Status of the Muon g-2 Experiment at Fermilab

Sean Foster, University of Kentucky
On behalf of the Muon g-2 Collaboration
August 9, 2024

2024 Joint Photonuclear Reactions
and Frontiers & Careers Workshop
MIT Laboratory for Nuclear Science

Wilson Hall
Fermilab
Batavia, IL

Photo taken in 2013!

Muon g-2 storage ring

https://vms.fnal.gov/asset/detail?recid=1819590

The Muon g-2 Collaboration

US Universities
- Boston
- Cornell
- UIUC
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central College
- Regis
- Virginia
- Washington

US National Labs
- Argonne
- Brookhaven
- Fermilab

181 collaborators
33 Institutions
7 countries

China
- Shanghai Jiao Tong

Germany
- Dresden
- Mainz

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

Korea
- CAPP/IBS/KAIST

Russia
- Budker/Novosibirsk
- JINR Dubna

United Kingdom
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London

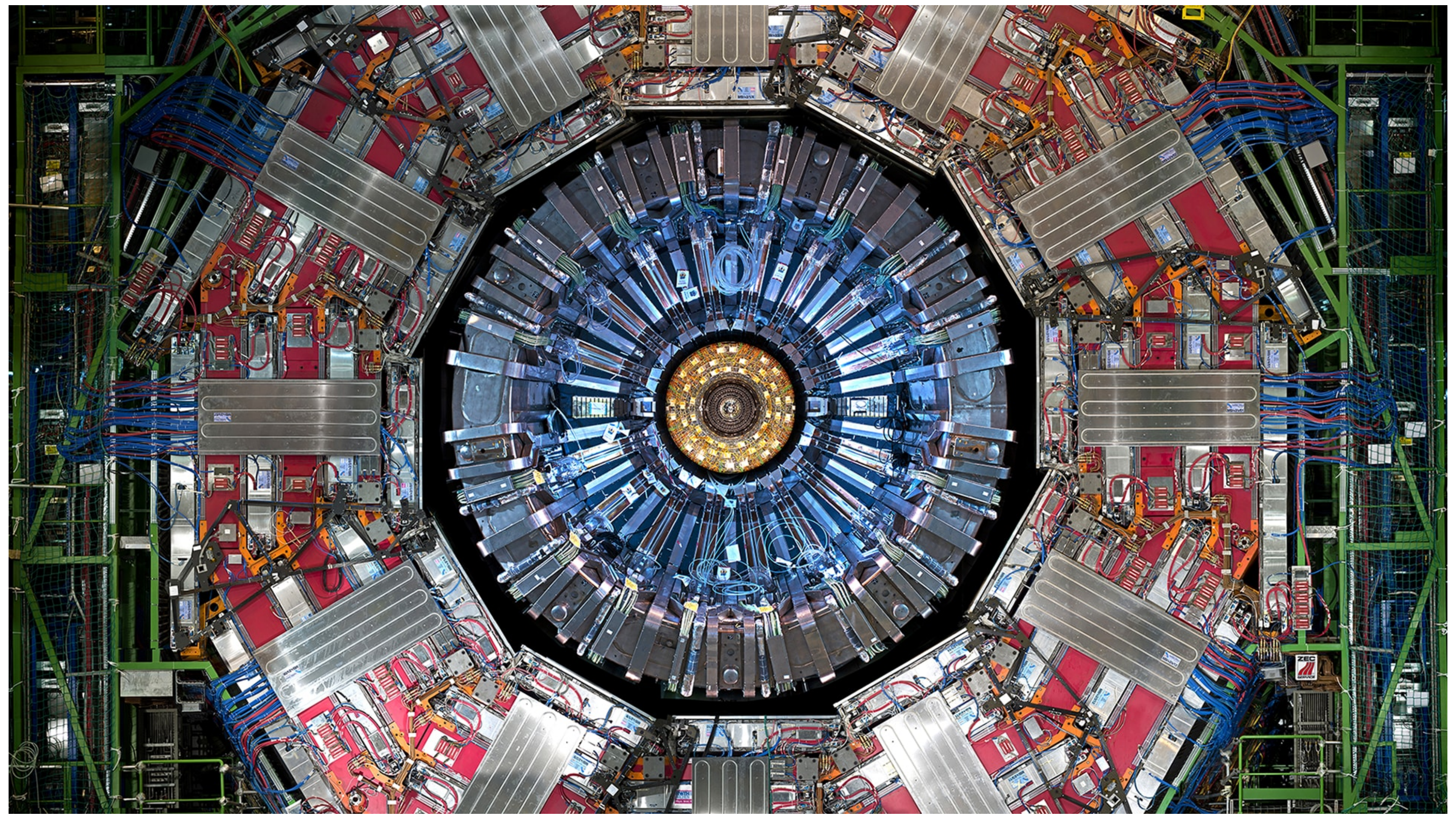
Collaboration Meeting
Ann Arbor, MI July 2024

- Collaboration formed in the mid/late 2000s
- Technical Design Report in 2015
- First beam in 2017 commissioning run
- Goal: measure the **muon magnetic anomaly** to a precision of **140 parts-per billion**, x4 more precise than previous best measurement

Motivation

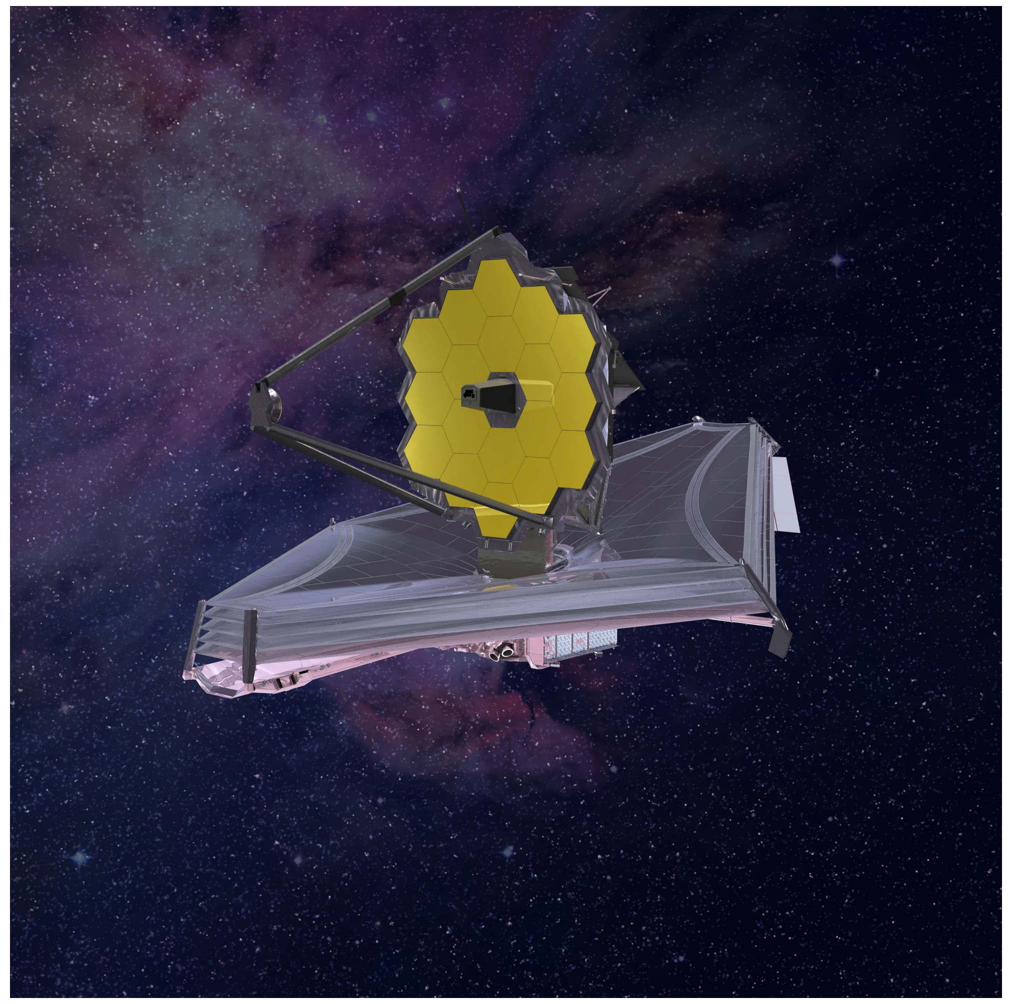
- **Test the Standard Model** (SM) of particle physics and **search for new physics**
    - Evidence aplenty that the SM is incomplete, e.g. what is the nature of dark matter? origin of matter/anti-matter asymmetry in the universe? etc.
- How to test SM and search for new physics?

Go to high energy!



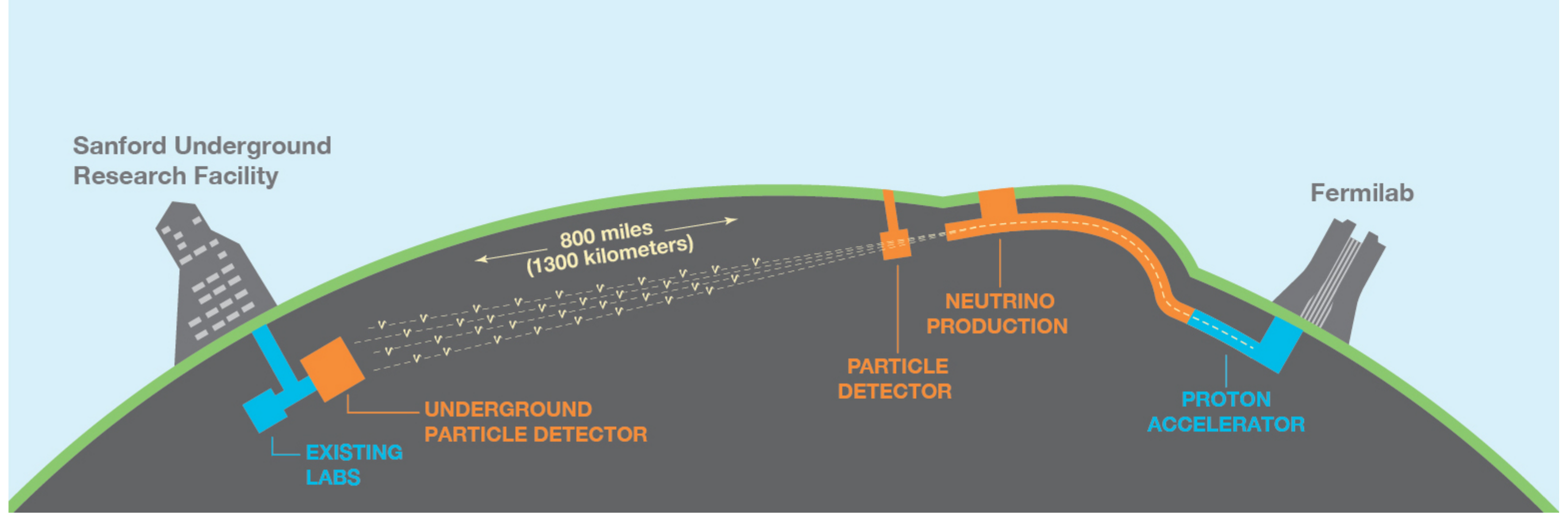
CMS, LHC CERN

Look out into the universe!



JWST, NASA

Study lots of particles!

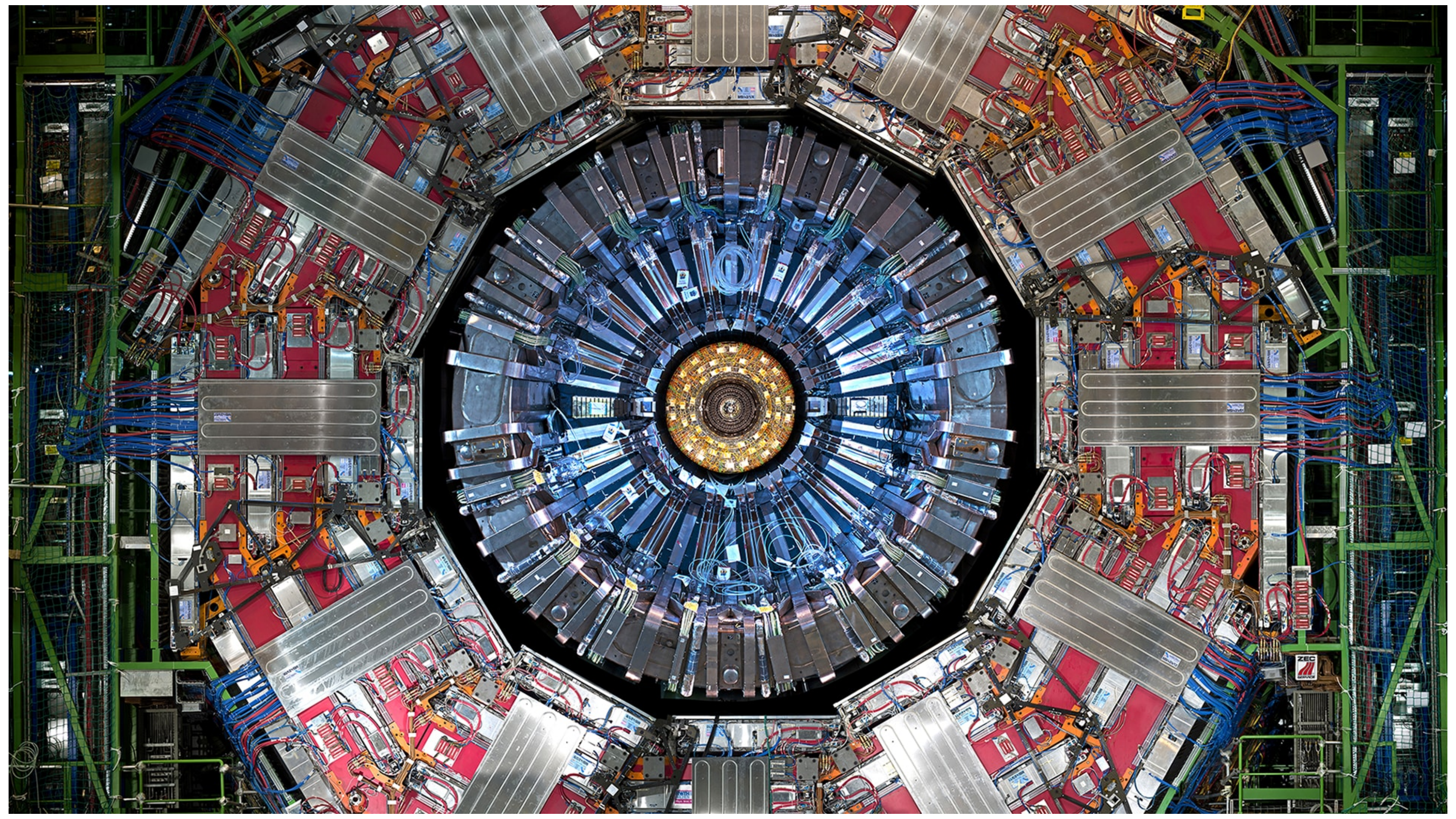


DUNE, Fermilab

Motivation

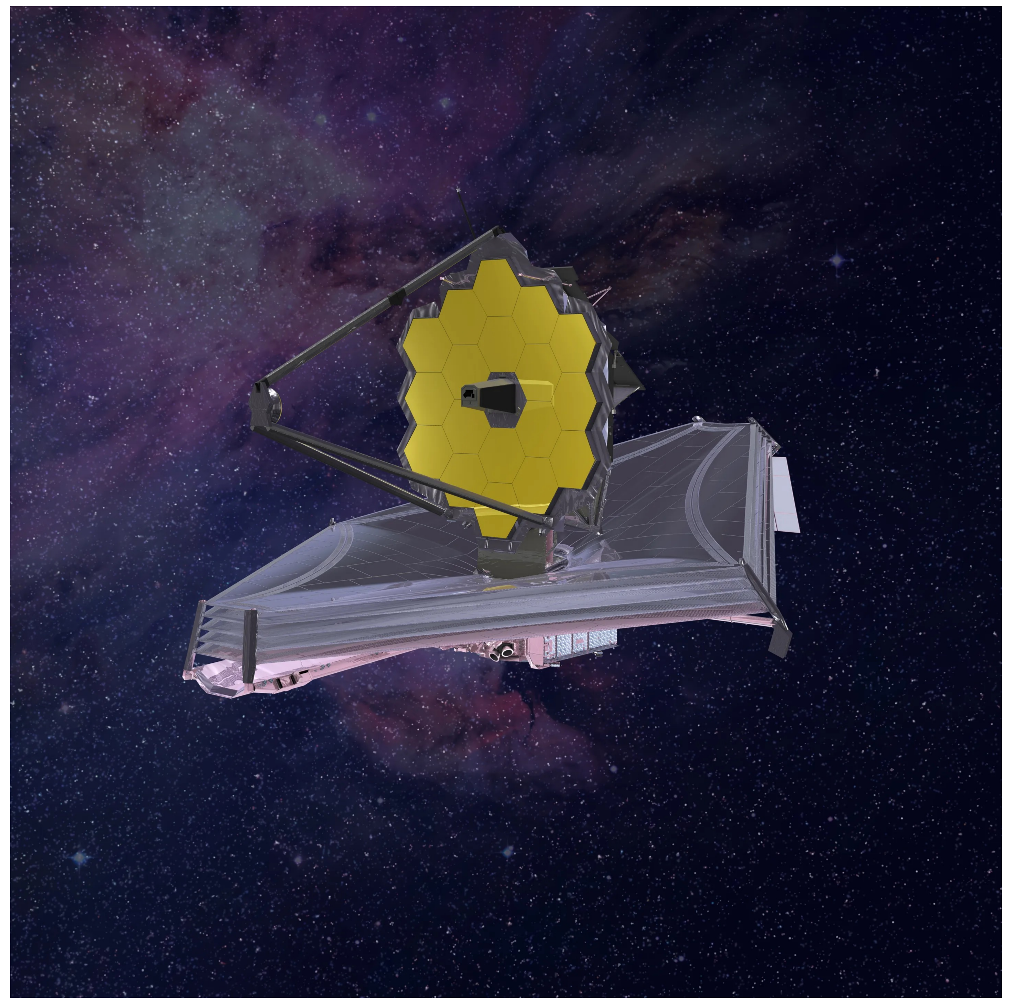
- **Test the Standard Model** (SM) of particle physics and **search for new physics**
  - Evidence aplenty that the SM is incomplete, e.g. what is the nature of dark matter? origin of matter/anti-matter asymmetry in the universe? etc.
- How to test SM and search for new physics?

Go to high energy!



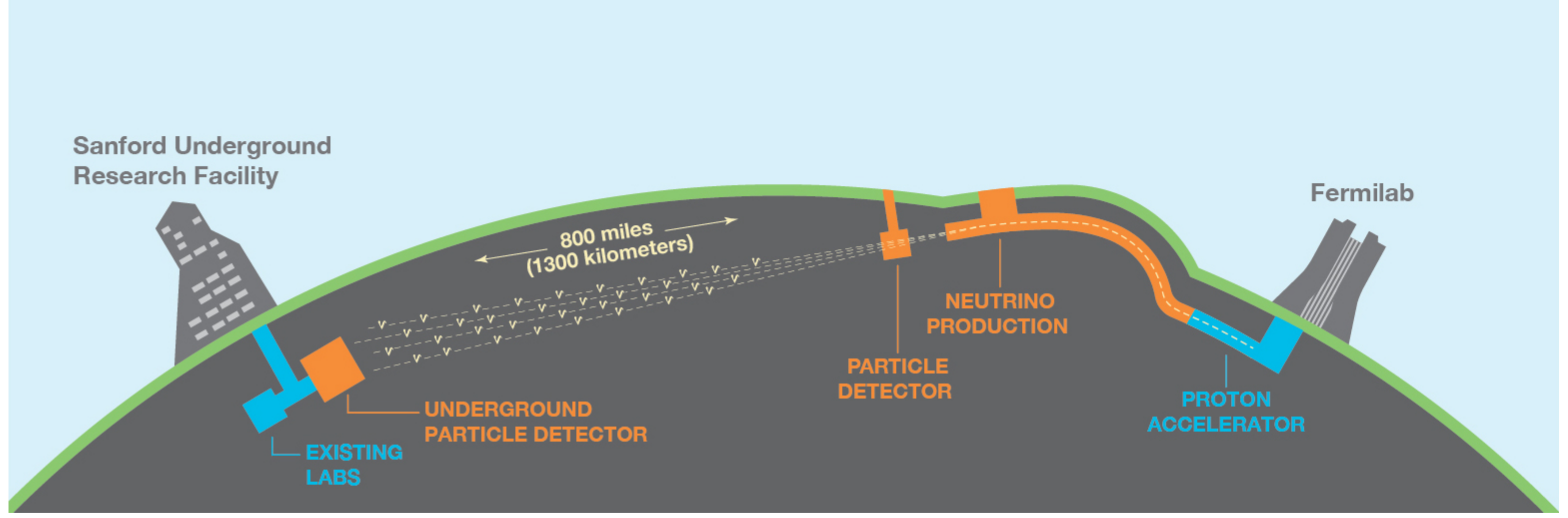
CMS, LHC CERN

Look out into the universe!



JWST, NASA

Study lots of particles!



DUNE, Fermilab

Magnetic moments can test the Standard Model

- Magnetic moments are sensitive to particles in nature through the “g-factor”

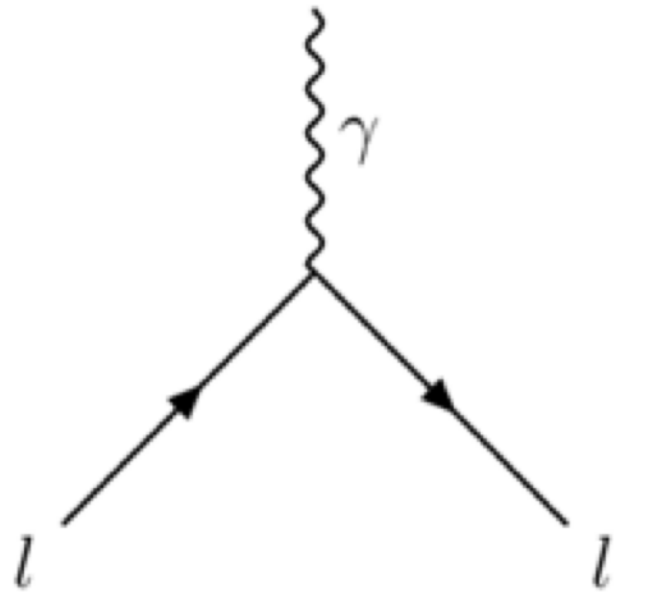
magnetic moment **spin**

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

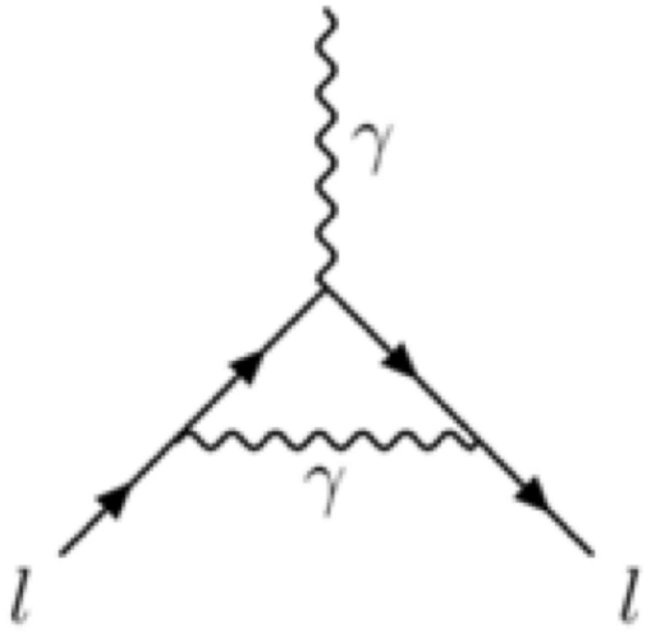
gyromagnetic (“g”) factor

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

magnetic anomaly



$$g = 2$$



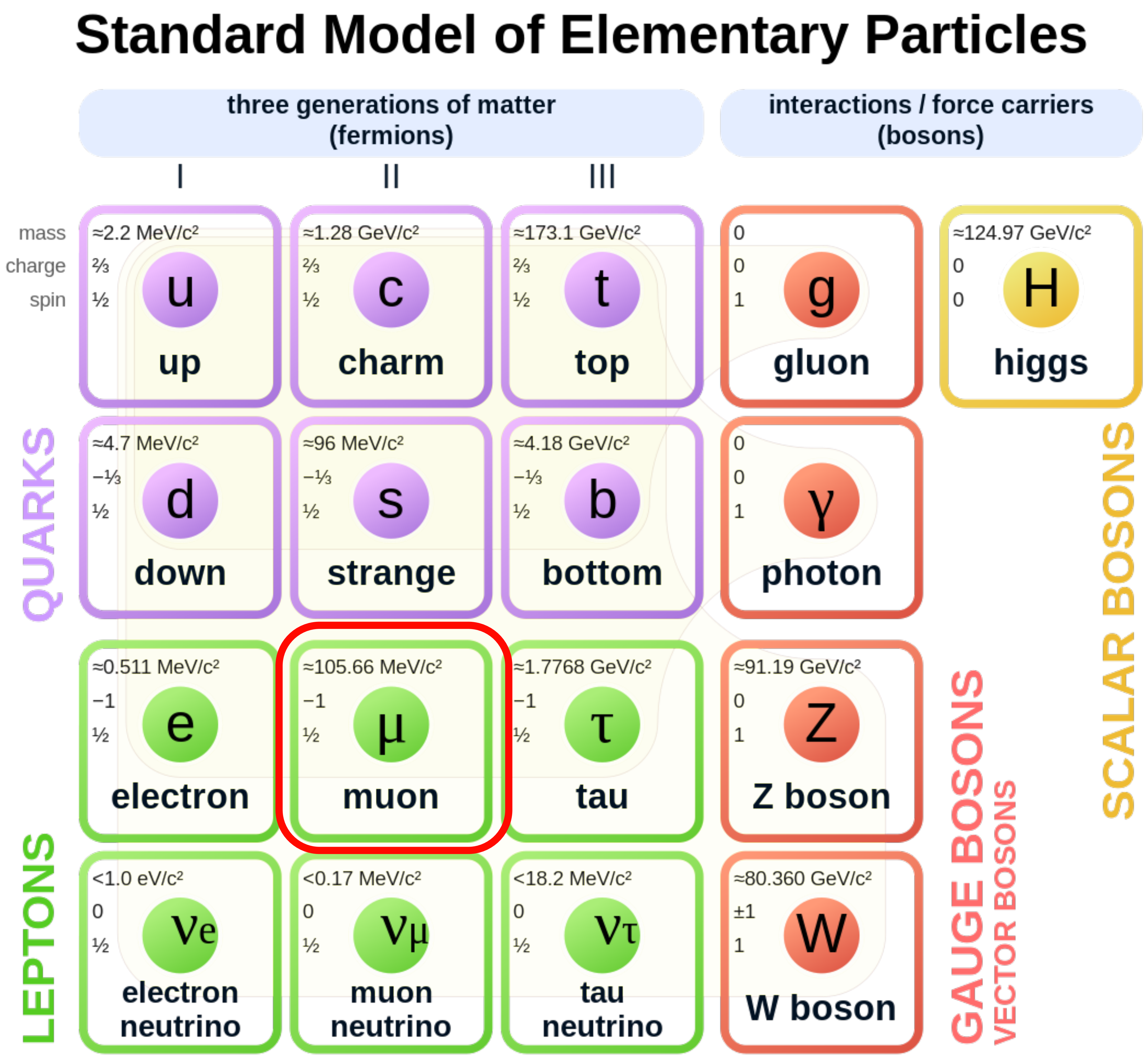
$$+\frac{\alpha}{\pi}$$

“Schwinger” term

$$+\ldots$$

- Dirac’s theory of spin-1/2 fermions predicts $g = 2$ ($a = 0$)
- Loop corrections cause g to deviate from 2 ($a \neq 0$)
- Size of a set by particles in nature, so a measurement of anomaly can test the **completeness of the Standard Model**

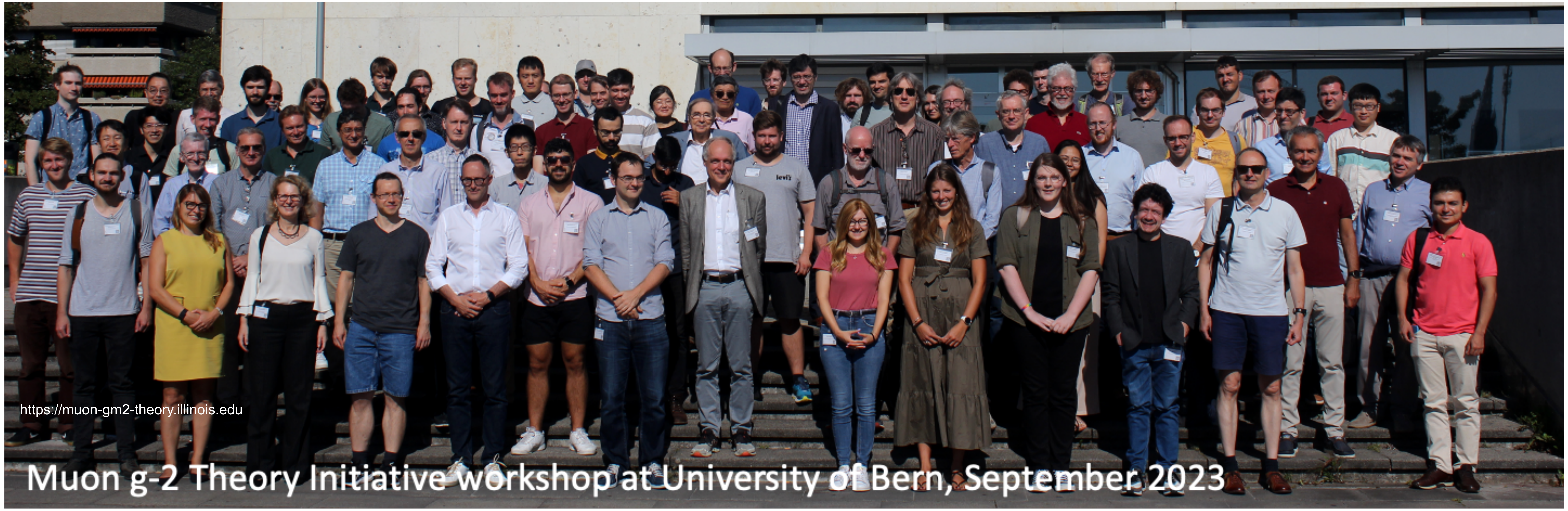
Pick the muon!



