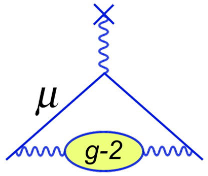
Muon $g-2$ in 10 minutes

Sam Grant
(on behalf of the $g-2$ collaboration)



New Perspectives
August 2021

The muon magnetic dipole moment

A charged fermion will react to an external magnetic field

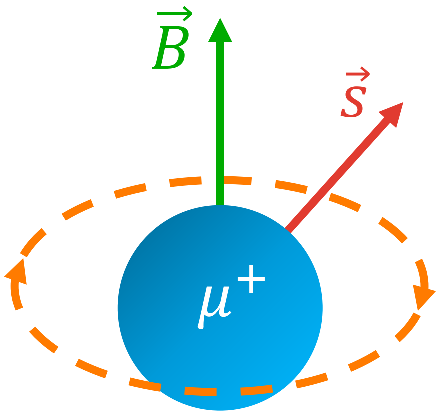
- Spin will precess about an external field
- The rate of precession depends on the size of the magnetic dipole moment, μ

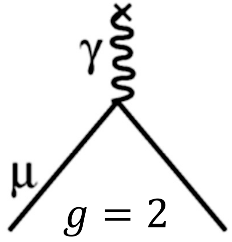
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B}$$

- μ depends on the dimensionless 'g-factor'

$$\vec{\mu} = g \left(\frac{q}{2m} \right) \vec{s}.$$

- Dirac found that $g = 2$ at **leading order**





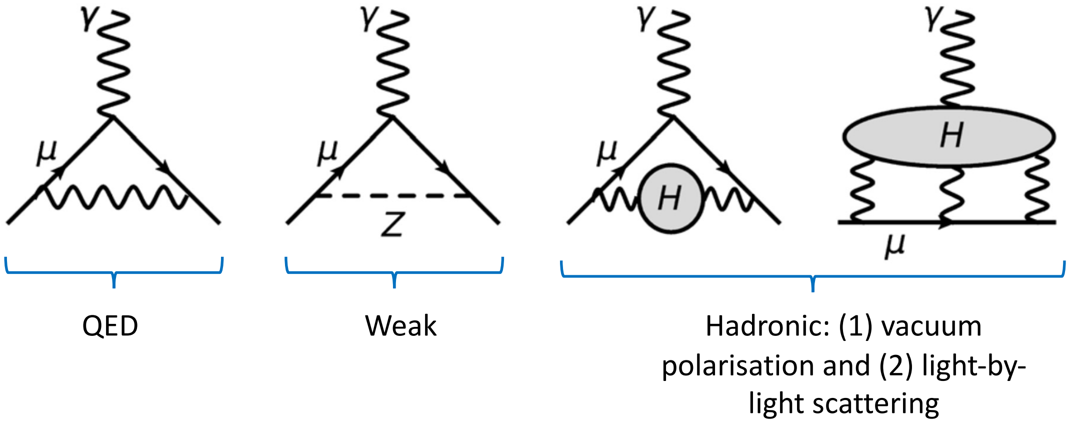
The magnetic anomaly

Loop contributions from all particles modify the magnetic moment, so that $g > 2$

