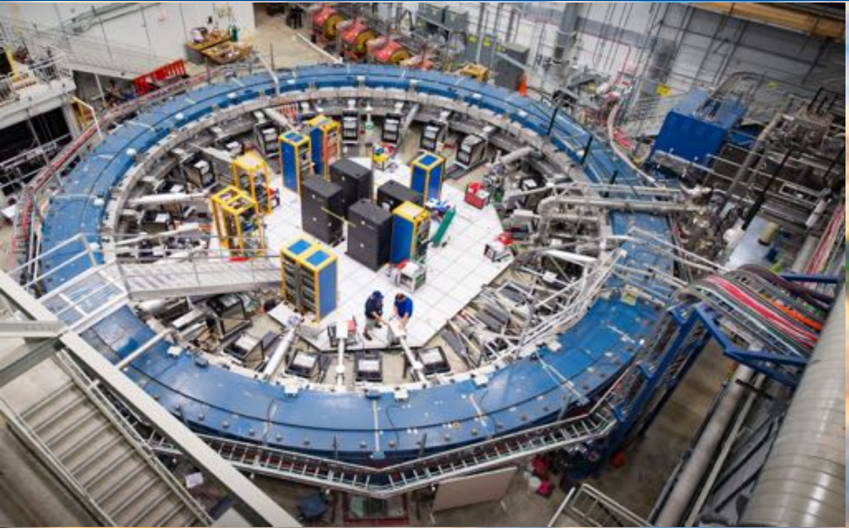


First results from the Muon g-2 Experiment at Fermilab

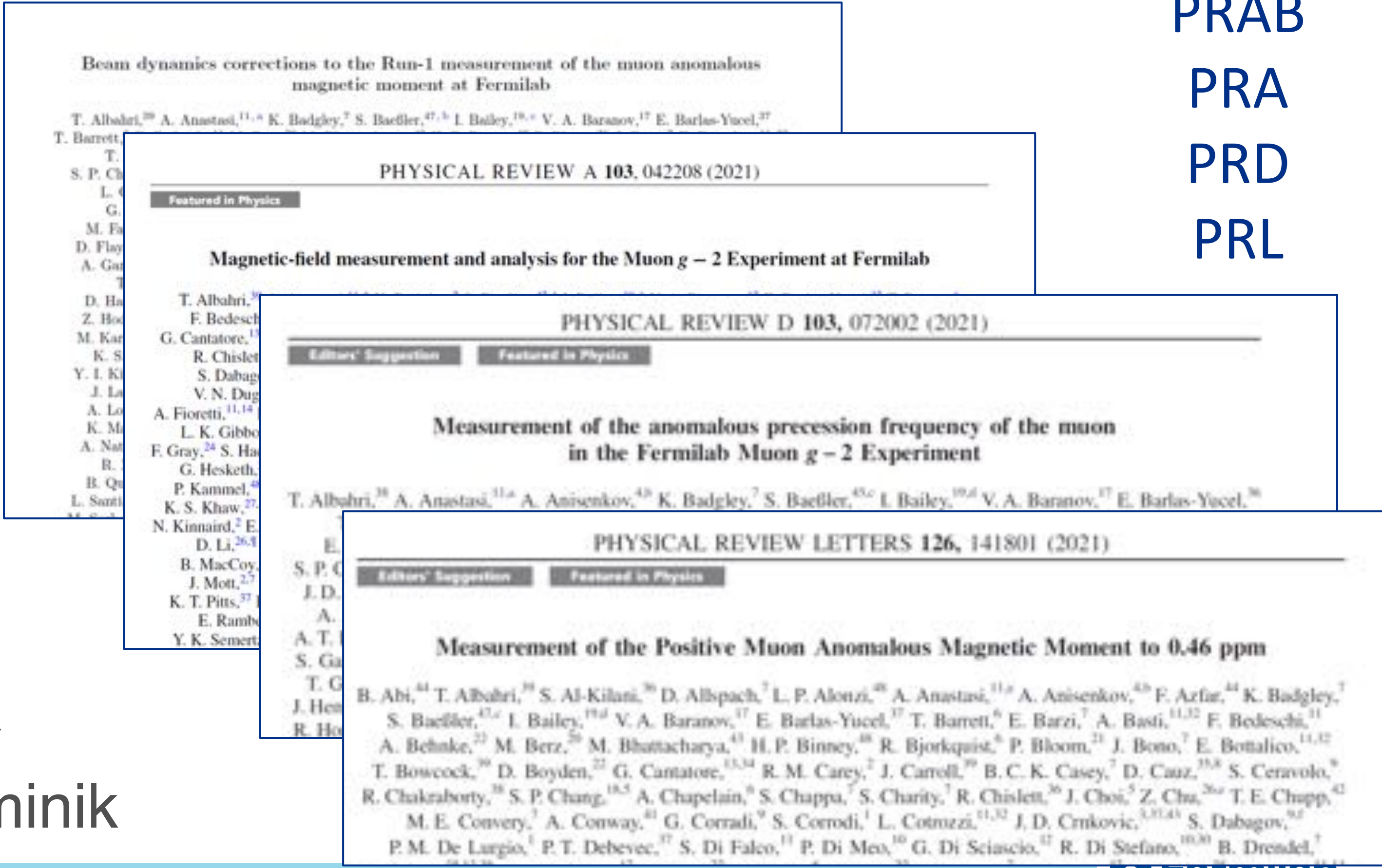
Brendan Kiburg, Fermi National Accelerator Laboratory
University of Warsaw Colloquium
26 April 2021

Exciting Month for the Muon g-2 Experiment

PRAB
PRA
PRD
PRL

Outline

- Brief Motivation
- Experimental Technique
- Measurements
- Results
- Brief Outlook → Part II from Dominik



Beam dynamics corrections to the Run-1 measurement of the muon anomalous magnetic moment at Fermilab

T. Albahri,[39] A. Anastasi,[11,a] K. Badgley,[7] S. Baeßler,[47,b] I. Bailey,[19,c] V. A. Baranov,[17] E. Barlas-Yucel,[37]

PHYSICAL REVIEW A **103**, 042208 (2021)

Featured in Physics

Magnetic-field measurement and analysis for the Muon *g* − 2 Experiment at Fermilab

PHYSICAL REVIEW D **103**, 072002 (2021)

Editors' Suggestion Featured in Physics

Measurement of the anomalous precession frequency of the muon in the Fermilab Muon *g* − 2 Experiment

T. Albahri,[38] A. Anastasi,[11,a] A. Anisenkov,[4,b] K. Badgley,[7] S. Baeßler,[45,c] I. Bailey,[19,d] V. A. Baranov,[17] E. Barlas-Yucel,[36]

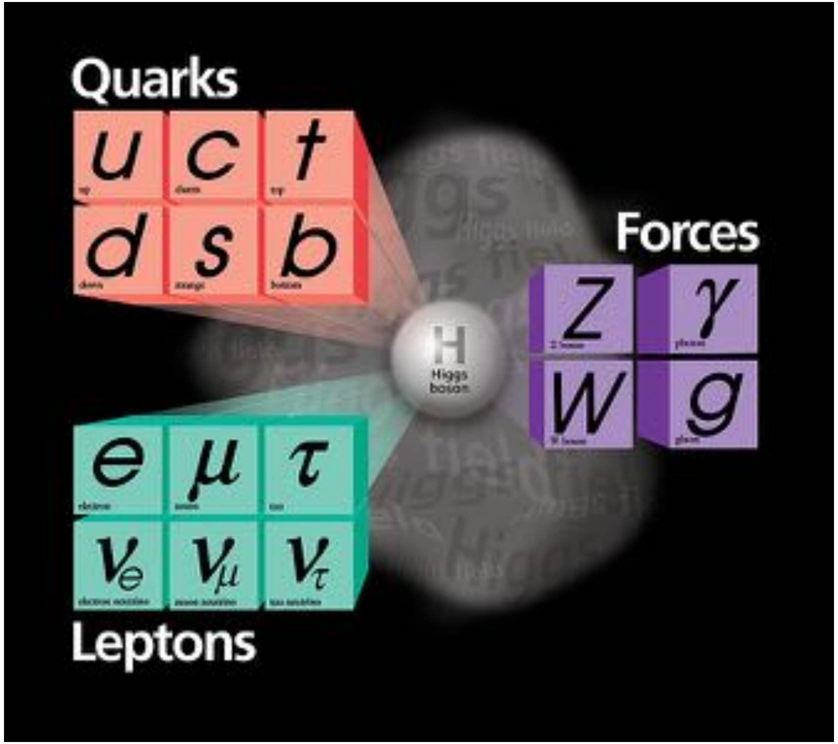
PHYSICAL REVIEW LETTERS **126**, 141801 (2021)

Editors' Suggestion Featured in Physics

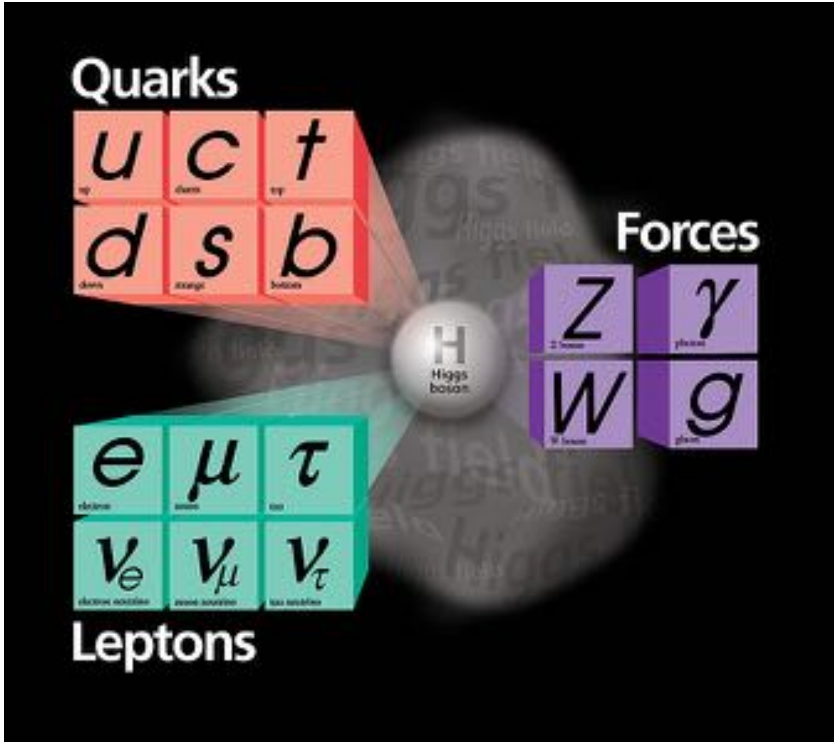
Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

B. Abi,[44] T. Albahri,[39] S. Al-Kilani,[36] D. Allspach,[7] L. P. Alonzi,[48] A. Anastasi,[11,a] A. Anisenkov,[4,b] F. Azfar,[44] K. Badgley,[7] S. Baeßler,[47,c] I. Bailey,[19,d] V. A. Baranov,[17] E. Barlas-Yucel,[37] T. Barrett,[6] E. Barzi,[7] A. Basti,[11,32] F. Bedeschi,[11] A. Behnke,[22] M. Berz,[20] M. Bhattacharya,[43] H. P. Binney,[48] R. Bjorkquist,[6] P. Bloom,[21] J. Bono,[7] E. Bottalico,[11,32] T. Bowcock,[39] D. Boyden,[22] G. Cantatore,[13,34] R. M. Carey,[2] J. Carroll,[39] B. C. K. Casey,[7] D. Cauz,[35,8] S. Ceravolo,[9] R. Chakraborty,[38] S. P. Chang,[18,5] A. Chapelain,[6] S. Chappa,[7] S. Charity,[7] R. Chislett,[36] J. Choi,[5] Z. Chu,[26,e] T. E. Chupp,[42] M. E. Convery,[7] A. Conway,[41] G. Corradi,[9] S. Corrodi,[1] L. Cotrozzi,[11,32] J. D. Crnkovic,[3,37,43] S. Dabagov,[9,f] P. M. De Lurgio,[1] P. T. Debevec,[37] S. Di Falco,[11] P. Di Meo,[10] G. Di Sciascio,[12] R. Di Stefano,[10,30] B. Drendel,[7]

The Standard Model: Great success, many open questions!