- The **muon** is a second generation charged lepton
- Decays into an electron and two neutrinos with a lifetime of $\sim 2.2\mu s$
- **207x** more massive than the electron
- Sensitivity to virtual particles $\propto m_l^2/M^2$, so muon is 40,000x more sensitive than electron

$$g = 2 + \frac{\alpha}{\pi} + \ldots$$

Muon g-2 Theory Initiative

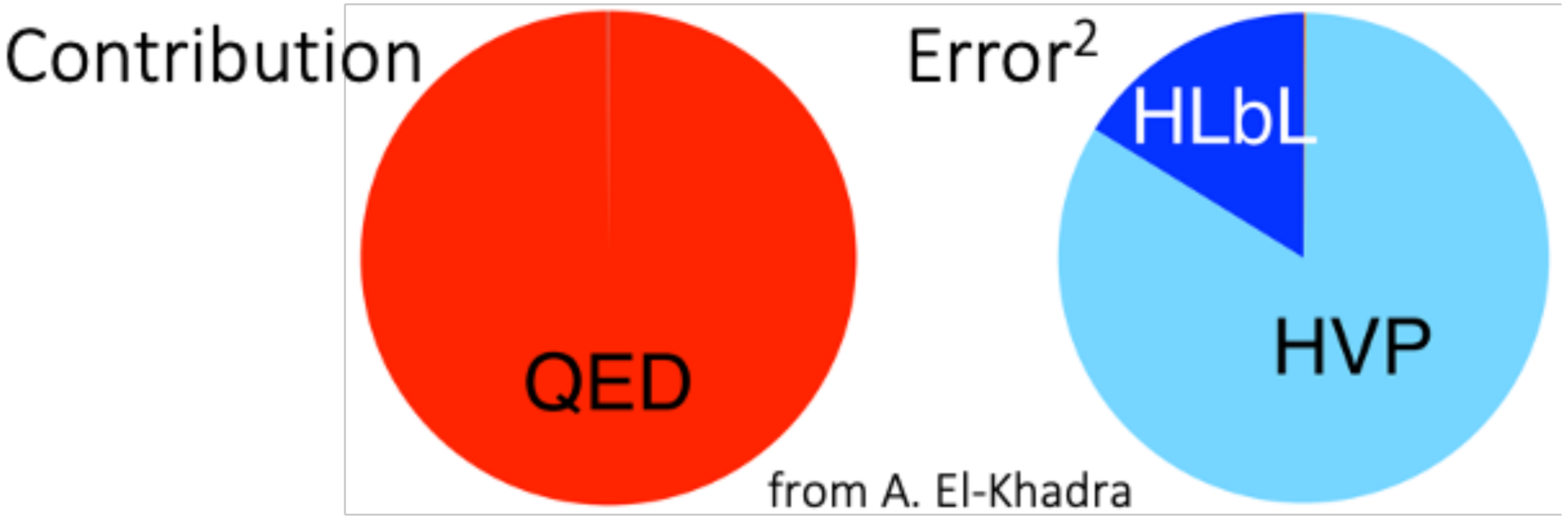


- Group of scientists working to compile all inputs to Standard Model prediction of the muon magnetic anomaly
- Published a White Paper in 2020

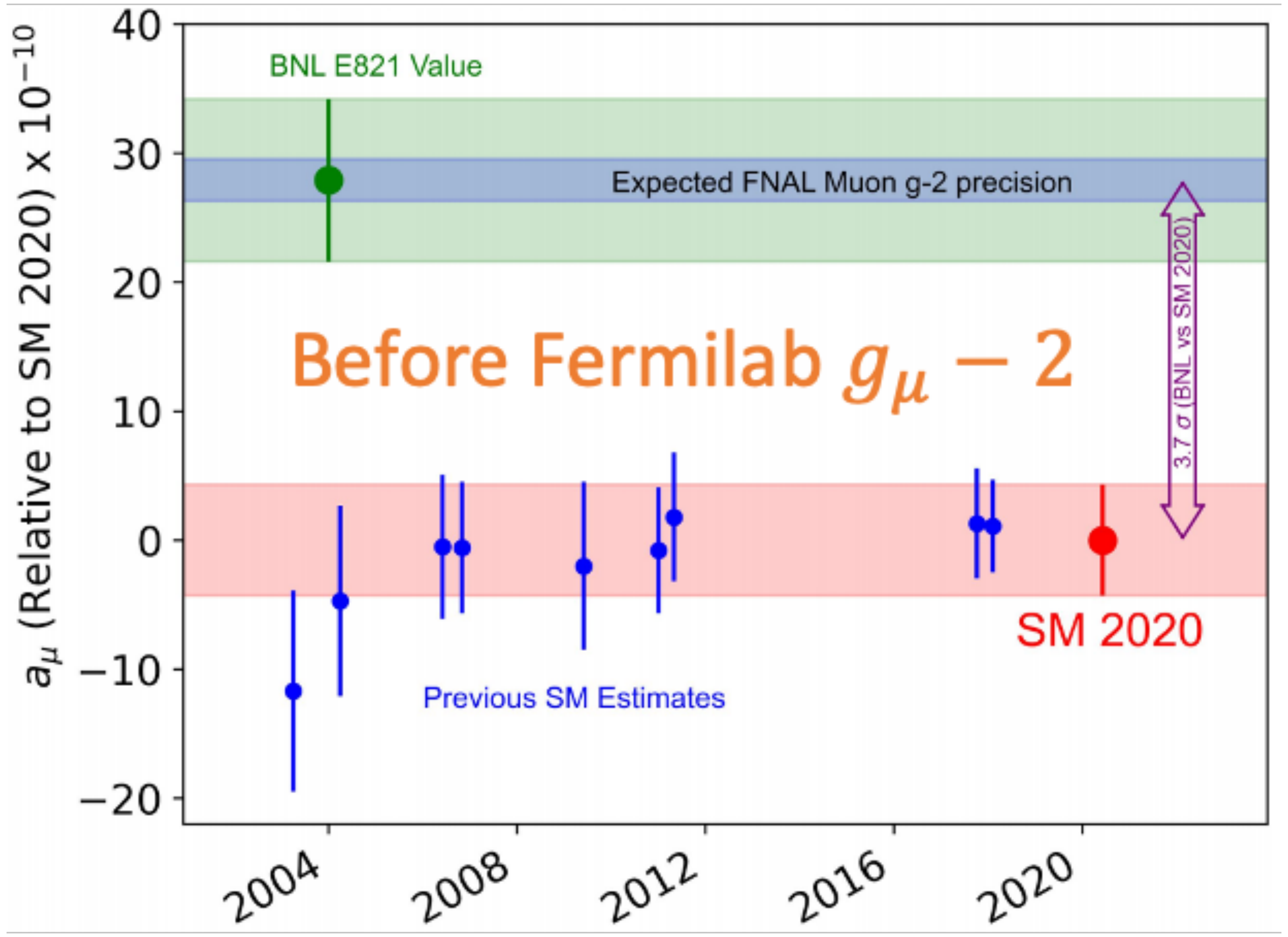
White Paper: Phys. Rept. 887 (2020) 1-166
https://doi.org/10.1016/j.physrep.2020.07.006

Theory prediction

- SM **value** is dominated by QED contributions, over 99.99% of total
- But, **uncertainty** is dominated by Hadronic contributions, which are notoriously difficult to calculate: hadronic light-by-light (HLbL) and hadronic vacuum polarization (HVP)



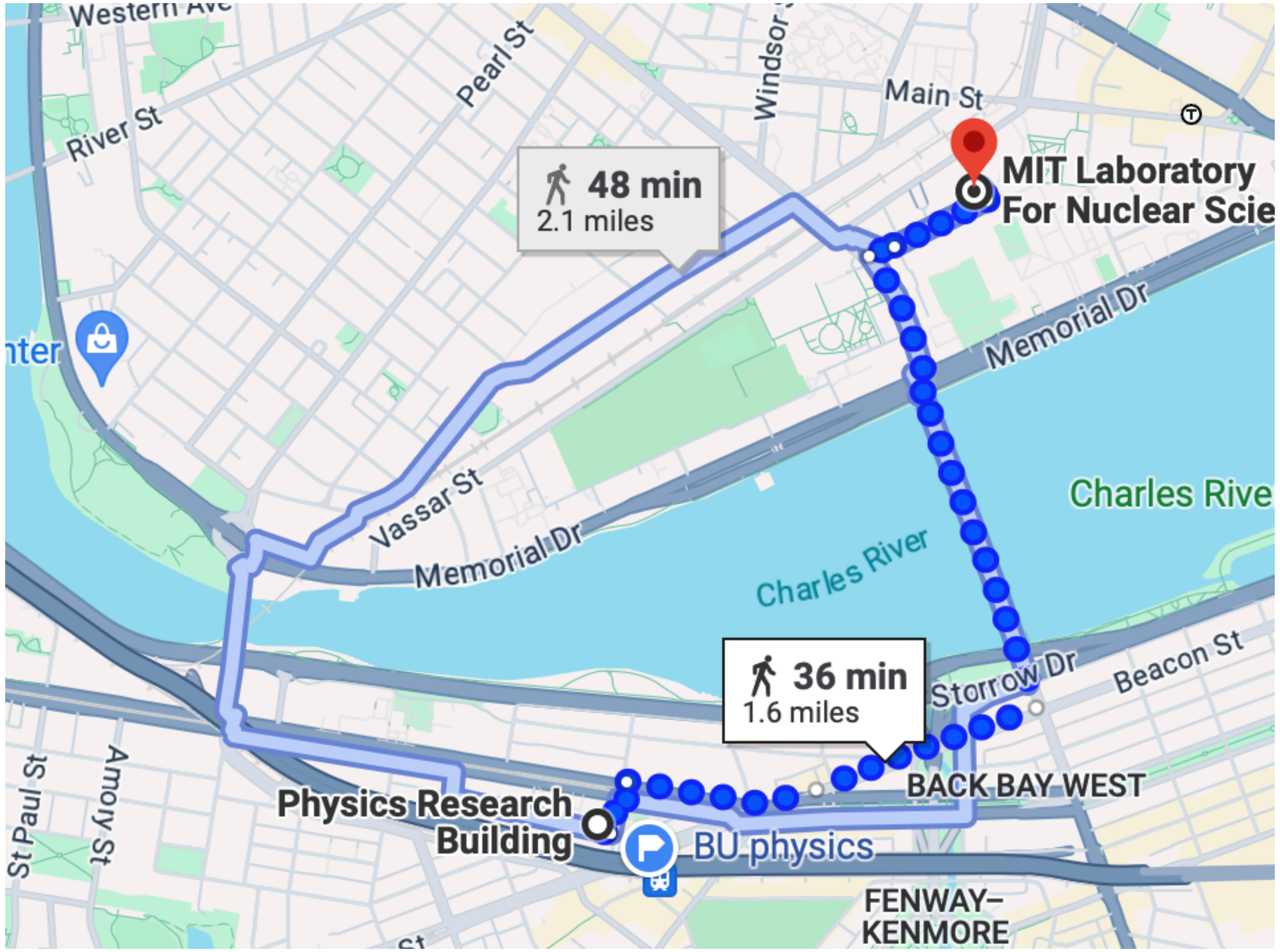
from A. El-Khadra



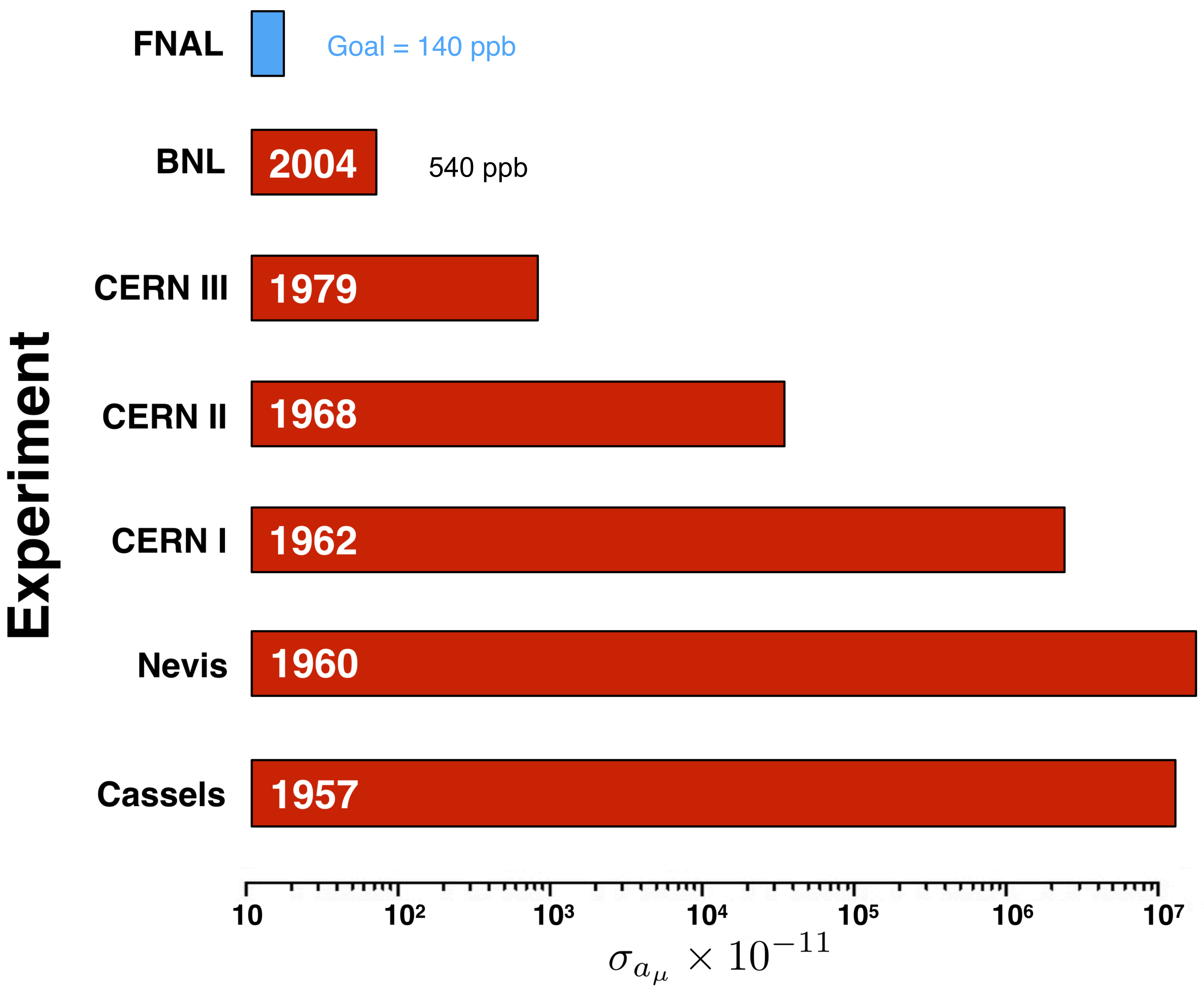
White Paper uncertainty: 369 ppb

How precise is 369 ppb?

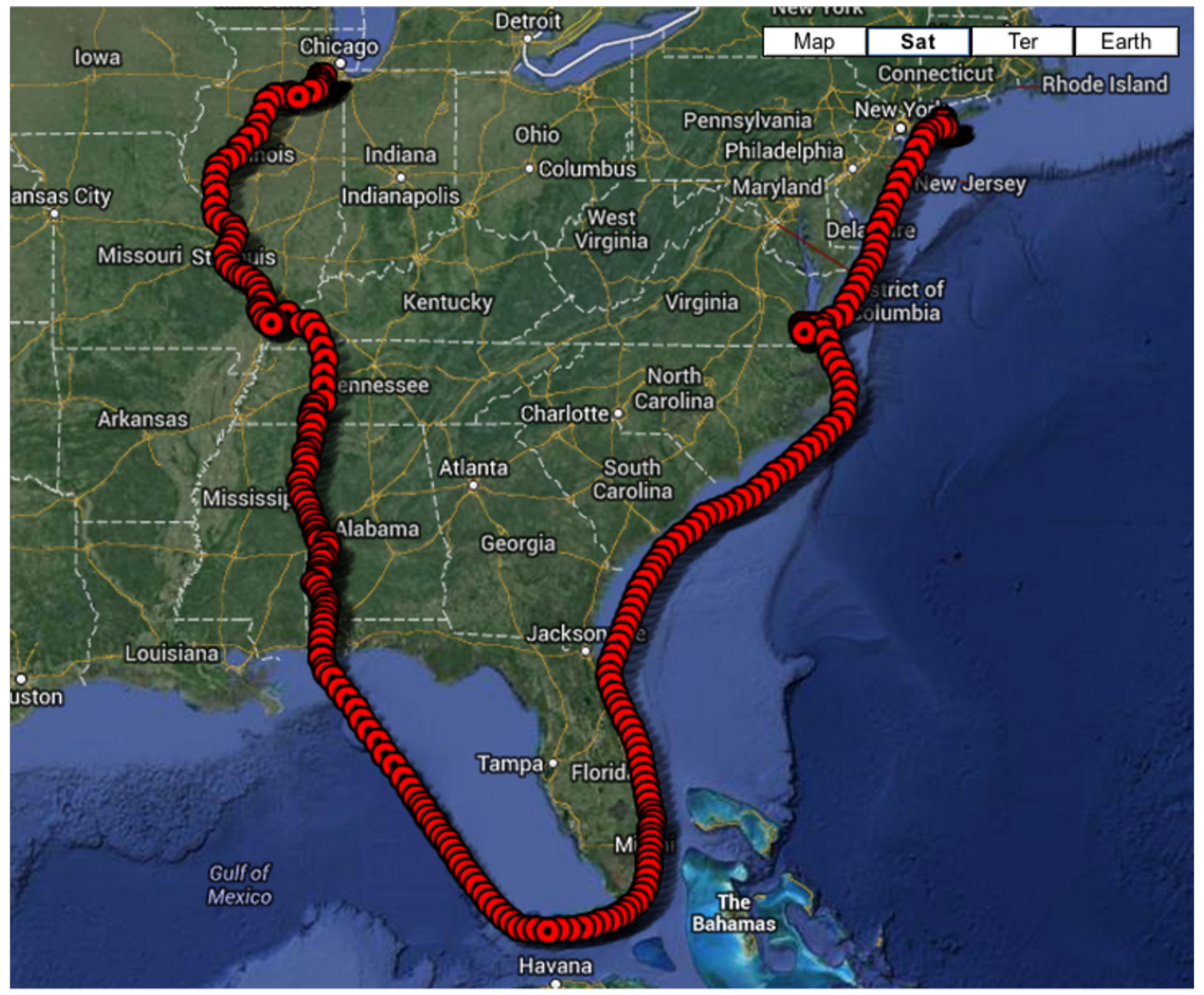
- I went to BU for my PhD and the physics department is about a 1.6 mile walk from here
- If I wanted to precisely determine that distance to 369 ppb: get it right to **1 mm!**
- 369 ppb sets scale for what experiment should achieve



Fermilab experiment continues the effort

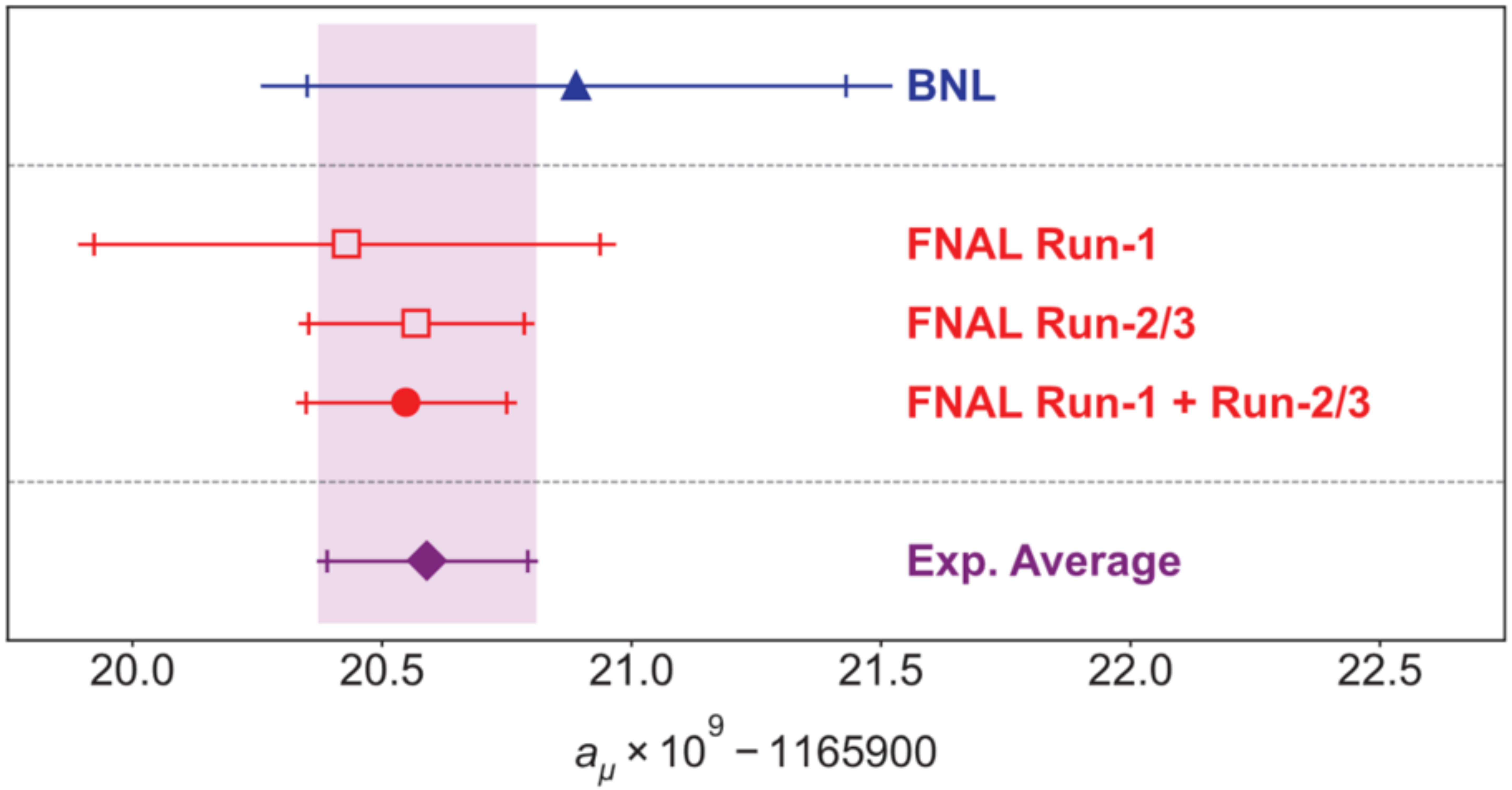


- 60+ year history of measuring muon g-2
- Previous experiment took place at Brookhaven National Lab (BNL)
- Fermilab experiment uses the same magnet -> the big move!