- Together, these amount to the muon magnetic anomaly, a_μ

$$a_\mu \equiv \frac{g-2}{2}$$

- Standard model (SM) contributions are split in four categories

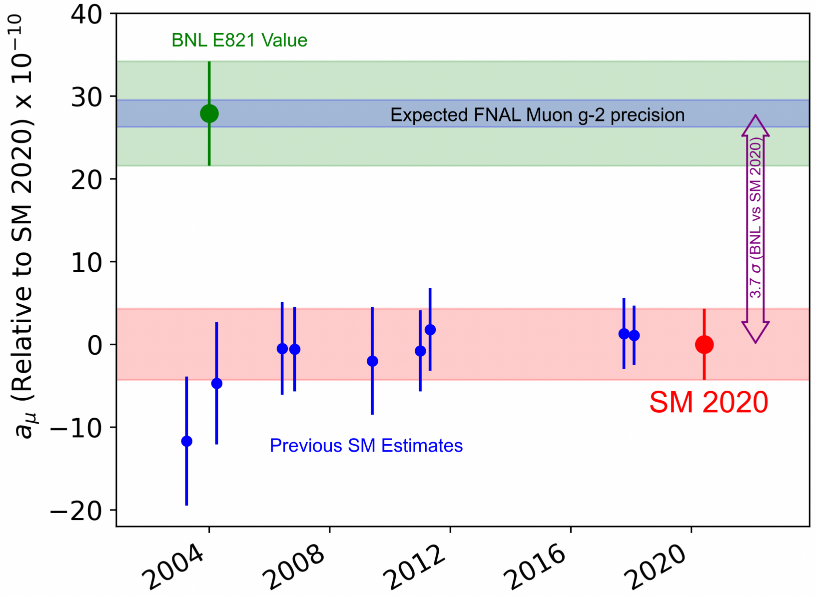


	Contribution $(\times 10^{-10})$
QED	11 658 471.8971(75)
Weak	15.36(10)
HVP	684.7(2.4)
HLbL	9.8(2.6)
Total SM	11 659 182.04(3.56)

Theory vs experiment

Any deviation between theory and experiment would indicate new physics contributions to the anomaly

Plot from Mark Lancaster



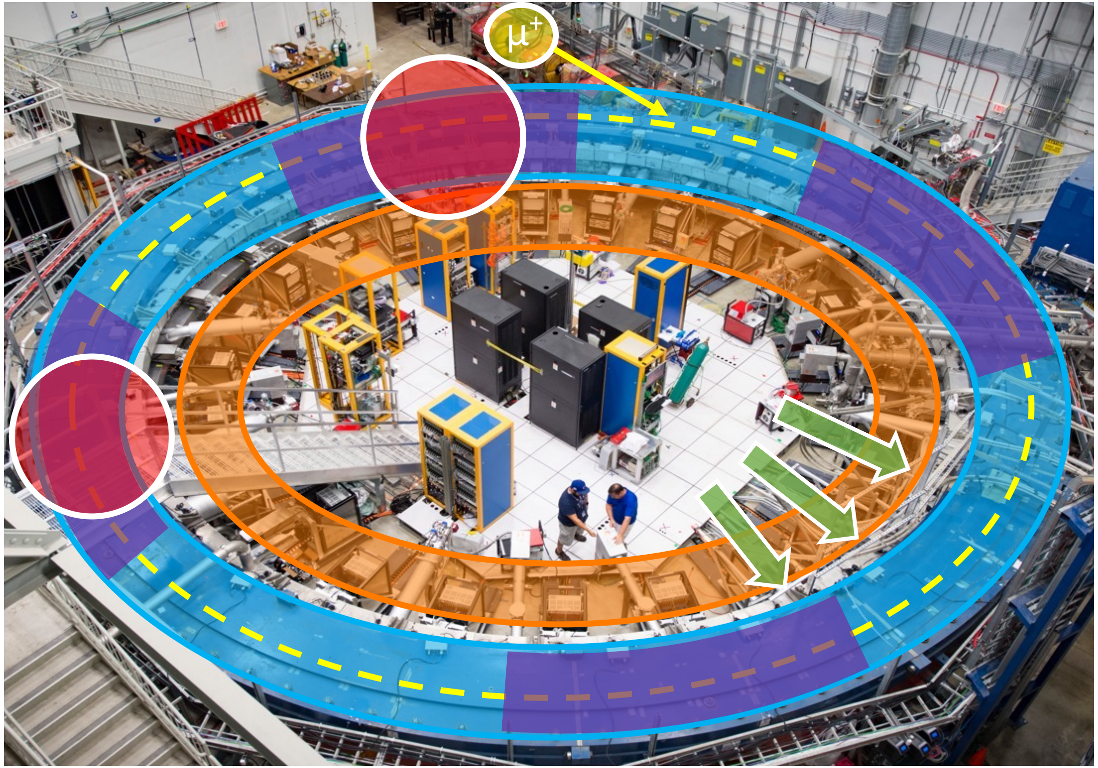
- The Brookhaven (BNL) $g-2$ experiment reported a <u>3.7σ tension with the SM</u>
- In order to resolve, this a more precise measurement of the a_μ is needed
- Cue the Fermilab $g-2$ experiment ...

