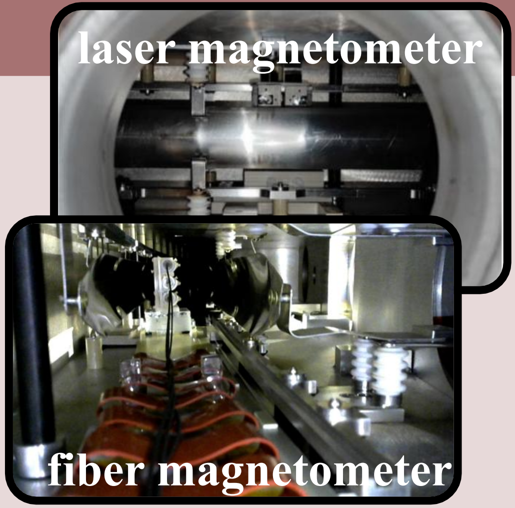
$$\tilde{\omega}'_p = \langle \omega'_p(\mathbf{r},\mathrm{t}) \cdot M(\mathbf{r},t) \rangle (1 + B_k + B_q)$$

muon-weighted field from trolley

corrections from kicker & quads

Kicker Transient (B_k)

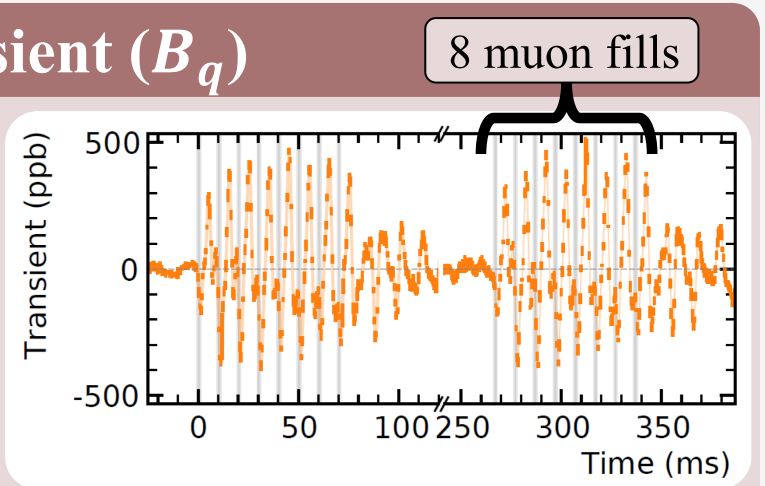




- kicker pulse **ringing** persists over muon fill
- fast signal requires special magnetometers
- two independent Faraday magnetometers:

typical $B_k \sim (-36 \pm 21)$ ppb

Quadrupole Transient (B_q)



- quad. plates vibrate when charging/discharging
  - in phase with beam arrival
- NMR probes on insulating scaffold:

$$B_q = (-21 \pm 20)\ \text{ppb}$$

Magnetic Field Results

(including transient corrections)

	Run-4/5/6 Analysis Datasets			
	No-RF	X-RF	5XY-RF	6XY-RF
$\tilde{\omega}'_p/2\pi = 61.7909\ldots$ (**MHz**)	…200	…389	…109	…036
statistical uncertainty (**ppb**)	8	11	11	15
systematic uncertainty (**ppb**)	57	55	55	57
NMR probe calibration	34	34	34	34
trolley mapping	30	30	29	32
fixed-probe interpolation	12	11	11	11
muon weighting	6	6	6	7
kicker transient	24	20	21	22
quadrupole transient	20	20	20	20

systematics limited

$$a_\mu = \frac{\omega_a^m}{\tilde{\omega}'_p \frac{\mu_B}{\mu'_p}\frac{m_e}{m_\mu}}(1 + C_{\mathrm{BD}})$$

external constants

Probe Calibration (34 ppb)

- variations between multiple calibration probes

Trolley Mapping (~30 ppb)