The Standard Model: Great success, many open questions!



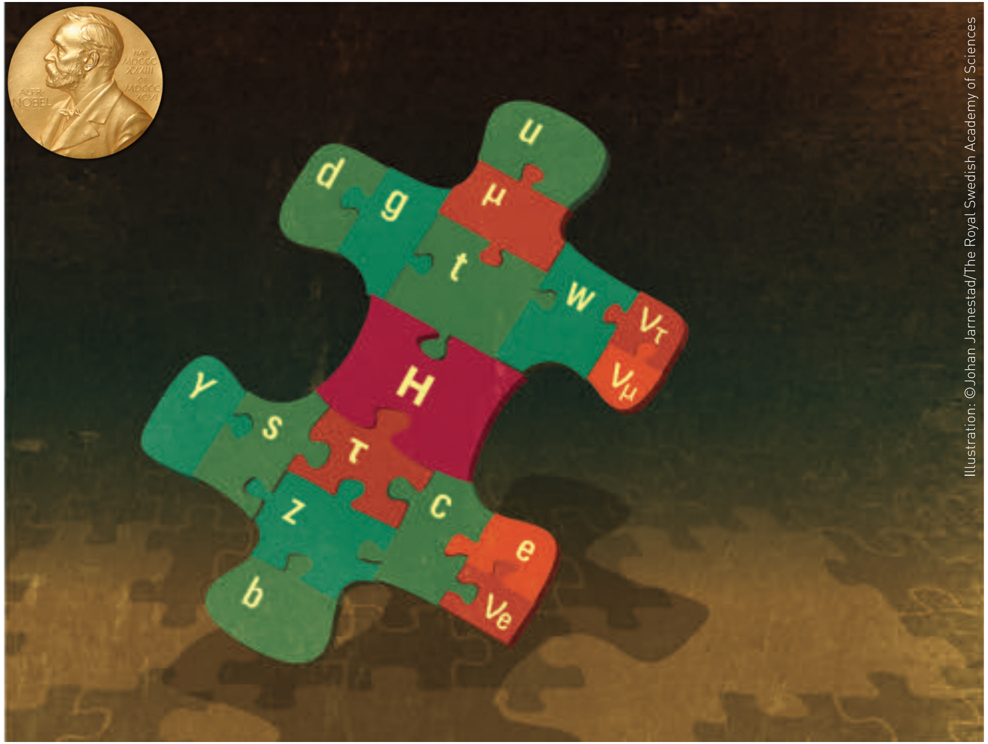
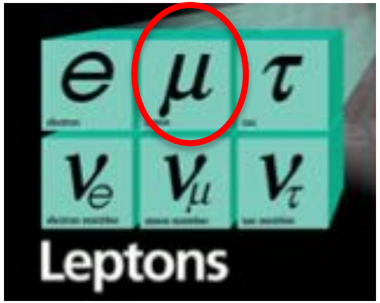


Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences

Our favorite probe: The muon

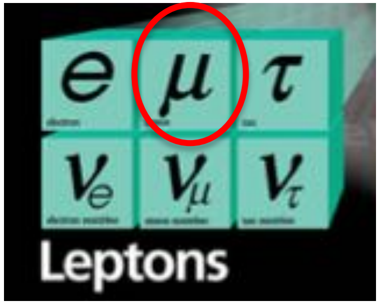


- Fortuitous lifetime = 2.2 μs
- Spin 1/2 particle
- Encodes information about spin in its decay

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

- This g-factor is the “g” in “g-2”
- g= 2 + contributions from virtual particles

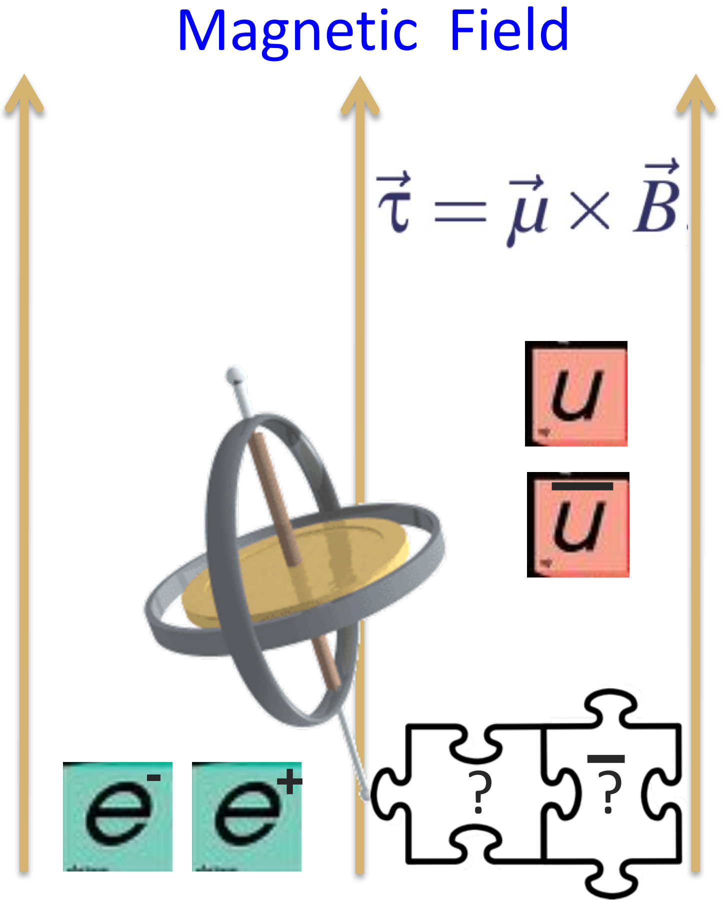
Our favorite probe: The muon



- Fortuitous lifetime = 2.2 μs
- Spin 1/2 particle
- Encodes information about spin in its decay

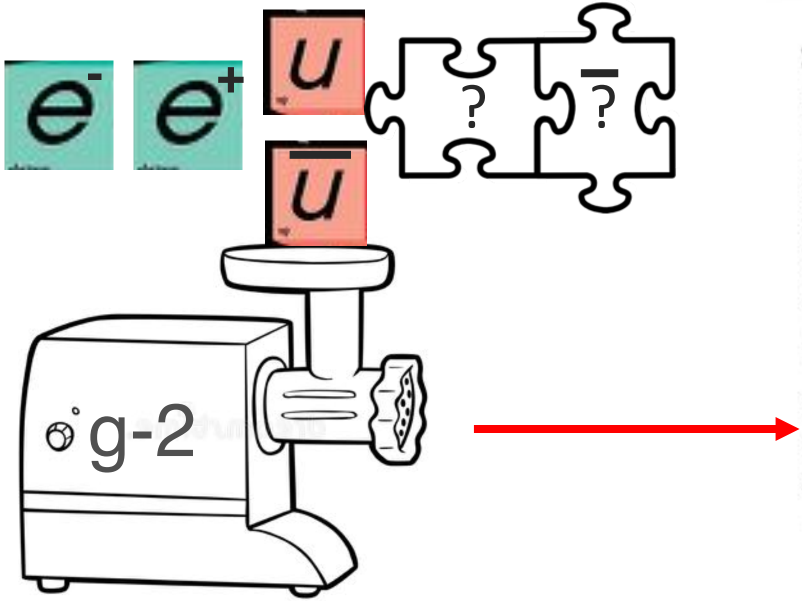
$$\vec{\mu} = g \frac{q}{2m} \vec{S}$$

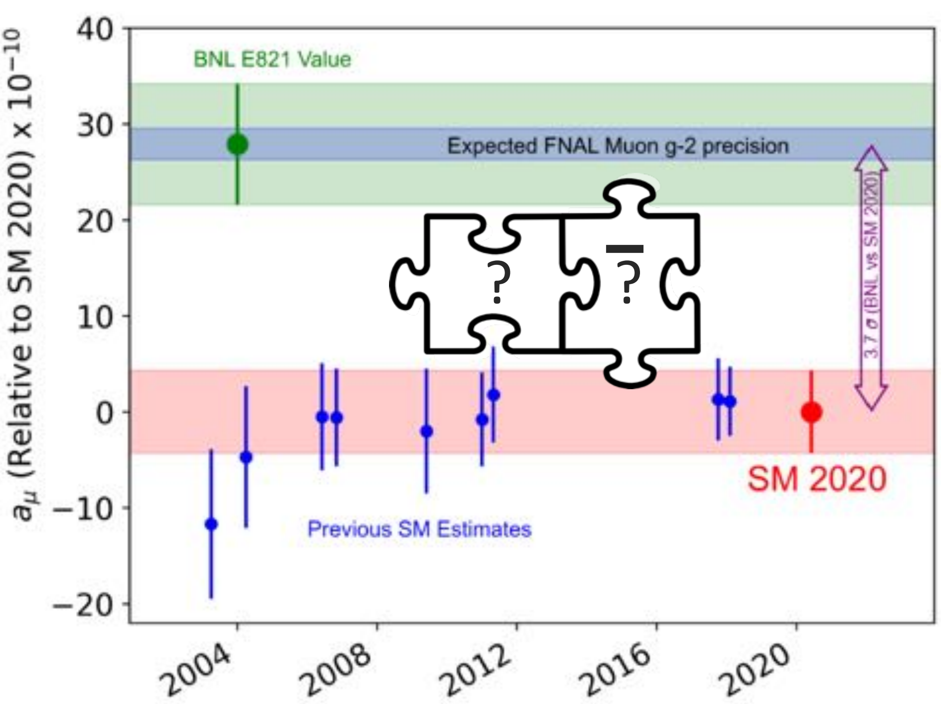
- This g-factor is the “g” in “g-2”
- g= 2 + contributions from virtual particles



$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

Motivation: Status of the muon anomaly before Fermilab Experiment





- Dominik’s talk: SM calculation, BSM physics, and possible interpretations

T. Aoyama, N. Asmussen, M. Benayoun et al., The anomalous magnetic moment of the muon in the Standard Model, Physics Reports (2020), https://doi.org/10.1016/j.physrep.2020.07.006.

