Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

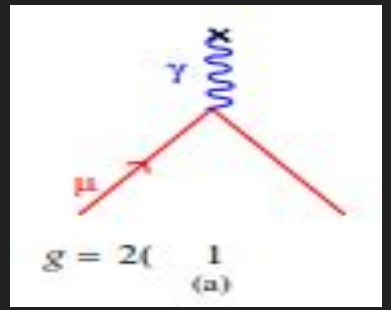
Philip Kim, Miles Knudtson, Riley Kibbee, Dhruv Kush, Io Kovach

https://arxiv.org/abs/2104.03281

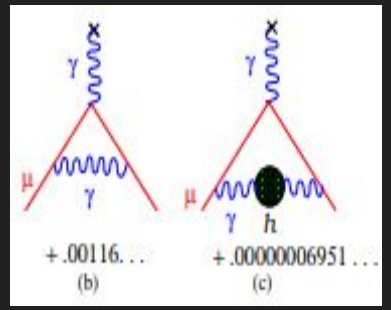
History of Magnetic Moment of the Muon

- Muons are heavy electrons with a g-factor in excess of 2

- The Dirac equation describes spin ½ particles => predicts a g-factor of 2

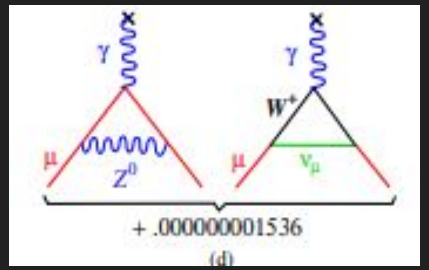


- Schwinger **(Phys. Rev. 82, 64, (1951))** showed g-factor >2 in Q.E.D.

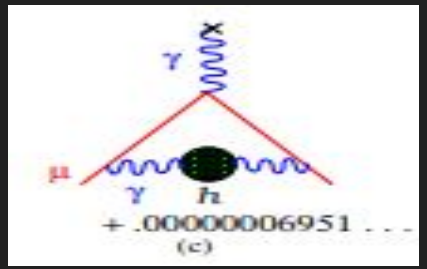


Higher Order Corrections of Magnetic Moment of Muon

- In SM, muons interact with W, Z, and Higgs bosons through the electro-weak interaction in addition to the EM field



- Muons do not directly interact with hadrons but there still are hadronic contributions to the magnetic moment

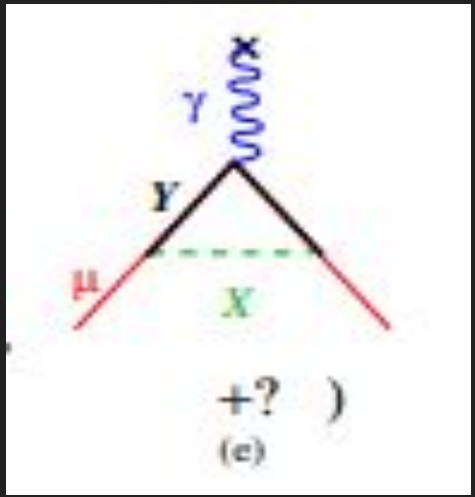


- If the magnetic moment of the muon can be affected by particles in the SM that it does not directly interact with, can the value of the moment help probe beyond standard model interactions as well?

Muons & Beyond Standard Model (BSM) Physics

- In 2021, magnetic moment of the muon measured was found to be 3.7 standard deviations away from the S.M. prediction. This is statistically significant!

- So, what do we do? Establish we are measuring the magnetic moment very accurately => provide information to phenomenologists to construct BSM models that reproduce this value of the magnetic moment



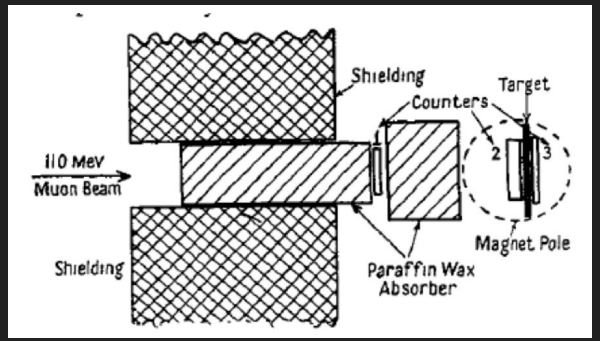
Historical Measurements of g_μ

Columbia-Nevis Measurement

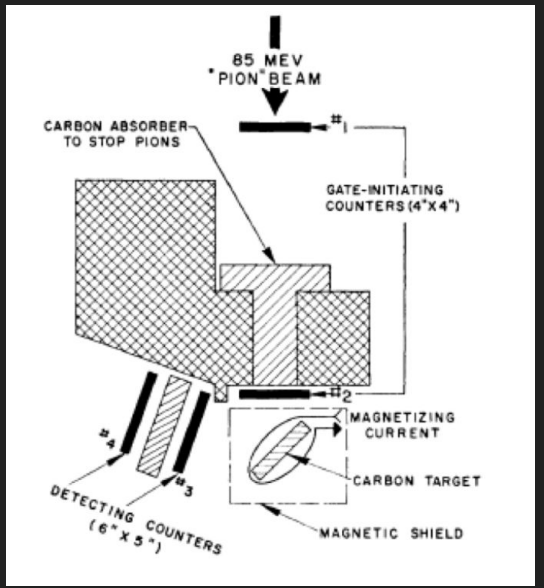
- g_μ = 2.0 with 10% accuracy

Liverpool-Cassels Measurement

- Proposed to measure difference of ω_c and ω_s
- g_μ = 2.004 ± 0.014



Experimental setup for Columbia and Liverpool measurements .



https://scipost.org/SciPostPhysProc.1.032/pdf

Historical Measurements of g_μ (cont.)

