First result from FNAL

Muon g-2



Gavin Hesketh, 12th May 2021



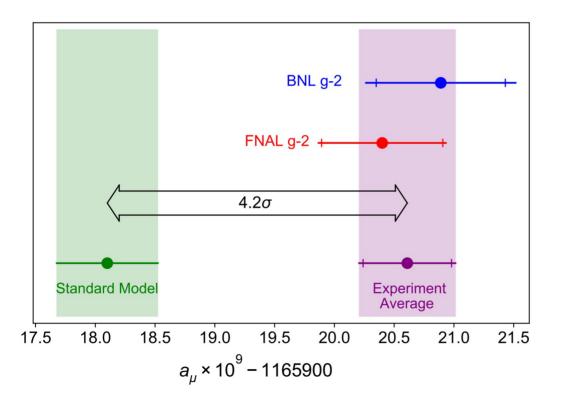


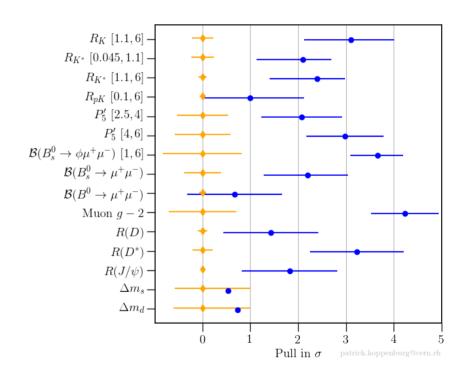


s theory-defying magnetism is confirmed by

Fermilab Muon g-2 (E989) confirms the Brookhaven (E821) results

- measured a to 0.46 ppm
- 4.2σ tension with consensus theory prediction





Some background

All fermions have an intrinsic magnetic moment:

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

For all fundamental fermions:

$$q = 2$$

(Dirac, 1927)



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Electron anomaly!

$$g = 2.00238 \pm 6$$
 (Kusch & Foley, 1948)

All fermions have an intrinsic magnetic moment: - spin + g-factor

$$\vec{\iota} = g \frac{q}{2m} \vec{s}$$

For all fundamental fermions:

$$g = 2.00232$$

(Schwinger, 1948)

$$\frac{\alpha}{2\pi} = 0.00232 \lim_{\mu \to \infty} \mu$$

Electron anomaly!

$$q = 2.00238 \pm 6$$
 (Kusch & Foley, 1948)

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

$q = 2.00231930436328 \pm 153$

Electrons today:

- spin + q-factor

Phys. Rev. D **97**, 036001 (2018)

 $q = 2.00231930436146 \pm 56$

All fermions have an intrinsic magnetic moment:

Phys. Rev. A 83, 052122 (2011)

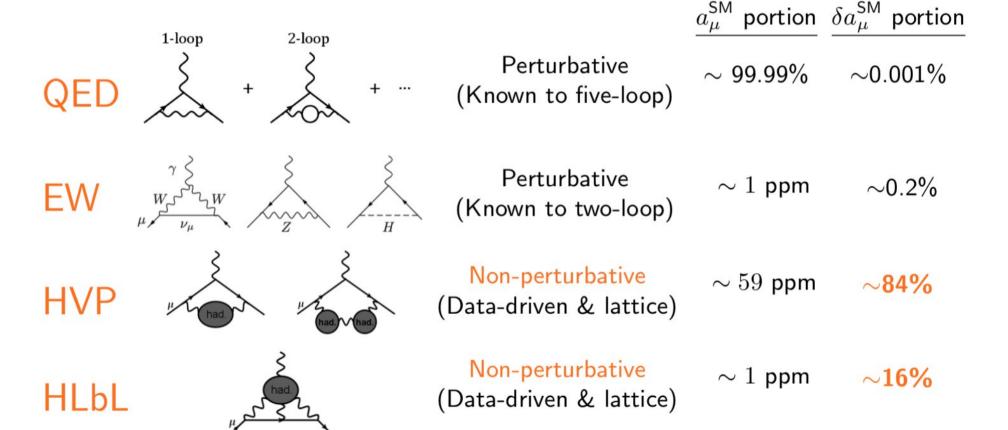
"the most precisely determined quantity in physics"

"Anomalous" term:
$$a = g - 2$$

- all the loop corrections
- contributions scale as $(m_1/M)^2 \rightarrow$ muons x43,000 more sensitive to higher mass effects

$$a_{\mu}^{\text{SM}} = a_{\mu}^{\text{QED}} + a_{\mu}^{\text{EW}} + a_{\mu}^{\text{HVP}} + a_{\mu}^{\text{HLbL}}$$

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g-2 Theory Initiative determination of SM value

T. Aoyama et al, arXiv:2006.04822, Phys. Repts. 887 (2020) 1-166

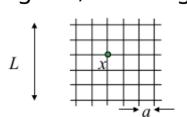
Consensus approach to HVP:

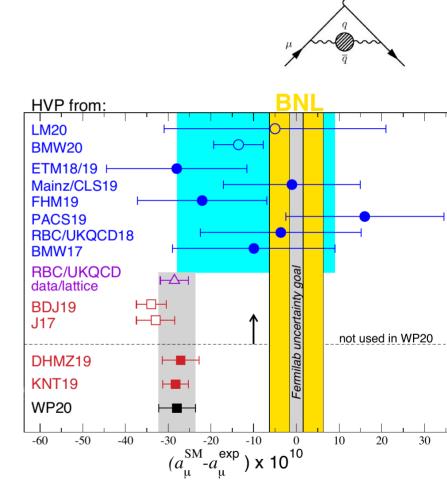
- e^+e^- → hadrons data + dispersion theory
- many data-sets + analyses, long-standing approach



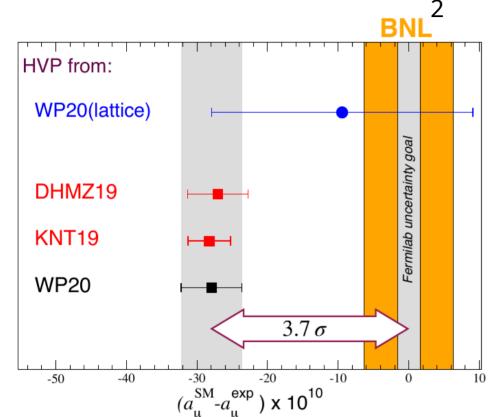
Lattice QCD:

- theory-based evaluation on super-computers
- huge recent progress, several groups





