Status of the FNAL muon $g - 2$ experiment

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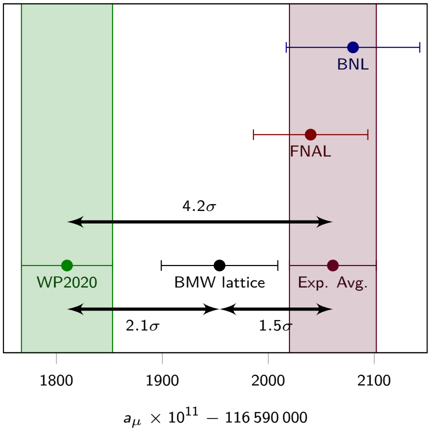
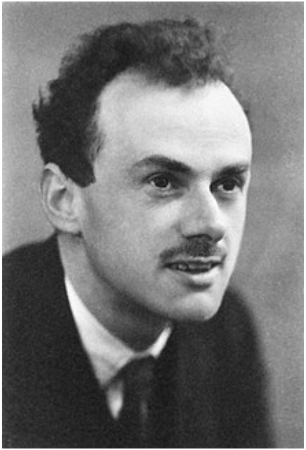
Spoilers (460 ppb Uncertainty)

- Fermilab measurement agrees with Brookhaven; reasonable to combine statistics-dominated measurements
- World average is 4.2σ from the Standard Model prediction (2020 white paper)
- BMW lattice results is 1.5σ from the world average



The history of the muon g-factor

- 1928, Dirac equation, $g = 2$



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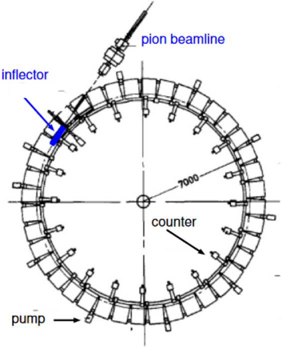

The history of the muon g-factor

- 1928, Dirac equation, $g = 2$
- 1947, Schwinger term, $a_l = \frac{\alpha}{2\pi}$
- 1962, CERN muon g-factor experiments
- 2006, BNL experiment finds hints of discrepancy with Standard Model

Spin precession equations

The “anomalous precession frequency” is the rate at which the muon’s spin and momentum accumulate relative angle.

$$\vec{\omega_a} = \vec{\omega}_s - \vec{\omega}_c = -\frac{q}{m} a_\mu \vec{B}$$

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

Extracting a_μ from spin precession measurements

With simultaneous measurements of anomalous precession frequency and magnetic field, we determine the anomalous magnetic moment, a_μ

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

This experiment measured the ratio of the anomalous precession frequency, ω_a, to the precession frequency of a spherical water sample in the same volume, $\tilde{\omega}'_p$. Other terms from the literature are used to convert this ratio to a_μ. ± 25 ppb

A schematical view of the ratio $\omega_a/\tilde{\omega}'_p(r, y, \theta, t)$

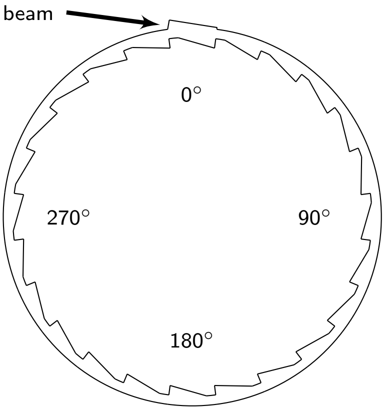
$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{g_e}{2} \frac{m_\mu}{m_e}$$

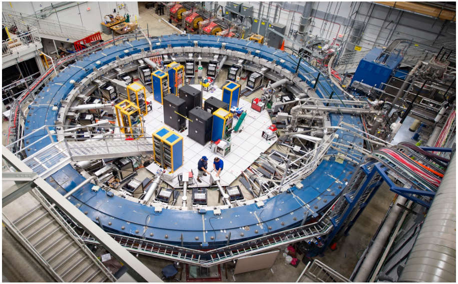
$$\vec{\omega_a} = -\frac{q}{m}\left(a_\mu \vec{B} - a_\mu \frac{\gamma}{\gamma+1}(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left[a_\mu - \frac{1}{\gamma^2-1}\right]\frac{\vec{\beta}\times\vec{E}}{c}\right)$$