Columbia-Nevis Measurement II

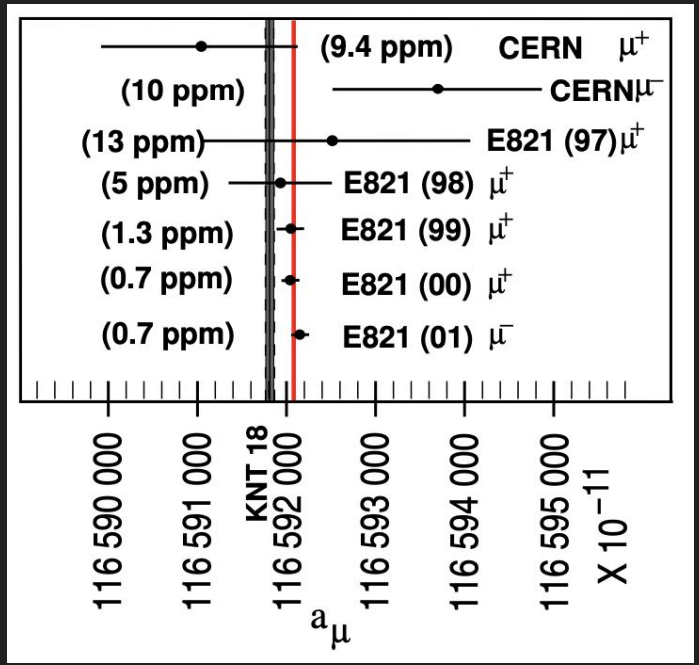
- Improved on previous experiments (agrees with SM)

CERN I,II,III

- CERN I: Lifetime too short
- CERN II: Too much noise
- CERN III: Only probed to 6th order no anomaly yet

BNL(E821)