Results for anomalous term: a = q - 2



Brookhaven Experiment (E821)

- 540 ppm precision
- 3.7 σ from Standard Model

Fermilab Experiment (E989)

- 540ppb → 140 ppb
- better muon beam

 - lower inst rate, higher int rate - higher purity
- new detectors

$$BNL \rightarrow FNAL$$

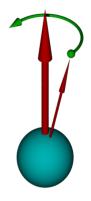
 $[50 \text{ (stat)} + 33 \text{ (syst)} \rightarrow 11 \text{ (stat)} + 11 \text{ (syst)}] \times 10^{-11}$

- = 0.00116591810 (43)
- = 0.00116592089 (63)

Measuring g-2

Spin precession in a magnetic field:

$$\omega_s = g \frac{eB}{2m} + (1 - \gamma) \frac{eB}{\gamma m}$$
$$= a_\mu \frac{eB}{m} + \frac{eB}{\gamma m}$$

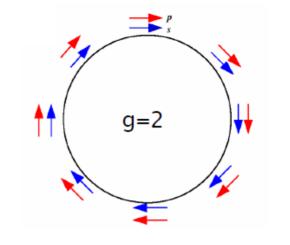


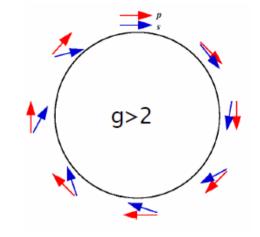
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$$\omega_s - \omega_c \equiv \omega_a = a_\mu \frac{eB}{m}$$

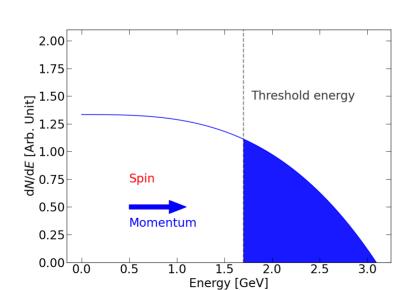


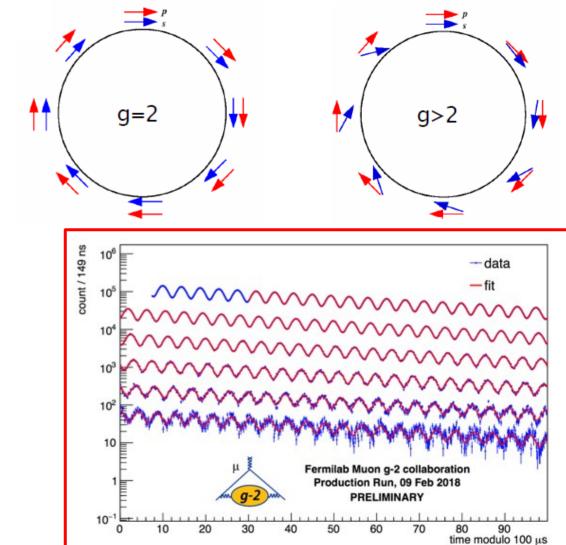


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$$eB$$

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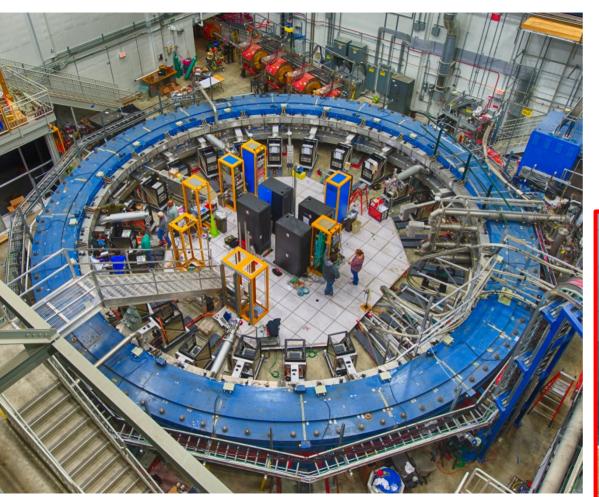


