Muon g-2 Experiment at FNAL - Here to Where

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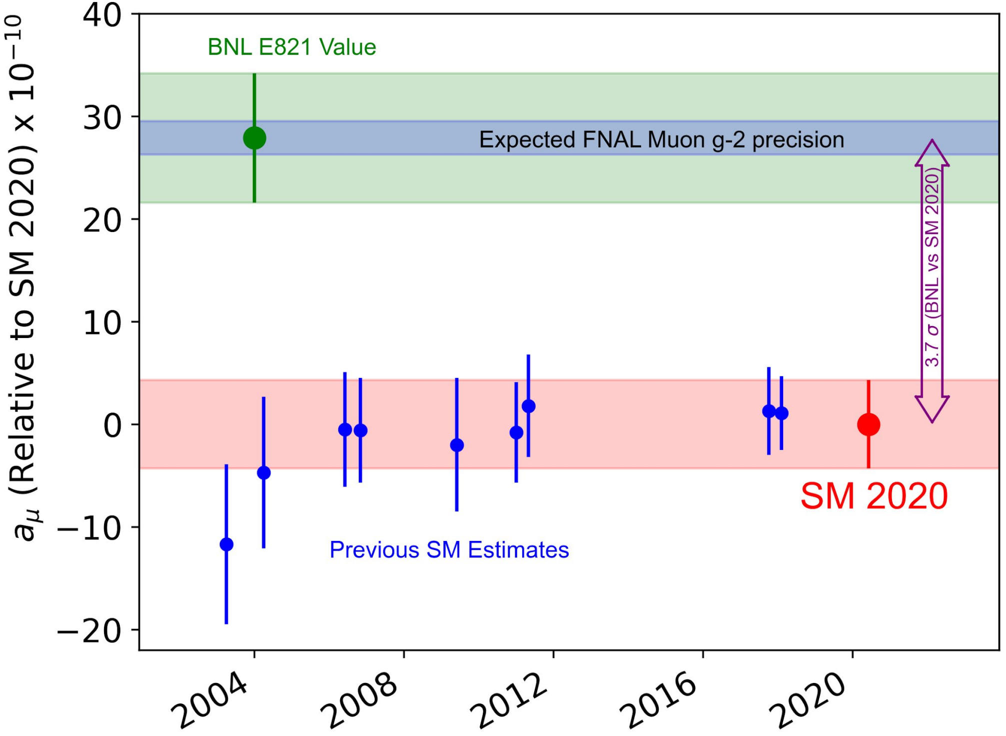
THE UNIVERSITY OF MISSISSIPPI

a_μ measured to 540 ppb at BNL



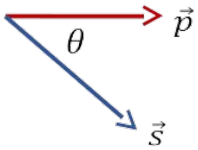
$$a_\mu^{exp} - a_\mu^{SM} = (27.9 \pm 7.6) \times 10^{-10}$$

$$a_\mu = \frac{g_\mu - 2}{2}, \ \vec{\mu} = (1 + a_\mu)\frac{e}{m}\vec{s}$$

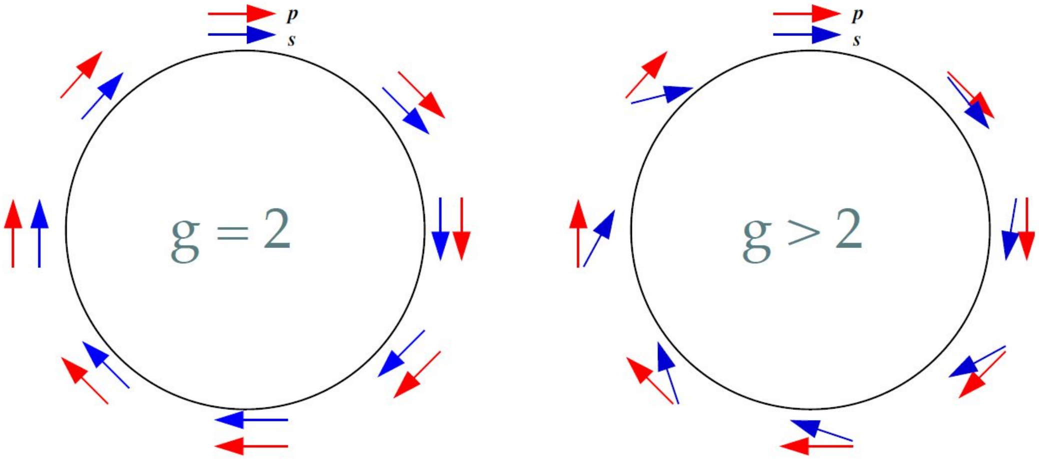
- ~ 3.7σ discrepancy b/w BNL measurement & SM prediction
- 540 ppb(BNL) → 140 ppb (**FNAL goal**)
- SM uncertainty dominated by hadronic contributions

Measurement of a_μ

- Anomalous precession frequency: $\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{m_\mu c}$ (Ideally)
- Magnetic field: $2\hbar\omega_{p'} = 2\mu_{p'}|B|$