Insert equation for ω_a into the measured ratio in equation for a_μ, collect correction terms to write a schematical equation:

$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}}\ \omega_{\text{a,meas}}\ (1 + c_e + c_p + c_{ml} + c_{pa})}{f_{\text{field}}\ \langle \omega_p \otimes \rho_\mu \rangle\ (1 + B_{qt} + B_{kick})}$$

The Muon $g-2$ storage ring





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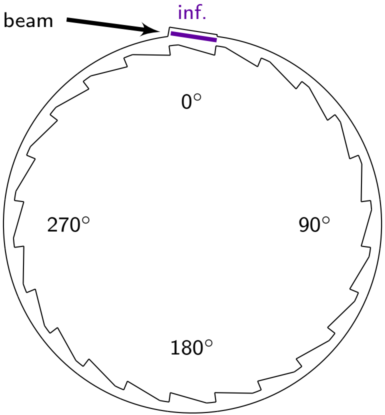

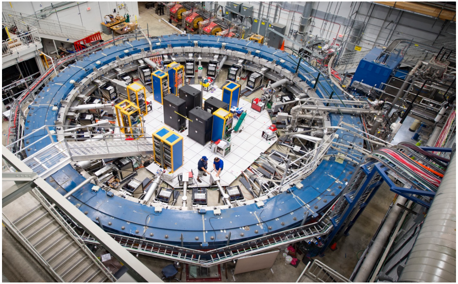

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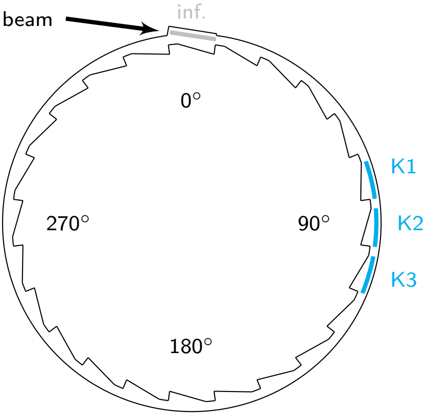

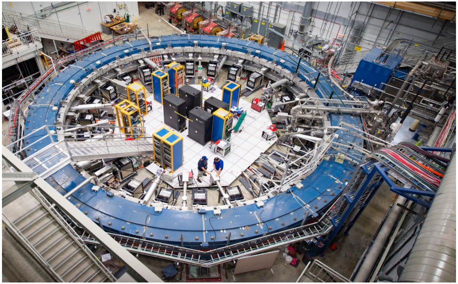

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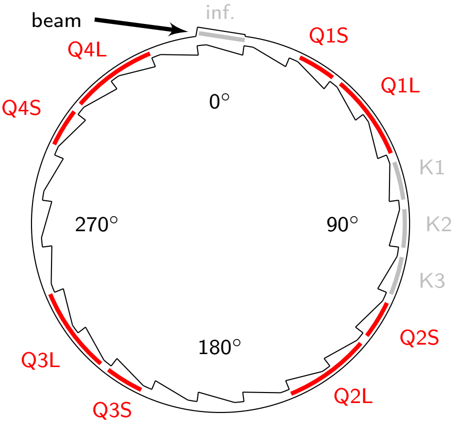

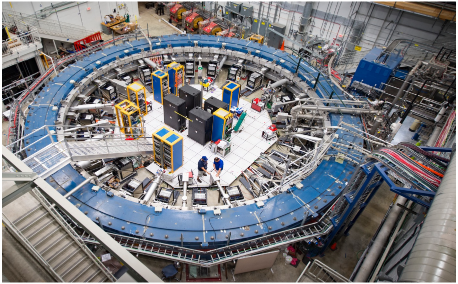

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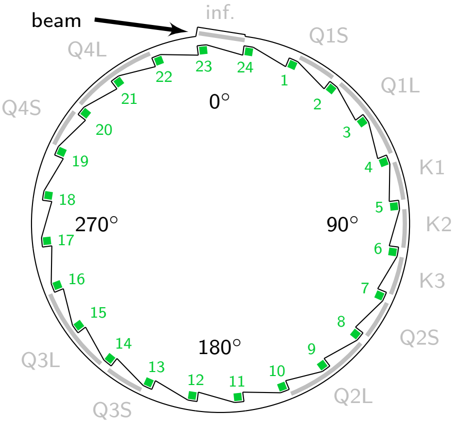