The Fermilab $g-2$ experiment (E989)

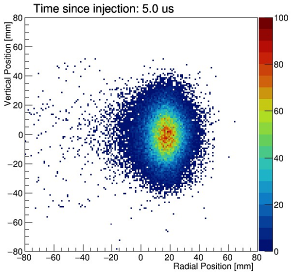
Build on the magnetic storage ring experiment at BNL, and measure the anomaly to $> 5\sigma$

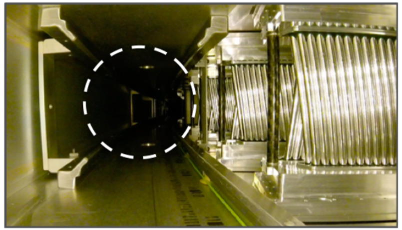
- Reuse BNL's storage ring:
  - Power it with Fermilab's cleaner, more intense muon beam
  - Improvements to instrumentation
- 100 ppb statistical uncertainty (21x collected positrons as BNL!)
- 100 ppb systematic uncertainty
- 4x the precision of BNL (540 ppb → 140 ppb)

E989 anatomy



- 14 m diameter, 1.45 T superconducting magnet
- Injection through inflector
- Electrostatic quadrupoles
- Magnetic kickers
- 24 PbF_2 calorimeters
- Straw tracking stations

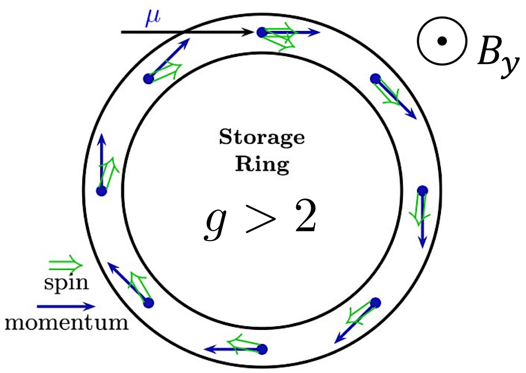




Measuring a_μ

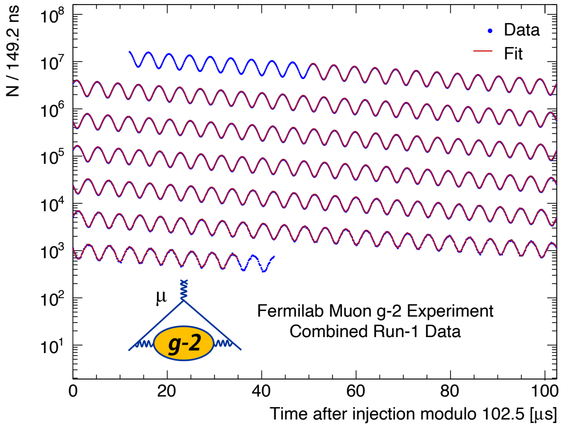
$$\vec{\omega}_a = -a_\mu \frac{q}{m_\mu} \vec{B} \quad \text{where,} \quad B = \omega_p / \mu_p$$

