Precision magnetic field measurement for the Muon $g-2$ experiment

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Physics context

The Fermilab Muon $g-2$ experiment aims to measure the anomalous magnetic moment of the muon, a_μ, to a precision of 140 ppb. It consists of muons stored at a "magic momentum" value of 3.94 GeV/c in a quasi-penning trap with a uniform vertical magnetic field of 1.45 T.

This experiment extracts a_μ as a ratio of two frequencies, the anomalous spin precession frequency of the muons, ω_a, and the muon weighted spin precession frequency of the shielded protons, $\tilde{\omega}'_p$.

Ratio measured by Muon $g-2$

Electron g-factor

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

Muon to electron mass ratio

Shielded proton to electron in hydrogen magnetic moment ratio

Electron in hydrogen to free electron magnetic moment ratio

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

Values contributing to the ratio:

- Clock blinding
- Anomalous spin precession frequency
- Muon beam dynamics corrections
- Magnetic field calibration
- Spatial muon distribution
- Spatial magnetic field distribution
- Transient magnetic fields

The spin precession frequency, ω'_p, is directly proportional to the magnetic field, B.

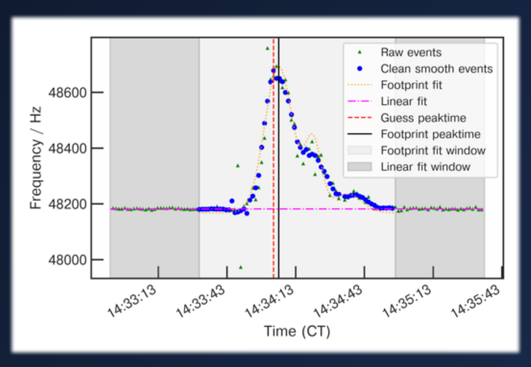
$$B = \frac{\hbar\omega'_p(T)}{2\mu'_p(T)}$$

Henceforth, by measuring the muon weighted magnetic field we derive the muon weighted spin precession frequency of the protons.

Analysis & Results

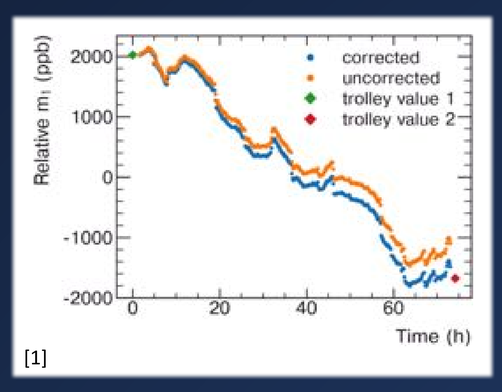
Trolley footprint

Trolley's magnetic footprint binds the trolley calibration data in position to the fixed probes.



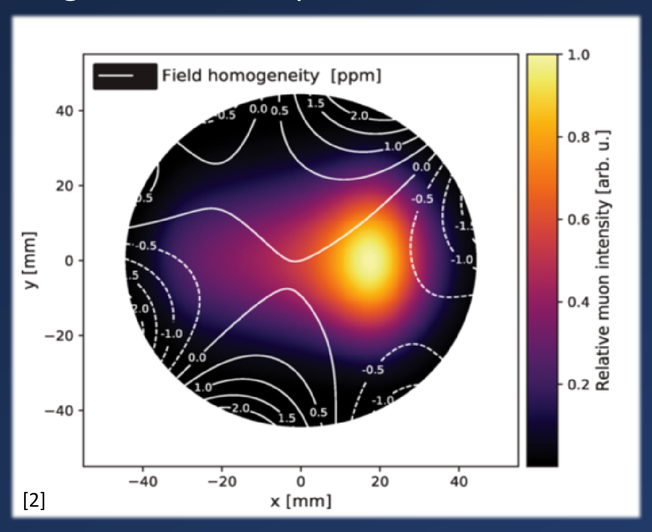
Fixed probe calibration

All fixed probes are calibrated to the magnetic field values in the muon storage volume (MSV) using book-ended trolley data for each beam down time.



Muon beam weighting

Muon beam density weighted MSV magnetic field map is obtained.



$\tilde{\omega}'_p$ uncertainty contribution (Run 1) [1]	
Frequency extraction, calibration, mapping, tracking, and averaging	56 ppb
Fast transient fields	99 ppb
Total	114 ppb

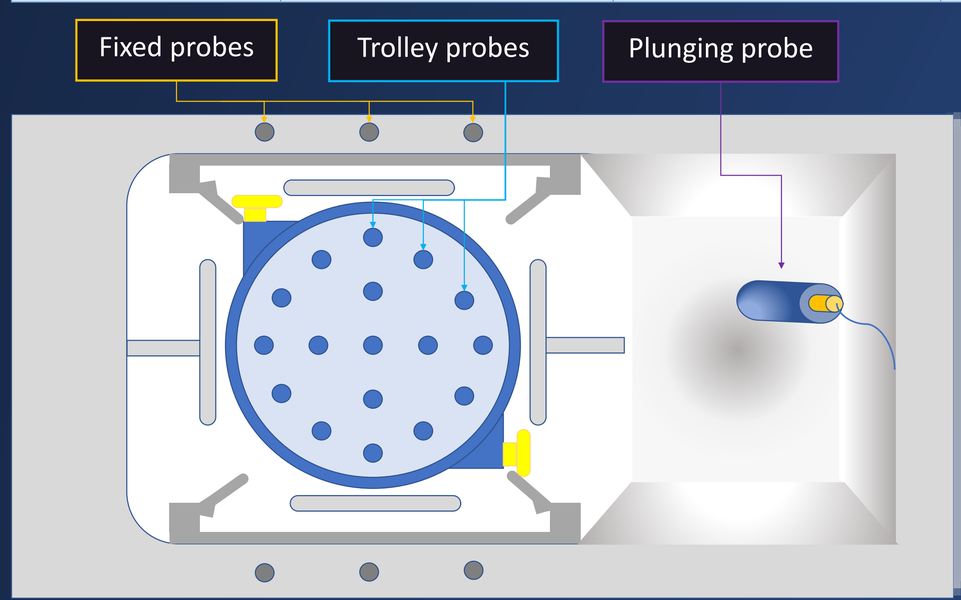
Combined with ω_a the FNAL Run 1 a_μ value was recorded to be [2] , $116592040(54)\times10^{-11}(0.46\text{ ppm})$.

Setting a new world average value for muon $g-2$, that is at a 4.2σ tension with the Standard Model prediction [2].

Measurement systems

The measurement of the magnetic field for this experiment is a three stage process whereby calibration is transferred from one system to another for accurate field measurement within the muon storage volume (MSV). The three stages/systems consist of:

	Plunging probe	Trolley probes	Fixed probes
Material	Water	Petroleum jelly	Petroleum jelly
Frequency	Biannual	3-4 days	Continuously
No. of probes	1	17	378
Mobility	Semi-fixed	Mobile	Fixed
Location	Inside - vacuum	Inside - vacuum	Outside - vacuum
Beam	Off	Off	On



References: [1] T. Albahri *et al.* Phys. Rev. A 103, 042208, [2] B. Abi *et al.* Phys. Rev. Lett. 126, 141801

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