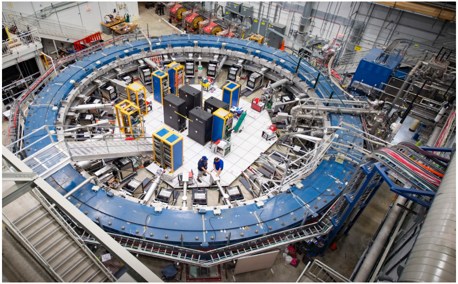

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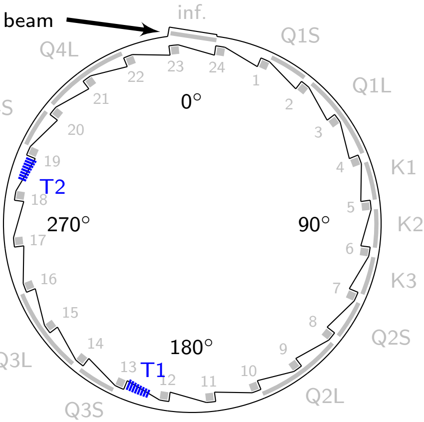
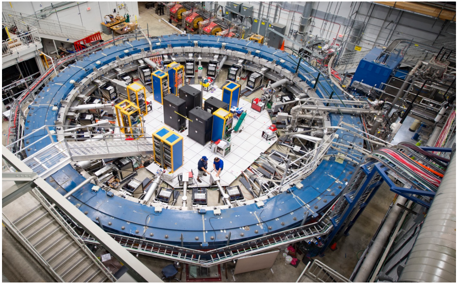
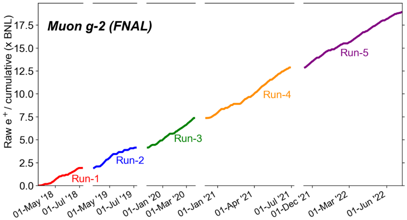




What's new in Run-2/3?



- Broken resistors in Run-1 replaced, fixed quad charging time
- Kicker system upgraded to kick at full spec
- Magnet insulation to stabilize temperature-dependent effects
- Heroic transient measurement efforts

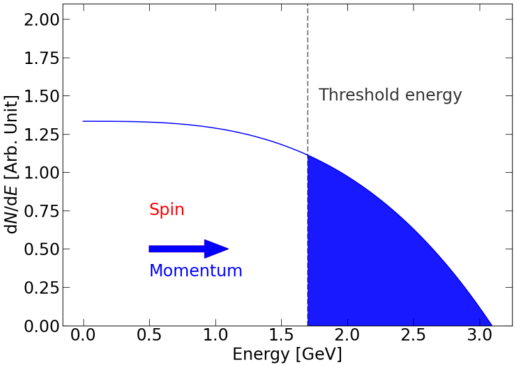
Collecting Uncertainties

Quantity	Correction (ppb)	Uncertainty(ppb)
ω_a (stats)	—	434
ω_a (syst)	—	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
f_{field} $\langle \omega_p \otimes \rho_\mu \rangle$	—	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
Systematic total	—	157
Fundamental factors	—	25
Totals	544	462

- Dominated by statistics
- Largest systematics uncertainties are phase acceptance and quadrupole transient

Measuring the precession frequency with positrons

- High-momentum positrons preferentially emitted along the muon's spin
- In lab frame, more high-energy positrons emitted when spin parallel to momentum



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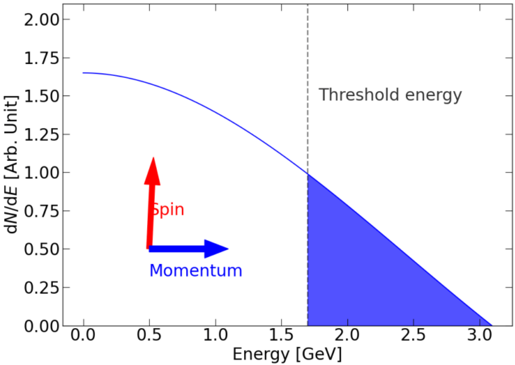

