Status of the Muon g – 2 Experiment at Fermilab

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Cornell University
Hadronic Contributions to New Physics Searches 2019
26 September 2019

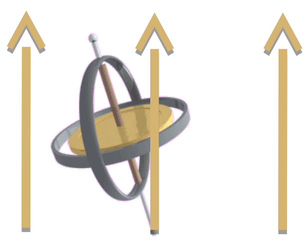
What is g?

The gyromagnetic ratio of a particle is the coupling of its spin to its magnetic moment:

$$M = \frac{ge}{2m} S$$

External magnetic field + magnetic moment

$\rightarrow$ torque + spin precession



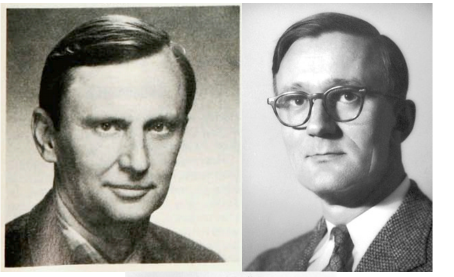
$$\omega_s = g \frac{eB}{2mc}$$

In Dirac theory, g = 2, with higher order corrections from interactions with virtual particles.

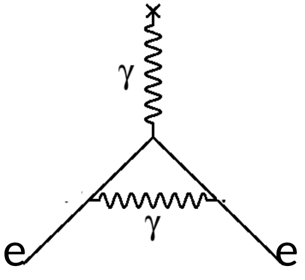
History of gyromagnetic ratios

Anomalous moment first observed for electrons in 1947 by Foley and Kusch:

$$g_e = 2 \times (1.00119 \pm 0.00005)$$



The result was explained by Schwinger in 1948



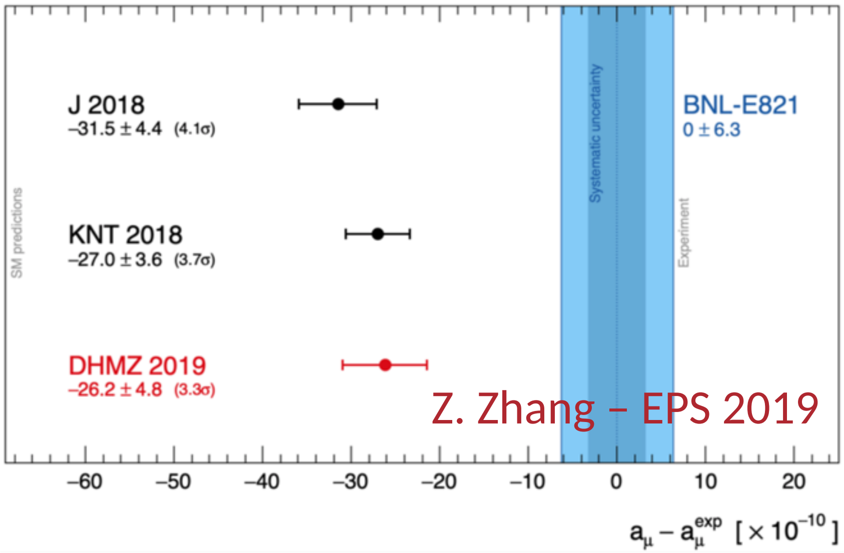
$$a = \frac{\alpha}{2\pi} = 0.001162$$

Along with Lamb shift, anomalous moment was an early success of QED, providing confidence in renormalization

New physics couples $\propto m_l^2$

$$\left(\frac{m_\mu}{m_e}\right)^2 \sim 43000$$

Brookhaven and the goals of the FNAL project



Uncertainty	Error Budget (E989)	Final Error (E821, 2006)
Statistics	100 ppb	463 ppb
Systematics	100 ppb	283 ppb
Total	140 ppb	540 ppb
Theory	300 ppb	620 ppb

Last measurement: Brookhaven (1997 – 2001)

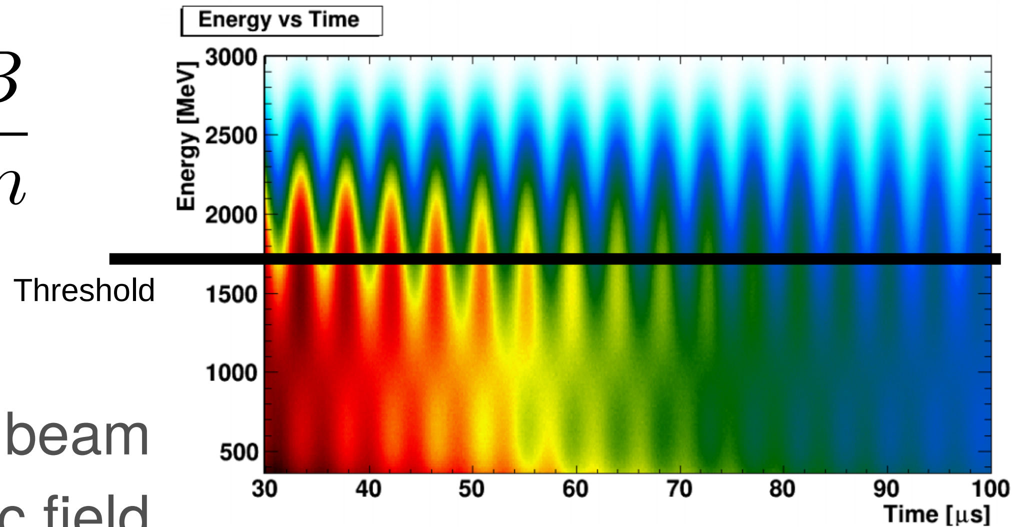
Roughly 3σ discrepancy with theory.

New experiment at Fermilab will reduce the statistical and systematic sources of uncertainty, with corresponding improvements to theory (T. Tuebner).

How is g measured in practice?