$$\omega_a = \dot{\theta}$$



Measured experimentally

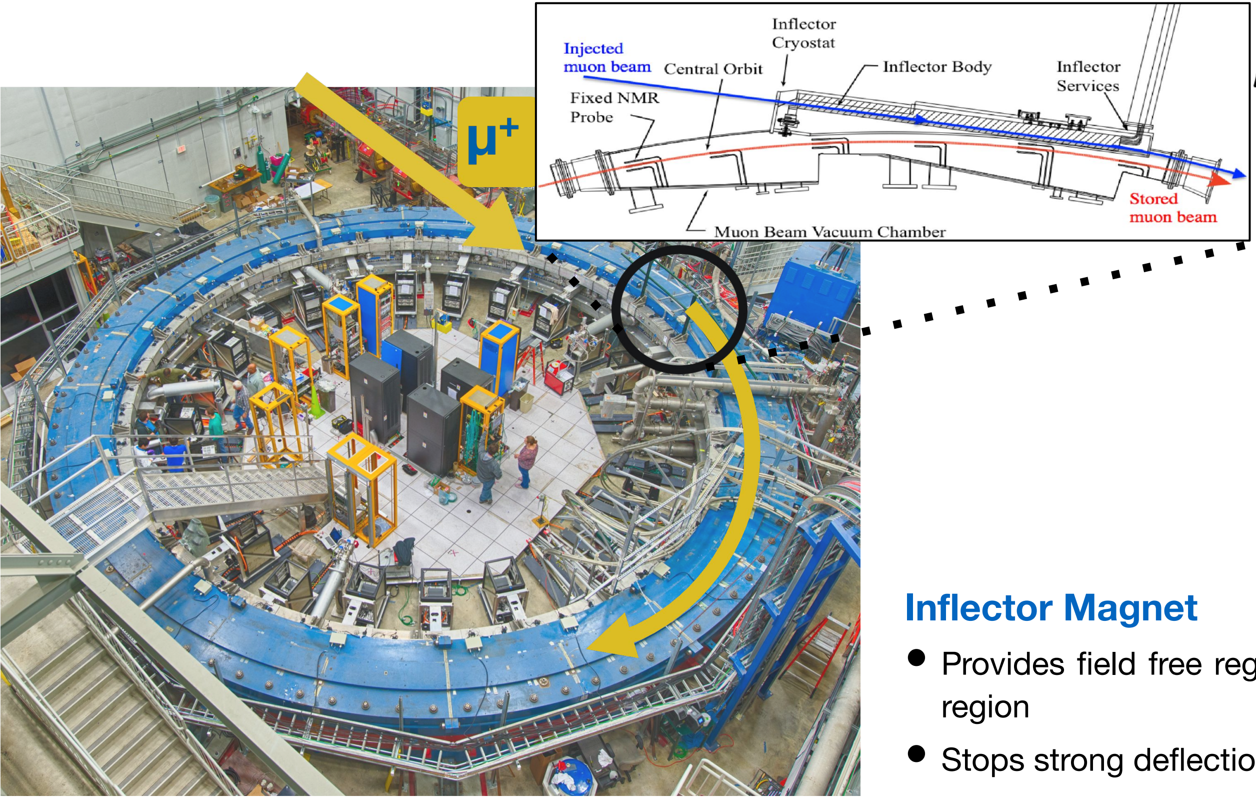
$$a_\mu = \frac{\omega_a}{\tilde{\omega}_{p'}} \frac{\mu_{p'}}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

