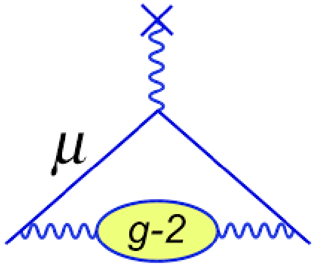
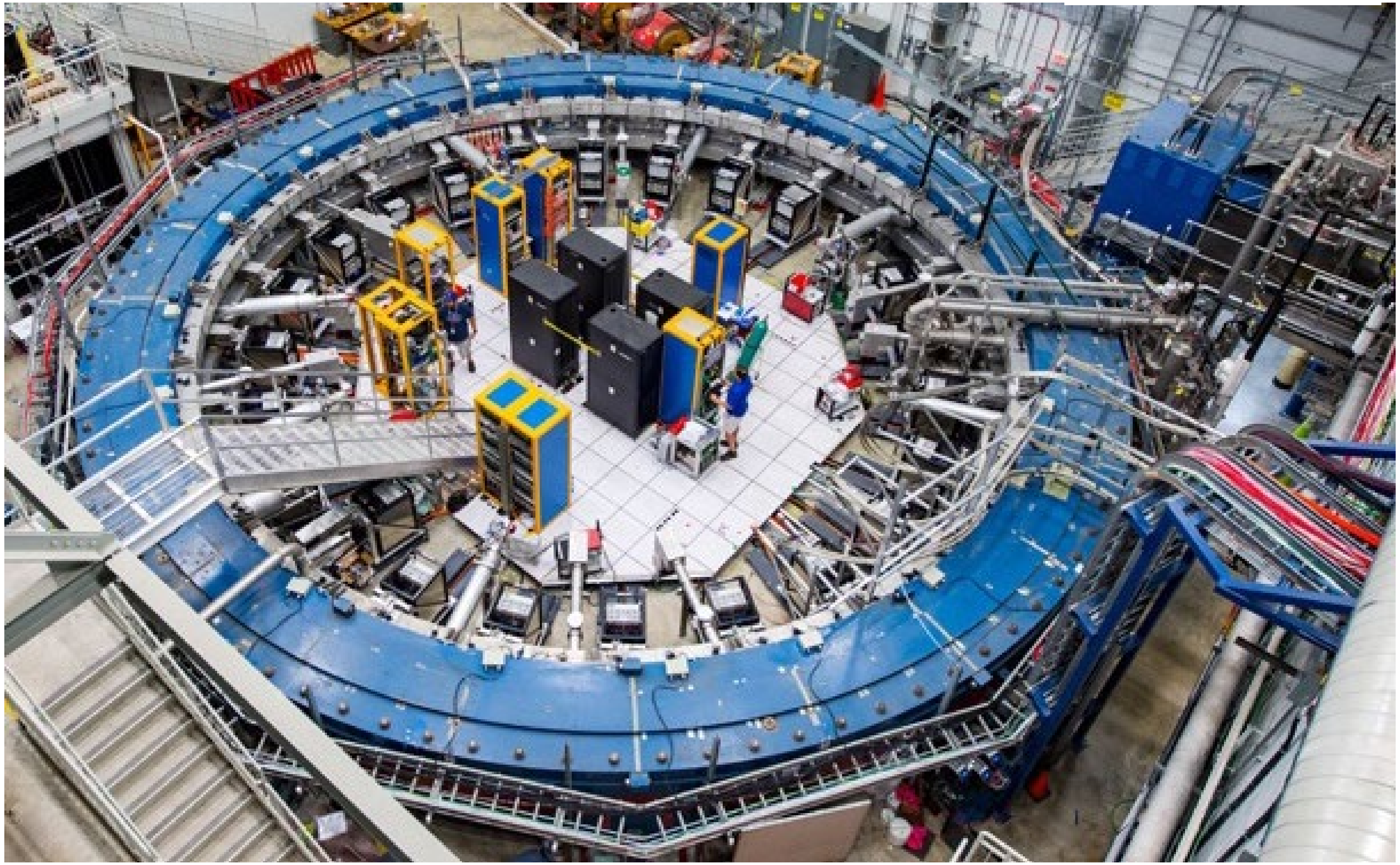

2

A New Measurement of the Muon Anomalous Magnetic Moment to 0.43 ppm





Chris Stoughton
Fermilab

FERMILAB-SLIDES-21-045-SCD
This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Muon g-2

>200 collaborators
35 Institutions
7 countries

Many experts
from BNL E821

USA
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

USA National Labs
- Argonne
- Brookhaven
- Fermilab

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

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A Measurement 20 years in the making

April 7-8
Announcement
Talks at Fermilab
and CERN

Aida El-Khadra and **Chris Polly**
Christoph Lehner and **Graziano Venanzoni**

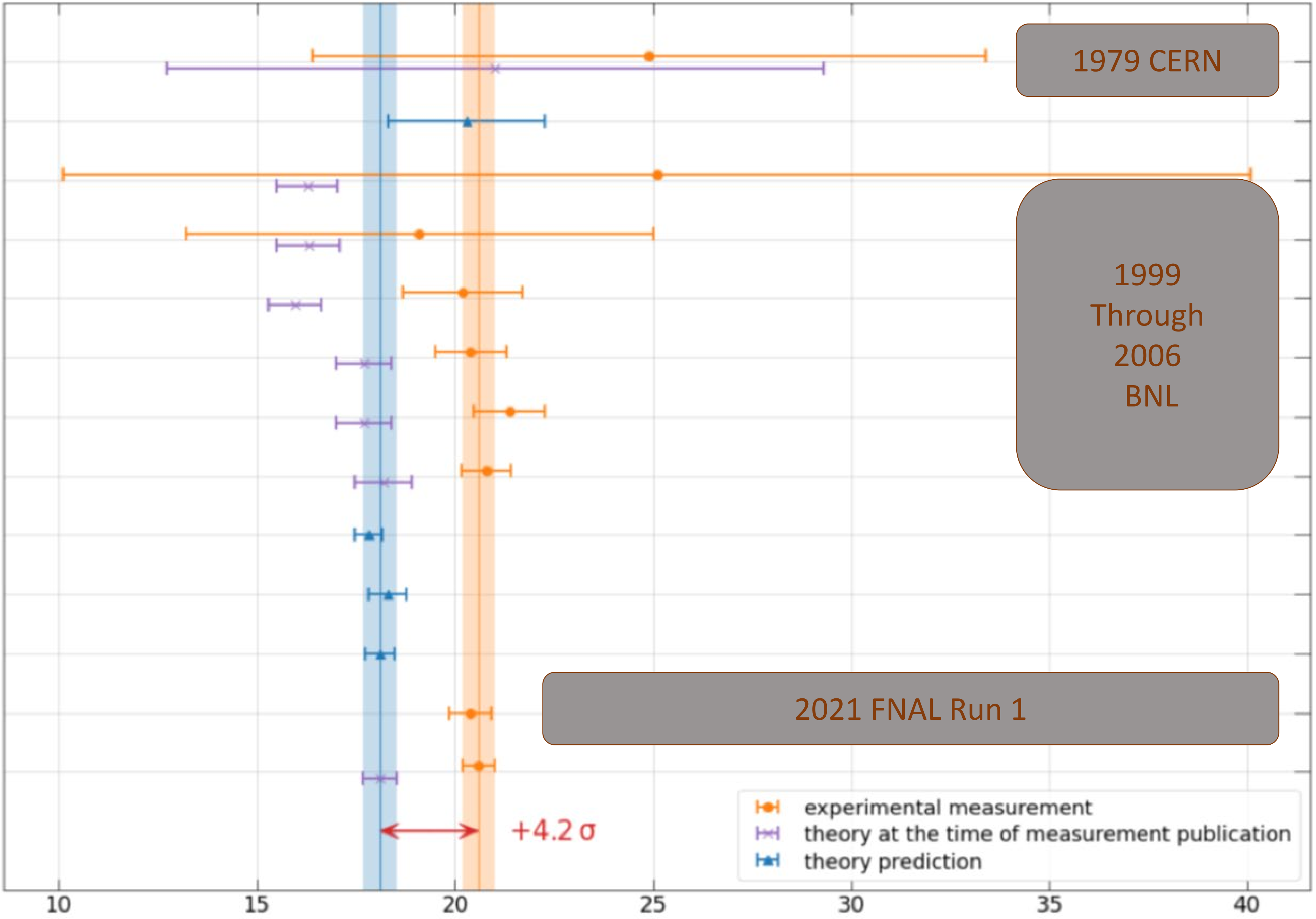
April APS
Meeting Talks

Thomas Teubner, **David Hertzog**, **Dominik Stoeckinger**

40+ seminars/colloquia worldwide; public interest

g-2 Theory Initiative Consensus (WP20) https://arxiv.org/abs/2006.04822
Measurement to 0.46 ppm: https://arxiv.org/abs/2104.03281
Muon Precession Frequency: https://arxiv.org/abs/2104.03247
Magnetic Field: https://arxiv.org/abs/2104.03201
Beam Dynamics: https://arxiv.org/abs/2104.03240
Kicker: https://arxiv.org/abs/2104.07805
+ methods and apparatus in theses, arXiv, proposals, ….

The Number



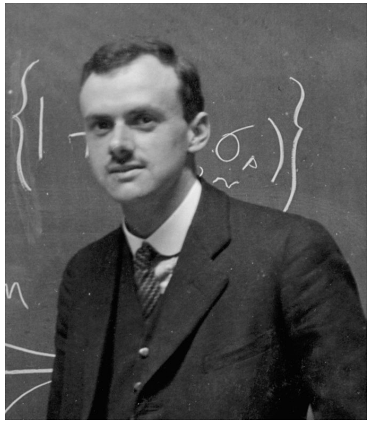
1979 CERN
1999
Through
2006
BNL
2021 FNAL Run 1
+4.2 σ
experimental measurement
theory at the time of measurement publication
theory prediction
10
15
20
25
30
35
40

Motivation

Why measure the magnetic moment of the muon so carefully?

Magnetic Moments of Particles

$$\boldsymbol{\mu} = g_x \frac{e}{2m_x} \boldsymbol{S}$$

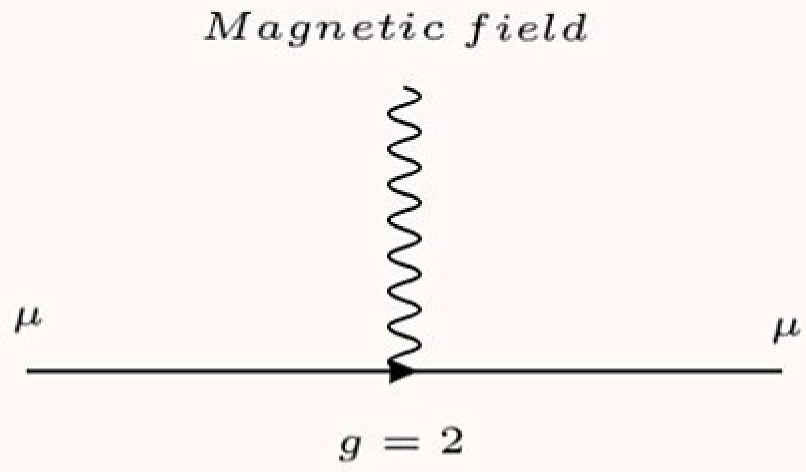


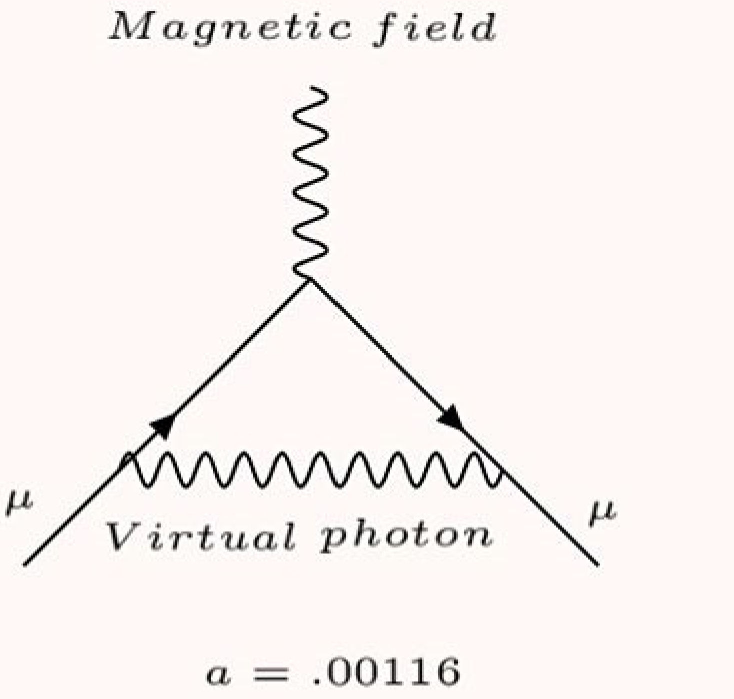
Dirac Theory Predicts $g_{POINT} = 2$

However, Quantum Corrections predicts $g_x \neq 2$

Schwinger was the first to calculate the 1-loop QED correction.

Probing High Energy Scales with Quantum Corrections





A few examples of g

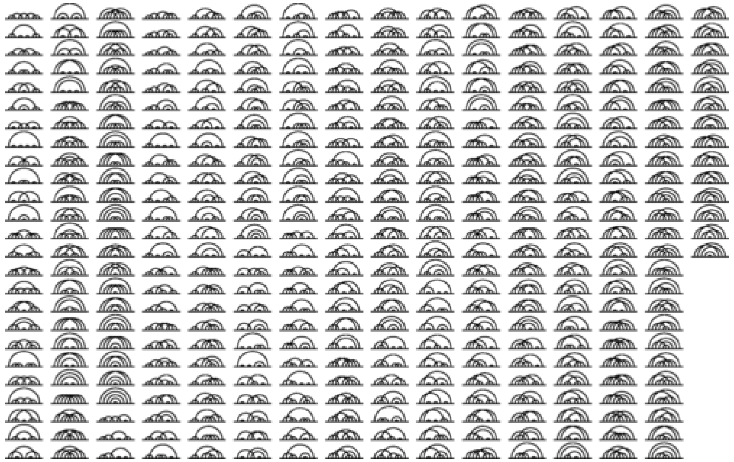
- Dirac's prediction for a point particle: 2
- $\boldsymbol{\mu} = g_{POINT} \frac{e}{2m_{POINT}} \boldsymbol{S}$

- Measured Proton: 5.6 (Otto Stern, 1933)
- Measured Neutron: -1.9 (Luis Alvarez and Felix Bloch 1940)

- Measured for the Electron
  - 2.00238 (Henry M. Foley and P. Kusch 1947)
- Theoretical calculation for the Electron
  - Agreement! (Julian Schwinger 1948)

Now, agreement is to 10 significant digits

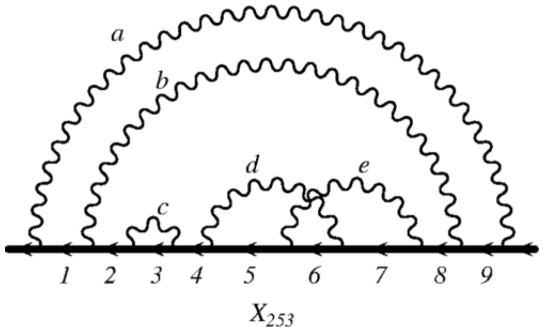
We understand how electrons and photons work.



