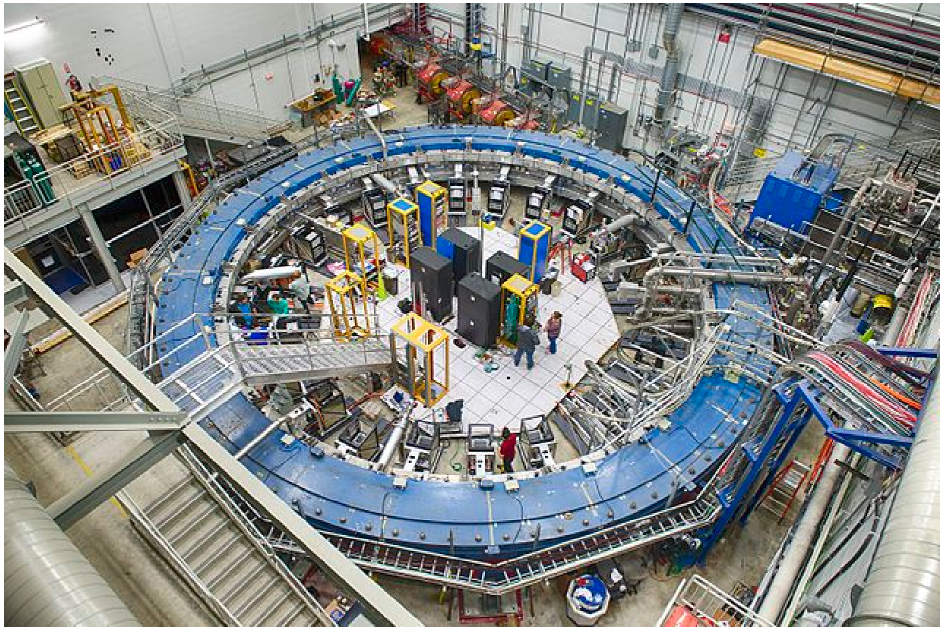
The Muon g-2 Experiment



Jenny Holzbauer
September 27, 2017

Overview

- Motivation and some history
  - Comment on theory and its inputs
- Moving from BNL to Fermilab
- The planned measurement
  - Experiment setup
  - Measurement strategy
- Field and ring installation
- Experiment status
- Short review of analysis work for other experiments

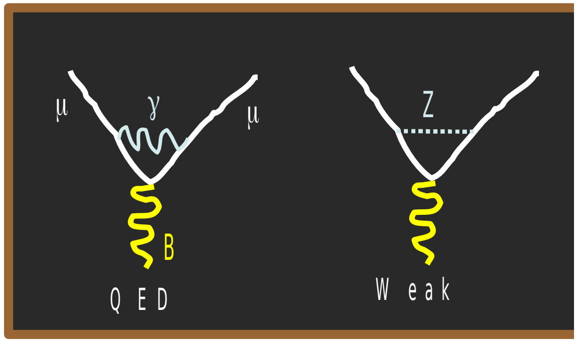
Why Muon g-2?

- g relates spin and magnetic moment
- Exactly 2 in Dirac theory
  - Higher order effects create contributions leading to values > 2
  - New physics could cause further deviations of this value
- Study the anomalous part, **a_μ**=(g-2)/2
- Muons used because mass is higher than electrons, giving ~43,000 increased sensitivity (and live much longer than taus)

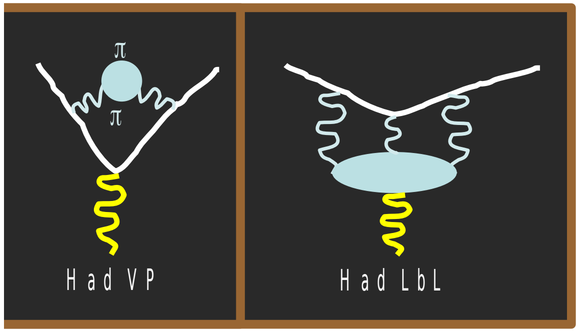
$$\vec{\mu} = g\frac{Qe}{2m}\vec{s}$$

Theory: Components

- Theorists calculating various terms that make g > 2, and uncertainties are comparable with experimental
  - Improved calculations, methods and data inputs to these terms are very important to reduce the uncertainty
- QED and weak terms are well known, but hadronic terms are less understood
- Hadronic vacuum polarization is studied with e+e- to hadrons data from various experiments and hadronic light by light is estimated with calculations, lattice and indirect data constraints