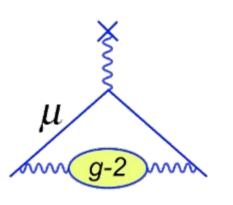




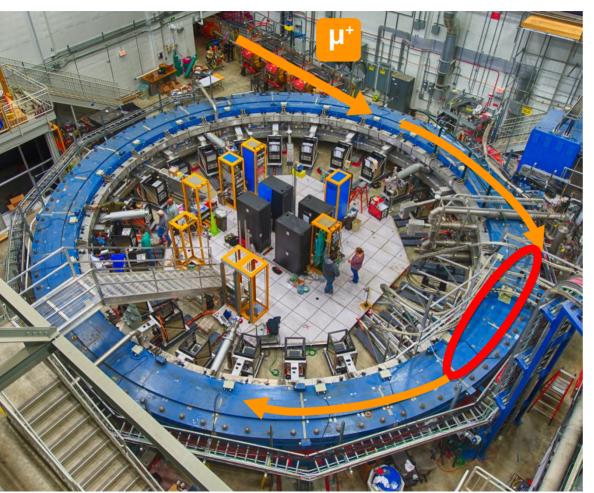








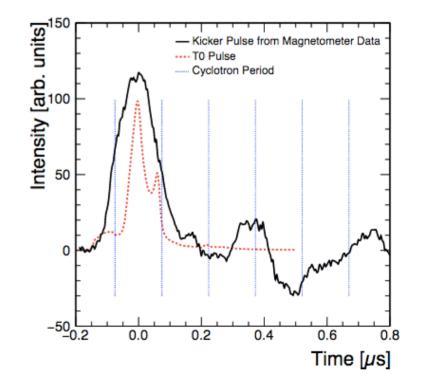


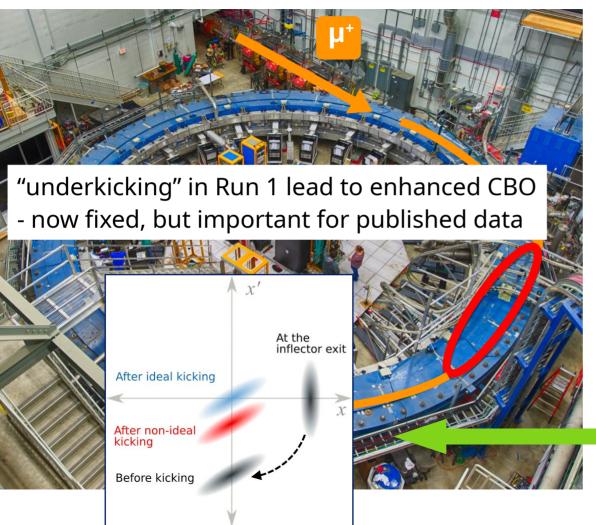


Beam pulse ~ 125 ns wide

Muons ~77 mm away from ideal radius

- "kick" them into right orbit

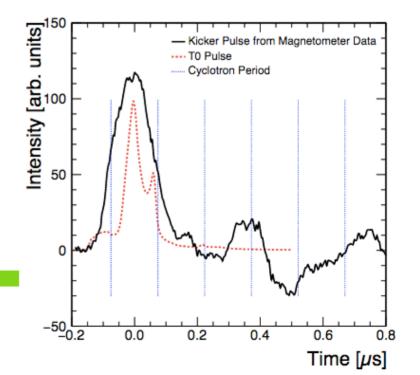




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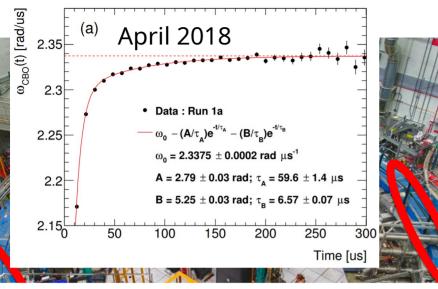
Scraping at the start of each fill:

- beam is moved to collimators
- momentum spread $0.15\% \rightarrow 0.1\%$

Electric quadrupoles:

~20 cm

- focus the beam vertically



2 (out of 32) damaged resistors in Run 1

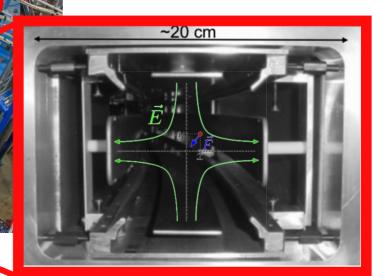
- affected quadrupole charging time
- drift in CBO
- enhanced phase-acceptance systematic

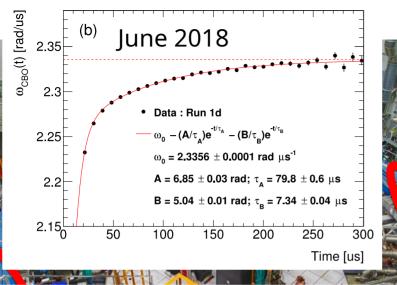
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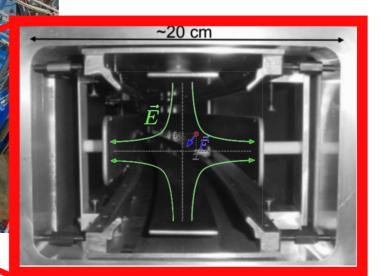
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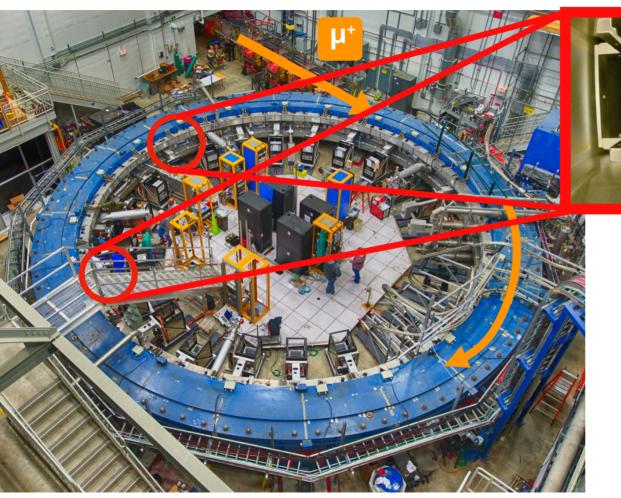


24 calorimeters:

- $6x9 \text{ PbF}_2 \text{ crystals } (2.5x2.5x14cm, 15X_0)$

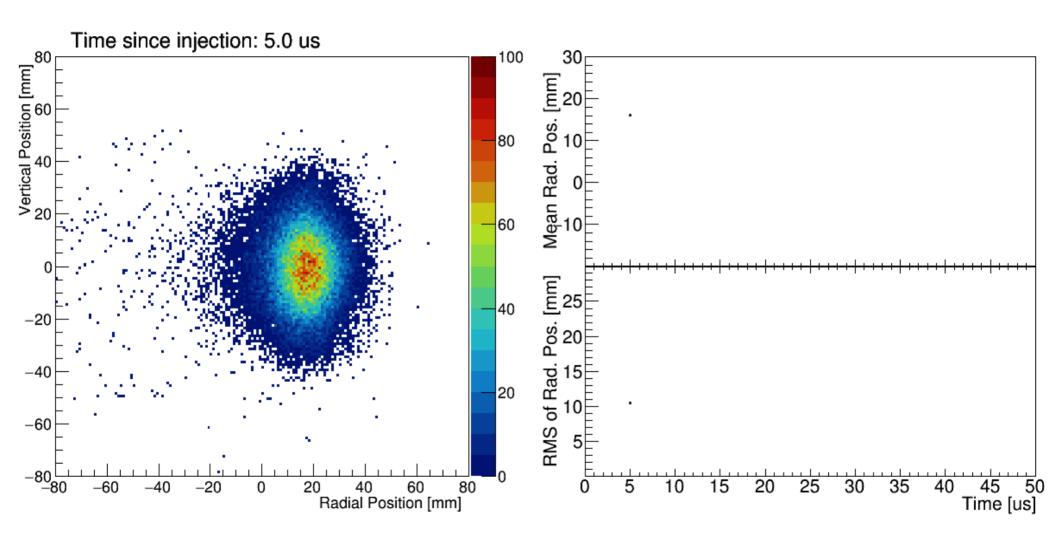
Read out by SiPMs, 1296 total channels

Dedicated laser calibration system



Two tracking stations:

- 8 modules, 128 straws in each
- stereo angle for vertical position
- trace positrons back to decay point
- UK built



The basic method:

- count positrons over threshold
- 5-parameter fit to determine $\boldsymbol{\omega}_{\text{a}}$