Anomalous spin precession frequency



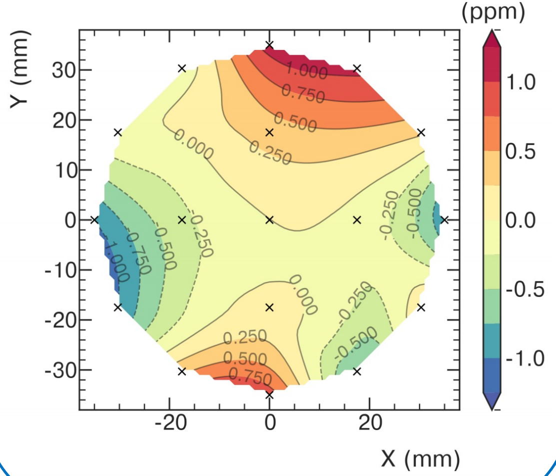
$$\omega_{\mathbf{a},\,(\text{anomaly})} = \omega_{\mathbf{s},\,(\text{spin})} - \omega_{\mathbf{c},\,(\text{cyclotron})}$$

High energy decay positrons: count and fit for ω_a



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

Magnetic field measured via NMR probes



ω_p is the Larmor precession frequency of a free proton

Measuring a_μ

What we measure

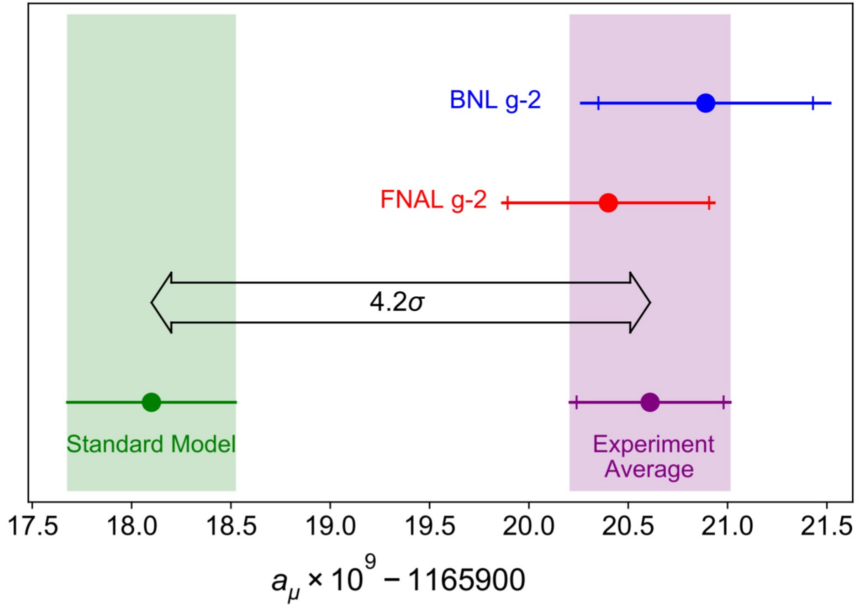
$$a_\mu = \frac{g_\mu - 2}{2} = \underbrace{\frac{\omega_a}{\omega_p}}_{\text{What we measure}} \frac{g_e}{2} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e}$$

Constants

Contribution	Relative error [ppb]	Experiment	Reference
$g_e/2$	0.00026	Quantum cyclotron spectroscopy	D. Hanneke *et al.* (2011).
μ_p/μ_e	3.0	Hydrogren spectroscopy	P. Mohr *et al.* (2016).
m_μ/m_e	22	Muonium spectroscopy	P. Mohr *et al.* (2016).
ω_a/ω_p	140	Fermilab $g-2$	J. Grange *et al.* (2015).

First results for a_μ!

Run-1 result!