- NMR frequency extraction, motion effects, temperature

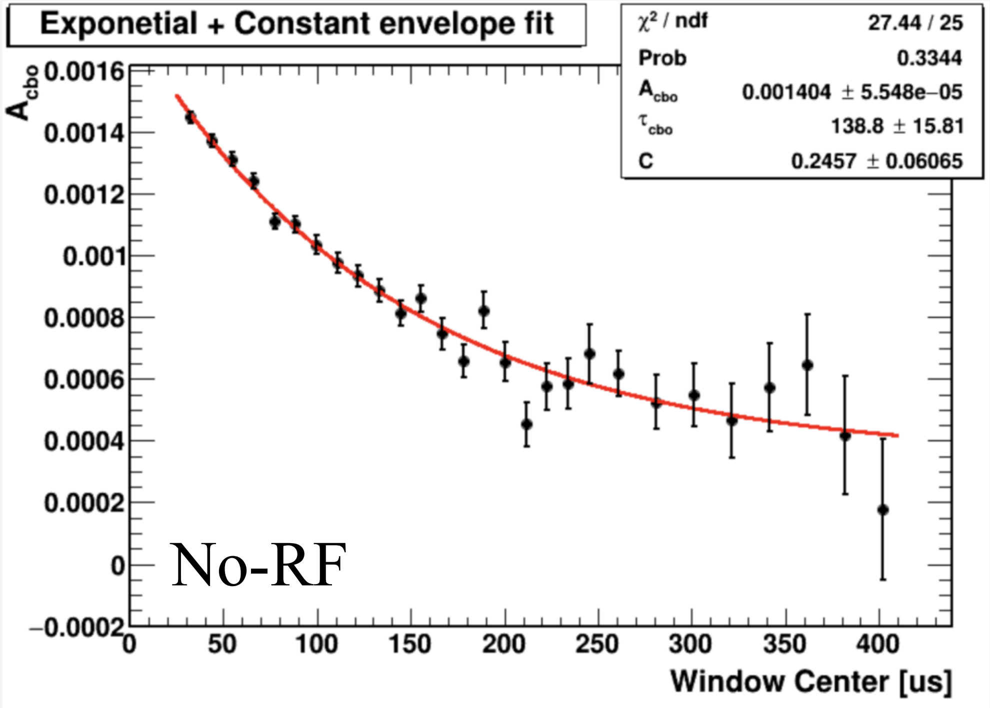
Transient Magnetic Fields (~20 ppb)

- spatial dependence, effects of measurement apparatus

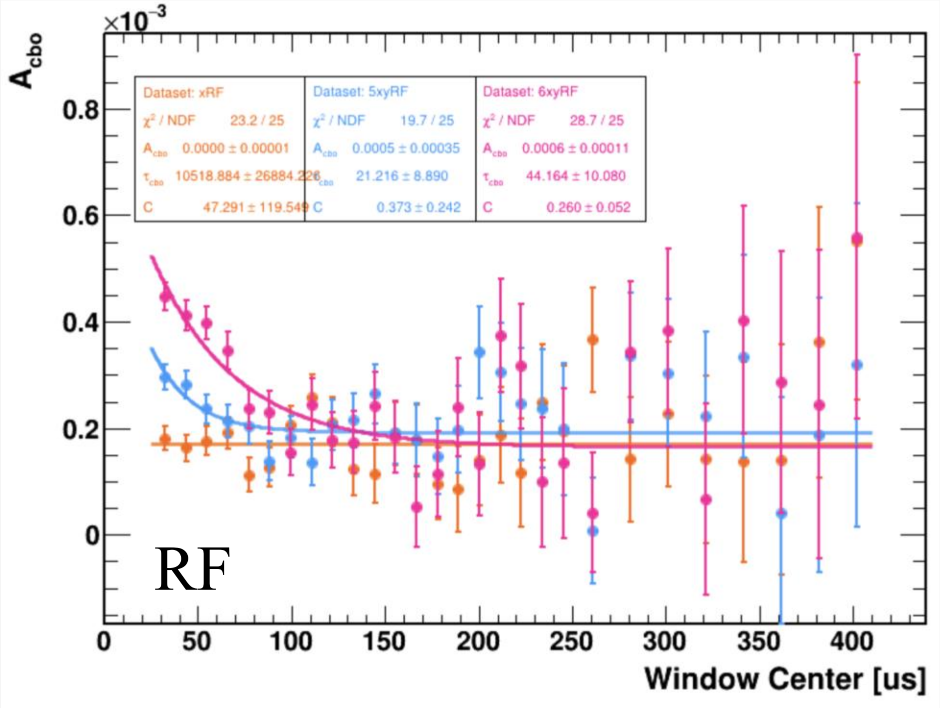
Precession Analysis

- A large CBO (thus a large bias) that can be well modeled, vs. a small CBO (thus a small bias) that is harder to model accurately