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

$$\frac{4000 \times 10^3}{3000}$$

$$\frac{\chi^2/\text{dof} = 9500/4150}{1000}$$

$$\frac{10}{20}$$

$$\frac{10}{20}$$

$$\frac{10}{20}$$

$$\frac{10}{20}$$

$$\frac{10}{20}$$

$$\frac{10}{20}$$

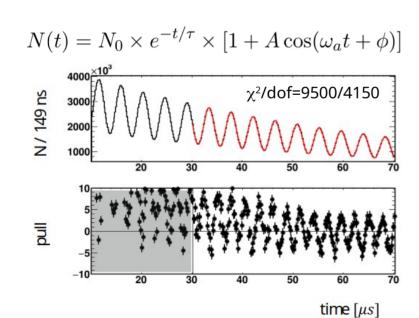
$$\frac{10}{30}$$

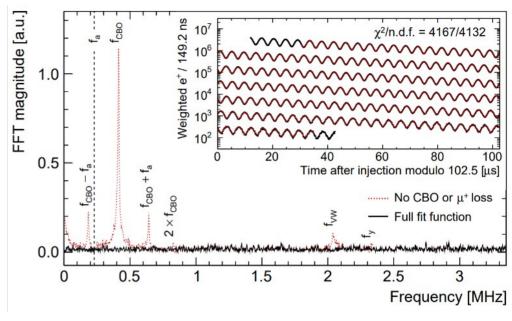
$$\frac{10}{20}$$

$$\frac{10}{30}$$

The basic method:

- count positrons over threshold
- 5-parameter fit to determine ω_a





G. Hesketh

 ω_{a}

Real fit function includes:

- calorimeter gain change (from laser data)
- positron pileup
- Muon losses
- Coherent betatron oscillations

$$N_{x}(t) = 1 + e^{-t/\tau_{\text{CBO}}} A_{N,x,1} \cos(\omega_{\text{CBO}} t + \phi_{N,x,1})$$

$$+ e^{-2t/\tau_{\text{CBO}}} A_{N,x,2} \cos(2\omega_{\text{CBO}} t + \phi_{N,x,2})$$

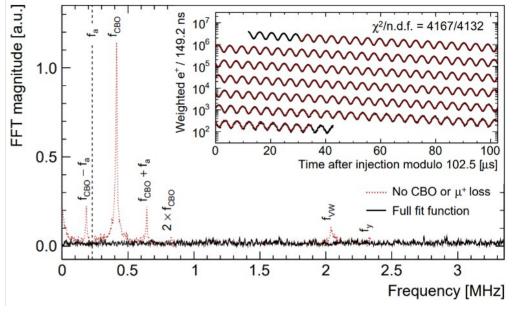
$$N_{y}(t) = 1 + e^{-t/\tau_{y}} A_{N,y,1} \cos(\omega_{y} t + \phi_{N,y,1})$$

$$+ e^{-2t/\tau_{y}} A_{N,y,2} \cos(\omega_{VW} t + \phi_{N,y,2})$$

$$\Lambda(t) = 1 - K_{\text{loss}} \int_{0}^{t} e^{t'/\gamma\tau_{\mu}} L(t') dt'$$

$$A_{x}(t) = 1 + e^{-t/\tau_{\text{CBO}}} A_{A,x,1} \cos(\omega_{\text{CBO}} t + \phi_{A,x,1})$$

$$\phi_{x}(t) = 1 + e^{-t/\tau_{\text{CBO}}} A_{\phi,x,1} \cos(\omega_{\text{CBO}} t + \phi_{\phi,x,1})$$



- 2 positron reconstruction methods
- 4 different analysis methods (T,A,R,Q)
- 6 independent analysis teams, using different combinations
- Many cross-checks performed, varying sensitivities to systematics

Just a few details

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

$$a_{\mu} = \omega_{a} \frac{m}{eB}$$
 \longrightarrow $a_{\mu} = \frac{\omega_{a}}{\tilde{\omega}_{p}(\text{Tr})} \frac{\mu_{p}(\text{Tr})}{\mu_{e}(\text{H})} \frac{\mu_{e}(\text{H})}{\mu_{e}} \frac{m_{\mu}}{m_{e}} \frac{g_{e}}{2}$

Total uncertainty from external inputs: 24 ppb

We determine the ratio:

$$\mathcal{R}'_{\mu} = \frac{\omega_a}{\tilde{\omega}_p(\mathrm{Tr})}$$

$$\frac{\mu_{\rm p}'\left(T_{\rm r}\right)}{\mu_{\rm e}\left(H\right)} = 10.5 \text{ ppb uncertainty}$$

$$\text{at } T_{\rm r} = 34.7^{\circ}\text{C}$$

$$\text{Metrologia } 13, 179 \text{ (1977)}$$

$$\frac{\mu_{\rm e}\left(H\right)}{\mu_{\rm e}} = \text{Bound state QED calculation,}$$

$$\text{exact}$$

$$\text{Rev. Mod. Phys. } 88, 035009 \text{ (2016)}$$

$$\frac{m_{\mu}}{m_{\rm e}} = \text{Muonium hyperfine splitting}$$

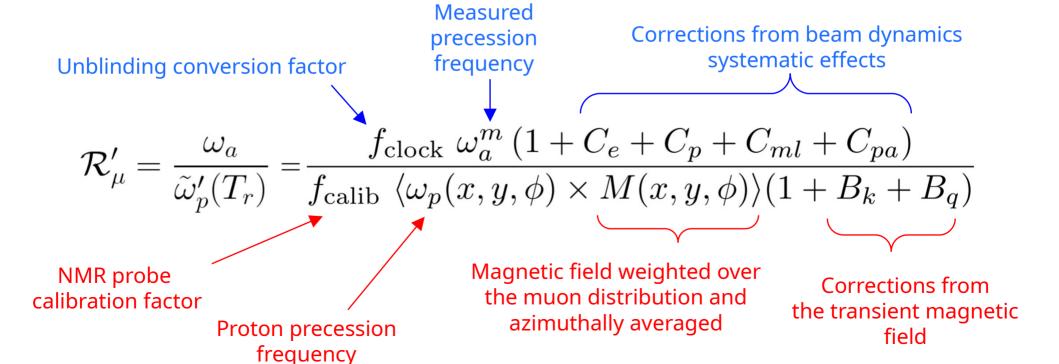
$$22 \text{ ppb uncertainty}$$

$$\text{Phys. Rev. Lett. } 82, 11 \text{ (1999)}$$

$$\frac{g_{\rm e}}{2} = \text{0.28 ppt uncertainty}$$

$$\text{Phys. Rev. A } 83, 052122 \text{ (2011)}$$

$$a_{\mu} = \omega_{\mathbf{a}} \frac{m}{eB}$$
 \longrightarrow $a_{\mu} = \frac{\omega_{\mathbf{a}}}{\tilde{\omega}_{p}(\text{Tr})} \frac{\mu_{p}(\text{Tr})}{\mu_{e}(\text{H})} \frac{\mu_{e}(\text{H})}{\mu_{e}} \frac{m_{\mu}}{m_{e}} \frac{g_{e}}{2}$



