Overview of Lepton g-2

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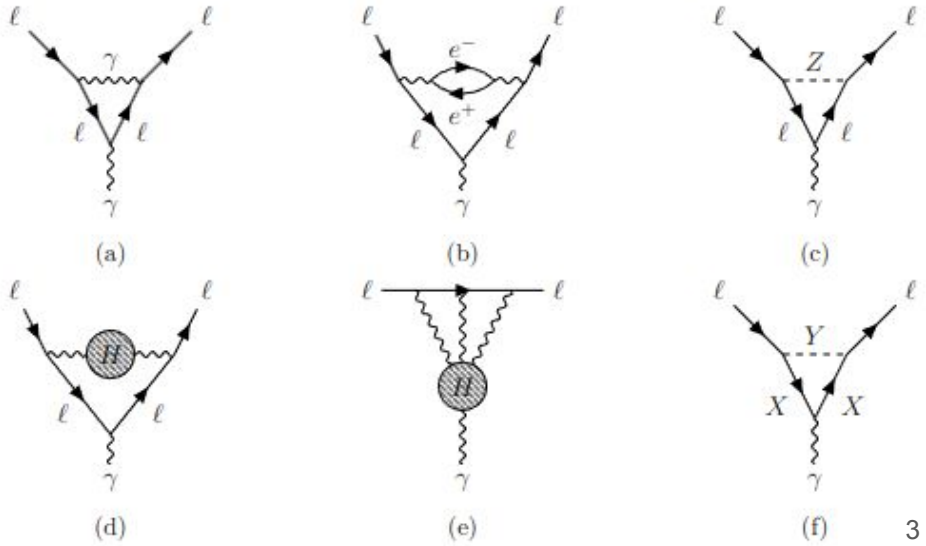
Overview

- What is g-2?
- Why do we care?
- History of g-2
- How it’s measured
- What is going on with muon g-2
- Future of g-2

g-2 Theory

- Spin leads to precession in a magnetic field $\omega_s = g\frac{eB}{2m}$
- Naively, Dirac equation implies g=2
- Loop corrections modify g factor through diagrams like:

a. Schwinger Contribution (on his tombstone)
b. Lowest Order Vacuum Polarization
c. First Order Weak Process
d. Leading Order Hadronic Vacuum Polarization
e. Hadronic Light-by-Light
f. Example BSM Contribution



- Precision g-2 measurement can have a large physics reach
- Need to get a lot of things right
- Usually talk about $a = \frac{g-2}{2}$

Electron g-2

- Low electron mass limits contribution from non-electroweak processes
- Calculated analytically to α^3, calculated to α^5
- Theory and experiment agree to 10 sig figs
- Most precisely verified prediction in physics
- Measured using a single electron in a Penning trap (2022)

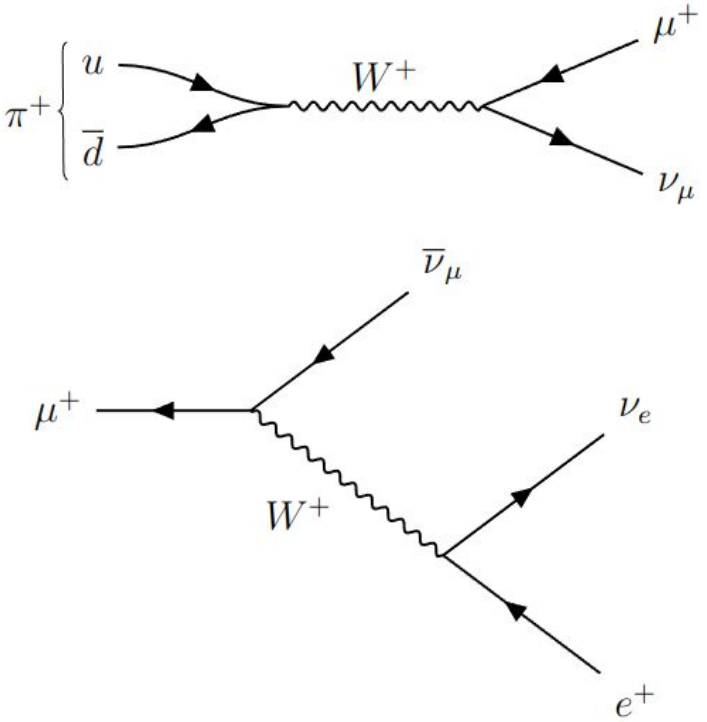
https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.130.071801