Fermilab results from first 3 Runs

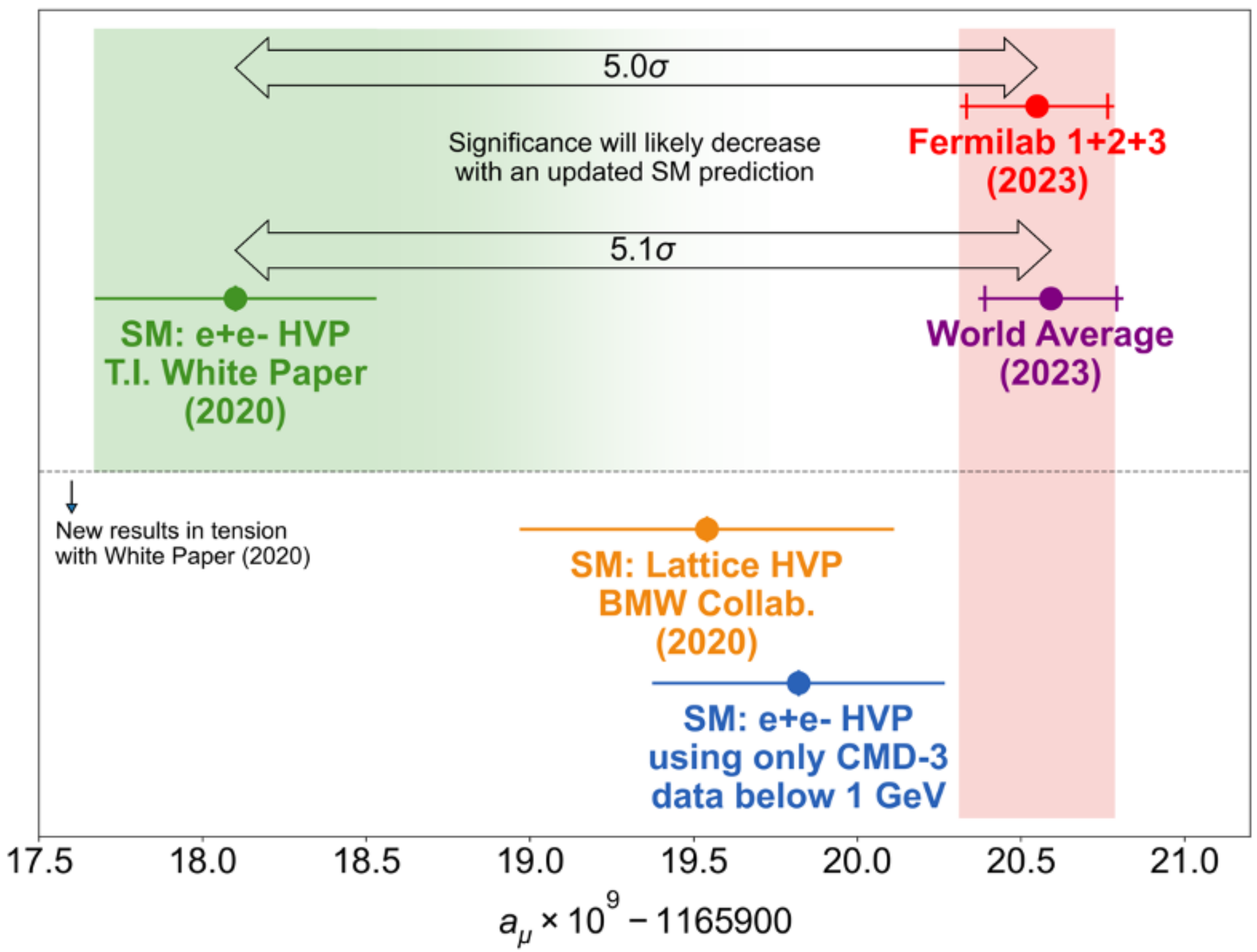
- First result (2021) based on Run-1 data: comparable uncertainty & consistent with BNL
- Second result (2023) based on Run-2/3 data: reduced uncertainty by x2 and consistent again!



$$a_\mu(\text{Exp}) = 0.00116592059(22)\ \textbf{[190 ppb]}$$

PRL 126, 141801 (2021)
PRL 131, 161802 (2023)
Published yesterday! PRD 110, 032009 (2024)

Compare to theory after our Run-2/3 result



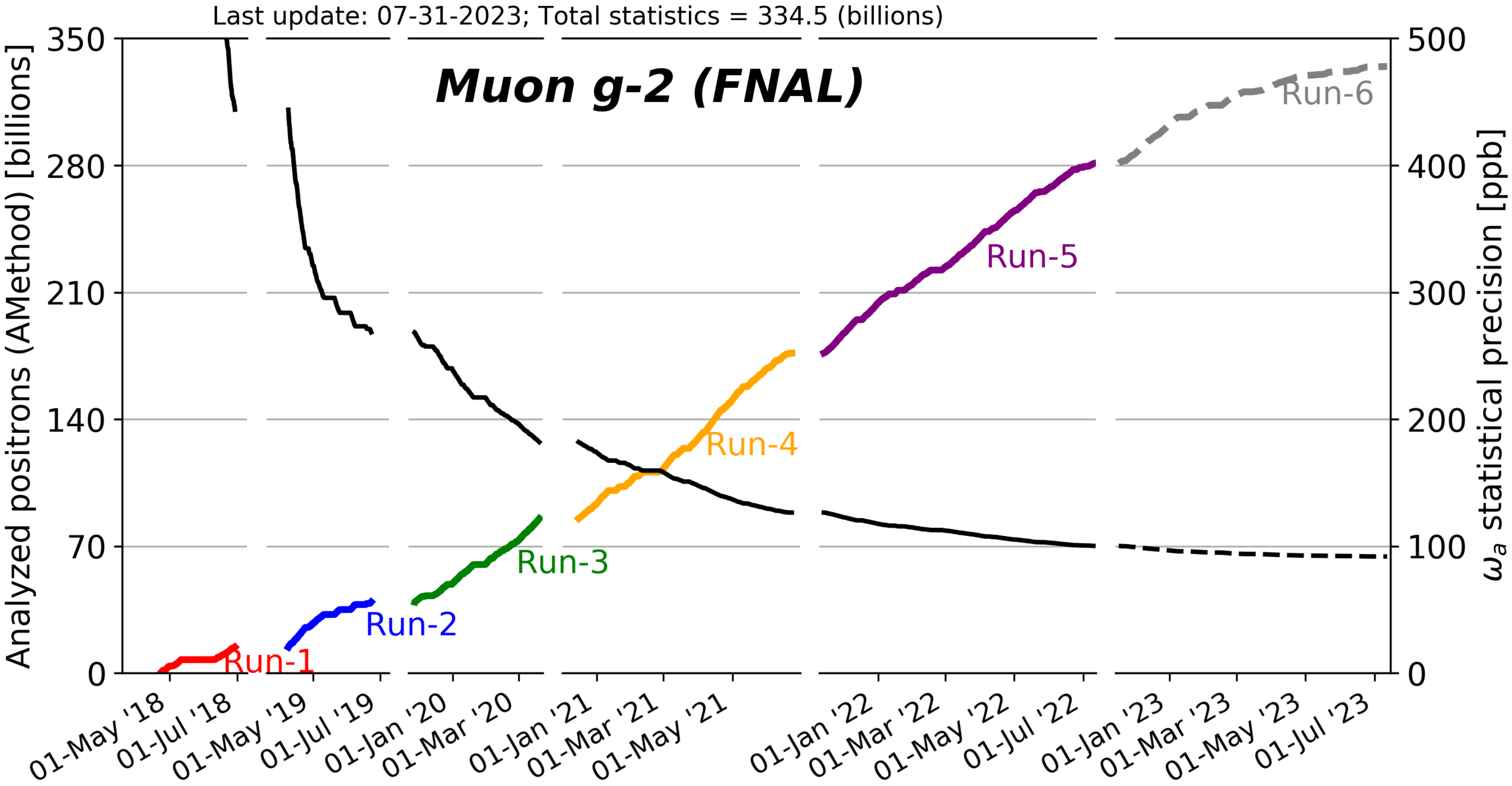
*Disclaimer from A. Keshavarzi's Lattice 2023 talk:

IMPORTANT: THIS PLOT IS VERY ROUGH!

- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → should not be taken as final!

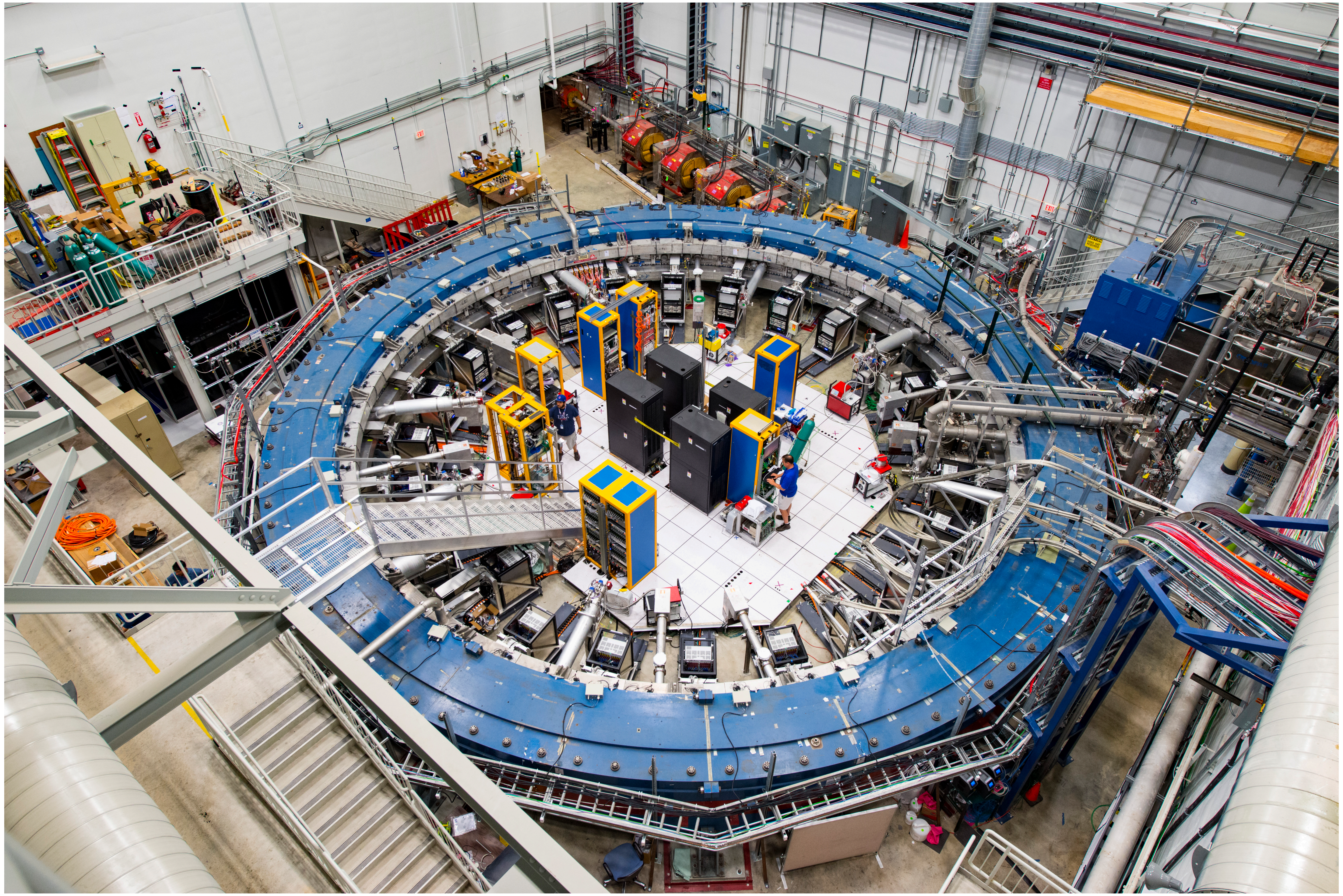
- Since theory White Paper, new results for HVP contributions
- Different methods disagree with each other
- Two methods are a **dispersive approach** (used in White Paper) and **lattice QCD**
- Theory initiative working to understand these tensions
- For now, hard to draw conclusions

We surpassed goal of x21 statistics of BNL

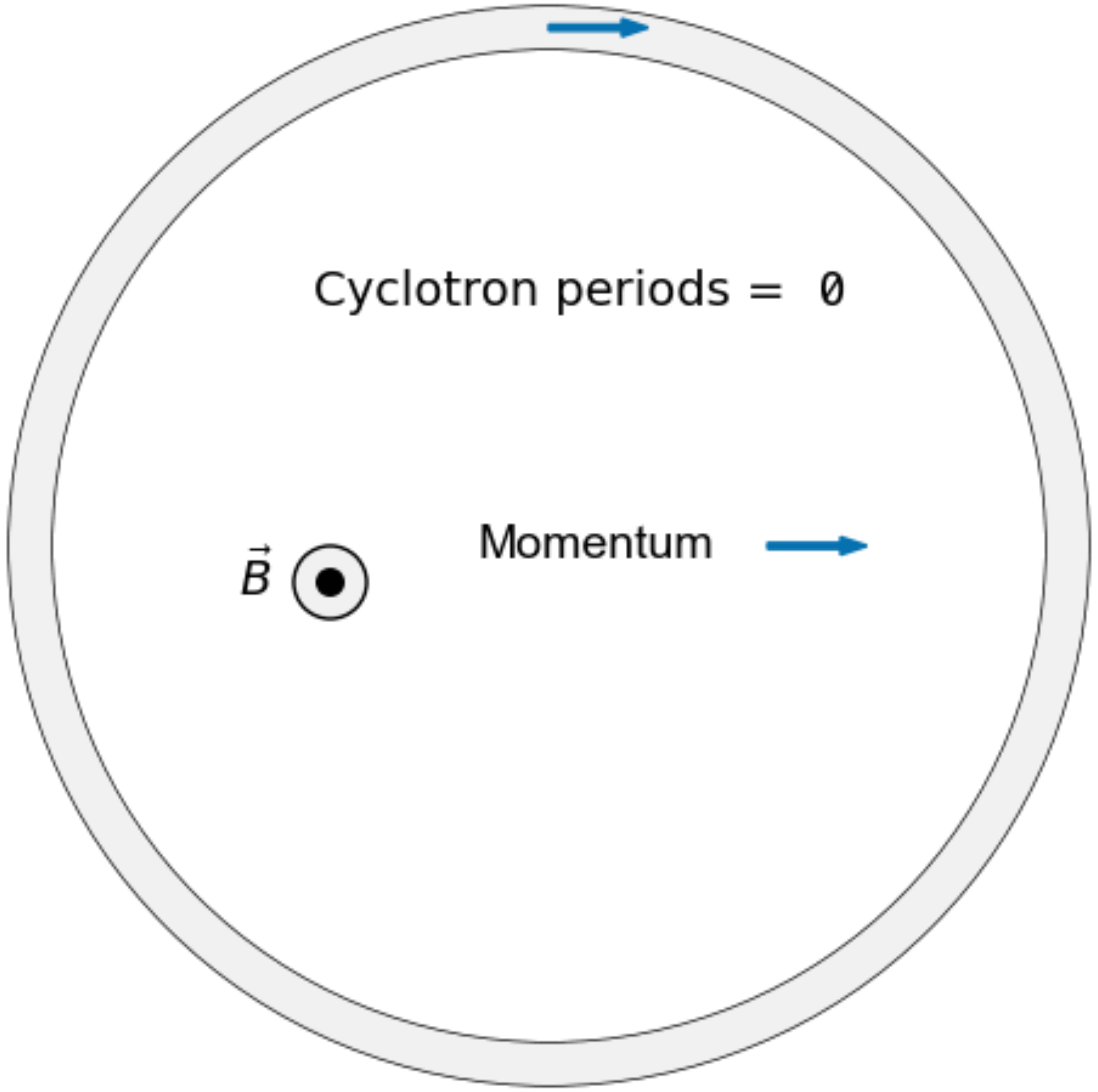


- Completed data collection in June 2023
- Reached TDR goal
- **Run-4/5/6**: analysis underway, expected to surpass target of 140 ppb
- Last result anticipated in 2025

Measurement details



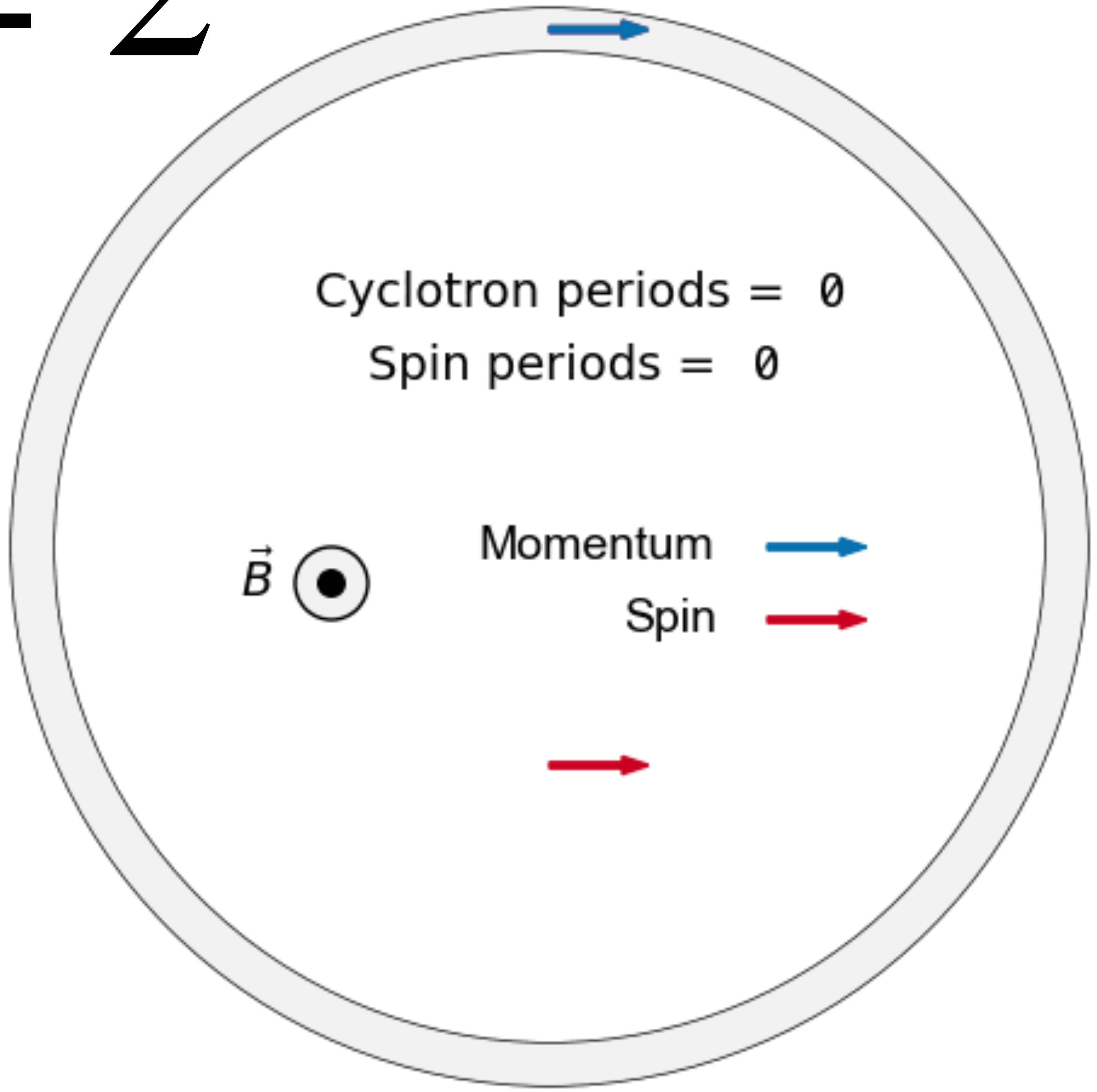
Place muon in a magnetic field



- Momentum vectors rotates at cyclotron frequency $\propto \vec{B}$

If $g = 2$ (not our universe!)

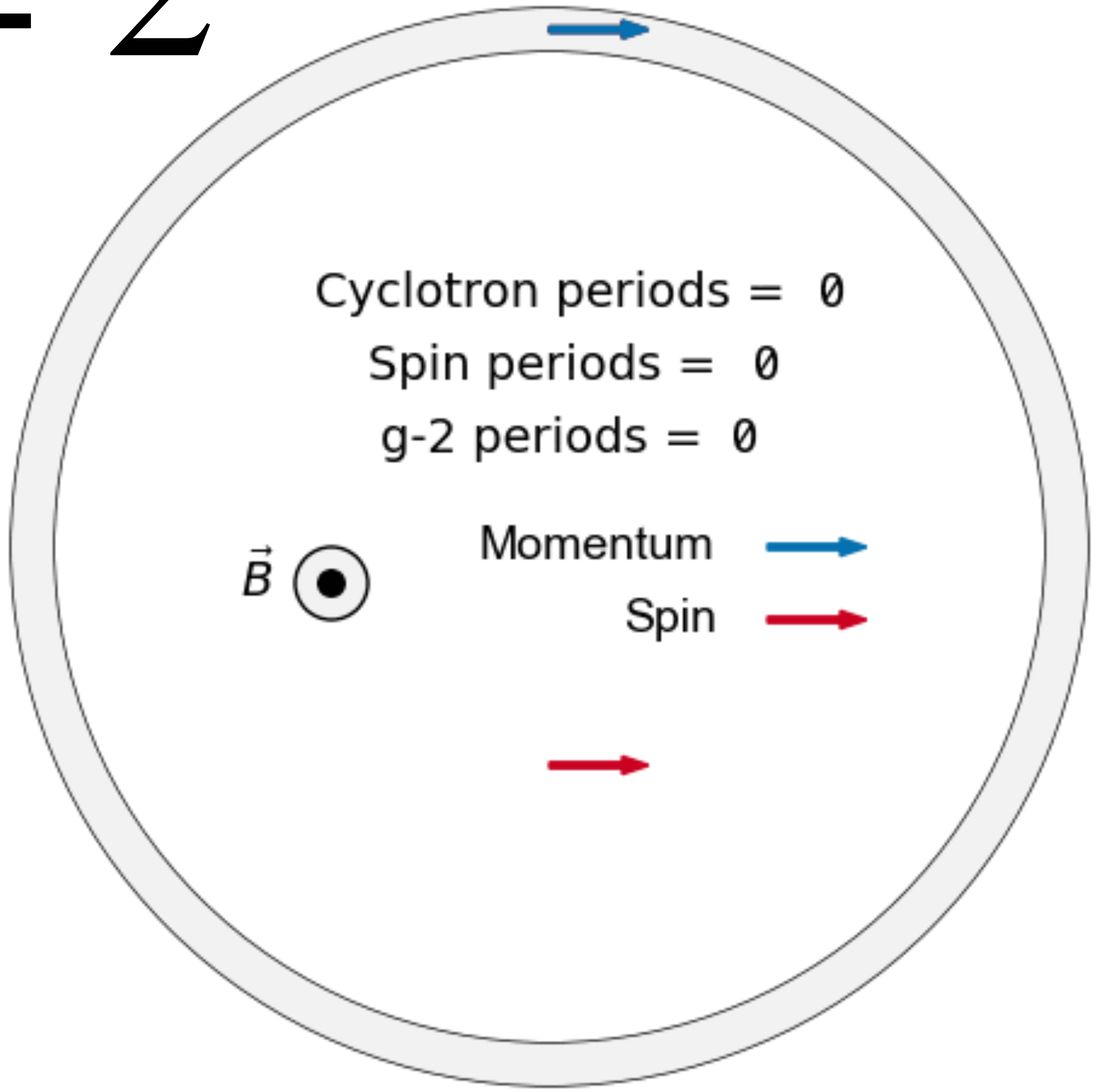
$$g = 2$$



- Momentum vectors rotates at cyclotron frequency $\propto \vec{B}$
- Spin precession is $\propto \vec{B}$ and g(want to measure this!)

If $g \neq 2$ (our universe!)

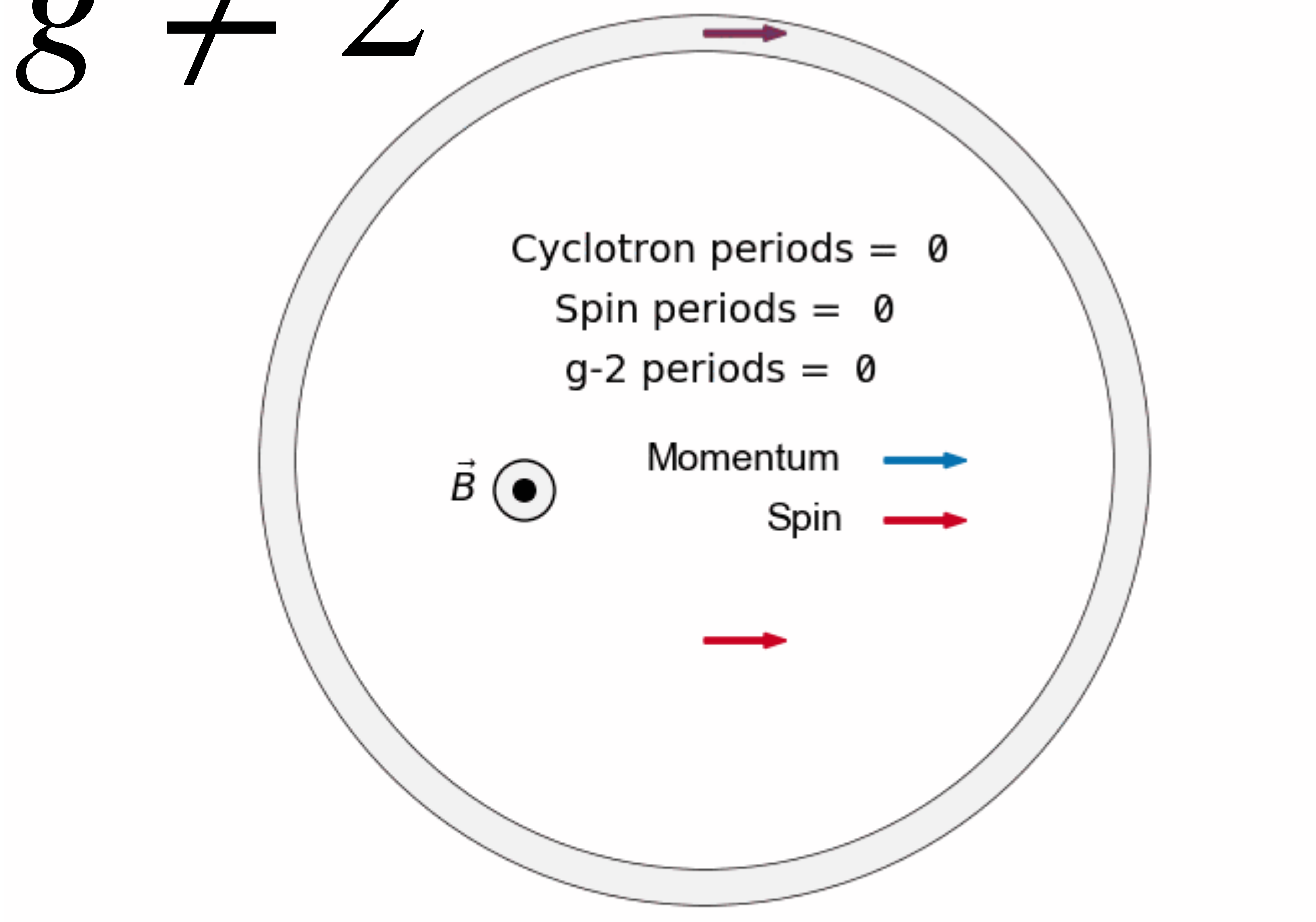
$$g \neq 2$$



- Momentum vectors rotates at cyclotron frequency $\propto \vec{B}$
- Spin precession is $\propto \vec{B}$ and g(want to measure this!)