Known well beyond current experimental precision



Known slightly better than current experimental precision - needs work

E821 (BNL) Results

	Value (x 10^{-11})
QED	116 584 718.951 ± 0.009 ± 0.019 ± 0.007 ± 0.077
HVP (lo)	6949 ± 42
HVP (ho)	-98.4 ± 0.7
HLBL	105 ± 26
EQ	154 ± 1
Total SM	116 591 802 ± 49

$$\boxed{a_\mu^{Expt.} - a_\mu^{SM} = (260 \pm 78) \times 10^{-11} \quad (3.3\,\sigma)}$$

*Values from TDR, 2015

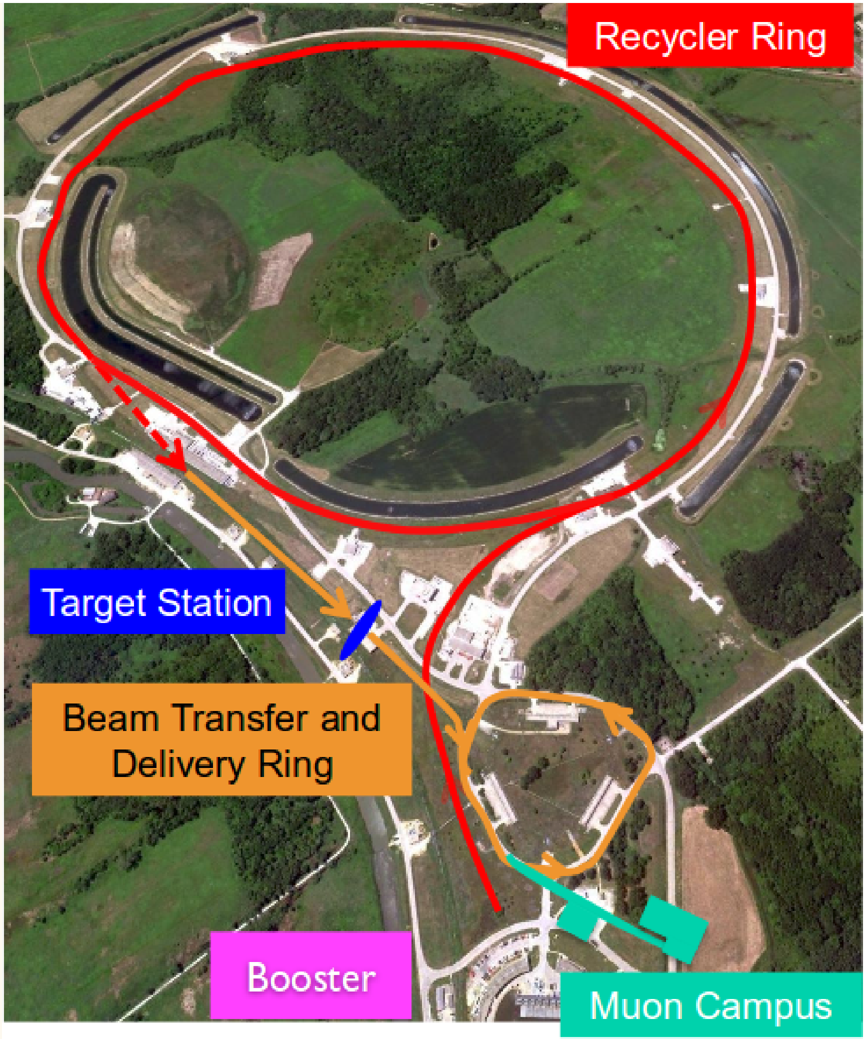
- Total SM uncertainty is roughly half the experimental uncertainty from E821 (BNL version)
- New E989 will reduce experimental uncertainty by about a factor of 4 (0.14ppm)
  - If current discrepancy remains at the same level, would give > 5 sigma deviation. Improvements to theory uncertainty could give > 8 sigma deviation.

Moving an Experiment

- After E821, was decided to form a new experiment E989 at Fermilab
- 15 ton cryostat ring moved from Long Island to Chicago by barge and truck- tricky, superconducting coils can't flex >3mm
- Vacuum chambers and other components shipped separately
- Magnet and related cryo-systems were cooled, powered in 2015
  - 1.45 Tesla field was achieved
  - Transportation was a success!

