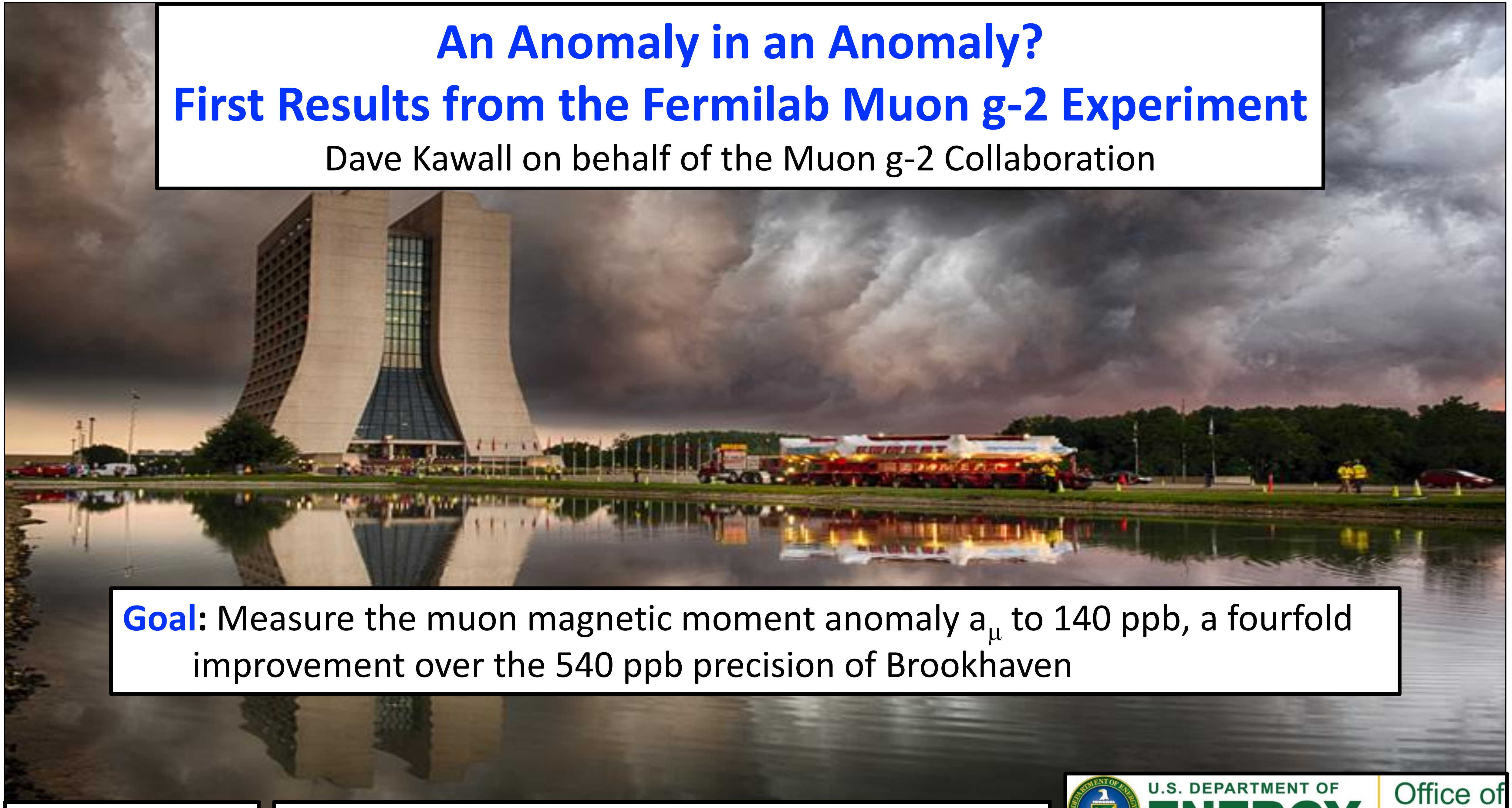
An Anomaly in an Anomaly?
First Results from the Fermilab Muon g-2 Experiment

Dave Kawall on behalf of the Muon g-2 Collaboration



Goal: Measure the muon magnetic moment anomaly a_μ to 140 ppb, a fourfold improvement over the 540 ppb precision of Brookhaven

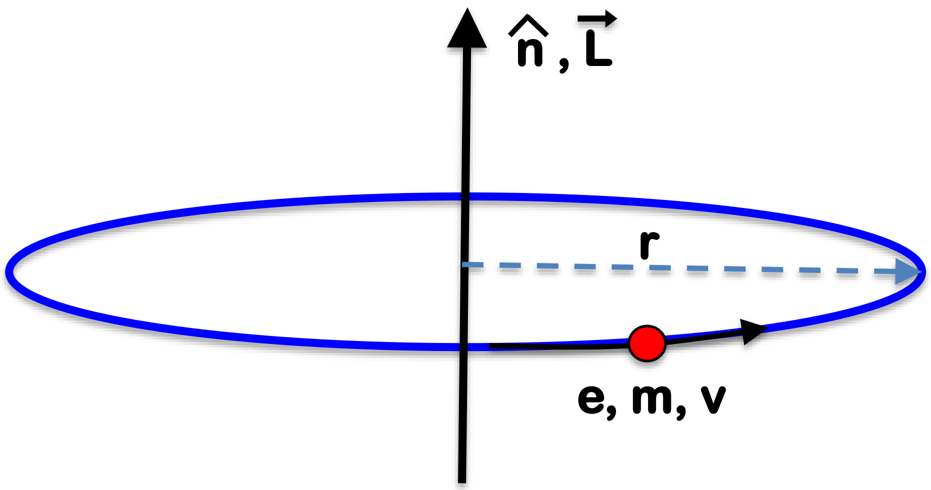
UMass Amherst

SSP2022, August 31st, 2022

U.S. DEPARTMENT OF ENERGY | Office of Science

- Magnetic dipole moment of current loop:

$$
\begin{aligned}
\vec{\mu} &= \frac{IA}{c}\,\hat{n} \\
&= \frac{1}{c}\,\frac{ev}{2\pi r}\,\pi r^2\,\hat{n} \\
&= \frac{e}{2mc}\,mvr\,\hat{n} \\
\vec{\mu} &= \frac{e}{2mc}\,\vec{L}
\end{aligned}
$$

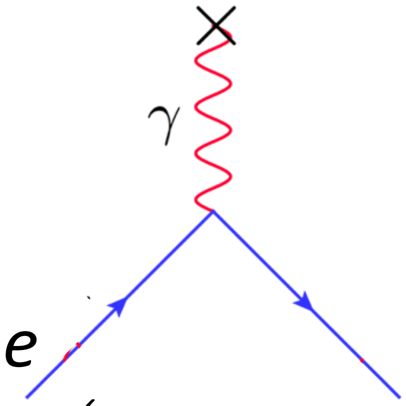


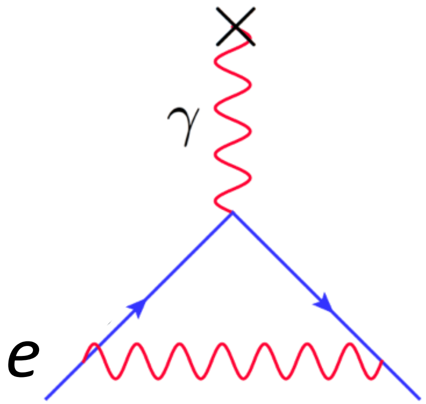
- 1925: Anomalous Zeeman effect could be explained by intrinsic electron spin with magnetic moment
- 1928: Dirac predicts g=2 for fundamental spin 1/2 particle, huge success
- 1933: Stern proposes measurement of g_{proton}. Pauli "Don't you know the Dirac theory? It's obvious $g_p = 2$"

The Magnetic Moment *Anomaly*

- 1947: Rabi 0.3% discrepancies in ground-state HFS of H,D
- 1947: Kusch and Foley discrepancy in Ga spectroscopy explained if $g_e = 2.00229(8)$
- 1947: Schwinger calculates correction $g_e = 2\,(1 + \alpha/2\pi) \;=\; 2.002324$
- $g_e = 2(1 + a_e)$ defines magnetic moment anomaly, $a_e \equiv \dfrac{(g_e - 2)}{2} \approx \dfrac{\alpha}{2\pi} \approx 0.001162$

J. Schwinger





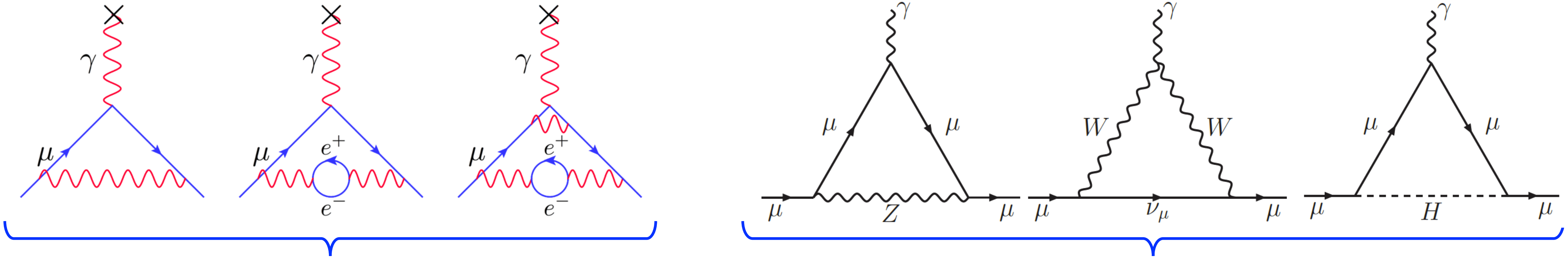
$$g_e \;=\; 2\left(\;1 \qquad + \qquad \frac{\alpha}{2\pi}\;\right)$$

Dirac — Schwinger

- Anomaly a_e due to radiative corrections from virtual particles in loops
- 1 part in 850 effect, huge success for QED !

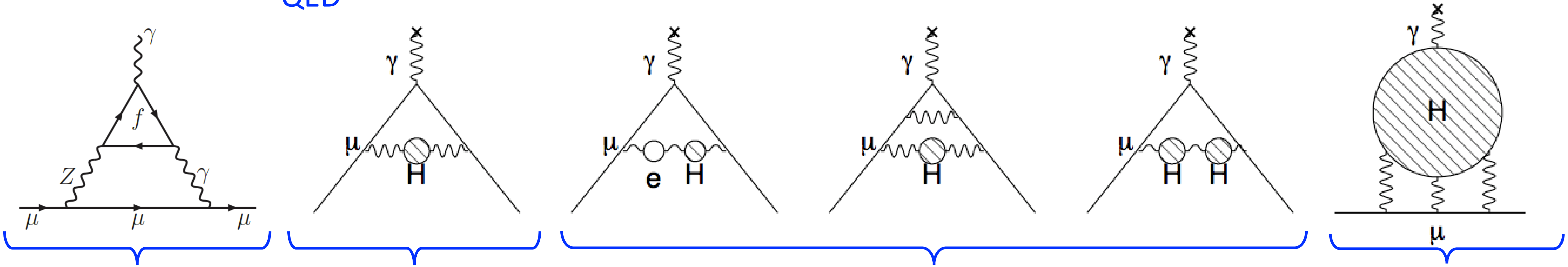
Contributions to the Magnetic Moment Anomaly of the Muon

$$a_\mu(\text{Standard Model}) = a_\mu(\text{QED}) + a_\mu(\text{Weak}) + a_\mu(\text{Hadronic})$$



QED

EW 1 Loop



EW 2 Loop

Hadronic Leading Order

Hadronic Higher Order

Light-by-Light

$\Rightarrow$ a_μ gets contributions from *all* physics - including the unknown

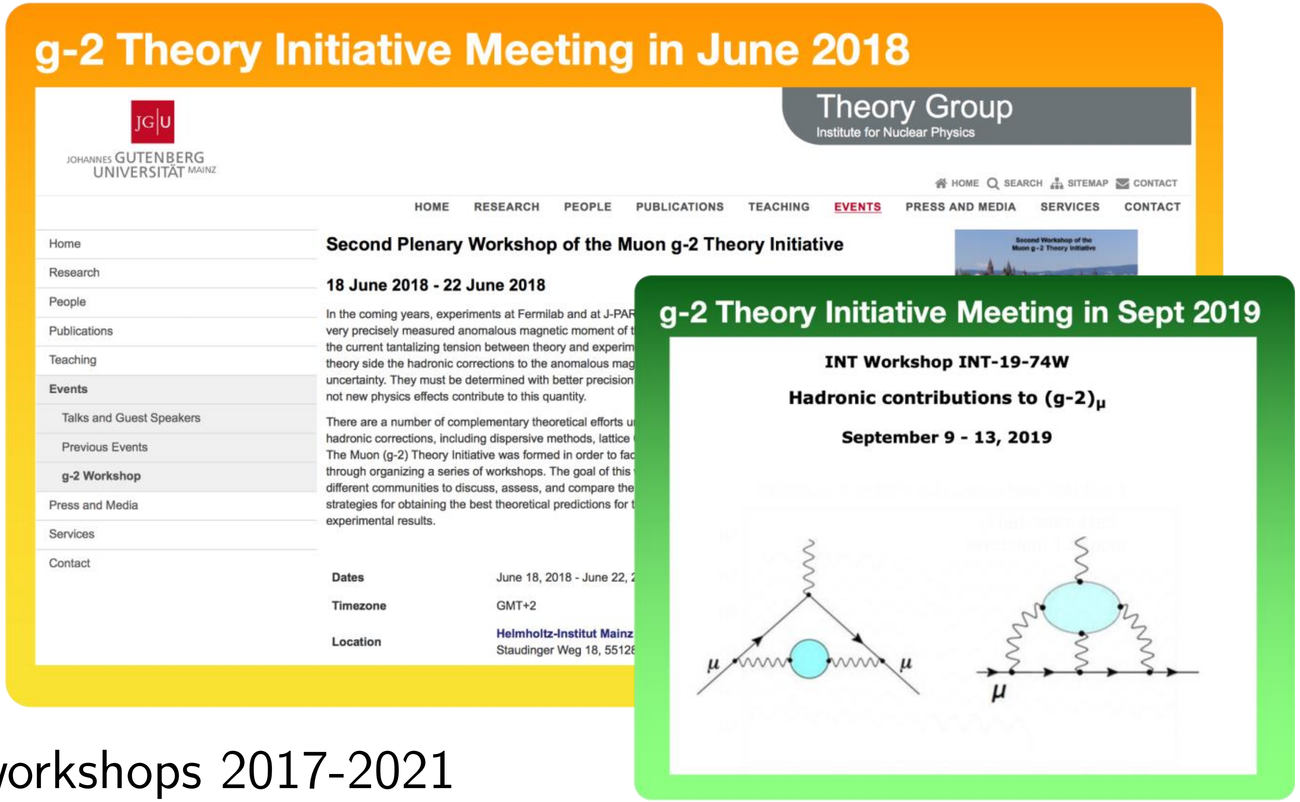
Muon g-2 Theory Initiative: Definitive Standard Model Prediction