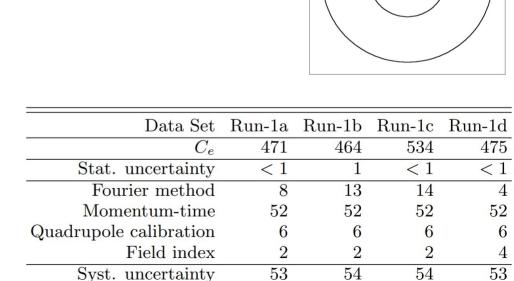
$$\omega_a = a_\mu \frac{eB}{m}$$

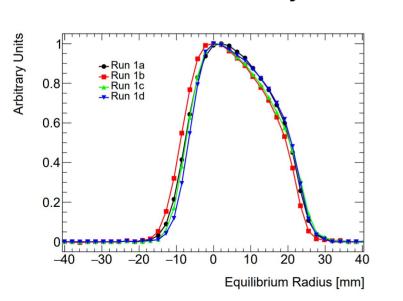
$$\vec{\omega}_a = \frac{e}{m} \left[a_{\mu} \vec{B} - \left(a_{\mu} - \frac{1}{\gamma^2 - 1} \right) \vec{\beta} \times \vec{E} - a_{\mu} \left(\frac{\gamma}{\gamma + 1} \right) (\vec{\beta} \cdot \vec{B}) \vec{\beta} \right]$$

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

Coupling to electrostatic quadrupoles:

- use "magic momentum" of 3.1 GeV, but momentum spread ~0.10%
 - → "E-field correction"
 - from Fourier analysis of "fast-rotation"

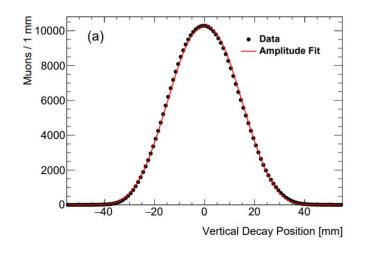




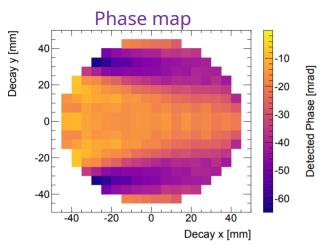
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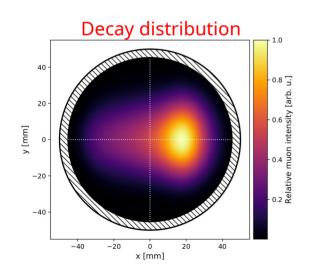
Small vertical momentum component:

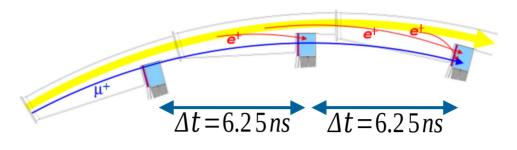
- → "Pitch correction"
- use tracking detectors to measure vertical width of beam



Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_p (ppb)	176	199	191	166
Stat. uncertainty	< 1	< 1	< 1	< 1
Tracker reco.	11	12	12	11
Tracker res. & acc	3	4	4	3
$\beta_y(\phi)$ & calo. acc.	1	1	2	1
Amplitude fit	1	< 1	1	3
Quad calibration	4	4	4	4
Syst. uncertainty	12	14	14	12







"Phase/Acceptance" correction:

- changes in beam distribution during fill
 - → time-dependent phase
- enhanced by damaged resistors in Run-1

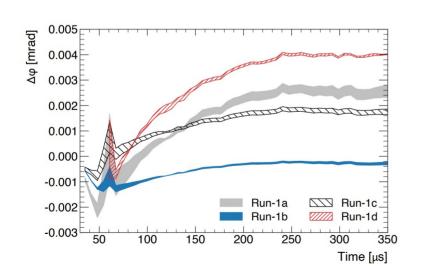
Muon Weighted Phase [mrad]	0 — Phase — Early Beam — Late Beam — — 25 — — — — — — — — — — — — — — — —
	-40 -30 -20 -10 0 10 20 30 40
	Decay X [mm]

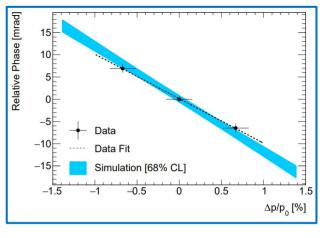
Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_{pa}	-184	-165	-117	-164
Stat. uncertainty	23	20	15	14
Tracker & CBO	73	43	41	44
Phase maps	52	49	35	46
Beam dynamics	27	30	22	45
Total uncertainty	96	74	60	80

Lost Muons:

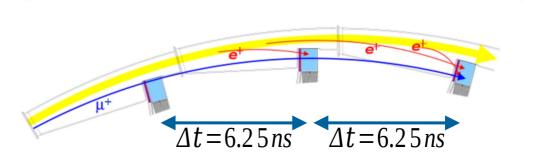
- low momentum muons are lost more quickly than high
- slightly different phase to ensemble
- causes change in overall phase vs time

$$\frac{d\varphi_0}{dt} = \frac{d\varphi_0}{d\langle p\rangle} \frac{d\langle p\rangle}{dt}$$