Difference frequency ∝ anomaly

$$g \neq 2$$

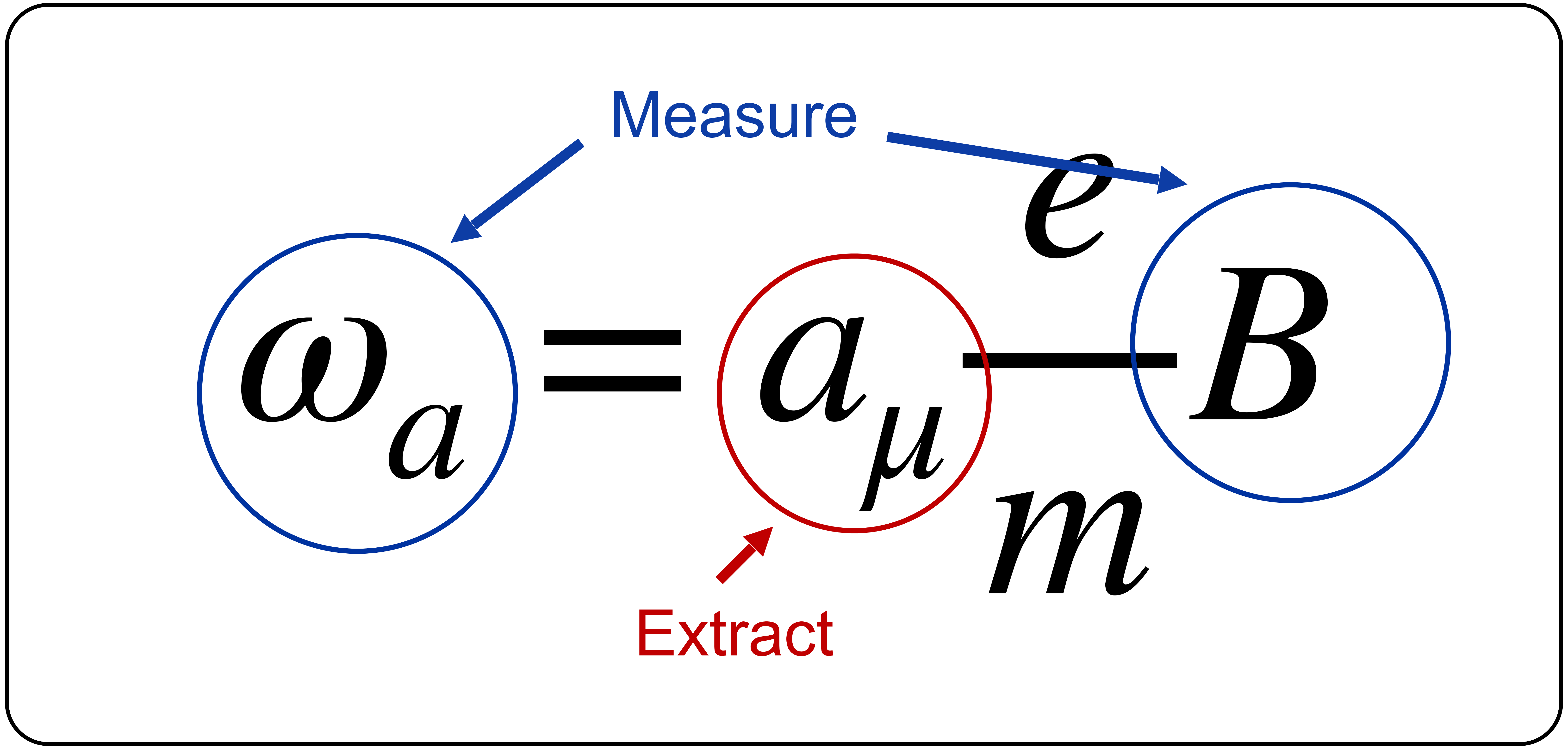


- **Difference** frequency ∝ **anomaly**!

$$\omega_a = a_\mu \frac{e}{m} B$$

- At **fixed locations** around ring, spins rotate at ω_a

Measurement recipe



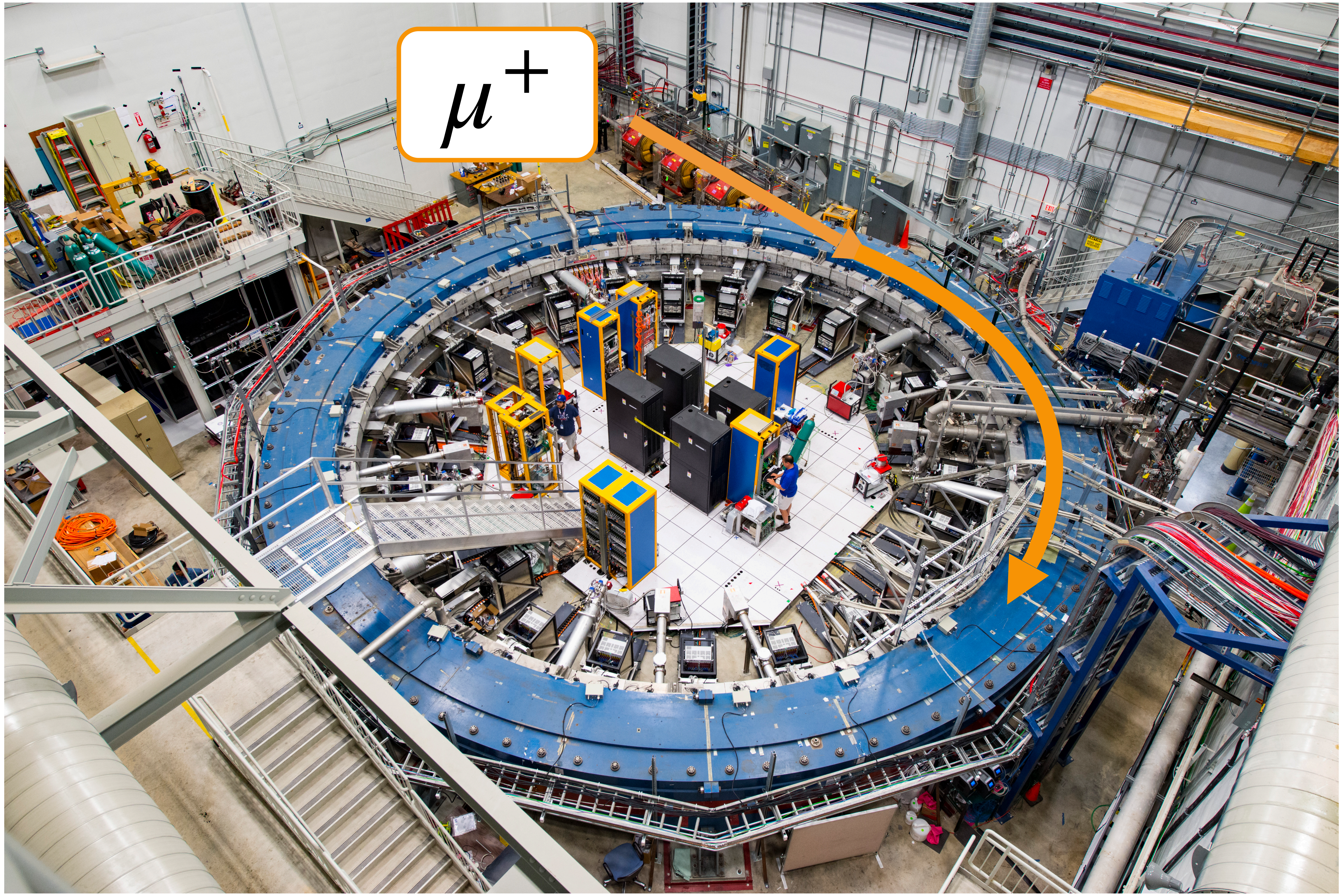
Measure

$$\omega_a = a_\mu \frac{e}{m} B$$

Extract

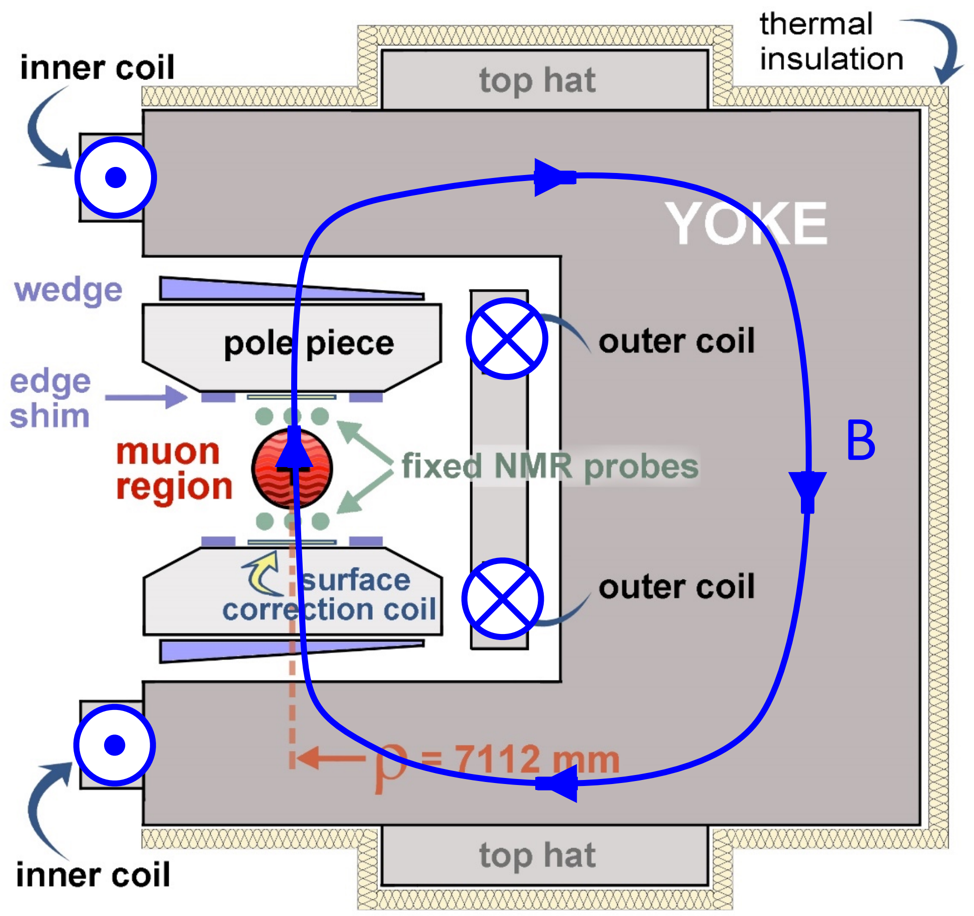
Experiment at Fermilab: Beam

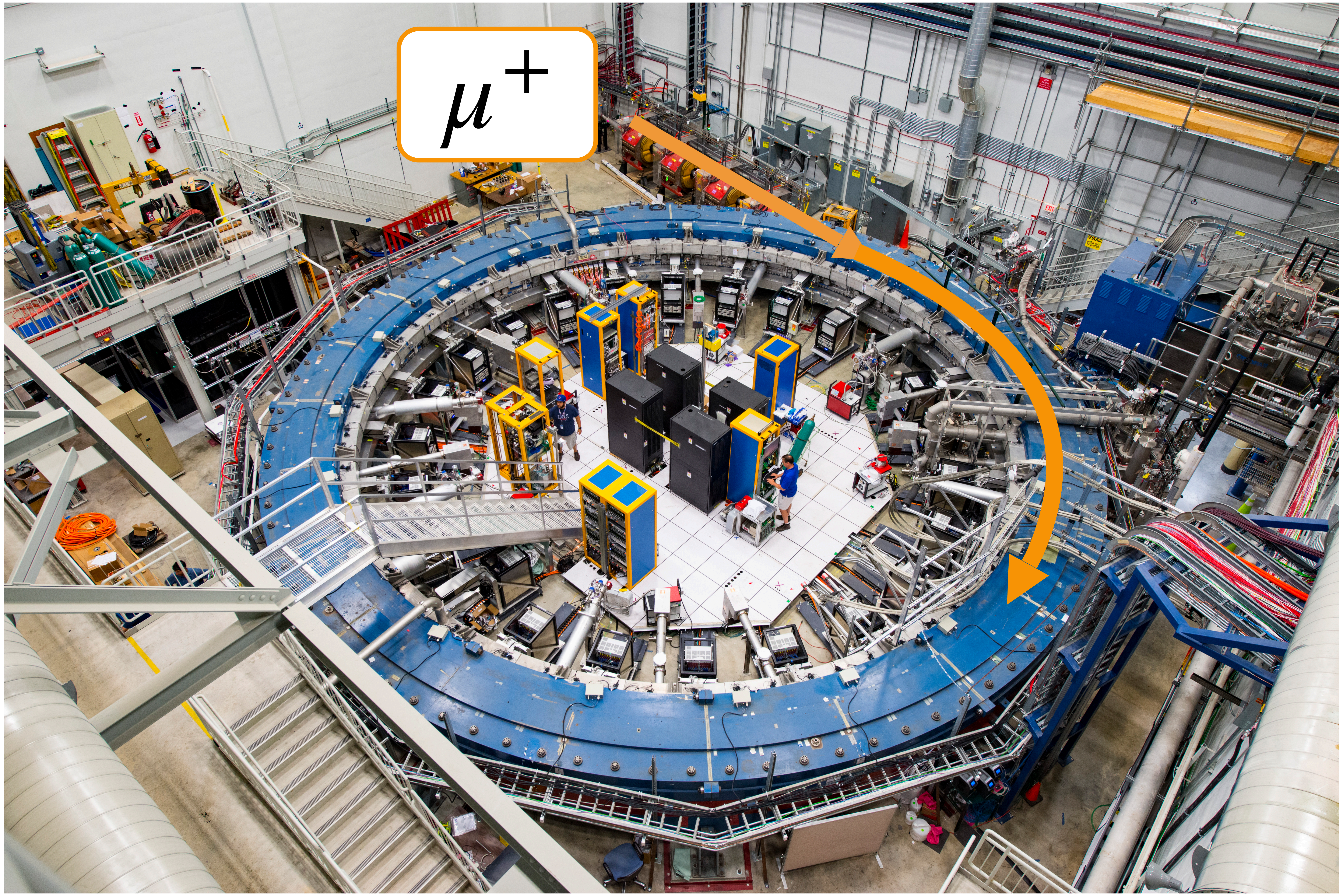
- Polarized muons from pion decay
- Momentum selected to ~3.1 GeV/c
- Stored muons are within $dp/p \sim 0.1\%$
- Average rate of 11.4 “fills” per second
- ~120 ns wide pulses
- ~10,000 stored muons per fill
- Each fill lasts about 1 ms



Experiment at Fermilab: Storage Ring Magnet

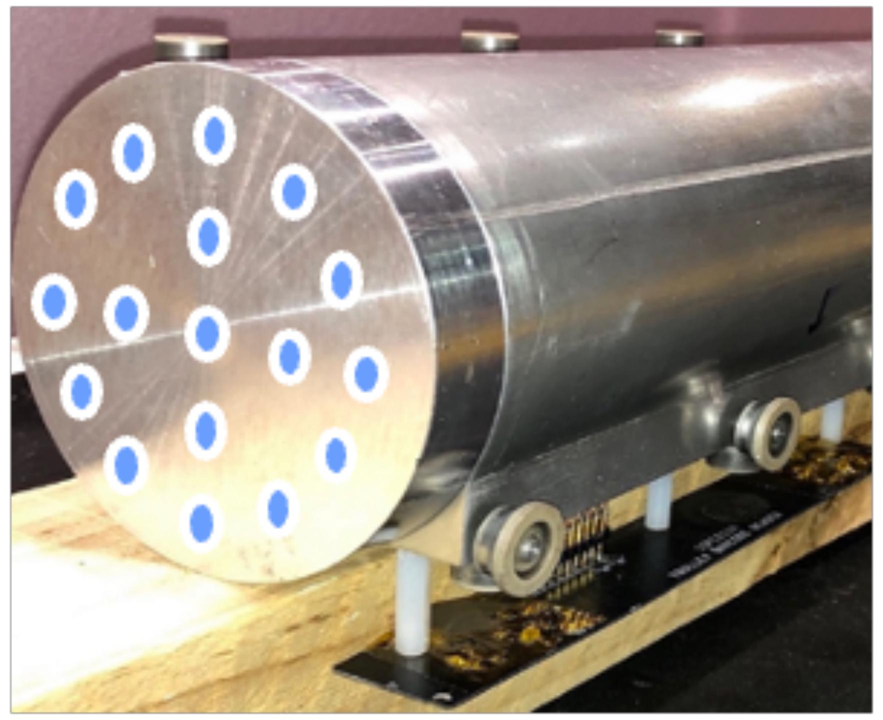
- 7.112 meter radius superconducting storage ring magnet
- 1.45 T uniform field
- Muons precess in the magnetic field



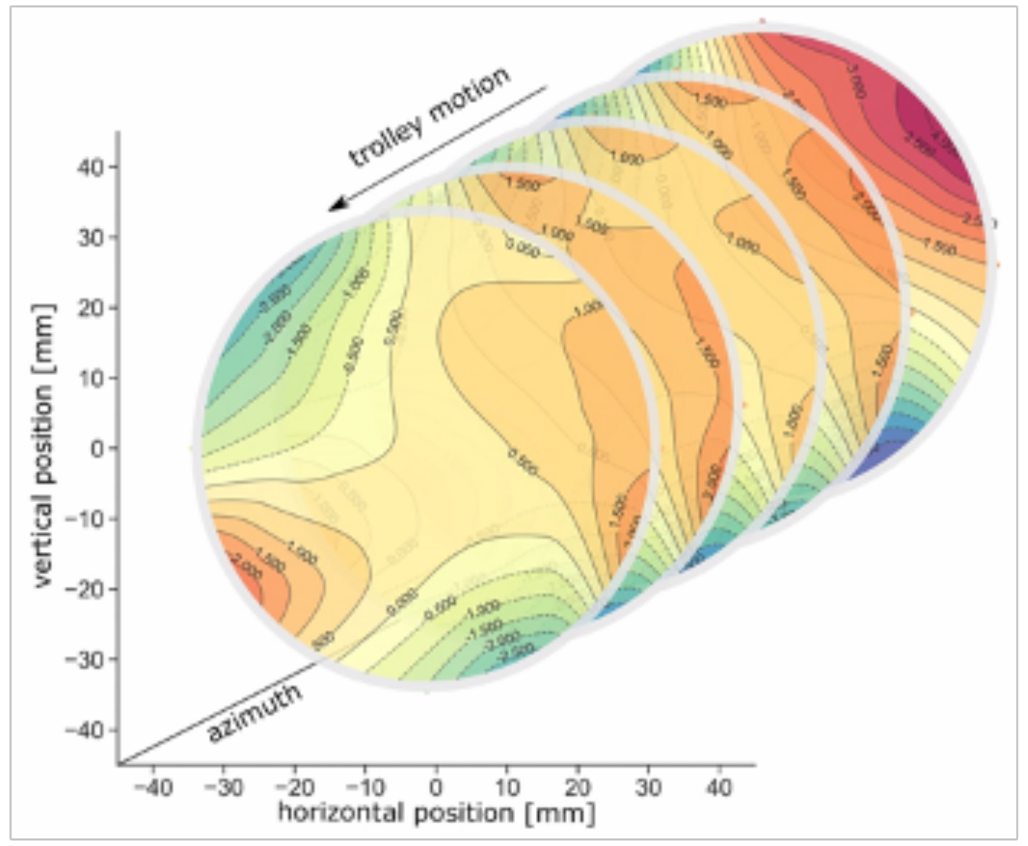


Field Measured with NMR

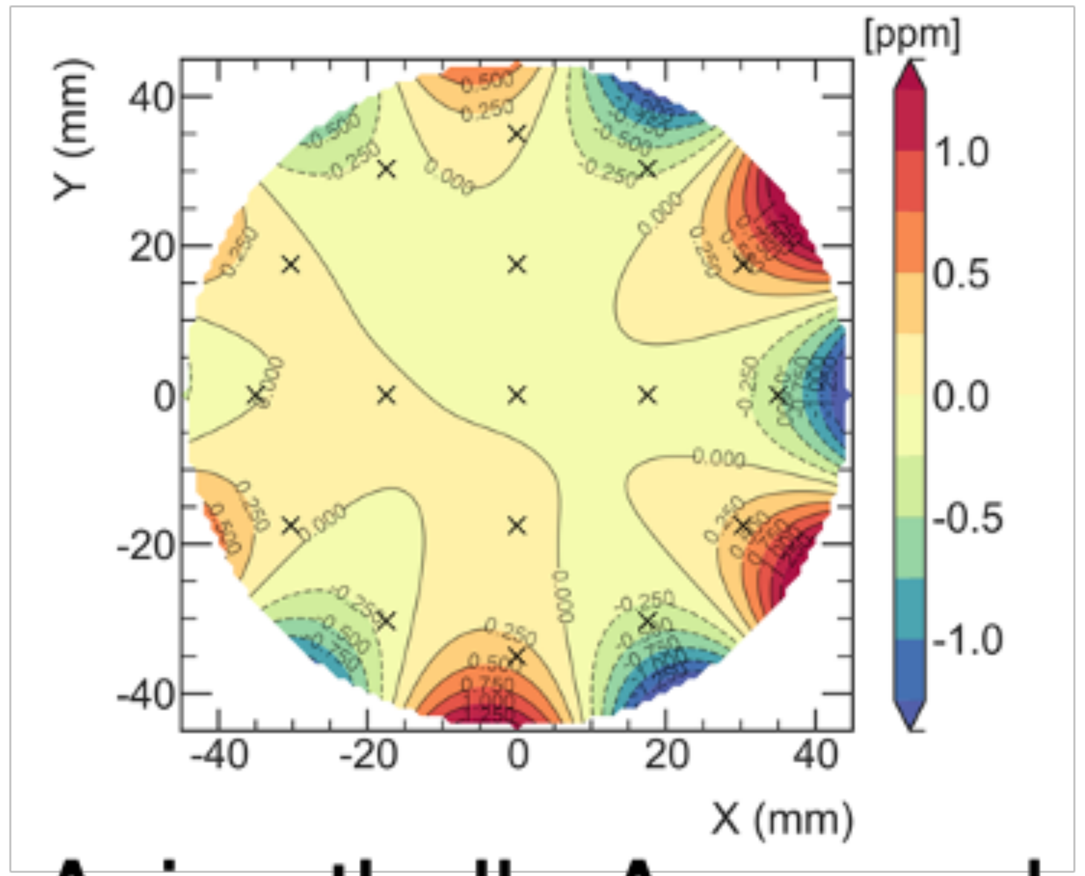
- Use proton nuclear magnetic resonance (NMR) to measure B-field (also a precession frequency!)



17 petroleum jelly NMR probes

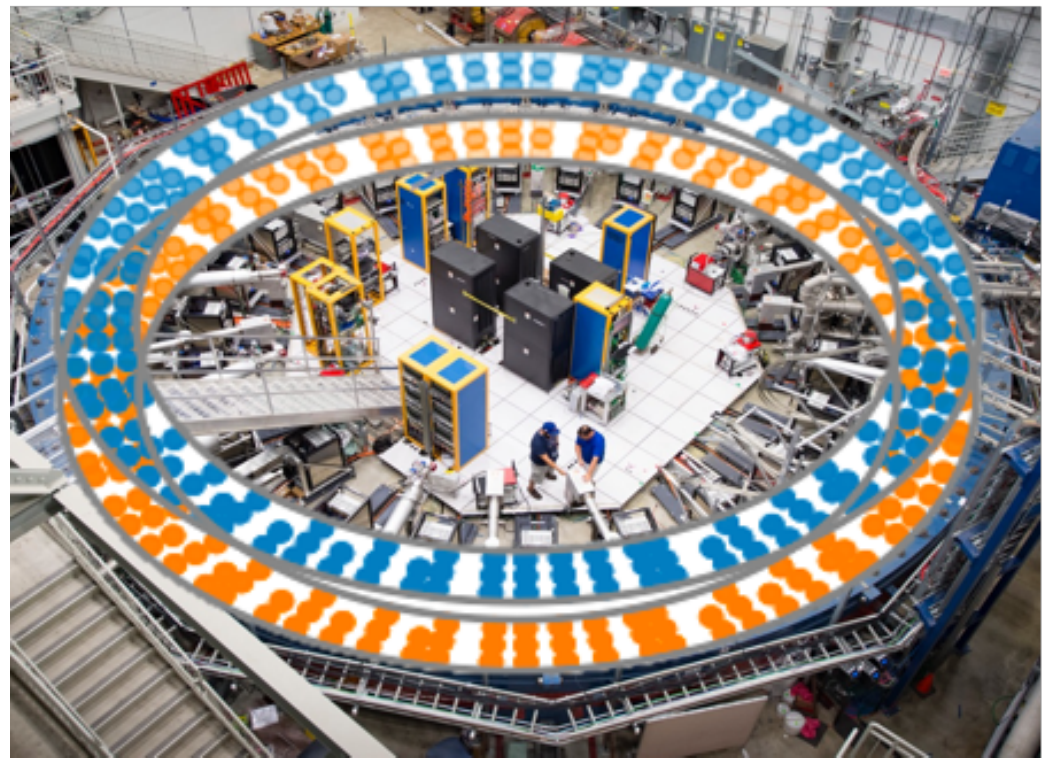


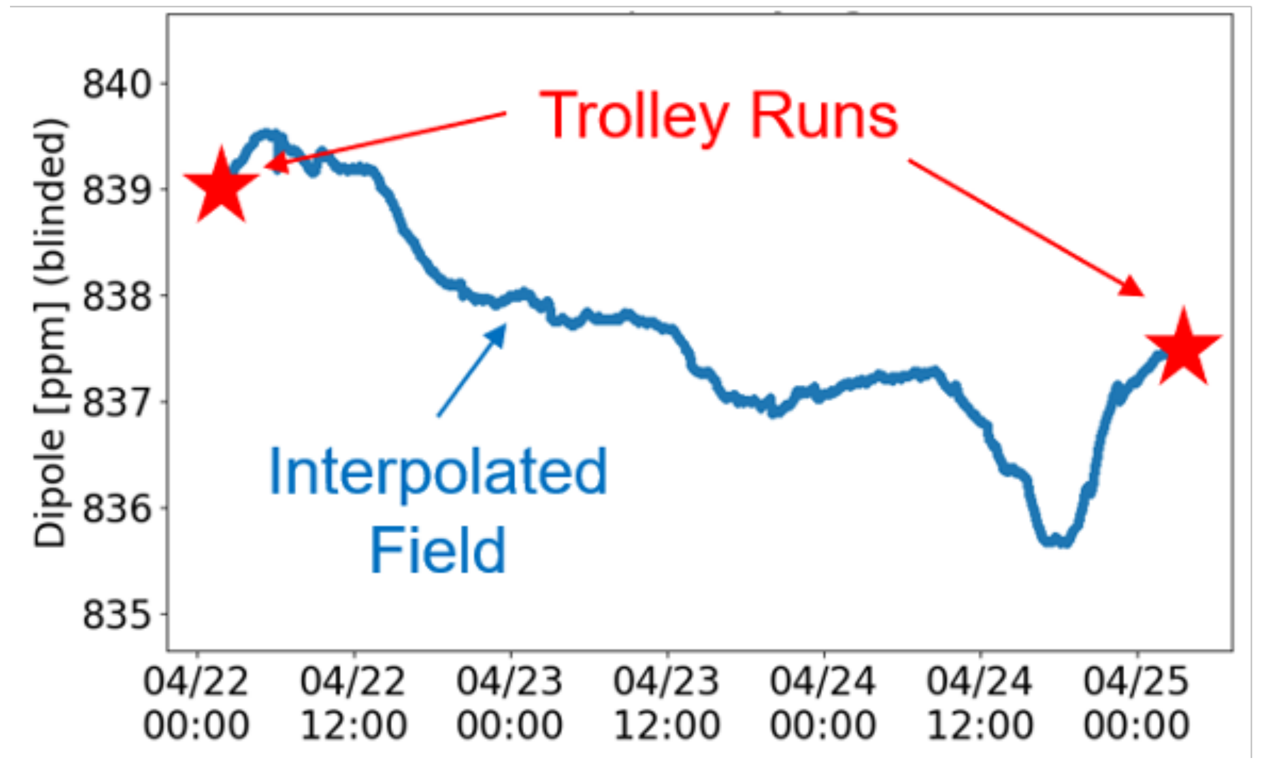
2D field maps (~8000 points)