Difference between cyclotron and spin precession frequencies gives direct access to g – 2:

$$\omega_a = \omega_s - \omega_c = (g-2)\frac{qB}{2m}$$



To measure ω_a :

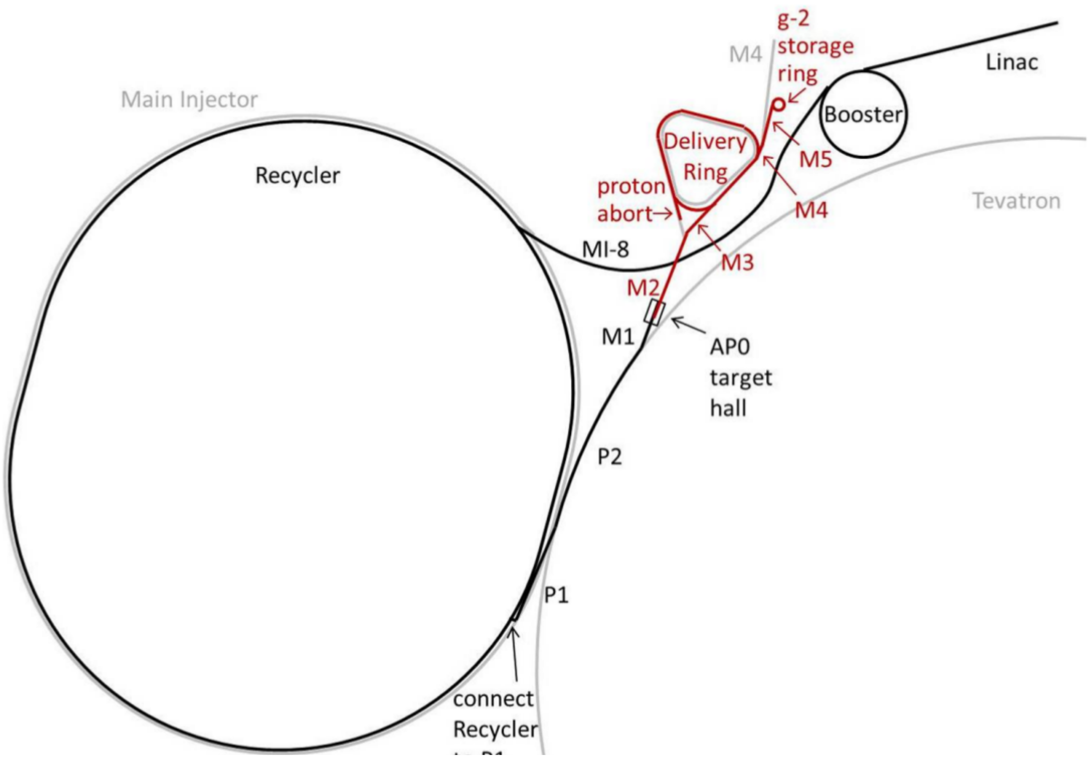
1. Start with spin polarized muon beam
2. Have spins precess in magnetic field
3. Measure spin direction w.r.t. momentum through self-analyzing decay

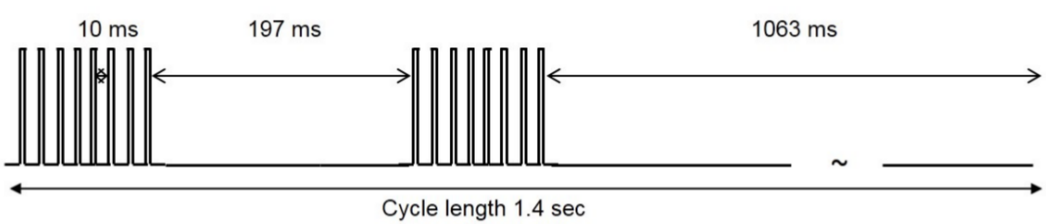
P violation → spin / $\vec{p}_{e^+}$ corr. (rest frame) → spin / E_{e^+} corr. (lab frame)

$$g_\mu - 2 = g_e \frac{\omega_a}{\omega_p}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}$$

Never measure anything but frequency

Muon Beam Delivery





Primary 8 GeV proton beam generated in the linac

Booster and recycler provide time structure

Bunches hits target station, creating secondary 3.1 GeV pion beam

Spin polarization comes via CP violation in pion decay

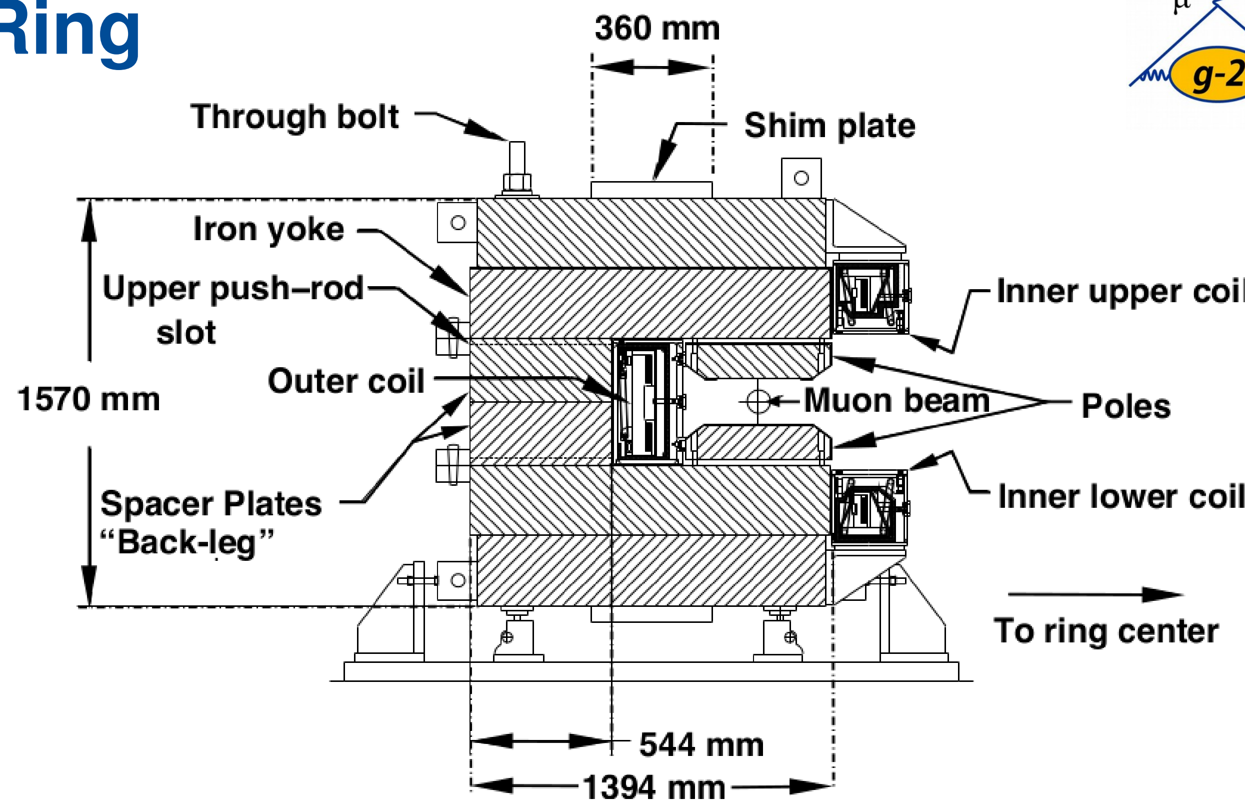
Beam contaminants removed in delivery ring