CBO separation via sliding window technique

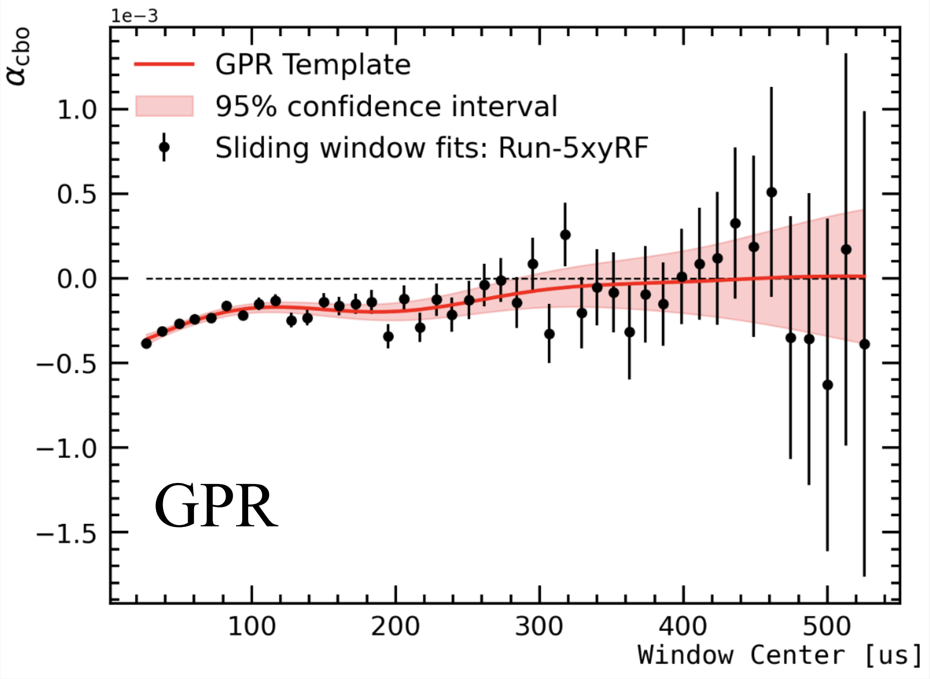


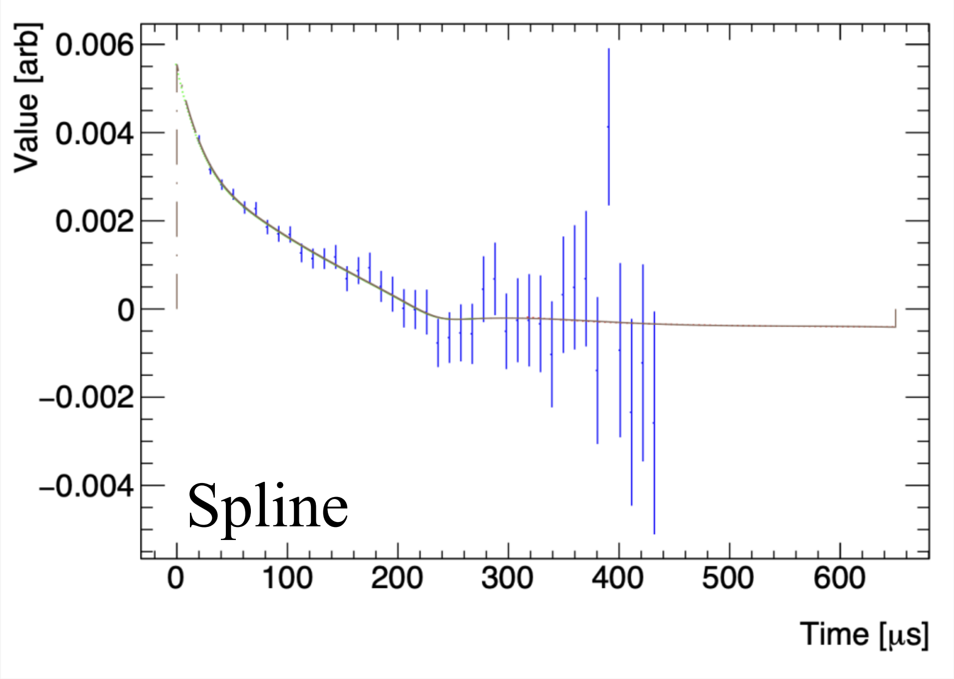
VS.