Muon g-2 basics in a storage ring

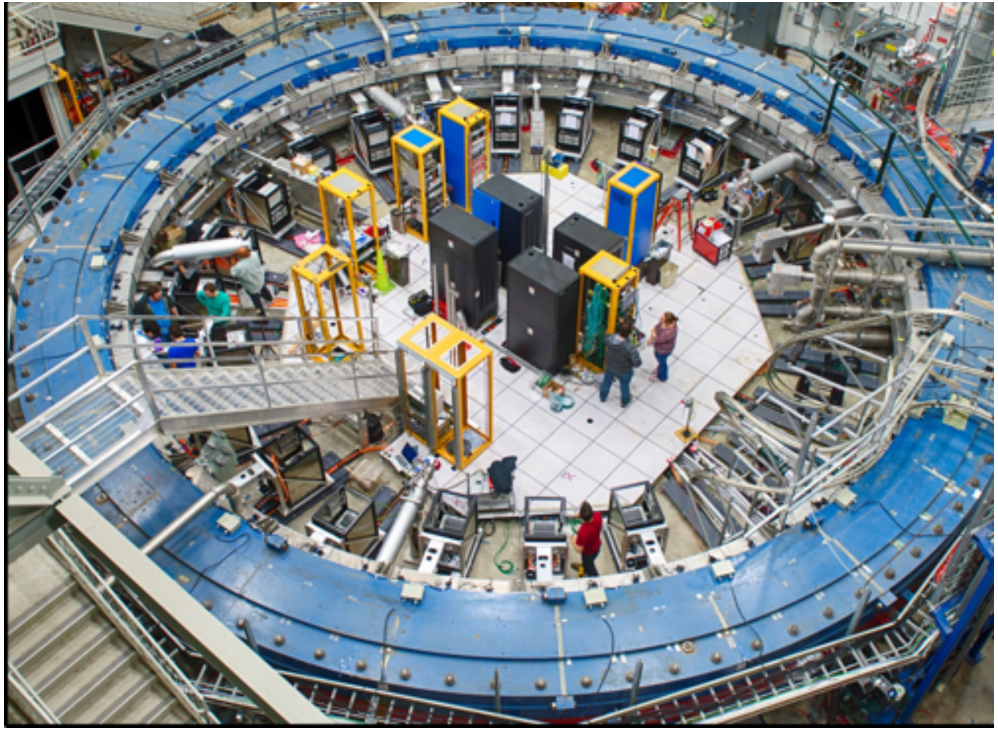
$$\boxed{\omega_a = \frac{eB}{m} a_\mu}$$

A precision measurement of the muon’s anomalous spin-precession frequency in a well-measured magnetic field will tell us how muons see the universe.

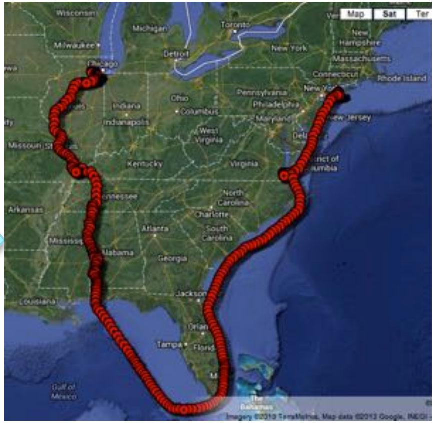
What are the main experimental steps to get a_μ ?

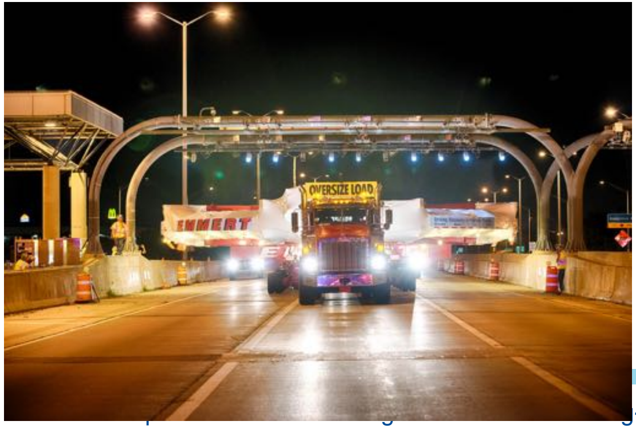
$$\boxed{\omega_a = \frac{eB}{m} a_\mu}$$

1. Build a racetrack for the muons
2. Inject and store polarized muons
3. Measure the decay electrons to determine the muons' properties
4. Map and track the magnetic field



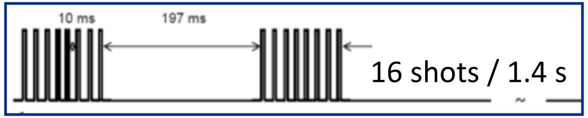
1. Build a racetrack for the muons: Bring the magnet to Fermilab



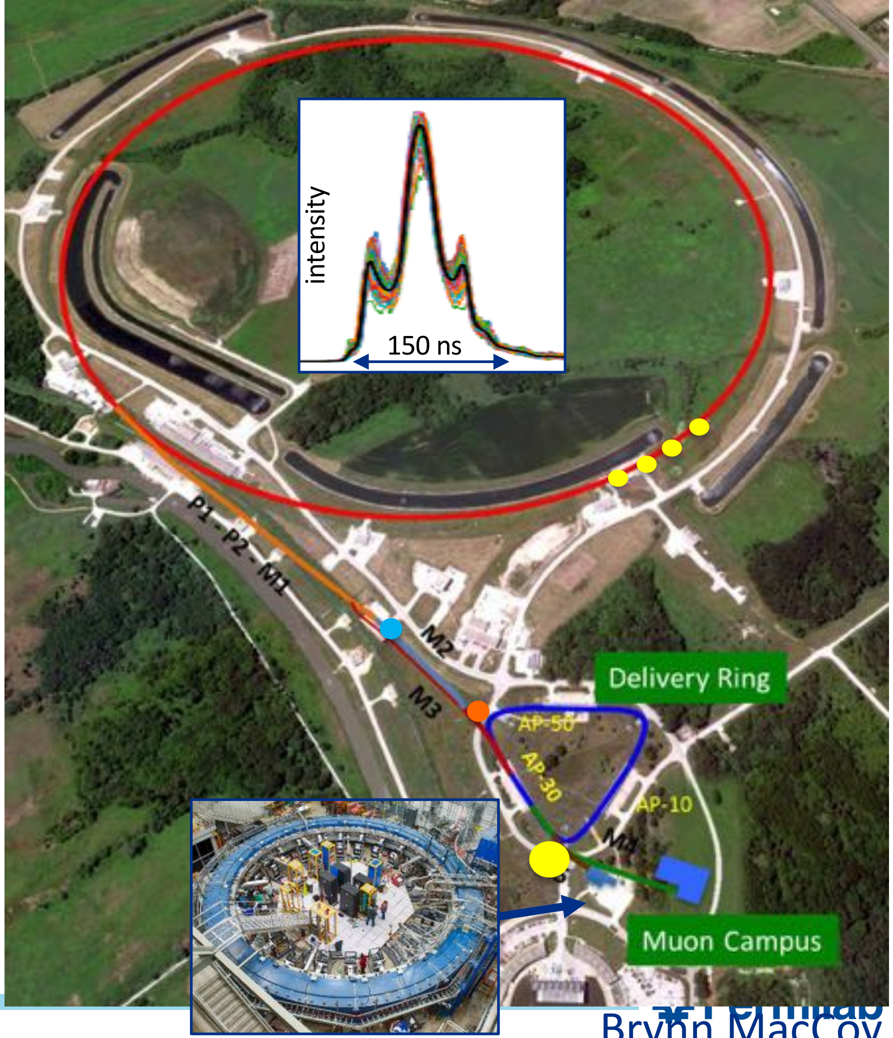


2. Inject and store polarized muons

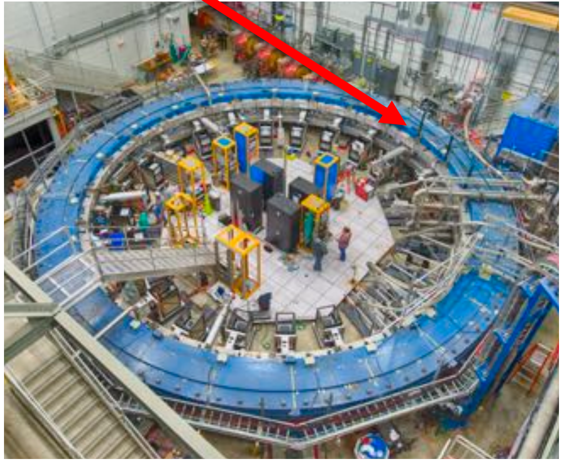
- 8 GeV protons
- Use RF to create bunches
- Create pions on a target
- Transfer and decay $\pi \rightarrow \mu\nu$, creating a polarized muon beam
- Delivery Ring kicks out remaining protons, lets pion
- **~5000 stored muons per pulse**

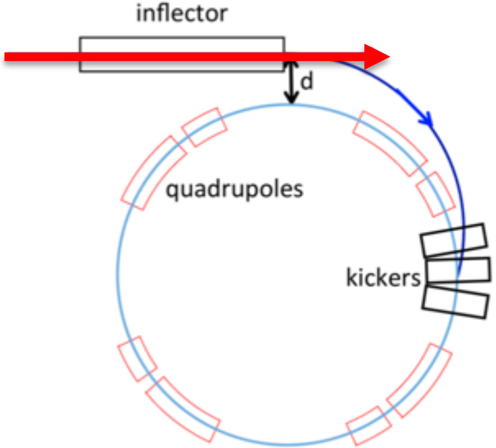


- Repeat!