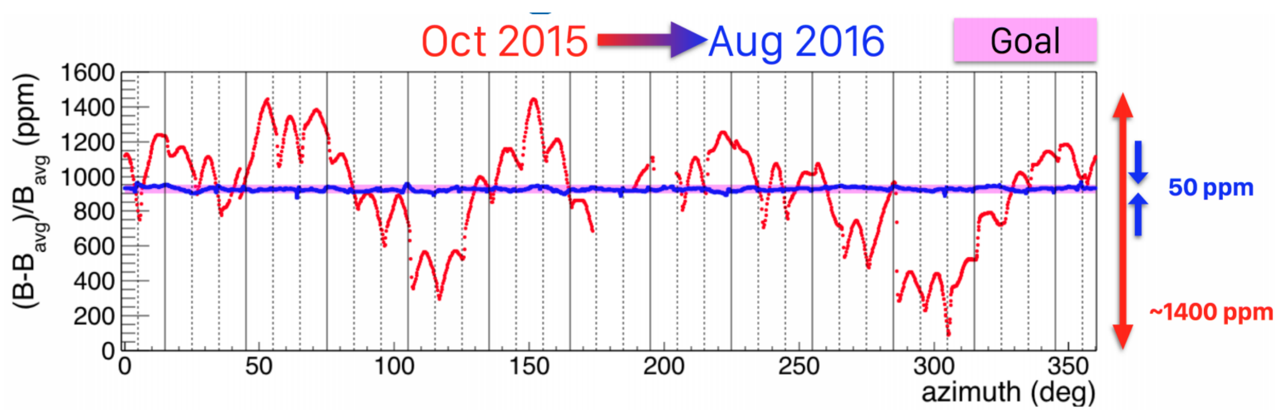
Muon Storage Ring

Superferric ring provides 1.45 T magnetic field to confine the muons radially

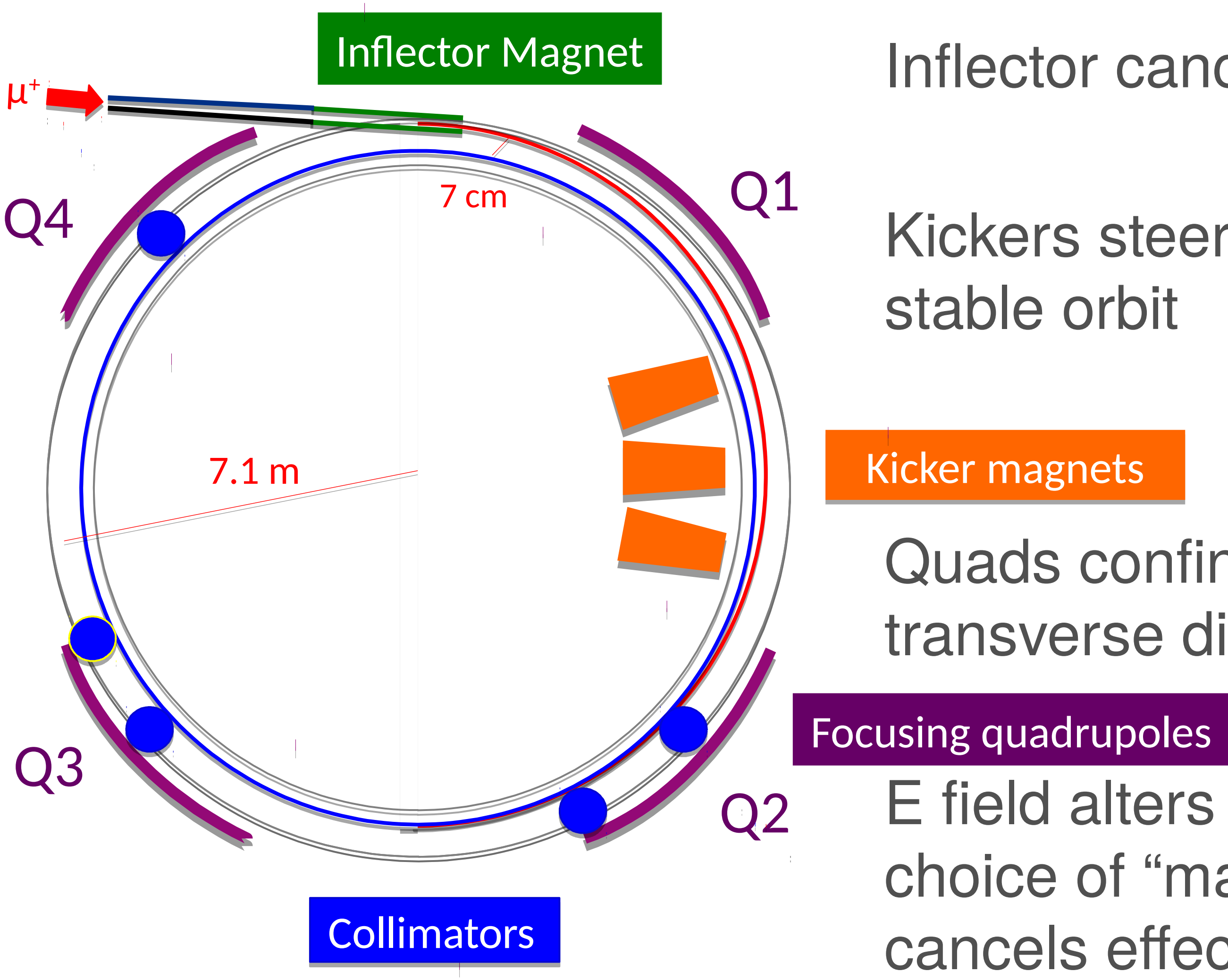
Adjustments to poles and wedges and a shimming program provide 50 ppm uniformity