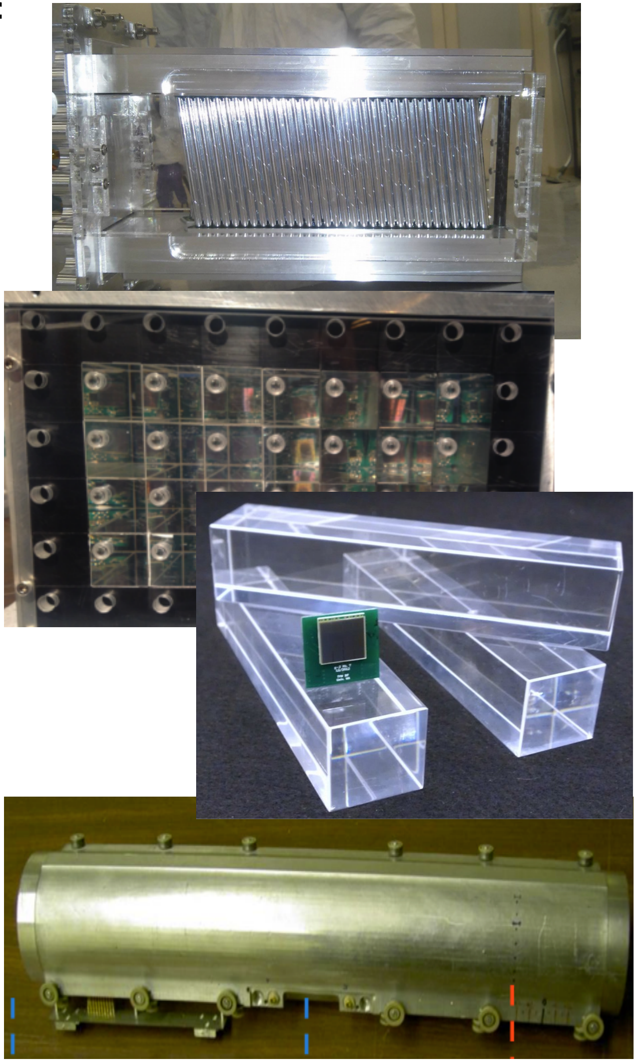
Fermilab Accelerator

- Reusing anti-proton source from Tevatron operation, 8 GeV input beam
- Long decay channel gives low pion/proton contamination- big improvement!
- Building new beamline to transport polarized mu+ beam to g-2 ring
- Accelerator at Fermilab will allow 20x more muons, reducing statistical error to 0.1ppm



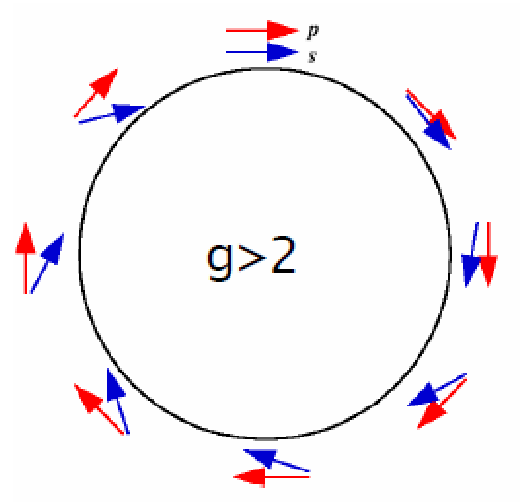
Ring, Detectors and Other Systems

- Experimental setup consists of
  - Ring and fields (dipole magnets and electrostatic quadrupole plates) to contain the muons
  - Straw trackers and calorimeters to detect the electrons which come from muon decays
  - Additional components to control or measure the beam (inflector, kickers, collimators, monitors), trolley to help measure the field