For the Electron, superb agreement

Use a = (g-2)/2 for convenience

6354 tenth-order Feynman diagrams
6318 previously published tenth-order diagrams

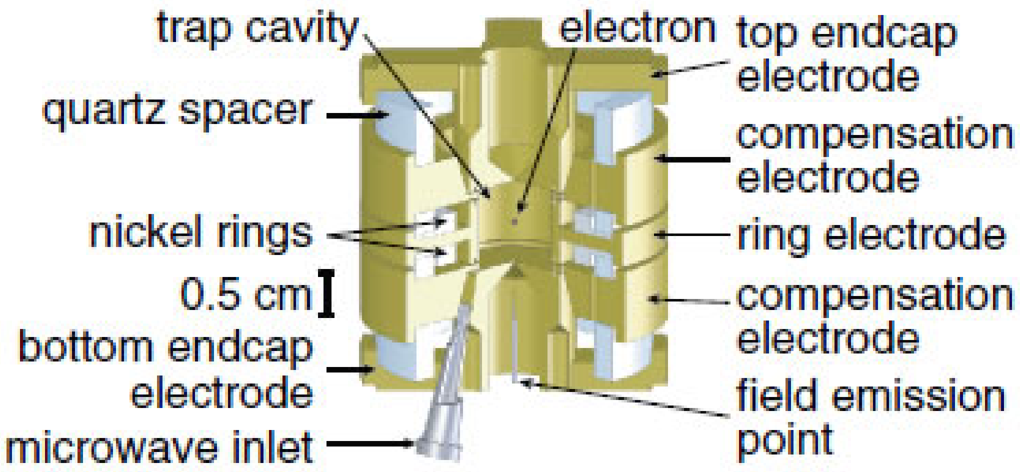


0.001 159 652 181 643(764)
0.001 159 652 180 73(28)

Theory PRD 91,033006 (2015) Aoyama, Kinoshita, Nio

Measured PRL 100, 120801 (2008) Henneke, Fogwell, Gabrielse

The measurement was carried out with a single electron that was suspended for months at a time in a cylindrical Penning trap

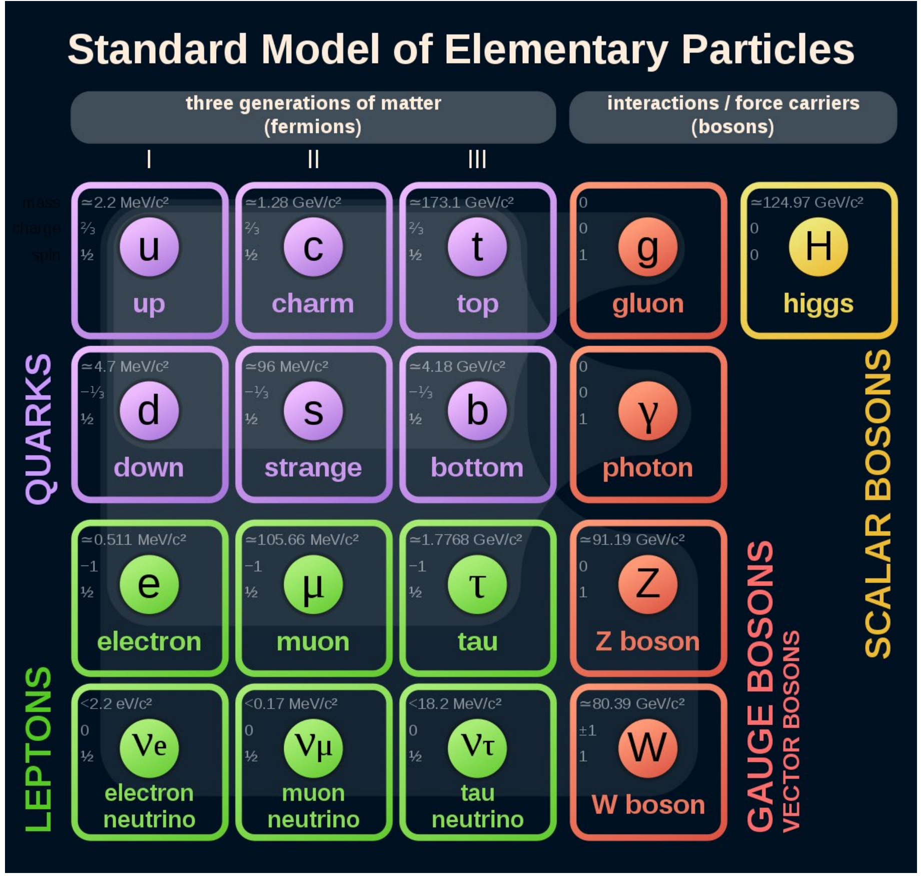


Why We Like Muons

Muons are more sensitive than electrons

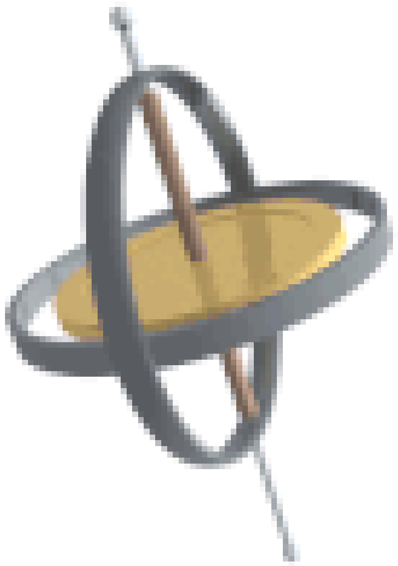
200 * 200 = 40,000

The muon g-2 theory initiative has done the calculation (much more carefully) and concludes:

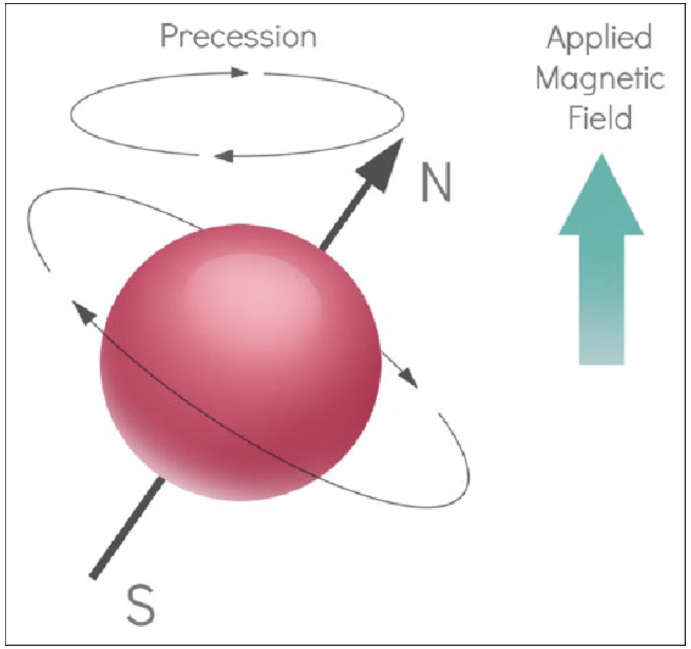


...this is one of the most promising places to look for evidence of new physics.

Muons PRECESS in a magnetic field



Spinning Top In
Gravitational Field



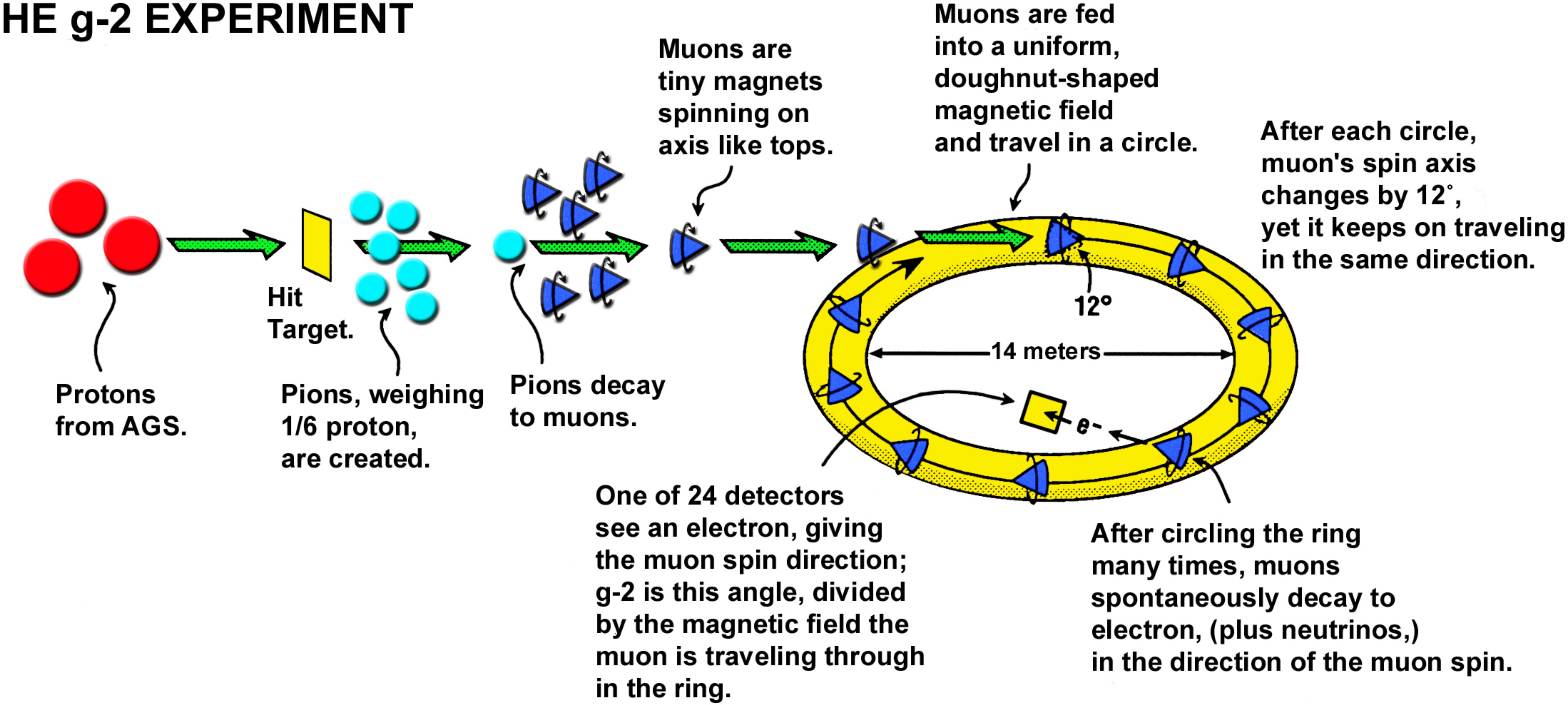
Spinning Charge In
Magnetic Field

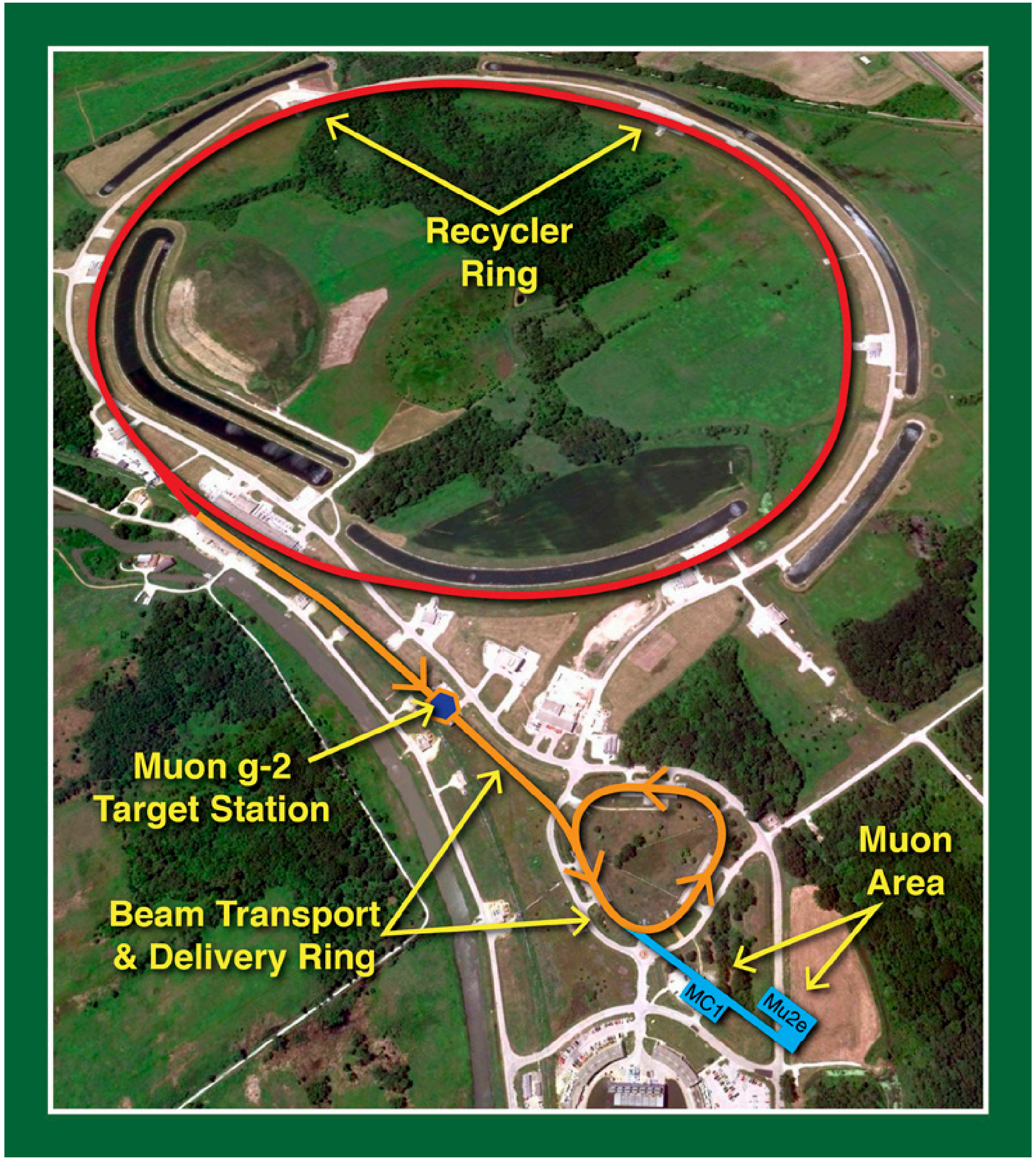
Precession Frequency depends on:
- Gravitational Field
- Angular momentum

Precession Frequency depends on:
- Applied Magnetic Field
- ½ * g

Muons: spin directions line up: 90% polarized

LIFE OF A MUON: THE g-2 EXPERIMENT

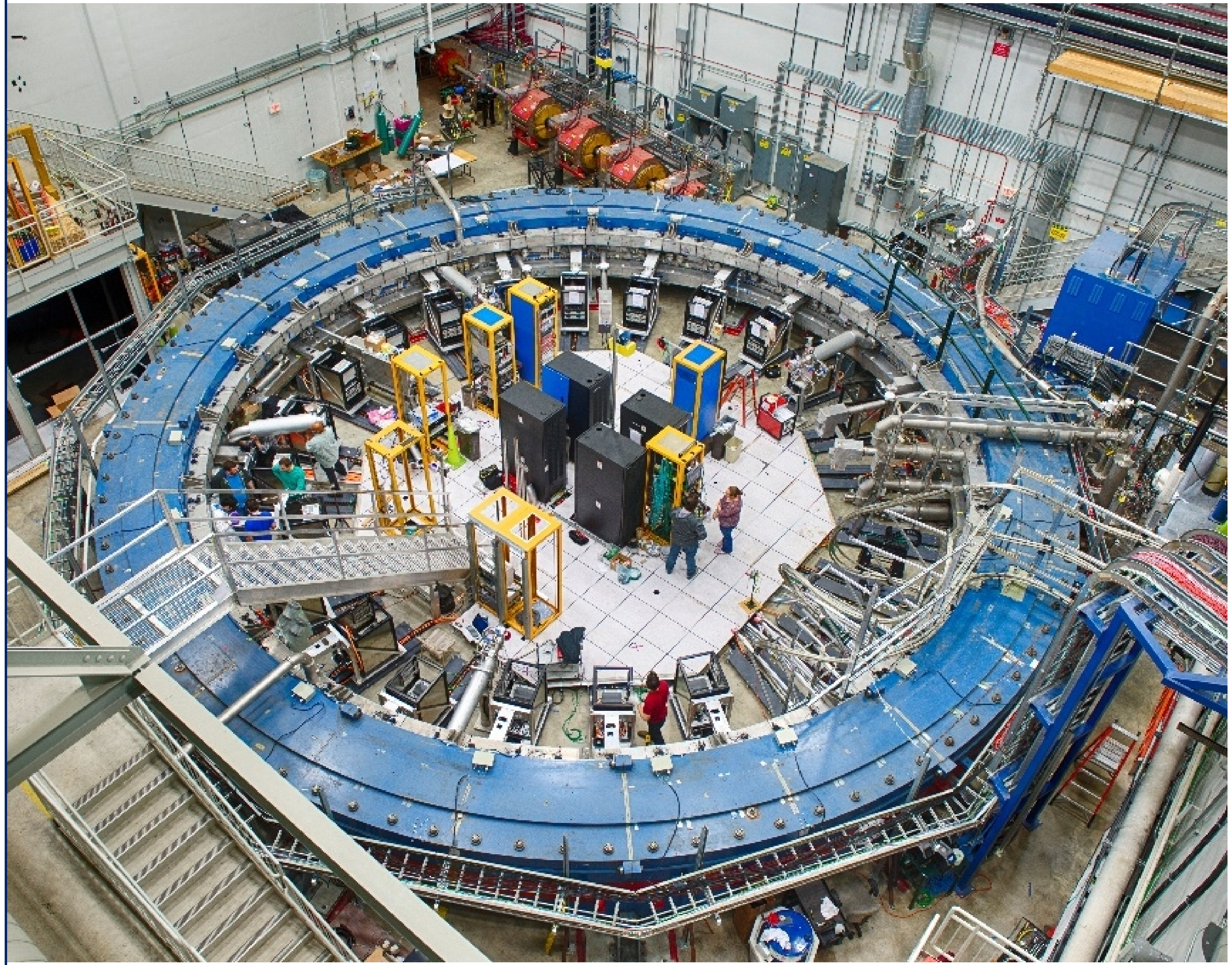




Fermilab Muon Campus

Fermilab Muon Campus

Overview of Muon $g-2$ Experiment at Fermilab (E989)