- Improved on essentially every aspect and got a 3.7 SD from Standard Model



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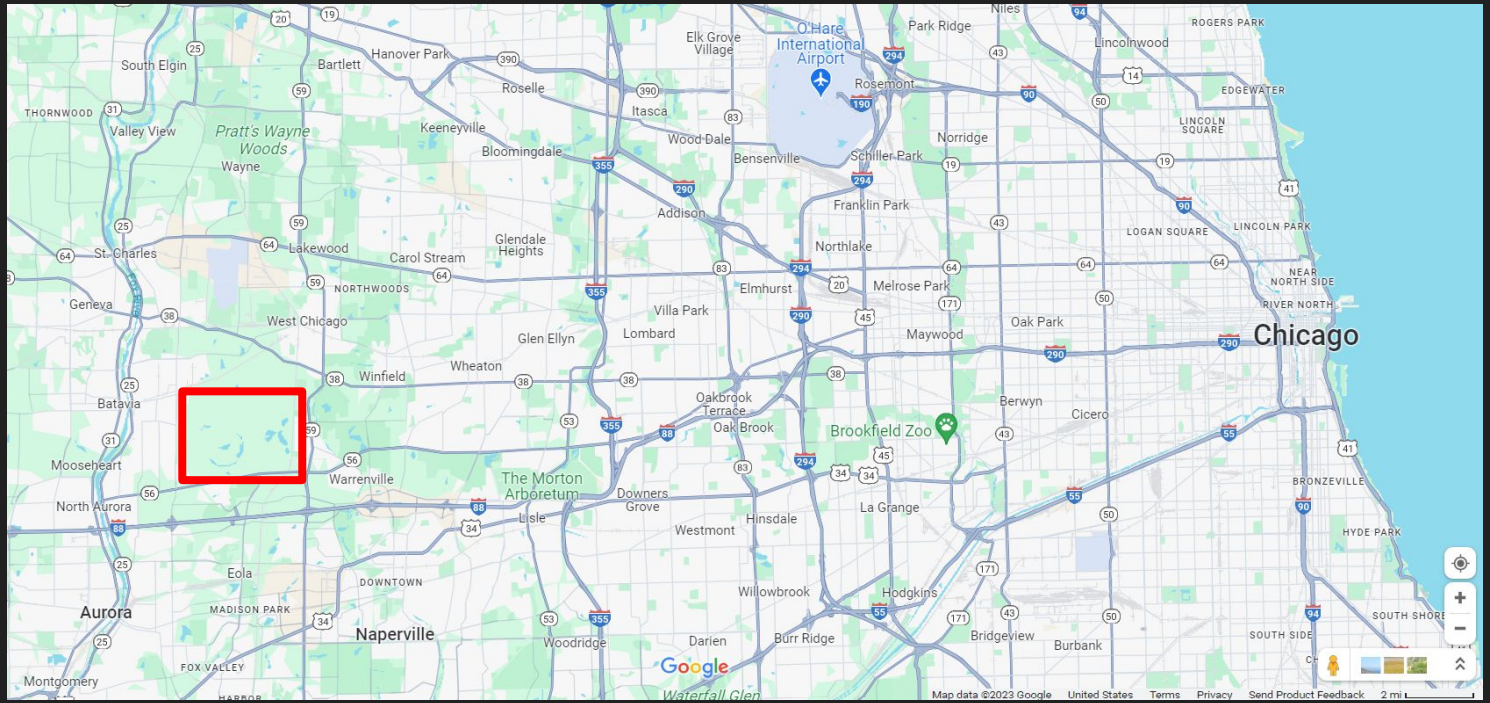
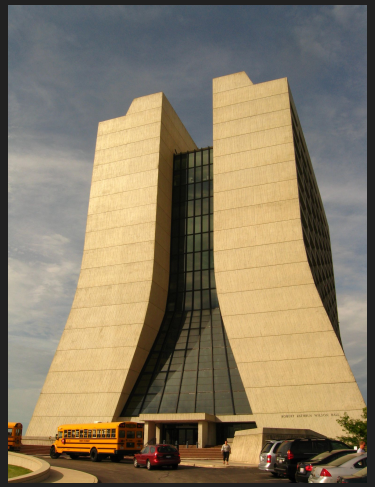
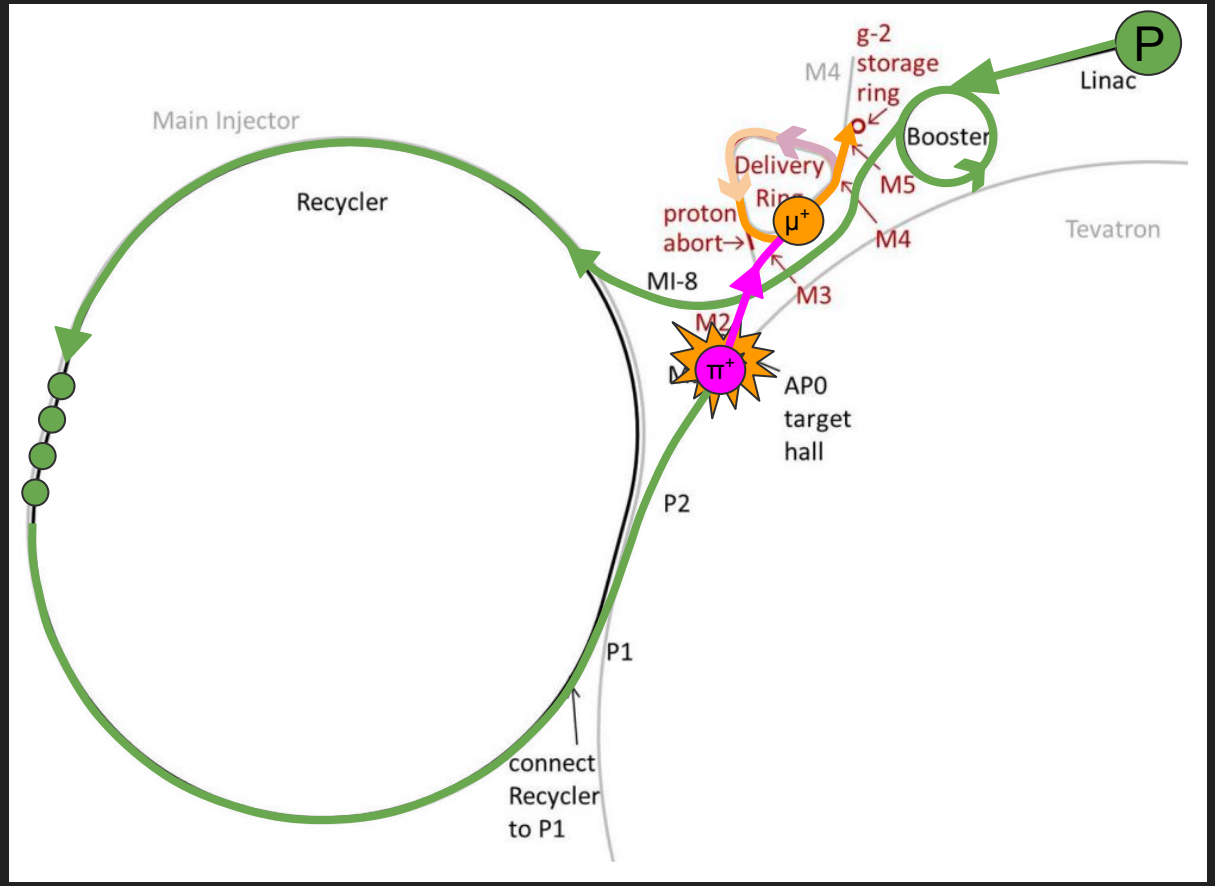
The g-2 Experiment at Fermilab