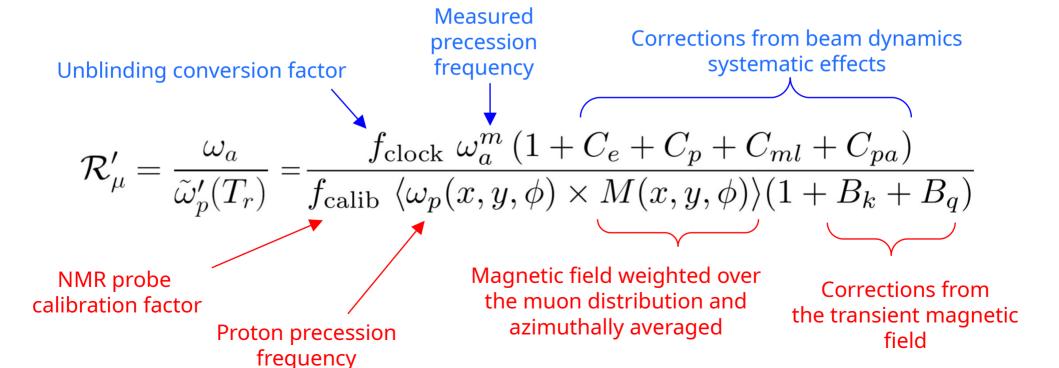




Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_{ml}	-14	-3	-7	-17
Phase-momentum	2	0	1	3
Form of $l(t)$	2	0	1	1
f_{loss} function	2	1	2	2
Linear sum $(\sigma_{C_{ml}})$	6	2	4	6

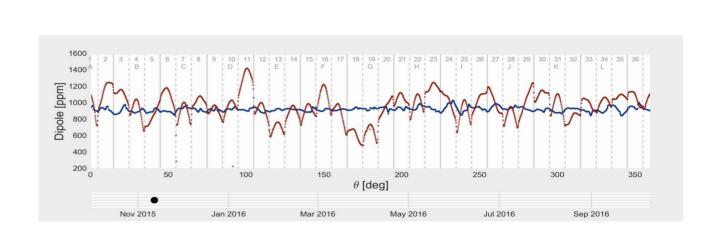


$$a_{\mu} = \omega_{a} \frac{m}{eB}$$
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7.112 m radius 'C'-shape magnet with vertically-aligned field B = 1.45 T, ppm-level uniformity

Magnet cross-section inner coil top hat YOKE wedge iron foil outer coil laminations shim fixed NMR probes pole piece outer coil correction coil top hat inner coil

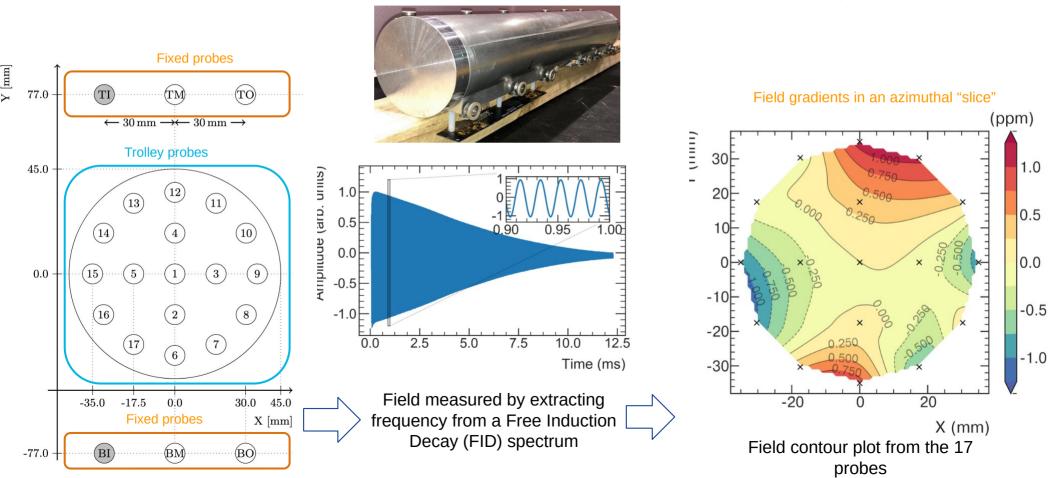


Temperature variations → ppm changes in magnet geometry, and drift in the field

- 378 'fixed' NMR probes around the ring measure the drift continuously
 - → feedback to the magnet power supply to keep the dipole (vertical) term constant

An in-vacuum trolley drives around the ring every ~3 days

- 17 NMR probes x 9000 measurements, mapping out the field components

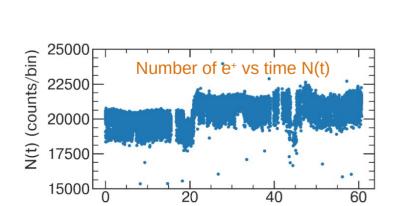


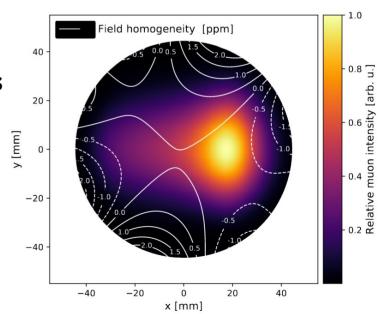
Frequency maps from trolley and fixed probe data need to be weighted by the muon distribution

$$\tilde{\omega}_{\bar{p}} = \left\langle \frac{\int \omega_{\bar{p}}(x, y, \phi) \ M(x, y, \phi) \ dx \ dy}{\int M(x, y, \phi) \ dx \ dy} \right\rangle$$

2D beam distribution obtained from the straw trackers

- includes beam dynamics information
- and detector acceptances

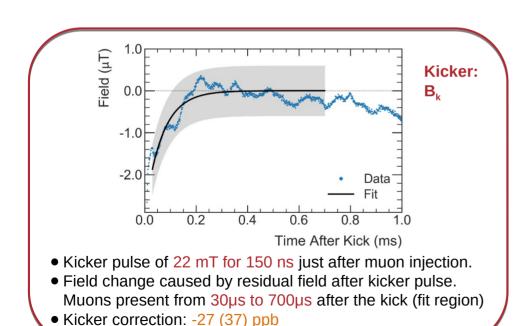


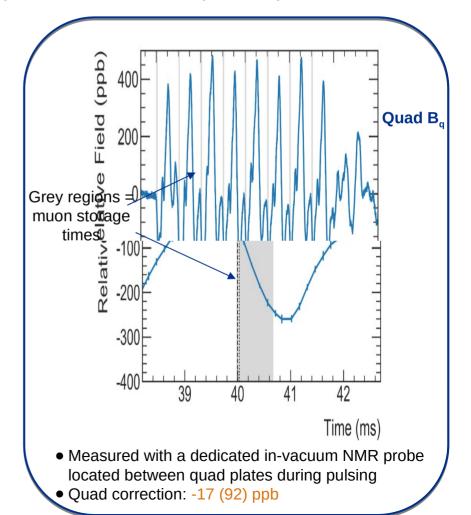


Muons experience "fast transient" fields from the pulsed kickers & quadrupoles

→ invisible to fixed probes due to shielding

Measured during dedicated campaigns





Specially designed "plunging probe":