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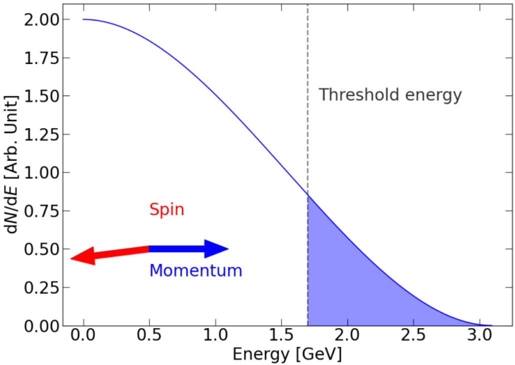

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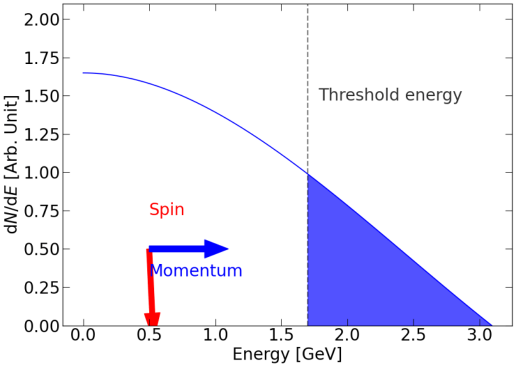

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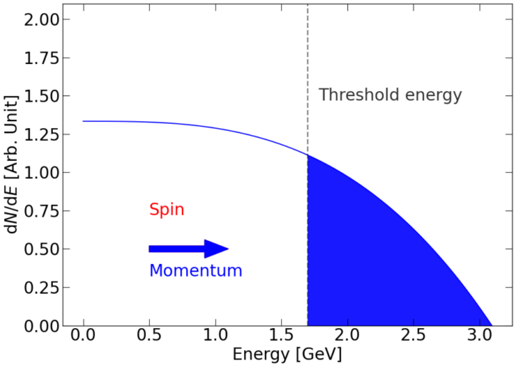
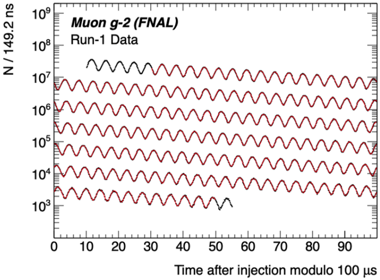


Measuring the precession frequency with positrons

- High-momentum positrons preferentially emitted along the muon's spin
- In lab frame, more high-energy positrons emitted when spin parallel to momentum
- Modulation of positron energy spectrum encodes anomalous precession frequency

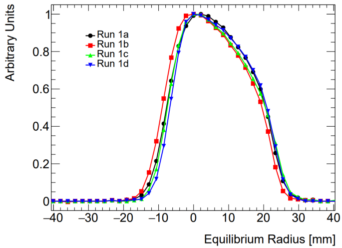
$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}}\ \omega_{a,\text{meas}}\ (1 + c_e + c_p + c_{ml} + c_{pa})}{f_{\text{field}}\ \left\langle \omega_p \bigotimes \rho_\mu \right\rangle\ (1 + B_{qt} + B_{kick})}$$



Stat.: ±434 ppb, Syst.: ±56 ppb

The corrections to ω_a

$$\frac{\omega_a}{\tilde{\omega}_p'} = \frac{f_{\text{clock}}\ \omega_{a,\text{meas}}\ (1 + c_e + c_p + c_{ml} + c_{pa})}{f_{\text{field}}\ \left\langle \omega_p \bigotimes \rho_\mu \right\rangle\ (1 + B_{qt} + B_{kick})}$$



$$c_e = 2n(1-n)\beta_0^2 \frac{\left\langle x_e^2 \right\rangle}{R_0^2}$$

489 ± 53 ppb

c_e E-field correction minimized using magic momentum, remainder corrected by studying mean radius which is correlated to momentum dispersion

$$\frac{q}{m}\left[a_\mu - \frac{1}{\gamma^2 - 1}\right]\frac{\vec{\beta} \times \vec{E}}{c}$$