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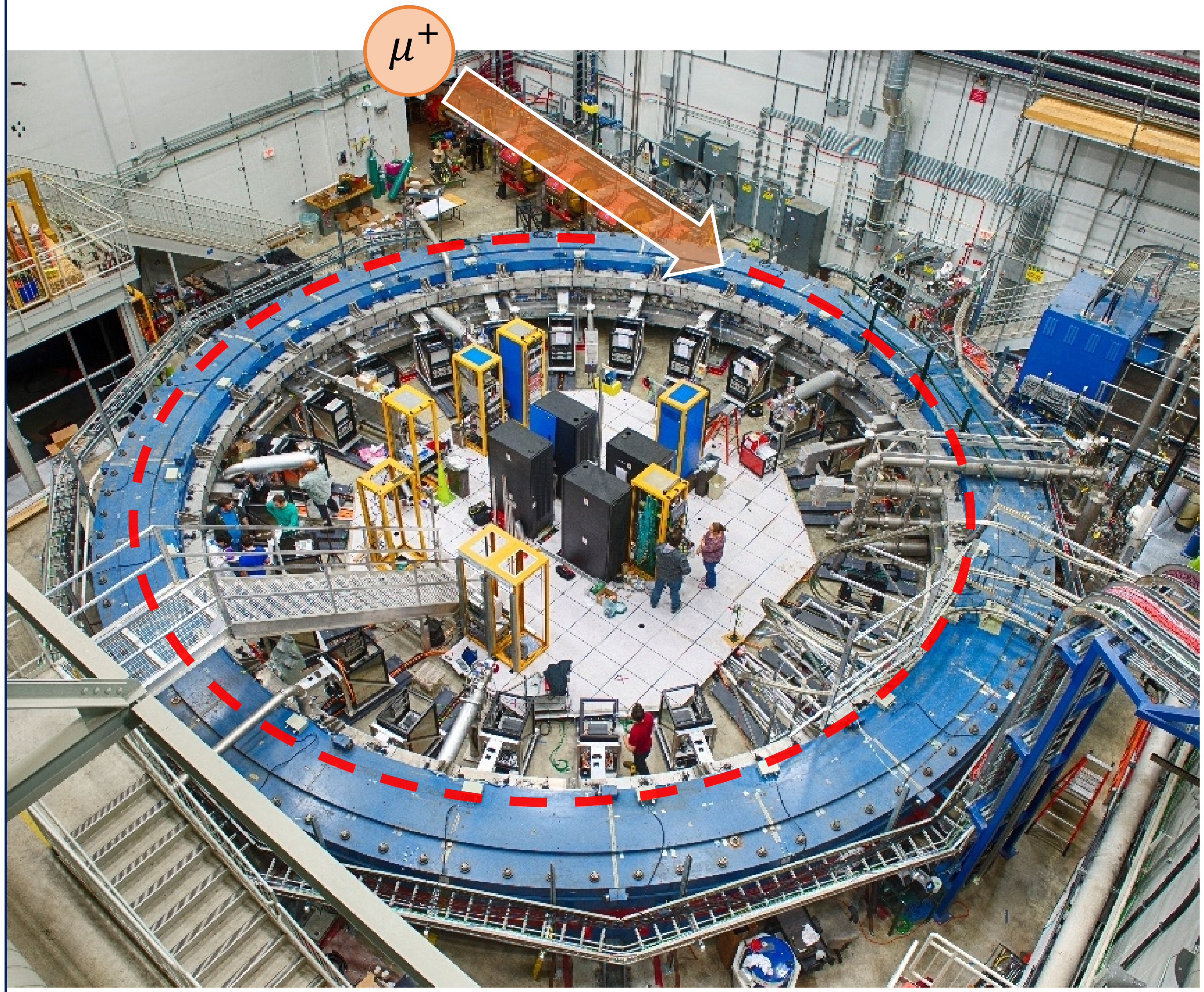
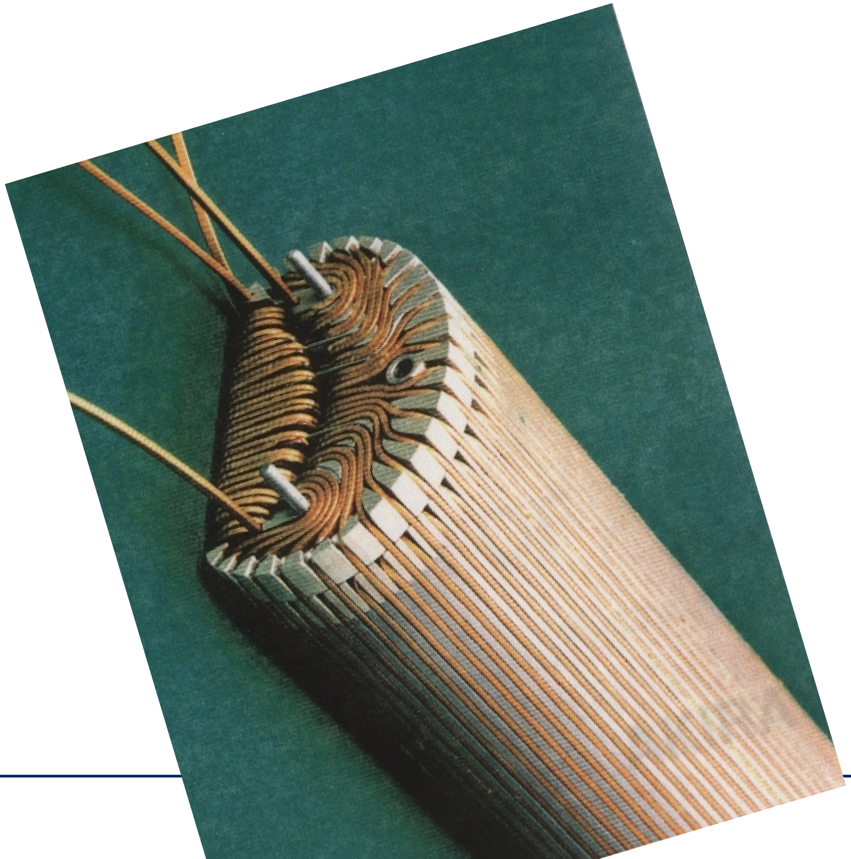
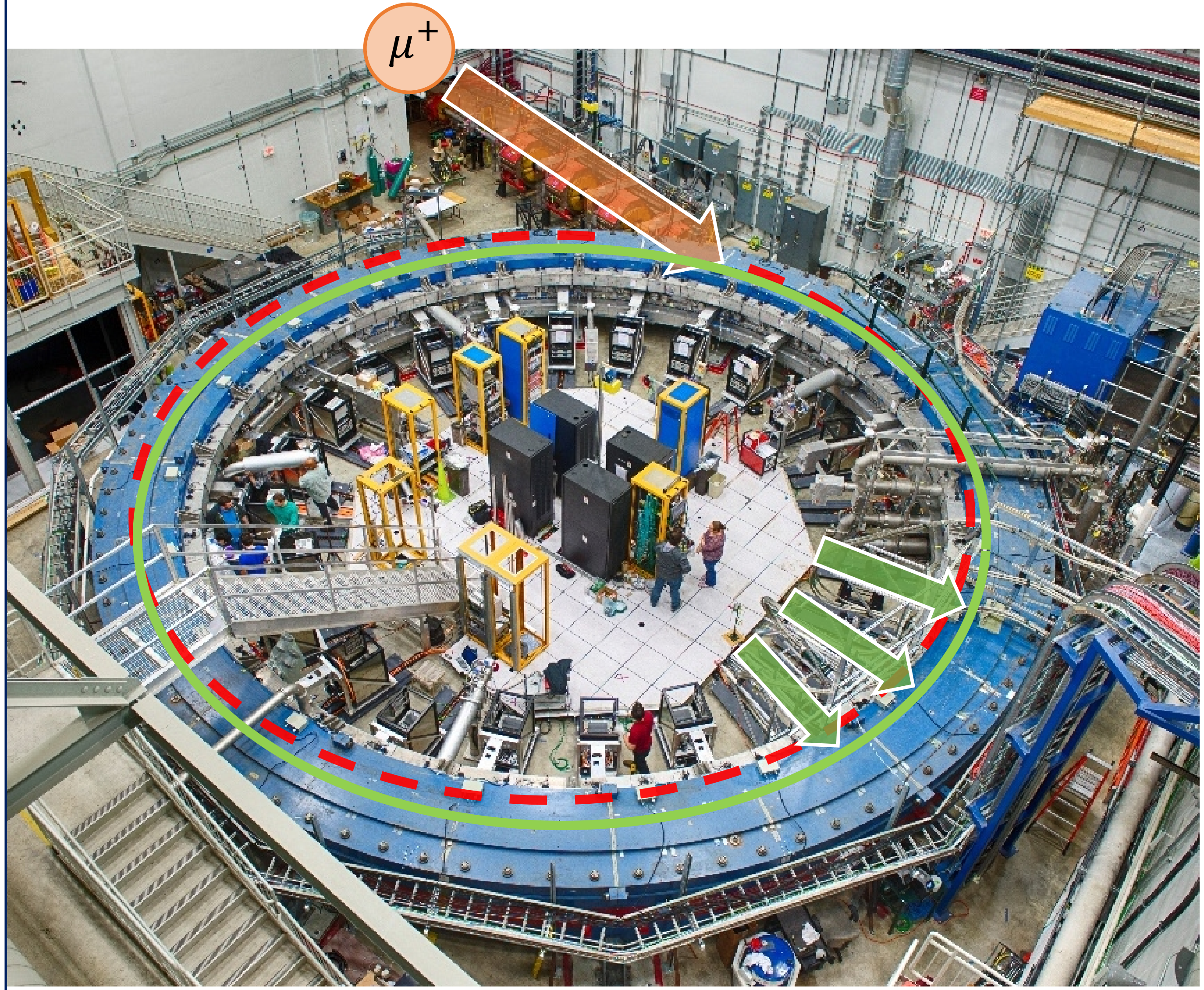


▶ Injection

- Polarized anti-muon bunch (3.1 GeV) is injected into the storage ring (15 m diameter).
- Superconducting **inflector magnet** cancels the main focusing magnetic field (1.5 T) to inject the bunch into the storage ring tangentially.



Overview of Muon $g-2$ Experiment at Fermilab (E989)



- **Injection**
  - Polarized anti-muon bunch (3.1 GeV) is injected into the storage ring (15 m diameter).
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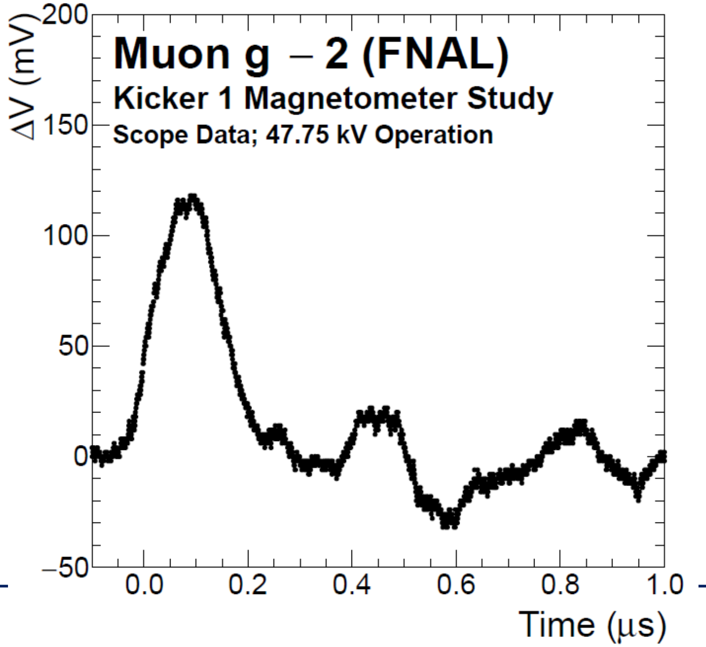
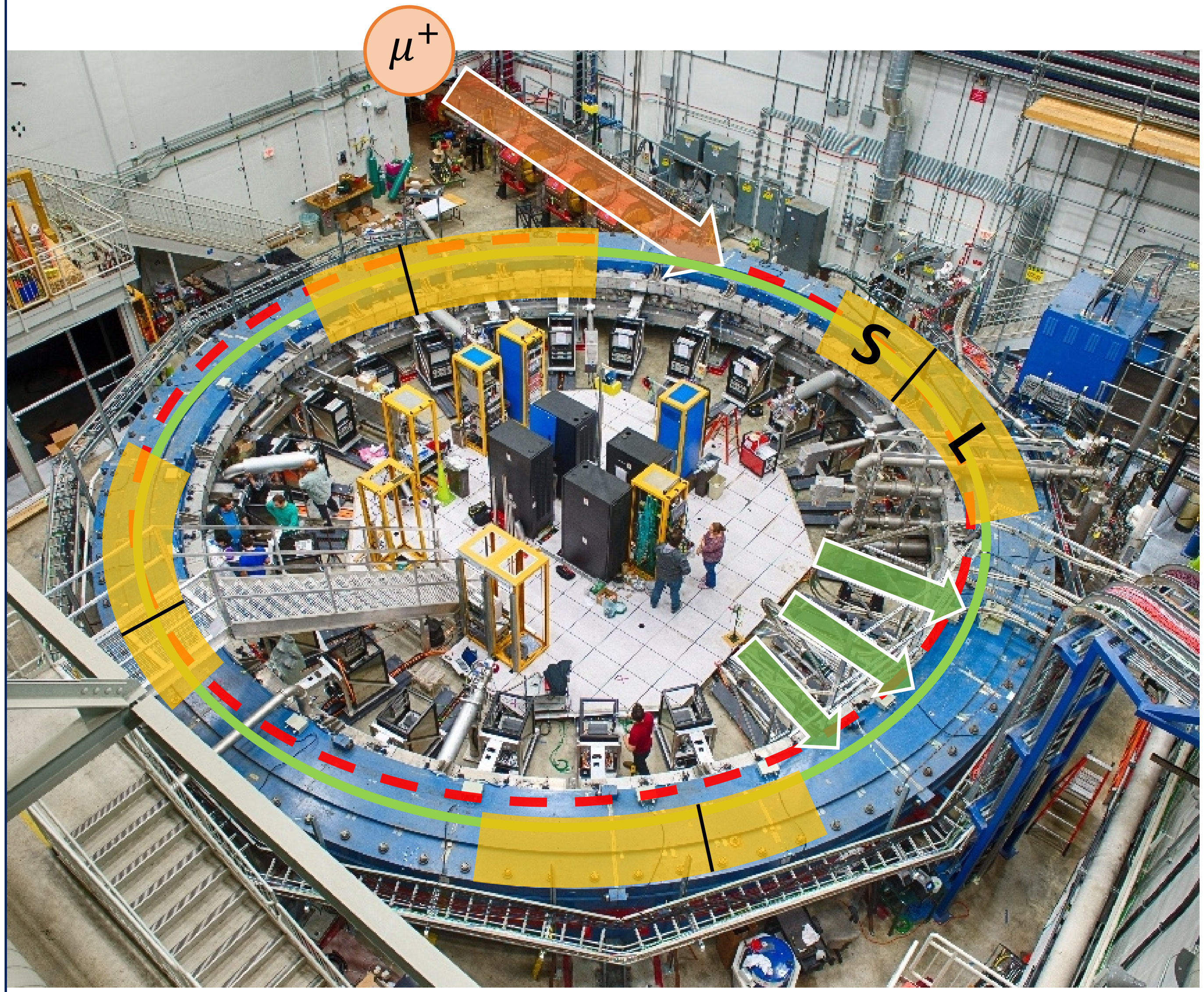
- **Kick**
  - Muons are kicked onto the design orbit by the fast non-ferric **kicker magnet** system.



Overview of Muon $g-2$ Experiment at Fermilab (E989)



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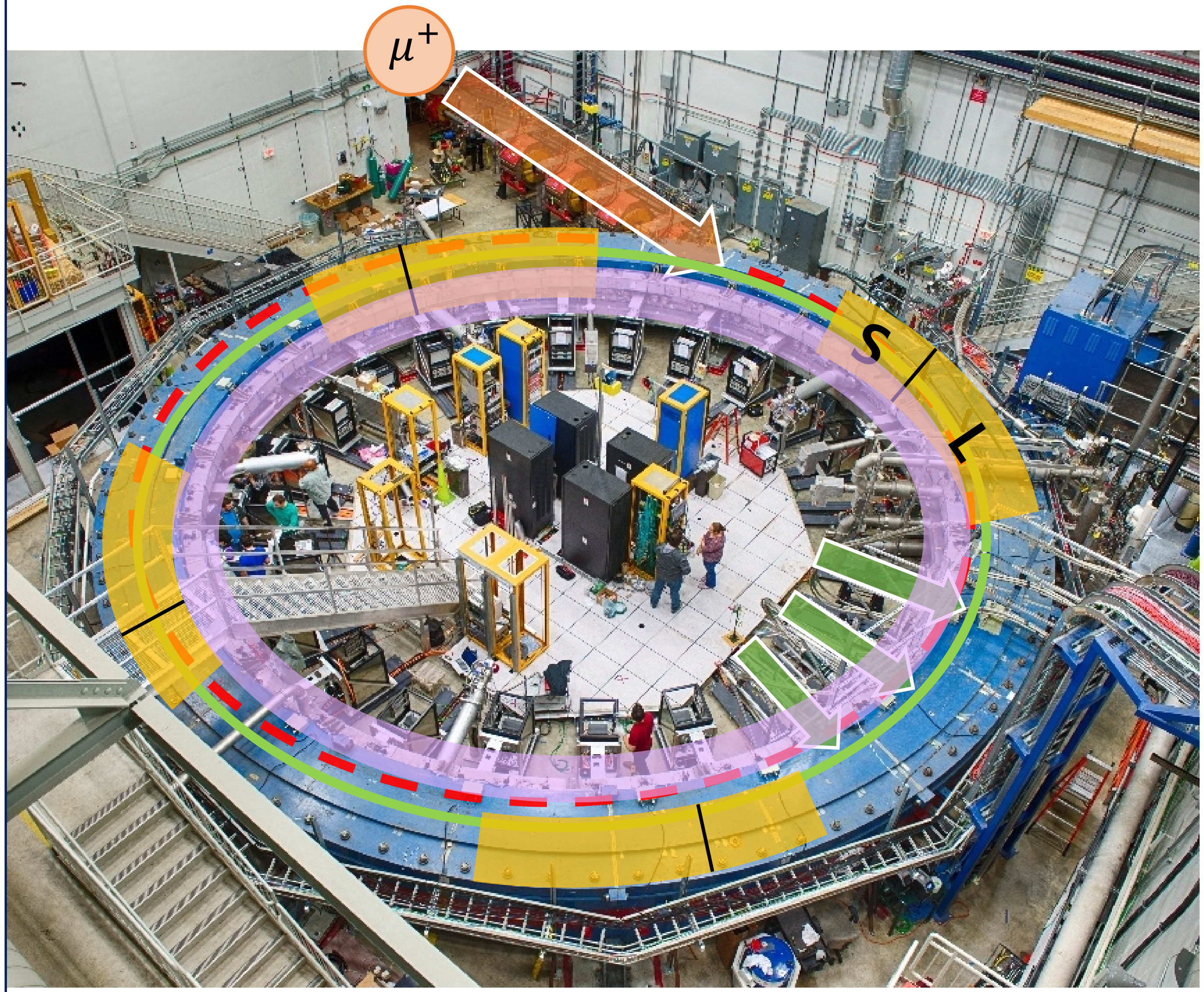
▶ Vertical focusing

- **Electrostatic Quadrupoles** (ESQ) focuses the beam vertically.
- 4 Quadrupole sections (long and short for each) cover 43% of the circumference.