arXiv:2006.04822v2 [hep-ph] 13 Nov 2020

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama[1,2,3], N. Asmussen[4], M. Benayoun[5], J. Bijnens[6], T. Blum[7,8], M. Bruno[9], I. Caprini[10], C. M. Carloni Calame[11], M. Cè[9,12,13], G. Colangelo[†14], F. Curciarello[15,16], H. Czyż[17], I. Danilkin[12], M. Davier[†18], C. T. H. Davies[19], M. Della Morte[20], S. I. Eidelman[†21,22], A. X. El-Khadra[†23,24], A. Gérardin[25], D. Giusti[26,27], M. Golterman[28], Steven Gottlieb[29], V. Gülpers[30], F. Hagelstein[14], M. Hayakawa[31,2], G. Herdoíza[32], D. W. Hertzog[33], A. Hoecker[34], M. Hoferichter[†14,35], B.-L. Hoid[36], R. J. Hudspith[12,13], F. Ignatov[21], T. Izubuchi[37,8], F. Jegerlehner[38], L. Jin[7,8], A. Keshavarzi[39], T. Kinoshita[40,41], B. Kubis[36], A. Kupich[21], A. Kupść[42,43], L. Laub[14], C. Lehner[†26,37], L. Lellouch[25], I. Logashenko[21], B. Malaescu[5], K. Maltman[44,45], M. K. Marinković[46,47], P. Masjuan[48,49], A. S. Meyer[37], H. B. Meyer[12,13], T. Mibe[†1], K. Miura[12,13,3], S. E. Müller[50], M. Nio[2,51], D. Nomura[52,53], A. Nyffeler[†12], V. Pascalutsa[12], M. Passera[54], E. Perez del Rio[55], S. Peris[48,49], A. Portelli[30], M. Procura[56], C. F. Redmer[12], B. L. Roberts[†57], P. Sánchez-Puertas[49], S. Serednyakov[21], B. Shwartz[21], S. Simula[27], D. Stöckinger[58], H. Stöckinger-Kim[58], P. Stoffer[59], T. Teubner[†60], R. Van de Water[24], M. Vanderhaeghen[12,13], G. Venanzoni[61], G. von Hippel[12], H. Wittig[12,13], Z. Zhang[18],

M. N. Achasov[21], A. Bashir[62], N. Cardoso[47], B. Chakraborty[63], E.-H. Chao[12], J. Charles[25], A. Crivellin[64,65], O. Deineka[12], A. Denig[12,13], C. DeTar[66], C. A. Dominguez[67], A. E. Dorokhov[68], V. P. Druzhinin[21], G. Eichmann[69,47], M. Fael[70], C. S. Fischer[71], E. Gámiz[72], Z. Gelzer[23], J. R. Green[9], S. Guellati-Khelifa[73], D. Hatton[19], N. Hermansson-Truedsson[14], S. Holz[36], B. Hörz[74], M. Knecht[25], J. Koponen[1], A. S. Kronfeld[24], J. Laiho[75], S. Leupold[42], P. B. Mackenzie[24], W. J. Marciano[37], C. McNeile[76], D. Mohler[12,13], J. Monnard[14], E. T. Neil[77], A. V. Nesterenko[68], K. Ottnad[12], V. Pauk[12], A. E. Radzhabov[78], E. de Rafael[25], K. Raya[79], A. Risch[12], A. Rodríguez-Sánchez[6], P. Roig[80], T. San José[12,13], E. P. Solodov[21], R. Sugar[81], K. Yu. Todyshev[21], A. Vainshtein[82], A. Vaquero Avilés-Casco[66], E. Weil[71], J. Wilhelm[12], R. Williams[71], A. S. Zhevlakov[78]



- Collaboration of 100+ theorists, held 7 workshops 2017-2021
- Goal: Study all theory inputs, provide definitive SM prediction for a_μ
- T. Aoyama *et al.*, Physics Reports **887**, 1-166 (2020)
- 166 pages, 132 authors, 82 institutions, 21 countries, 822 references

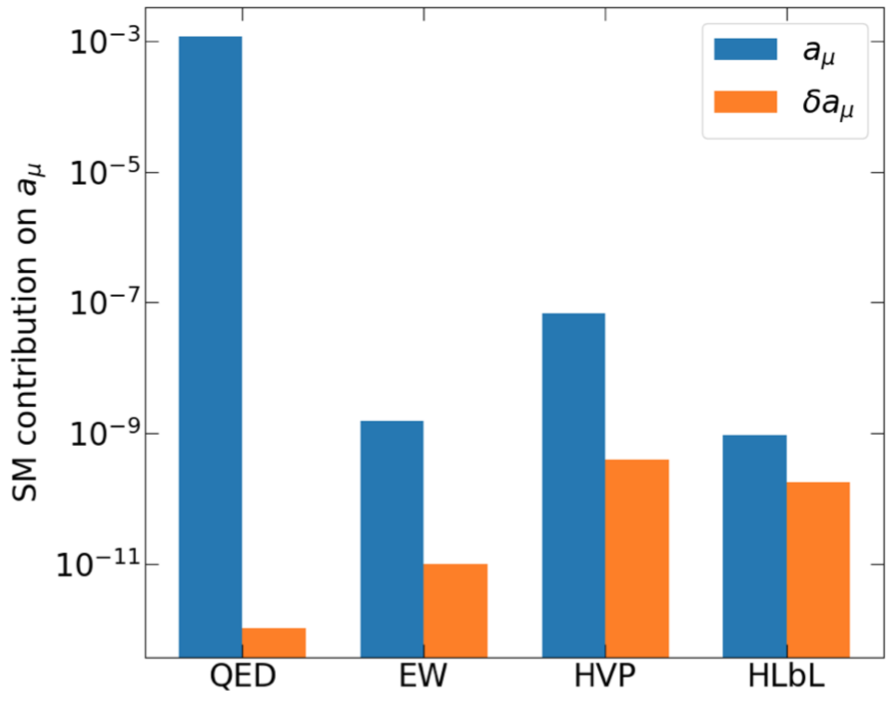
⇒ We compare experiment result with this recommended value

⇒ Theory work ongoing, Sept 2022 workshop, update in 2023

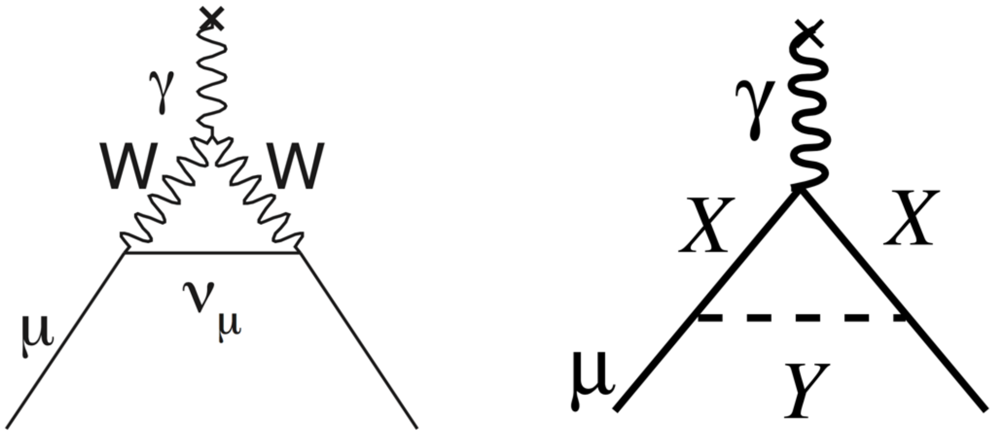
The Standard Model Prediction of a_μ

$$
\begin{array}{lcrl}
a_\mu(\text{QED}) & = & 116\;584\;718.931 & \pm\; 0.104 \\
a_\mu(\text{HadVP};\, e^+e^-,\ \text{LO+NLO+NNLO}) & = & 6\;845. & \pm\; 40 \\
a_\mu(\text{Weak; 2 loops}) & = & 153.6 & \pm\; 1.0 \\
a_\mu(\text{Had; LBL}) & = & 92. & \pm\; 18 \\
\hline
a_\mu(\text{Standard Model}) & = & 116\;591\;810. & \pm\; 43 \;\times 10^{-11}
\end{array}
$$

- T. Aoyama *et al.* (Theory Initiative Whitepaper), "The anomalous magnetic moment of the muon in the Standard Model", Physics Reports **887**, 1-166, Dec 2020.
- Uses data-driven approach to HVP
- Prediction has impressive precision: 370 ppb



- $a_e = (g_e - 2)/2$ determined to 0.24 ppb
- Muons live 2.2 μseconds - why measure a_μ ?



$$a_\mu(W) \approx \frac{10}{3}\frac{G_F m_\mu^2}{8\sqrt{2}\pi^2} = g^2 \frac{10}{192\pi^2}\left(\frac{m_\mu}{M_W}\right)^2 \approx 195 \times 10^{-11}$$

⇒ Contribution of new physics $\approx \left(\frac{m_{e,\mu}}{M_X}\right)^2$

⇒ Muon mass 206 times electron mass ⇒ new physics contribution 43,000 times larger

⇒ New physics contribution of 0.24 ppb on a_e ⇔ 9 ppm on a_μ

⇒ With much lower precision, a_μ sensitive to much higher mass scales


Muon g-2 Collaboration
7 Countries, 35 Institutions, 203 Collaborators
Argonne National Laboratory
Boston University
Brookhaven National Laboratory
Budker Institute of Nuclear Physics
CAPP/IBS Korea
Cornell University
Fermi National Accelerator Lab
INFN, Sezione di Napoli
INFN, Sezione di Pisa
INFN, Sezione di Roma Tor Vergata
INFN, Sezione di Trieste
James Madison University
Johannes Gutenberg Univ. Mainz
JINR Dubna
KAIST
Laboratory Nazionali di Frascati
Lancaster University
Michigan State University
North Central College
Northern Illinois University
Regis University
Shanghai Jiao Tong University
Technische Universitat Dresden
Universita di Molise
Universita di Udine
University College London
University of Illinois at Urbana-Champaign
University of Kentucky
University of Liverpool
University of Manchester
University of Massachusetts Amherst
University of Michigan
University of Mississippi
University of Virginia
University of Washington

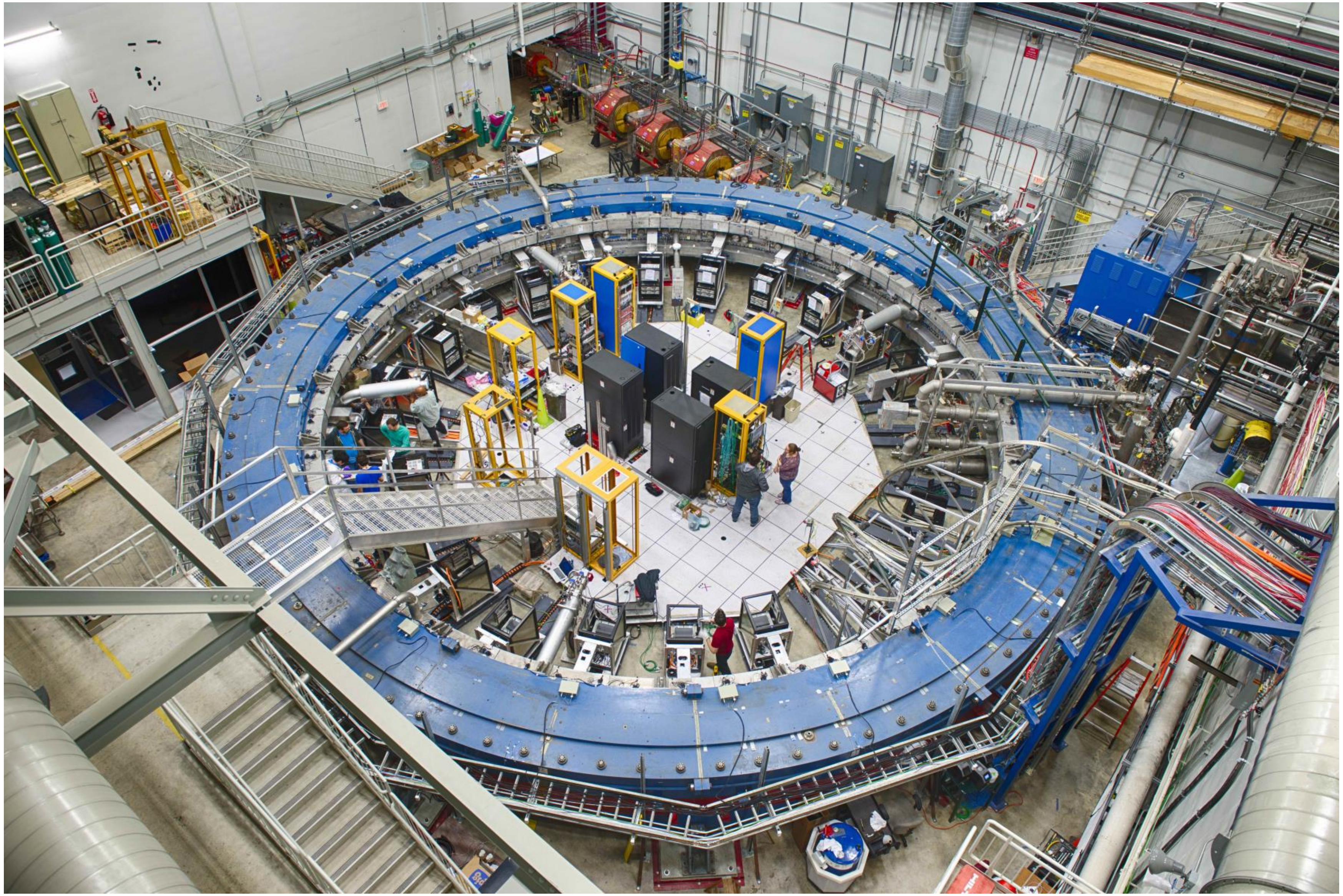
The Big Move: From Brookhaven to Fermilab in 2013

- Martin Perl: Nature is hard and unyielding

Transporting the Coils to Fermilab: Shut down 2 interstates!