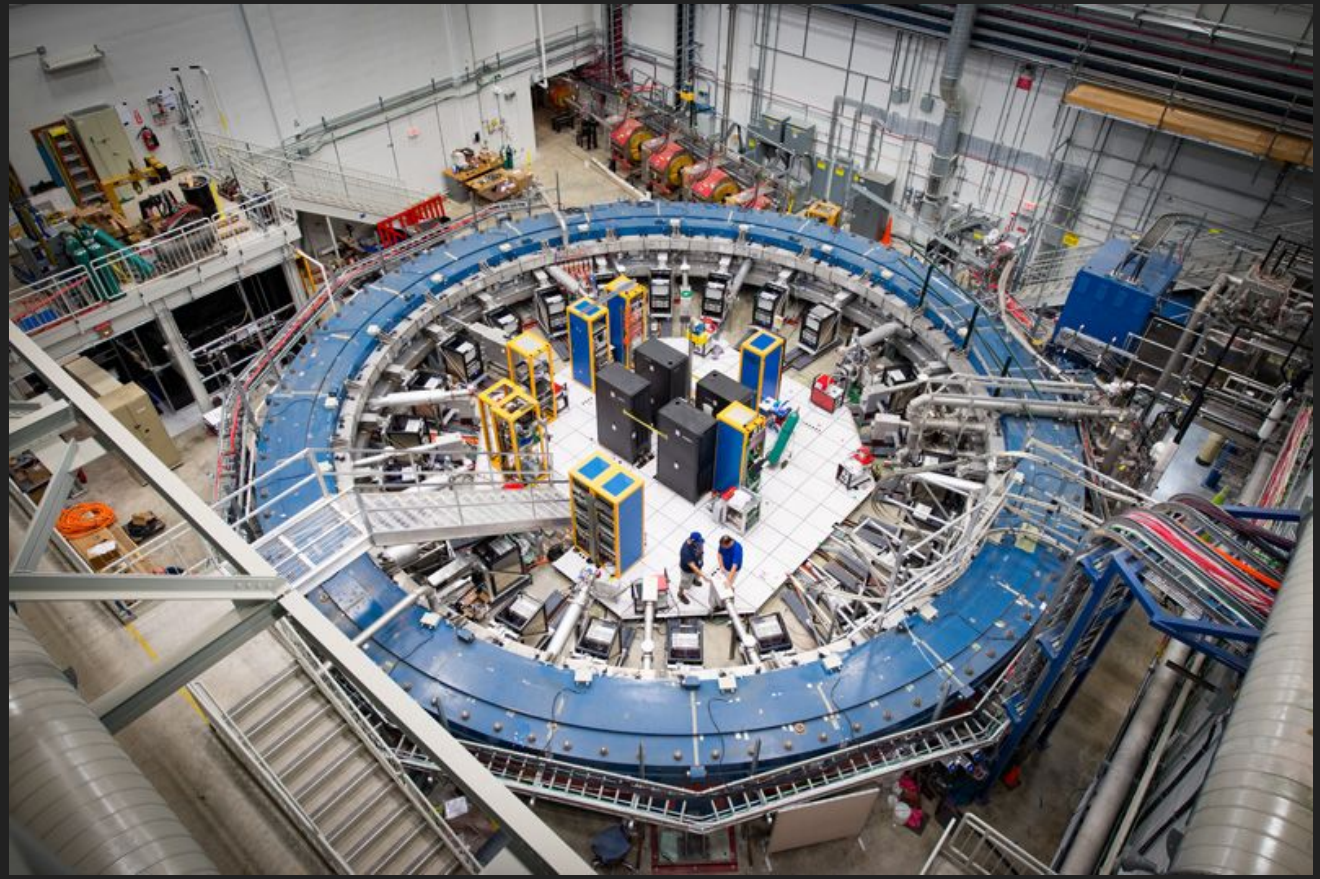
Courtesy: Google

Beam Delivery Scheme to get Muons to the Storage Ring



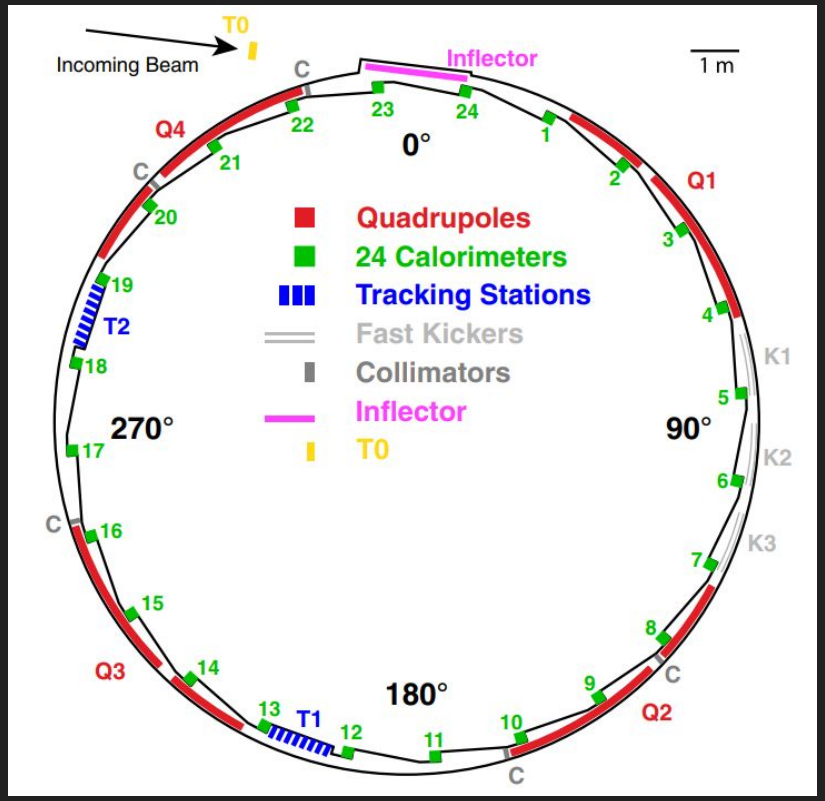
https://arxiv.org/ftp/arxiv/papers/1501/1501.06858.pdf