Overview of Muon $g-2$ Experiment at Fermilab (E989)



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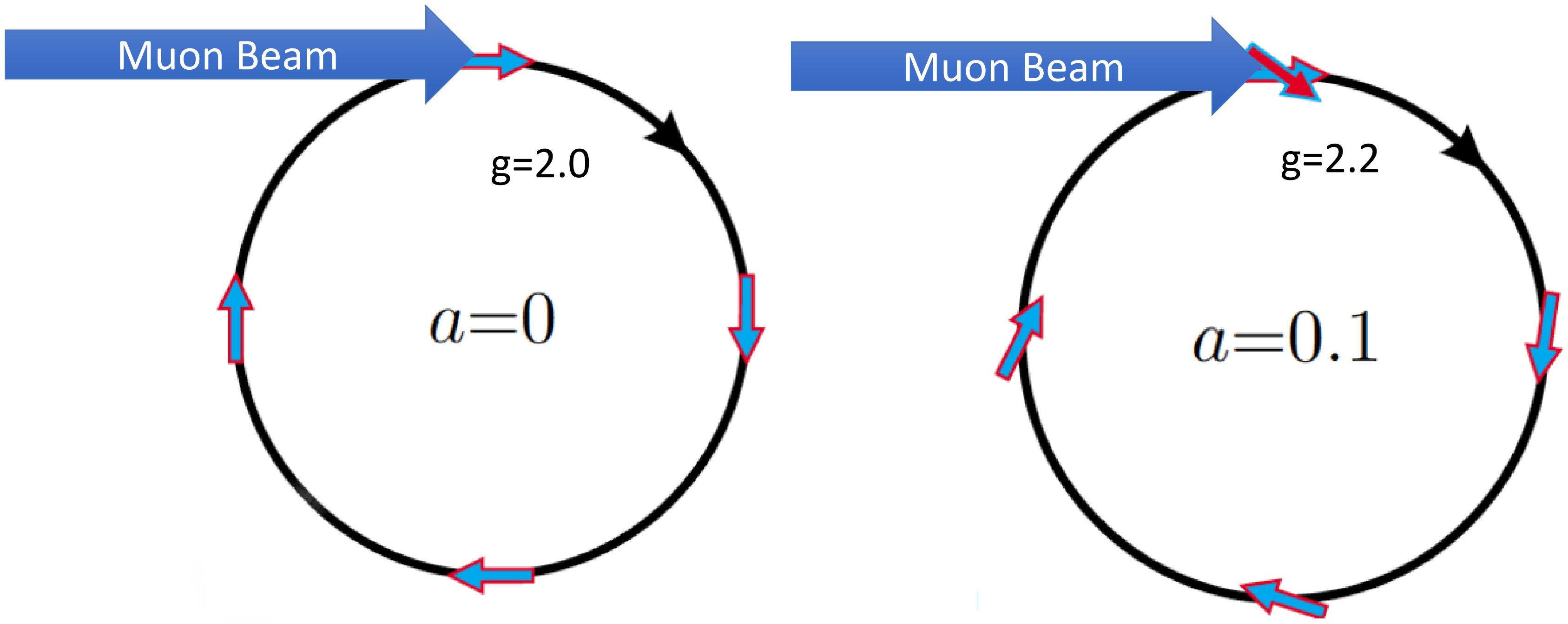
- 4 Quadrupole sections (long and short for each) cover 43% of the circumference.

▶ Detection

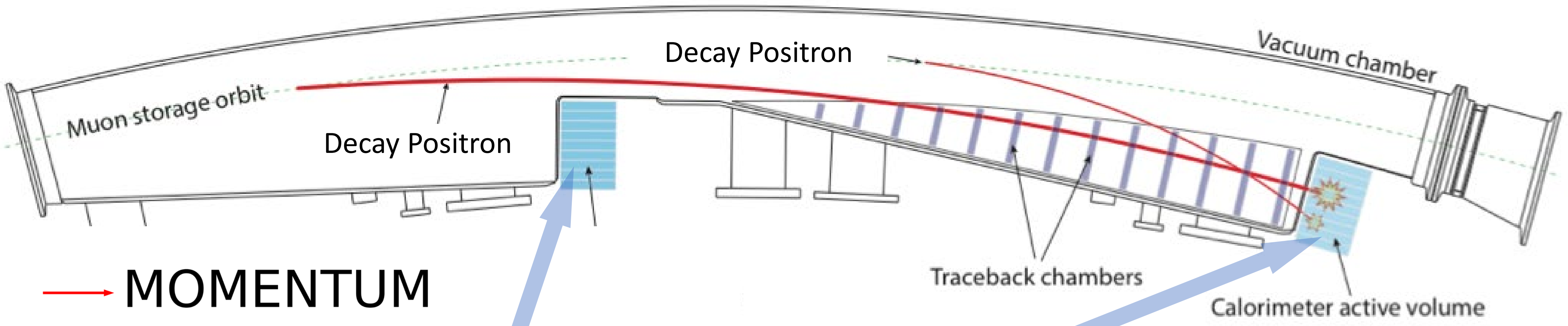
- Muons decay into positrons which curl into 24 electromagnetic **calorimeters** surrounding the storage ring.

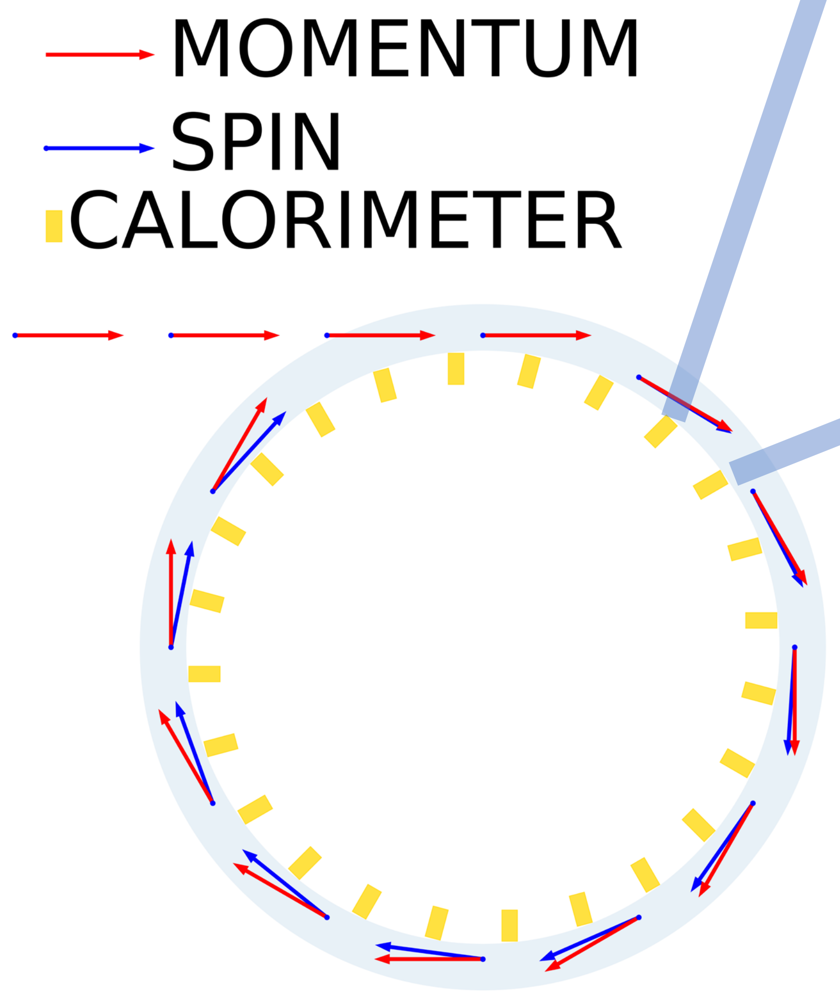
Muons are made with the spin pointing forward
Muons decay to positrons, aligned with the spin

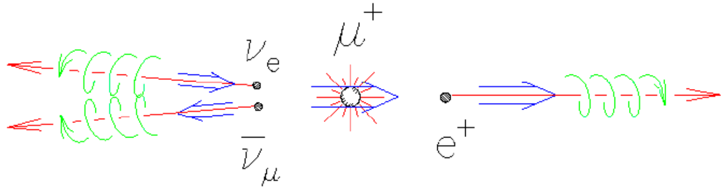


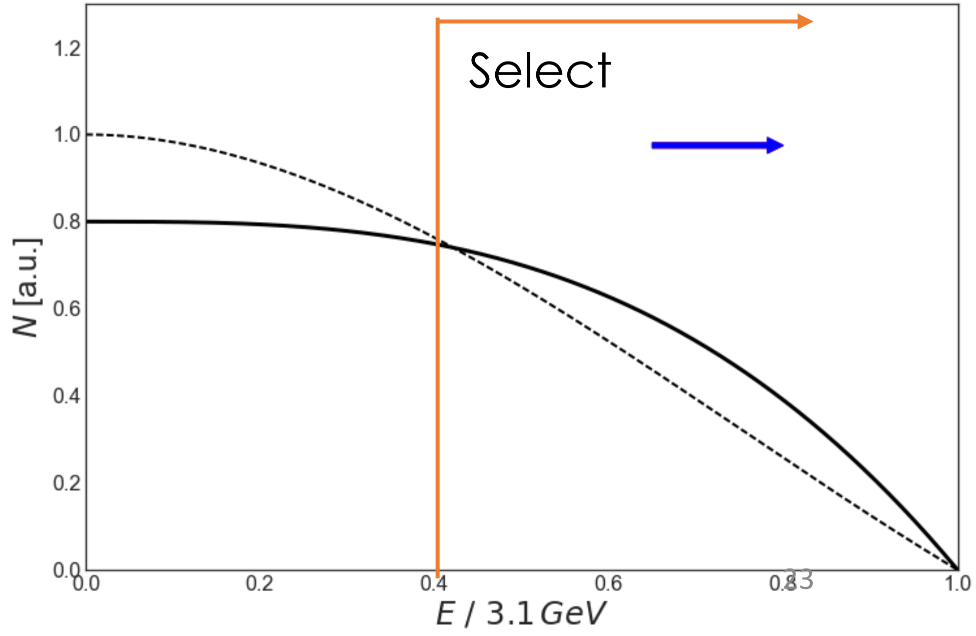
$$\boldsymbol{\omega_a} = \boldsymbol{\omega_s} - \boldsymbol{\omega_c} = -\frac{q}{m_\mu}(a_\mu \boldsymbol{B})$$

For convenience, use a=(g-2)/2, the "Anomalous Magnetic Moment of the Muon"

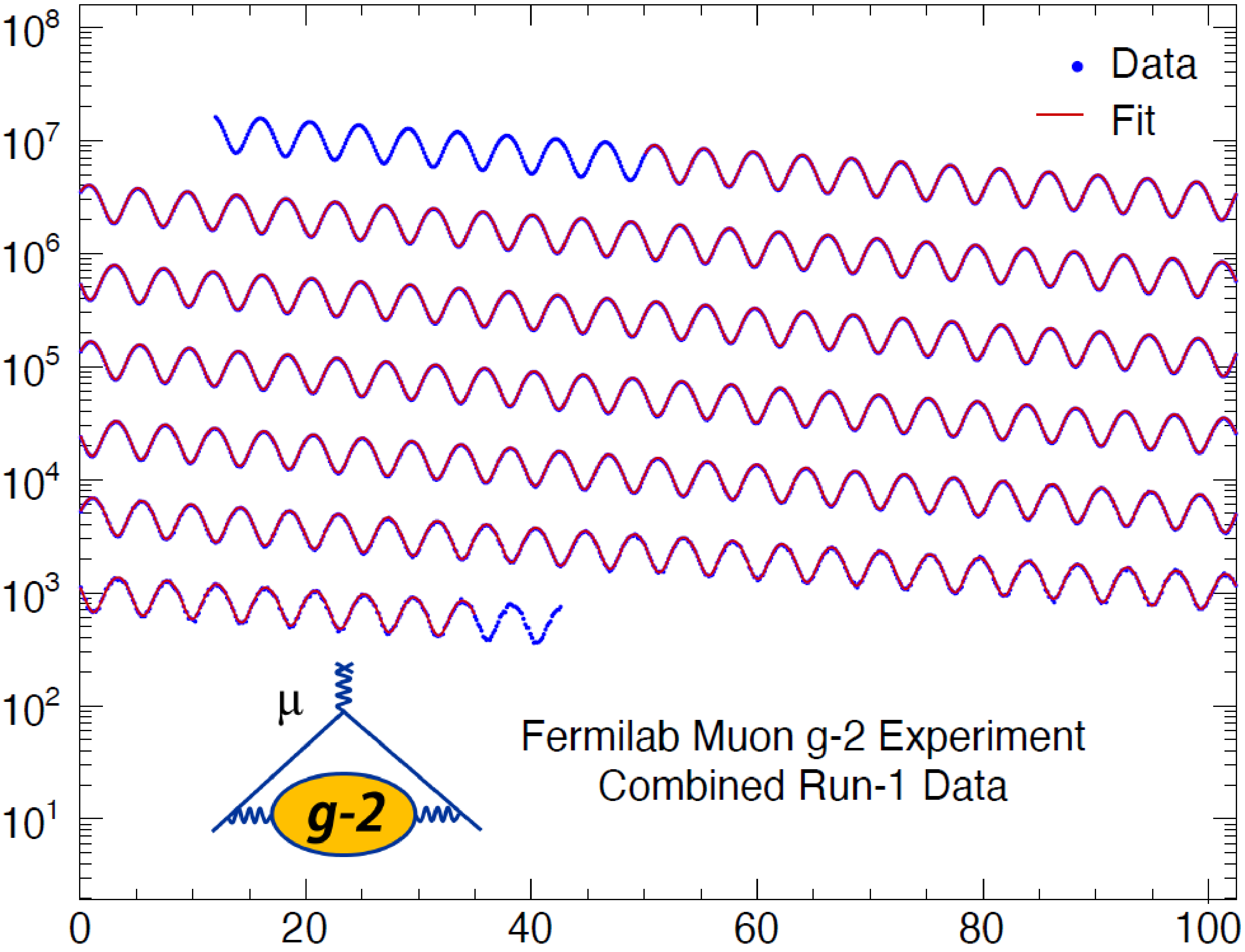

Decay Positron
Vacuum chamber
Muon storage orbit
Decay Positron
Traceback chambers
Calorimeter active volume