The Measured Quantities

$$\omega_c = \frac{e}{m\gamma} B \qquad \omega_s = \frac{e}{m\gamma} B(1+\gamma\, a_\mu)$$



$$\omega_S - \omega_C = \omega_a = e/m\, \mathbf{a}_\mu\, B$$

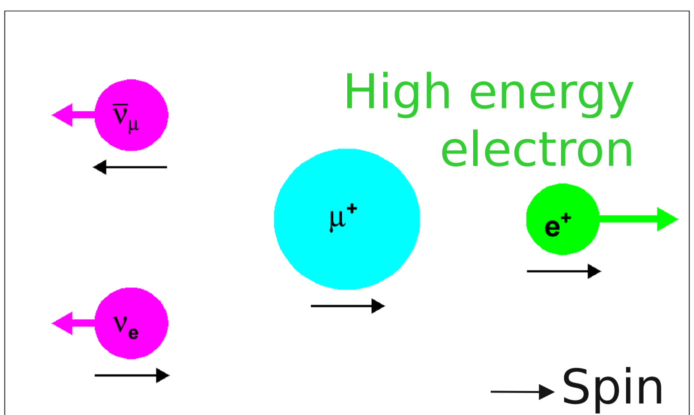
- We can rewrite this as below:

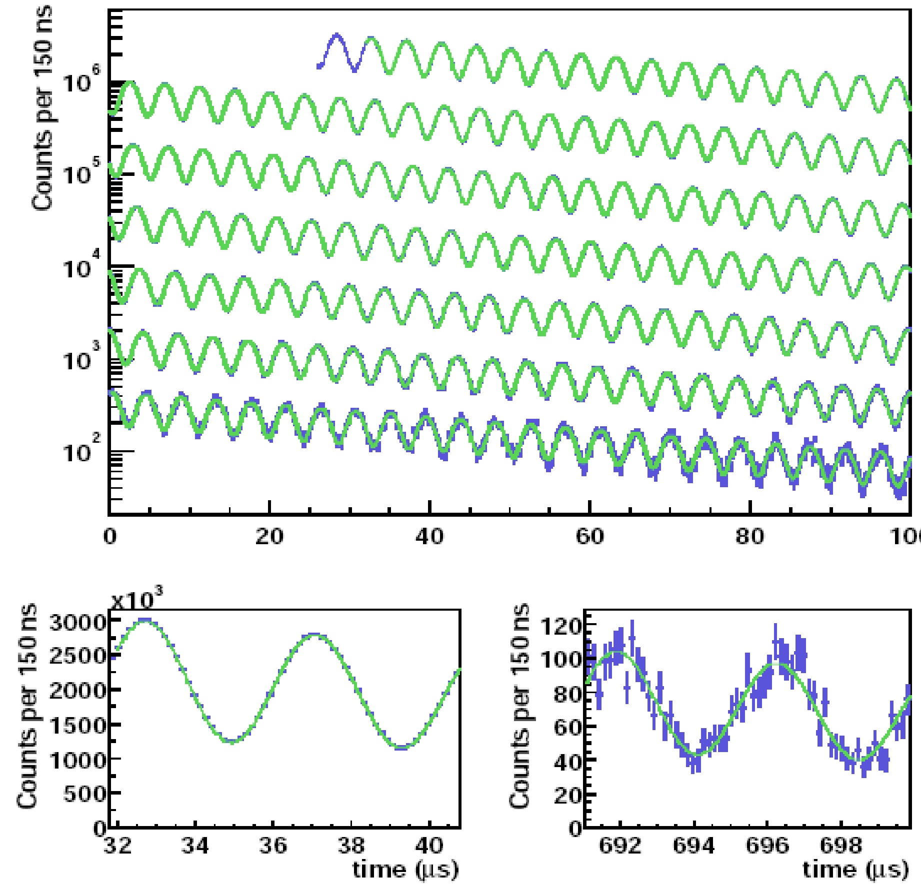
$$\mathbf{a}_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

- ω_p is the proton Larmor frequency measured in a field B
- ω_a is the precession frequency measured with decay positrons
- μ_μ/μ_p magnetic moment ratio from muonium hyperfine measurement

Measuring spin precession frequency ω_a

- Positrons retain muon spin info
- 24 calorimeter stations
  - Measure counts, time and energy
- Time spectrum of positrons with E > 1.8 GeV is fit with 5 parameter fit to determine ω_a





*Plots from E821, green line shows fit

Magic!