History of Muon g-2

- First measurements at CERN in the 1950s using SynchroCyclotron
  - Early evidence that muon is a lepton and validation of EW theory
  - Measured to within 0.4% at SC
  - Measured to within 0.0007% at PS
  - PS measurements revealed error in SM calculations
- First hints of tension at E821 at BNL
  - 14-fold improvement over CERN results showed ~2.5σ deviation from theory
- Tension remains in Fermilab Muon g-2 Results
  - First results published in 2021 showed 4.2σ deviation from 2020 theory calculation
  - Subsequent runs increase discrepancy to 5.1σ from 2020 theory results
  - Data taking complete and final result expected in 2025
  - Lattice calculations agree with experiment to within ~1σ

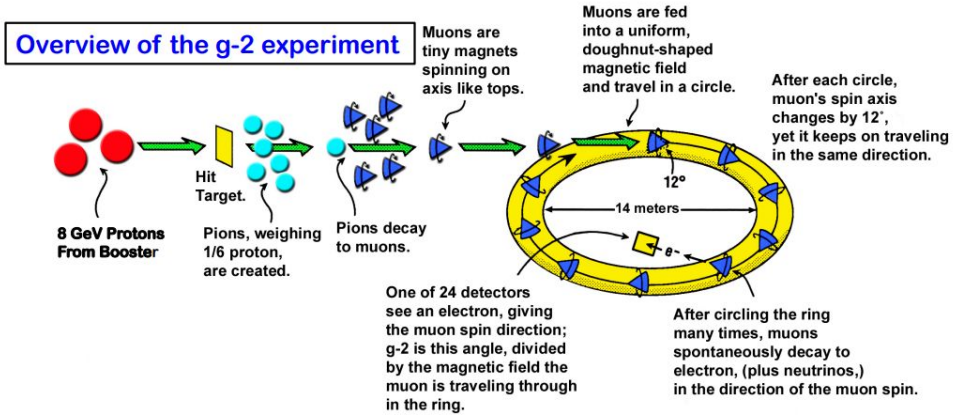
How muon g-2 is measured

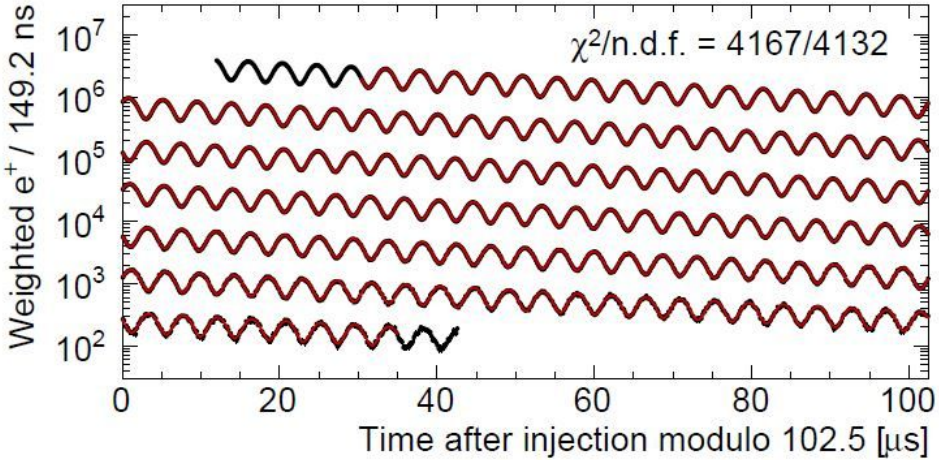
- Take advantage of parity violation in weak interactions to get polarized muon beam
- Muons precess in magnetic field of storage ring
- Electron resulting from muon decay boosted in direction of muon spin
- Electron orbit decays and is measured in calorimeters and trackers



How muon g-2 is measured

- Direction of electron boost changes as muons precess
- Gives ‘wiggle plot’ which is fit to extract the muon g factor