The g-2 Storage Ring

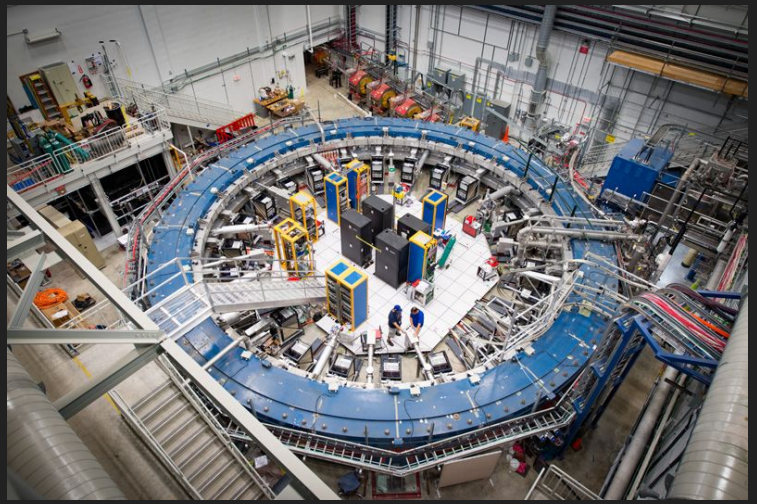


Courtesy:
Fermilab

Schematic Design of Apparatus in Storage Ring

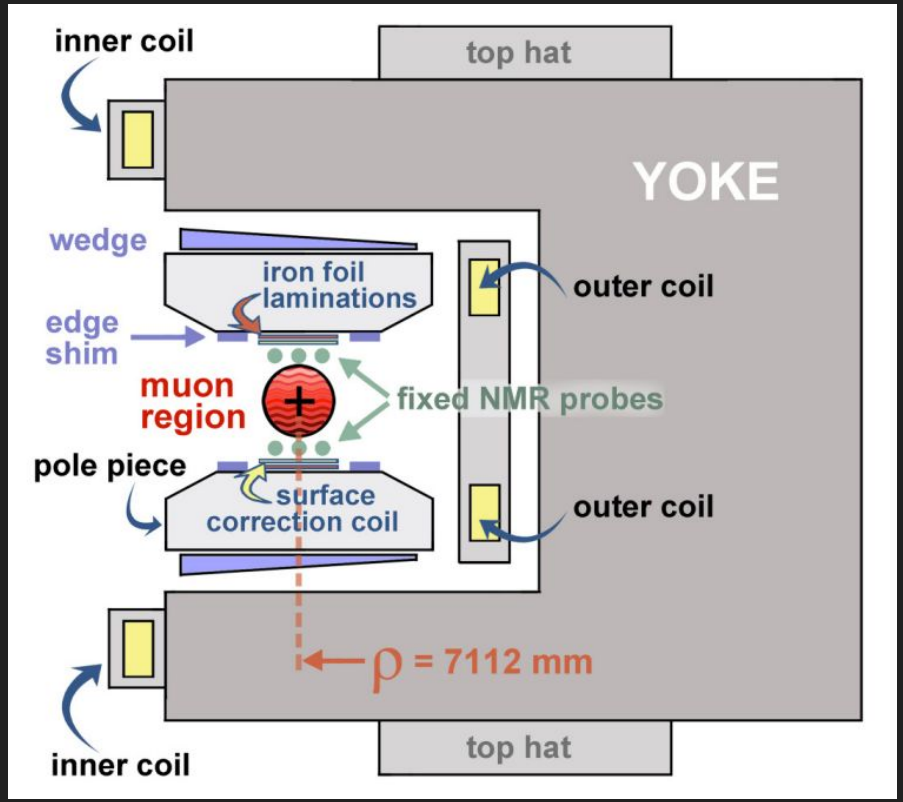


- Muons stored for lifetime in SR
- Bent by ESQs
- Decay into positrons and hit calorimeter detectors (green)