- More formally:

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

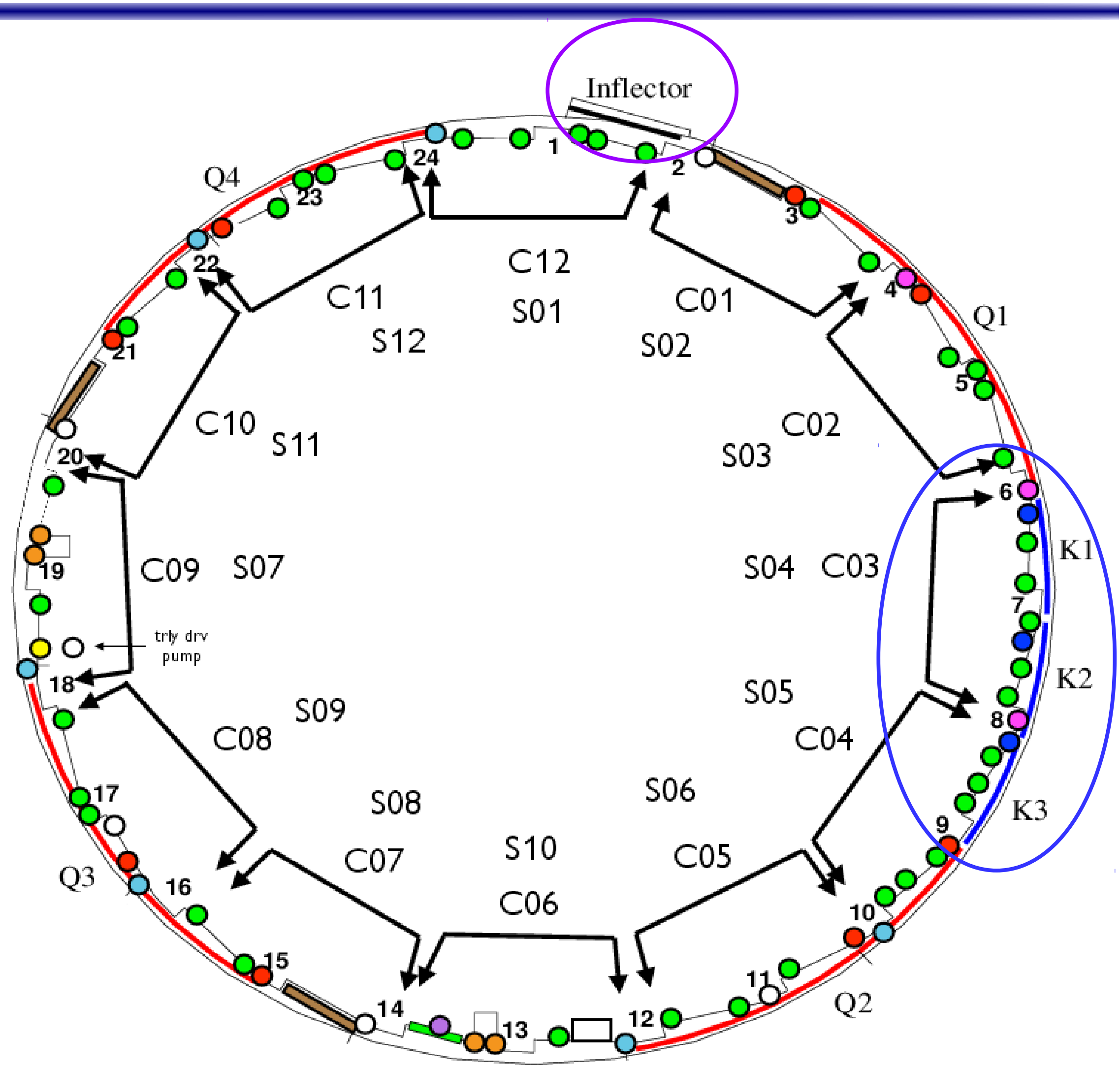
- With the appropriate choice of p, boxed term will drop out
  - This is the “magic momentum”

$$p_{magic} = m/\sqrt{a_\mu} \simeq 3.09 \text{ GeV/c}$$

- In real life not all muons are exactly at this momenta (an uncertainty). Alignment efforts to ensure muon conformity are important.