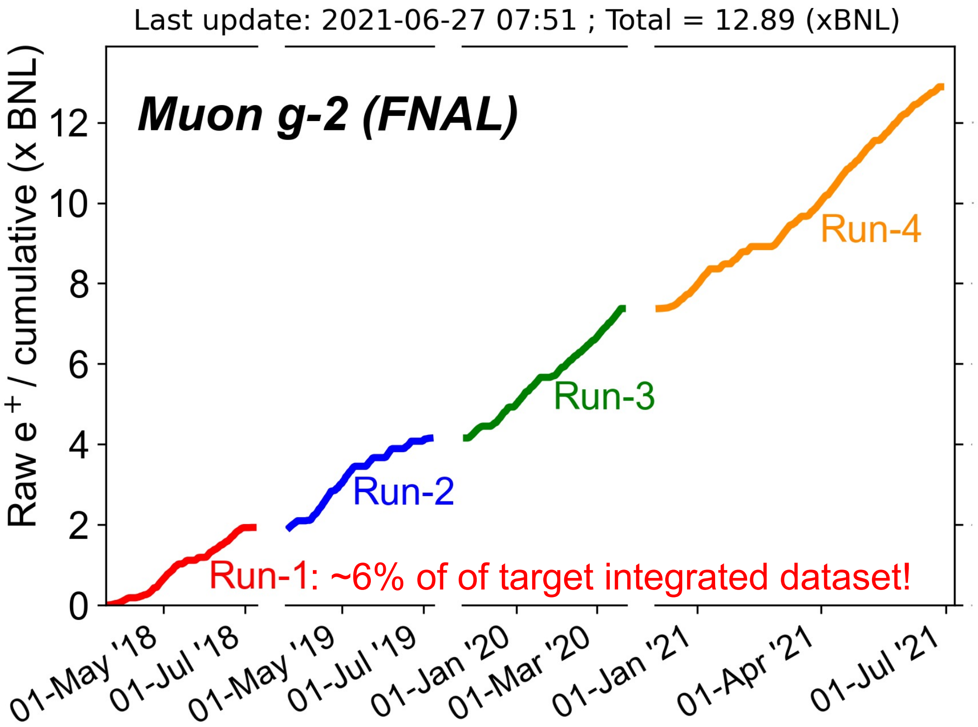


$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

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

Status and outlook

- First result comprises a small subset of the total projected dataset (Run-1)
- Run-2/3 analysis underway
- Run-4 running recently completed
- Run-5/6 to come
- $> 5\sigma$ result in future



Summary

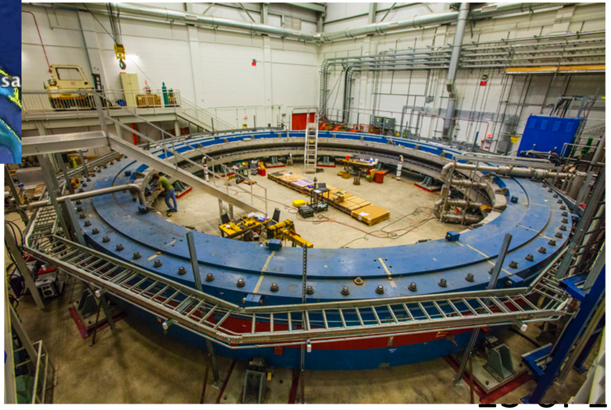
- First result from Fermilab $g-2$ is consistent with BNL
- FNAL and BNL together present a 4.2 sigma tension with the SM at a precision of 350 ppb
- Much more data to be folded into a_μ, 140 ppb precision on the horizon!

Thanks & stay tuned!

Extra slides

BNL to FNAL: the big move (2013)

- 3200 miles over ~3 months
- Magnet cooled and powered by 2015



More physics potential: the muon EDM search

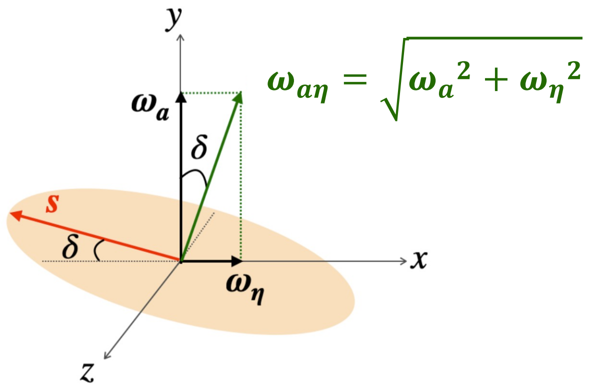
Fermilab will improve on the current μ^+ electric dipole momentum (EDM) limit by two orders of magnitude!