A Fun Detail

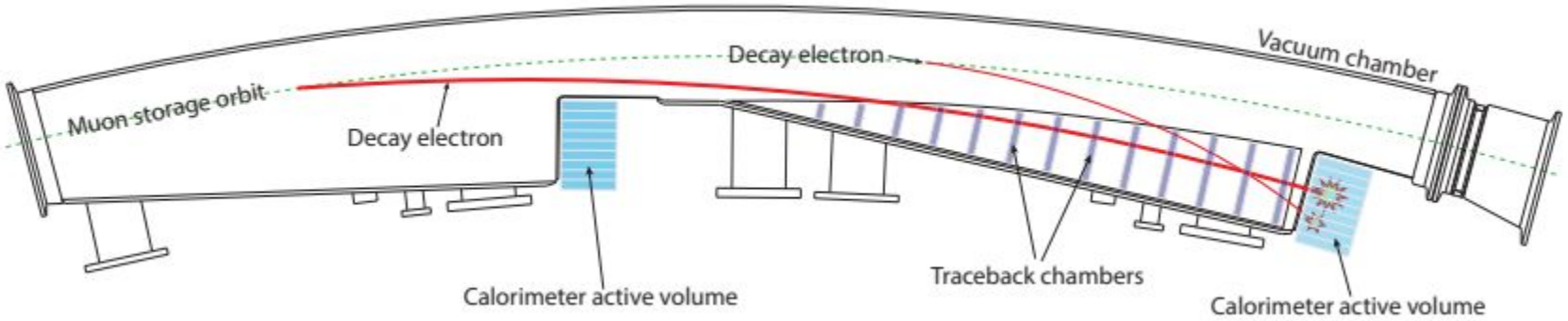
- Focusing a challenge where uniform magnetic field is a high priority
- Relativistic effects modify spin precession frequency

$$\vec{\omega_a} = -\frac{Qe}{m}\left[a_\mu \vec{B} - \left(a_\mu - \left(\frac{mc}{p}\right)^2\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

- At ‘magic momentum’ of ~3.09 GeV, electric field component cancels to first order
- Electric quadrupoles are used for focusing

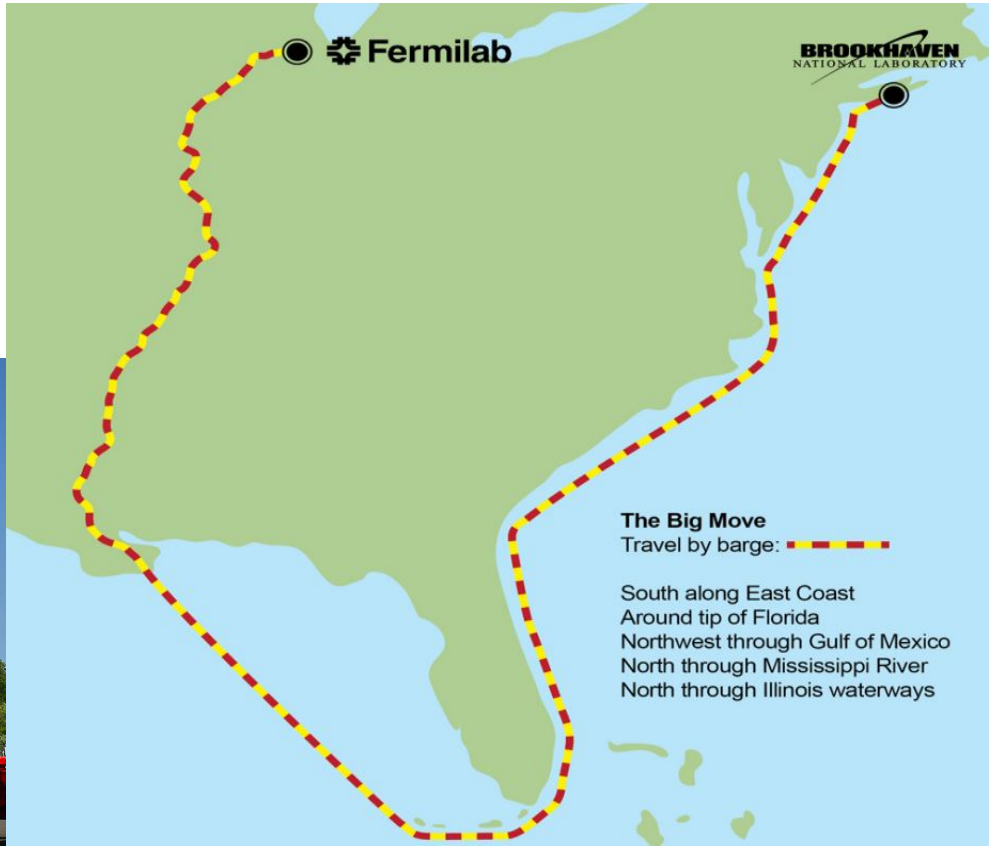
Fermilab g-2 Specifics

- More intense muon beam needs pileup reduction
- Fermilab experiment used tracking and segmented calorimeters to reduce pileup