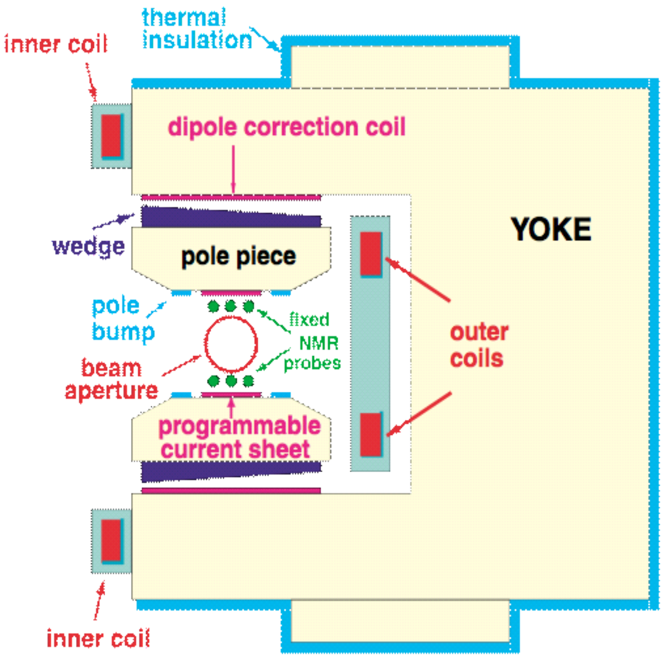
Ring Set-up

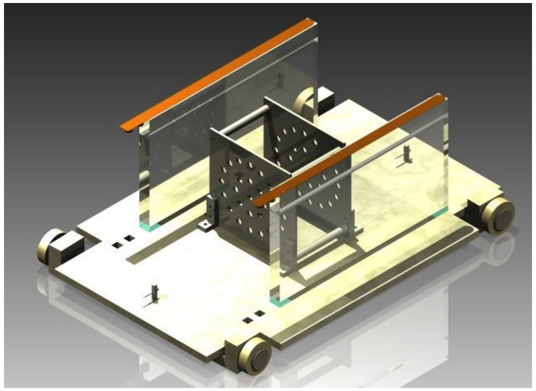
- Inflector in black, kickers in blue, quads in red
- Beam comes in through inflector, which compensates for the 1.45T dipole field
- Kickers then kick the beam into a closed orbit
- Quads offer weak vertical focusing
- Other components used to measure the beam or muons (mostly inside ring)



Storage Ring Magnet

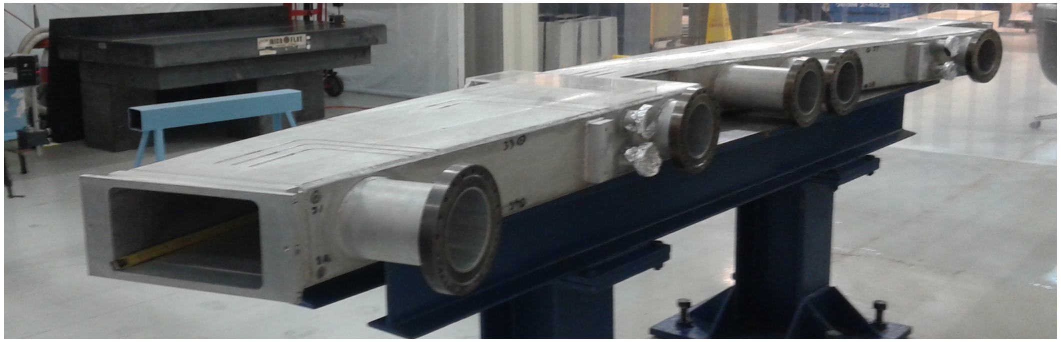
- Storage ring magnet produces the 1.45 T dipole field
  - Field must be very uniform
  - C-shape required for detectors to fit inside the ring- also dictates shape of vacuum chambers inside the C
- Measured with survey trolley (more range, before vacuum chambers installed), in-vacuum trolley (no beam), and fixed NMR probes on vacuum chambers (with beam, farther away)