- characterised in very stable, homogenous solenoid
 - \rightarrow accuracy of 15 ppb
- used to calibrate trolley probes in-situ



Calibrated against spherical, water-based probe from BNL to 6ppb

A novel 3He NMR probe also developed (different systematics)

→ provides cross-check to 38 ppb (PRL 124, 223001 (2020))

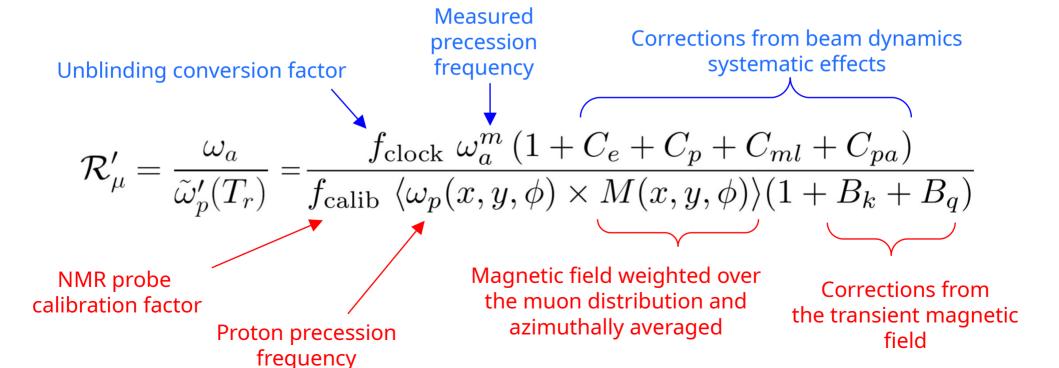
Ongoing effort to cross-calibrate E989 probe with J-PARC Muon g-2/EDM probe





Quantity	Symbol	Value (ppb)	Uncertainty (ppb)
Diamagnetic Shielding T dep	δ^{T}	-99.1 to -86.0	5
Bulk Magnetic Susceptibility	δ^{b}	-1505.9 to -1505.6	6
Material Perturbation	δ ^s	15.2	12
Water Sample and Sample Holder	δ ^w	0	2
Radiation Damping	δ^{RD}	0	3
Proton Dipolar Fields	δ ^d	0	2
TOTAL		-1589.8 to -1576.4	15

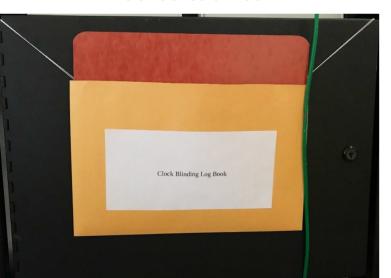
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Hardware-blinded clock with frequency (40 + x) MHz - offset was ~25ppm (approx 10x the BNL-SM difference)

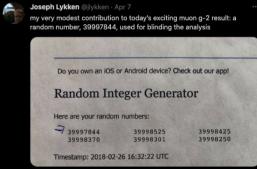
Set by two people outside the collaboration, stored in locked cabinet!

Locked cabinet



Greg Bock and Joe Lykken (2018)





"The code was picked by the Fermilab theorist, and he is the only person to know it.

> This theorist now refuses to give away the code. *It is not clear why.*

> > One time he said he had forgotten the envelope with the code on a train, another time he said the dog had eaten it."

Unblinding meeting 25th Feb 2021

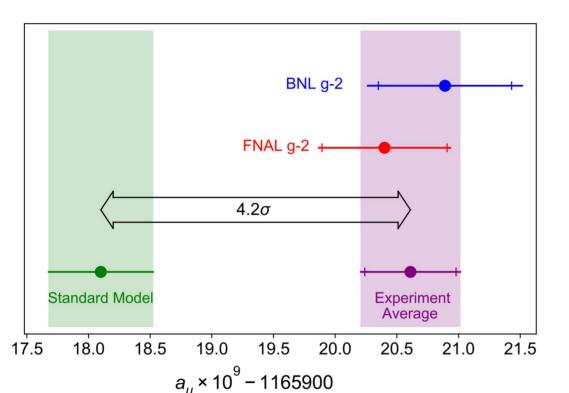
After all corrections uncertainties were finalized, the collaboration unanimously vote to unblind.



No changes to the result were made since then



UCL



Quantity	Correction Terms	Uncertainty
	(ppb)	(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

$$a_{\mu}(\text{FNAL}) = 116592040(54) \times 10^{-11}$$

 $a_{\mu}(\text{Exp}) = 116592061(41) \times 10^{-11}$
 $a_{\mu}(\text{SM}) = 116591810(43) \times 10^{-11}$

Discrepancy is ~2.5 ppm

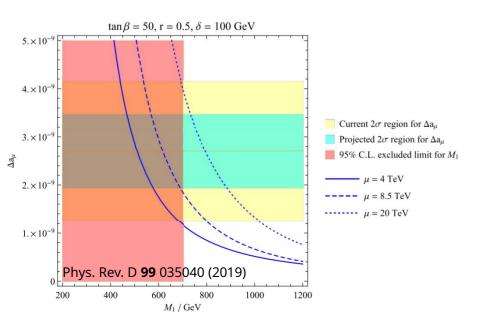
- x2 the size of the electroweak contribution, x1/30 the size of QCD

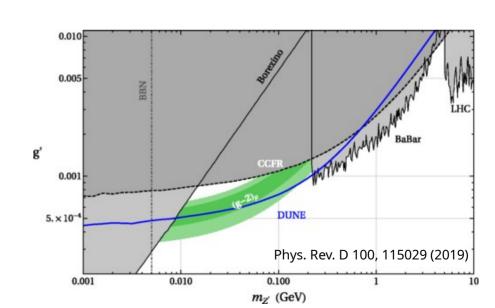
Many models can explain the anomaly and evade other constraints (dark matter, LHC limits, ...)

- TeV leptoquarks, Z', ALPs, SUSY, 2-Higgs doublets, ...