- Trailer with coils passes toll arches with 6" clearance on each side

The new Muon g-2 Experiment at Fermilab



Goal: Measure the muon magnetic moment anomaly a_μ to 140 ppb, a fourfold improvement over the 540 ppb precision of Brookhaven

$\Rightarrow$ Brookhaven statistics limited:

$$a_\mu^{\mathrm{BNL}} = 0.001\,165\,920\,89\,(54)_{\mathrm{stat}}\,(33)_{\mathrm{sys}}$$

- BNL ± 540 ppb uncertainty $\Leftrightarrow$ 9×10^9 events

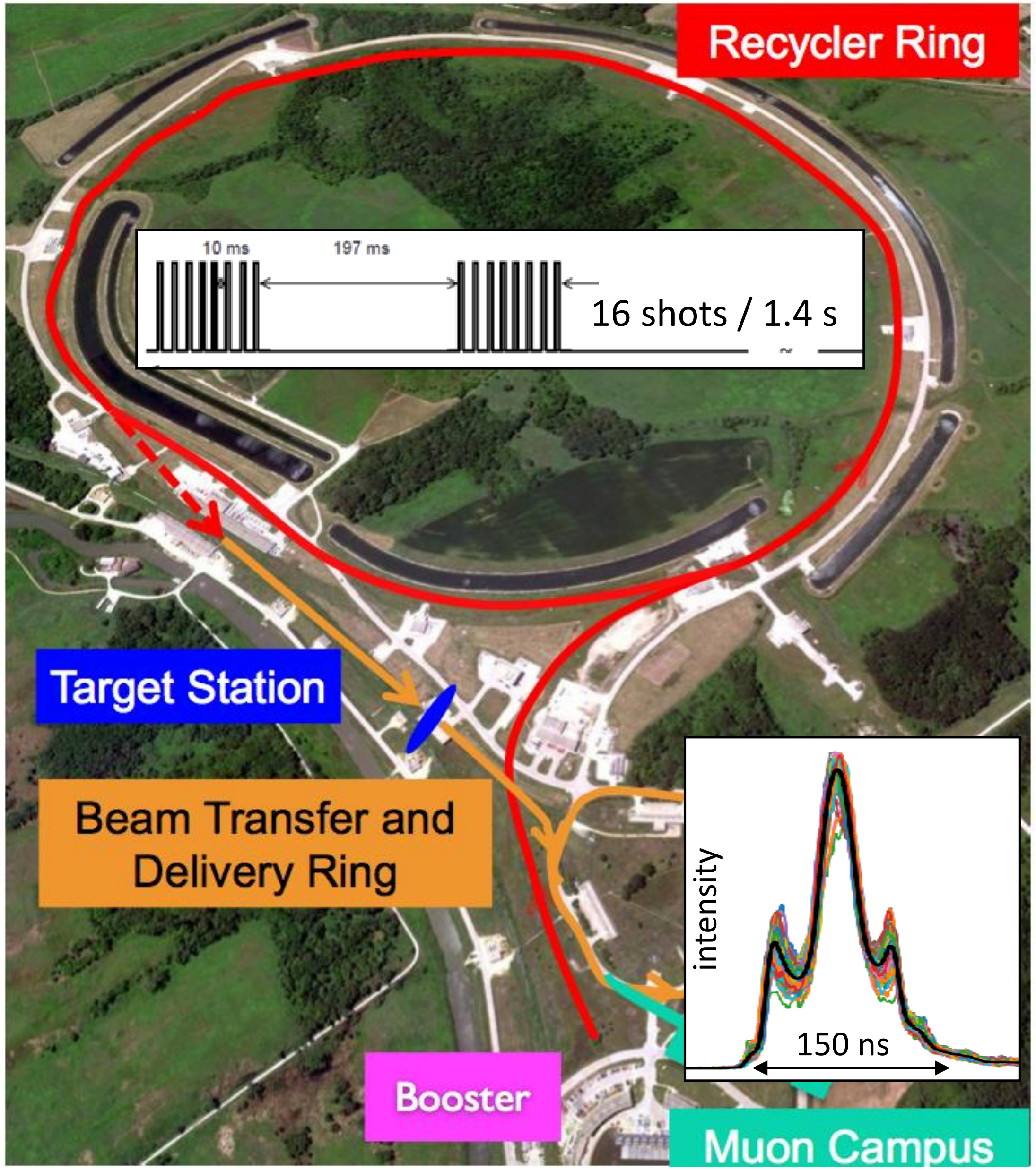
$\Rightarrow$ Fermilab goal factor 21, $2 \times 10^{11}\, e^+$

Fermilab Advantages:

- 4 bunches of 10^{12} protons at 8 GeV
- Hit target, p, π, μ to delivery ring
- Long decay channel for $\pi \Rightarrow \mu$
- Only μ enter ring, minimal hadronic flash

$\Rightarrow$ $4\times$ higher fill frequency than BNL

$\Rightarrow$ Muons per fill similar



How do we measure a_μ? Overview of Measurement Technique

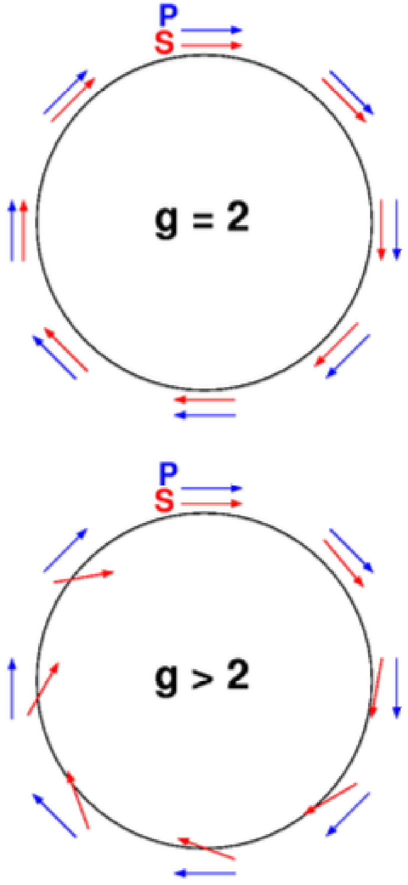
- Inject polarized muons into magnetic storage ring **(B=1.45 T)** with **electric vertical focusing**

- Muon cyclotron frequency $\omega_c \approx 2\pi \times 6.7\,\text{MHz}$
- Muon spin vector precession $\omega_s \approx 2\pi \times 6.9\,\text{MHz}$

$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C$$

$$\vec{\omega}_a \approx \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \left[\frac{mc}{p}\right]^2\right)\vec{\beta}\times\vec{E}\right]$$

$$\vec{\omega}_a \approx 229\,\text{kHz}$$

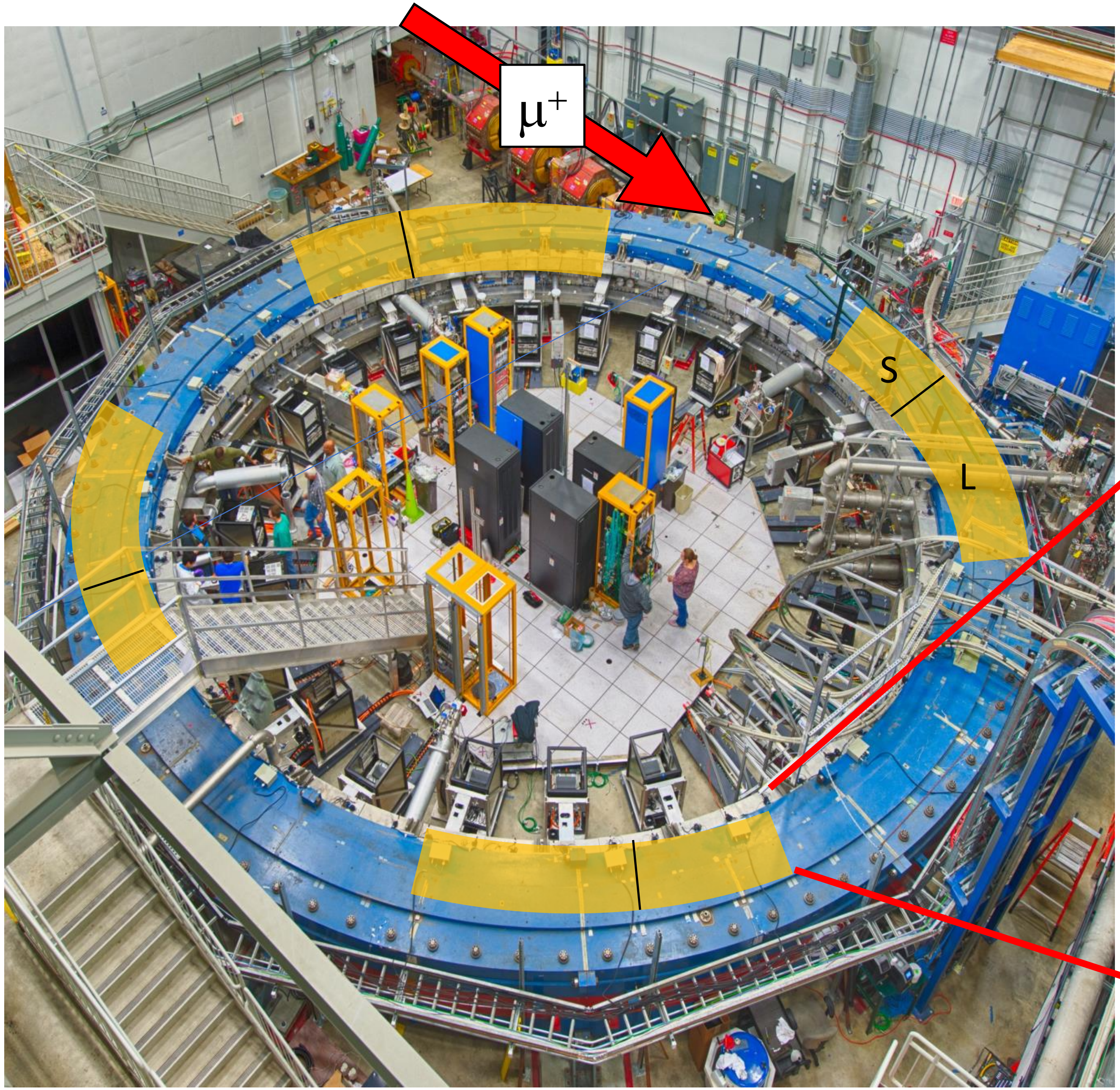


⇒ Cancel term from electrostatic vertical focusing at $p_{\text{magic}} = \frac{mc}{\sqrt{a_\mu}} \approx 3.094\ \text{GeV}/c$

⇒ Experiment measures two quantities:

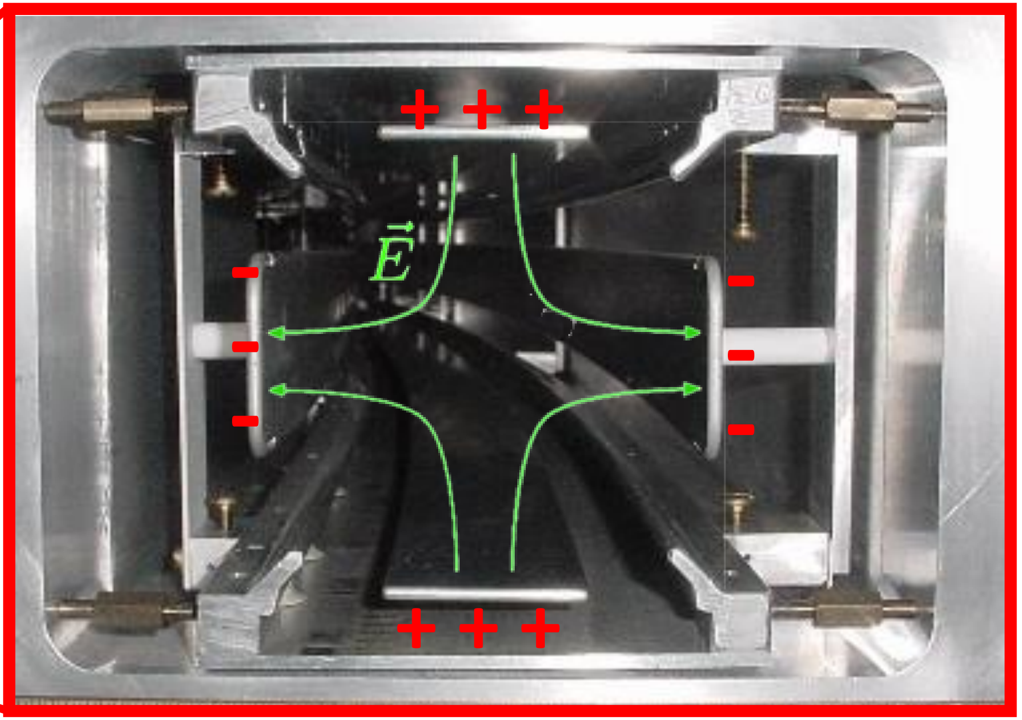
(1) Muon anomalous precession frequency ω_a to ± 100 ppb (stat) ± 70 ppb (syst)

(2) Magnetic field $\vec{B}$ in terms of proton NMR frequency ω_p to ± 70 ppb (syst)