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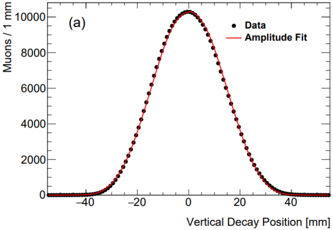

$$c_p = \frac{n}{2}\frac{\left\langle y^2 \right\rangle}{R_0^2}$$

180 ± 13 ppb

c_e The E-field

c_p Pitch correction from the small vertical component of muons' momentum, calculated by studying vertical position distribution from trackers

$$\frac{q}{m} a_\mu \frac{\gamma}{\gamma+1}(\vec{\beta}\cdot\vec{B})\vec{\beta}$$

The corrections to ω_a

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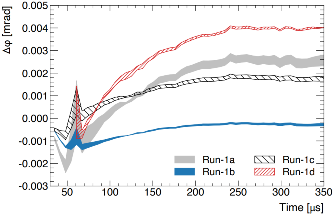

$$\frac{\mathrm{d}\phi_0}{\mathrm{d}t} = \frac{\mathrm{d}\phi_0}{\mathrm{d}\langle p\rangle}\frac{\mathrm{d}\langle p\rangle}{\mathrm{d}t}$$

-11 ± 5 ppb

- c_e The E-field
- c_p Pitch correction
- c_{ml} Muon loss correction from initial phase-momentum correlation in muons, as muons are lost in time, there is time dependent change in phase

The corrections to ω_a

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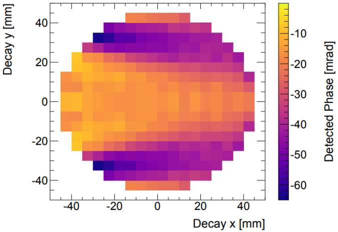
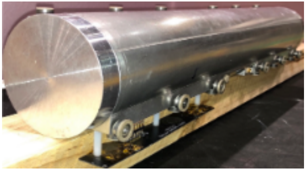
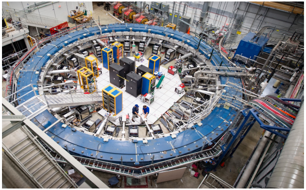


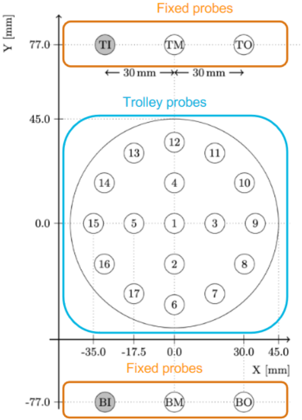
-158 ± 75 ppb

- c_e The E-field
- c_p Pitch correction
- c_{ml} Muon loss correction
- c_{pa} Phase acceptance correction caused by decay-position dependence of positron phase, early-to-late beam motion modulation leads to time-dependent phase

The magnetic field measurement systems



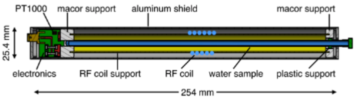


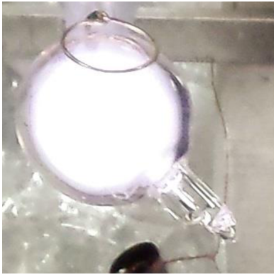


The field calibration chain

$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}}\ \omega_{a,\text{meas}}\ (1 + c_e + c_p + c_{ml} + c_{pa})}{f_{\text{field}}\ \left\langle \omega_p \bigotimes \rho_\mu \right\rangle\ (1 + B_{qt} + B_{kick})}$$

- Absolute calibration done at ANL, cross-checked with ^{3}He





± 32 ppb

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- Plunging probe calibrates trolley