Feedback maintains 15 ppm stability





Muon Confinement



Inflector cancels ring B field

Kickers steer the beam on to a stable orbit

Quads confine the beam in the transverse dimensions

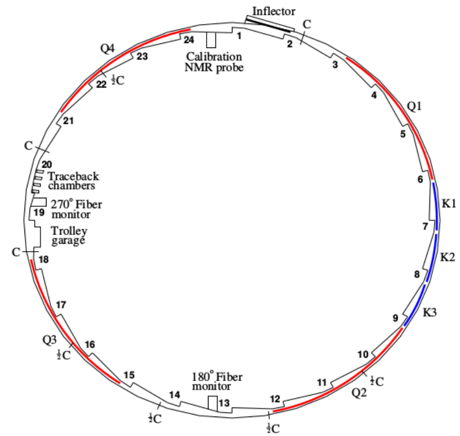
E field alters the spin equations: choice of “magic” momentum cancels effects to first order; corrected at second order

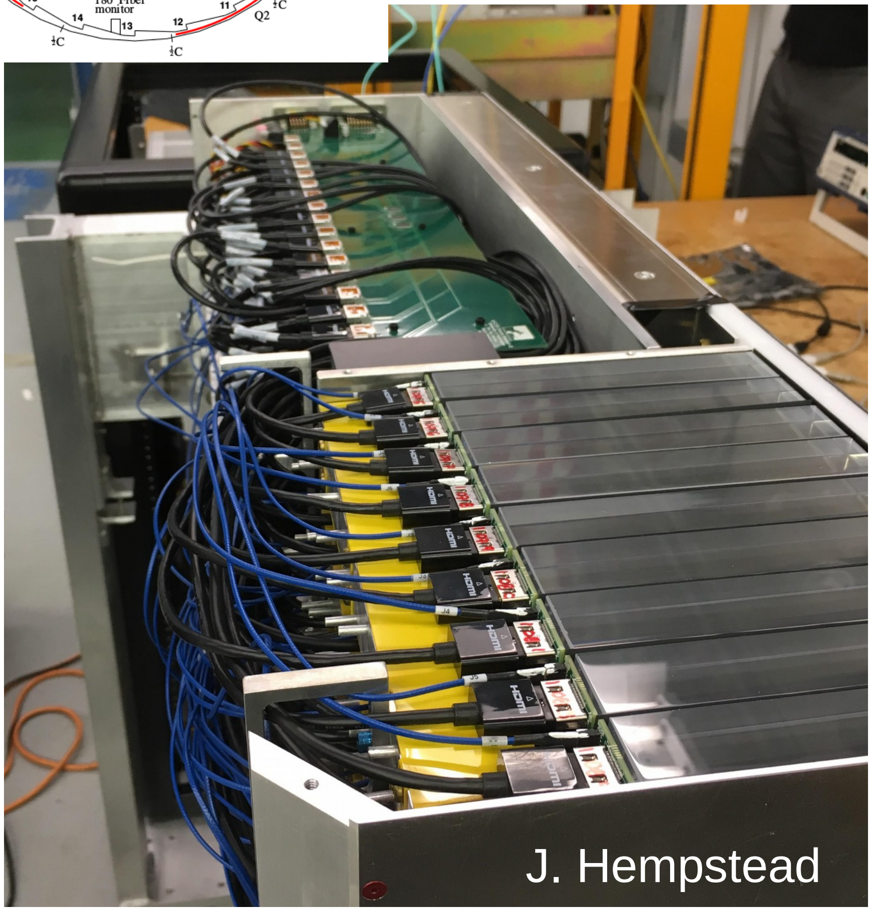
Calorimeters

Positron energies measured with 24 segmented lead fluoride electromagnetic calorimeters, instrumented with sipms and read out with digitizers

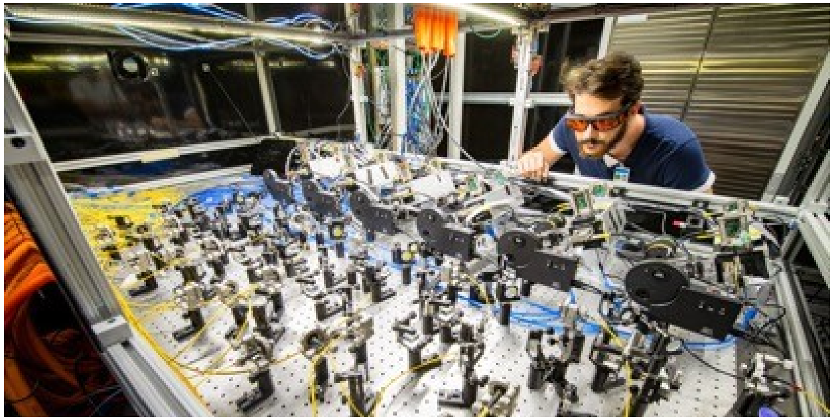
Segmentation significantly reduces pileup systematic