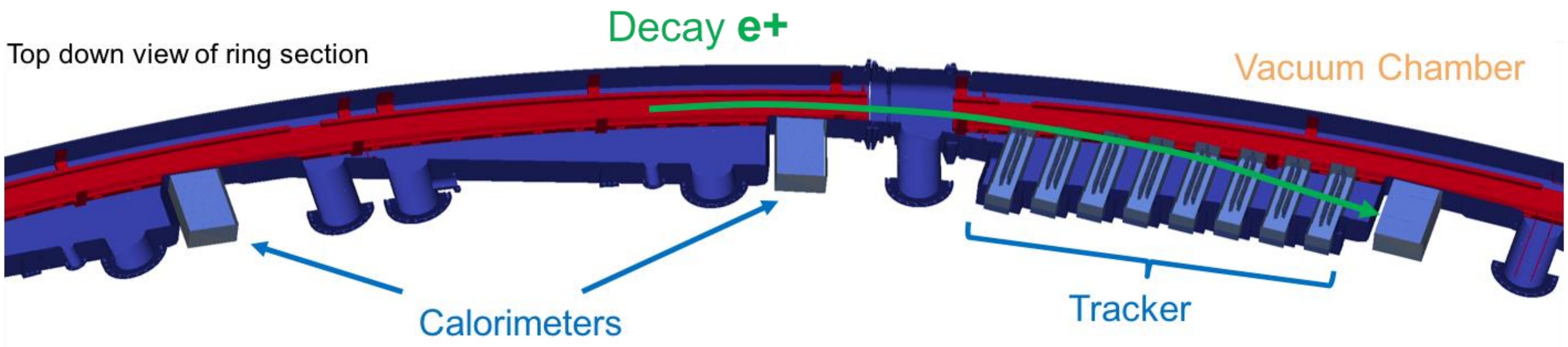


Electrostatic Quadrupoles (ESQ)

- Electric quadrupole field provides vertical focusing
- Beam: simple harmonic motion about closed orbit
- Quads cover 43% of azimuth



Measuring ω_a: Detecting the e^+ from muon decay with calorimeters



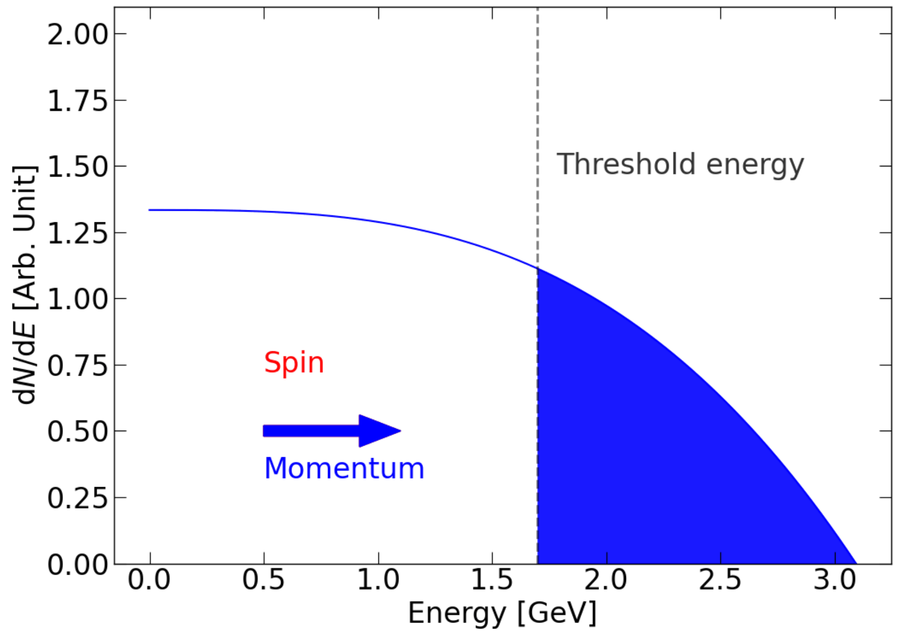
$\Rightarrow$ Parity violation in decay: $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$

$\Rightarrow$ Muon Rest Frame: highest energy decay e^+ emitted in precessing muon spin direction

$\Rightarrow$ Lab Frame Positron Energy: $E_{\text{lab}} \approx \gamma E^* \left[1 + \cos\left(\omega_a t\right)\right]$

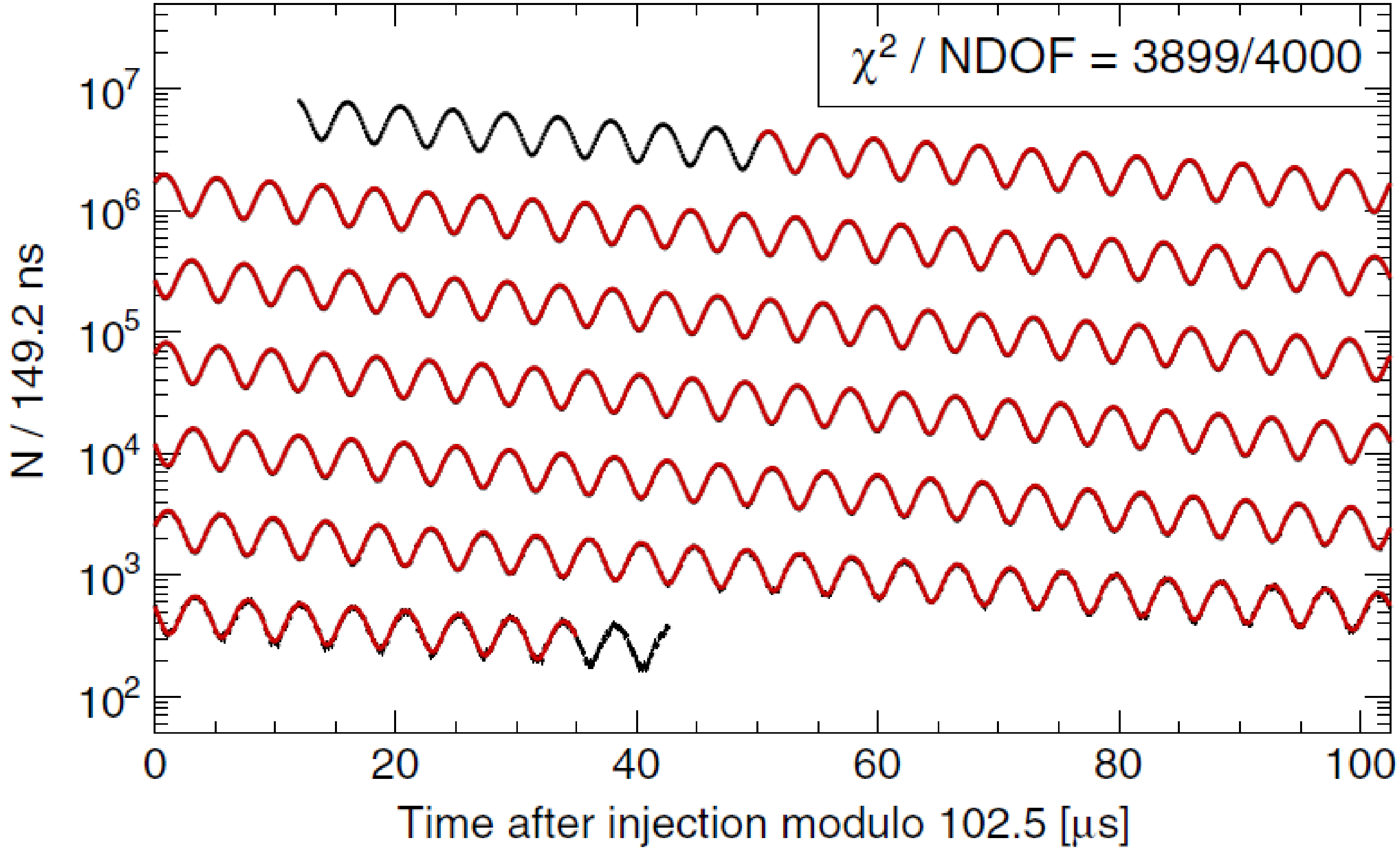
$\Rightarrow$ Positron detection rate above threshold $\propto \cos\left(\omega_a t\right)$

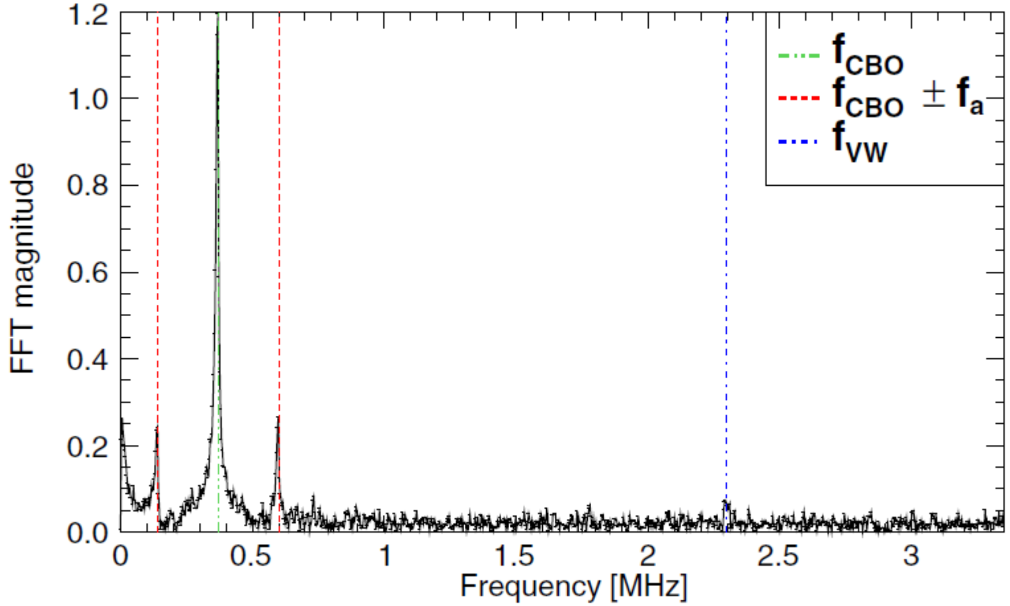
- Reconstruct e^+ energy and time
- Extrapolate for phase of μ^+ spin at decay



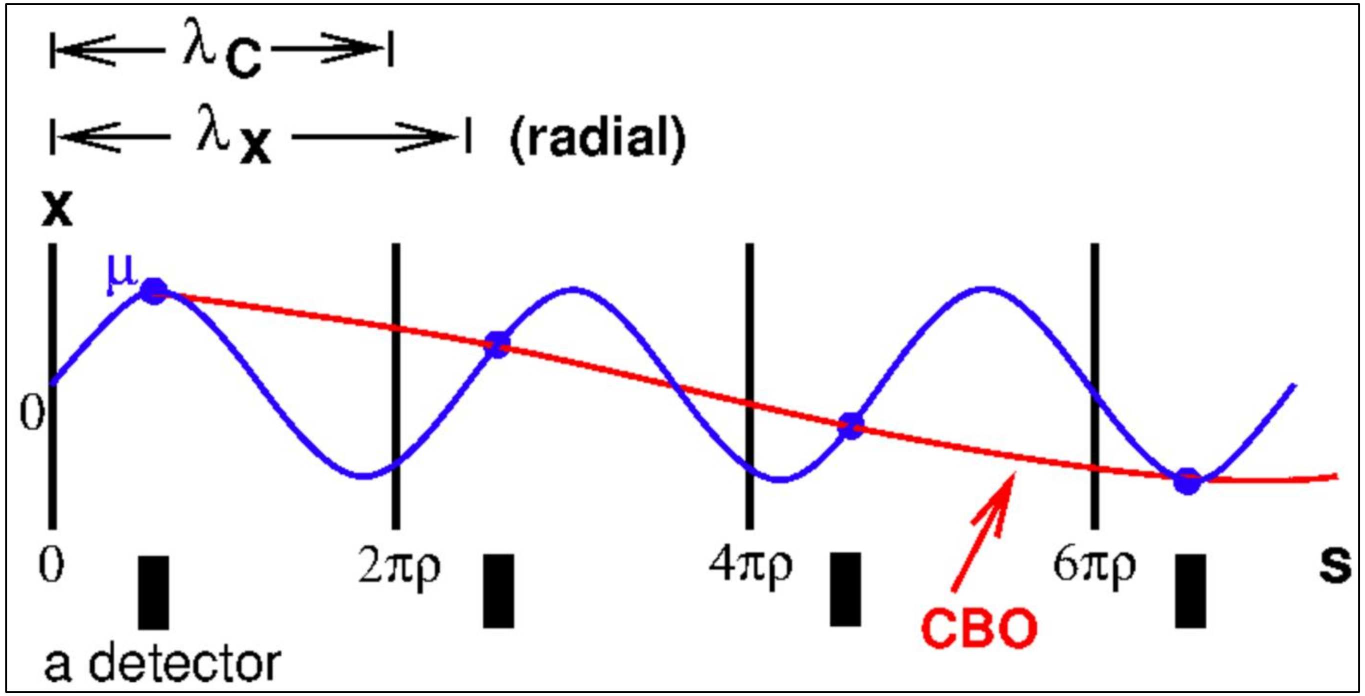
The Wiggle Plot: Extracting ω_a

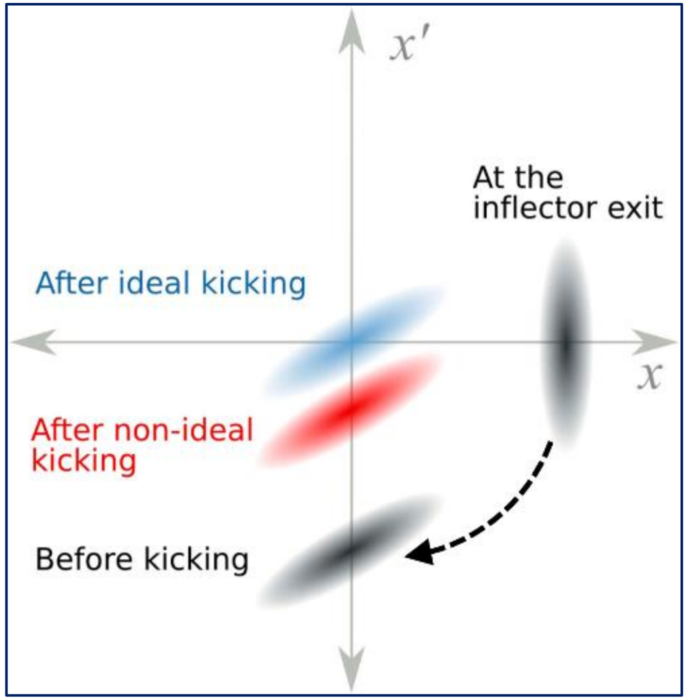
e^+ Signal from Muon Decay: $N_{\mathrm{ideal}}(t) = N_0 \exp\left(-t/\gamma\tau_\mu\right)\left[1 + A\cos\left(\omega_a t + \phi\right)\right]$