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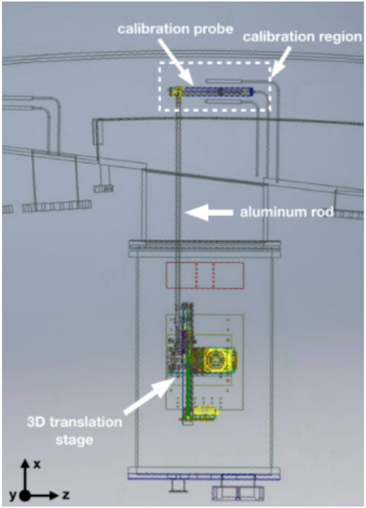

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- Absolute calibration done at ANL, cross-checked with ^{3}He
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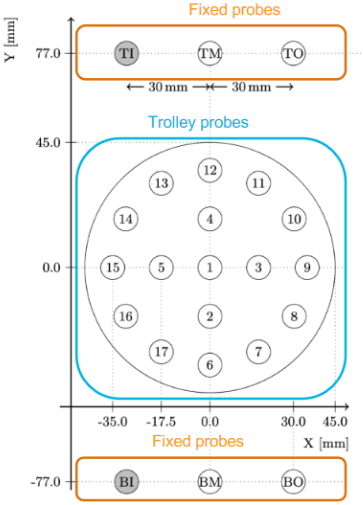
- Trolley synchronizes with fixed probes

±32 ppb



Getting field maps from the trolley

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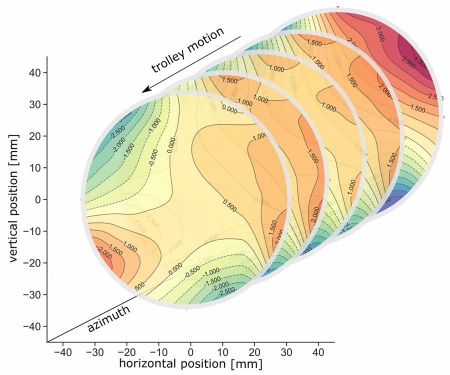
- Trolley has an array of 17 NMR probes, travels around ring, takes measurements at $\sim$ 8000 azimuthal locations
- Measurements in same volume muons are stored in

-13 ± 25 ppb



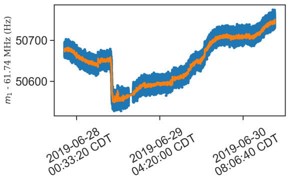
Interpolating between trolley runs with the fixed probes

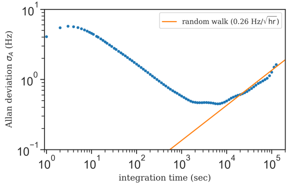
$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}}\ \omega_{a,\text{meas}}\ (1 + c_e + c_p + c_{ml} + c_{pa})}{f_{\text{field}}\ \left\langle \omega_p \bigotimes \rho_\mu \right\rangle\ (1 + B_{qt} + B_{kick})}$$

- Fixed probes synchronized to the trolley during the trolley runs
- Fixed probes track field between trolley runs, additional data points to interpolate field

$\pm$(24 to 44) ppb

Super-long Trolley Runs



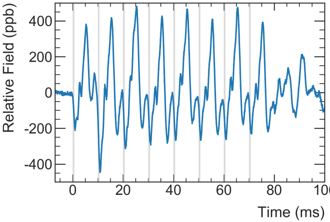


The fast transient systematics

- Electric quadrupoles vibrate generating eddy currents that perturb the field
- Perturbation too fast for fixed probes to pick up normally, shielded by the vacuum chambers
- Measurements made with special probe to determine effect of perturbation

-17 ± 92 ppb

$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}}\ \omega_{a,\text{meas}}\ (1 + c_e + c_p + c_{ml} + c_{pa})}{f_{\text{field}}\ \left\langle \omega_p \bigotimes \rho_\mu \right\rangle\ (1 + B_{qt} + B_{kick})}$$



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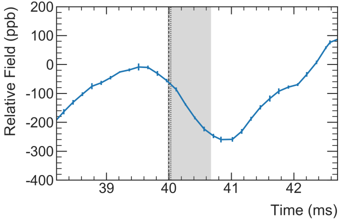

The fast transient systematics

- Pulsed magnetic kick generates larges eddy currents, perturb the magnetic field
- Like quad transient, too fast to be picked up by regular analysis
- Used optical Faraday magnetometer to study the transient