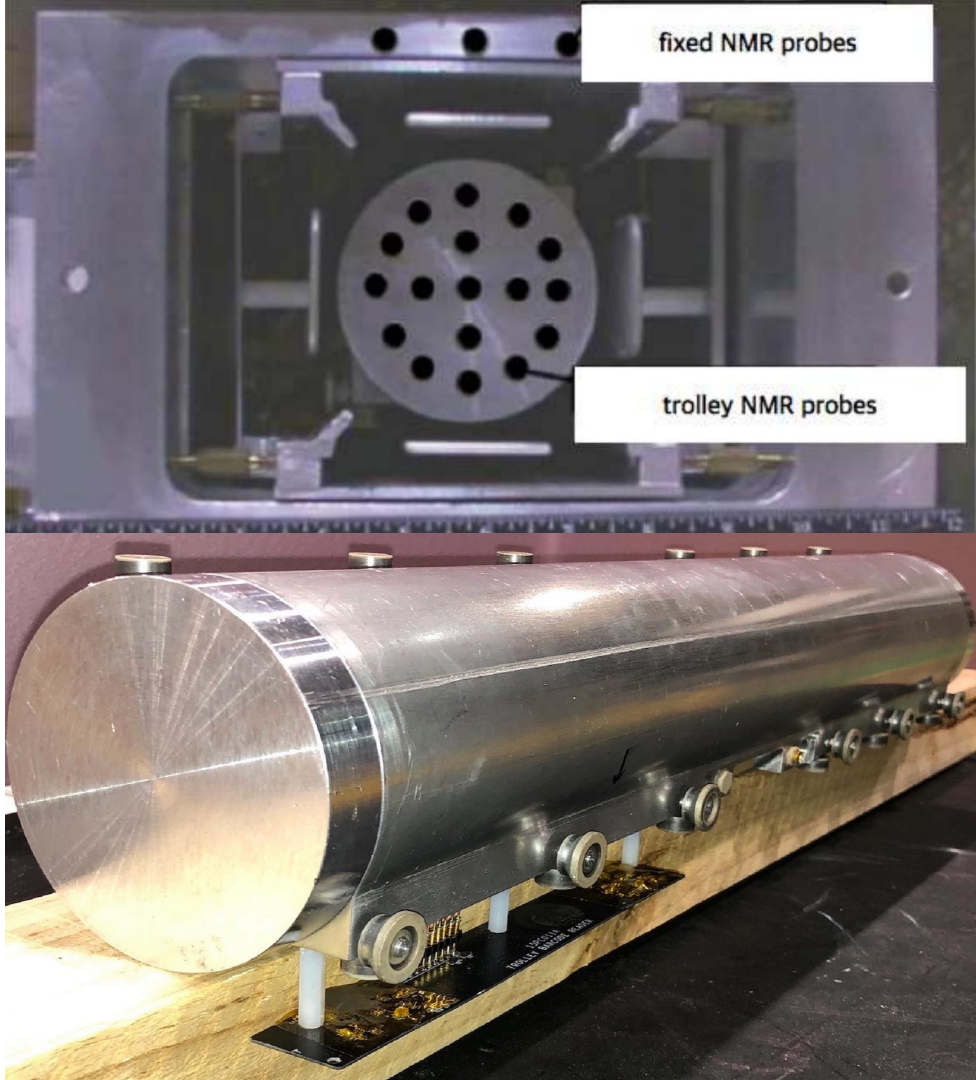
Fermilab g-2 Specifics

- Reused storage ring from E821
- Transported by barge from Long Island, around Florida, up the Mississippi, then eventually via road to Fermilab