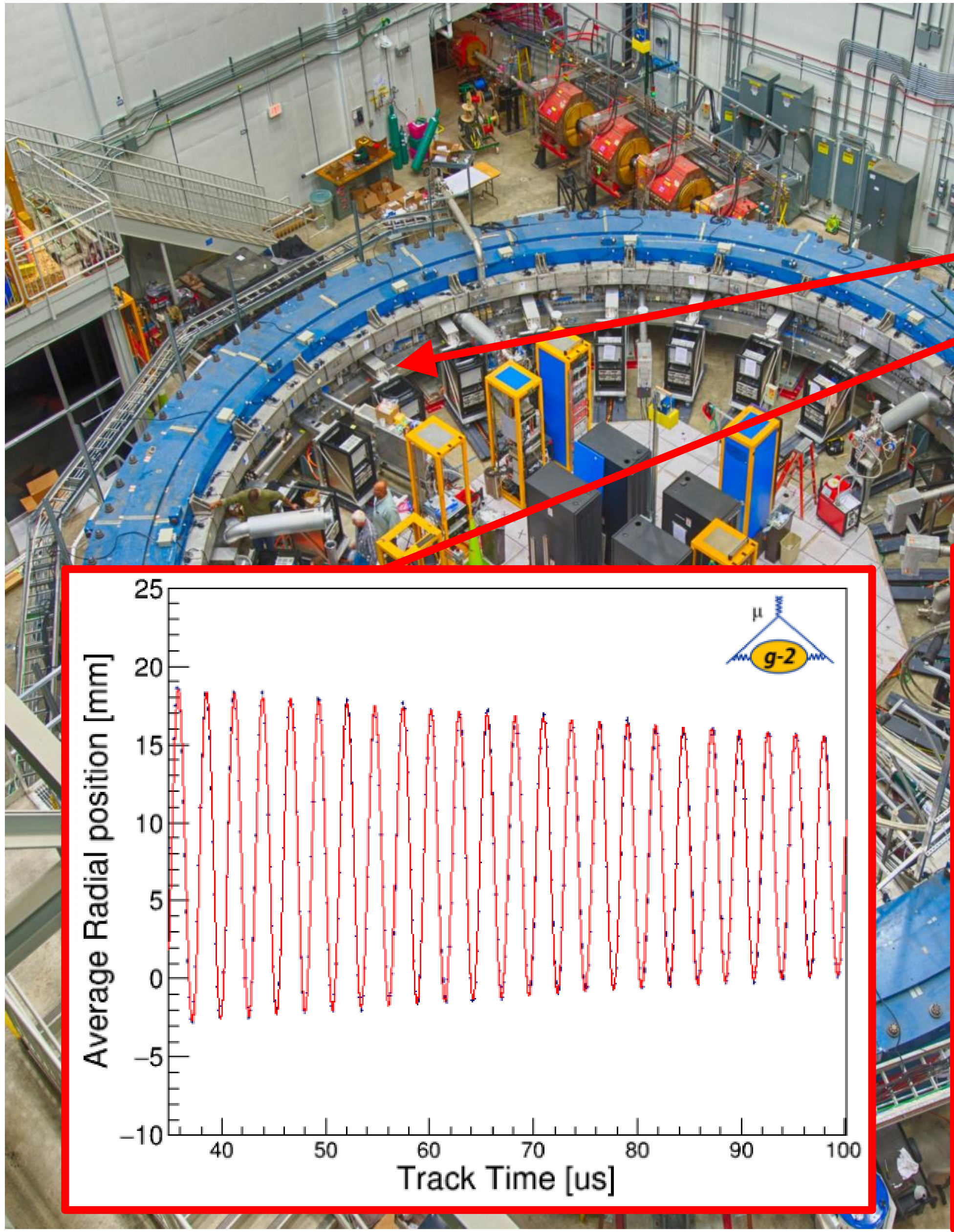
- FFT of residual to fit shows many features: 5 parameter entirely inadequate

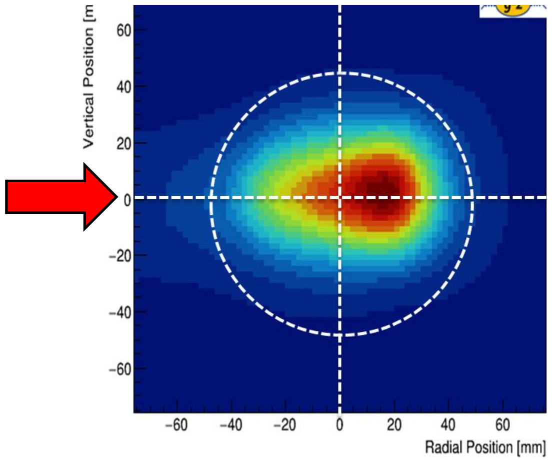




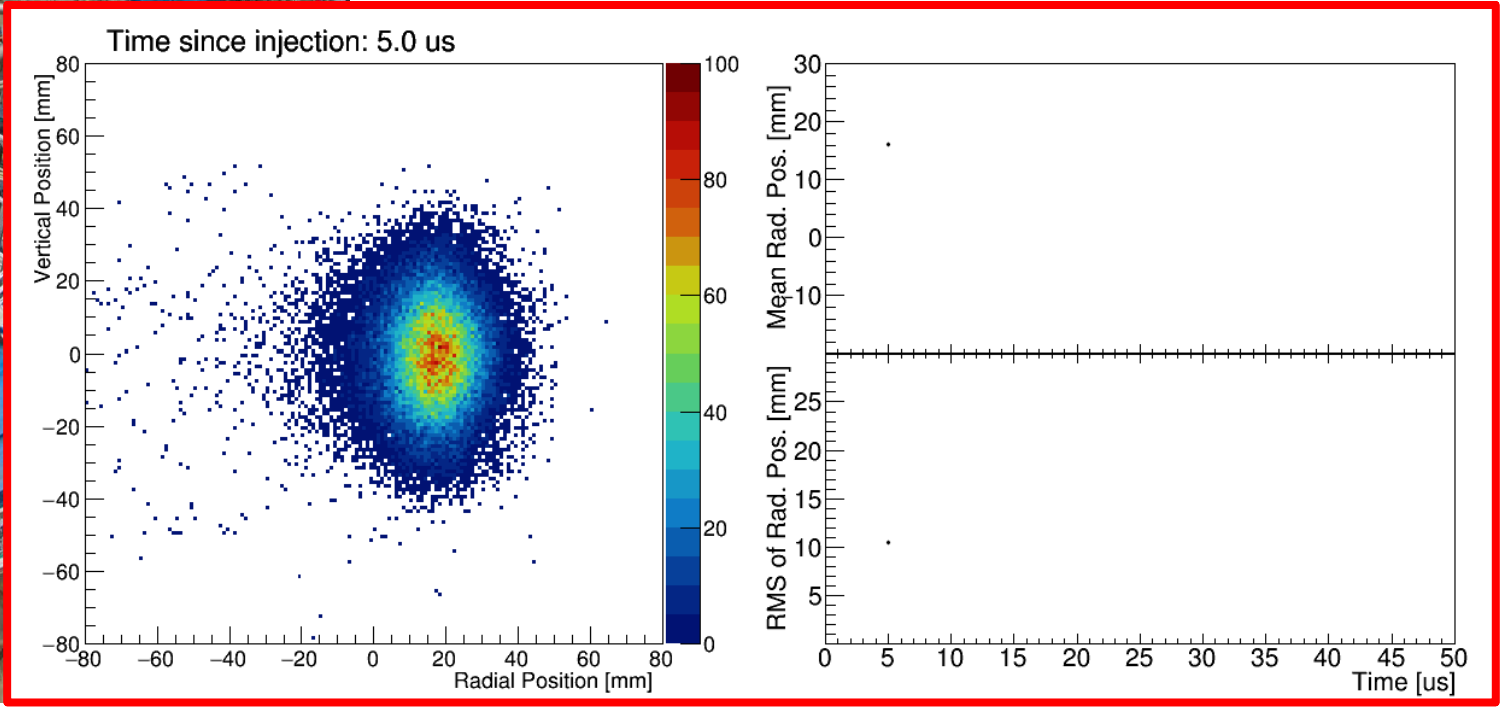
- Calo acceptance depends on muon radius at decay: coherent beam motion modulates e^+ time spectrum
- Radial betatron wavelength (blue line) $\neq$ circumference (cyclotron wavelength)
- Red line: apparent radial breathing in and out of beam at alias frequency $f_{\text{CBO}} = f_{\text{cyclotron}} - f_{\text{betatron}}$
- Effect dephases gradually, nearly cancels when all detectors added together

Need to know where the muon are: **Straw Tracker Stations at 180^0 and 270^0**

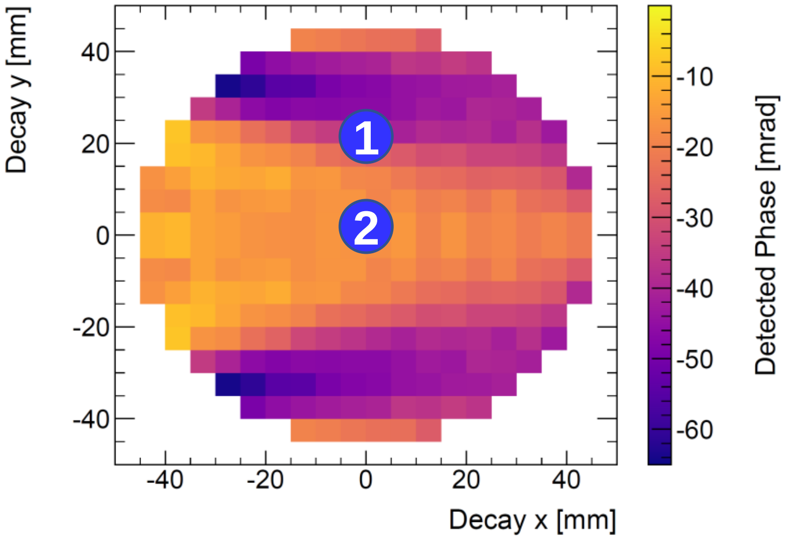




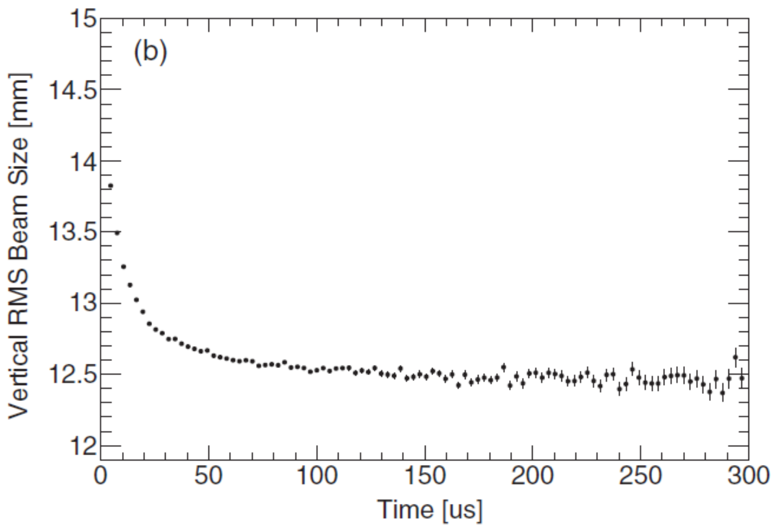
- Eight UV planes per tracker station



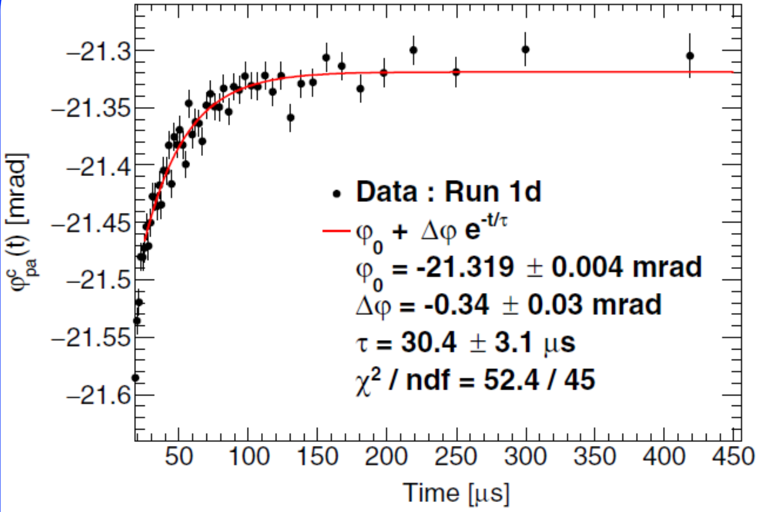
Run-1 Challenge: Phase Acceptance Correction: C_{pa}



- Detector acceptance couples g-2 phase of detected e^+ to parent muon decay position (x,y,ϕ)
- Wiggle plots for (1) $\neq$ (2)



- Problems with 2/32 HV resistors
- Beam vertical width changed during fill
- $\Delta\omega_a = \frac{d\phi}{dt} = \frac{d\phi}{dY_{rms}} \frac{dY_{rms}}{dt} \neq 0$