Azimuthally-Averaged **Variation < 1 ppm**

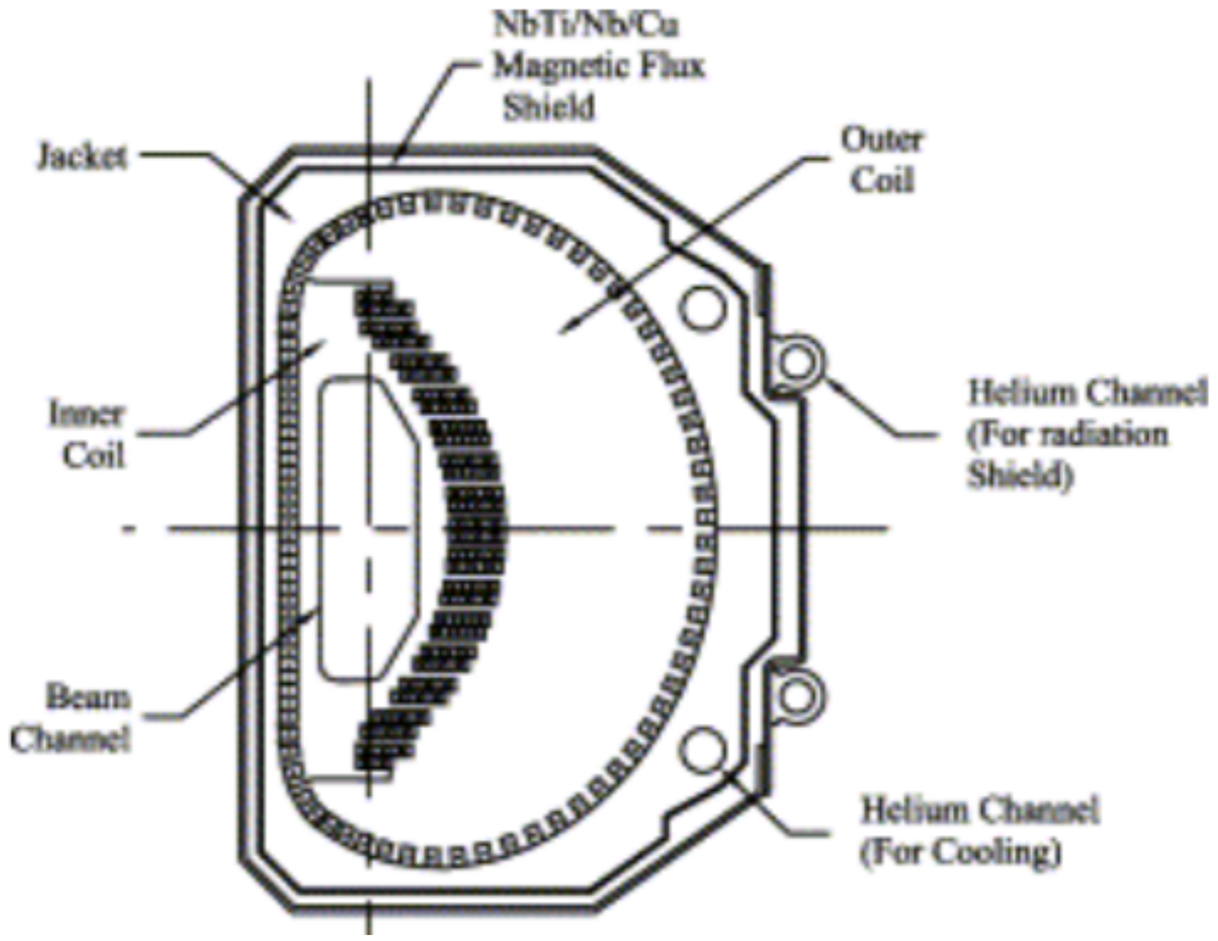
Fixed probes above/below muon storage region

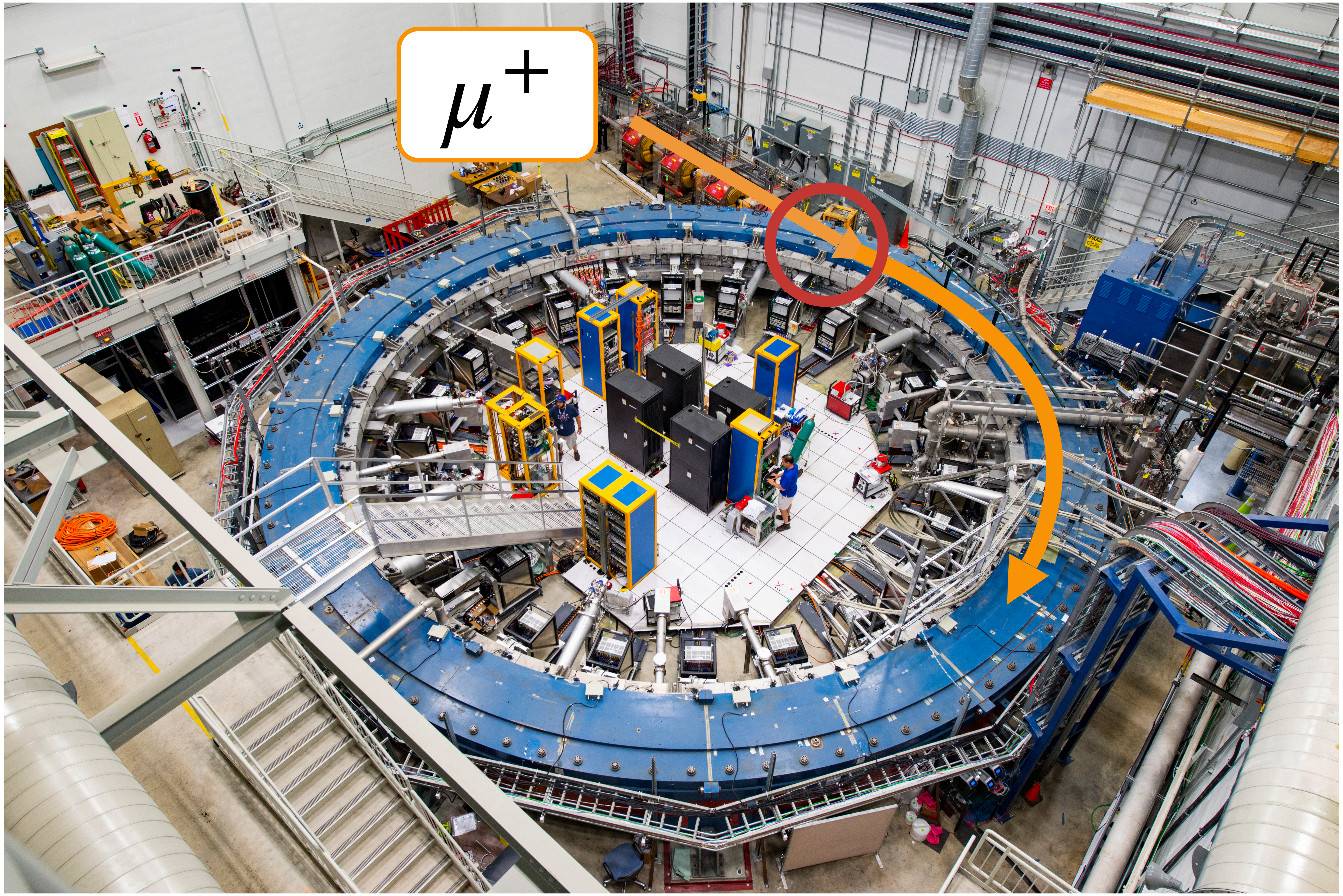




Experiment at Fermilab: Injection

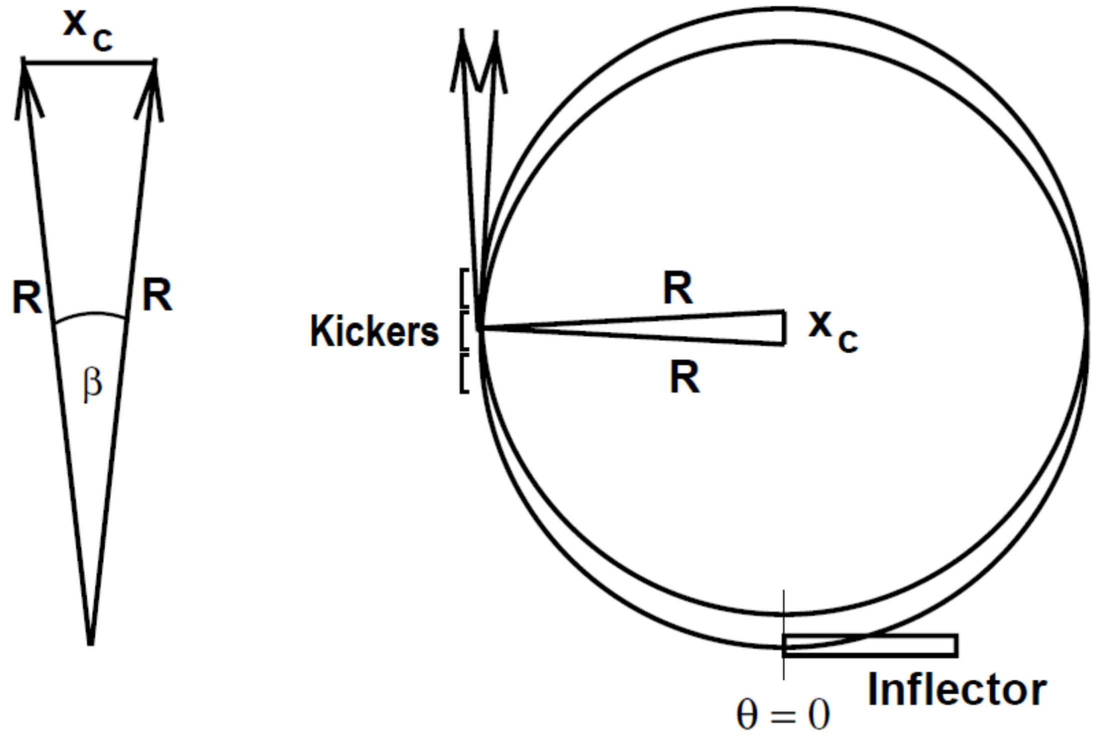
- Muons injected through hole in backleg of the magnet
- Inflector magnet cancels main field to allow muons straight path into the ring

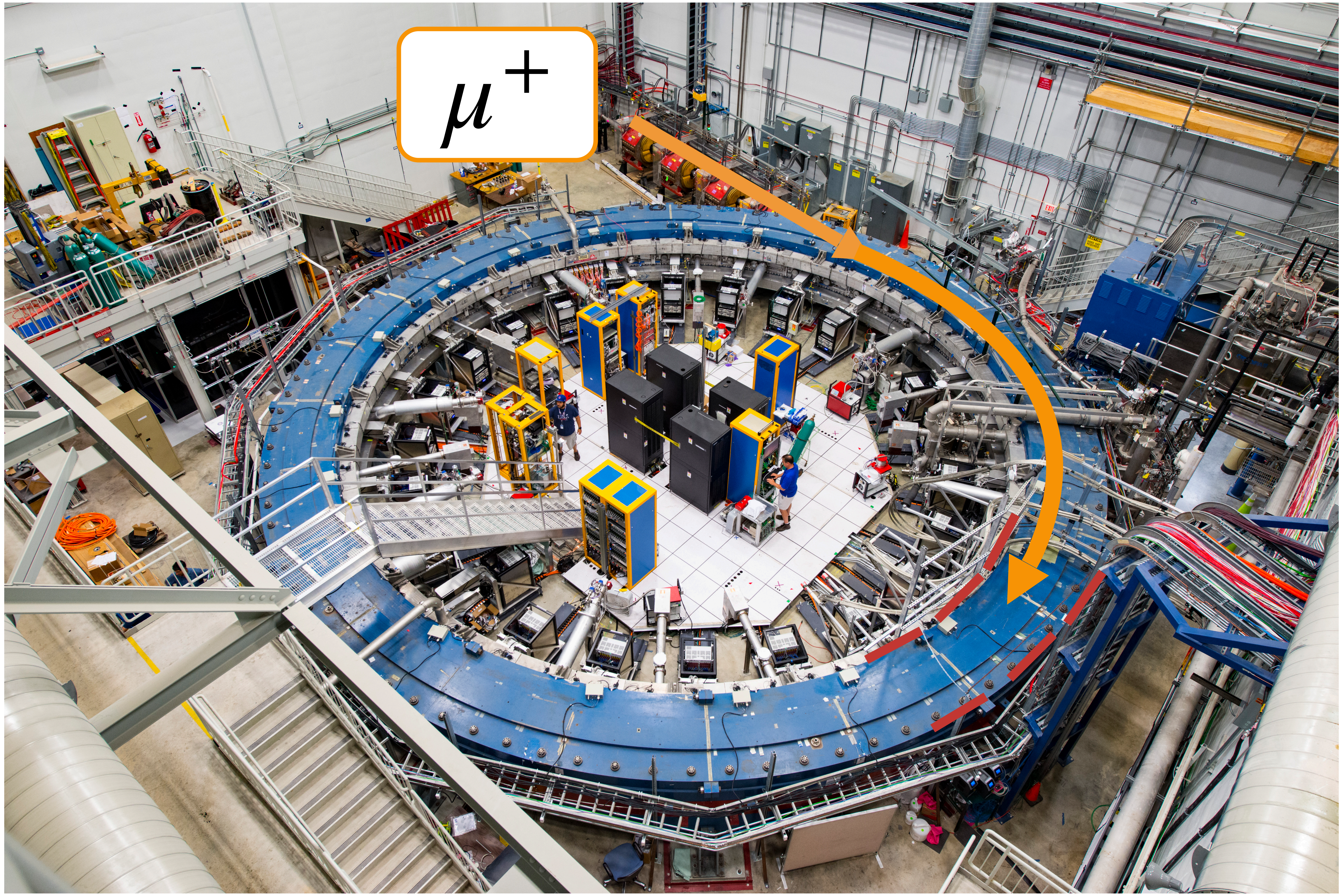




Experiment at Fermilab: Kickers

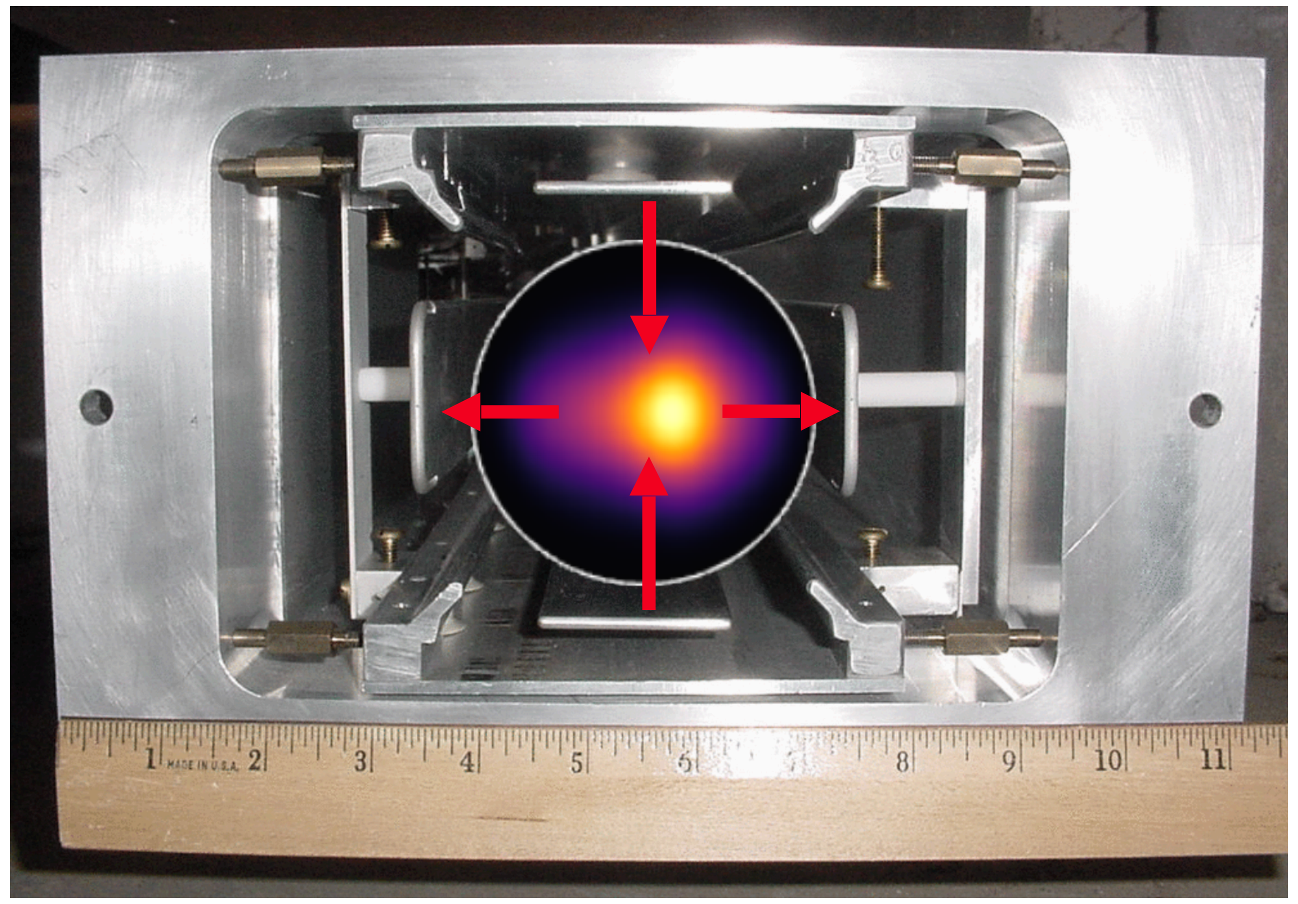
- Muons initial phase space not matched to ring admittance
- Needs ~10 mrad radial “kick” to get onto design orbit
- Kick achieved with **three** fast kicker magnets, 90 degrees from injection

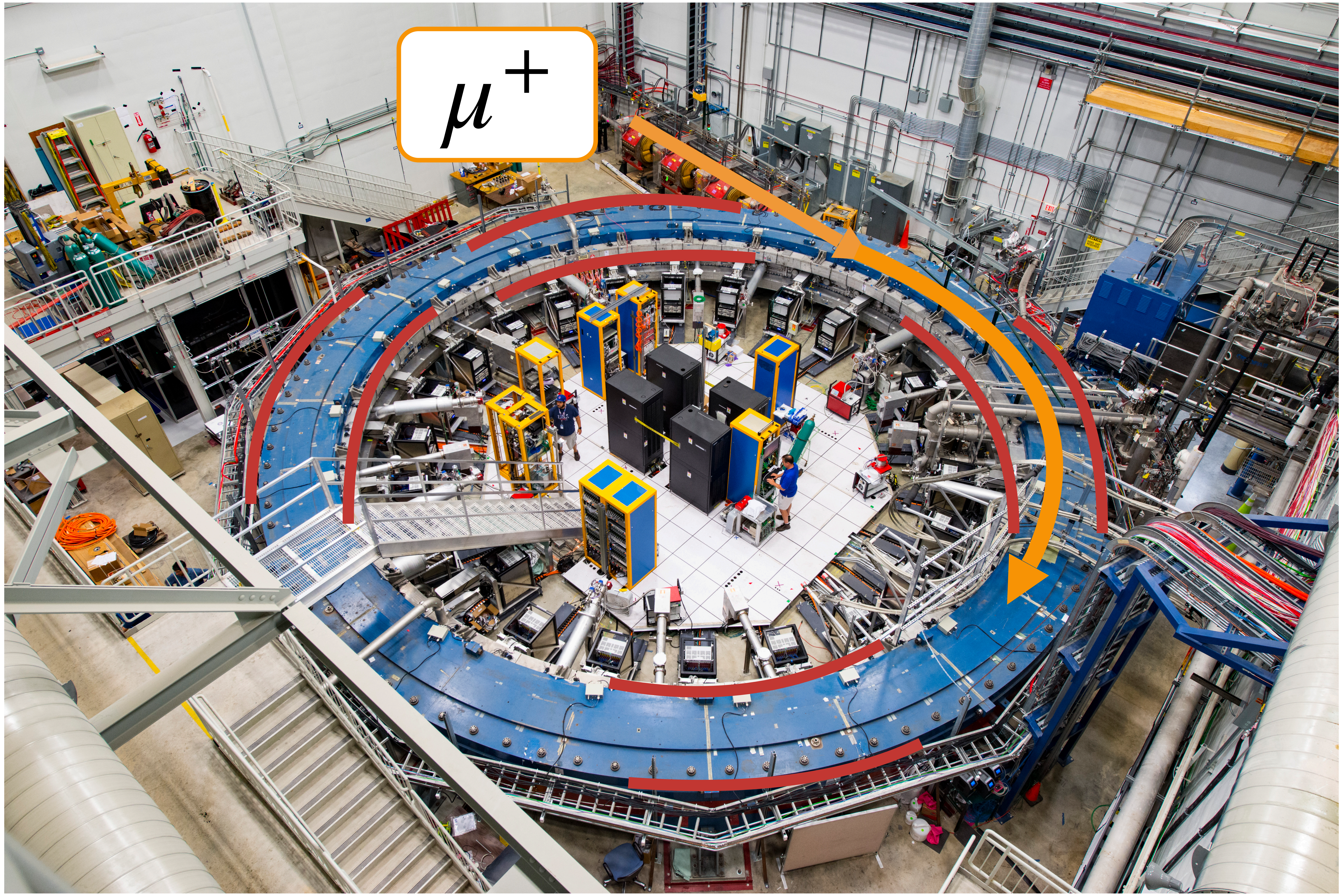




Experiment at Fermilab: Quadrupoles

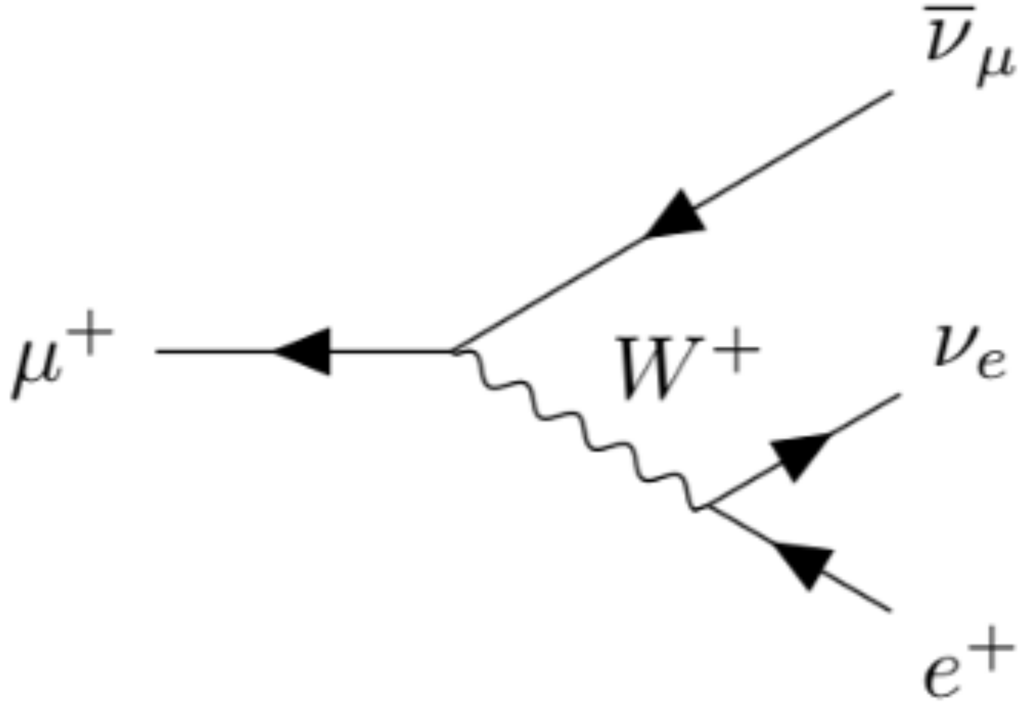
- Vertical focusing achieved with electrostatic quadrupoles
- Spans ~43% of the ring azimuth, symmetrically
- E and B fields lead to betatron motion; muon beam “swims” around the storage region radially and vertically

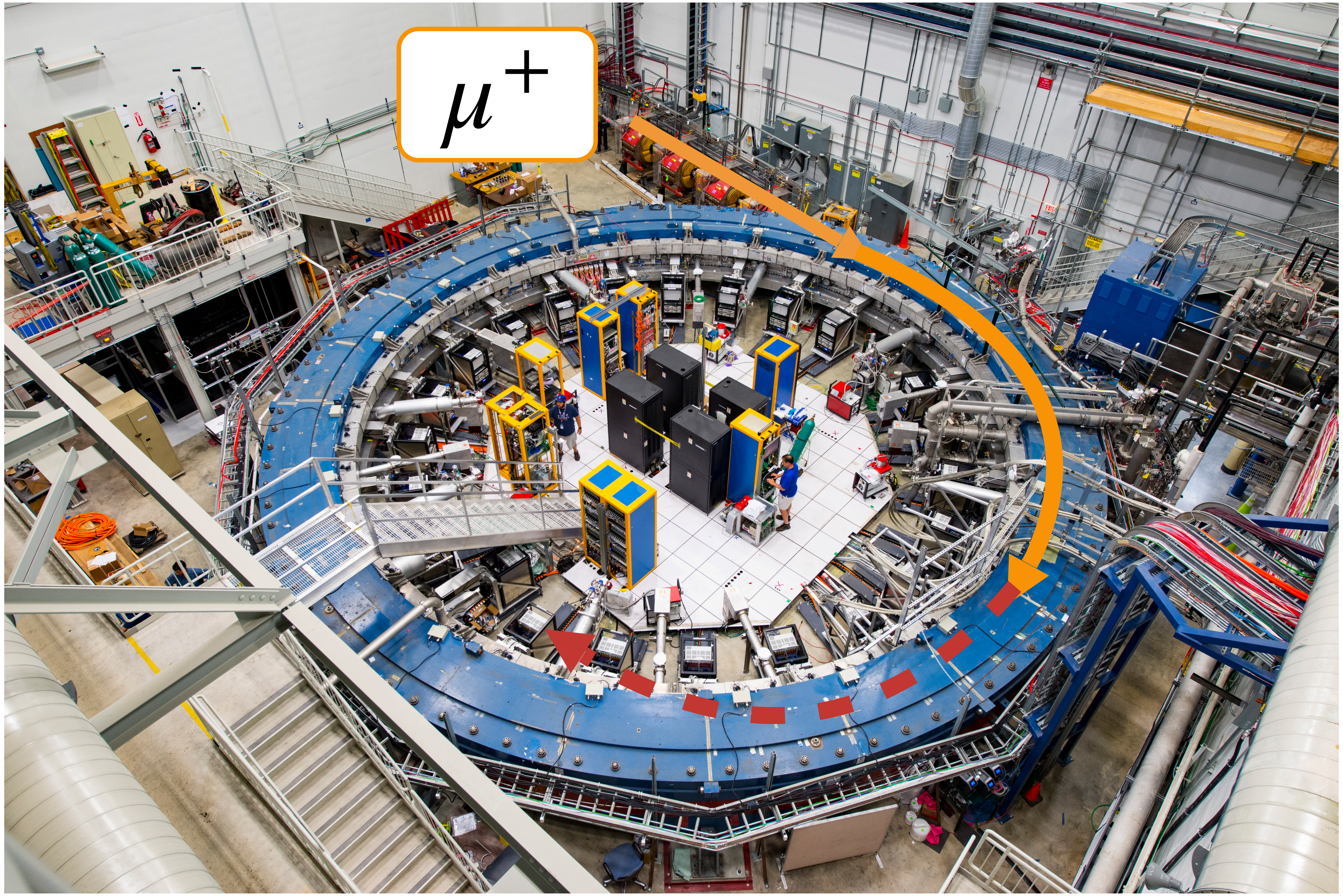




Experiment at Fermilab: Storage & Decay

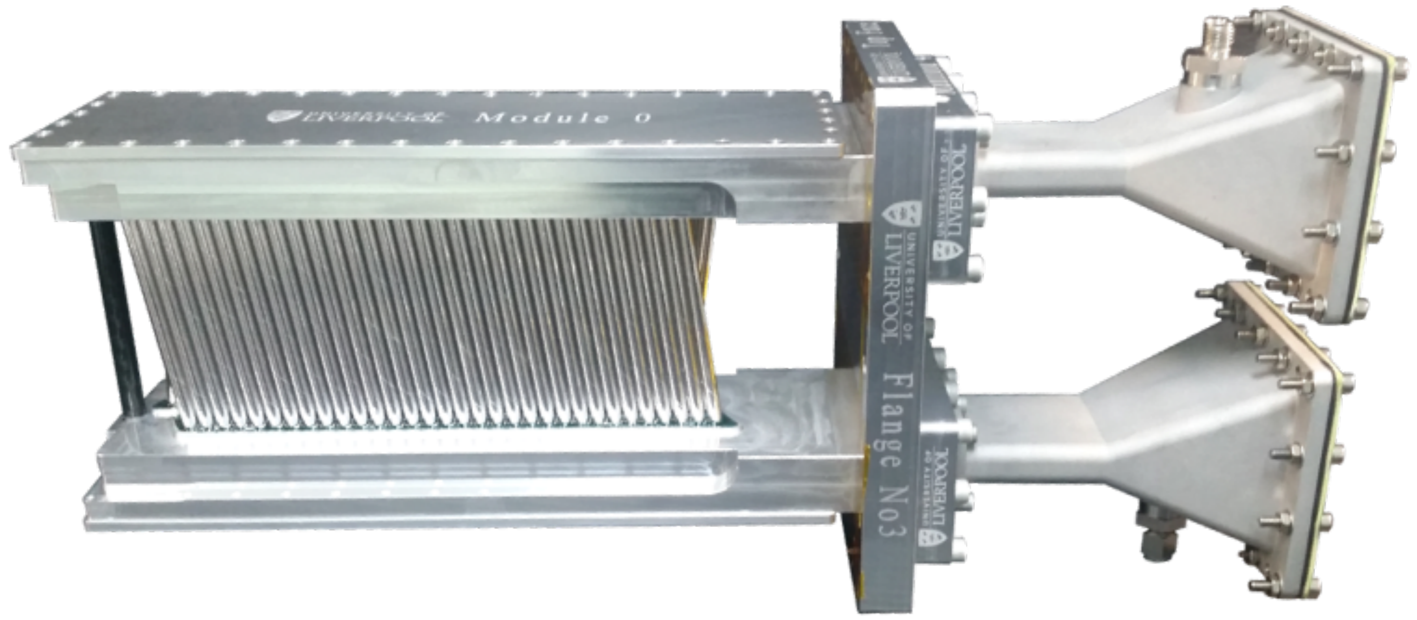
- At this point, muons are stored and importantly the spins are precessing!
- With a momentum of ~3.1 GeV/c, our muons have a boosted lifetime ~64us
- Then, they decay and **decay positron spirals inwards**