MOMENTUM
SPIN
CALORIMETER


ν_e
μ^+
$\bar{\nu}_\mu$
e^+


Select
N [a.u.]
E / 3.1 GeV
0.0
0.2
0.4
0.6
0.8
1.0
1.2

Here is what we see from the decays of muons



$$f(t) = N_0 e^{-t/\tau}(1 + A\cos(\omega_a t + \phi))$$

$$\omega_a = -\frac{q}{m_\mu}(a_\mu B)$$

$$\rightarrow a_\mu = -\frac{\omega_a m_\mu}{q\,B}$$

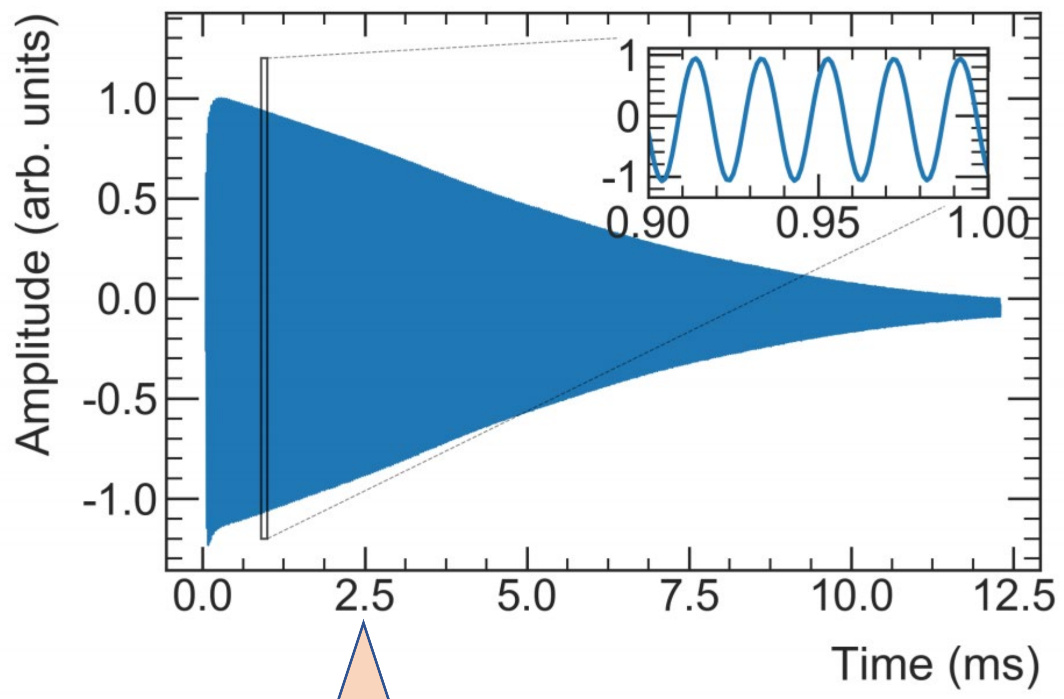
Reality Check

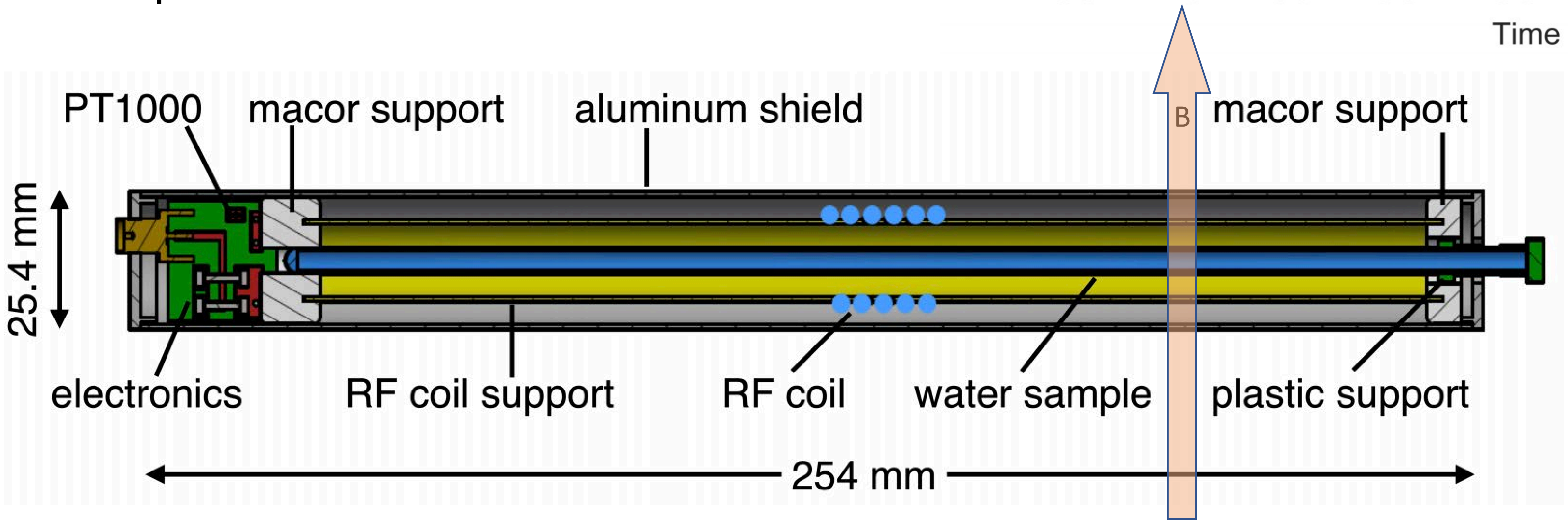
If all the muons saw the same calibrated magnetic field perpendicular to their momentum, and all detectors had 100% acceptance and efficiency, then this would be a much shorter talk!

Use protons to calibrate and monitor B

Free Induction Decay (FID) signals

Extracted $\omega_p/2\pi \approx 61.79$ MHz which corresponds to $B \approx 1.45$ T.





Measure two frequencies; convert with precision results from others

$a_\mu = -\frac{\boldsymbol{\omega_a}\, m_\mu}{q\, B}$ from previous slide becomes

$$a_\mu = \boxed{\left[\frac{\omega_a}{\tilde{\omega}'_p(T_r)}\right]} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

$\frac{\mu'_p(T_r)}{\mu_e(H)}$ 10.5 ppb
Metrologia **13**, 179 (1977)

$\frac{\mu_e(H)}{\mu_e}$ Exact (Bound-state QED)
Rev. Mod. Phys. **88**, 035009 (2016)

$\frac{m_\mu}{m_e}$ 22 ppb (muonium hyperfine splitting)
Phys. Rev. Lett. **82**, 711 (1999)

$\frac{g_e}{2}$ 0.28 ppt
Phys. Rev. A **83**, 052122 (2011)

The Measurement to 0.46 ppm arXiv:2104.03281v1

$$\left[\frac{\omega_a}{\tilde{\omega}'_p(T_r)}\right]$$

Repeat the measurement of this ratio many times.
Group together four similar run conditions
Apply the corrections below
Calculate combined average (with correlations)
Apply the actual clock frequency

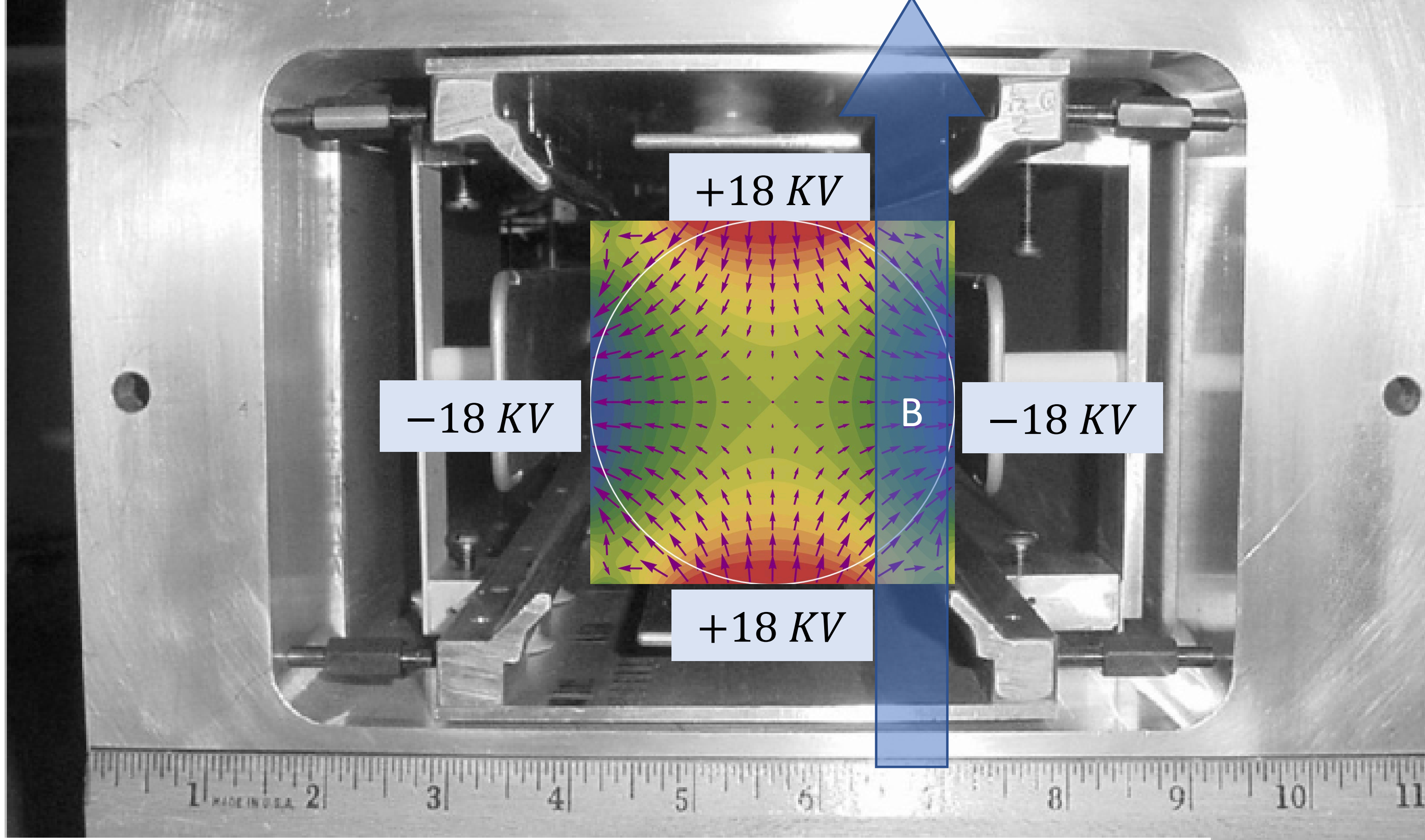
$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)}\right)$$

Beam Dynamics (arXiv:2104.03240v1)

Electrostatic Quadrupoles

Vertical Focusing

Horizontal Defocusing

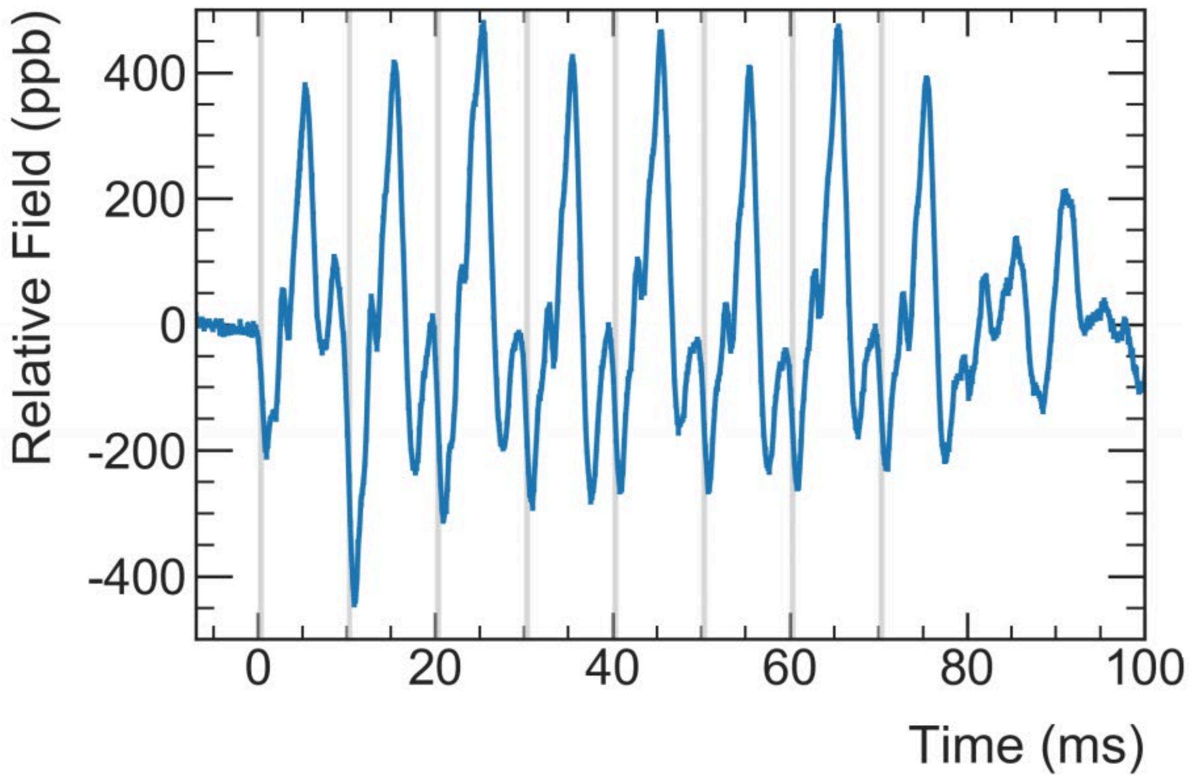


$$\frac{d(\hat{\beta}\cdot\vec{S})}{dt} = -\frac{q}{m}\vec{S}_T\cdot\left[a_\mu\hat{\beta}\times\vec{B} + \cancel{\beta\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{E}}{c}}\right], \tag{5}$$

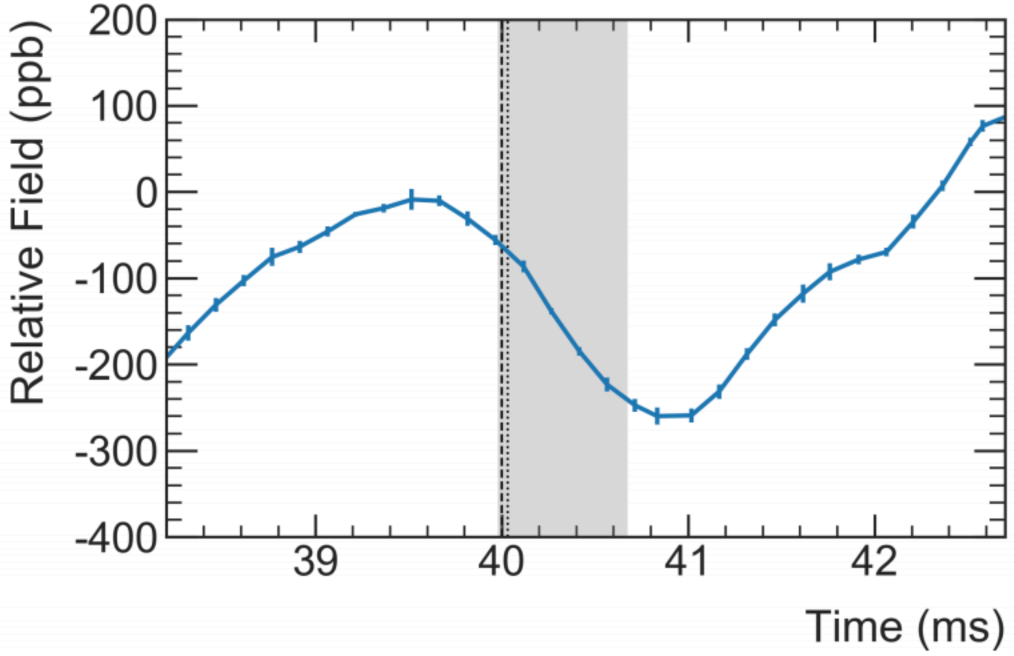
$$p_0 = 3.094\,\mathrm{GeV}/c\;(\gamma\sim 29.3)$$

Quadrupole Transient – Magnetic Field (arXiv:2104.03201v1)

Train of 8 Pulses of the Quad system



Transient during Muon Fill



Small Correction with large error

Beam Dynamics (arXiv:2104.03240v1)

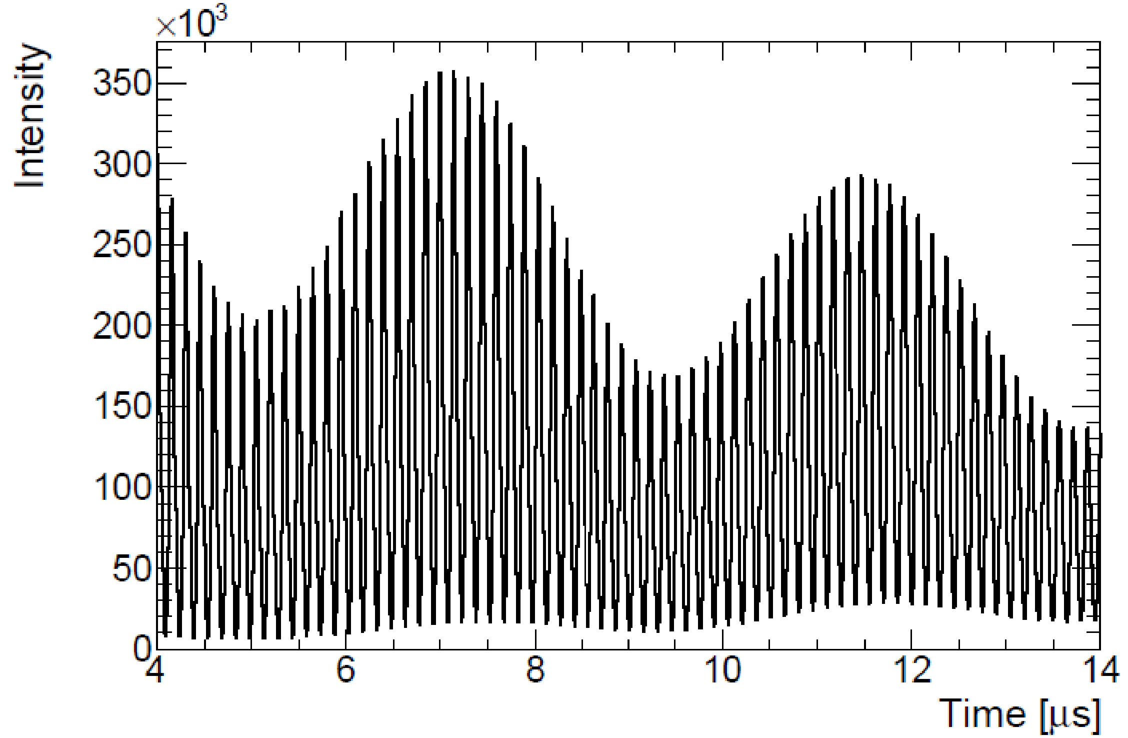


FIG. 4. Positron counts as a function of time as seen by all the calorimeters combined for the Run-1d data set for the time range $4-14\,\mu$s with respect to the beam injection. The time binning period is 1 ns. The amplitude modulation is from the muon spin rotation frequency ω_a^m.