Chirality-flipping, flavour conserving

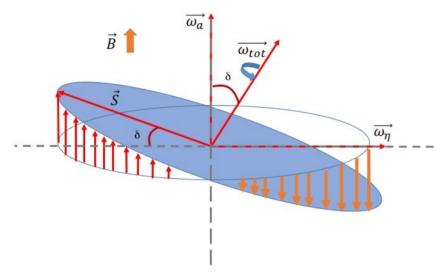
$$\Delta a_{\mu}^{
m BSM} = C_{
m BSM} \left(rac{m_{\mu}}{M_{
m BSM}}
ight)^2$$
 arXiv:2104.03691





Search for a muon electric dipole moment:

- ~zero in the Standard Model
- possible source of CP-violation



Tilts precession plane towards center of ring

- vertical oscillation, 90° out of phase with a
- tracking detectors key to sensitivity

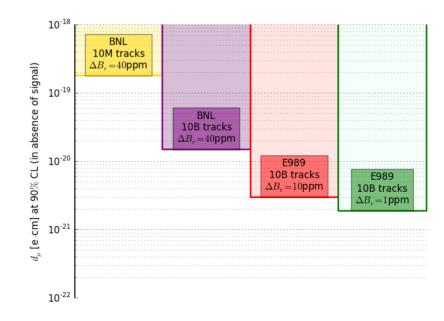
$$ec{d} = \eta \left(rac{Qe}{2mc}
ight) ec{s}$$

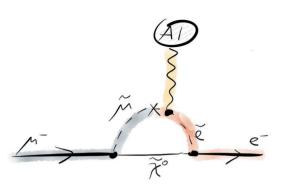
World's best limit:

$$|d_{\mu}| > 1.9 \times 10^{-19} \text{ e.cm}$$
 (BNL)

Target:

$$|d_{u}| \approx 1.9 \times 10^{-21} \text{ e.cm}$$





Charged lepton flavour violation:

- again, ~zero in the Standard Model
- predicted by many BSM models (particularly leptogenesis)

Mu2e:

- follows g-2 at Fermilab
- decay of captured muons



Mu3e:

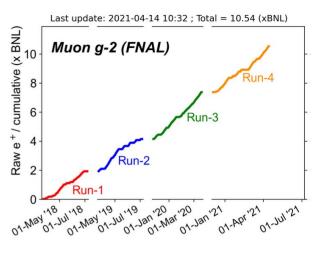
- data taking in 2023 @ PSI
- full reconstruct μ \rightarrow eee final state

Aim to push limits on Br to 10⁻¹⁷ (factor x 10⁴)

- mass scales up to 10,000 TeV

The FNAL Muon g-2 experiment measured a_u to 0.46 ppm

- result consistent with BNL
- combined result differs from SM by 4.2σ
- statistics limited, based on 6% of target stats



Upgrades since Run-1:

- Replaced damaged resistors, reducing C_{pa}
- Higher kicker voltage to center beam radially
- Thermal magnet insulation & hall cooling improve field stability

EDM search & CLFV: complementary information on any BSM scenario

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

Beam dynamics: Phys. Rev. Accel. Beams **24**, 044002

T. Albahri, 30 A. Anastasio, 10 K. Badgley, 7 S. Baeßler, 36, a I. Bailey, 17, b V. A. Baranov, 15 E. Barlas-Yucel, 28

T. Barrett. 6 F. Bedeschi. 10 T. Bowcock, 30 G. Cantat A. Chapelain, 6 S. Charit J. D. Crnkovic, 34 S. Daba A. Driutti, 26, 29 V. N. Dugin A. Fiedler, 20 A. T. F C. Gabbanini, 10, h M. D. K. L. Giovanetti, 13 P S. Haciomeroglu.⁵ T D. W. Hertzog, 37 G. He M. Iacovacci, 9, k M. Incas L. Kelton, 29 A. Keshav B. Kiburg, O. Kim, N. A. Kuchinskiy, 15 K. R. L. Li. 22, e I. Logashenk B. MacCoy, 37 R. Mad W. M. Morse, J. Mott, 2, G. M. Piacentino.²⁵, B. Quinn, 34 N. Raha, 10 L. Santi, 26, d D. Sathya M. Sorbara, 11, q D. Stöcki G. Sweetmore, 31 D. A. S

K. Thomson, 30 V

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Magnetic Field Measurement and Analysis for the Muon q-2 Experiment at Fermilab

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K. R. Labe, J. LaBour

I. Logashenko, 4, g A. Lorente B. Madrak.⁷ K. Makino.²⁰ J. Mott. 2, 7 A. Nath. 10, 31 R. N. Pilato, 11, 32 K. T. Pitts, N. Raha, 11 S. Ramachand C. Schlesier, 37 A. Schred

M. Sorbara, 12, 33 D. Stöcking G. Sweetmore, 40 D. A. Swei K. Thomson, 39 V. Ti: G. Venanzoni, 11 T. Walton Measurement of the anomalous precession frequency of the muon in the Fermilab

Muon q-2 experiment T. Albahri, 39 A. Anastasi, 11, a A. Anisenkov, 4, b K. Badgley, 7 S. Baeßler, 47, c I. Bailey, 19, d V. A. Baranov, 17

E. Barlas-Yucel. 37 T. Barr P. Bloom. 21 J. Bono. 7 E. D. Cauz, 35,8 R. Chakraborty T. E. Chupp, 42 S. Corrodi, 1 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 P. Di Meo. 10 G. Di Sciascio M. Farooq, 42 R. Fatemi, 38 C N. S. Froemming, 48, 22 J. Fr L. K. Gibbons, 6 A. Gioiosa S. Grant. 36 F. Grav. 24 S. A. T. Herrod, 39, d D. W. He R. Hong, 1, 38 M. Iacovacci, D. Kawall, 41 L. Kelto N. V. Khomutov, 17 B. Kiburg A. Kuchibhotla, 37 N. A. Kuc B. Li, 26, 1, e D. Li, 26, g L. Li, 2 A. L. Lyon, B. MacCoy. S. Miozzi, 12 W. M. Morse G. M. Piacentino, 29, 12 R. N. J. Price, 39 B. Quinn, 43 N. Ral L. Santi, 35, 8 C. Schlesier, 37 M. Sorbara, 12, 33 D. Stöckin G. Sweetmore. 40 D. A. Swe K. Thomson, 39 V.

G. Venanzoni, 11 T. Walt

Field: Phys. Rev. A **103**, 042208

Analysis: Phys. Rev. D **103**, 072002

Phys. Rev. Lett. **126**, 141801

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

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