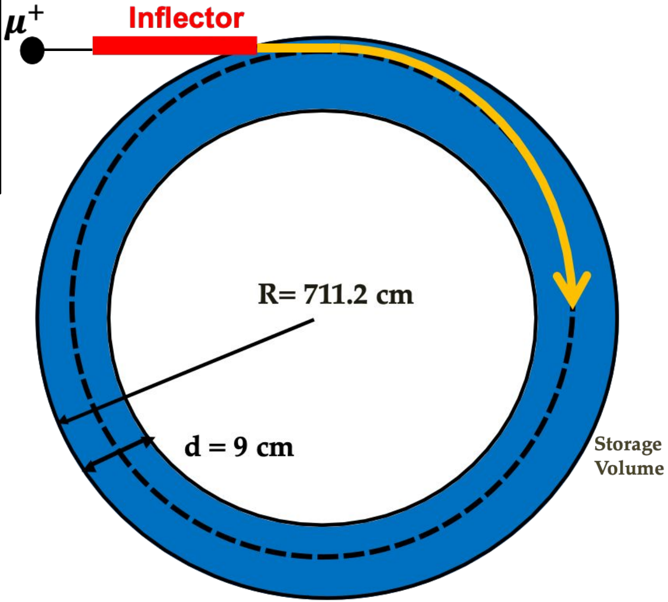
10.5 ppb Hydrogen Maser

22 ppb Muonium

0.26 ppt Electron g-2/QCD

Muon Beam Injection

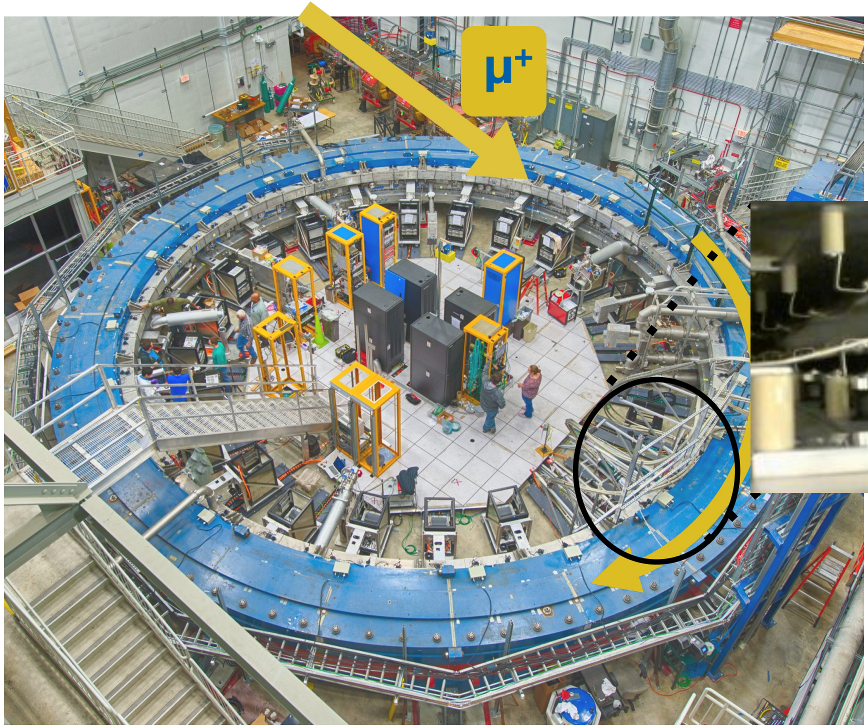


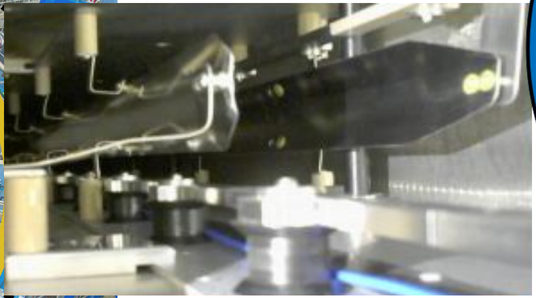


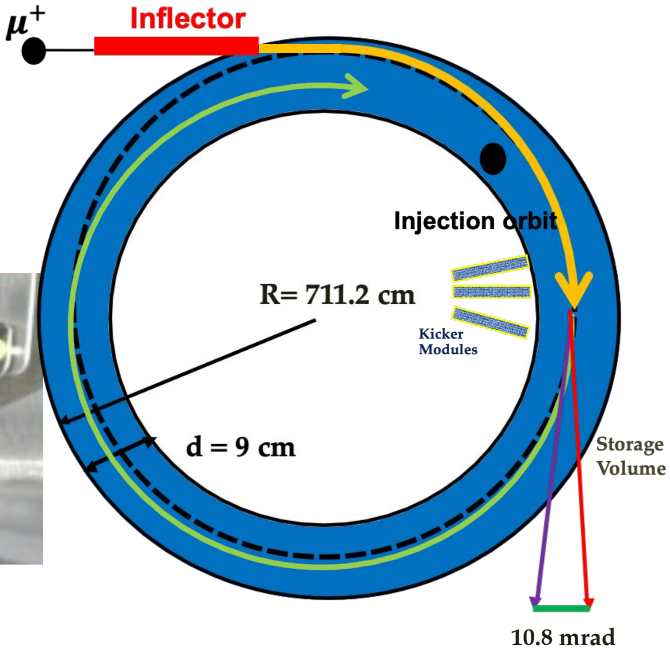
Inflector Magnet

- Provides field free region to deliver beam to edge of storage region
- Stops strong deflection of the beam
- Incident beam center 77mm off from storage region center

Storing the Muons



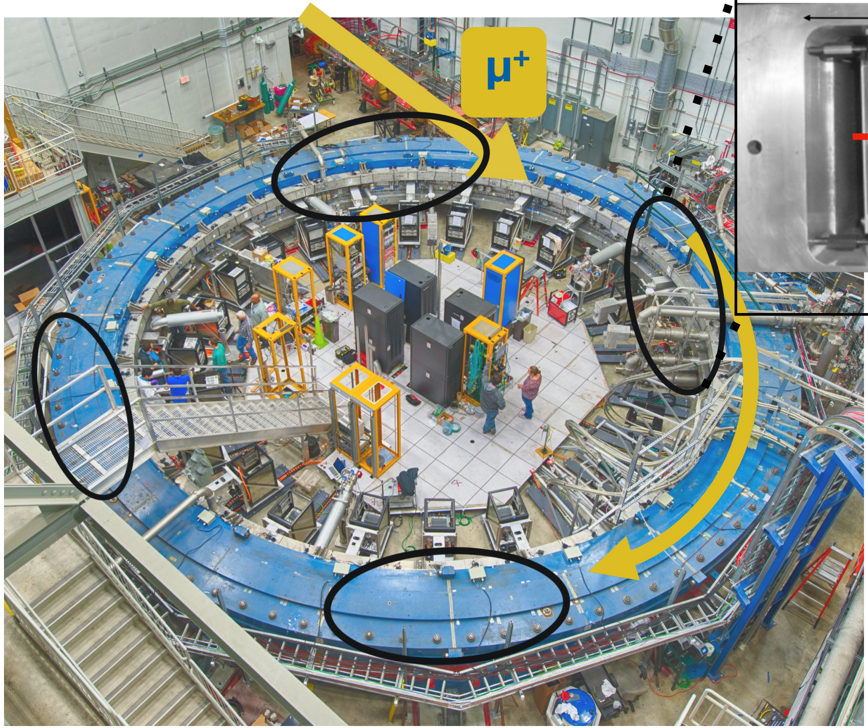


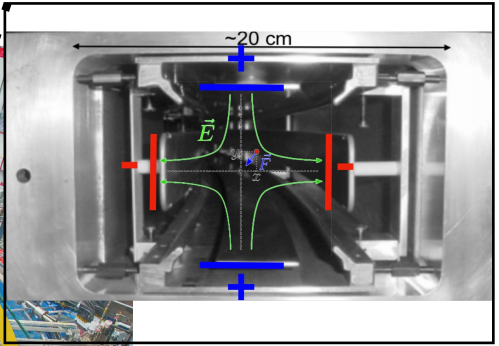


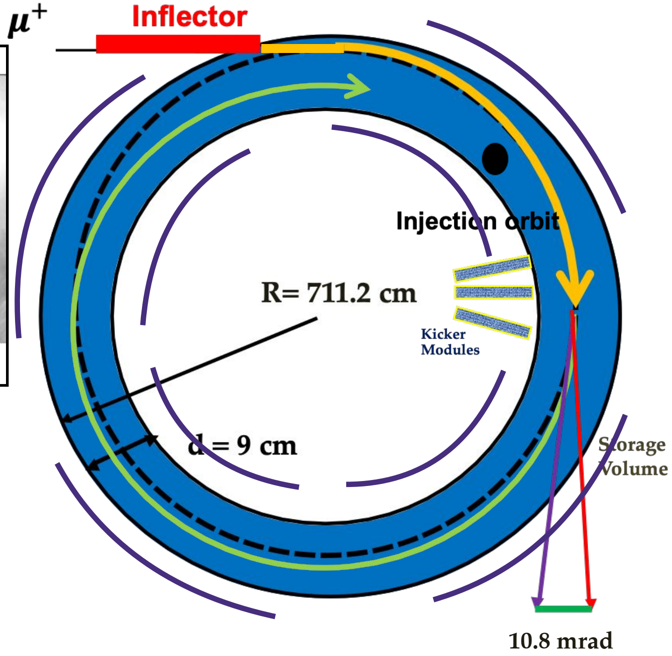
3 Kicker Magnets

- Provide 10.8 mrad “kick” to direct muons into ideal orbit (< 149 ns)