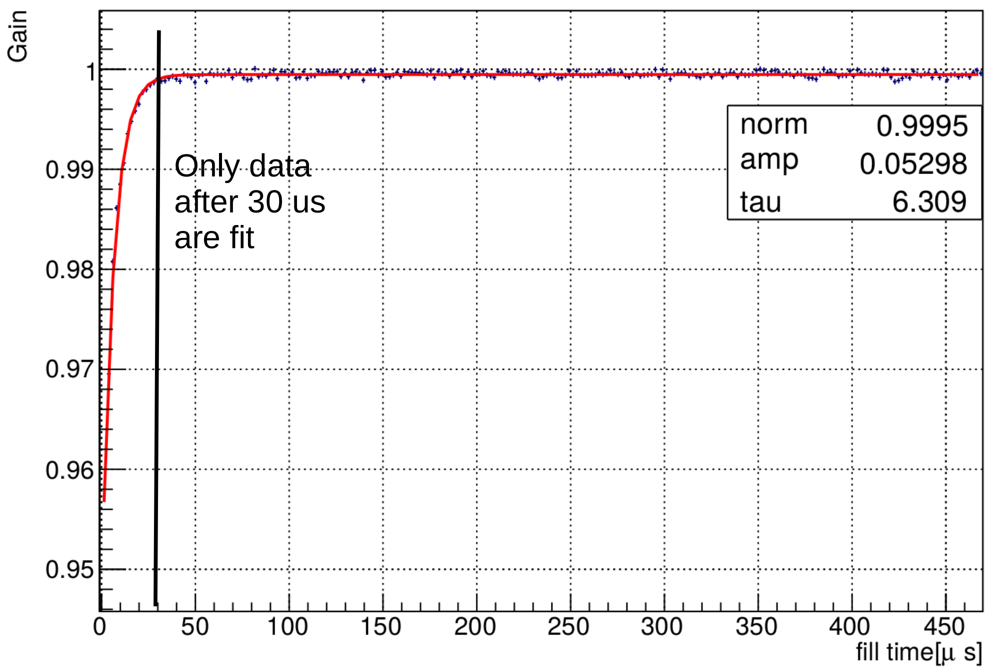
Reconstructed times good to about 100 ps, reconstructed energies known to about 5%