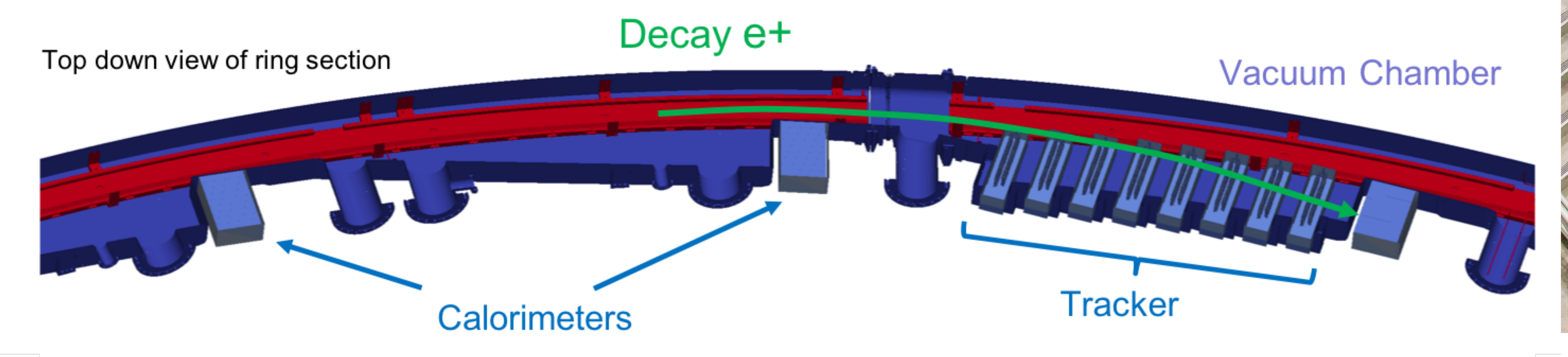


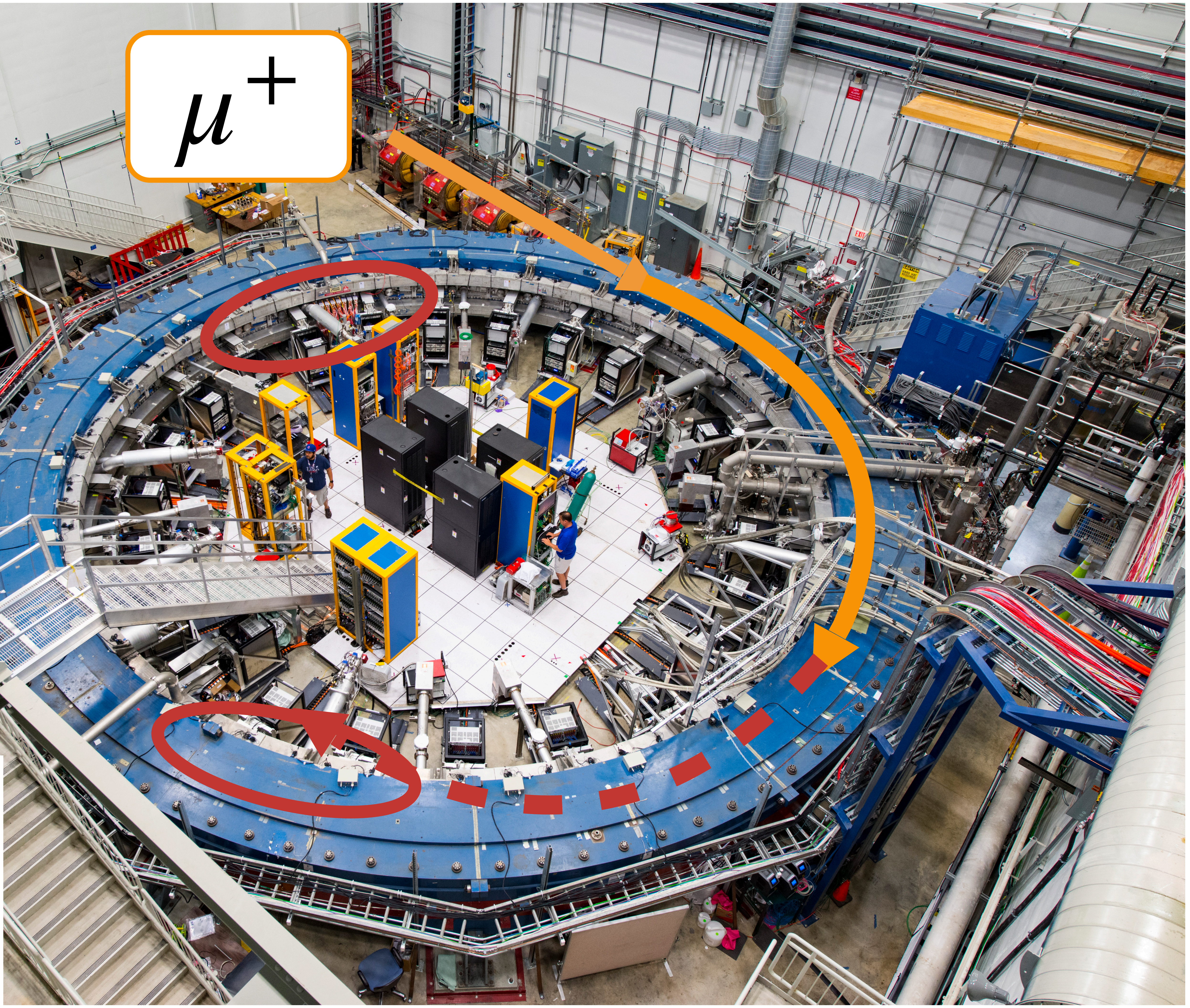


Experiment at Fermilab: Trackers

- Two straw tube tracker stations placed on inside of the ring 180 and 270 degrees from injection
- Each station composed of 8 “modules"

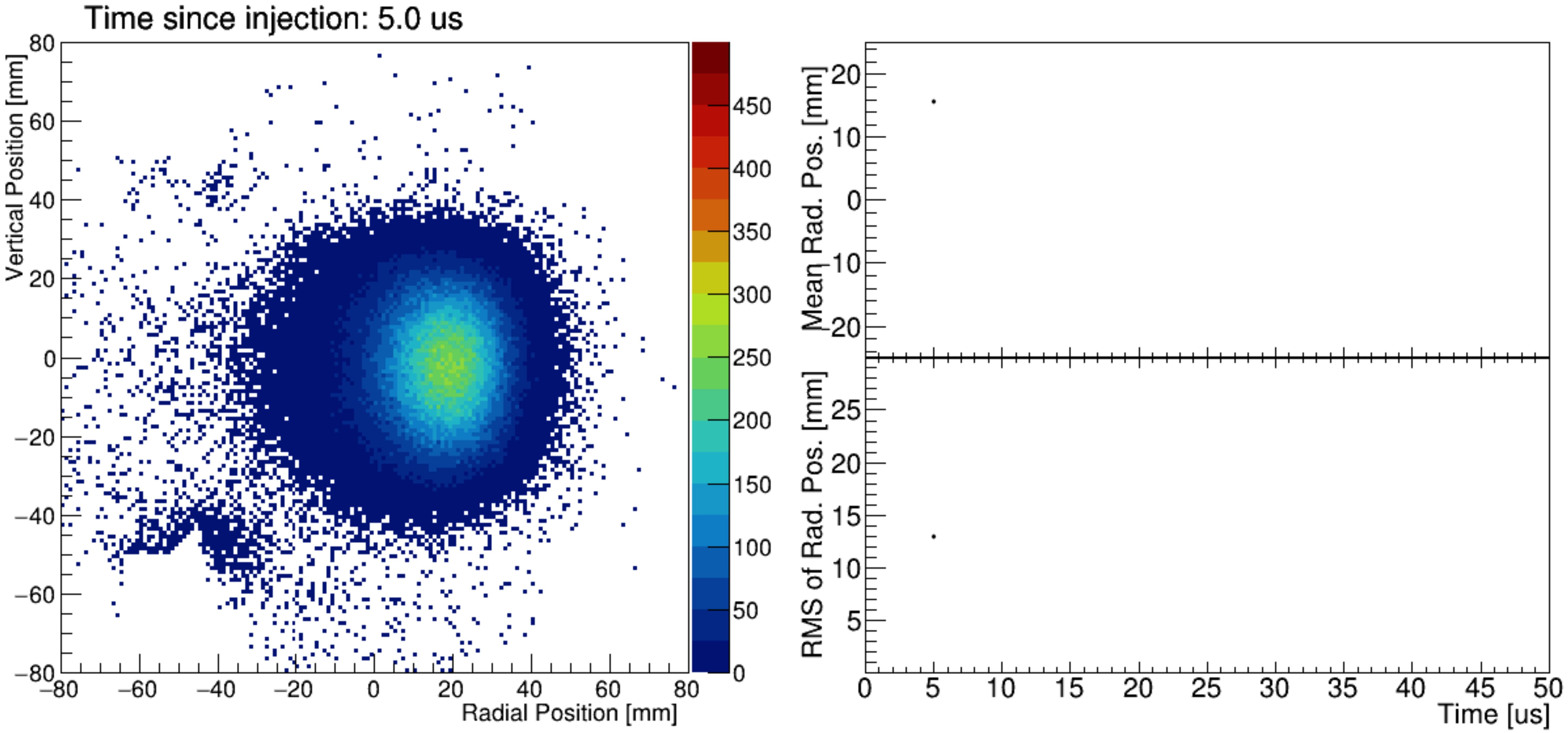


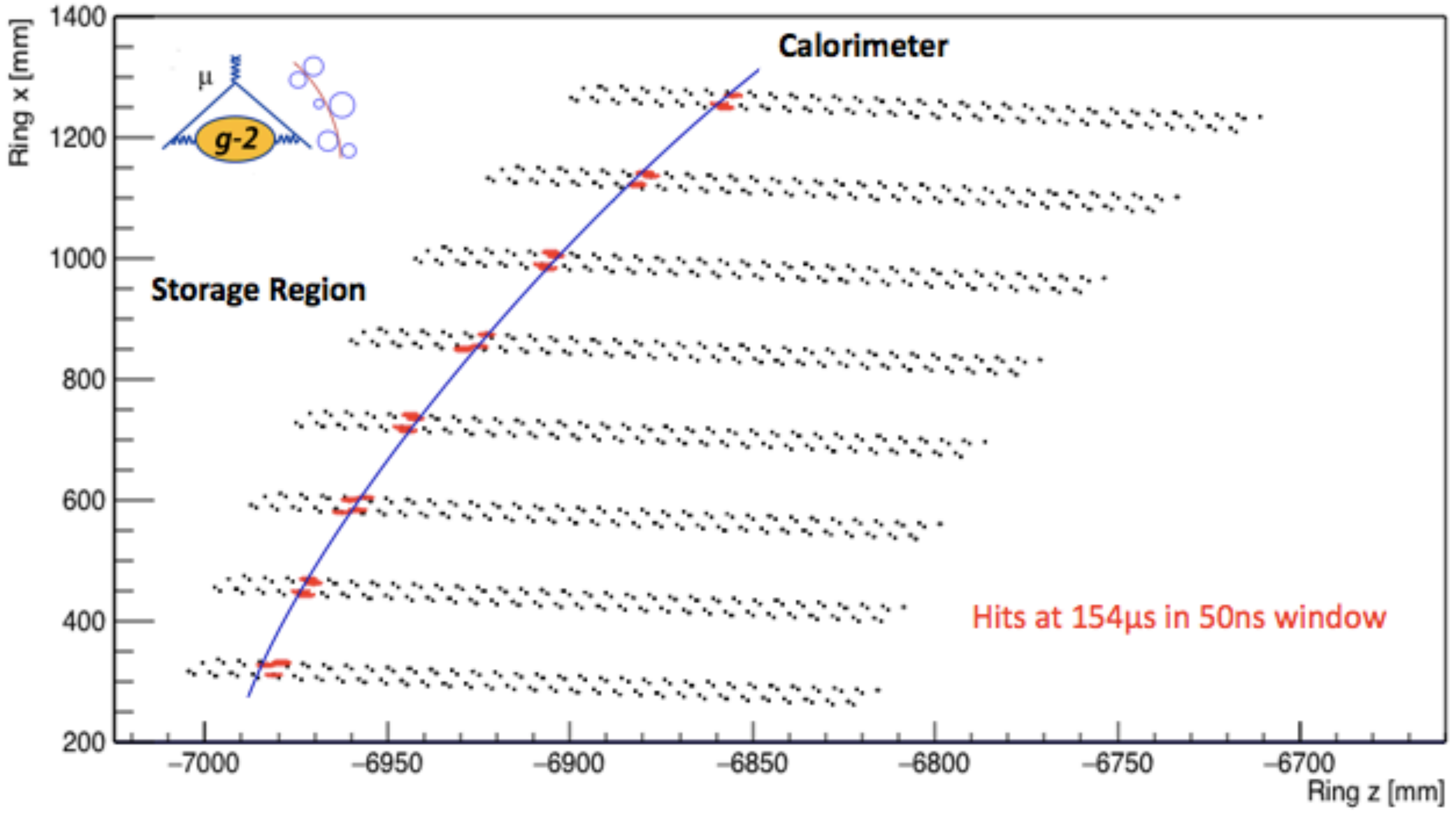




Experiment at Fermilab: Muon Distribution from Trackers

- Form tracks from straw hits
- Extrapolating backwards allows reconstruction of the muon beam over time
- Muons undergo betatron motion

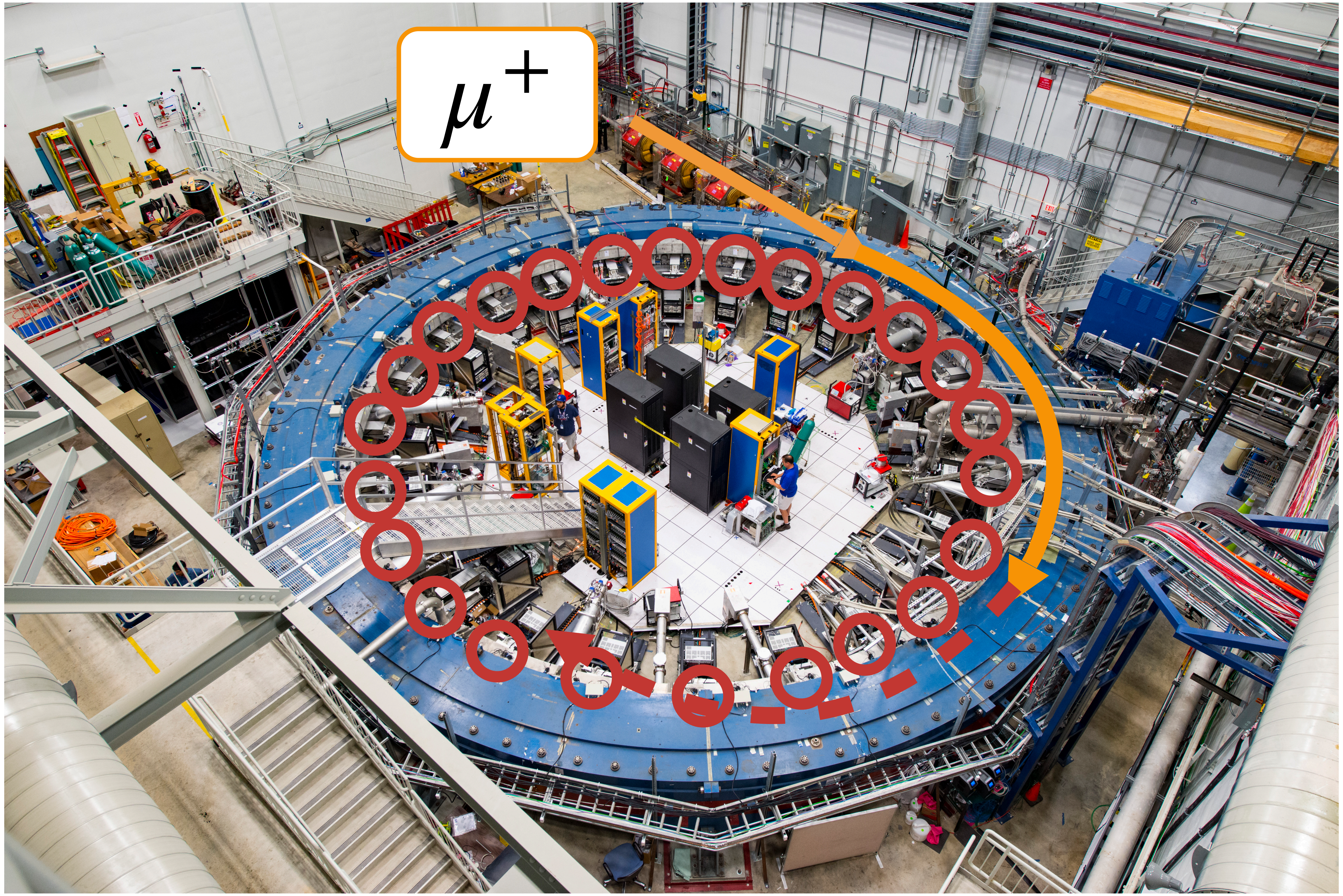




- Need to weight magnetic field with muon distribution to get magnetic field “seen” by the muons

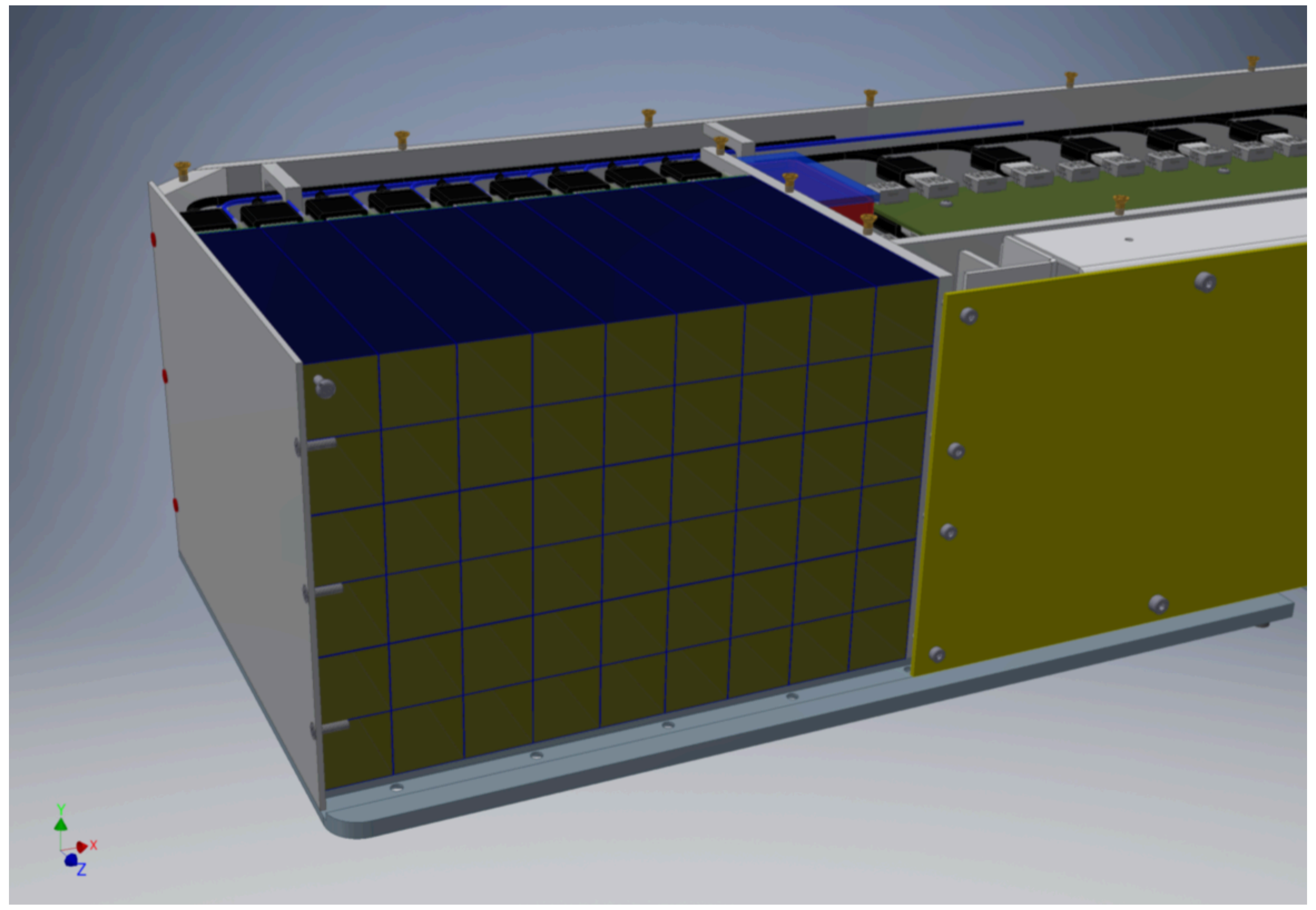
Experiment at Fermilab: Calorimeters

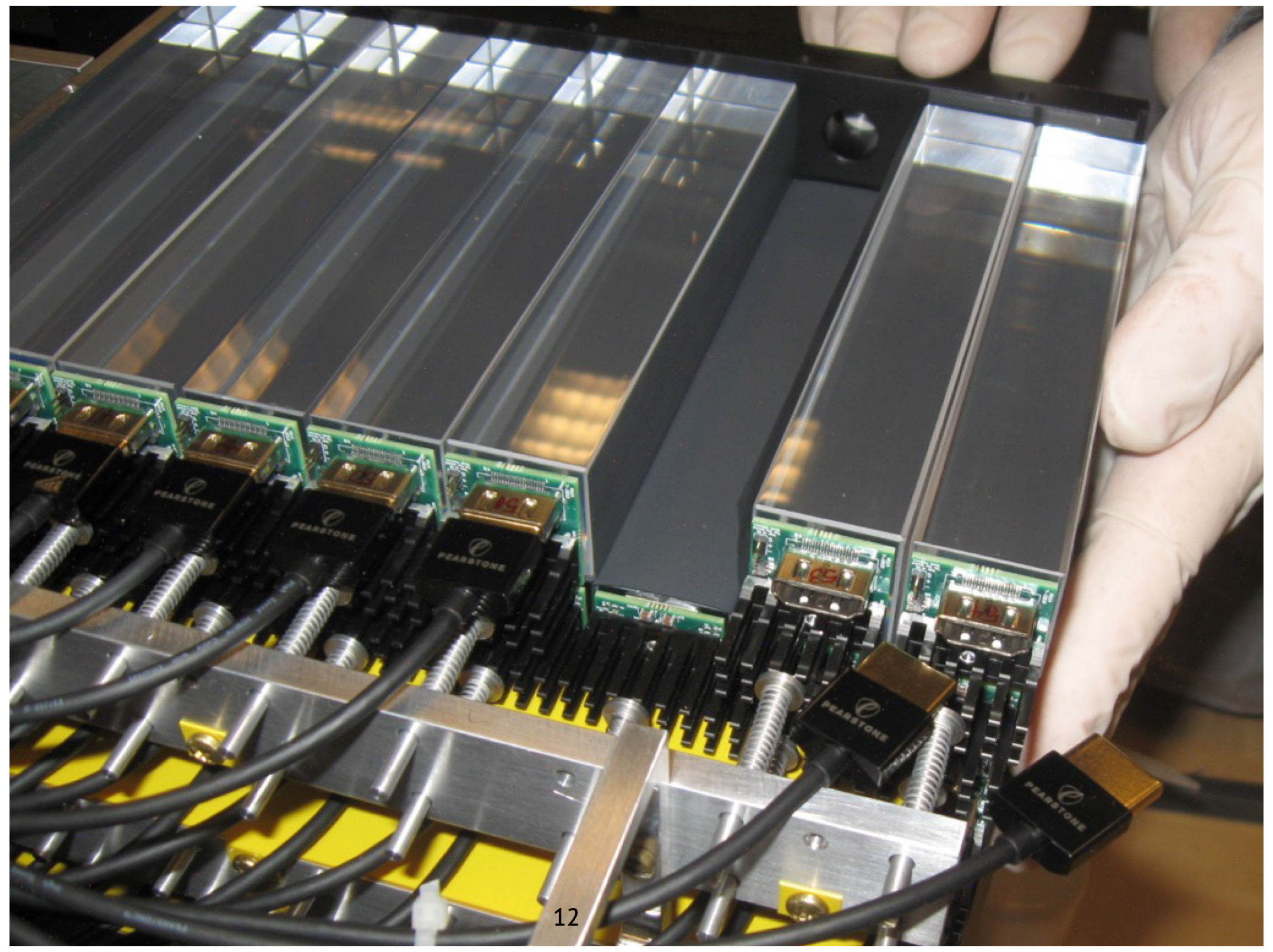
- 24 electromagnetic calorimeters line inside of ring to decay spiraling positrons