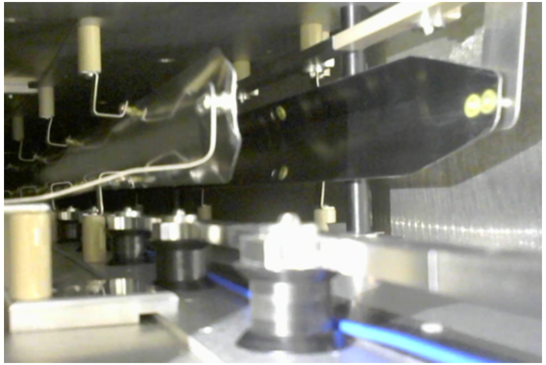


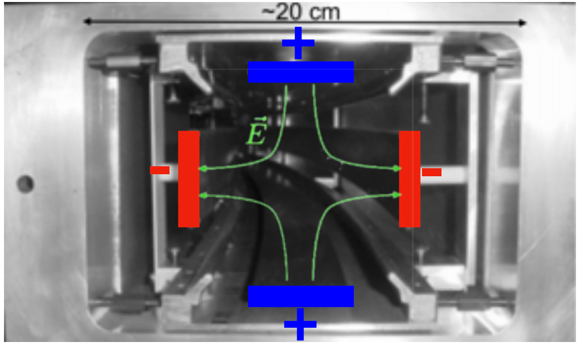
2. Inject and store polarized muons





Fast **kicker** pulse transfers muons to central orbit





Pulsed **quads** provide vertical focusing (restoring force)

2. Inject and store polarized muons

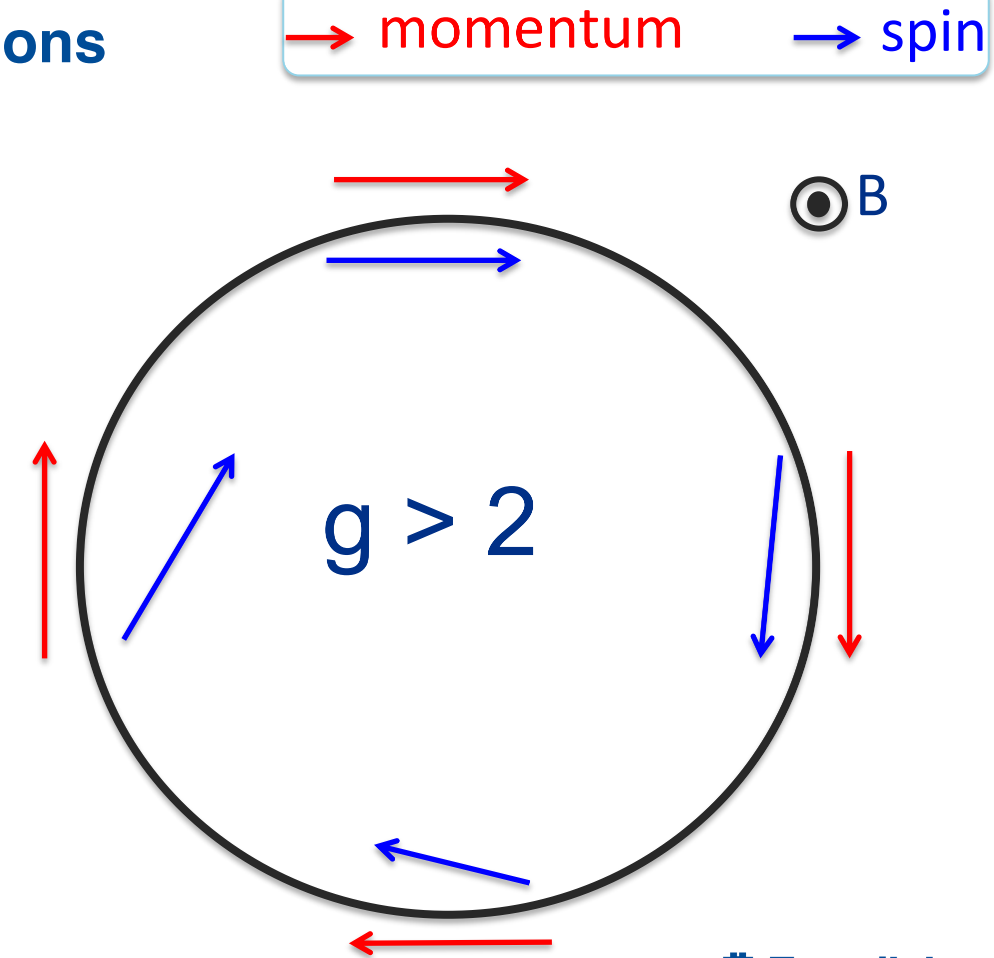
1. Cyclotron frequency:

$$\omega_c = \frac{e}{m\gamma} B$$

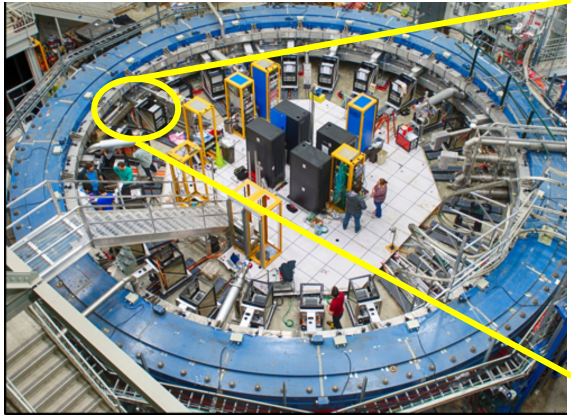
2. Spin precession frequency

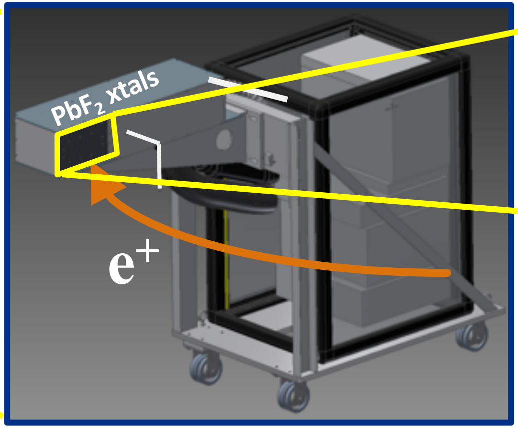
$$\omega_s = \frac{e}{m\gamma} B \left(1 + \gamma \frac{g-2}{2}\right)$$

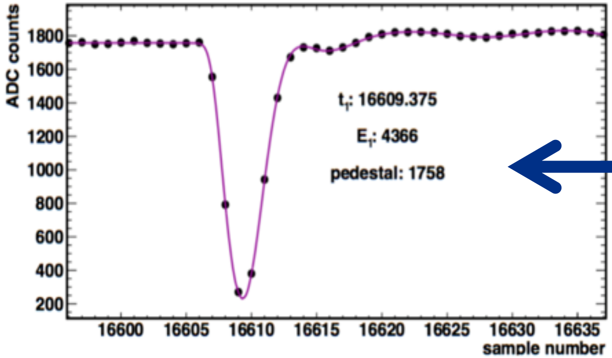
$$\boxed{\omega_s - \omega_c \equiv \omega_a = \frac{eB}{m} \frac{g-2}{2} = \frac{eB}{m} a_\mu}$$



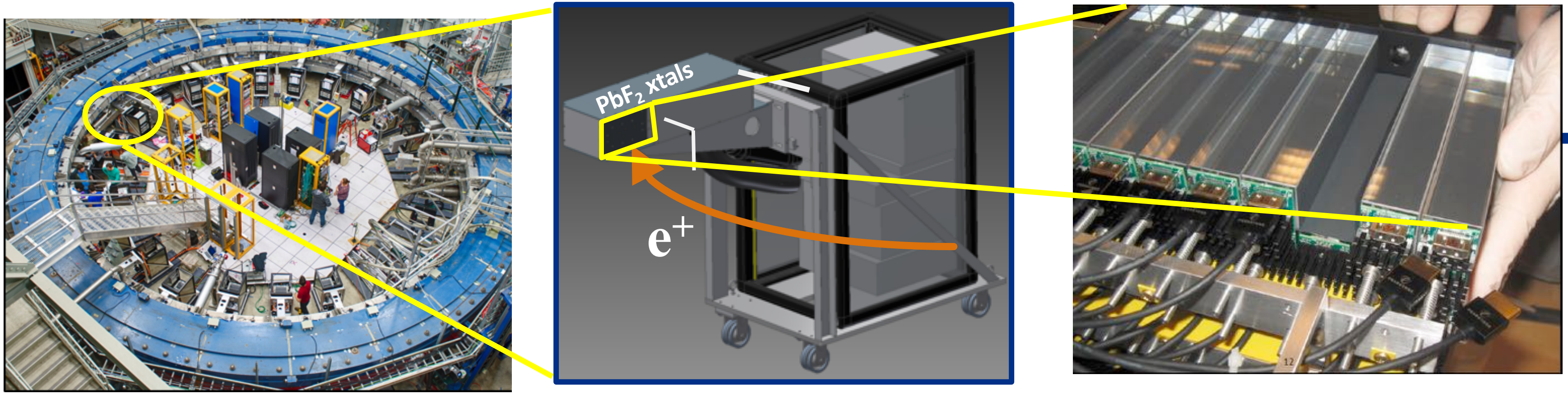
3. Measure decay electrons to determine the muons’ properties



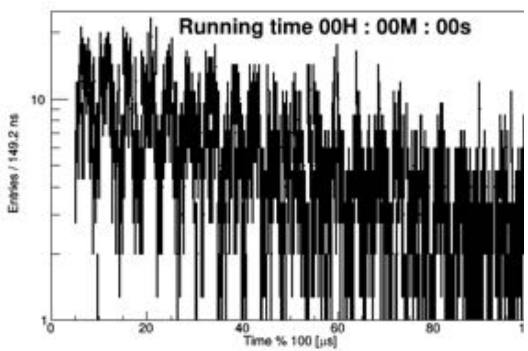


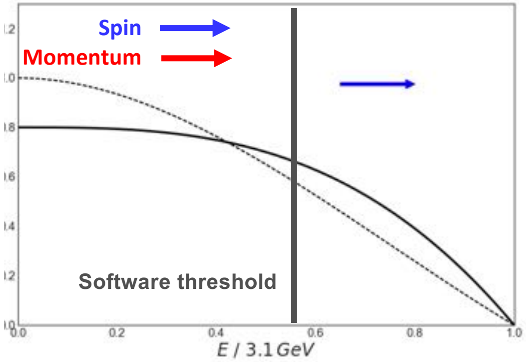


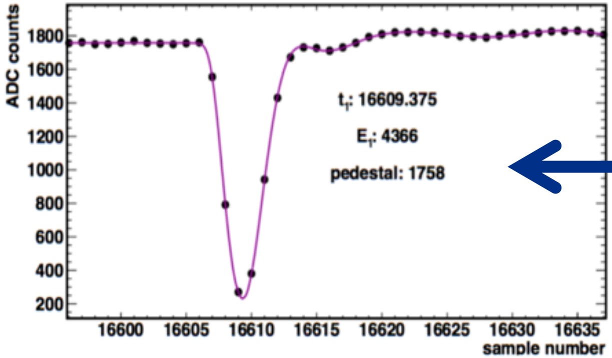
3. Measure decay electrons to determine the muons’ properties