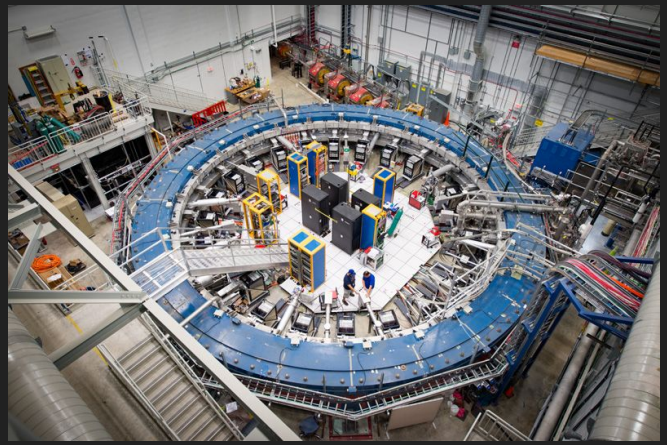


https://journals.aps.org/prd/pdf/10.1103/PhysRevD.103.072002

Cross-Section of Storage Ring that Muons Occupy



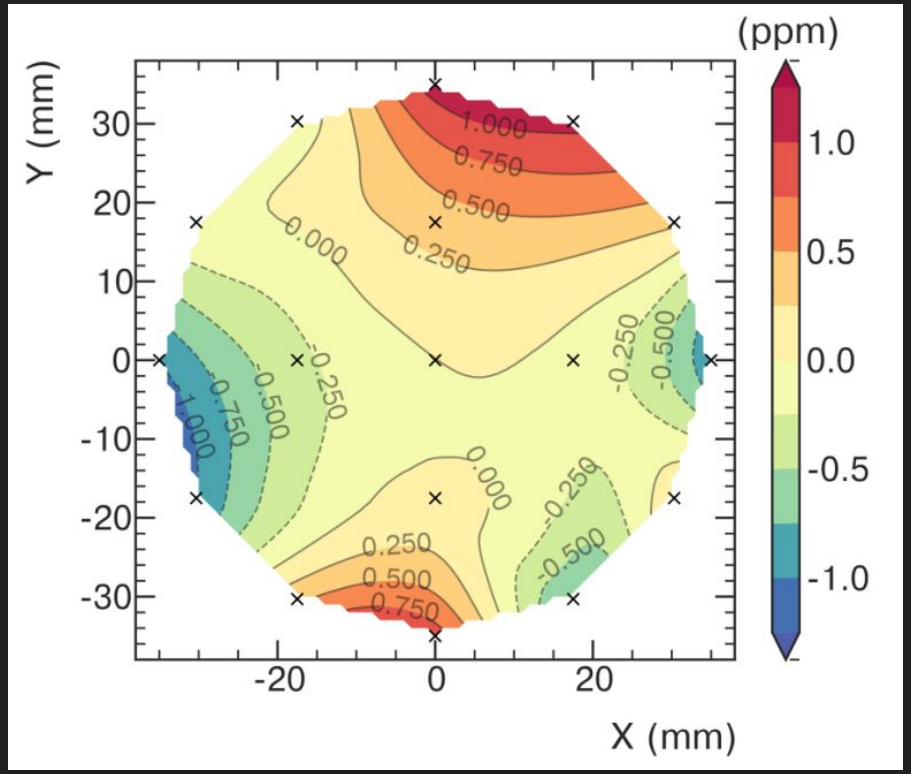
- Desire as uniform magnetic field as possible
- Necessary to measure magnetic field and variations
- “Trolley Runs”



https://journals.aps.org/pra/pdf/10.1103/PhysRevA.103.042208

Magnetic Field Measurement in Muon Occupation Region

- Measure muon region ~ every 3 days to map mag. field
  - “Trolley”
- Field is monitored with NMR probes above/below region

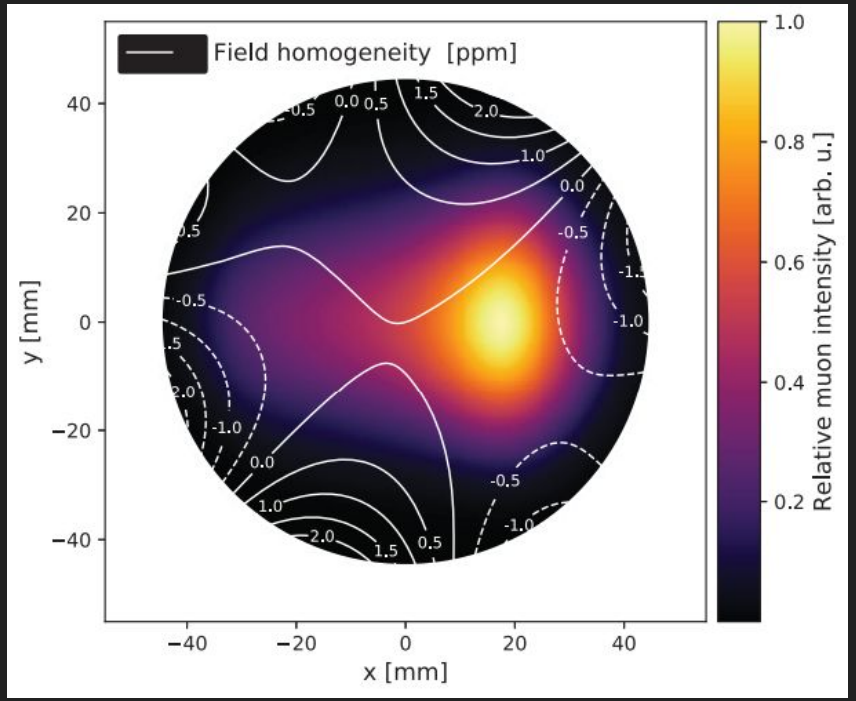


Variations in the azimuthally averaged, relative frequency for the central probe.

https://journals.aps.org/pra/pdf/10.1103/PhysRevA.103.042208

Muon Distribution in the Magnetic Field

- Magnetic field experienced by the muons is put into frequency map
  - determined by frequency map of B
  - weighted with muon distribution