Precession Analysis

- A large CBO (thus a large bias) that can be well modeled, vs. a small CBO (thus a small bias) that is harder to model accurately
- Non-parametric approaches developed: Gaussian Process Regression (GPR), Spline





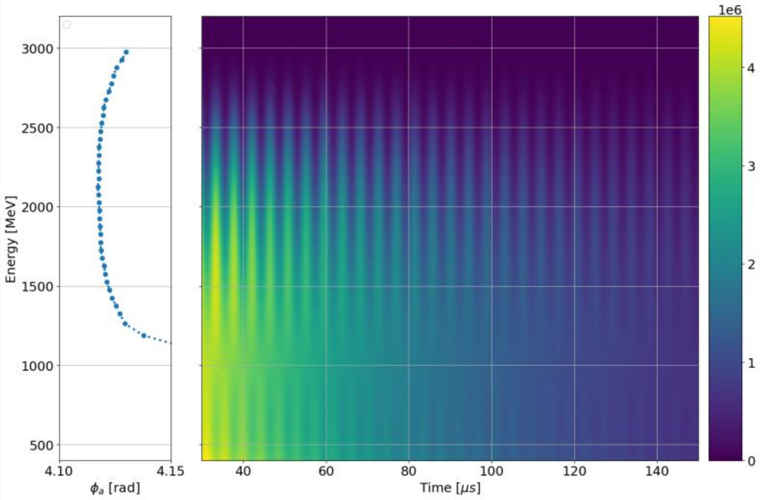
New!

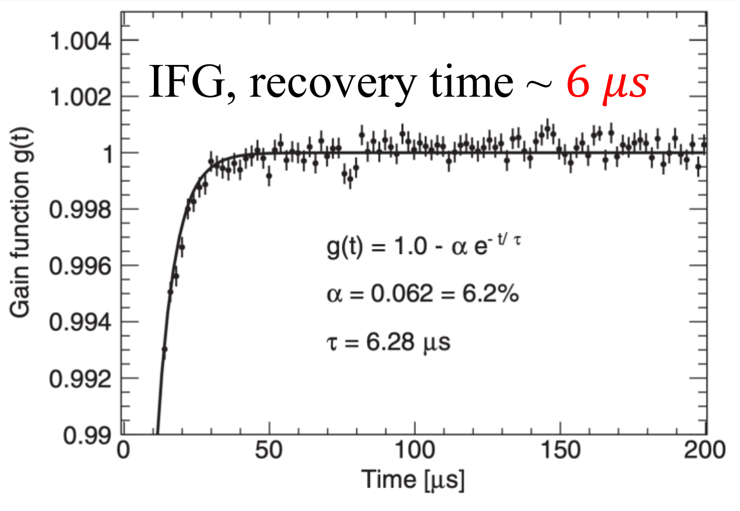
Precession Analysis

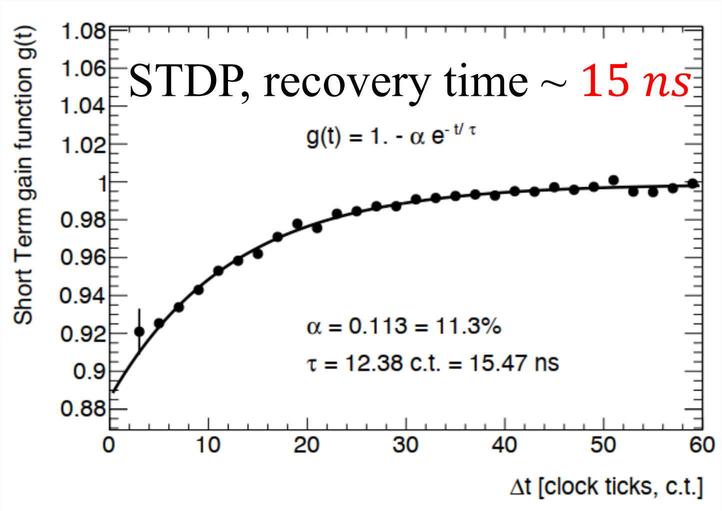
Early-to-late

- Time-dependent phase change leads to a bias: $\omega_a t + \varphi \rightarrow \omega_a t + \varphi(t) = \left(\omega_a + \frac{d\varphi}{dt}\right) t + \cdots$
- The detector effect because of SiPM gain sag
- Gain Correction in Run-1/2/3:
  - In-Fill Gain (IFG): caused by initial flash
  - Short-Term Double Pulse (STDP): caused by single pulse