Focusing the Muon Beam







Electrostatic Quadrupoles

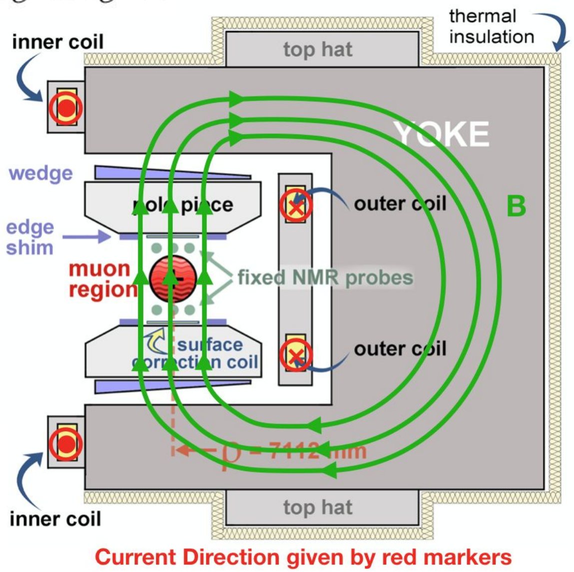
- Focuses muon beam vertically

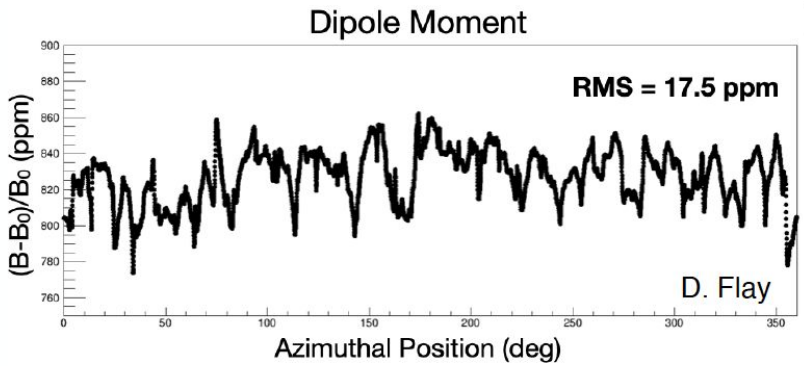
Muon Beam Storage and Focusing

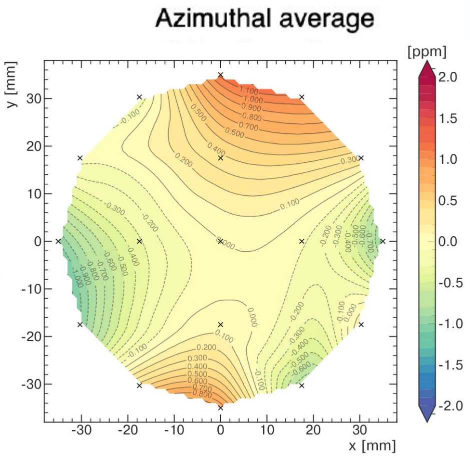
$$a_\mu = \frac{\omega_a}{\tilde{\omega}_{p'}} \frac{\mu_{p'}}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

Storage Ring Magnetic Field :

- Needed for physics measurement (determine at all times)
- Provides radial confinement
- Pulsed NMR of protons: $2\hbar\omega_{p'} = 2\mu_{p'}|B|$