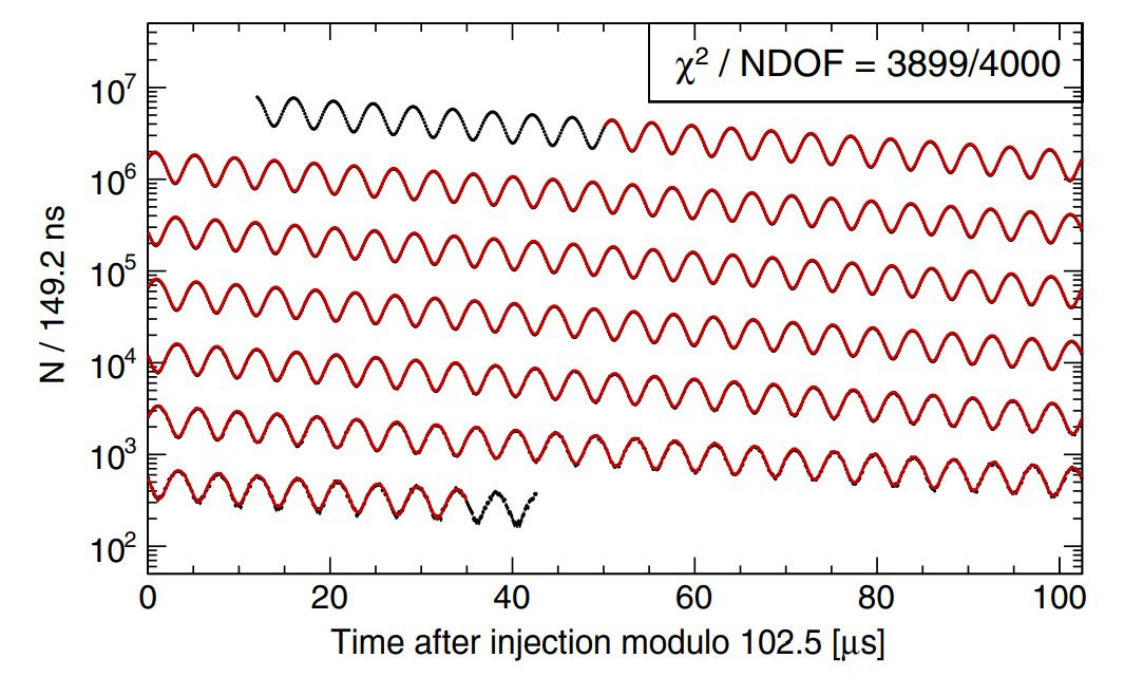


Azimuthally averaged magnetic field contours overlaid on the time and azimuthally averaged muon distribution.

https://arxiv.org/ftp/arxiv/papers/1501/1501.06858.pdf

Measurement of Muon Decay and Associated Anomaly

- Muons' spins precess.
  - $\omega_a = \omega_s - \omega_c$
- Muons decay into positrons in the direction of the spins.
- Positrons emitted into calorimeters varies as $\cos(\omega_a t + \phi)$.
- F.T. for anomalous frequency ω_a.



https://journals.aps.org/prd/pdf/10.1103/PhysRevD.103.072002

Corrections to the Measurement of Anomalous Frequency

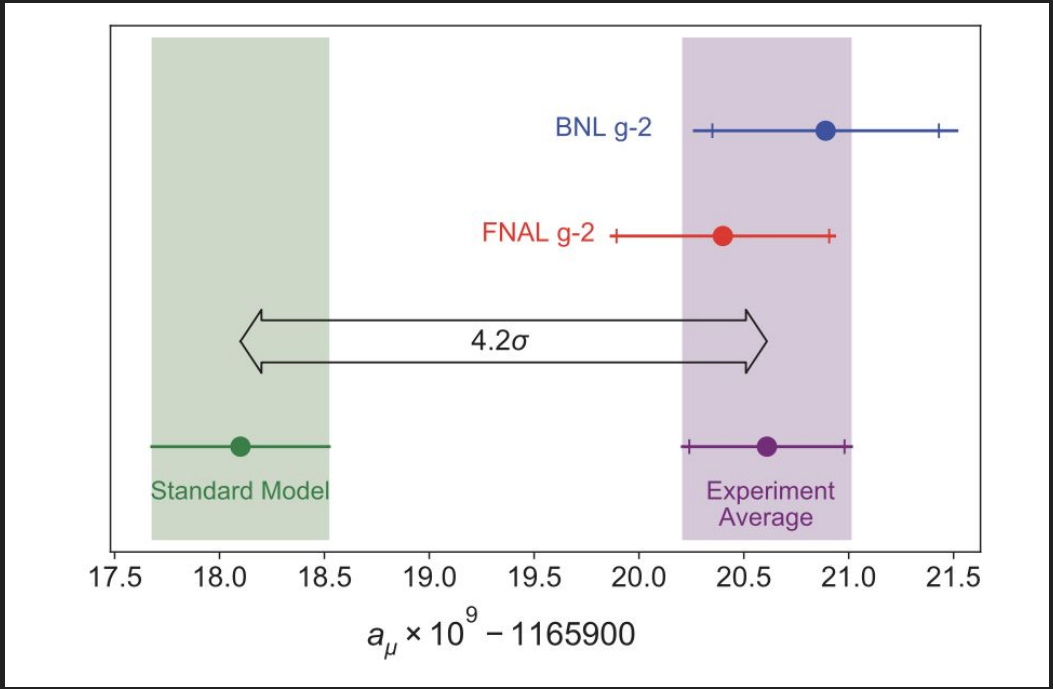
- Corrections to Anomalous Frequency:
  - Electric Field
  - Magnetic Field
- Corrections to Measurement:
  - Electric Field
  - Pitch
  - Lost Muons
  - Phase-Acceptance

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

$$\omega_a \approx \omega_a^m(1 + C_e + C_p + C_{ml} + C_{\mathrm{pa}}).$$

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.103.072002
https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.24.044002

4.2 sigma discrepancy between theory and experiment!