Energy-dependent Phase



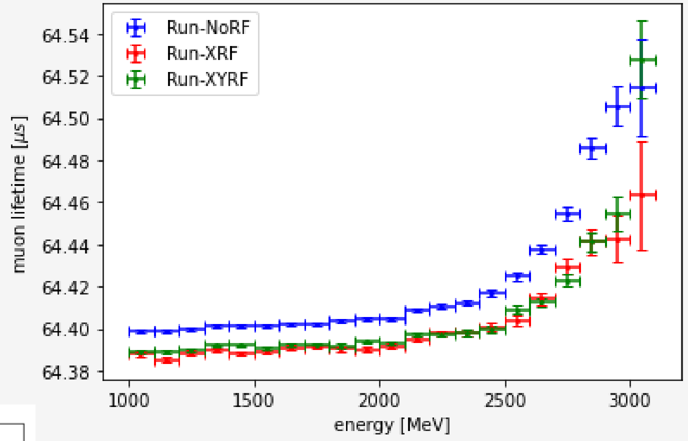


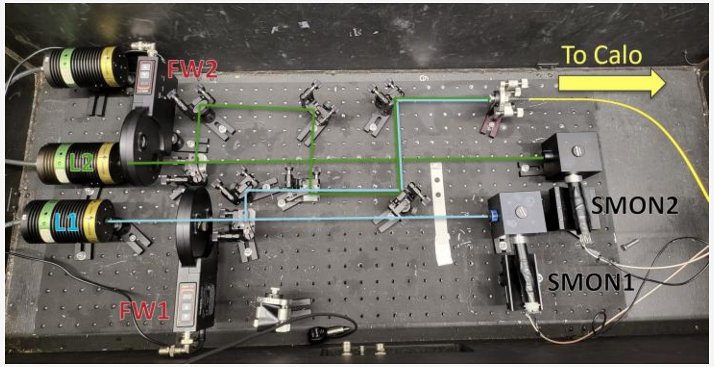


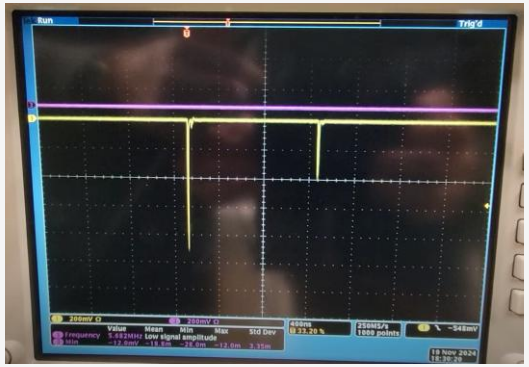
Precession Analysis

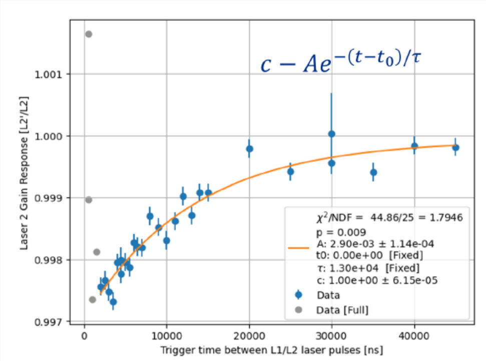
- ➤ Still remained in Run-4/5/6
- ➤ Identified: Intermediate-Term Double Pulse (ITDP)
  - Similar to STDP, but longer time scale, recovery time ~ 6 μs
  - Specialized hardware study

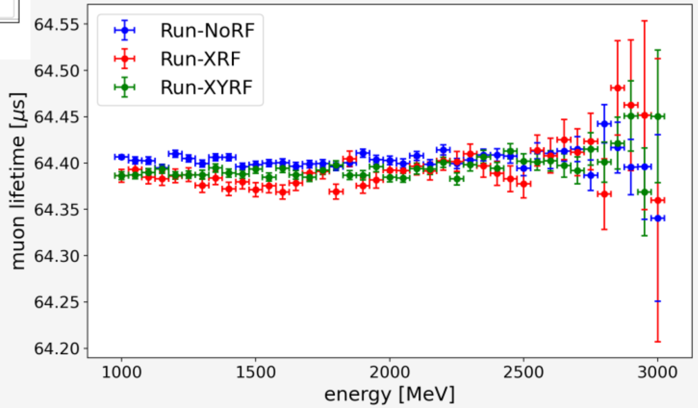
New!