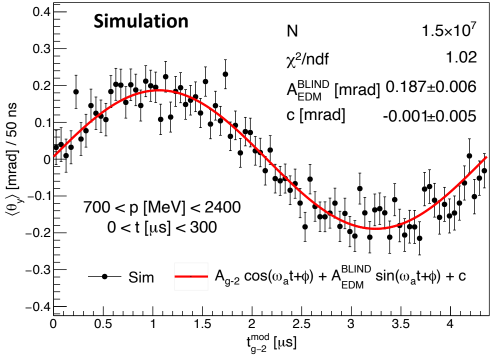
- The EDM has a similar formulism to the MDM

$$\vec{d} = \eta \frac{q\hbar}{4mc}\vec{S}$$

- Manifests as a tilted spin precession plane

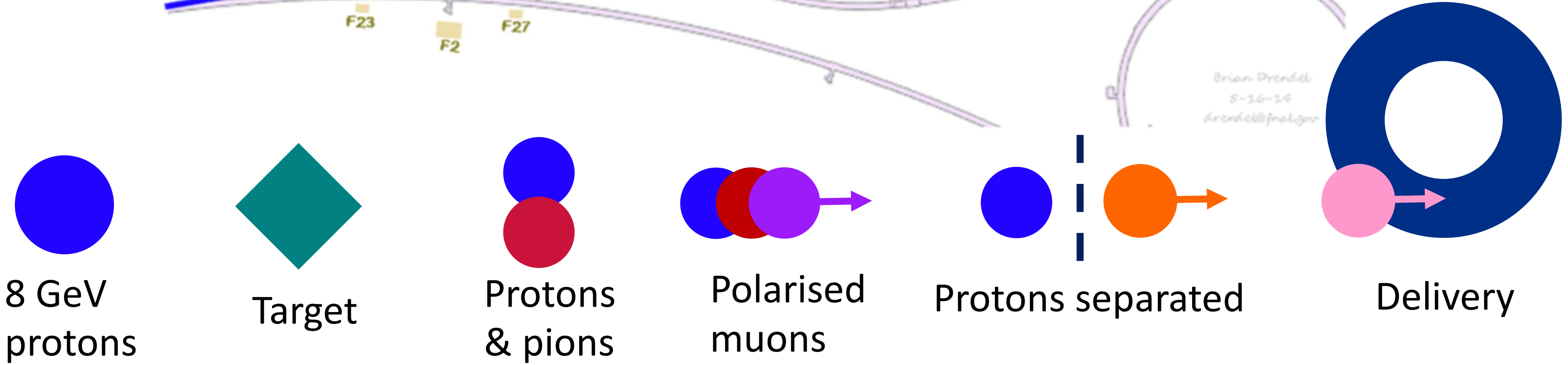
- Detected by measuring a vertical oscillation $\pi/2$ out of phase with ω_a





Run-1 analysis underway!

Muon delivery



Full treatment of ω_a

The full treatment of ω_a goes like this:

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

Goes to zero if the momentum is set to the **magic momentum** (3.094 GeV, ɣ=29.3)

Goes to zero if the momentum vector is perpendicular to the field (**the pitch**)

More on ω_a

- If g=2, we can see that the cyclotron and spin precession frequencies would be equal
- Radiative corrections cause the spin to rotate slightly faster
- We can therefore access the anomaly directly!

$$\boldsymbol{\omega}_c = -\frac{e\boldsymbol{B}}{m_\mu \gamma},$$

$$\boldsymbol{\omega}_s = -g_\mu \frac{e\boldsymbol{B}}{2m_\mu} - (1-\gamma)\frac{e\boldsymbol{B}}{m_\mu \gamma}$$

$$\boldsymbol{\omega}_a \equiv \boldsymbol{\omega}_s - \boldsymbol{\omega}_c = -a_\mu \frac{e\boldsymbol{B}}{m_\mu}$$