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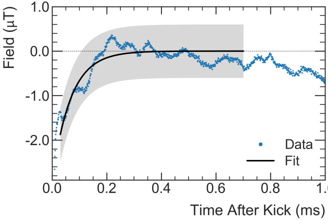
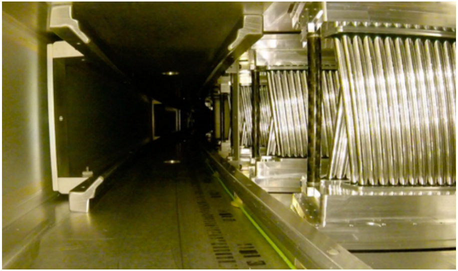


-27 ± 37 ppb

Straw trackers

$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}}\ \omega_{\text{a,meas}}\ (1 + c_e + c_p + c_{ml} + c_{pa})}{f_{\text{field}}\ \left\langle \omega_p \bigotimes \rho_\mu \right\rangle\ (1 + B_{qt} + B_{kick})}$$

- Straw trackers track decay positron path
- Tracks can be extrapolated back to muon decay position
- Decay vertices used to determine muon distribution in storage region.



$(-3 \text{ to } 1) \pm (11 \text{ to } 20)$ ppb

Straw trackers

$$\frac{\omega_a}{\tilde{\omega}_p'} = \frac{f_{\text{clock}}\ \omega_{a,\text{meas}}\ (1 + c_e + c_p + c_{ml} + c_{pa})}{f_{\text{field}}\ \left\langle \omega_p \bigotimes \rho_\mu \right\rangle\ (1 + B_{qt} + B_{kick})}$$

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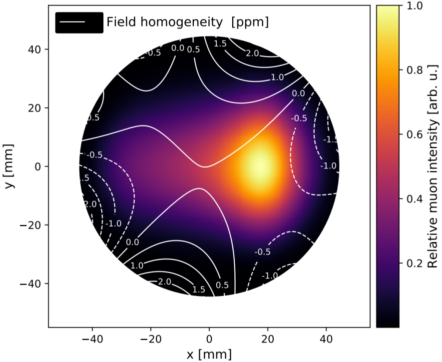
$(-3 \text{ to } 1) \pm (11 \text{ to } 20)$ ppb



Straw trackers

$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}}\ \omega_{\text{a,meas}}\ (1 + c_e + c_p + c_{ml} + c_{pa})}{f_{\text{field}}\ \left\langle \omega_p \bigotimes \rho_\mu \right\rangle\ (1 + B_{qt} + B_{kick})}$$

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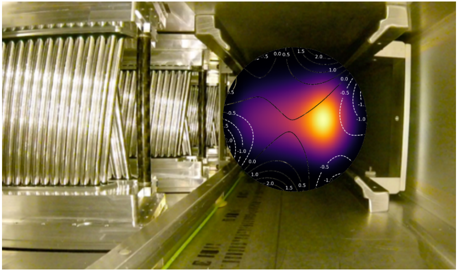
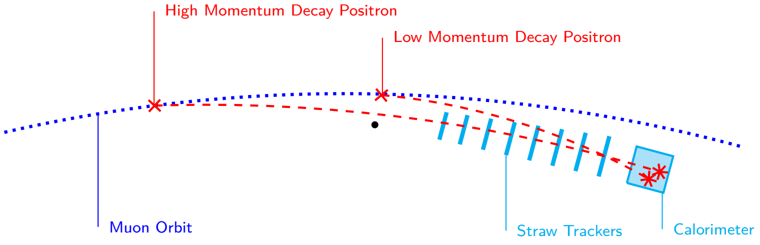