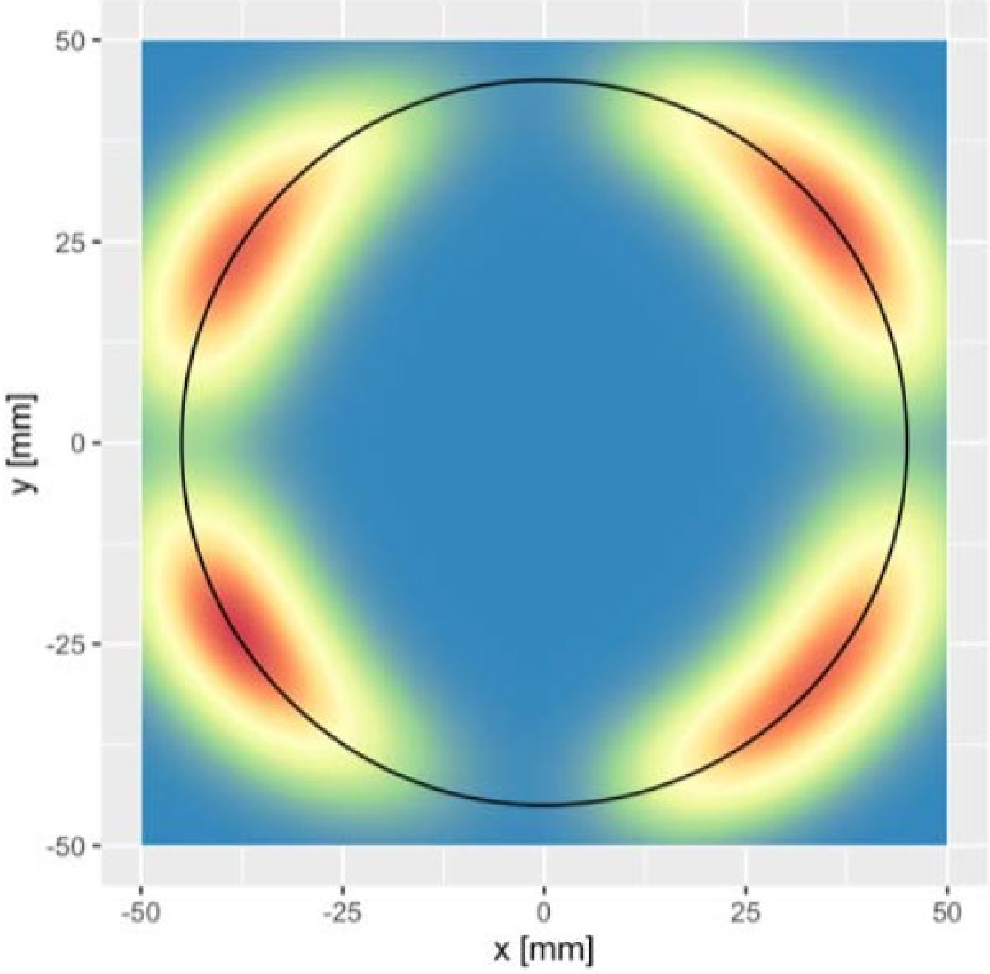


FIG. 13. The intensity distribution of where muons first strike the $r_0 = 45$ mm radius collimators (black circle). For any particular muon, this will occur when its horizontal and vertical betatron oscillations conspire such that the transverse displacement is at r_0 and, at the same time, it is at the azimuthal location in the storage ring of a collimator. Some muons, which will eventually be lost, can survive hundreds to thousands of turns before this condition is met.

Beam Dynamics (arXiv:2104.03240v1) Phase-Acceptance Correction

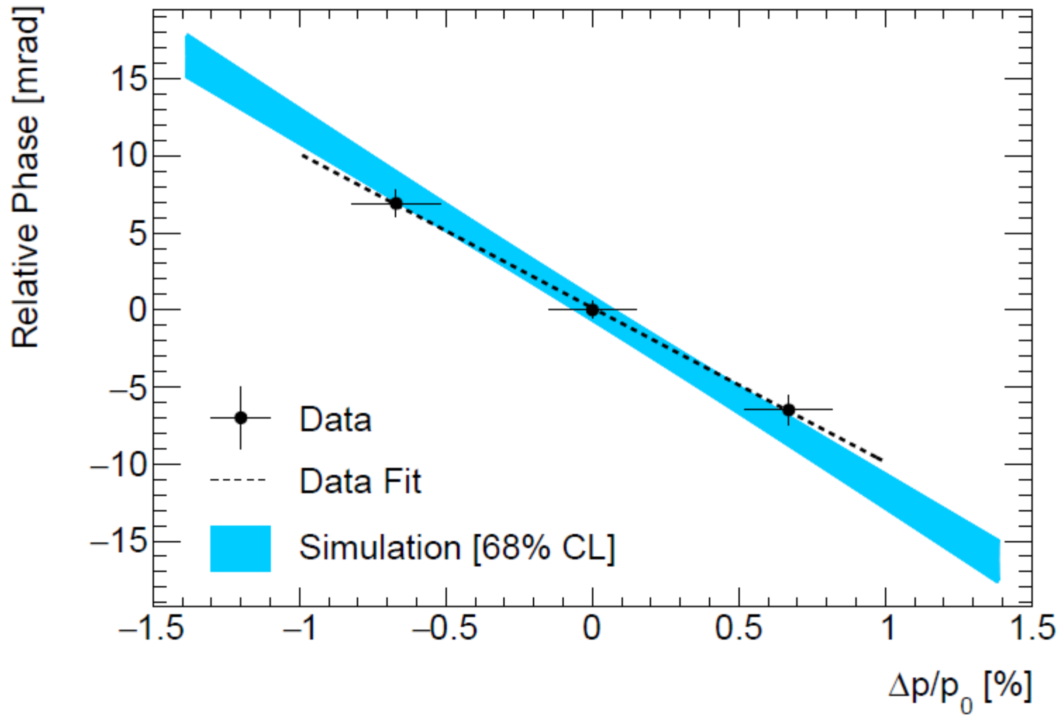


FIG. 15. Phase-momentum correlation from an end-to-end simulation (blue band) and from a data-driven approach (black). The simulation gives the result at the entrance to the storage ring. The three data points are obtained by fits to muon precession frequency data at nominal, reduced, and increased central magnetic field values. The phase reported for these data represented muons stored and fit during the measuring period. The phase dependence on momentum from the data is -10.0 ± 1.6 mrad/%$\Delta p/p_0$.

Expressing $\phi(t)$ as a power series $\phi_0 + \frac{d\phi}{dt}t + \mathcal{O}(\frac{d^2\phi}{dt^2})$, with the derivatives evaluated at $t = 0$,

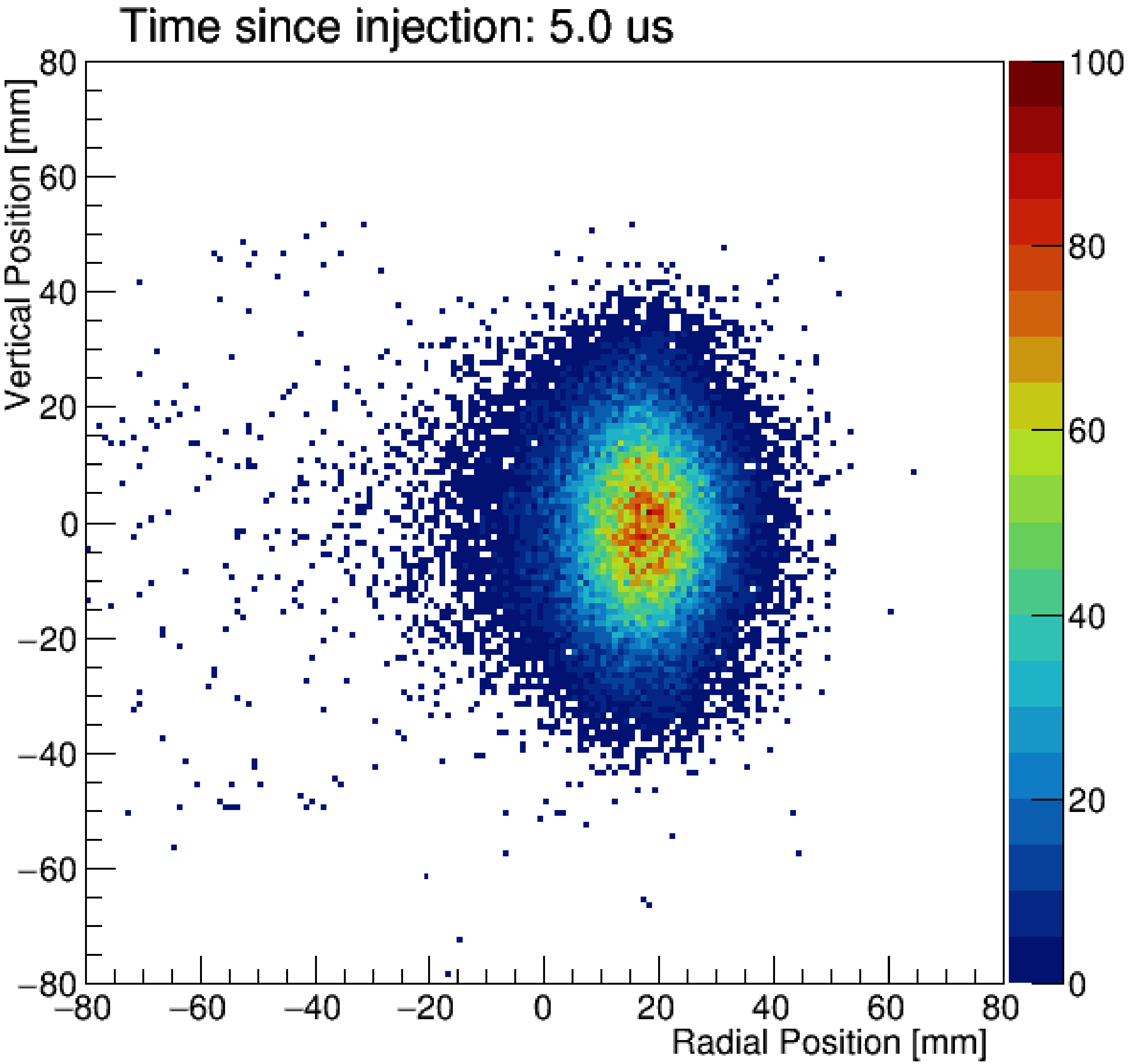
$$\begin{aligned}\cos(\omega_a t - \phi) &= \cos\left[\omega_a t - \phi_0 - \frac{d\phi}{dt}t + \mathcal{O}(\frac{d^2\phi}{dt^2})\right]\\ &= \cos\left[\left(\omega_a - \frac{d\phi}{dt}\right)t - \phi_0 + \mathcal{O}(\frac{d^2\phi}{dt^2})\right]\\ &= \cos\left[\omega'_a t - \phi_0 + \mathcal{O}(\frac{d^2\phi}{dt^2})\right] \qquad (3.3)\end{aligned}$$

One finds an observed precession frequency of $\omega'_a = \omega_a - d\phi/dt$.

The delivered beam has a mild phase vs. momentum dependence

Losses during a fill depend on momentum

The resulting phase change can not be distinguished from a frequency shift



Beam Dynamics
(arXiv:2104.03240v1)

Anomalous Precession Frequency (2014.03247v1)

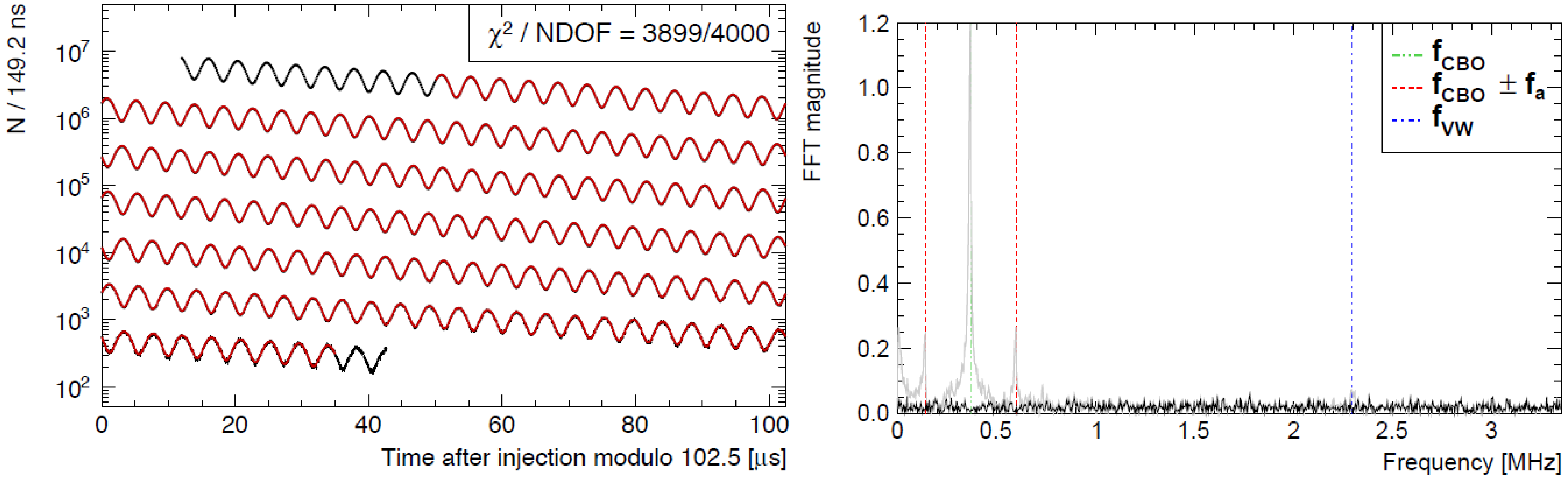


FIG. 16. Left: the overlay of the fit described in the text on the Run-1d precession data. Right: the FFT of the time distribution of residuals to that fit (black), which shows no remaining characteristic frequencies in the spectrum. For contrast, the residuals of the 5-parameter fit with no beam modeling are also shown (light gray), which helps to highlight the excellent performance of the fit including the modeling.

Magnetic Field (arXiv:2104.03201v1)

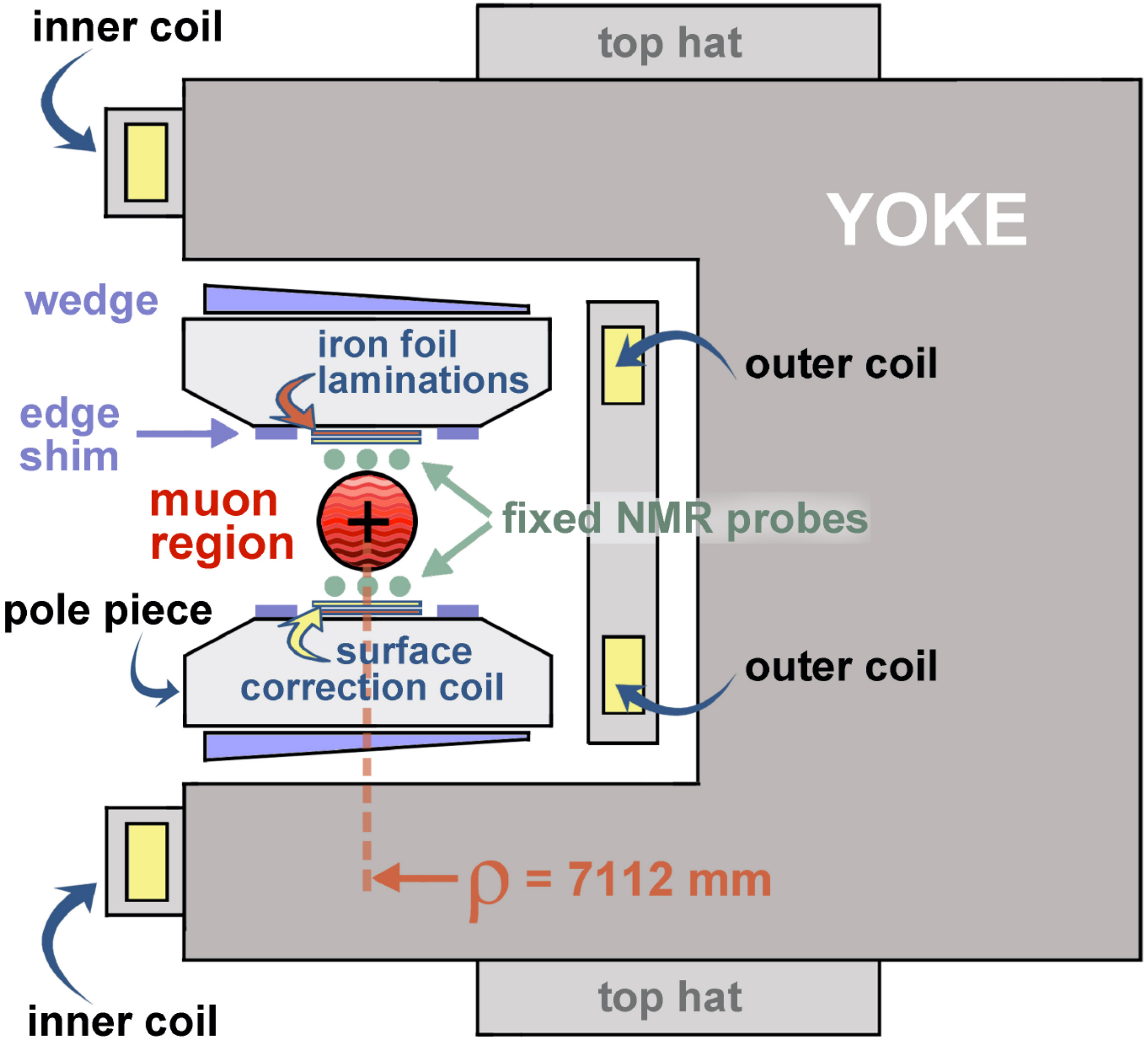


FIG. 2: A cross section of the storage ring magnet featuring the components used to generate the highly uniform 1.45 T magnetic field in the Run-1 configuration.