Laser calibration system



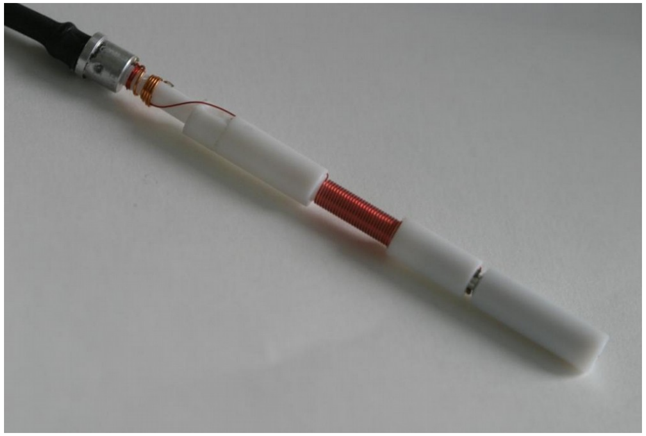


Laser calibration system injects light into each channel

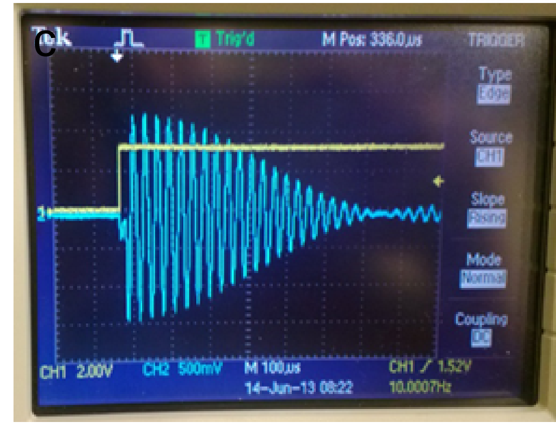
Controls for gain changes

Short-term gain variations from beam “splash” a direct systematic error

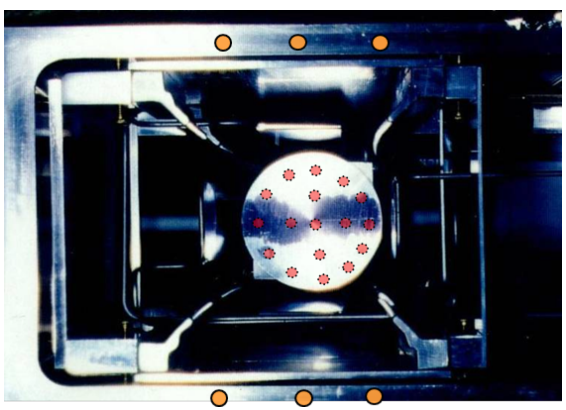
Measurement of the field strength



Use NMR to measure proton spin precession



“Ladder” of different probes with different spatial, temporal resolution

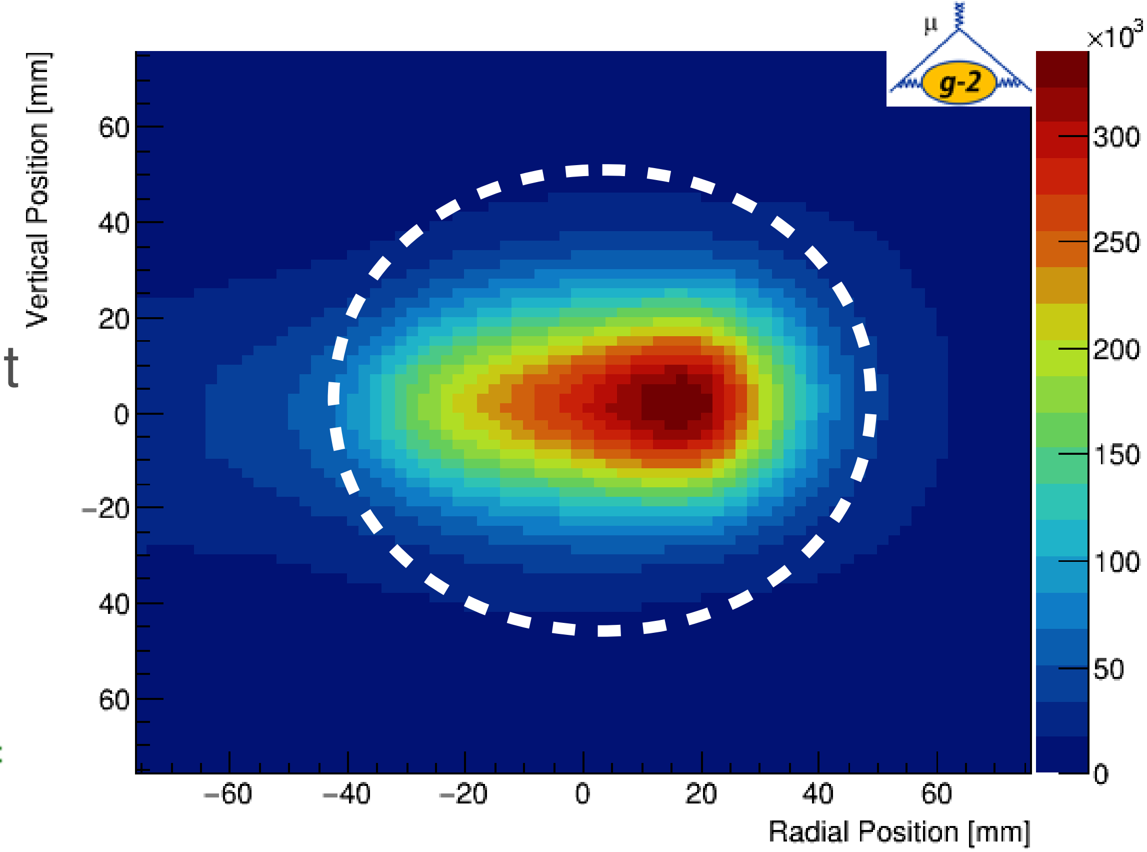


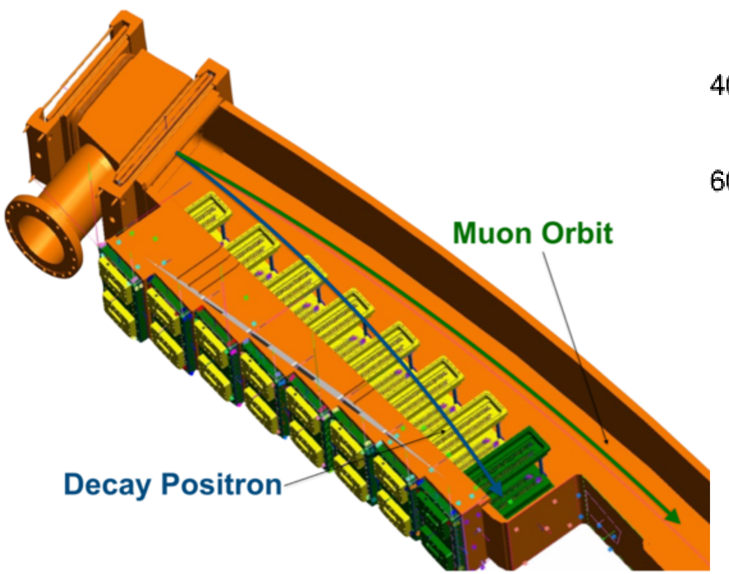
System	Spatial Resolution	Time Resolution
Fixed Probes	360 positions	1 second
Trolley	150k positions	Twice Weekly
Plunging Probe	1 position	Annually
Absolute Calibration	Outside Ring	Twice

Convolution with beam profile

What field do the muons experience?

Convolve field map with beam profile measurement from tracker stations

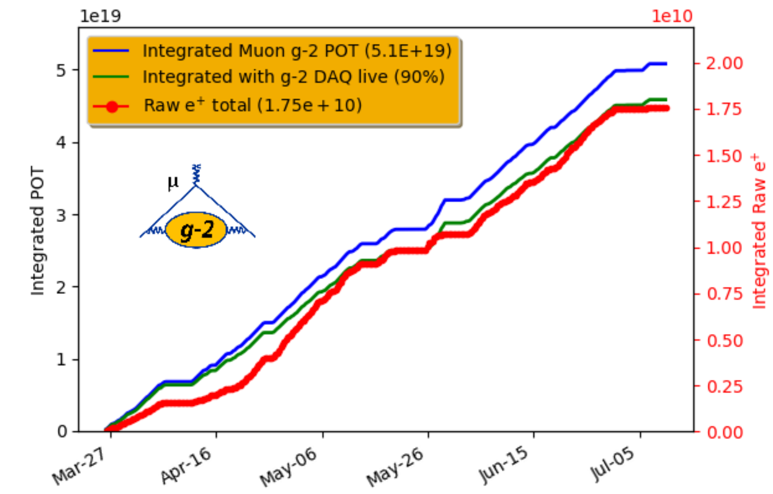




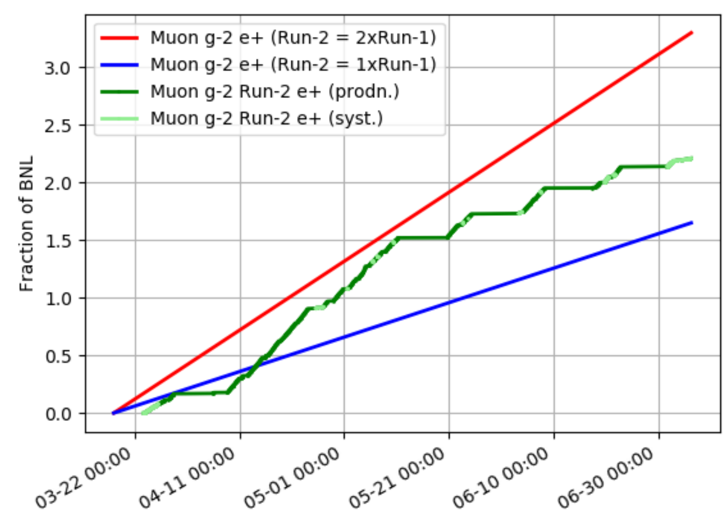
Also used for measuring beam dynamics and for planned EDM measurement

Data collection in Runs I and II

Run I was conducted from Mar – Jun 2018, collected about 1.4x Brookhaven. So far analysis has focused on this dataset.



Run II was conducted from Mar – June 2019, collected about 1.8x Brookhaven with better systematics.