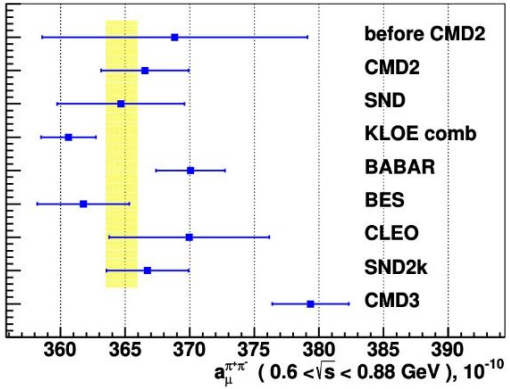
Fermilab g-2 Specifics

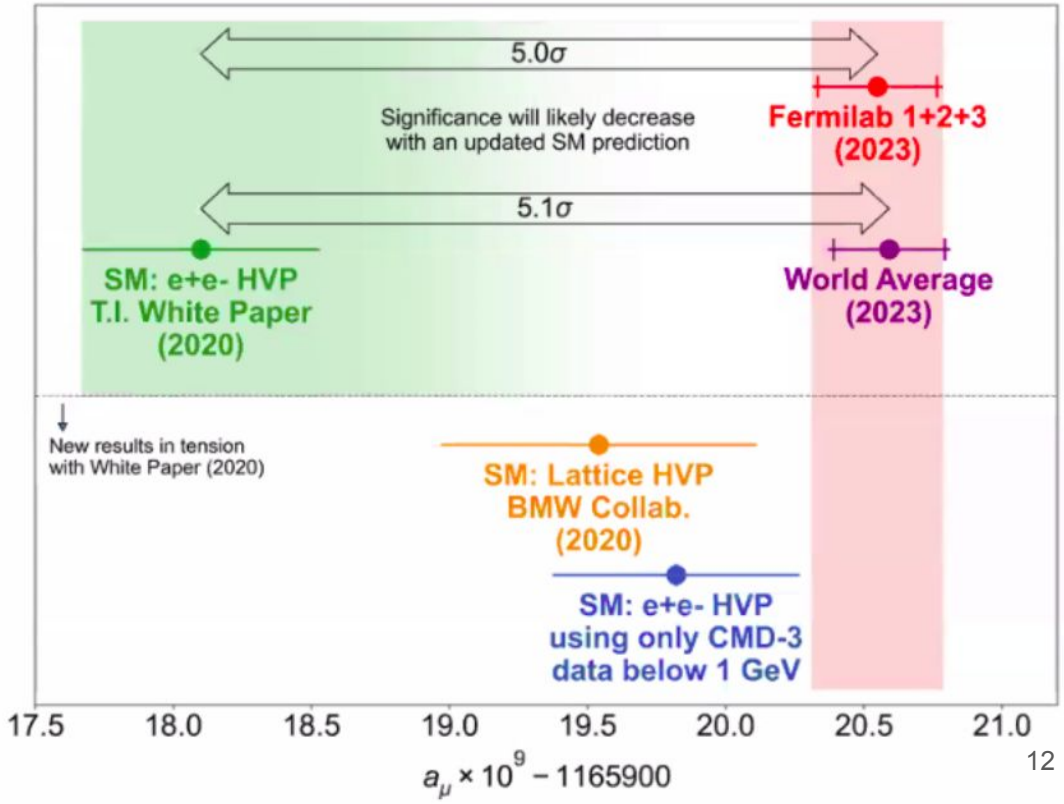
- Heavily modified BNL magnet by hand to increase field uniformity
- ‘NMR Trolley’ runs around ring occasionally to measure field
- Returns to a garage out of beamline so vacuum is maintained
- Allows much better understanding of magnetic field systematics



g-2 Theory Results

- Significant tension between various theory predictions
- Mainly due to different HVP calculation methods
- Data driven hadronic contributions used in 2020 theory paper
- New Novosibirsk result eliminates tension, but is in tension with other measurements





Conclusion

- Lepton g-2 an interesting, broad probe for new physics
- Clever measurement techniques allow very high precision
- Muon g-2 shows a longstanding tension with the Standard Model…Or does it?
- Theory predictions very difficult, and are a bit of a mess
- Interesting case where next round of theory results are now more exciting than next generation of experiments
- Tau g-2 is hard to measure because of short lifetime and agrees with theory