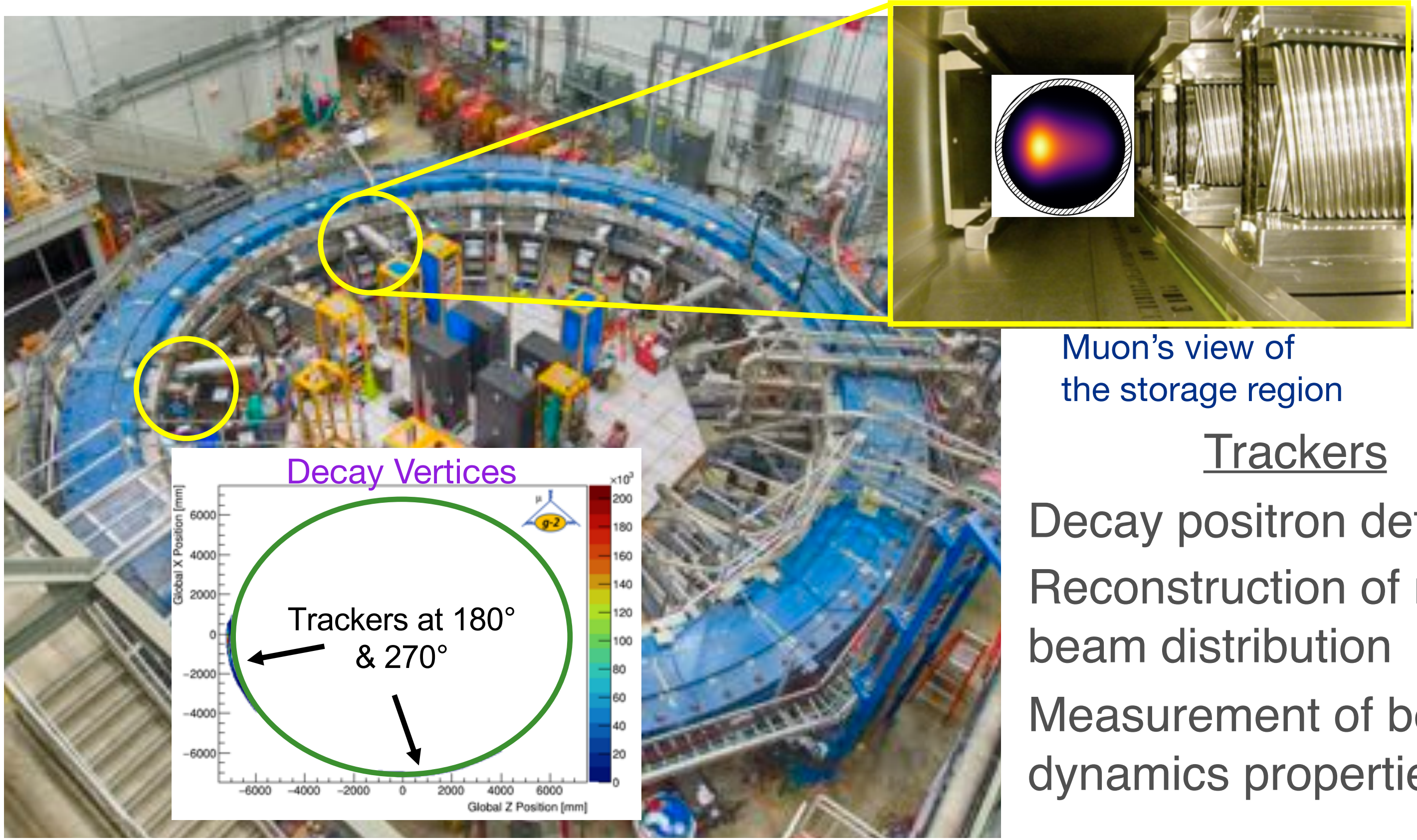
Events above threshold



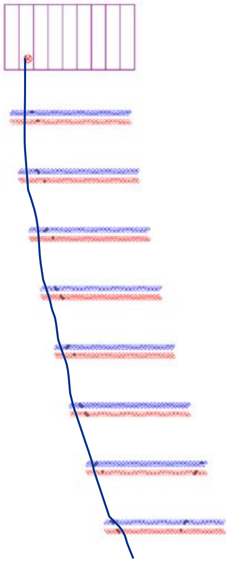




3. Measure decay electrons to determine the muons’ properties



Muon’s view of
the storage region



Trackers

Decay positron detected

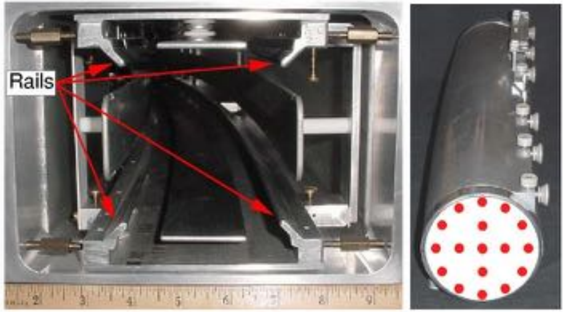
Reconstruction of muon beam distribution

Measurement of beam dynamics properties

4. Map and track the magnetic field

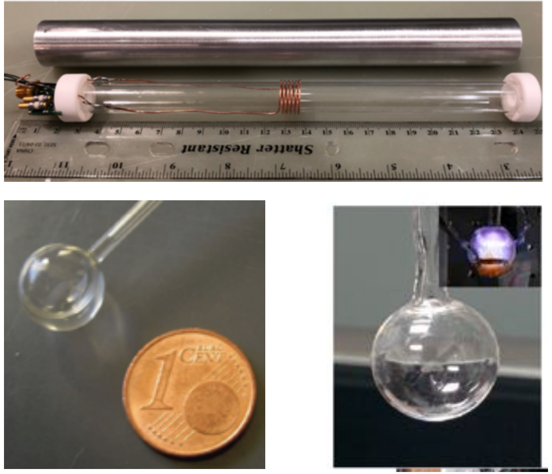
- Use Nuclear Magnetic Resonance (NMR)
  - Tip spins of NMR probe sample’s protons
  - Determine the field in terms of the proton precession frequency ω_p

NMR trolley **maps** field every 3 days



378 fixed probes **monitor** continuously

Trolley cross-**calibrated** to absolute probes



We can rewrite a_μ : our observables plus external measurements

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

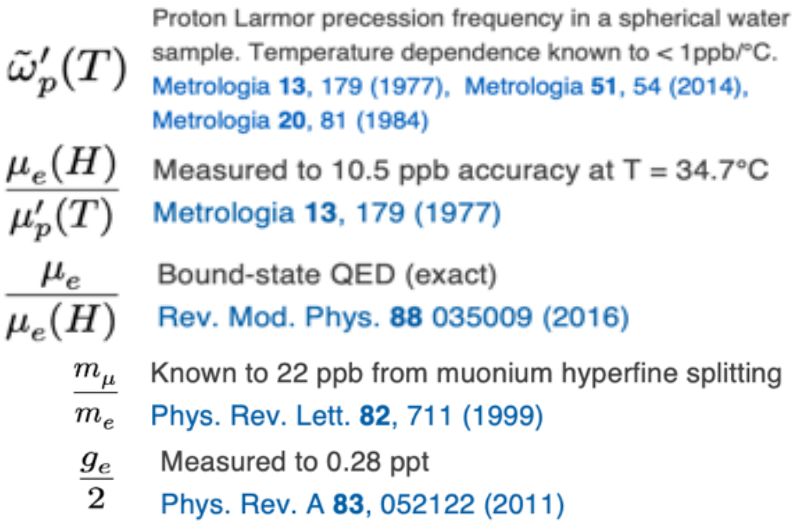
Quantities we measure

ω_a : the muon anomalous spin precession frequency

$\tilde{\omega}'_p(T_r)$: precession of protons in water sample mapping the field and weighted by the muon distribution

Ultimate Goal: 140 ppb =
100 ppb (stat) ⊕ 100 ppb (syst)

Determined externally to 25 ppb



$\tilde{\omega}'_p(T)$	Proton Larmor precession frequency in a spherical water sample. Temperature dependence known to < 1ppb/°C. Metrologia **13**, 179 (1977), Metrologia **51**, 54 (2014), Metrologia **20**, 81 (1984)
$\frac{\mu_e(H)}{\mu'_p(T)}$	Measured to 10.5 ppb accuracy at T = 34.7°C Metrologia **13**, 179 (1977)
$\frac{\mu_e}{\mu_e(H)}$	Bound-state QED (exact) Rev. Mod. Phys. **88** 035009 (2016)
$\frac{m_\mu}{m_e}$	Known to 22 ppb from muonium hyperfine splitting Phys. Rev. Lett. **82**, 711 (1999)
$\frac{g_e}{2}$	Measured to 0.28 ppt Phys. Rev. A **83**, 052122 (2011)

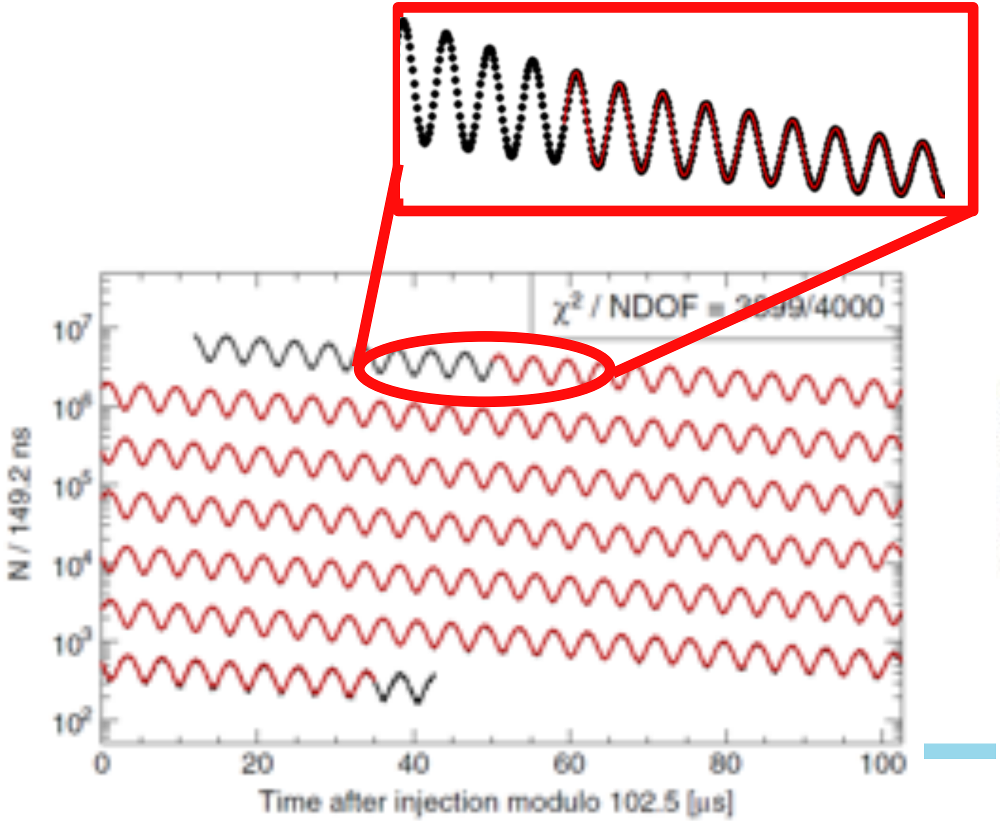
We relate our observables to the quantities that determine a_μ