- ➤ **20 ppb ~ 40 ppb** effect on ω_a, **10 ppb ~ 20 ppb** uncertainty

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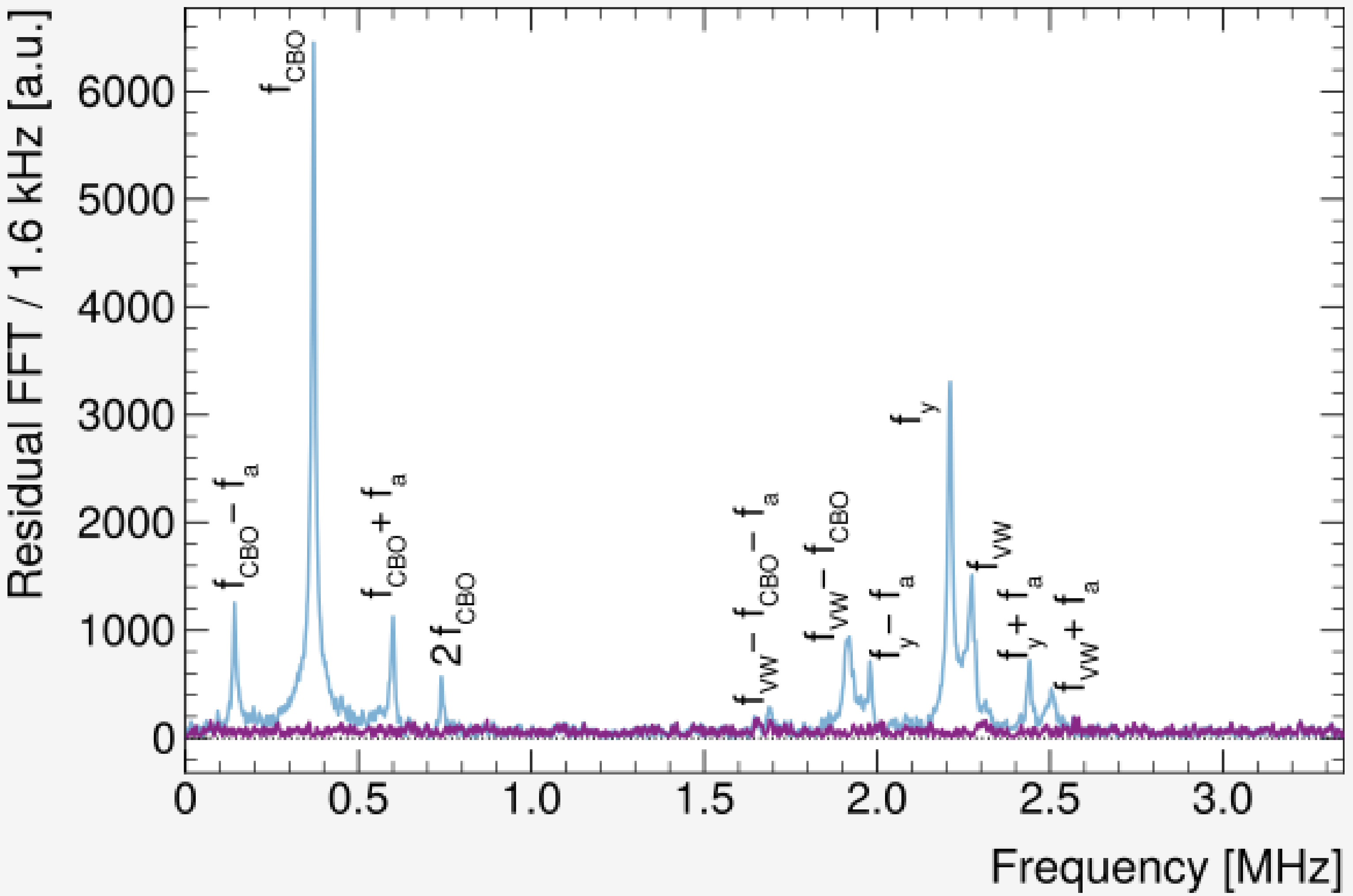
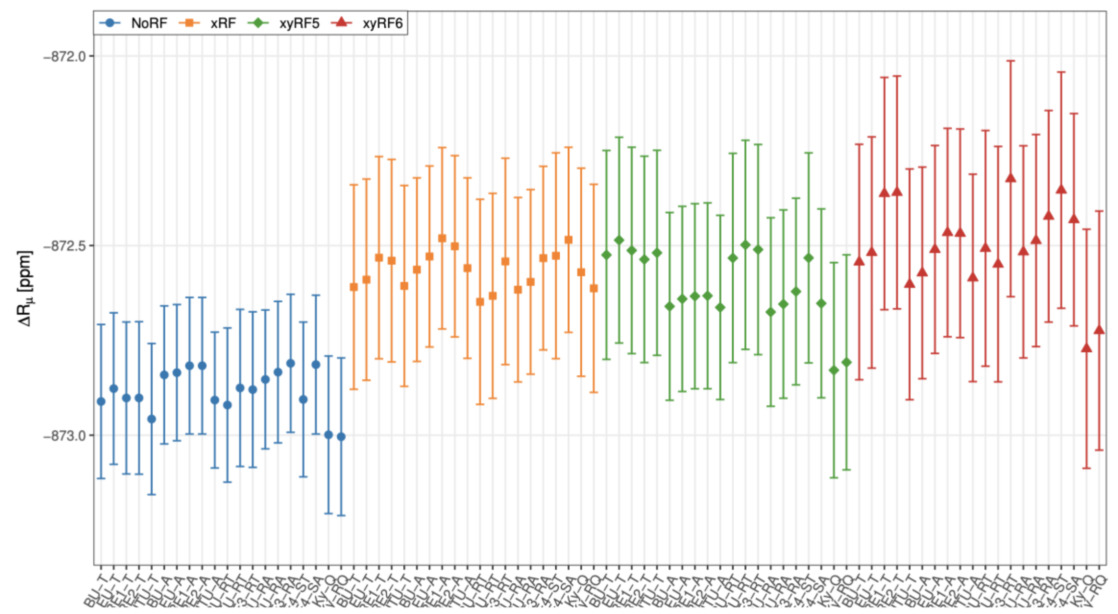
Precession Analysis