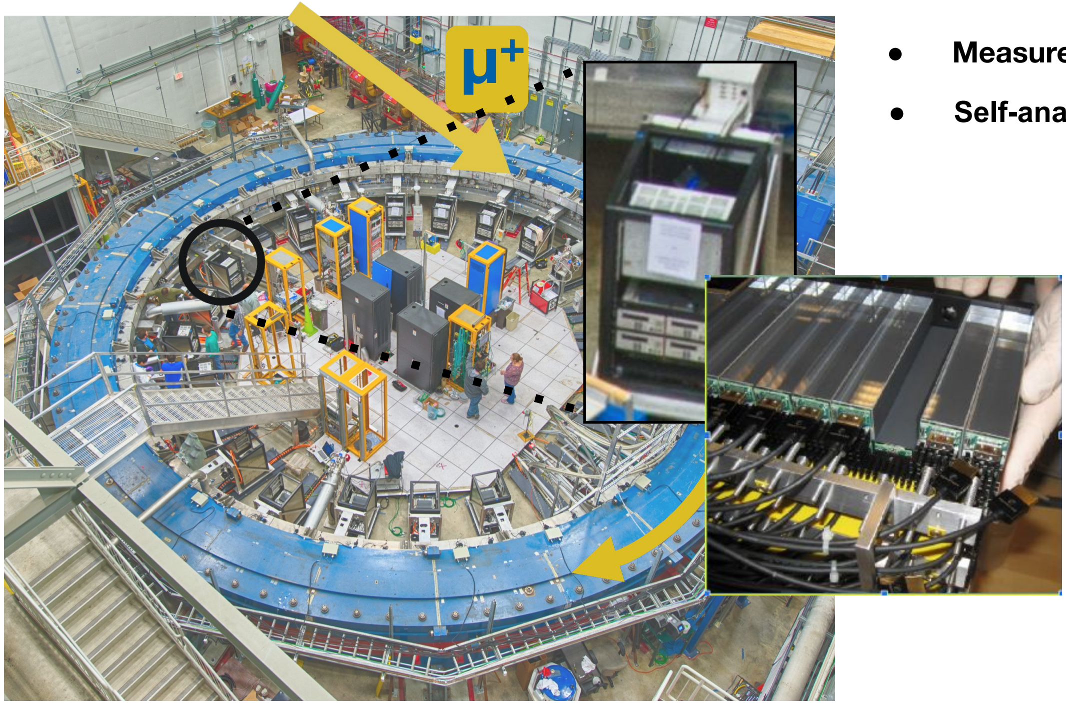




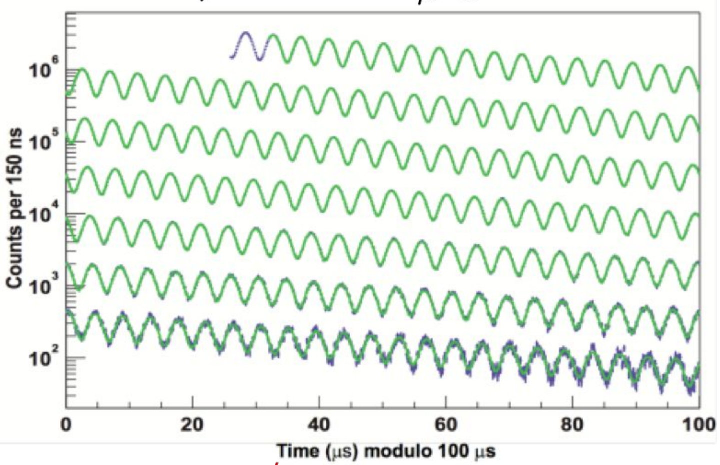


Fermilab

Muon Spin Precession (ω_a) in g-2 Ring



- **24 Calorimeters with 54 Cherenkov PbF_2 crystals with very fast SiPMs stationed around the ring**
- **Measure arrival time & energy of the decay e^+**
- **Self-analyzing decay:** $\mu^+ \longrightarrow e^+ \bar{\nu}_\mu \nu_e$

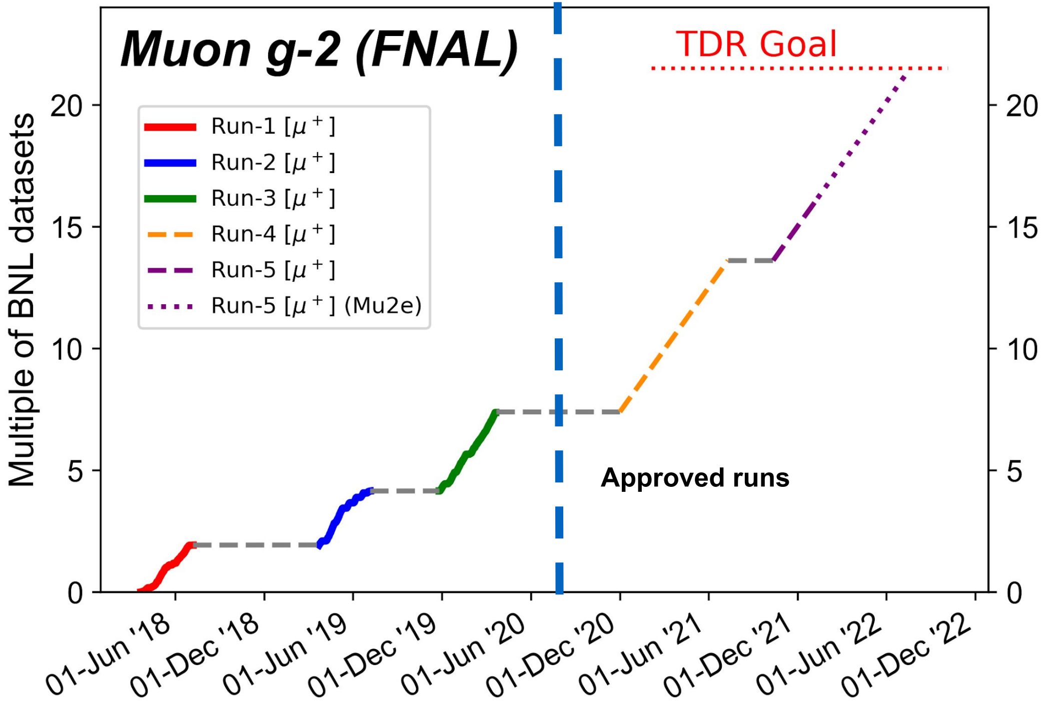


$$N(t) = N_0 e^{-t/\tau_\mu}[1 + A\cos(\omega_a t + \phi)]$$

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_{p'}} \frac{\mu_{p'}}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