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

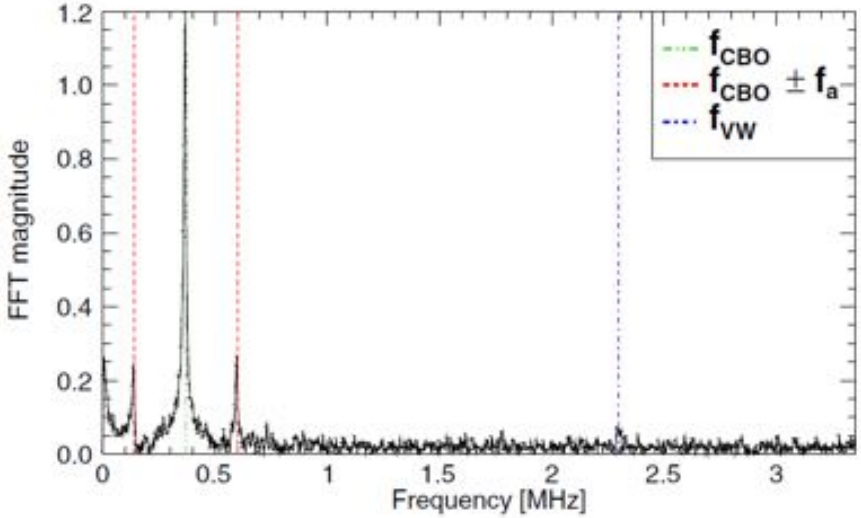
		Systems used
f_{clock}	Blinded clock	
ω_a^m	Measured precession frequency	Calorimeters
C_e	Electric field correction	Trackers and simulations
C_p	Pitch correction	
C_{ml}	Muon loss correction	
C_{pa}	Phase-acceptance correction	
f_{calib}	Absolute magnetic field calibration	NMR
$\omega_p(x,y,\phi)$	Tracked field map distribution	
$M(x,y,\phi)$	Tracked muon spatial distribution	Trackers
B_k	Transient field from the kicker	Magnetometer & dedicated NMR
Bq	Transient field from the quad charging	

Muon Precession Frequency

Start with simple 5 parameter fit: $F(t) = N_0 e^{-t/\gamma\tau_\mu}\left[1 + A_0 \cos(\omega_a^m t + \phi_0)\right]$



FFT of fit residuals



Muon Precession Frequency

- Account for
  - beam dynamics effects (transverse oscillations)
  - muons that escape in a time-dependent manner, etc..

22 parameter fit

$$N_0 e^{-\frac{t}{\tau}} \left(1 + A \cdot A_{BO}(t) \cos(\omega_a t + \phi \cdot \phi_{BO}(t))\right) \cdot N_{\mathrm{CBO}}(t) \cdot N_{\mathrm{VW}}(t) \cdot N_y(t) \cdot N_{2\mathrm{CBO}}(t) \cdot J(t)$$

$$A_{\mathrm{BO}}(t) = 1 + A_A \cos(\omega_{\mathrm{CBO}}(t) + \phi_A) e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

$$\phi_{\mathrm{BO}}(t) = 1 + A_\phi \cos(\omega_{\mathrm{CBO}}(t) + \phi_\phi) e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

$$N_{\mathrm{CBO}}(t) = 1 + A_{\mathrm{CBO}} \cos(\omega_{\mathrm{CBO}}(t) + \phi_{\mathrm{CBO}}) e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

$$N_{2\mathrm{CBO}}(t) = 1 + A_{2\mathrm{CBO}} \cos(2\omega_{\mathrm{CBO}}(t) + \phi_{2\mathrm{CBO}}) e^{-\frac{t}{2\tau_{\mathrm{CBO}}}}$$

$$N_{\mathrm{VW}}(t) = 1 + A_{\mathrm{VW}} \cos(\omega_{\mathrm{VW}}(t)t + \phi_{\mathrm{VW}}) e^{-\frac{t}{\tau_{\mathrm{VW}}}}$$

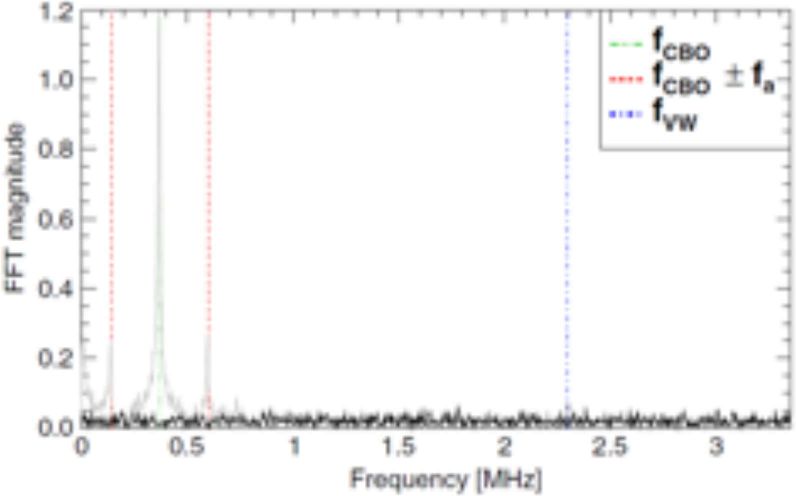
$$N_y(t) = 1 + A_y \cos(\omega_y(t)t + \phi_y) e^{-\frac{t}{\tau_y}}$$

$$J(t) = 1 - k_{LM} \int_{t_0}^{t} \Lambda(t) dt$$

$$\omega_{\mathrm{CBO}}(t) = \omega_0 t + A e^{-\frac{t}{\tau_A}} + B e^{-\frac{t}{\tau_B}}$$

$$\omega_y(t) = F \omega_{\mathrm{CBO}(t)} \sqrt{2\omega_c / F \omega_{\mathrm{CBO}}(t) - 1}$$

$$\omega_{\mathrm{VW}}(t) = \omega_c - 2\omega_y(t)$$

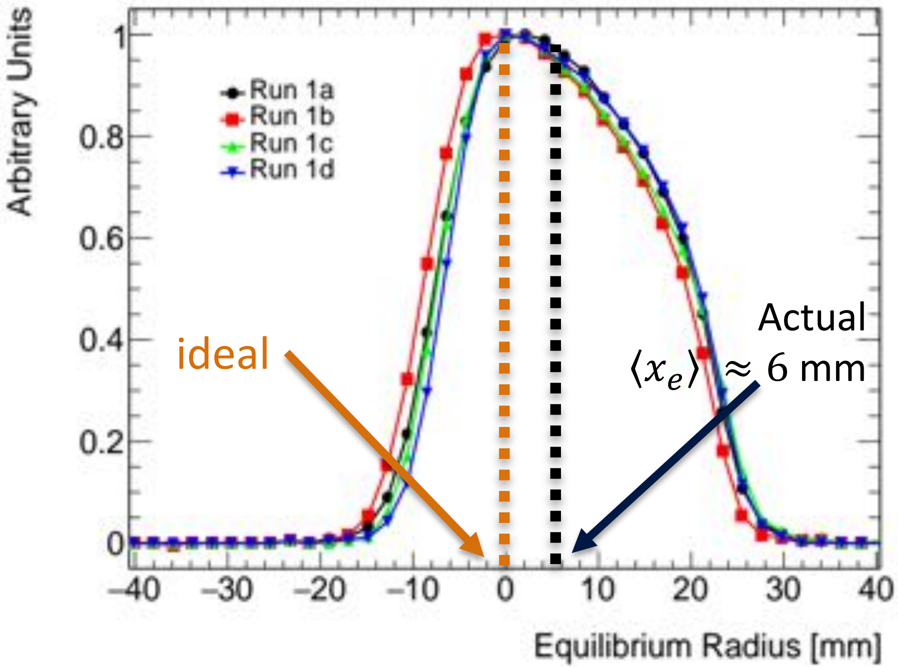


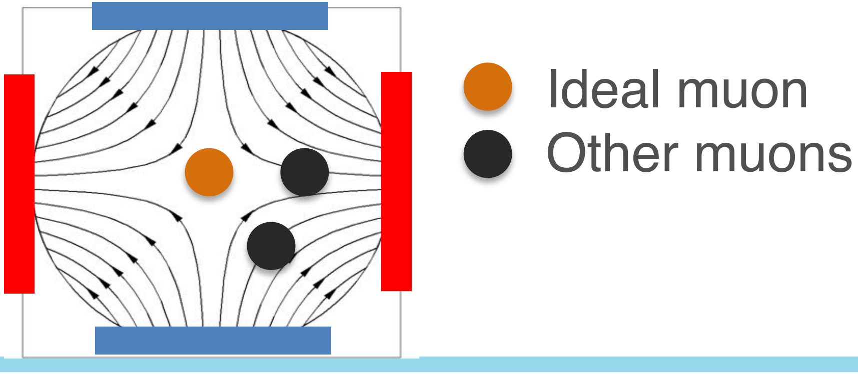
Beam Dynamics: E-field

Quads E-field transforms as motional B

$$\vec{\omega}_a = -\frac{e}{mc}\left[a_\mu \vec{B} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)}_{}\vec{\beta} \times \vec{E}\right]$$

Term vanishes for appropriate choice of
γ = 29.3
Momentum spread in beam of 0.15%

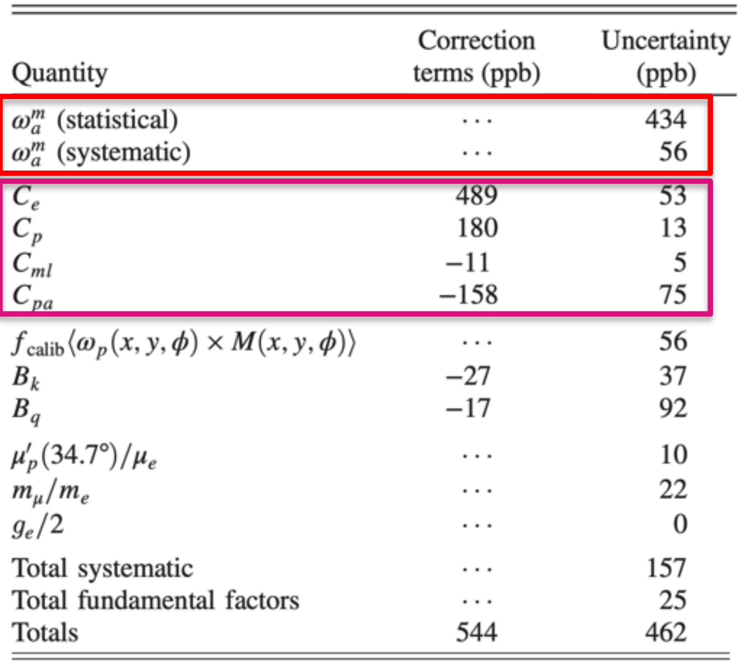




$$C_e \approx 2n(1-n)\beta_0^2 \frac{\langle x_e^2 \rangle}{R_0^2}$$

$$\boldsymbol{C_e} = \mathbf{489\ ppb}, \boldsymbol{\delta_{C_e}} = \mathbf{53\ ppb}$$