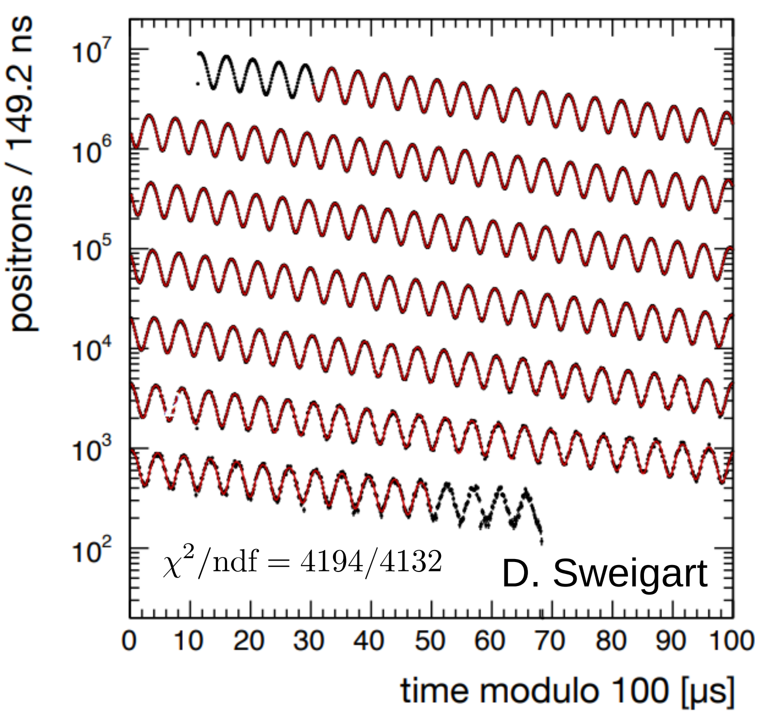


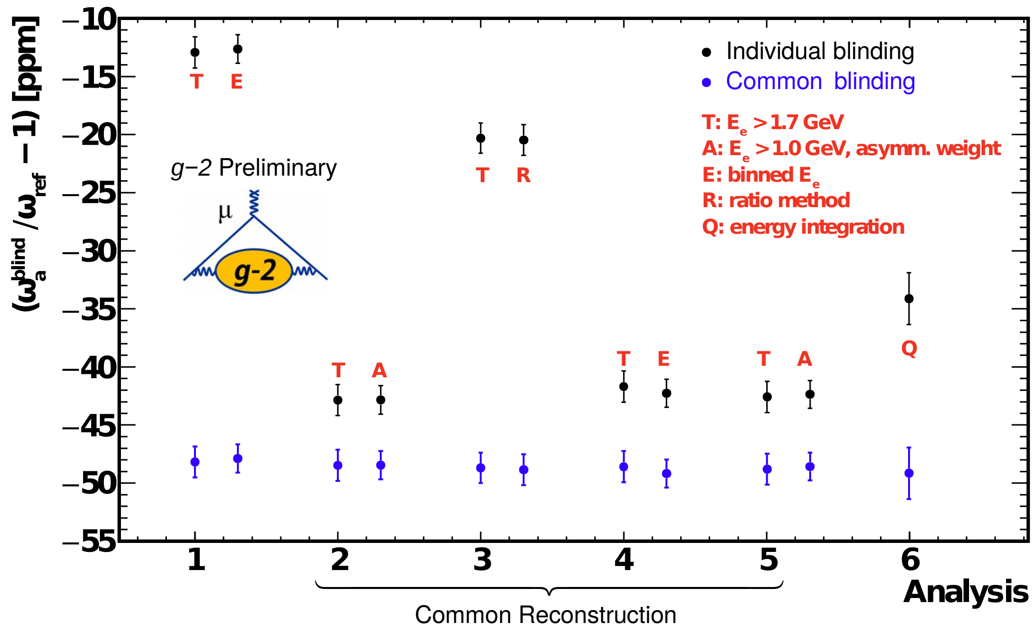
Run III is about to begin. Goal is to collect 8x Brookhaven this year.

Status of precession analysis

Numerous independent analyses using different reconstructions and different analysis techniques

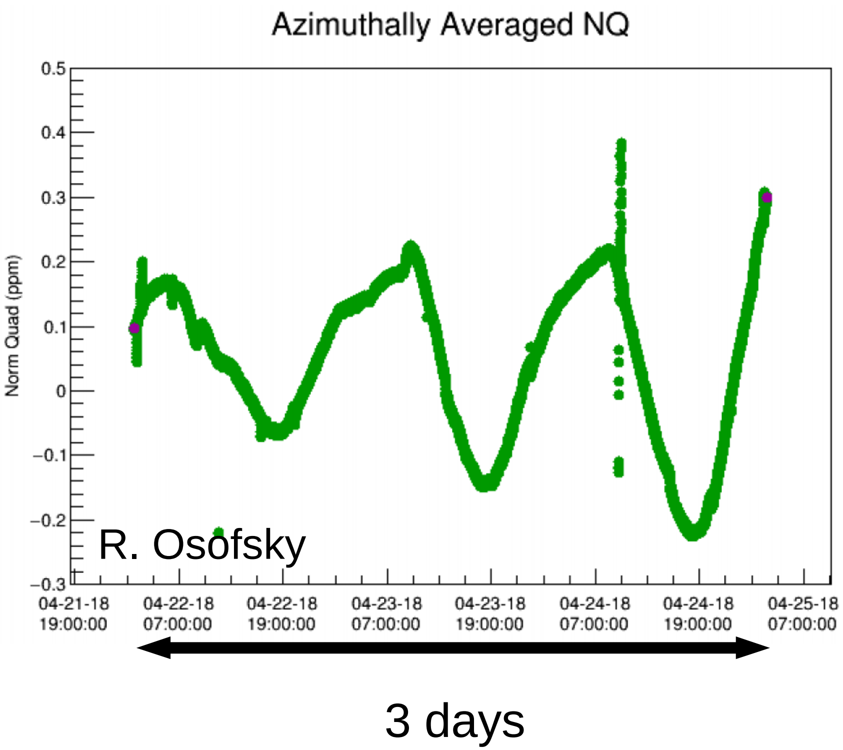
Successful **relative** unblinding of a small data sample