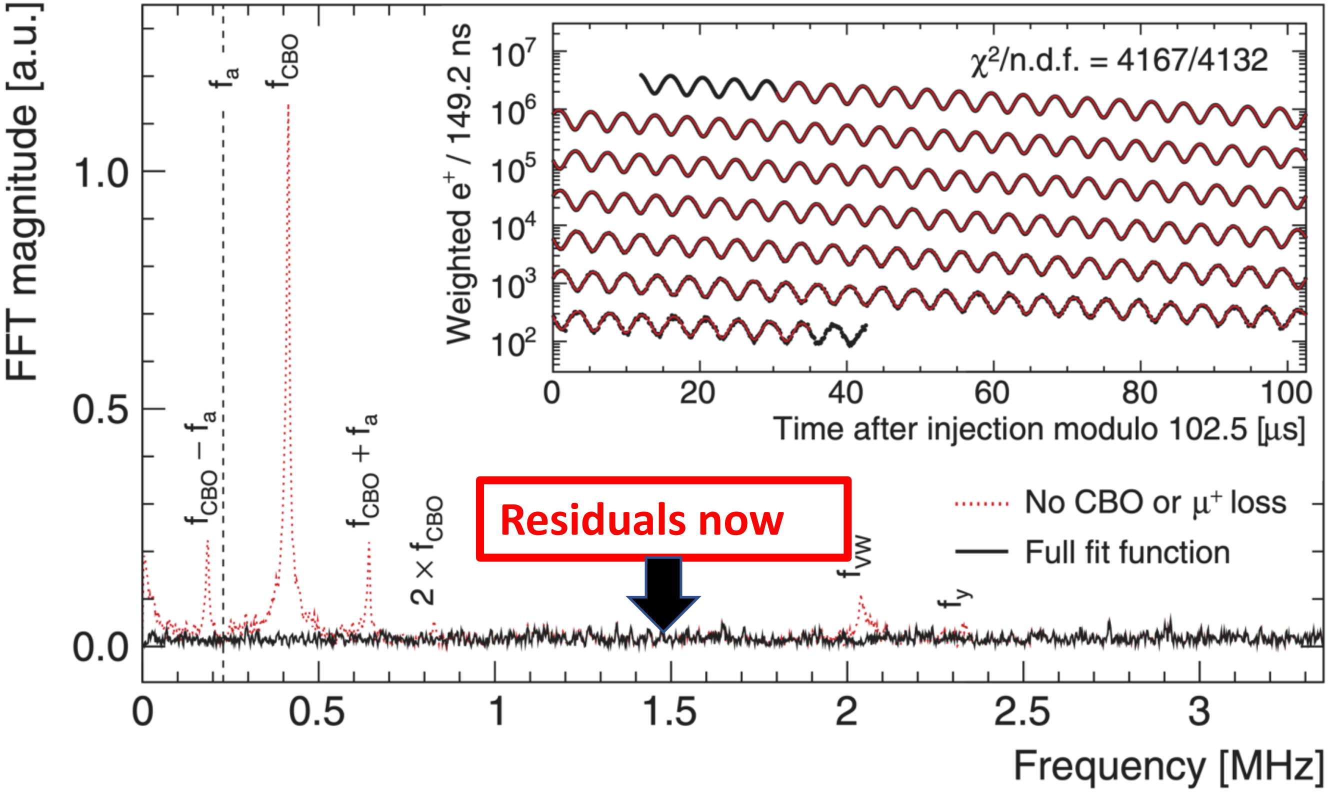
- Account for $\phi(t)$ in fit
- Took a year to understand
- $C_{pa} = (-158 \pm 75)$ ppb

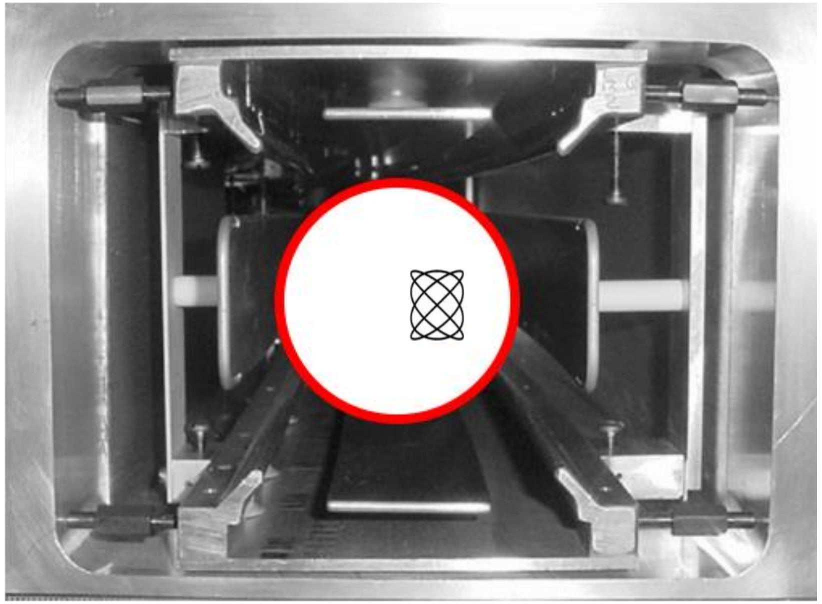
Extracting ω_a^m: measured $g-2$ frequency

Incorporating beam dynamics, detector effects, muon losses, fit function becomes:

$$N(t) = N_0 \cdot N_x(t) \cdot N_y(t) \cdot \Lambda(t) \cdot e^{-t/\gamma\tau_\mu} \cdot [1 + A_0 \cdot A_x(t) \cdot \cos(\omega_a^m t + \phi_0 \cdot \phi_x(t))]$$

$$\begin{aligned}
N_x(t) &= 1 + e^{-t/\tau_{\mathrm{CBO}}} A_{N,x,1} \cos(\omega_{\mathrm{CBO}} t + \phi_{N,x,1}) \\
&\quad + e^{-2t/\tau_{\mathrm{CBO}}} A_{N,x,2} \cos(2\omega_{\mathrm{CBO}} t + \phi_{N,x,2}) \\
N_y(t) &= 1 + e^{-t/\tau_y} A_{N,y,1} \cos(\omega_y t + \phi_{N,y,1}) \\
&\quad + e^{-2t/\tau_y} A_{N,y,2} \cos(\omega_{VW} t + \phi_{N,y,2}) \\
\Lambda(t) &= 1 - K_{\mathrm{loss}} \int_0^t e^{t'/\gamma\tau_\mu} L(t')\, \mathrm{d}t' \\
A_x(t) &= 1 + e^{-t/\tau_{\mathrm{CBO}}} A_{A,x,1} \cos(\omega_{\mathrm{CBO}} t + \phi_{A,x,1}) \\
\phi_x(t) &= 1 + e^{-t/\tau_{\mathrm{CBO}}} A_{\phi,x,1} \cos(\omega_{\mathrm{CBO}} t + \phi_{\phi,x,1})
\end{aligned}$$





- Muons occupy volume determined by vertical and radial $\boldsymbol{B}$ fields, betatron oscillations
- Muon spin precesses ω_a according to $\boldsymbol{B}$ in small volume $\Rightarrow$ $\omega_a(\vec{r}) \approx a_\mu \left[\frac{eB(\vec{r})}{m_\mu}\right]$
- Need $\boldsymbol{B}$ field weighted by stored muon distribution
- Reasons for homogeneous field:
  - Stable beam dynamics, adiabaticity
  - Smaller uncertainty on $\tilde{\omega}_p$ from convolution of muon distribution with field
  - Easier to measure

Measuring the Magnetic Field B using Pulsed Proton NMR in Water

$$\omega_a \approx a_\mu \left[\frac{eB}{m_\mu}\right] \qquad a_\mu = \frac{\omega_a}{\omega'_p}\frac{2\mu'_p}{\hbar}\frac{m_\mu}{e} \Rightarrow \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \times \frac{\mu'_p(T_r)}{\mu_e(H)}\frac{\mu_e(H)}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

$\Rightarrow$ Extract B using NMR: $\hbar\,\omega'_p(T_r) = 2\,\mu'_p(T_r)\,B$

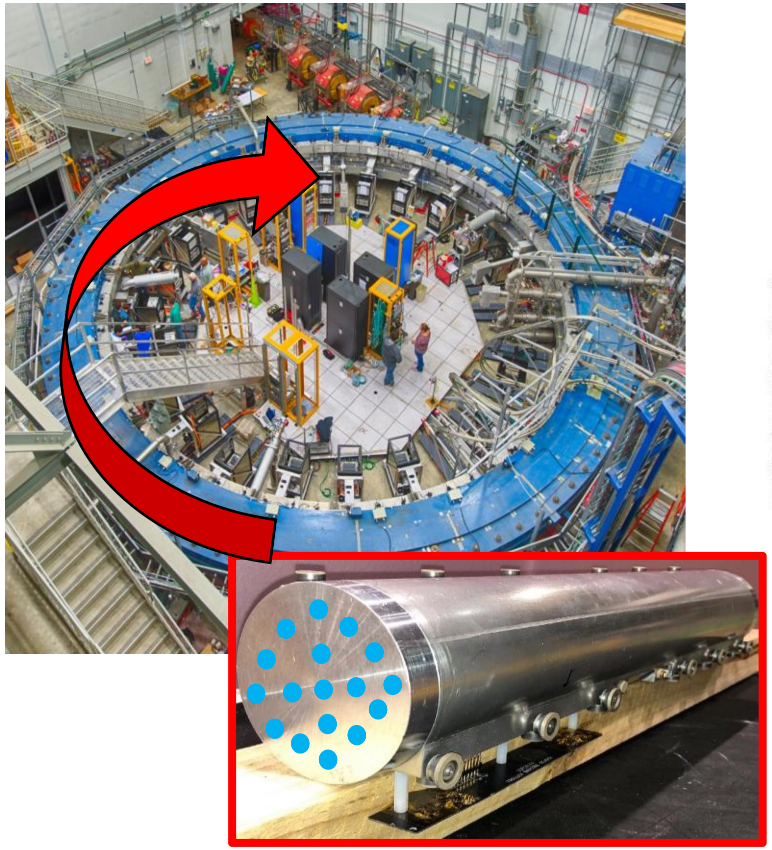
- Magnetic moment of proton in spherical water sample $\mu'_p(34.7°C)$ measured to 10.5 ppb

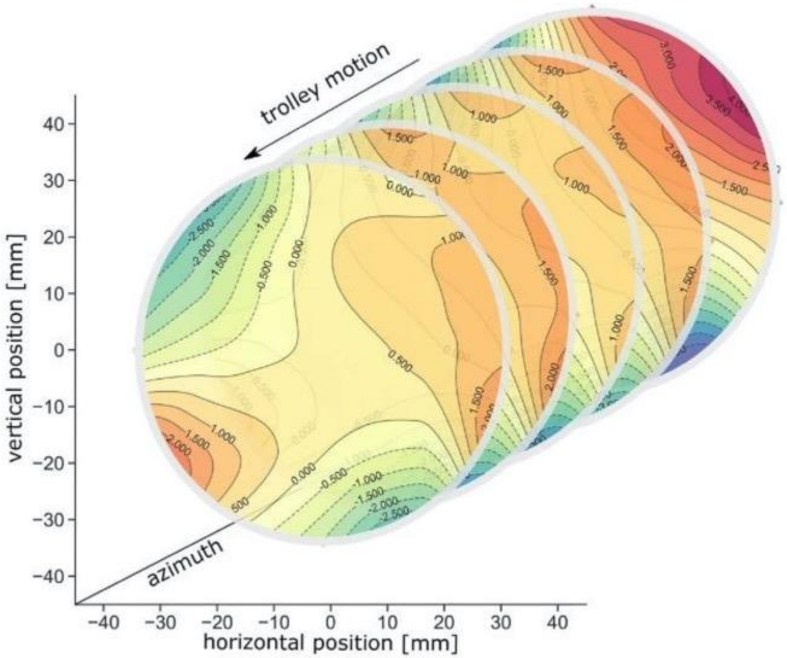
$\Rightarrow$ Want NMR precession frequency protons in spherical water $\omega'_p(T_r)$ in storage volume while muons stored

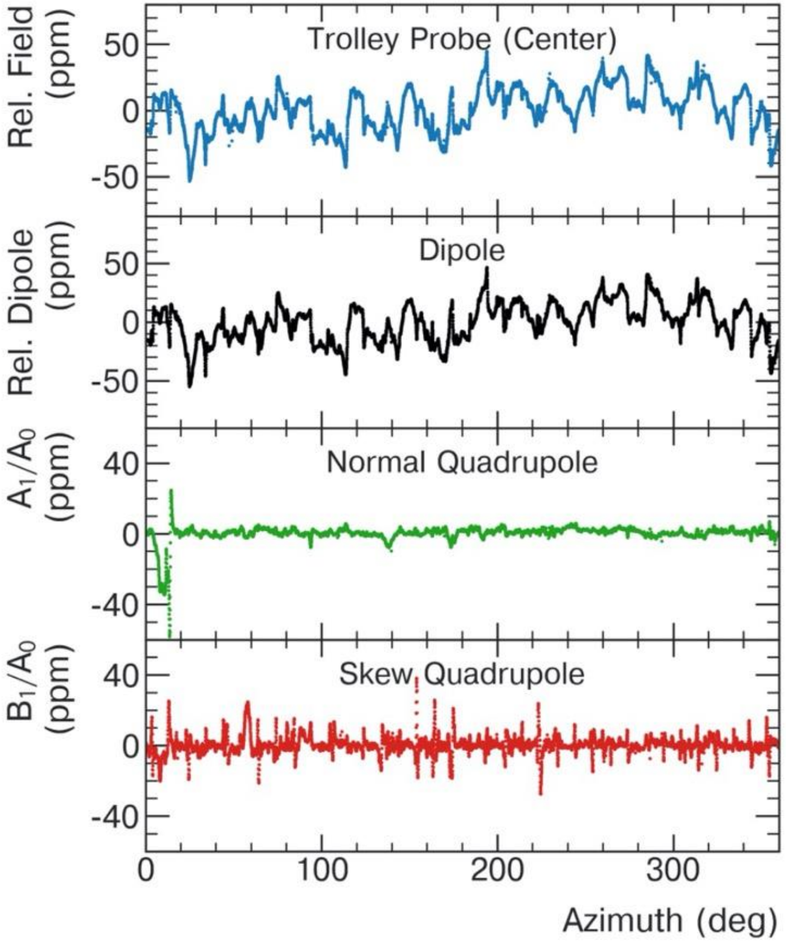
- Some Problems:
  - Can't have NMR probes in storage volume at same time/place as muons!
  - Whatever we use to measure B-field perturbs the local field! $\Rightarrow$ measured B-field different than what muons see!