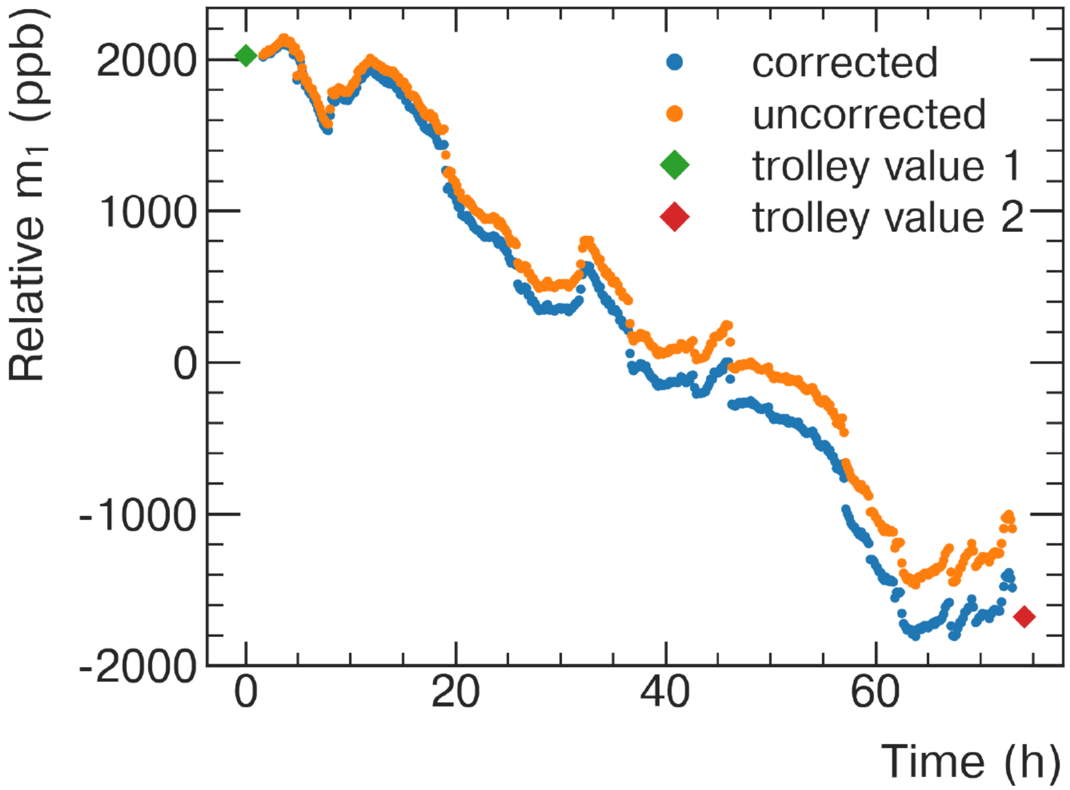


FIG. 17: Before the backward correction, the uncorrected tracking curve (light) can disagree with the measurement from the second trolley run. After the correction (dark), $\mathbf{m}_s^{tr}(t)$ is equal to the corresponding trolley measurements $\mathbf{m}_s^{tr}(0)$ (left diamond) and $\mathbf{m}_s^{tr}(T = 74\,\mathrm{h})$ (right diamond) at both bookending trolley runs. Note that this plot shows only a single station.

Magnetic Field (arXiv:2104.03201v1)

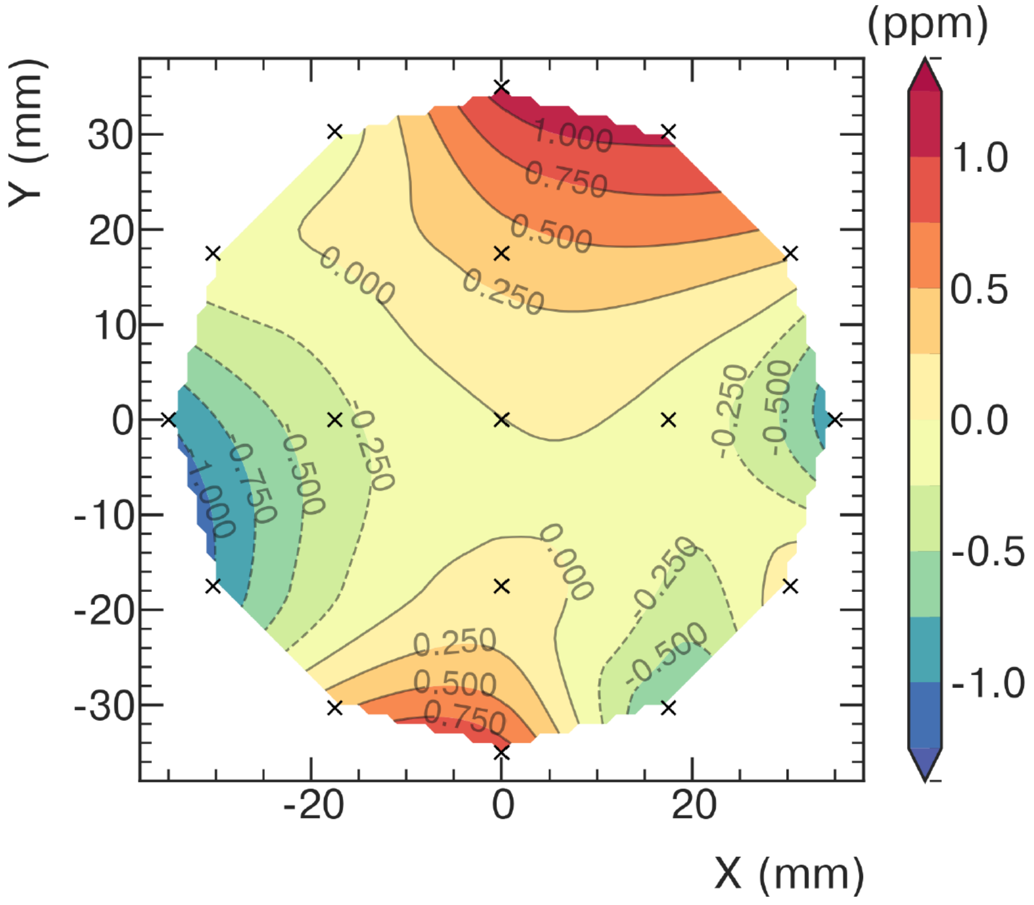
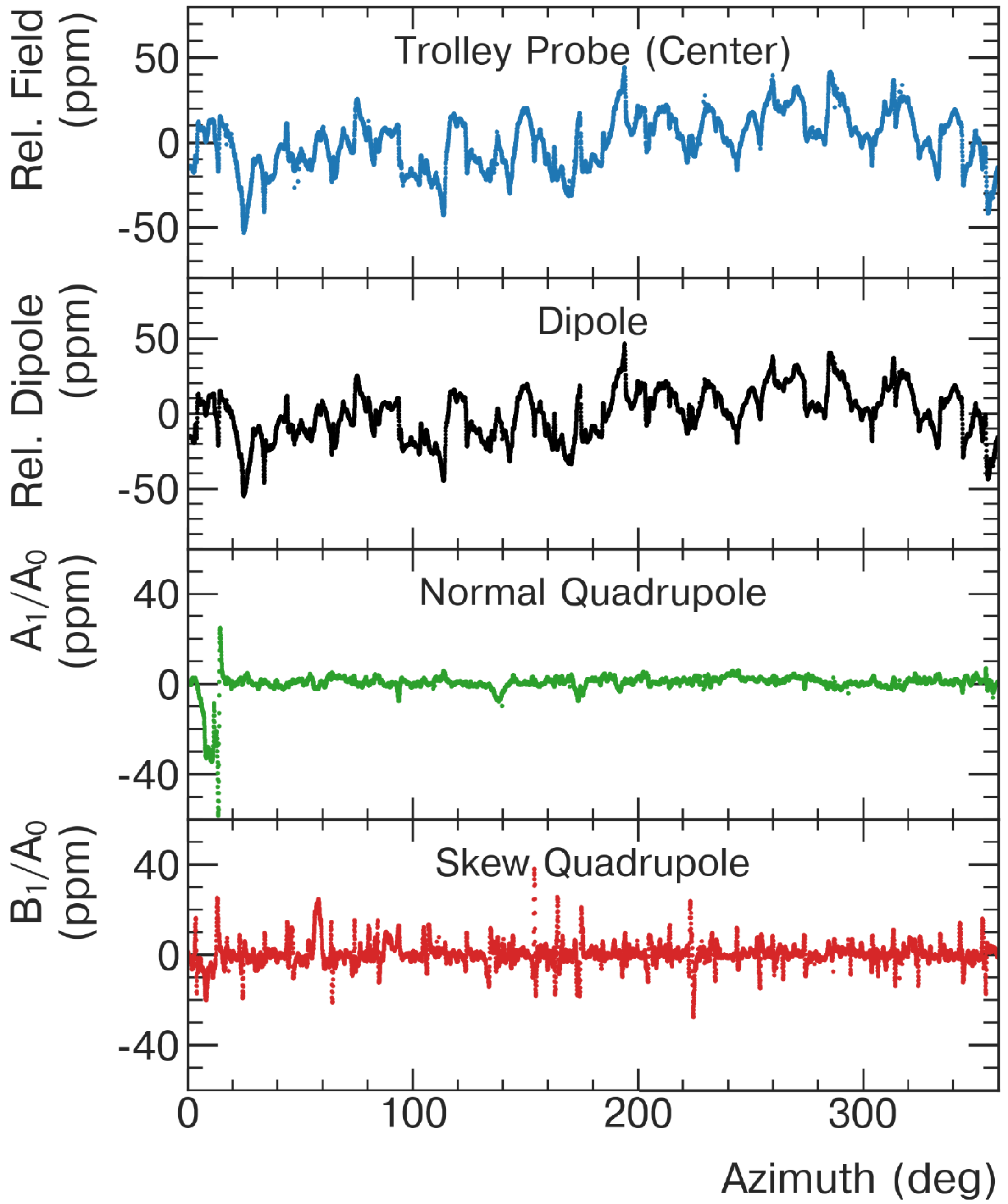


FIG. 13: Variations in the azimuthally averaged, relative frequency $(\omega_j^{\rm tr}(\phi,0) - \langle\omega_j^{\rm tr}\rangle)/\langle\omega_j^{\rm tr}\rangle$, for the central probe ($j = 1$). The locations of the 17 trolley probes are indicated by (x). Their raw frequencies are averaged and the field variations are interpolated.



Kicker (arXiv:2104.07805v1)

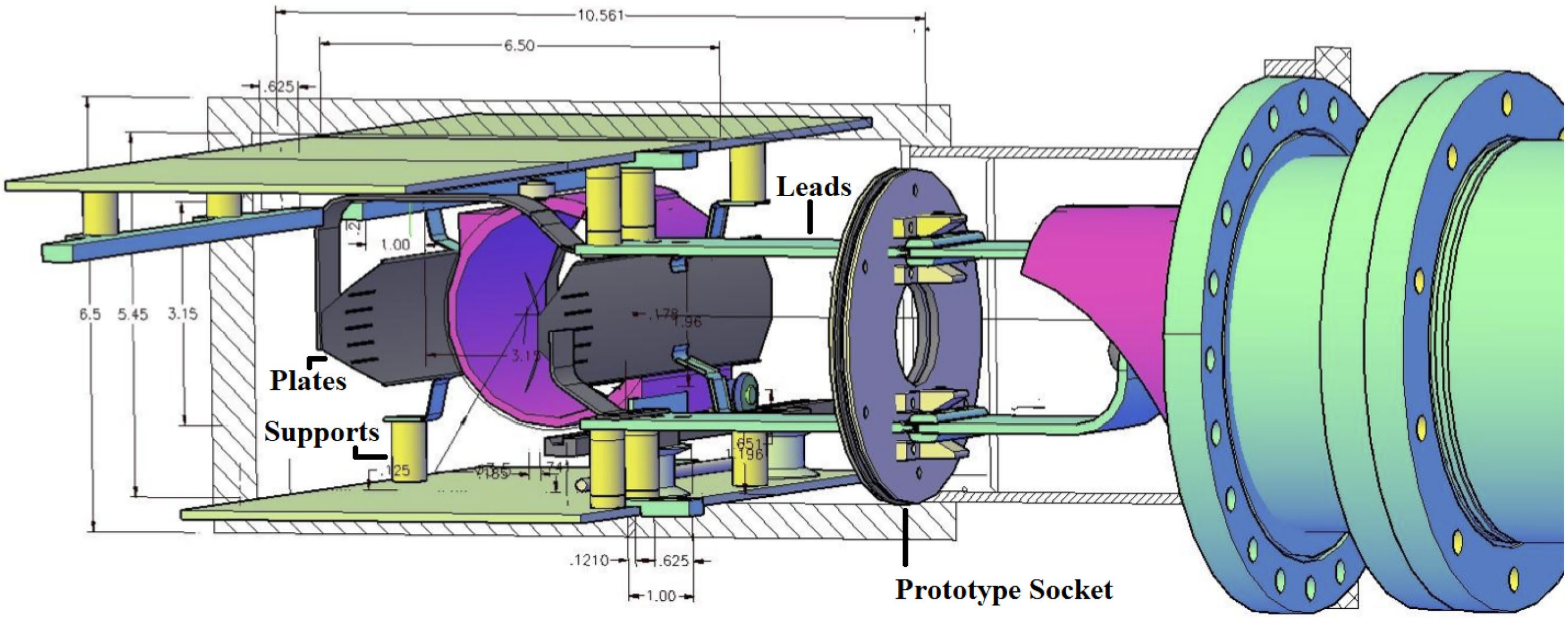
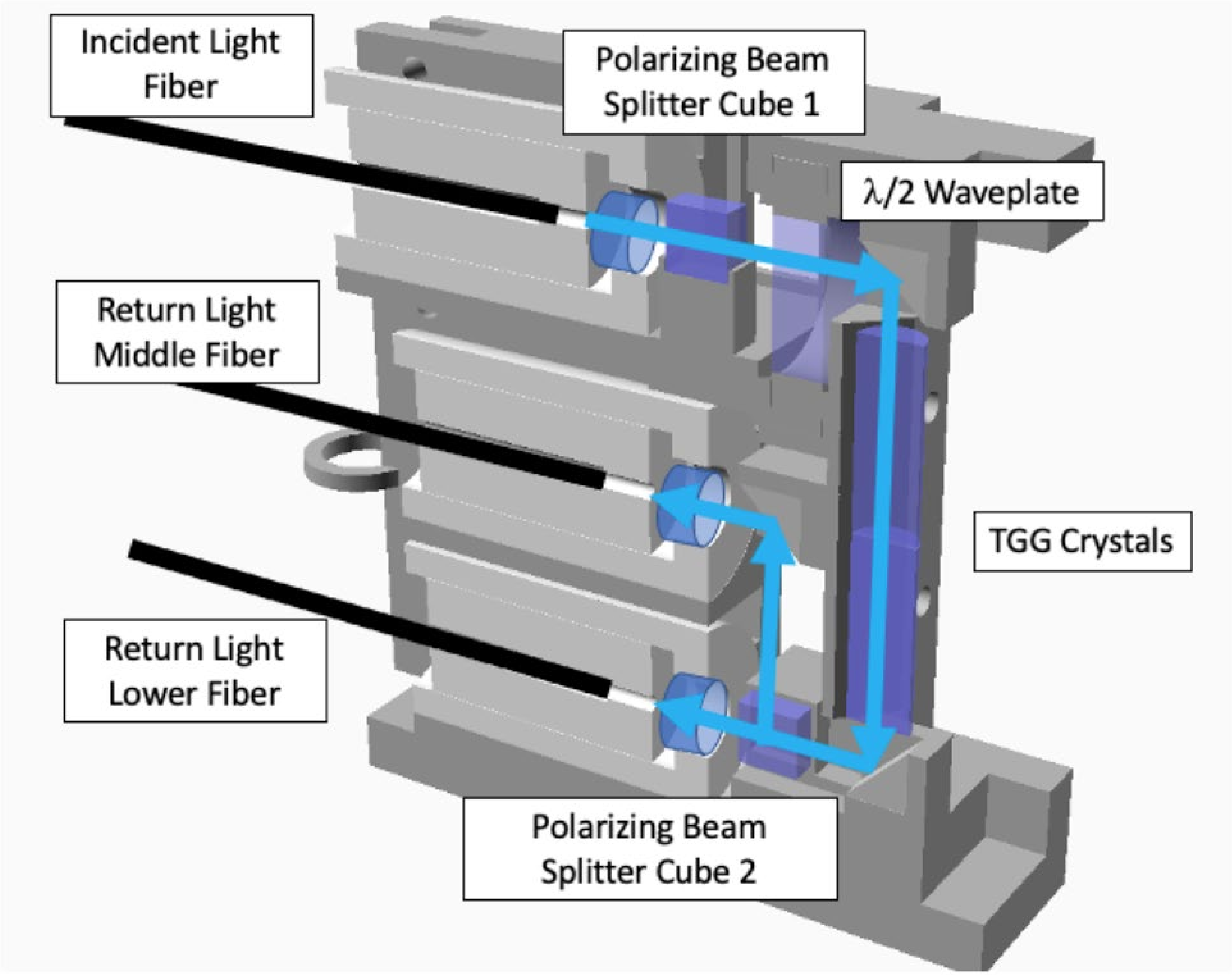
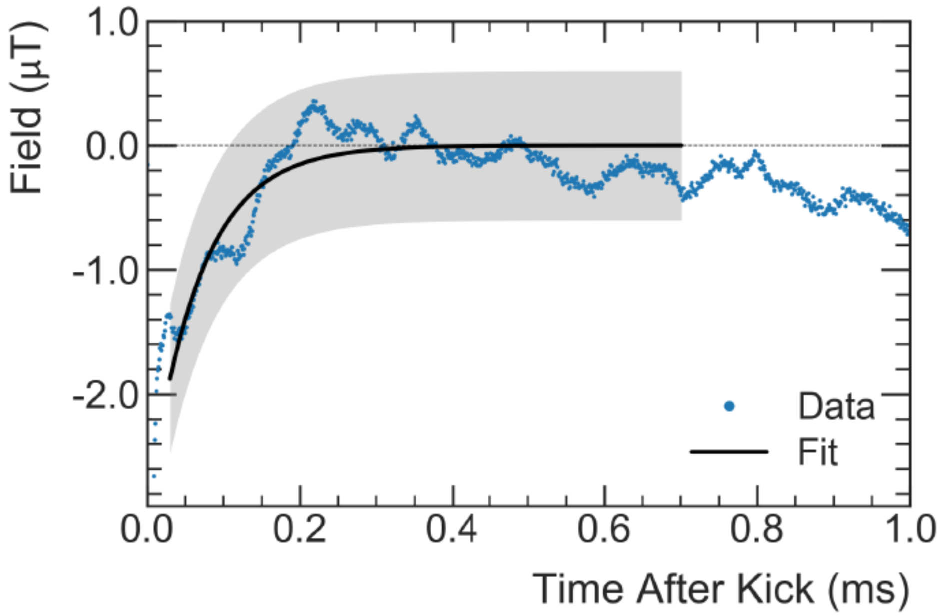