Muon g-2 Theory Initiative standard model calculation compared with experimental average between BNL E821 and the recent Fermilab measurement.

Figure 4 from: https://arxiv.org/abs/2104.03281

Next Steps in Experiment

FNL has more data and is going to release an even more precise result ~2025

Hadronic Vacuum Polarization (HVP) corrections are the biggest remaining source of error

Dispersive method

- Unresolved disagreement about hadron cross section from CMD-3

CERN: MuonE offers a novel (independent!) approach to measure hadronic contributions

https://news.fnal.gov/2023/07/what-does-the-standard-model-predict-for-the-magnetic-moment-of-the-muon/

https://arxiv.org/pdf/1306.4970.pdf

https://www.sciencedirect.com/science/article/pii/S0370269315003573?via%3Dihub

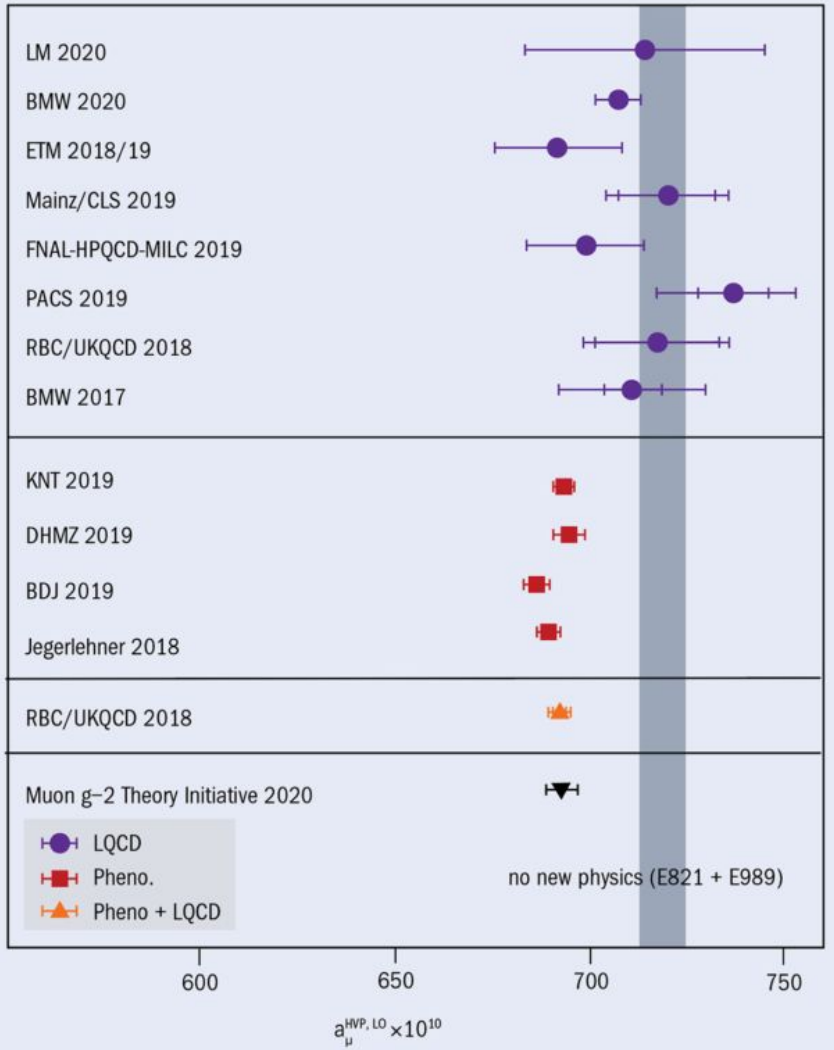
Next Steps in Theory

Lattice QCD: solve equations ab initio, no experimental input

- 2021: BMW collaboration announced significant disagreement with dispersive results
- Yet to be replicated!

https://www.nature.com/articles/s41586-021-03418-1

Figure from: https://cerncourier.com/a/an-anomalous-moment-for-the-muon/#:~:text=It%20is%20defined%20to%20be,radiative%20corrections%20increase%20its%20value



Citation evaluation

- Based on Scopus, the total number of citations of the paper is 951.
- Notable citing papers are:
  - Measurement of the anomalous precession frequency of the muon in the Fermilab Muon g-2 Experiment (PRD, 2021)
  - New physics explanations of aμ in light of the FNAL muon g − 2 measurement (JHEP, 2021)
  - The Forward Physics Facility at the High-Luminosity LHC (Journal of Physics G, 2023)

Sources

https://muon-gm2-theory.illinois.edu/

https://cerncourier.com/a/an-anomalous-moment-for-the-muon/#:~:text=It%20is%20defined%20to%20be,radiative%20corrections%20increase%20its%20value.

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