Fermilab

The experiment has completed 3 data runs

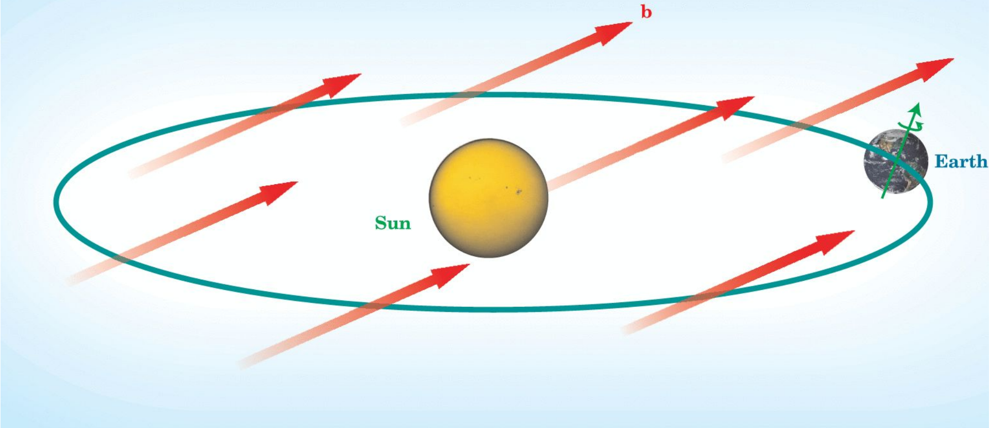


- ~8X BNL statistics as of Run 3
- ~18.5X BNL - goal to achieve the projected precision
- 1st publication soon!
- Short to mid time scale **-** more μ^+ stats. and CPT LV tests
- Future options(**post Run-5**) - measurement of Muon g-2 using a μ^- beam
  - additional tests of CPT and Lorentz invariance

CPT and Lorentz Violation (LV)

Existence of a preferred direction, Uniform constant vector, ***b*** ➡ **Lorentz Violation**

Presence of b in vacuum changes the behavior and properties of particles and antiparticles



In a Lab on the Earth's surface, measurements change as the Earth rotates, as the orientation changes relative to b, leading to a cyclic variation in the measurement over a sidereal day.

Standard Model Extension(SME) and CPT LV for Muon :

- For the muon, SME lagrangian:

$$\mathcal{L}' = -a_\kappa \overline{\psi}\gamma^\kappa\psi - b_\kappa \overline{\psi}\gamma_5\gamma^\kappa\psi - \frac{1}{2}H_{\kappa\lambda}\overline{\psi}\sigma^{\kappa\lambda}\psi + \frac{1}{2}ic_{\kappa\lambda}\overline{\psi}\gamma^\kappa \overleftrightarrow{D}^\lambda\psi + \frac{1}{2}id_{\kappa\lambda}\overline{\psi}\gamma_5\gamma^\kappa \overleftrightarrow{D}^\lambda\psi$$

- All terms violate Lorentz symmetry
- a_κ, b_κ terms are CPT-odd, all others are CPT-even

b_κ ⟶ **Can be determined by Muon g-2 experiment**

CPTLV Signals with Muon g-2 experiment at Fermilab

CPT LV Signatures

Current

Sidereal Oscillation in $\mathcal{R}(=\omega_a/\tilde{\omega}_{p'})$

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_{p'}}\frac{\mu_{p'}}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

Measured experimentally

- **Spectral analysis on a run-by-run basis**
- **Multi-parameter fit (run ~ 1 hour of data collection)**

$$b_\perp^{\mu^\pm} = \frac{\hat{\omega}_a^{\mu^\pm}}{2|sin\chi|} < 1.4\times10^{-24}\text{GeV}$$

(BNL limit)

Future prospects

$$\Delta\omega_a \equiv < \omega_a^{\mu^+} > - < \omega_a^{\mu^-} >$$

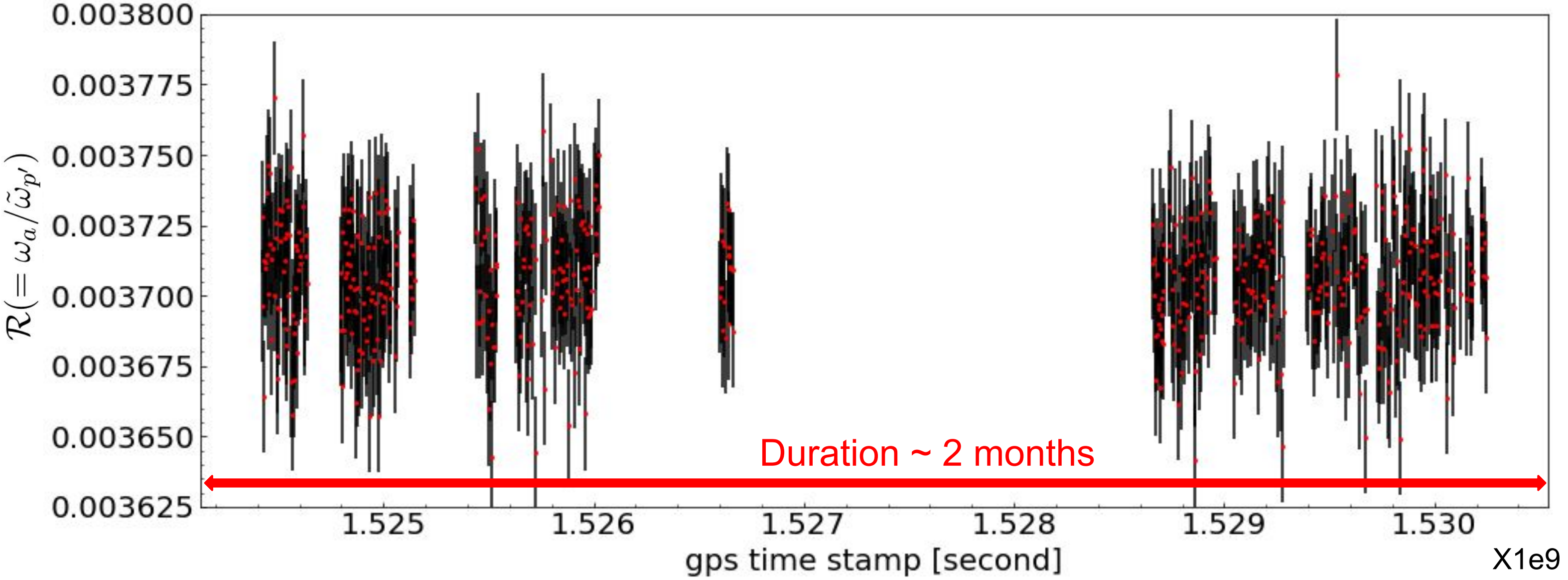
Currently only μ^+ data for Fermilab Muon g-2 experiment

$$\Delta\omega_a = \frac{4b_Z}{\gamma}cos\chi$$

CPT LV Test : (Sidereal Search)