Figure 14: Isometric diagram of the SRV feedthrough, high voltage leads, and upstream end of the kicker magnet. This depiction represents the system prior to the start of Run-1. Aluminum sleds and Teflon sockets replaced the prototype socket shown. The beam storage region is displayed at left. We illustrate the kicker plates, current return, and support structures. The pictured ceramic standoffs are still used. However, we implemented a fluted design to opportunistically address breakdown points.

Kicker Transient – Magnetic Field (arXiv:2104.03201v1)



(a)



(b)

FIG. 22: (a) Schematic of the fiber magnetometer. The device is about 6 cm tall. (b) The signal measured by the fiber magnetometer after subtracting the vibration background. The measurements and a fit to the transient are shown. The gray shaded band represents the associated uncertainty of $\pm 0.6\,\mu\mathrm{T}$. Muon data are fit from $30\,\mu\mathrm{s}$ to $700\,\mu\mathrm{s}$ after the kick.

The Measurement to 0.46 ppm
arXiv:2104.03281v1

Quantity	Correction terms (ppb)	Uncertainty (ppb)	
ω_a^m (statistical)	–	434	Anomalous Precession Frequency (wiggle plot fit)
ω_a^m (systematic)	–	56	
C_e	489	53	Electric Field Correction
C_p	180	13	Pitch correction
C_{ml}	-11	5	Muon loss → changing phase correction
C_{pa}	-158	75	Phase acceptance correction
$f_{\text{calib}} \langle \omega'_p(x, y, \phi) \times M(x, y, \phi) \rangle$	–	56	Absolute calibration of NMR; B monitors; muon locations
B_k	-27	37	Residual field from Kicker
B_q	-17	92	Residual field from Quad Focusing
$\mu'_p(34.7^\circ)/\mu_e$	–	10	
m_μ/m_e	–	22	
$g_e/2$	–	0	
Total systematic	–	157	
Total fundamental factors	–	25	
Totals	544	462	

TABLE II. Values and uncertainties of the $\mathcal{R}'_\mu$ correction terms in Eq. 4, and uncertainties due to the constants in Eq. 2 for a_μ. Positive C_i increase a_μ and positive B_i decrease a_μ.

We quote all errors as “gaussian errors” and combine normally, with correlations.

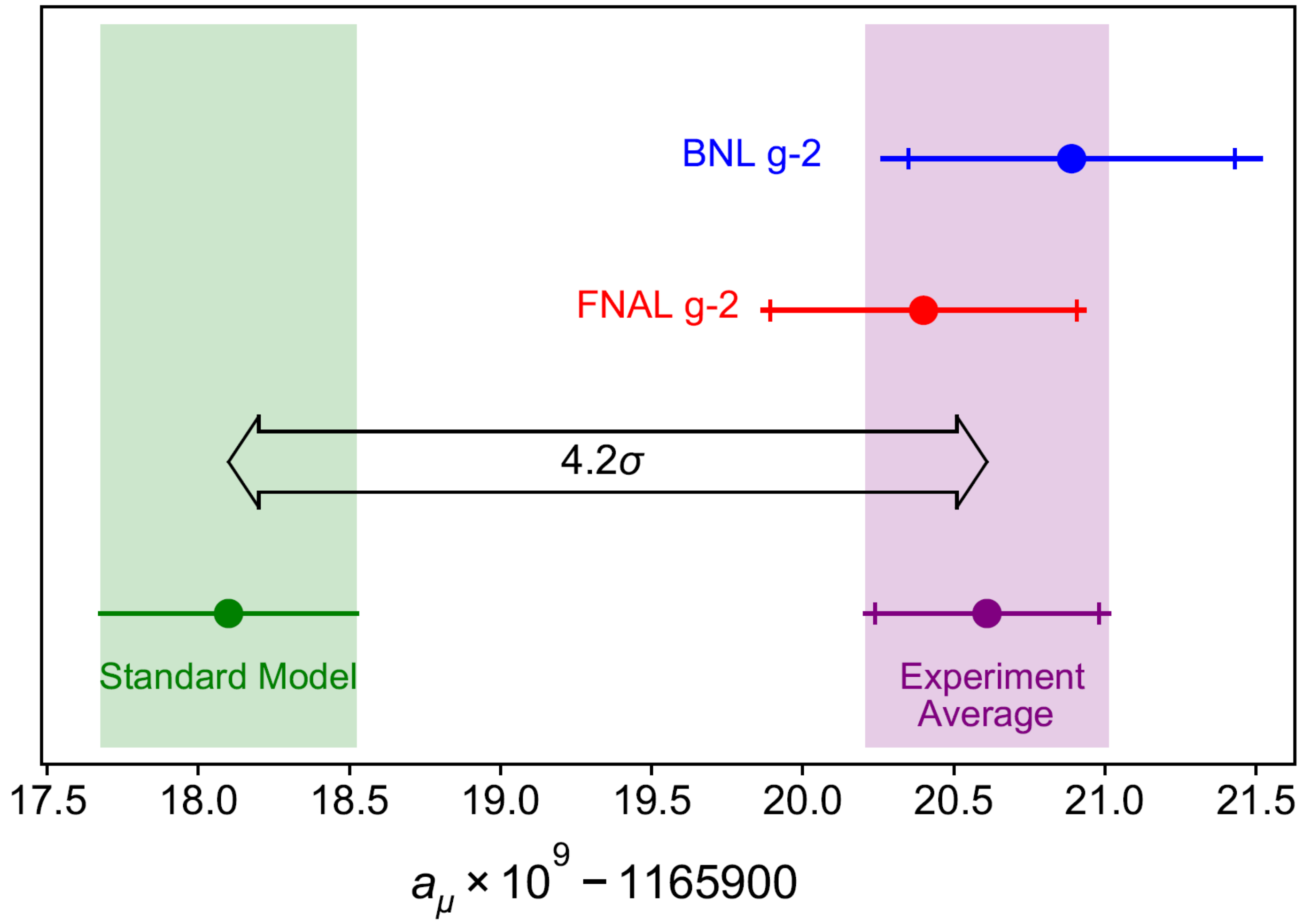


FIG. 4. From top to bottom: experimental values of a_μ from BNL E821, this measurement, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g-2$ Theory Initiative recommended value [13] for the standard model is also shown.

What does it all mean?

An “expert” weighs in

Conclusions

- The Fermilab g-2 experiment works!
- We are increasing statistics x16 or more
- We are reducing systematics
- Two challenges (non-centered beam and quad focusing) test our systematic corrections
- Both of these have been addressed
- We will do more systematic studies

- No evidence of anything worth changing in the BNL result. (Except for updating external constants.)

Speculation

When two numbers that you think should agree do not agree, at least one of the following is true:

A) The first number (this measurement) is mistaken.

- Unlucky statistics; Extremely subtle systematics; Plain old mistakes

➔Continue running FNAL g-2

➔J-PARC experiment

B) The second number (theory) is mistaken.

- Hadronic corrections are notorious
- Lattice calculation

➔Motivation for renewed theoretical work

➔MUonE measurements of difficult terms

C) Our thinking (the Standard Model) is mistaken

- New particles/forces

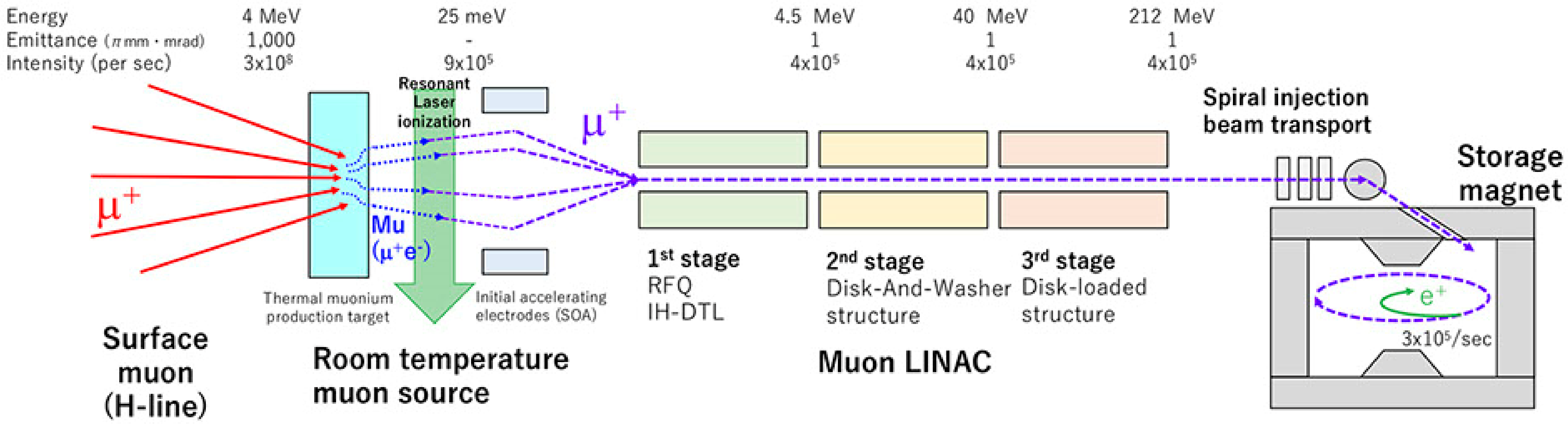
➔ New physics explanations (via Dominik's Stoeckinger) arXiv:2104.03691v2

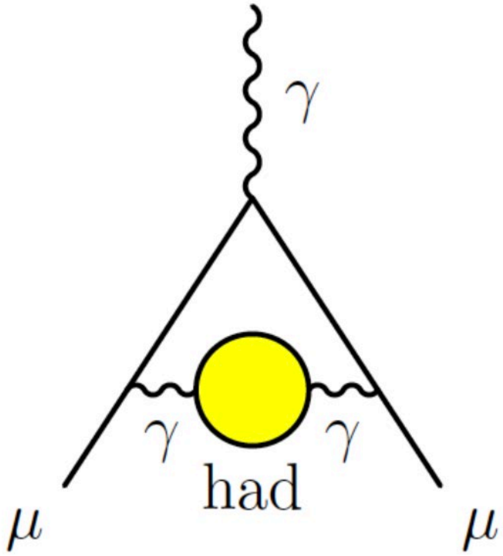
➔Speculation abounds on arXiv:

Supersymmetry! Leptoquarks! LHCb mu/e! CKM non-unitarity! Dark Matter! Fifth Force!

The Future

Orthogonal experiment: J-PARC https://g-2.kek.jp/portal/index.html





The Future

MUonE

The MUonE experiment aims at a completely independent and very precise measurement of the leading hadronic contribution to the muon magnetic moment, achievable with a novel method, as proposed in Eur.Phys.J. C77 (2017) 139.

https://www.bo.infn.it/gruppo1/en/the-muone-project/

Workshop: Potential Muon Campus & Storage Ring Experiments

https://indico.fnal.gov/event/48469/

Virtual Workshop May 24-27 2021

This workshop provides a venue for exploring ideas to build short-, medium-, and long-term muon- and non-muon-based experiments that will have a small incremental cost on top of existing infrastructure investments. The goal of this workshop is to promote the development of proposals for the Fermilab PAC review process and current Snowmass exercise.

Program Committee

Esra Barlas-Yucel	*University of Illinois*
André de Gouvêa	*Northwestern University*
Anna Driutti	*University of Kentucky*
Aida El-Khadra	*University of Illinois*
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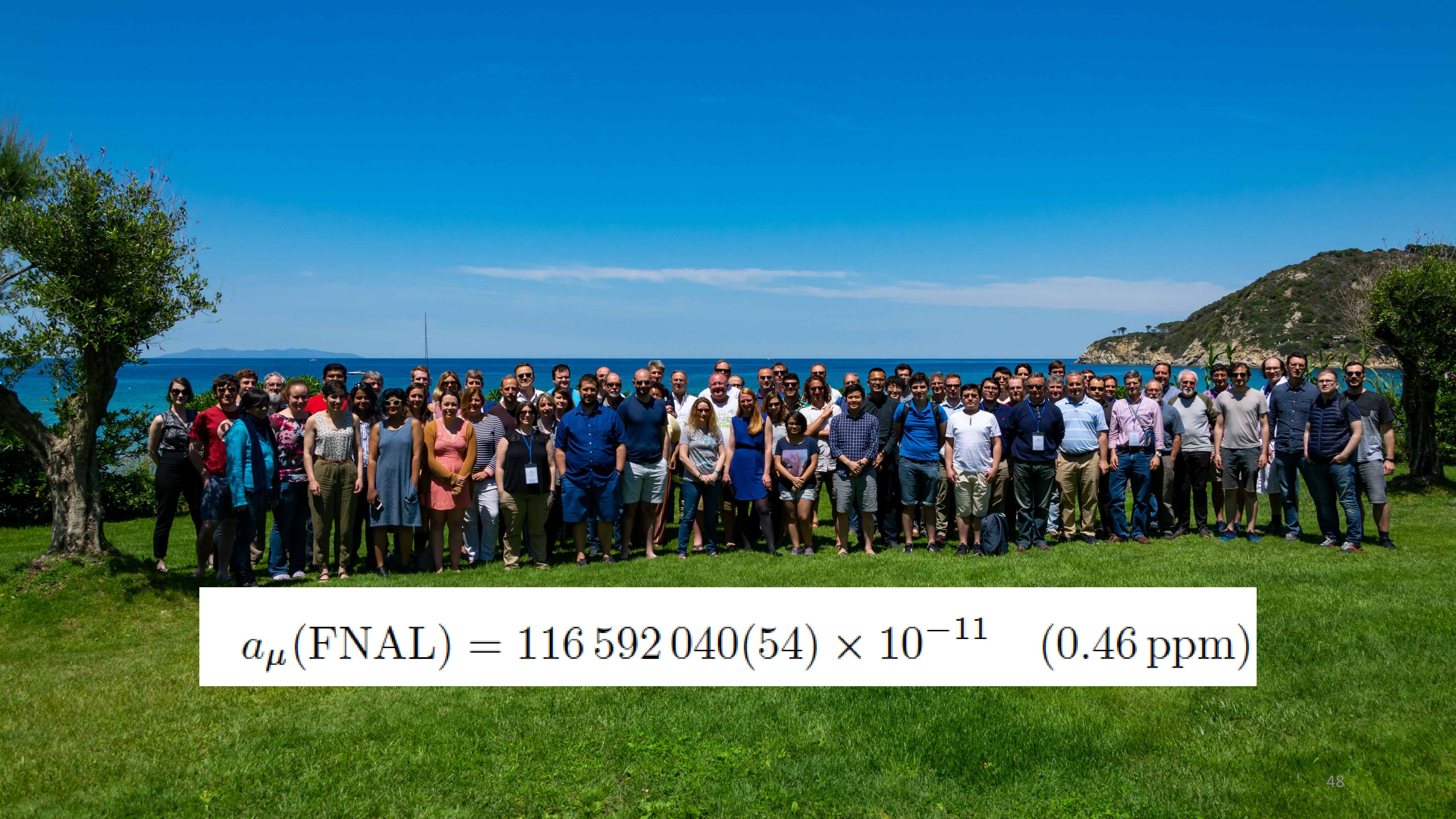

$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$