Precession Analysis

- Acquisition clocks are hardware blinded, analysis is software blinded
- Four major datasets based on the presence or absence of RF: Run-noRF, Run-xRF, Run-5xyRF, and Run-6xyRF
- 5 analysis groups, 20 methods in total
- 7 analyses are used in the average



Beam Dynamics Corrections

$$a_\mu = \frac{\omega_a^m}{\frac{q}{m}B}\left[1 + \frac{n}{4}\left(\frac{A_y}{r_0}\right)^2 + \frac{2n\beta_0^2}{1-n}\left(\frac{\Delta p}{p_0}\right)^2\right]$$

ambiguity

$$\cos\left[\omega_a t - \langle\phi_a\rangle(t)\right]$$

from Spin Dynamics

- **pitch** and **electric field** effects change relationship between ω_a, a_μ
- both effects reduce measured ω_a^m, corrections **increase** to compensate
- largest corrections: ~200 – 400 ppb

from Changing Phase

- changing average $\langle\phi_a\rangle(t)$ biases ω_a
- relevant phase-changing correlations:
  - **phase-acceptance**: slow drifts in beam dynamics change $\langle\phi_a\rangle$
  - **differential decay & muon loss**: drift in avg. μ^+ momentum changes $\langle\phi_a\rangle$
- smaller corrections, ~30 ppb or below

$$C_{\mathrm{BD}} = C_E + C_P$$

electric field | pitch | phase acceptance | differential decay | muon loss

- The vertical angle measurable in the trackers is reduced by four effects:

Measured tilt $= R_\gamma\, R_p\, R_{e^+}(\lambda)\, R_{acc}(\lambda)$ True tilt

- R_γ : boost factor from muon rest frame to lab frame.
  - Factor is 1/γ, so ~ 1/29.
- R_p : beam polarization reduction (as is < 100%).
- $R_{e^+}(\lambda)$: muon decay asymmetry shape.
  - Has an analytical form, f(λ), where λ is fractional momentum, calculated up to first order radiative corrections.
- $R_{acc}(\lambda)$: acceptance effects, from the finite size of the tracker + reconstruction capabilities.
  - No analytical form, determined from MC ratios.

(Tilts not to scale)