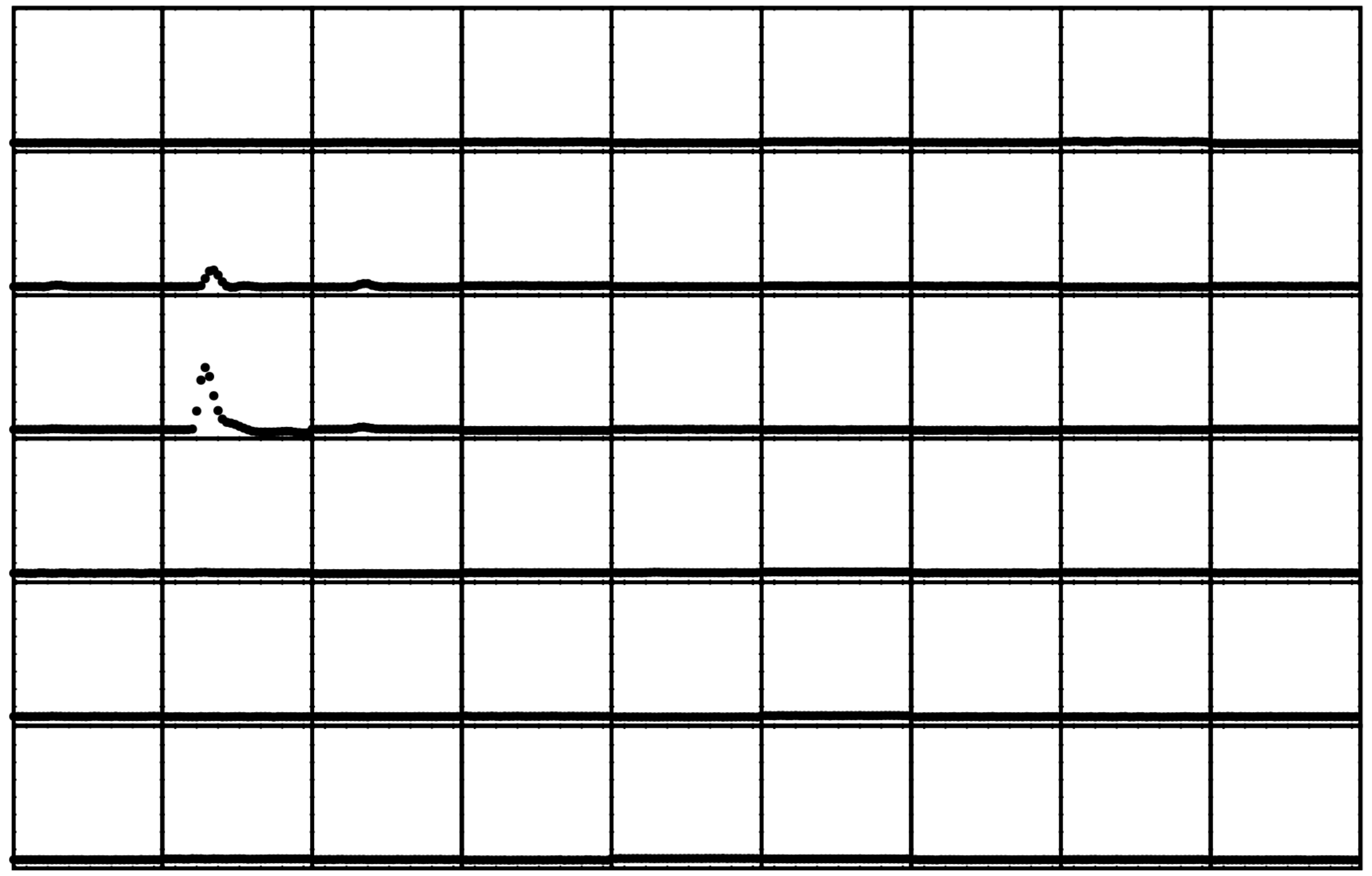


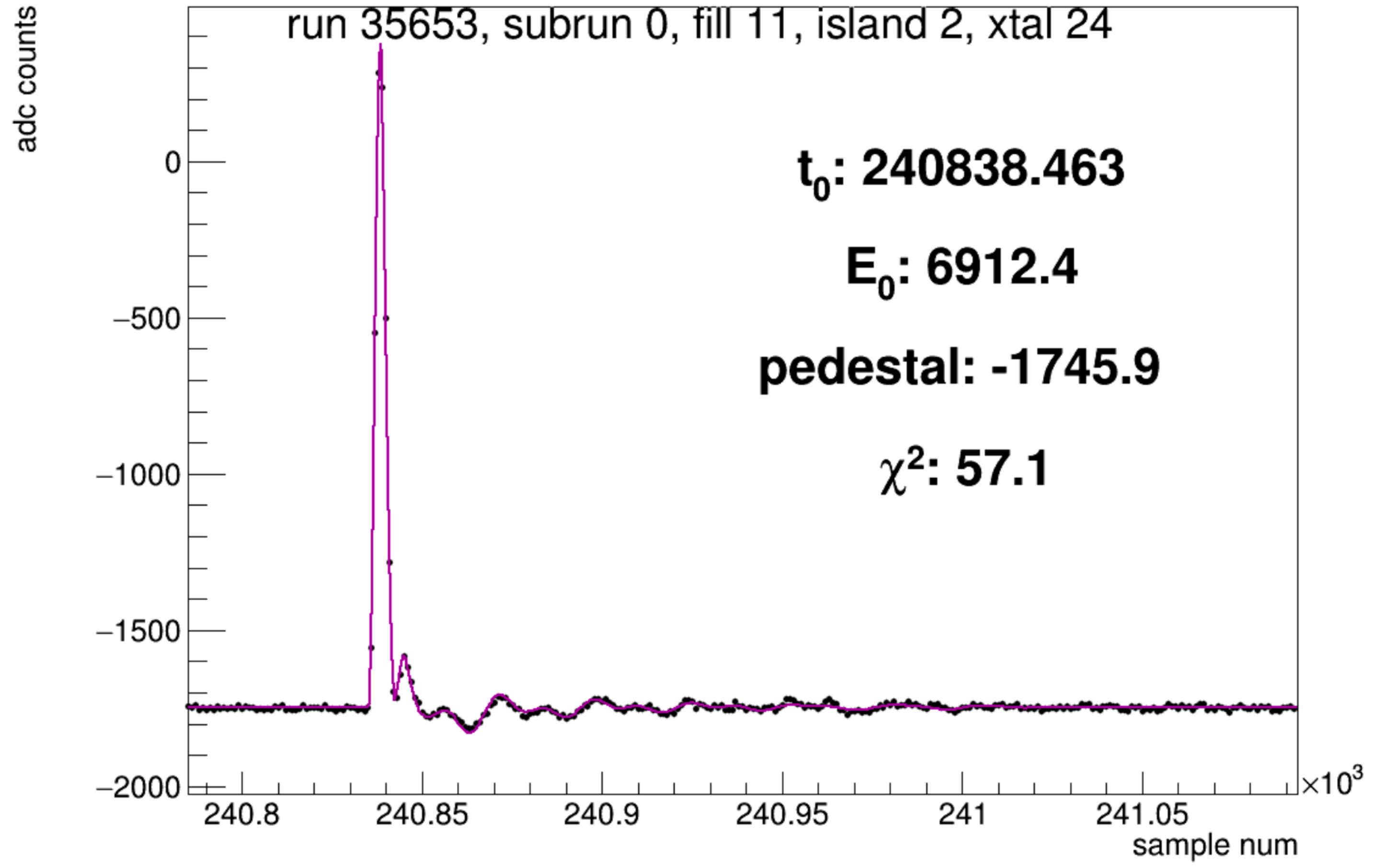
Experiment at Fermilab: Calorimeters

- 24 electromagnetic calorimeters line inside of ring
- Each "calo" is a 6x9 grid of PbF_2 Cherenkov crystals
- Light collected by SiPMs
- Laser calibration system ensures gain stability
- Energy & time of each positron arrival is reconstructed





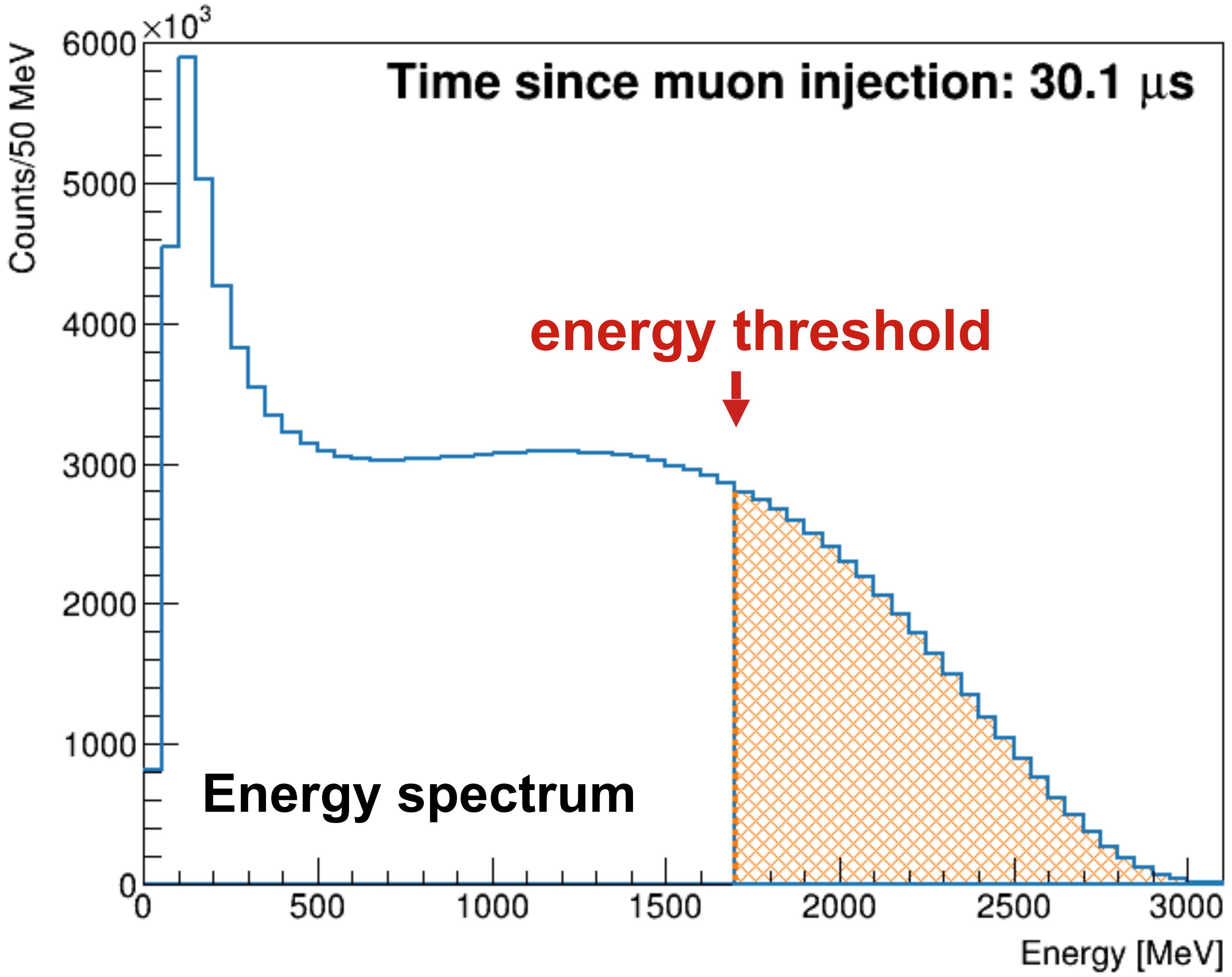


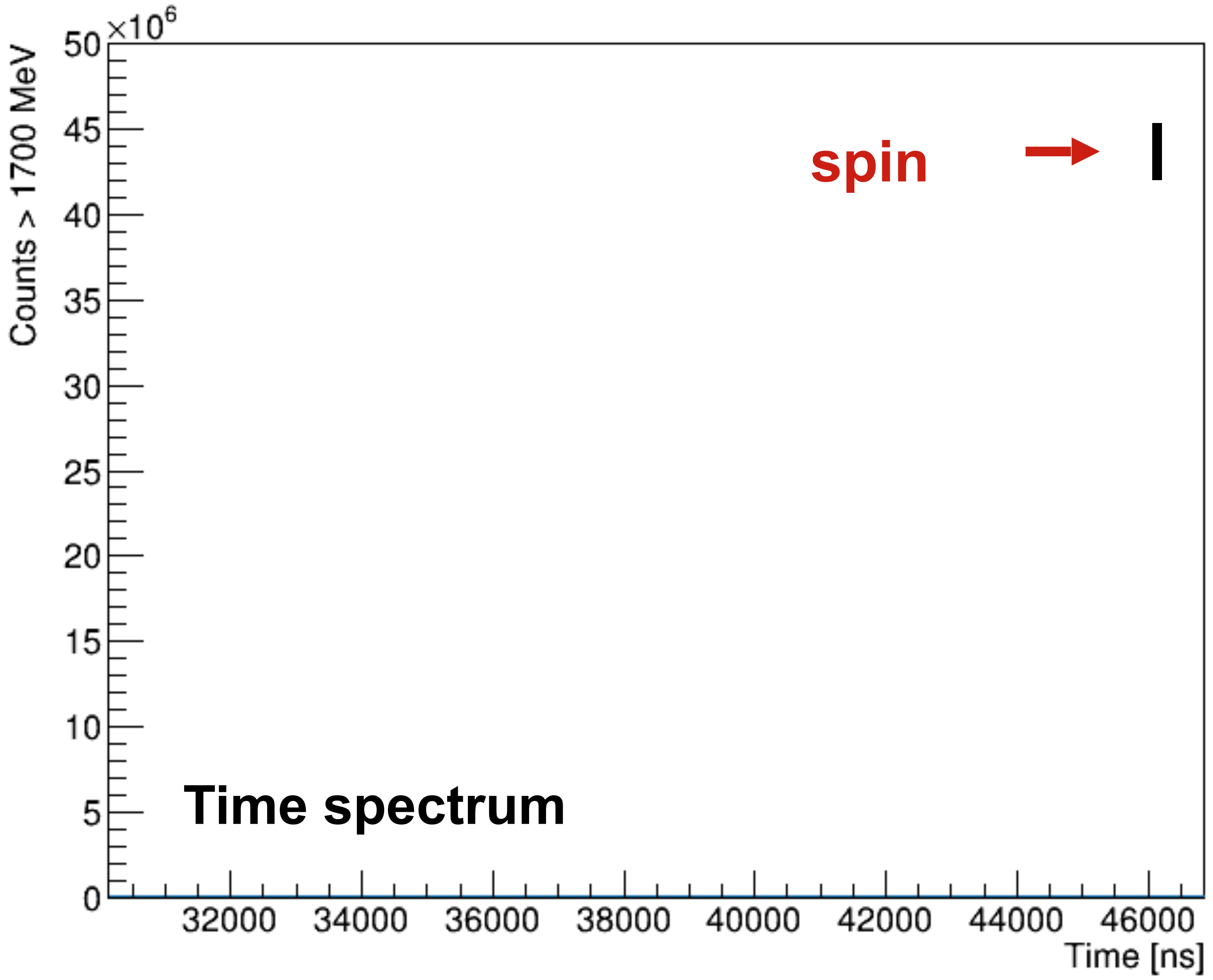


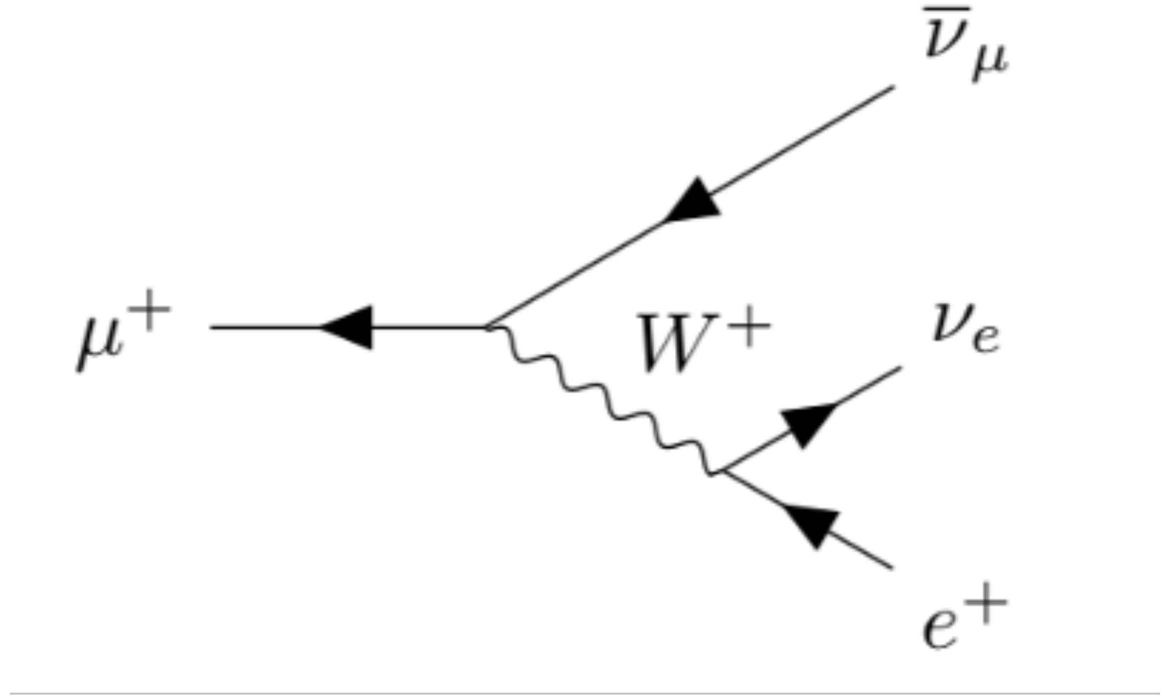
Use muon decay to access ω_a

- Parity violation of muon decay leads to a correlation between momentum direction of **highest energy decay positron** and the **muon spin**

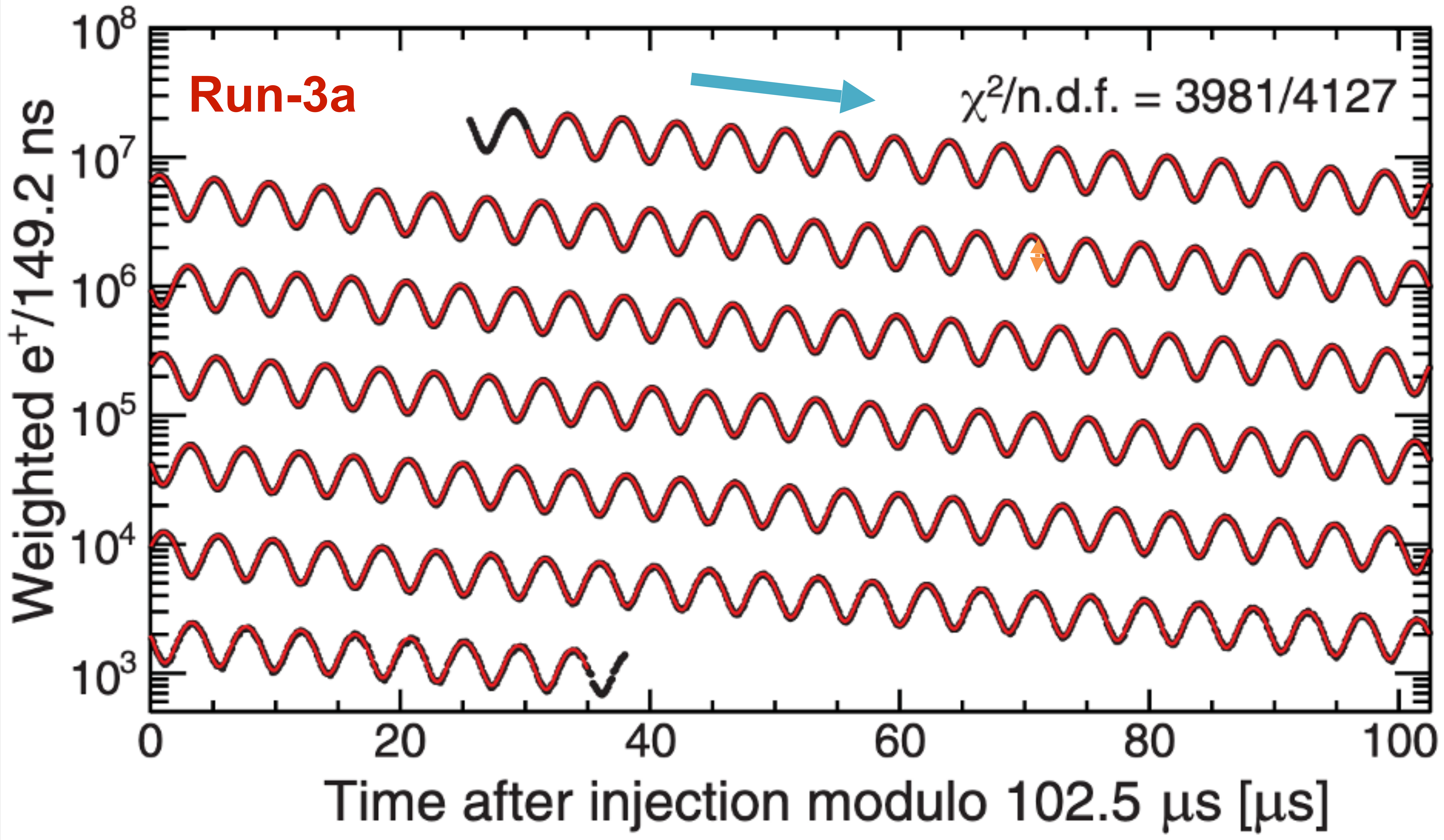
- In lab frame, decay positron energy spectra is modulated by ω_a







"Wiggle" plot from Run-3a



exponential decay:
boosted lifetime $\approx 64.4\mu s$

***wiggle* is** $\omega_a \propto g - 2$ **(signal!)**

relative size of wiggle:
asymmetry ≈ 0.35

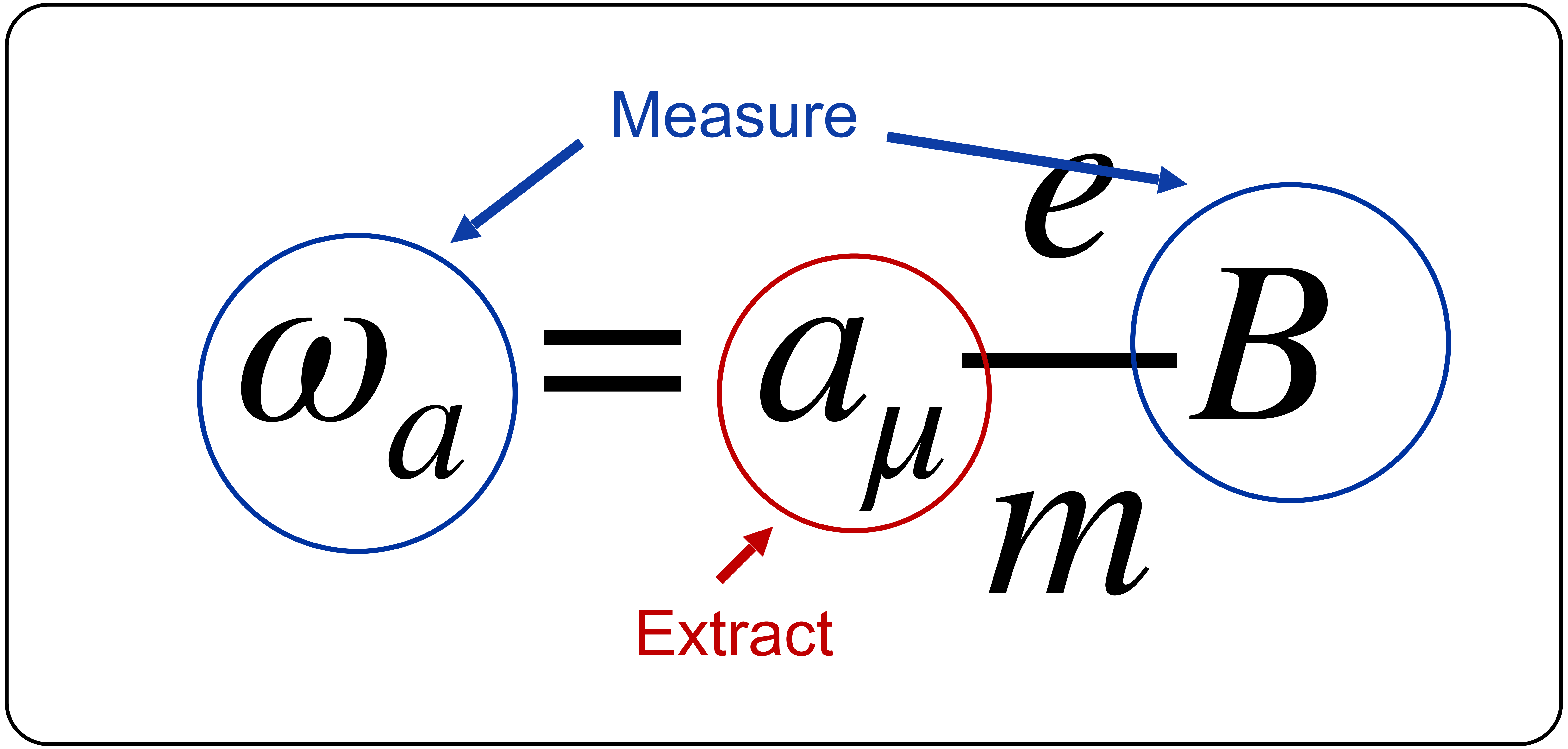
Fit to extract frequency
(simplified function):

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

$$\delta\omega_a(\text{stat}) = \frac{\sigma_{\omega_a}}{\omega_a} = \frac{\sqrt{2}}{\sqrt{NA\gamma\tau\omega_a}}$$