Muon Precession Frequency ω_a and Beam Dynamics Results



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

- Statistically dominated (434 ppb)
- Muon precession systematic effects (56 ppb)
- Some large corrections (< 500 ppb) from beam dynamics effects → uncertainties understood and will improve in subsequent runs

- Beam Dynamics: https://arxiv.org/abs/2104.03240
- Muon Precession:
- https://journals.aps.org/prd/abstract/10.1103/PhysRevD.103.072002

We relate our observables to the quantities that determine a_μ

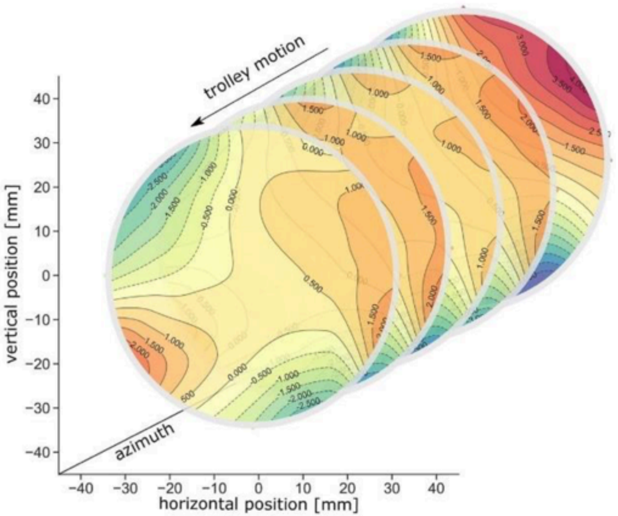
$$a_\mu \propto \frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}}\, \omega_a^{\text{meas}} \left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{f_{\text{calib}} \left\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \right\rangle \left(1 + B_k + B_q\right)}$$

f_{clock}	Blinded clock	Systems used
ω_a^m	Measured precession frequency	Calorimeters
C_e	Electric field correction	
C_p	Pitch correction	Trackers and simulations
C_{ml}	Muon loss correction	
C_{pa}	Phase-acceptance correction	
f_{calib}	Absolute magnetic field calibration	NMR
$\omega_p(x,y,\phi)$	Tracked field map distribution	
$M(x,y,\phi)$	Tracked muon spatial distribution	Trackers
B_k	Transient field from the kicker	Magnetometer & dedicated NMR
Bq	Transient field from the quad charging	

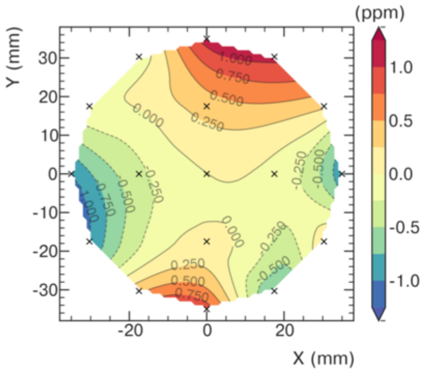
Trolley Magnetic Field Maps

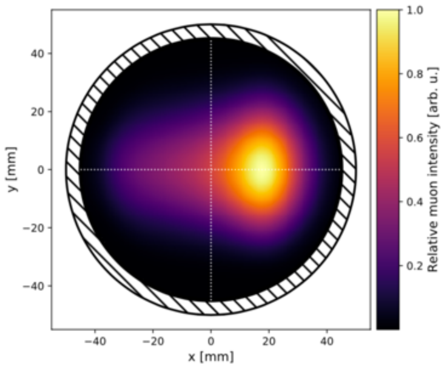
- Create a highly uniform field
- Trolley has 17 probes, produces map at 8000 azimuthal locations
- Determines strength of the field vs space

- Field maps are weighted by muon distribution
- Gradients shift the <B> by ~ 100 ppb, uncertainties ~ 20 ppb



Produce azimuthally averaged field

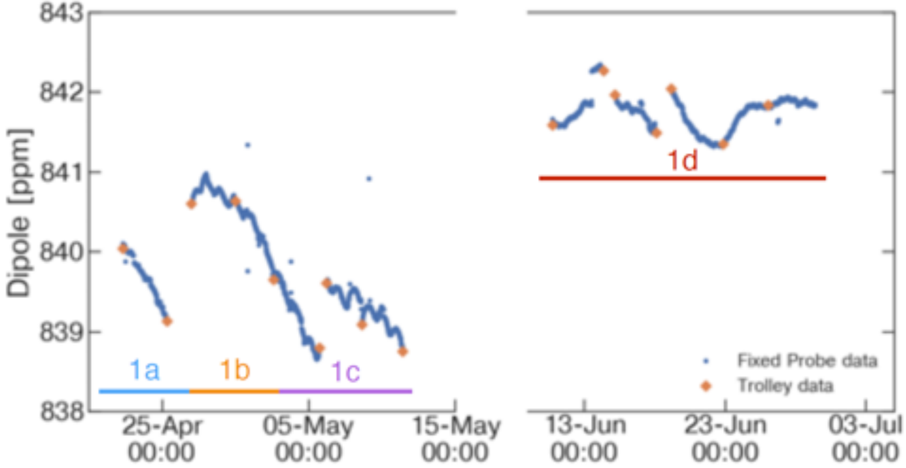


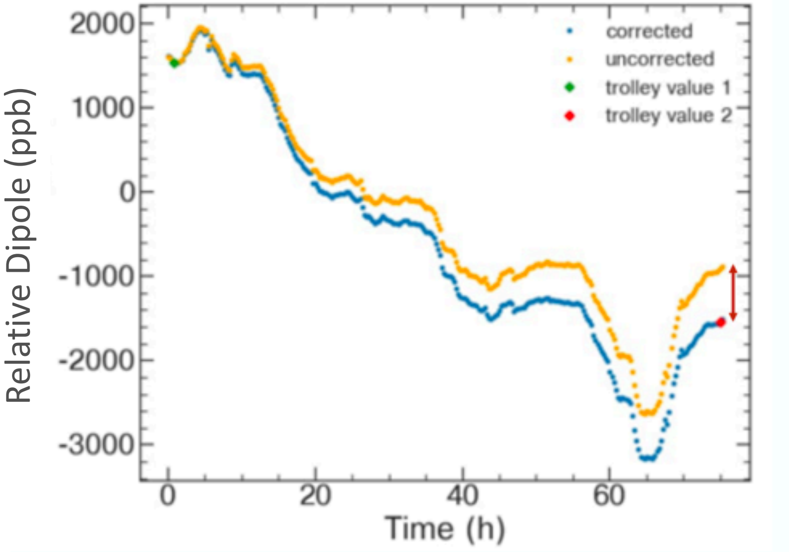


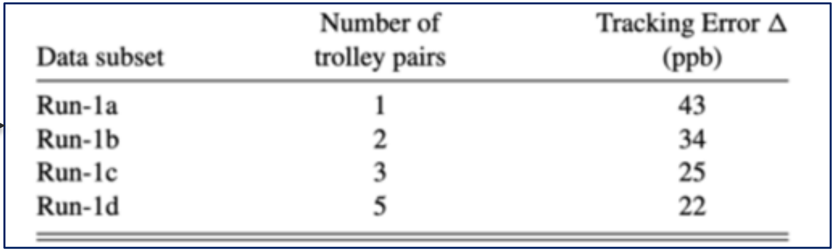
Field Tracking

- Trolley measures when beam is off
- Fixed probes monitor while beam is on
- Magnet temperature drifts
- Drifts in higher-order field gradients untracked → tracking error

Field tracked in run 1



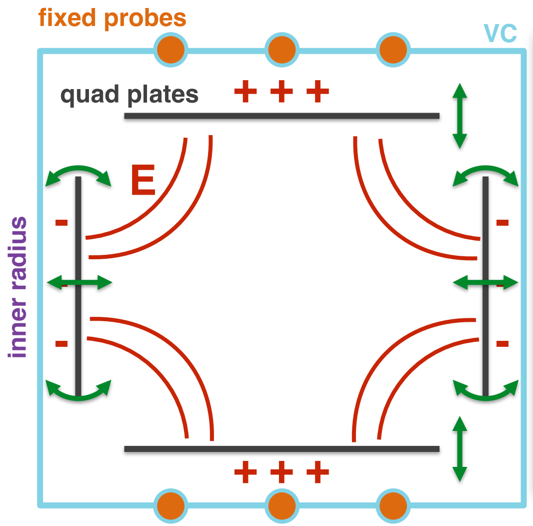




Data subset	Number of trolley pairs	Tracking Error Δ (ppb)
Run-1a	1	43
Run-1b	2	34
Run-1c	3	25
Run-1d	5	22

Transient Fields affect the muons

- Quads are pulsed synchronously with muon injection
- We observed a motion of the quad plates associated with these pulses
- Affects field observed by muons, but **not** the field mapped by trolley (quads off)

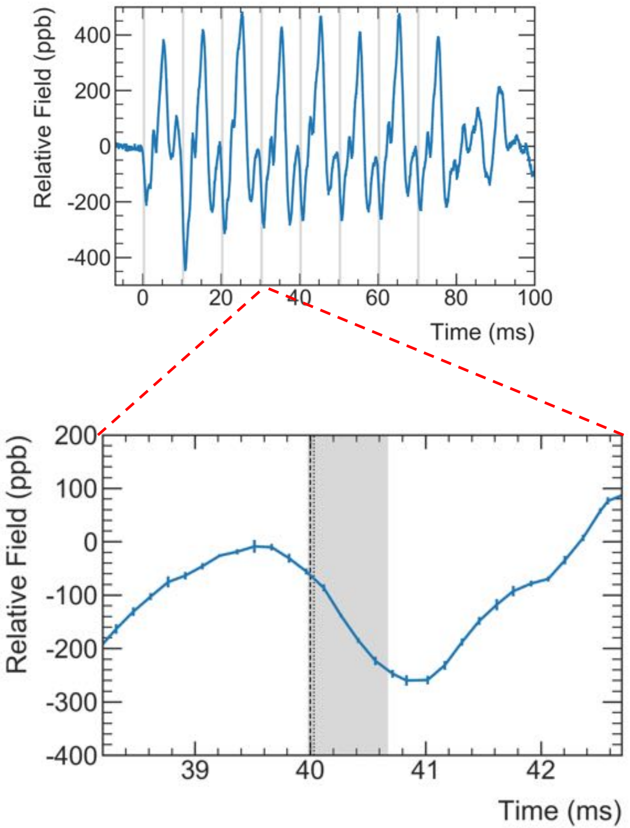


Pulsing Quads

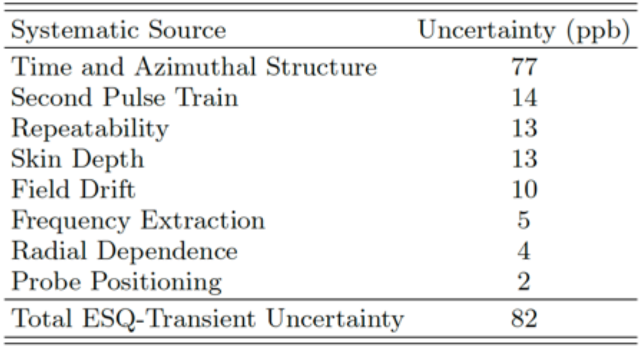
- Side plates oscillate radially
- Oscillating conductor perturbs B-field
- **Fixed probes** sensitive to oscillation