- Calibration/corrections necessary to go from raw magnetometer frequency $\omega_{\rm raw}$ to equivalent $\omega'_p(T_r)$
- Essential steps:
  - Develop calibration probe whose NMR frequency ω_{cp} can be related to $\omega'_p(T_r)$
  - Transfer calibration to device (NMR Trolley) that measures field inside muon storage volume $\Rightarrow$ $\omega'_p(x, y, \phi, t_0)$
  - Use NMR probes outside storage volume to monitor field while muons stored $\omega'_p(x, y, \phi, t)$

Mapping the field in the storage volume every 3 days with the trolley:

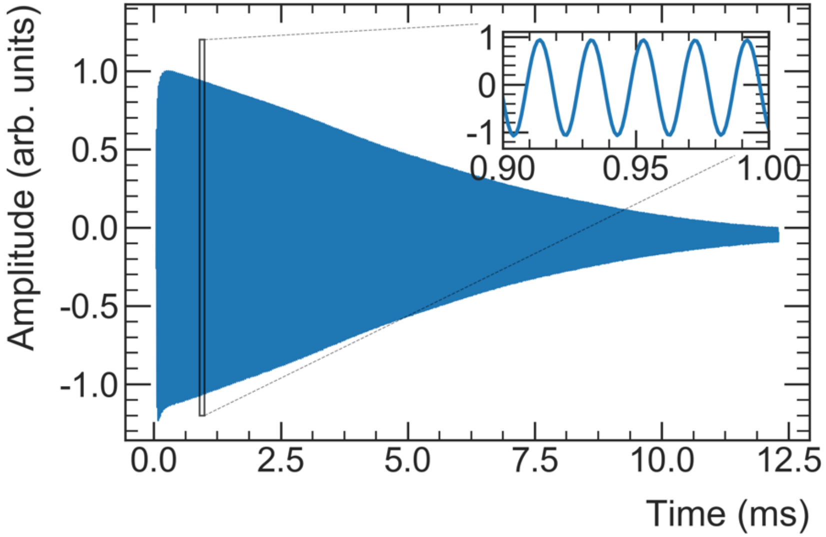


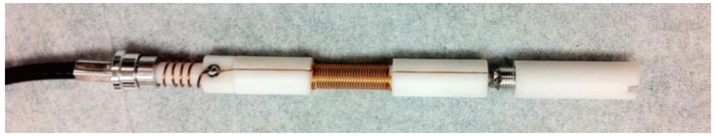




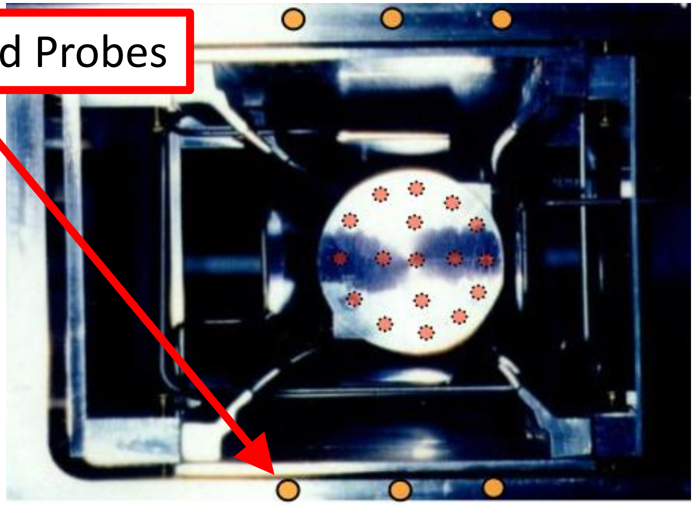
- Trolley with 17 NMR probes maps magnetic field in muon storage volume every $\approx$ 3 days
- 9000$\times$ 17 data points (every 5 mm)
- Takes a few hours

During Muon Storage: track the field with the fixed probes





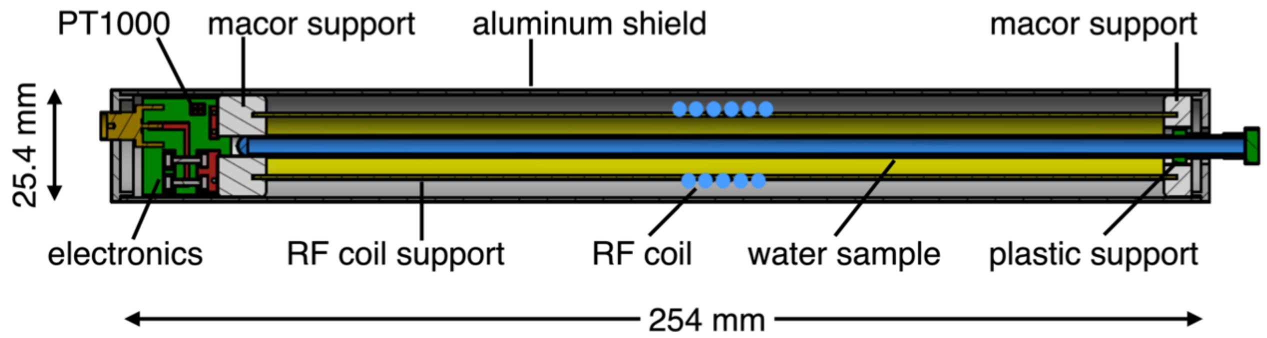
Fixed Probes



- 378 fixed NMR probes, above/below storage volume
- NMR probe stations every 5°, read every 1.4 seconds
- Determine offset between fixed probes and trolley when it passes by

$\Rightarrow$ Infer what trolley would read while muons stored

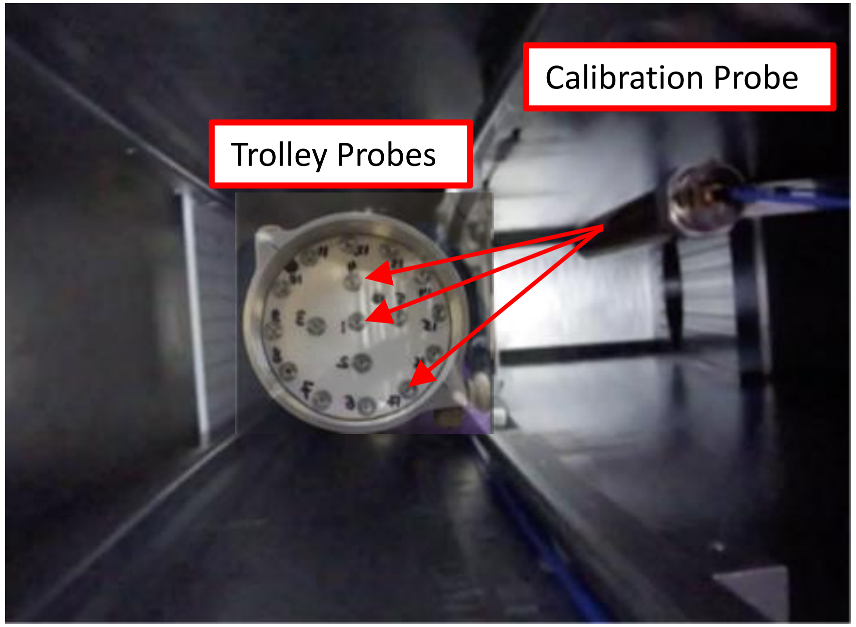
The Absolute Calibration Probe (CP) and Calibrating the Trolley



$$\omega'_p(T_r) = \omega^{cp}(T)\left[1 + \delta^T(\mathrm{H_2O}, T_r - T) + \delta^b(\mathrm{H_2O}, T) + \delta^s + \delta^w + \delta^{\mathrm{RD}} + \delta^d\right]$$

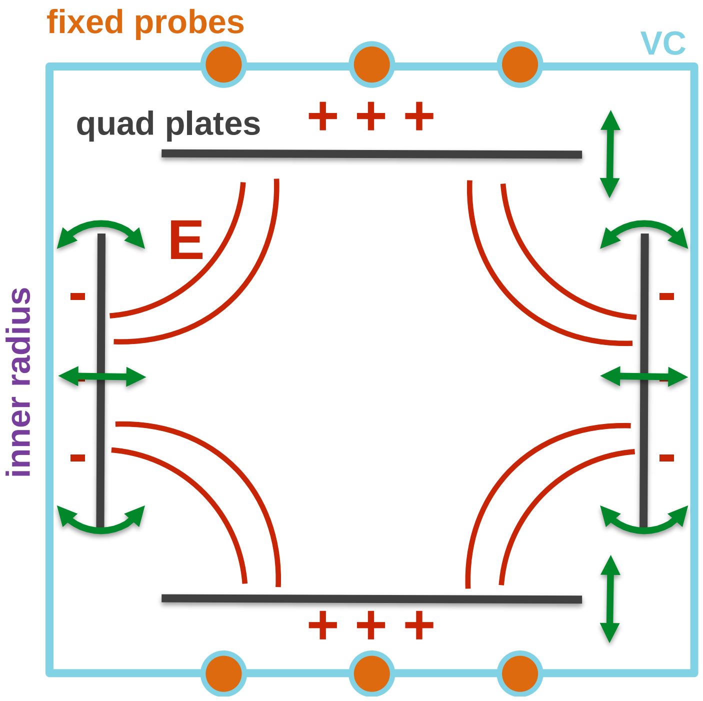
- Determine corrections relating ω^{cp} to $\omega'_p(T_r)$ to 20 ppb
- Cross-checked with ^{3}He probe to 38 ppb

MRI Test Magnet at ANL 1.45 T
Highly uniform: few ppb/mm
Highly stable: 10 ppb/hr



- Alternately measure B in same location with trolley, CP
- Relates $\omega_{\text{trolley}}(\vec{r})$ to $\omega^{CP}(\vec{r})$ to $\omega'_p(T_r, \vec{r})$
- Takes 4-8 hours to calibrate single trolley probe
- Results consistent to 30 ppb

Largest Field Systematic Uncertainty: Field Transients from the Electrostatic Quads: B_q



- When muons injected, electrostatic quads are pulsed
- **Impulse causes motion** of quad plates
- Moving conductor in B → magnetic field perturbation
- *Not* seen by trolley
- Seen by fixed probes but attenuated, phase shifted
- Must measure separately
- **Inserted NMR probes between pulsing quads**

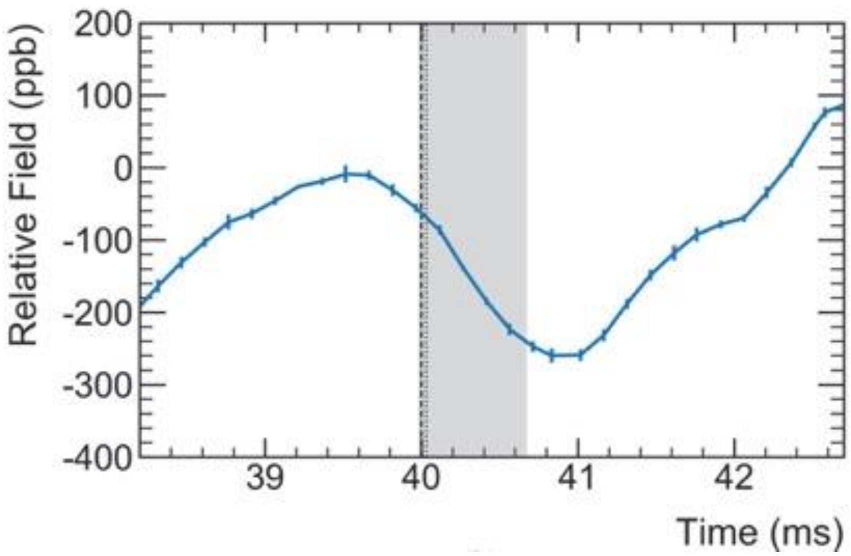


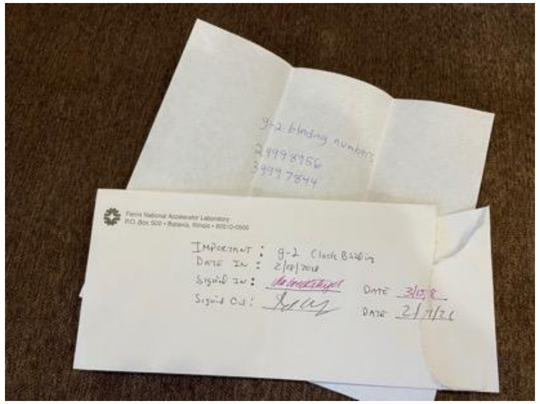
Table of Muon g-2 Run-1 Statistical and Systematic Uncertainties

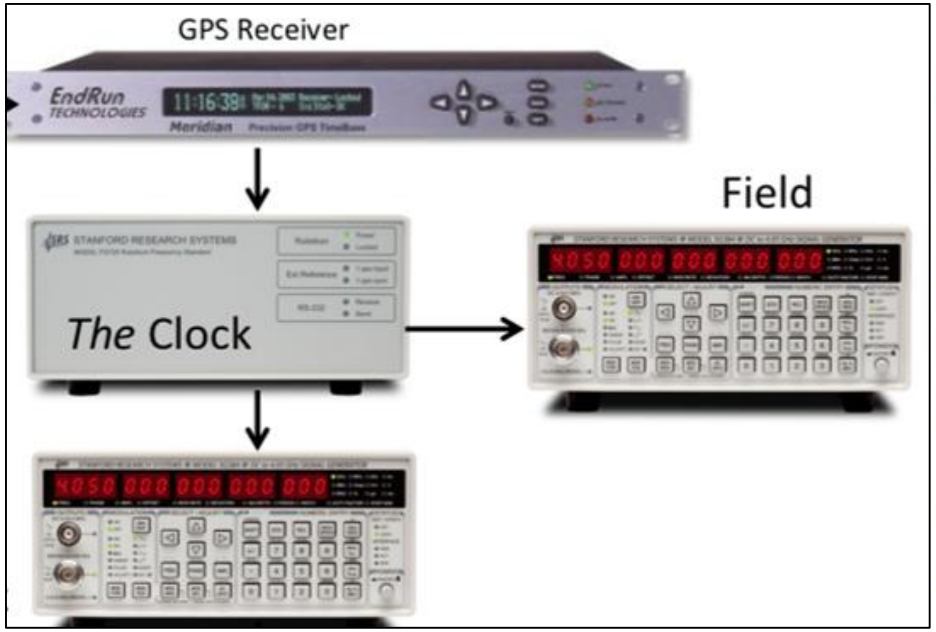
Quantity	Correction terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	$\cdots$	434
ω_a^m (systematic)	$\cdots$	56
C_e	489	53
C_p	180	13
C_{ml}	−11	5
C_{pa}	−158	75
$f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle$	$\cdots$	56
B_k	−27	37
B_q	−17	92
$\mu'_p(34.7°)/\mu_e$	$\cdots$	10
m_μ/m_e	$\cdots$	22
$g_e/2$	$\cdots$	0
Total systematic	$\cdots$	157
Total fundamental factors	$\cdots$	25
Totals	544	462

Data set	$\tilde{\omega}'_p(T_r)/2\pi$ (Hz)	Uncertainty (ppb)
Run-1a	61,791,871.2	115
Run-1b	61,791,937.8	127
Run-1c	61,791,845.4	125
Run-1d	61,792,003.4	108
	Average over all data sets	
	Field Measurements	56
	ESQ Transient	92
	Kicker Transient	37
	Total	114

- Took three years to analyze Run 1 (2018)
- Field measurement uncertainty: calibration, trolley maps, tracking uncertainty, muon convolution, ...
- ω_a^m(systematic): pileup, gain correction, modeling CBO decoherence
- Results stable vs fit start/stop times, individual calorimeters, Run 1a, b, c, d (different quad and kicker settings)