Bringing it all together

ω_a from fitting the "wiggle" plot

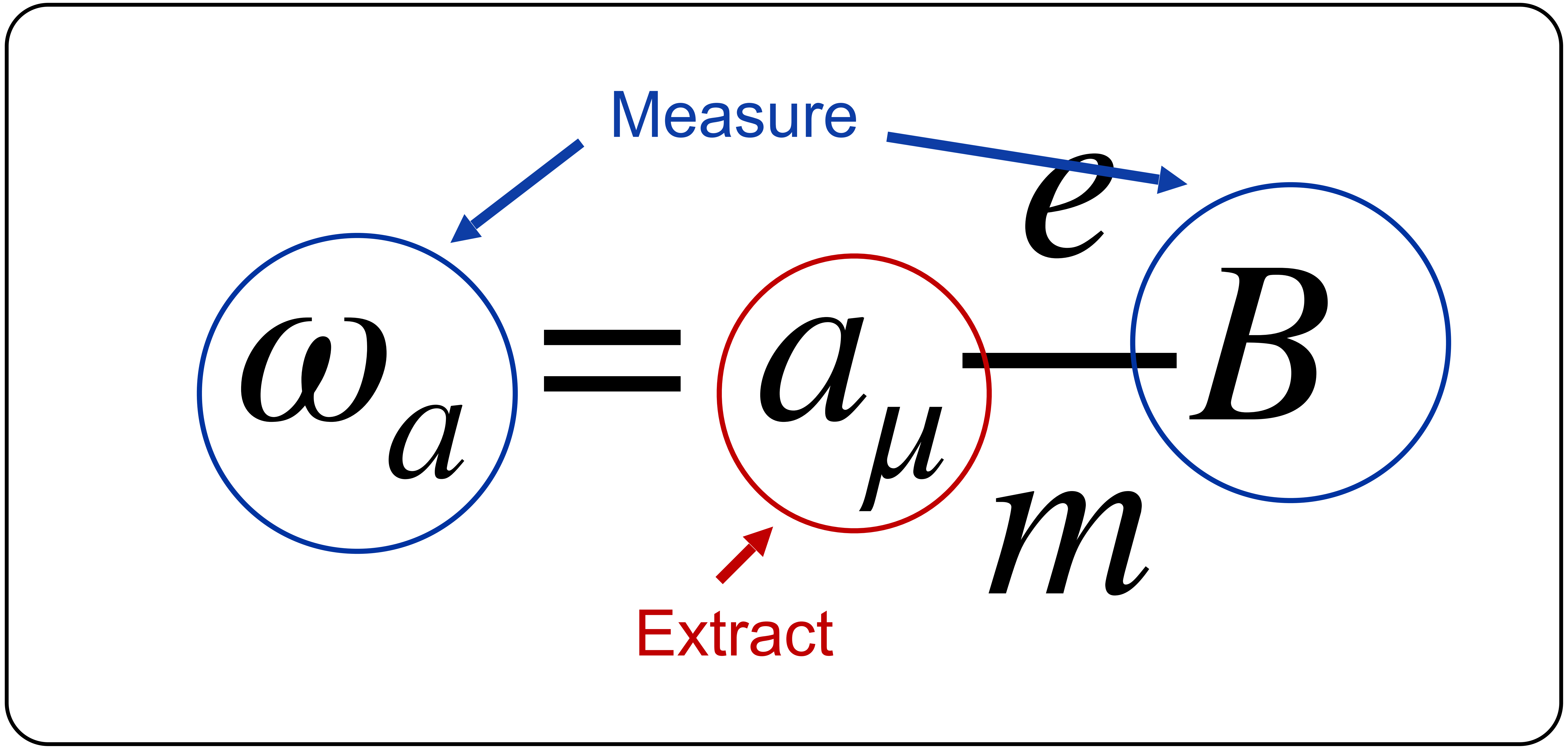


$$\omega_a = a_\mu \frac{e}{m} B$$

B-field from **proton NMR** and weighted by **muon distribution from trackers**

Bringing it all together

ω_a from fitting the "wiggle" plot



Measure

$$\omega_a = a_\mu \frac{e}{m} B$$

Extract

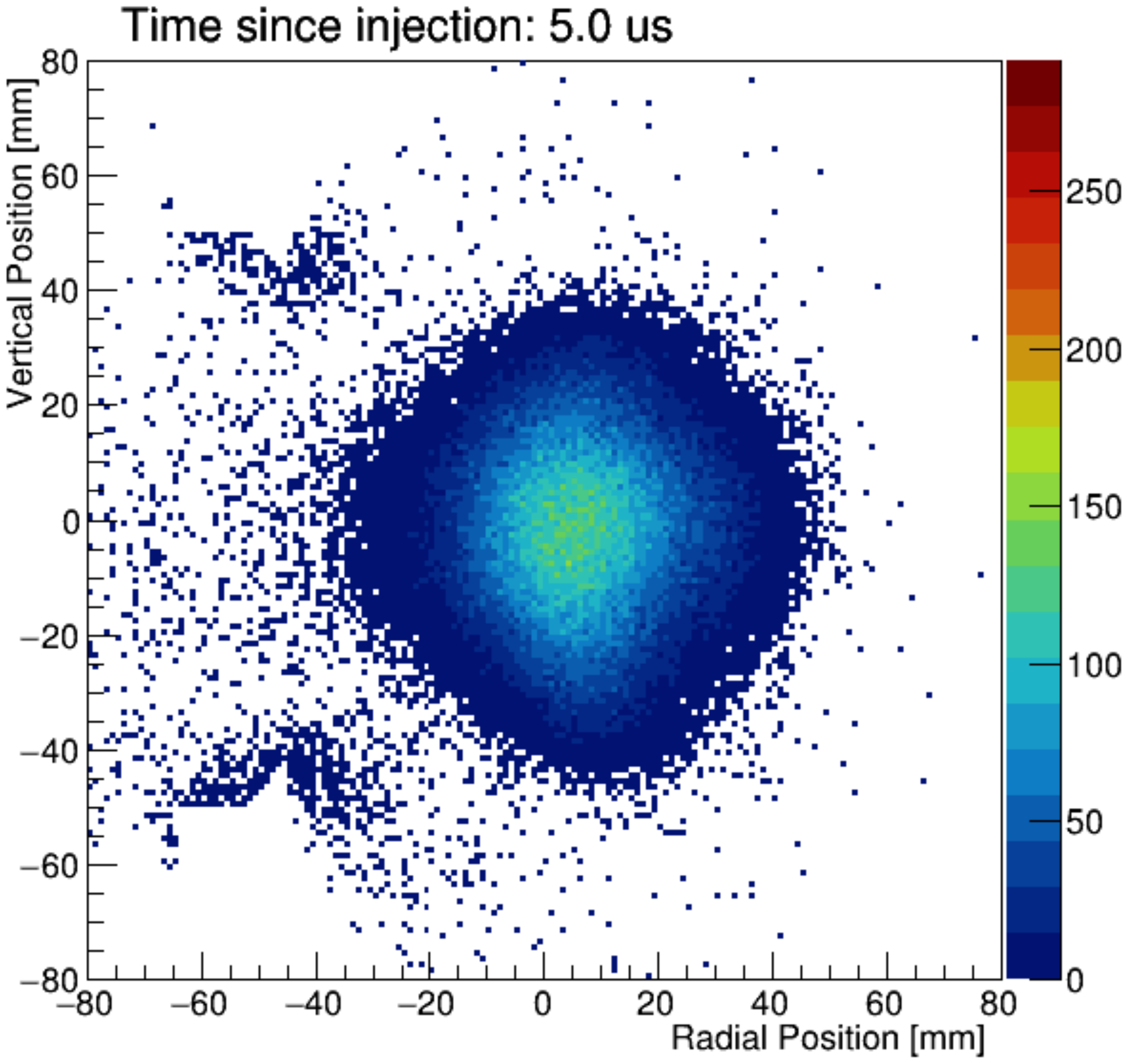
B-field from **proton NMR** and weighted by **muon distribution from trackers**

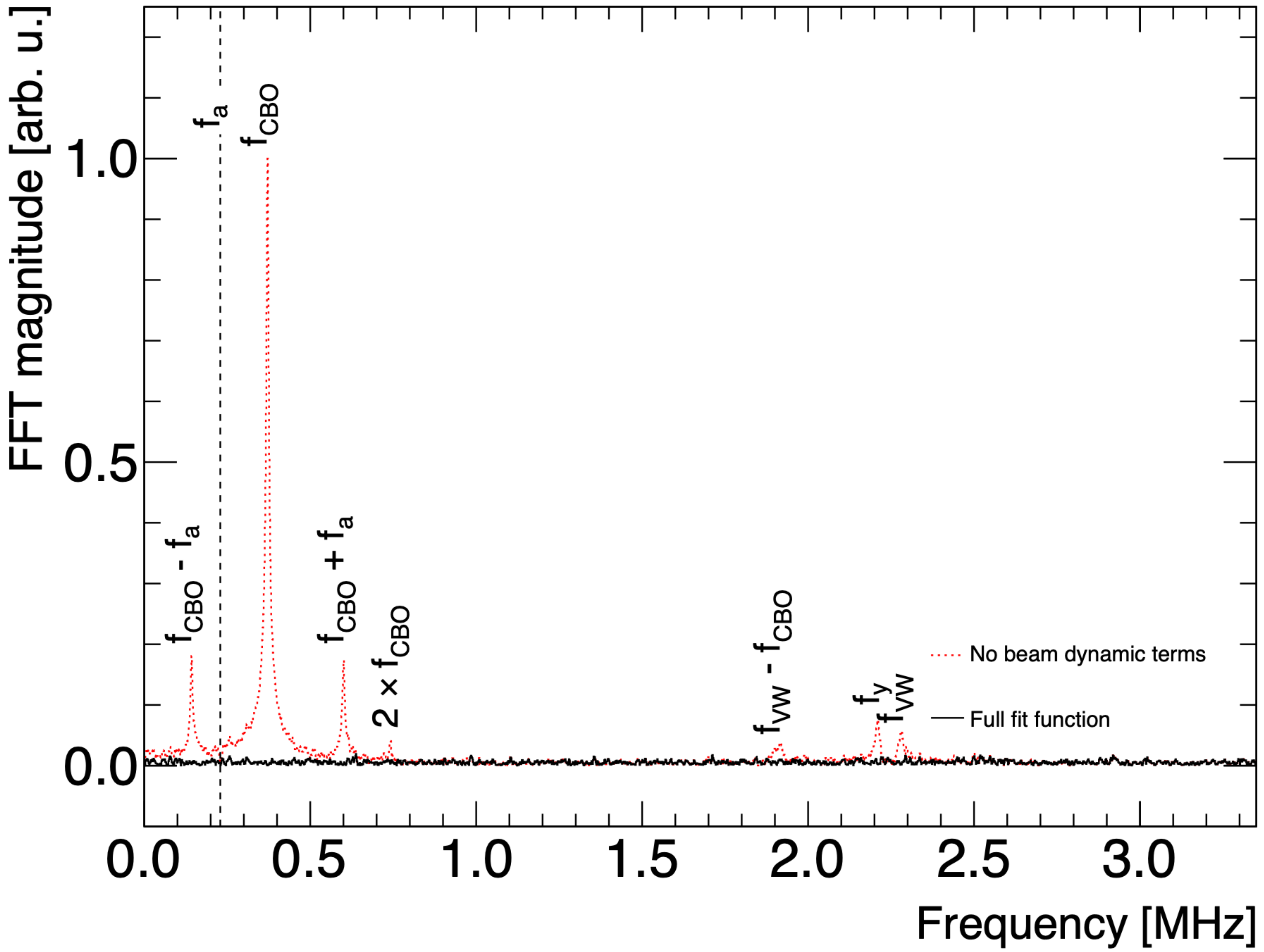
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\,\omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd})}{f_{\text{calib}} \left\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \right\rangle (1 + B_k + B_q)}$$

In reality, some complications from beam dynamics and magnetic transients

Systematic uncertainty example

- Coherent betatron oscillation (CBO) is the radial motion of the beam
- Visible in the calorimeter data and must be accounted for in fit





Uncertainties in Run-2/3 and improvements

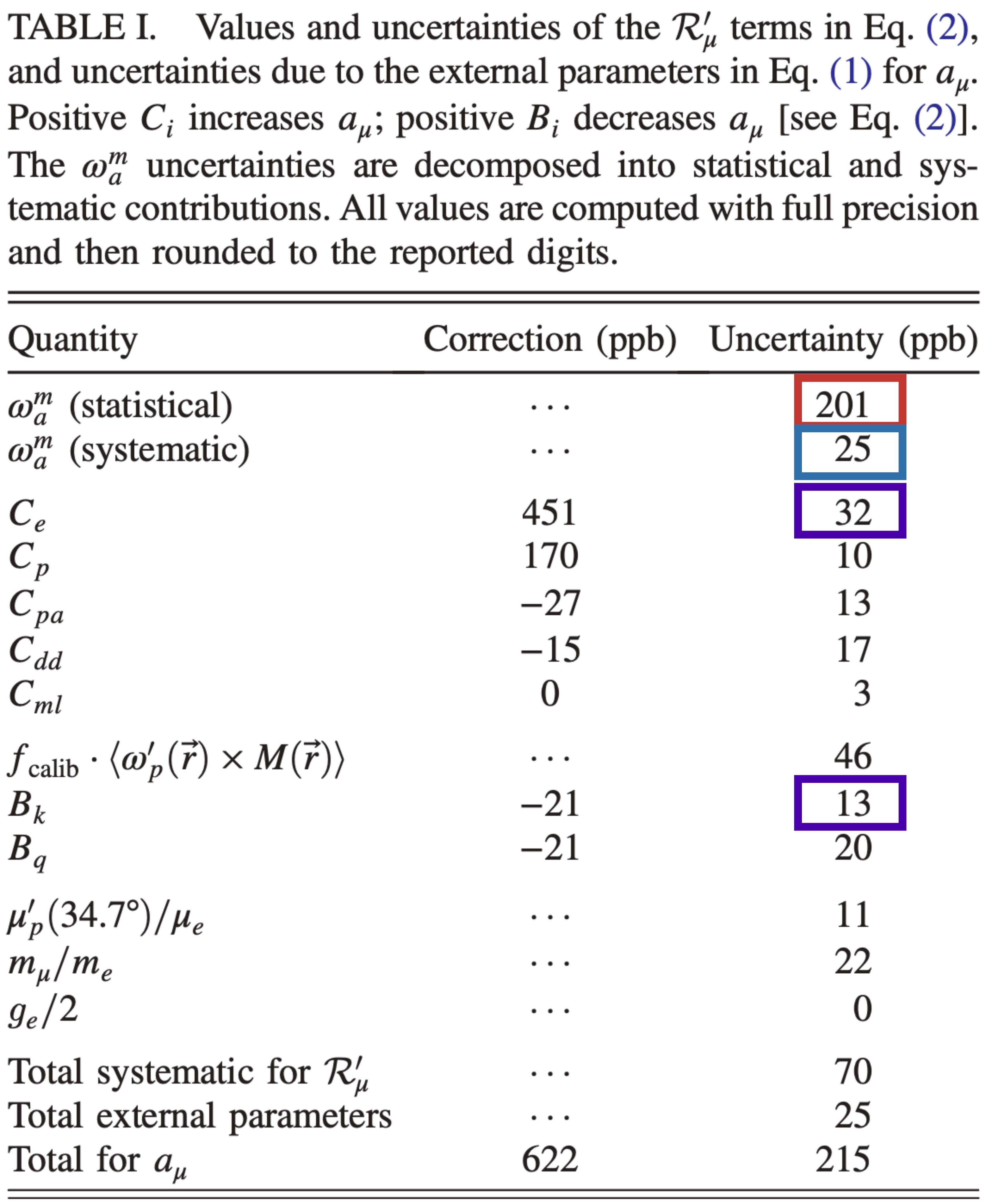
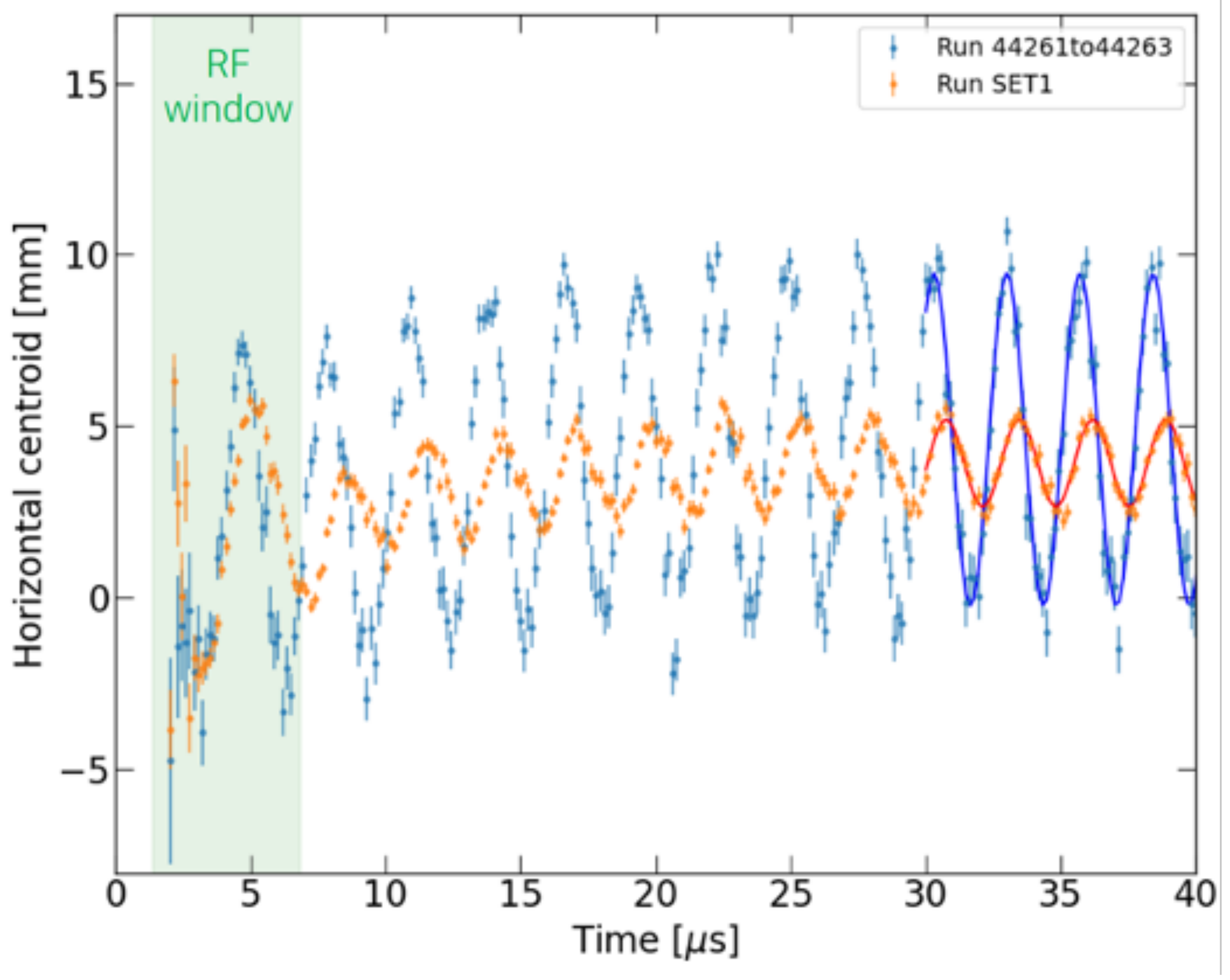
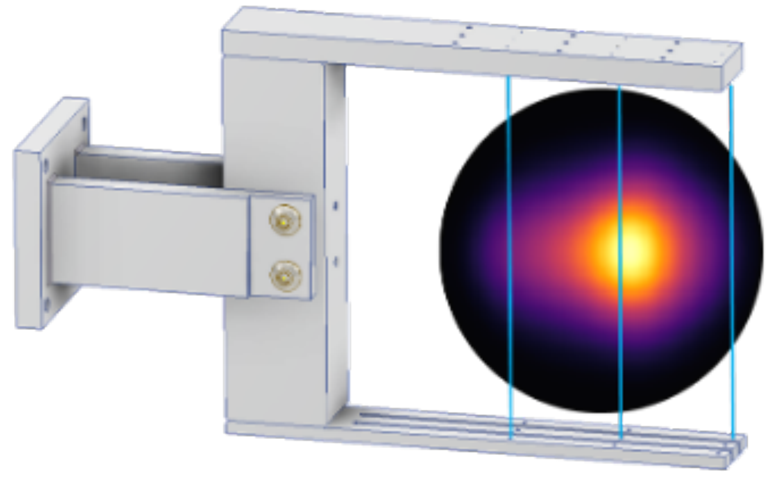


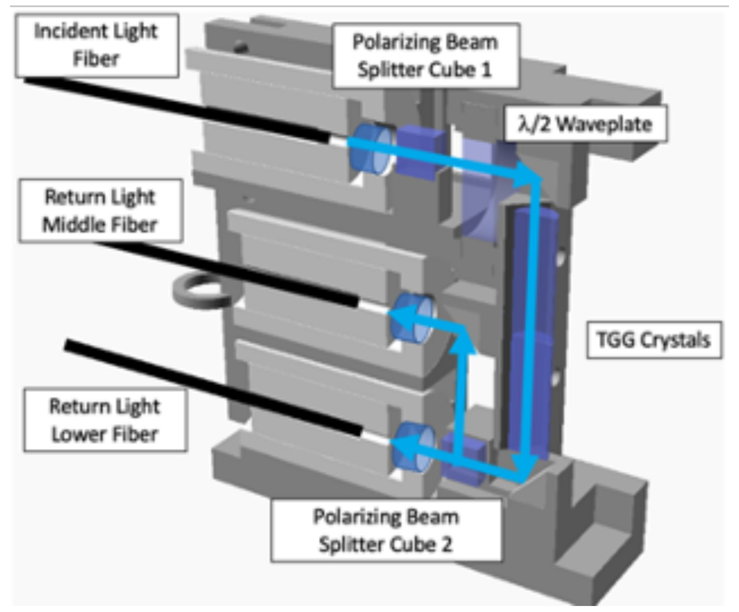
TABLE I. Values and uncertainties of the $\mathcal{R}'_\mu$ terms in Eq. (2), and uncertainties due to the external parameters in Eq. (1) for a_μ. Positive C_i increases a_μ; positive B_i decreases a_μ [see Eq. (2)]. The ω_a^m uncertainties are decomposed into statistical and systematic contributions.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

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

- Run-2/3 uncertainty was **statistics** dominated 201 ppb
  - Run-4/5/6 to reduce this to ~100 ppb!
- Run-5 onwards, implemented RF pulse to electrostatic quadrupole plates to dampen CBO signal
- Dedicated measurements to better constrain beam dynamics corrections and magnetic transients

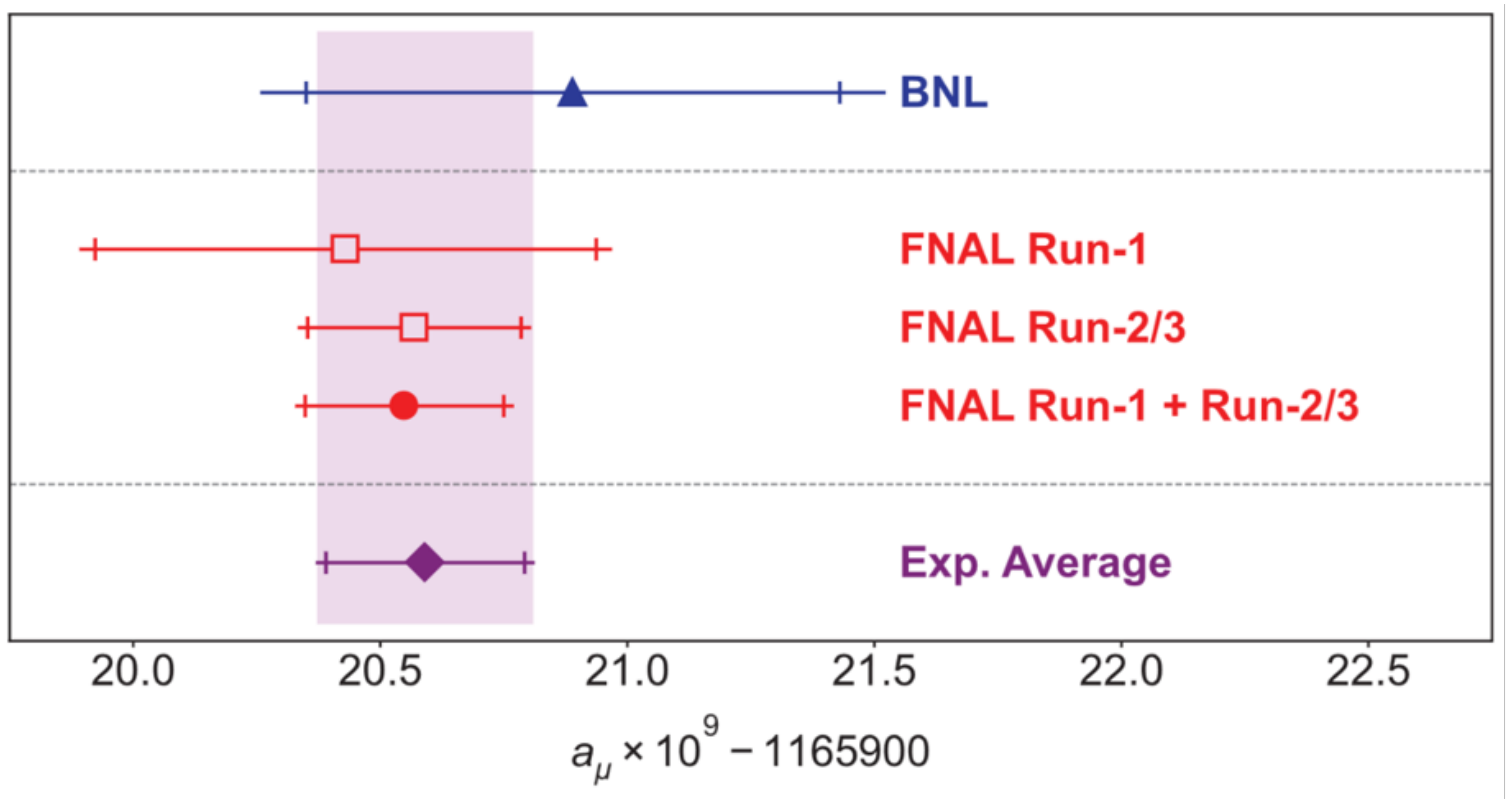


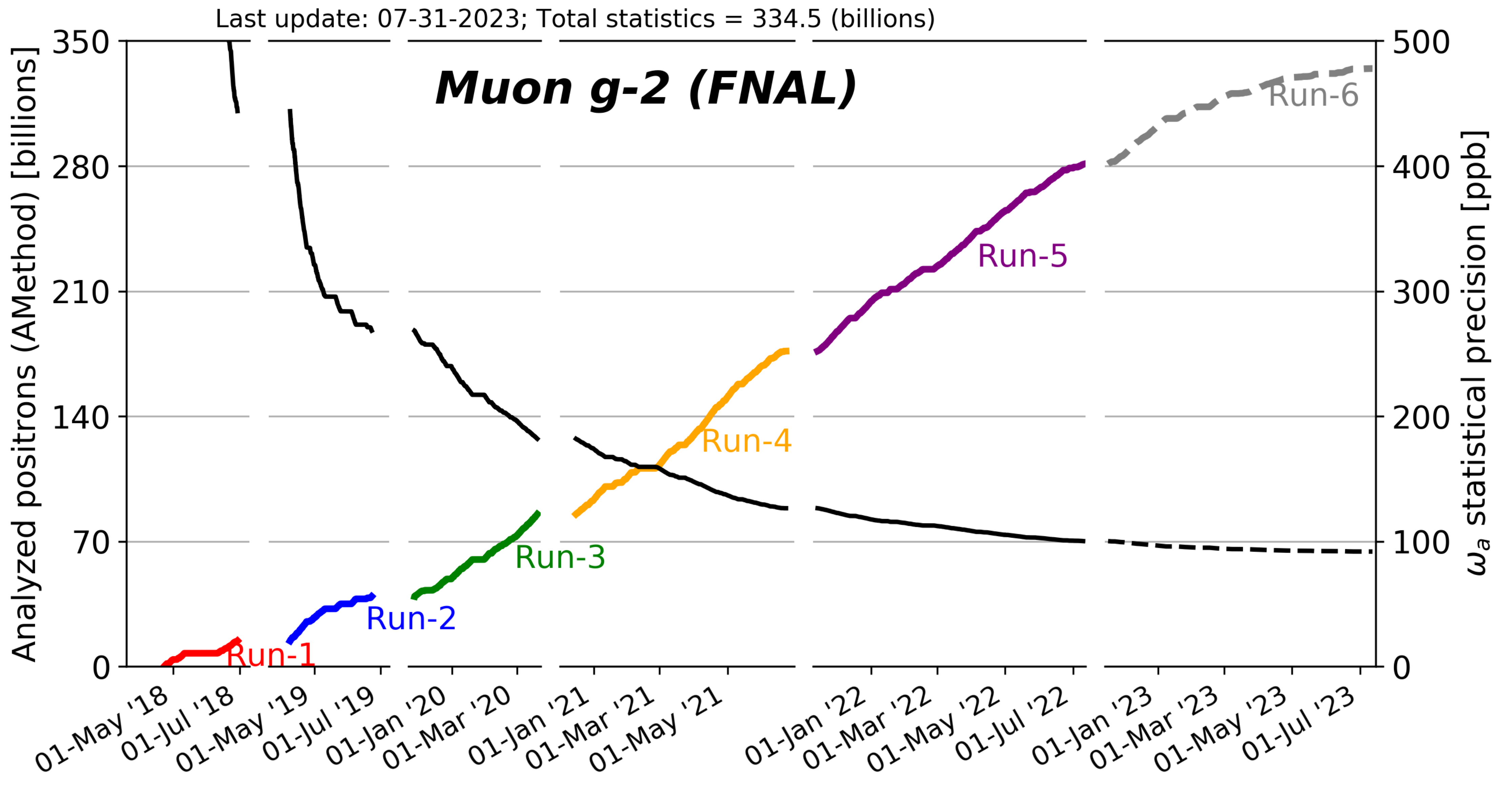




Summary and Outlook

- Muon g-2 experiment at Fermilab poised to surpass goal of 140 ppb measurement of muon magnetic anomaly
- Based on first three years of data, we've determined a_μ to **203 ppb**
- Current comparison with theory is difficult due to tension among different HVP calculations; lots of active work in theory community
- We also have other measurement efforts: muon EDM, CPT/Lorentz violation, dark matter search





Acknowledgments

- Department of Energy (USA)
- National Science Foundation (USA)
- Istituto Nazionale di Fisica Nucleare (Italy)
- Science and Technology Facilities Council (UK)
- Royal Society (UK)
- Leverhulme Trust (UK)
- 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)