Dedicated measurement

B_q – Quad transients

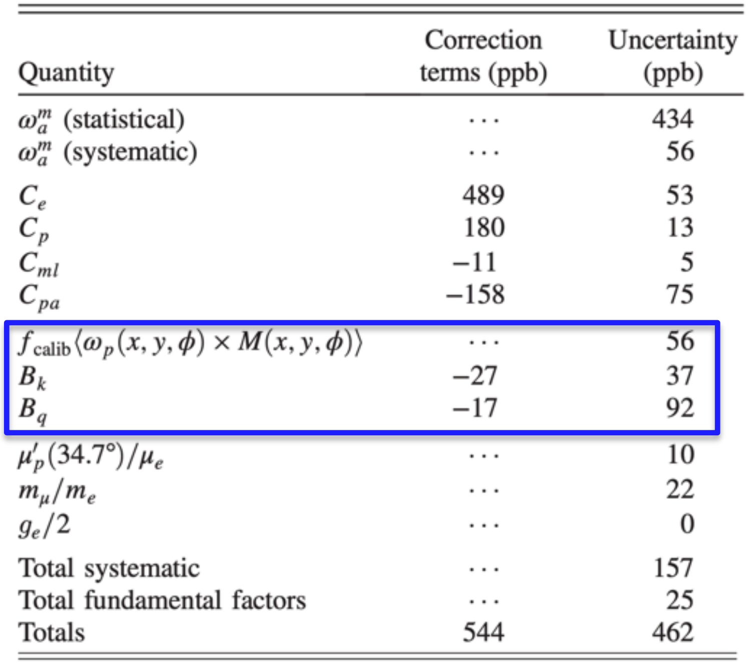


- Map effect along the quad for all beam pulses and account for the quad
- Correction = -17 ppb
- Conservative Uncertainty 82 ppb
- More detailed maps exist →
  - Will quantify long term stability
  - Further map quad region



Systematic Source	Uncertainty (ppb)
Time and Azimuthal Structure	77
Second Pulse Train	14
Repeatability	13
Skin Depth	13
Field Drift	10
Frequency Extraction	5
Radial Dependence	4
Probe Positioning	2
Total ESQ-Transient Uncertainty	82

Magnetic Field Results



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

- Magnetic field measurement 56 ppb includes field mapping, tracking, weighting absolute calibration
- Dedicated measurements for transient field yield 99 ppb → improvements for future runs

- Magnetic Field Analysis: https://journals.aps.org/pra/abstract/10.1103/PhysRevA.103.042208

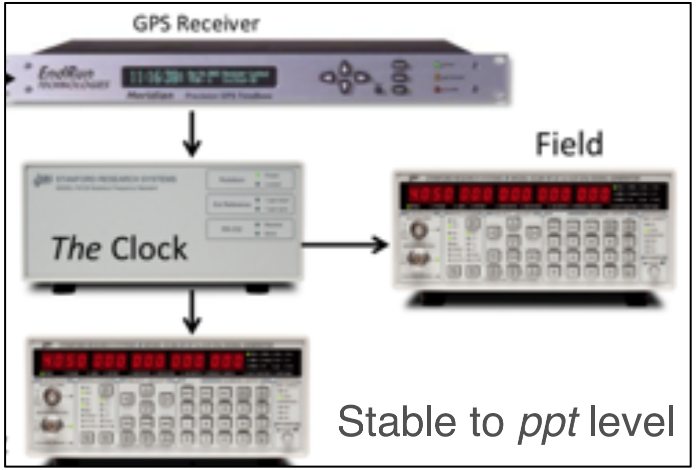
Clock and Unblinding

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

- Muon clock is hardware blinded +/- 25 ppm

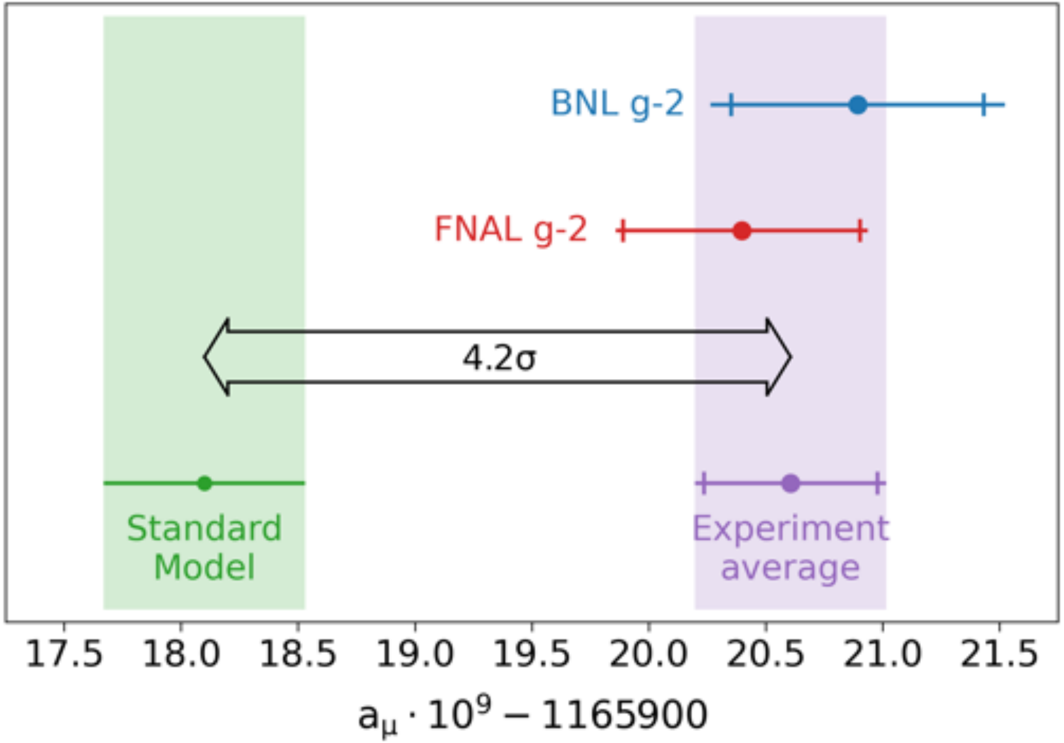
- Sets the *metric* for the wiggle plot

- Once analysis was completed → collaboration unblinded and learned the clock frequency and a_μ



Stable to *ppt* level

First Results



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

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

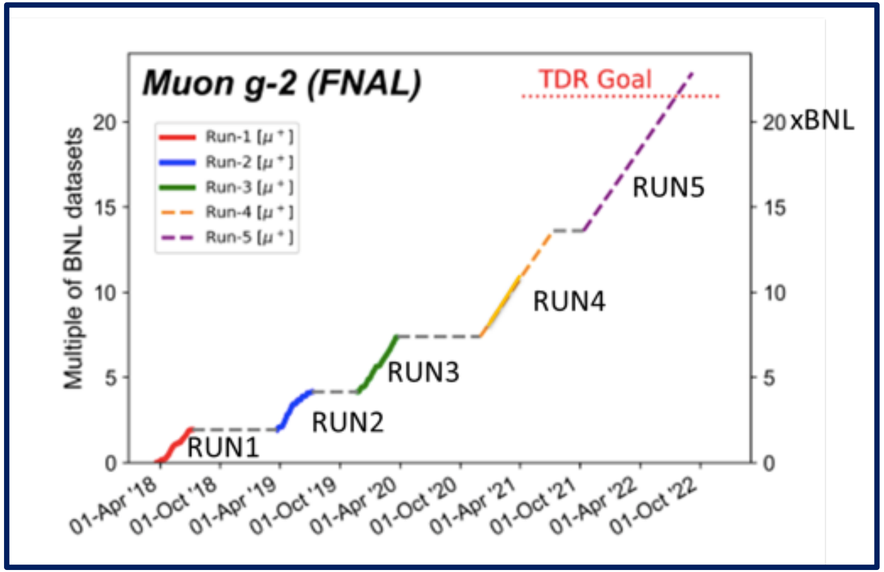
$$a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35 \text{ ppm})$$

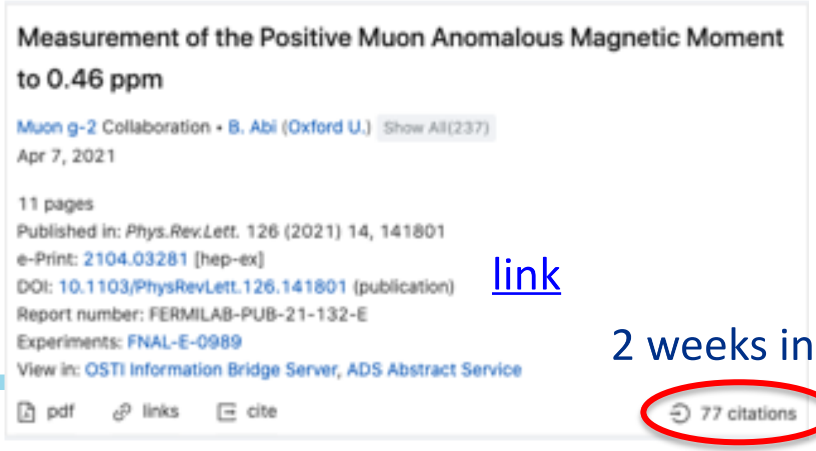
$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

Summary and Outlook

- FNAL measurement agrees well with past experiment
  - Experiment on solid footing
- Analyzed 6% of the planned data
  - Statistically limited: 434 ppb
  - Systematics: 157 ppb
- Collected more than 50% of our planned data
  - Aim to analyze Run 2-3 for summer of 2022

- Meanwhile … theory steps in: What could it all mean?





Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

Muon g-2 Collaboration • B. Abi (Oxford U.) Show All(237)

Apr 7, 2021

11 pages

Published in: Phys.Rev.Lett. 126 (2021) 14, 141801

e-Print: 2104.03281 [hep-ex]

DOI: 10.1103/PhysRevLett.126.141801 (publication)

Report number: FERMILAB-PUB-21-132-E

Experiments: FNAL-E-0989

View in: OSTI Information Bridge Server, ADS Abstract Service

link

2 weeks in:

77 citations