Simulated Data :
All plots shown here are simulated data based on the average $\mathcal{R}$ = 0.0037072083 ($\delta\mathcal{R}$ = 20 ppm) [2001, BNL results]

Ingredient : $\mathcal{R}(=\omega_a/\tilde{\omega}_{p'})$ on a run-by-run basis along with the GPS timestamps



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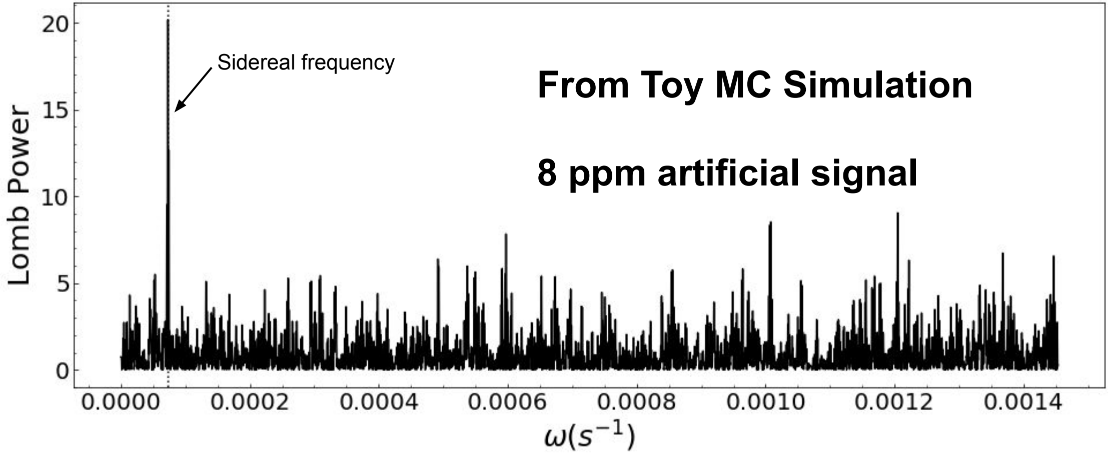
Lomb-Scargle Test :

- Scan frequencies, calculate Spectral Power $P_N(\omega)$ at each ω
- $P_N(\omega)$ is a measure of the statistical significance, or likelihood, of a signal at a given frequency
- Higher $P_N(\omega) \rightarrow$ more significant periodic signal at ω



From Toy MC Simulation

8 ppm artificial signal

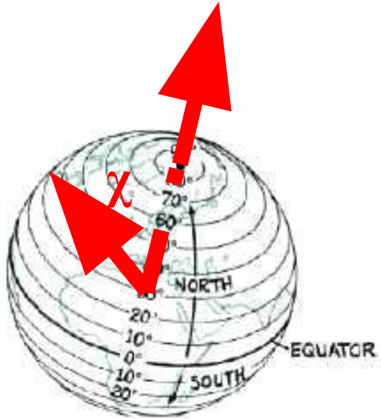
CPTLV: μ^+/μ^- ω_a Difference

$$\Delta\omega_a \equiv < \omega_a^{\mu^+} > - < \omega_a^{\mu^-} > = \frac{4b_Z}{\gamma} cos\chi$$

- the magnetic field can vary, when comparing frequencies, instead of ω_a, use $\mathcal{R}(= \omega_a/\omega_p)$
- BNL E821 Results (2008) :

$$\Delta\mathcal{R} = -(3.6 \pm 3.7) \times 10^{-9}$$

$$b_Z = -(1.0 \pm 1.1) \times 10^{-23}\ \text{GeV}$$



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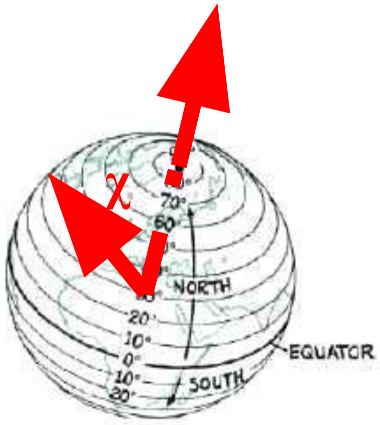
CPTLV: μ^+/μ^- ω_a Difference

$$\mathcal{L}' = -a_\kappa \overline{\psi}\gamma^\kappa\psi - b_\kappa\overline{\psi}\gamma_5\gamma^\kappa\psi - \frac{1}{2}H_{\kappa\lambda}\overline{\psi}\sigma^{\kappa\lambda}\psi + \frac{1}{2}ic_{\kappa\lambda}\overline{\psi}\gamma^\kappa \overleftrightarrow{D}^\lambda\psi + \frac{1}{2}id_{\kappa\lambda}\overline{\psi}\gamma_5\gamma^\kappa \overleftrightarrow{D}^\lambda\psi$$

- For two experiments at different colatitude:
  - BNL & CERN, FNAL & BNL , **JPARC & FNAL**

$$\Delta\mathcal{R} = \frac{2b_Z}{\gamma}\left(\frac{cos\chi_1}{\omega_{p1}} + \frac{cos\chi_2}{\omega_{p2}}\right) + 2(m_\mu d_{Z0} + H_{XY})\left(\frac{cos\chi_1}{\omega_{p1}} - \frac{cos\chi_2}{\omega_{p2}}\right)$$