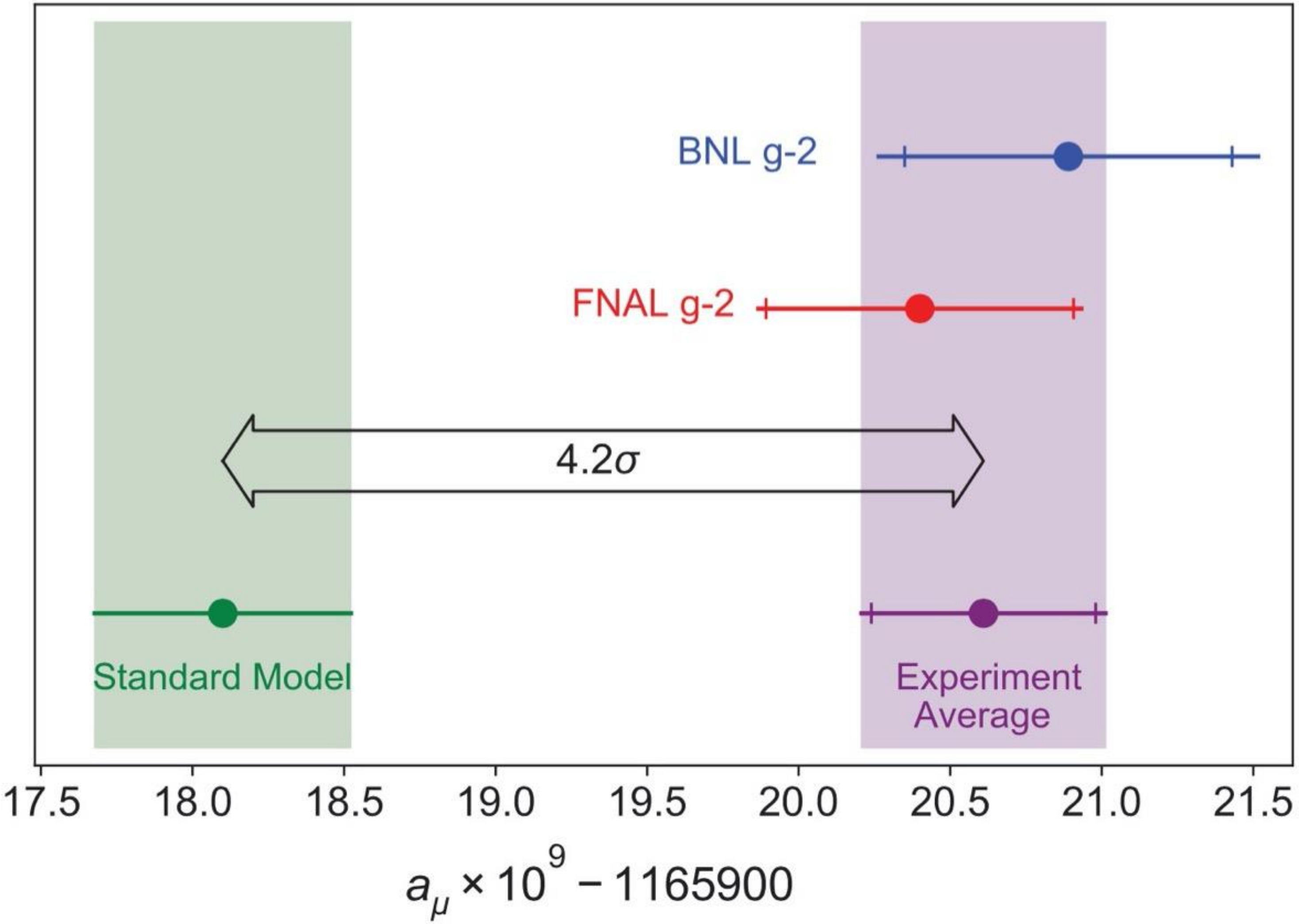
- Both ω_a and ω_p share common clock
- ω_a clock hardware "blinded"
- Obscures timebase for the "wiggle" plot
- Blinding factor set by people outside collaboration, stored in envelopes
- Unblinding: yields $\omega_a \Rightarrow a_\mu$





Clock stability monitored weekly by non-collaborators

Final Result: Run-1 Muon g-2



$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\ \mathrm{ppm})$$
$$a_\mu(\mathrm{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\ \mathrm{ppm})$$

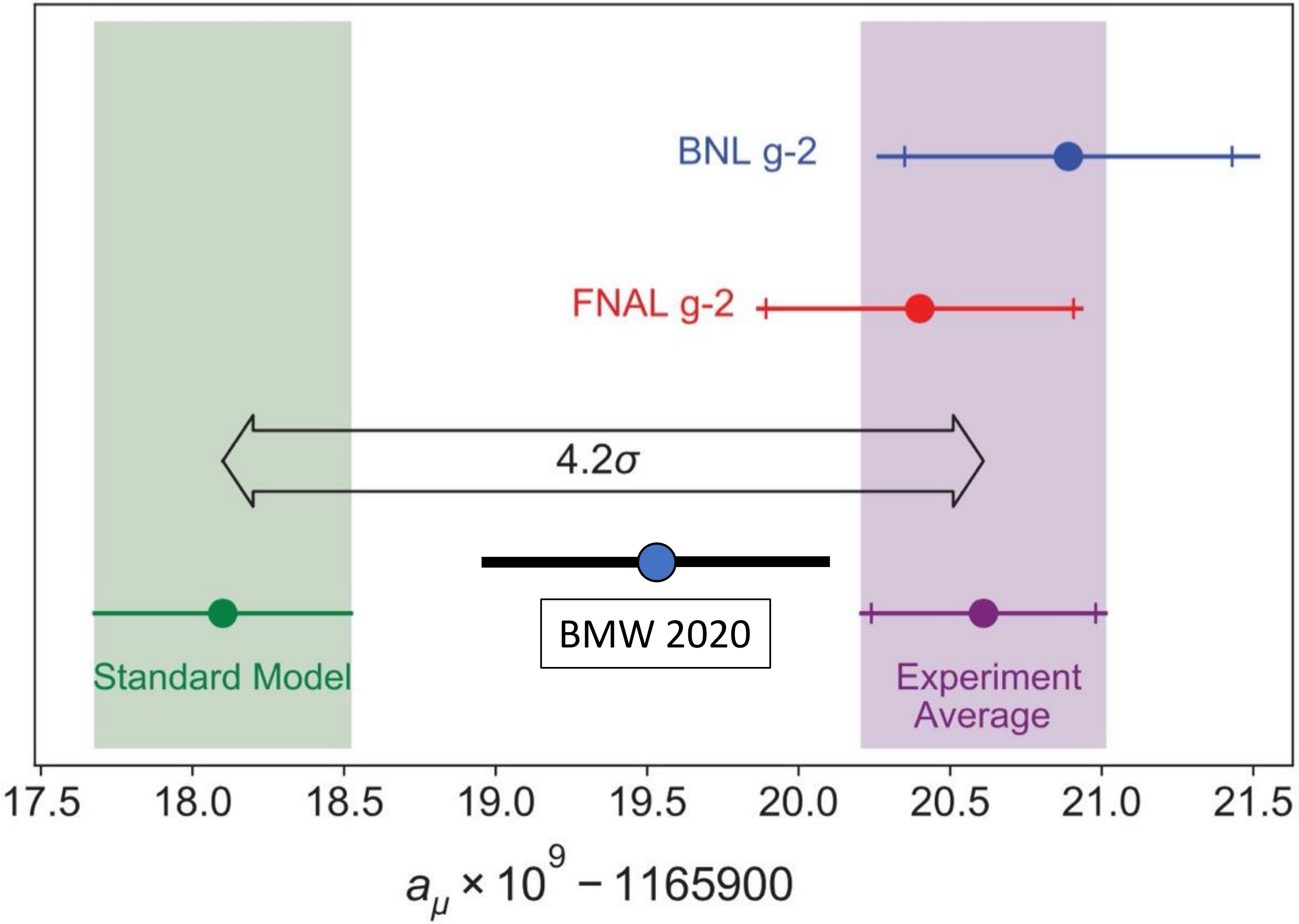
- FNAL results consistent with BNL
- Statistical uncertainty 434 ppb
- Systematic uncertainty 157 ppb
- Fund. constants uncertainty 25 ppb

⇒ Discrepancy large compared to weak $(251 \pm 59 \text{ vs } 153.6) \times 10^{-11}$

$$a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \times 10^{-11}$$

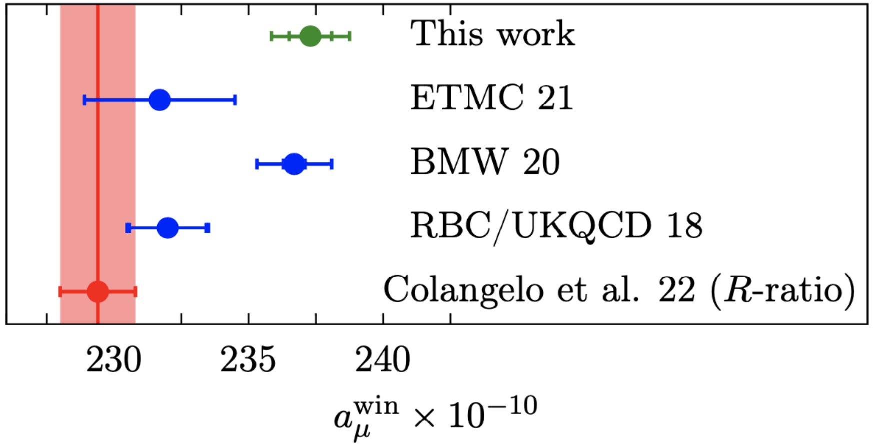
Significance: 4.2σ

What about the BMW20 Result? (Sz. Borsanyi et al., Nature **593**, 51-55, Apr 7, 2021)



- BMW 2020: First lattice QCD estimate of HadVP below a percent
- Huge accomplishment !
- Too late to include in WP result
- In tension with dispersive approach
- Members of BMW in Theory Initiative

⇒ Important to resolve



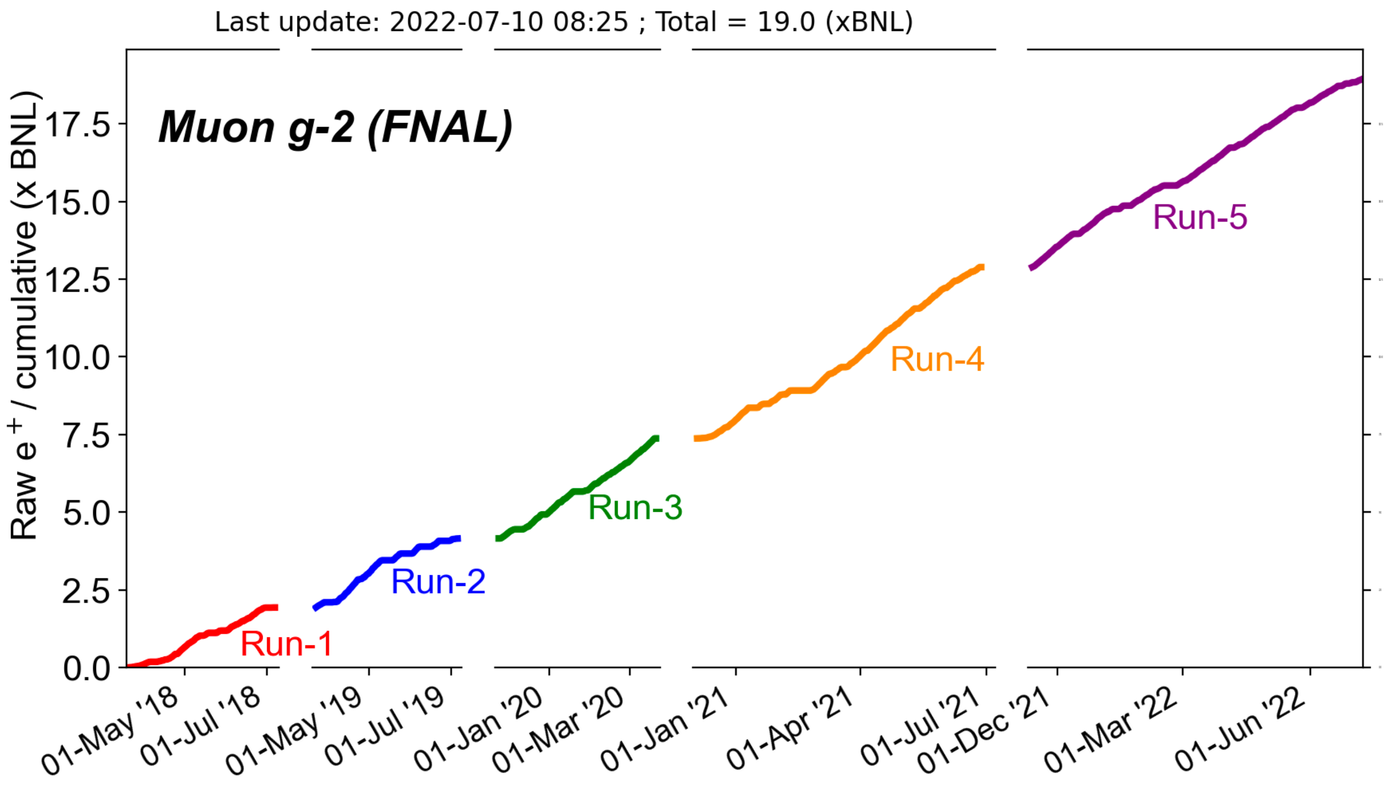
M. Ce *et al.,* (Mainz) arXiv:2206.06582v1

$$a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{BMW2020}) = (107 \pm 71) \times 10^{-11}$$

- FNAL result consistent with BNL
- Combined result differs from SM prediction by 4.2 σ
- Run-1 is 6% of final data set
  - μ^- data run not approved
  - Taking more μ^+ data

g-2 Theory Initiative workshop Sep 2022

- Update in 2023
- HVP(lattice) below 0.5% by 2025?
- HVP: MUonE, other exp inputs
- HlbI(dispersive) $\lesssim 10\%$ by 2025?
- HlbI(lattice) $\lesssim 10\%$ by 2025?
- HVP(lattice) below 0.5% by 2025?



- Looking forward to result from J-PARC g-2