$(-3 \text{ to } 1) \pm (11 \text{ to } 20)$ ppb

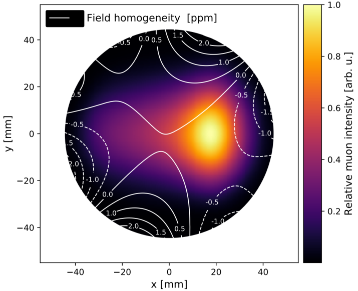
Straw trackers



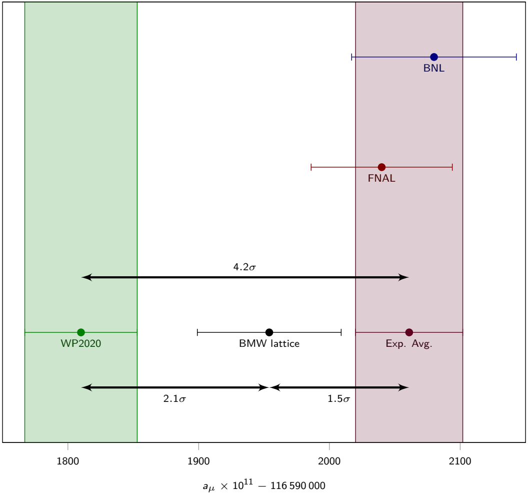
Combining the field maps and muon distribution

$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}}\ \omega_{\text{a,meas}}\ (1 + c_e + c_p + c_{ml} + c_{pa})}{f_{\text{field}} \left\langle \omega_p \bigotimes \rho_\mu \right\rangle (1 + B_{qt} + B_{kick})}$$

- Magnetic field maps weighted by muon distribution determined by trackers
- Trackers measure at two locations storage ring, use beam dynamics simulations to extrapolate distribution around ring



Recap (460 ppb Uncertainty)



Acknowledgments

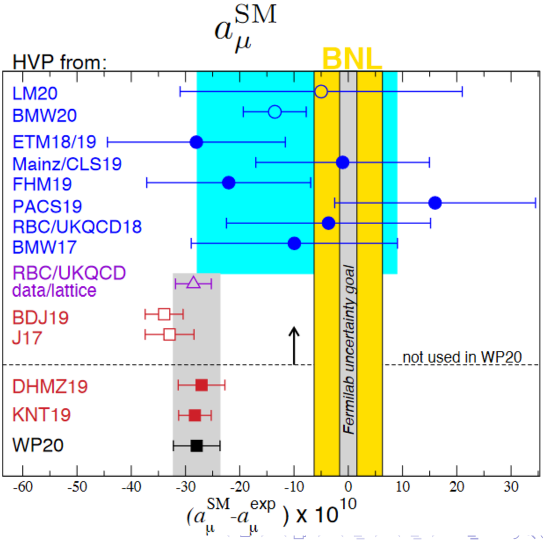
Thanks to:

- University of Kentucky
- Muon $g-2$ field team
- Muon $g-2$ team in general
- Fermilab and Argonne

Backup Slides

Lattice QCD Results

- Large range of lattice values that agree with both 2020 white paper and experiment
- The BMW20 calculation still needs to be vetted by independent lattice groups
- More lattice results are upcoming, worth keeping an eye on

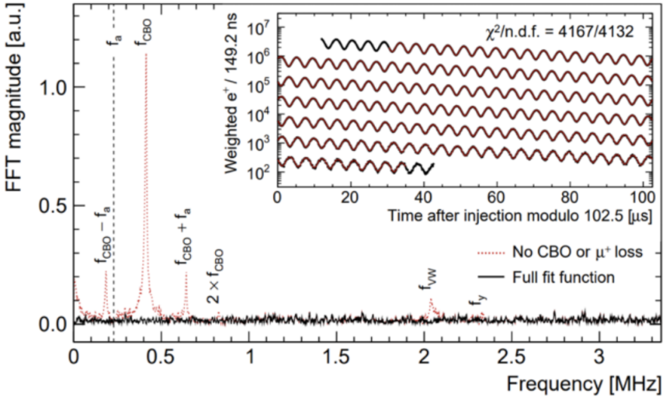


Blinding

$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}}\ \omega_{\text{a,meas}}\ (1 + c_e + c_p + c_{ml} + c_{pa})}{f_{\text{field}}\ \left\langle \omega_p \bigotimes \rho_\mu \right\rangle\ (1 + B_{qt} + B_{kick})}$$

- Experiment blinded at ω_a clock
- Blinders not part of Muon $g-2$, Fermilab personnel
- Clock frequencies kept in sealed envelopes until unblinding

The frequencies in the measurement



The Muon $g-2$ storage ring