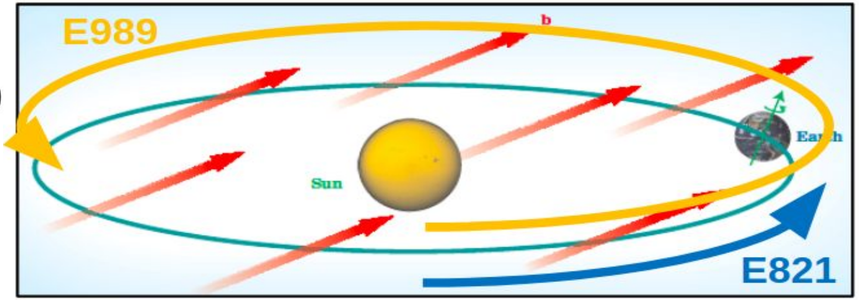
$$(m_\mu d_{Z0} + H_{XY}) = (1.6 \pm 5.6 \times 10^{-23})\ \text{GeV}$$



Prospects

Sidereal Measurement

- Fermilab Muon g-2 experiment (E989) aims X4 improvement of limits on CPT/LV parameters
  - sensitivity to sidereal variation should be $\sim 5 \times 10^{-25}$ GeV
  - Can use Fourier Transform after binning the data in equally spaced time periods as all the events are time stamped
- First search for **annual variation** in $\mathcal{R}(=\omega_a/\tilde{\omega}_{p'})$ will be made using E989 data

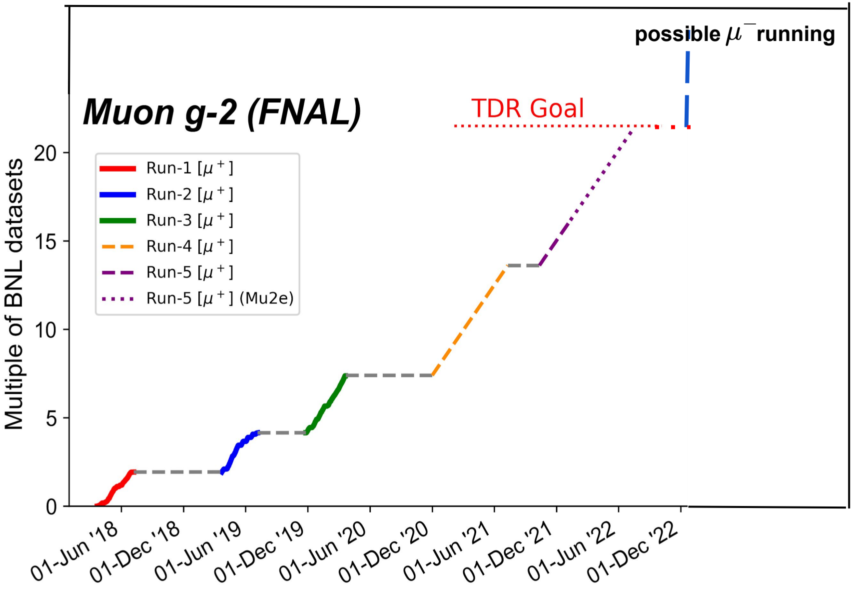


Prospects

μ^+/μ^- Differences

$$\mathcal{L}' = -a_\kappa \overline{\psi}\gamma^\kappa\psi - b_\kappa\overline{\psi}\gamma_5\gamma^\kappa\psi - \frac{1}{2}H_{\kappa\lambda}\overline{\psi}\sigma^{\kappa\lambda}\psi + \frac{1}{2}ic_{\kappa\lambda}\overline{\psi}\gamma^\kappa \overleftrightarrow{D}^\lambda\psi + \frac{1}{2}id_{\kappa\lambda}\overline{\psi}\gamma_5\gamma^\kappa\overleftrightarrow{D}^\lambda\psi$$

- μ^- run opens door to a whole new set of CPT LV measurements - the only opportunity in the coming decade
- no sensitivity to **Z**-component of b without μ^-
- no sensitivity to ***d*** and ***H*** coefficients
  - possibility of a factor of 20 better - comparing FNAL-BNL instead of CERN-BNL
- Full μ^+ stats - top priority!



Possible future μ^- runs

- **2-3X improvement on BNL μ^- g-2 measurement with ~1 year of FNAL μ^- running**

Experimental Modifications for μ^- running at FNAL :

- Coordination with Mu2e
  - unable to run simultaneously

- Technical challenges:
  - Invert magnet polarities (switch leads)
    - Beam line
    - Main magnet
    - Inflector
    - Kicker
  - Improve vacuum quality
    - More negative charge build up $\longrightarrow$ additional pump system (infrastructure exists)
  - Kickers - Invert the kicker leads to change the polarity of the kick - at full voltage

- ~2.5 less flux compared to μ^+ running due to reduced production rates of π^- compared to π^+
  \- **6X BNL μ^- data sample with ~1 year of running at Fermilab**

Summary :

- The **only** opportunity to measure a_μ with the Muon g-2 experiment at FNAL using μ^- beam in the coming decades
  - JPARC only uses μ^+ beam

- Not just one measurement of CPTLV, sensitive to at least 3 CPTLV coefficients
  - $b_\perp^{\mu^\pm}$ ⟶ FNAL μ^+ data
  - b_Z ⟶ FNAL $\mu^\pm$ data
  - $(m_\mu d_{Z0} + H_{XY})$ ⟶ JPARC μ^+ and FNAL μ^-

- Repurpose what we already have and make the most out of JPARC and FNAL g-2 experiments

Cross links with other frontiers :

- Muon g-2 Theory initiative - https://muon-gm2-theory.illinois.edu/

- Energy/ Accelerator -
  - discovery at Muon g-2 (μ^+ or μ^-) strongly motivates the muon collider (Capdevilla et. al)
- Cosmic -
  - Interesting models to look for DM in existing g-2 data (Janish, Ramani)

Thanks to the organizers for the virtual EDM/MDM Workshop!