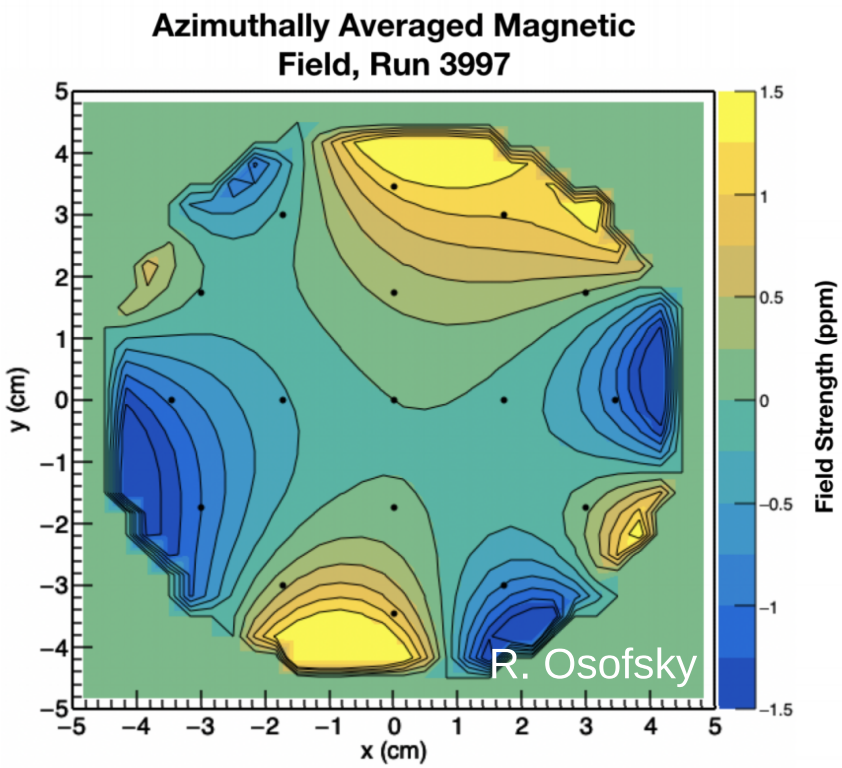




Status of field analysis

Two analysis teams are developing techniques for interpolating between trolley measurements and convolving with beam position.





Summary

The Muon g – 2 Experiment at Fermilab is well underway. We have already collected significantly more data than at Brookhaven with improved control over systematic uncertainties. Data collection to continue for at least two more years.

Analysis is maturing and first results (from Run I) expected by the end of this calendar year. Stay tuned!

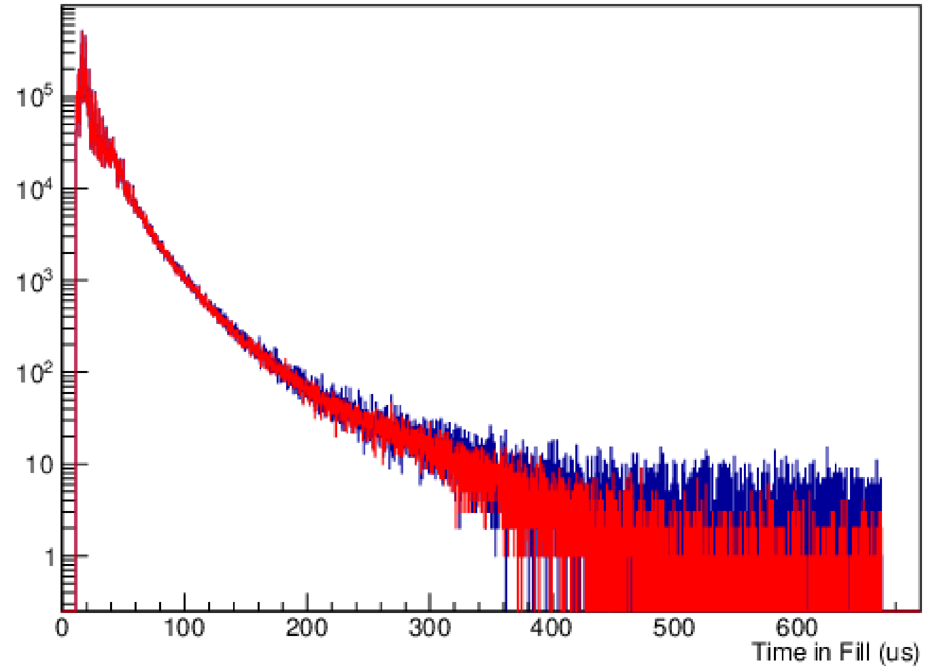
An example

About 1% of muons are "lost" (scattered) before decaying

These must be corrected for when fitting by counting such particle losses in the calorimeters

But sometimes other particles are lost too, and these shouldn't be counted

… about a 0.1 ppb effect



E-field, Pitch corrections

$$\omega_E = -\frac{Qe}{m}\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}$$

$$C_E = -2n(1-n)\beta^2 \frac{\langle x_e^2 \rangle}{R_0^2}$$

$$\omega_P = -\frac{Qe}{m} a_\mu \frac{\gamma}{\gamma + 1}(\vec{\beta} \cdot \vec{B})\vec{\beta}$$

$$C_P = -\frac{n}{4}\frac{\langle y^2 \rangle}{R_0^2}$$

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Difference between cyclotron and spin precession frequencies gives direct access to g – 2:

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To measure ω_a :

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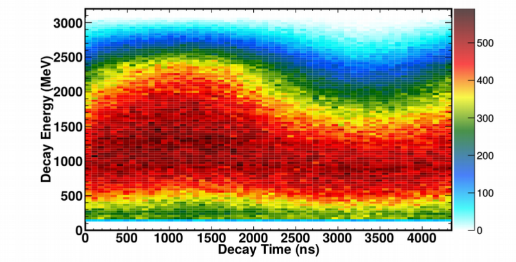

Uncertainty is minimized by rewriting this as:

$$g_\mu - 2 = g_e \frac{\omega_a}{\omega_p} \frac{m_\mu}{m_e} \frac{\mu_p}{\mu_e}$$

g_e : 0.3 ppt (Gabrielse)
m_μ/m_e : 22 ppb (Muonium spec.)
μ_p/μ_e : 3 ppb (H maser)

Never measure anything but frequencies