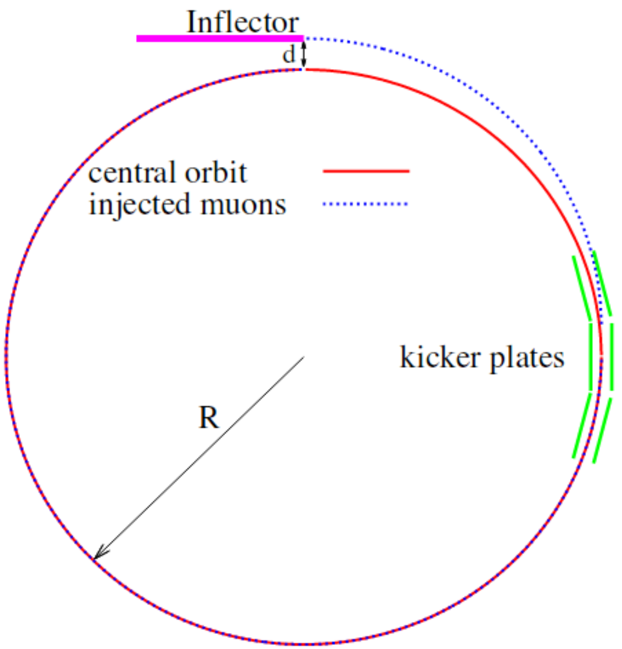
Storage Ring Alignment: Where the Magic Happens

- g-2 ring contains cryogenic systems, magnets to generate dipole B fields, and within those, vacuum chambers
- Chambers contain quadrupole plates, giving the beam vertical focusing, and the beam itself is within these plates
- Alignment of chambers, metal structures (cages) holding the plates, and the plates themselves, is required to get the beam (ω_a), and B field measurement trolley (ω_p) in the right spot
  - Critical to reach the magic momenta!



Some interesting Variations

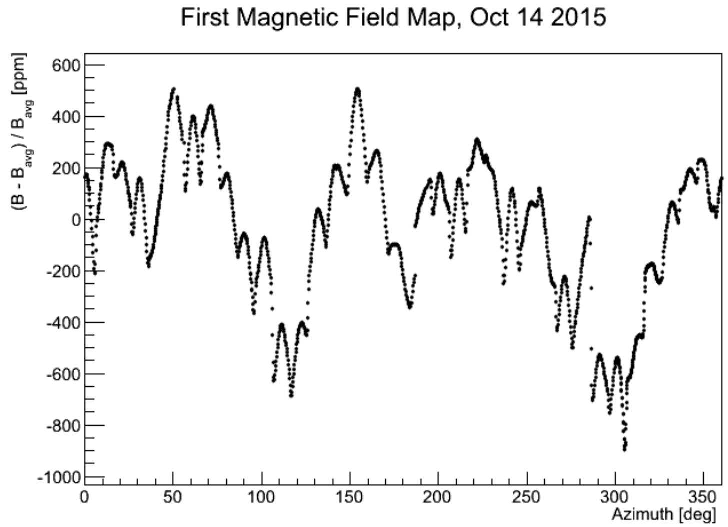
- Most of the quadrapole plates are reused from BNL. However, near the inflector, the first quad section (Q1) on the outer radius is made from aluminized mylar
  - This is a much thinner plate, which prevents lost muons in this region, when the beam is still being positioned on the central orbit
- The kickers are made of two curved plates, one at the inner and one at the outer radius which have equal and opposite current, divided into three sections with 10.8 mrad kick to push the muons into the central orbit



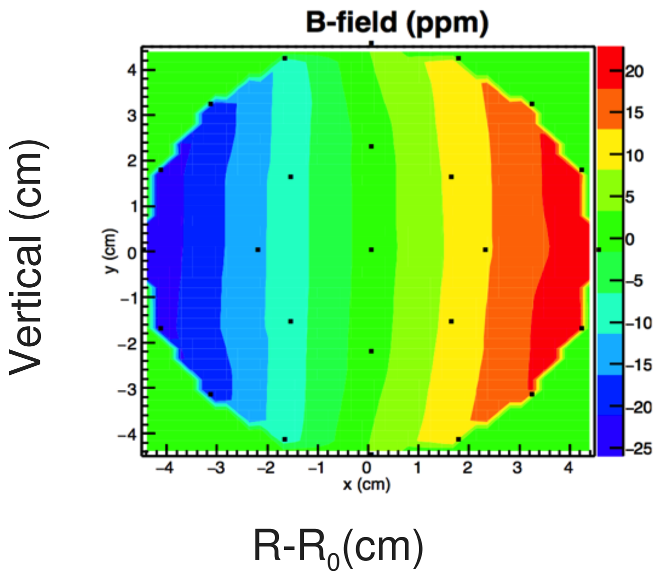
Initial Field Plots and Goals

- Similar to BNL- in both cases, improved with metal shims:

Field vs. Azimuth



Azimuthally Averaged Field vs r, z

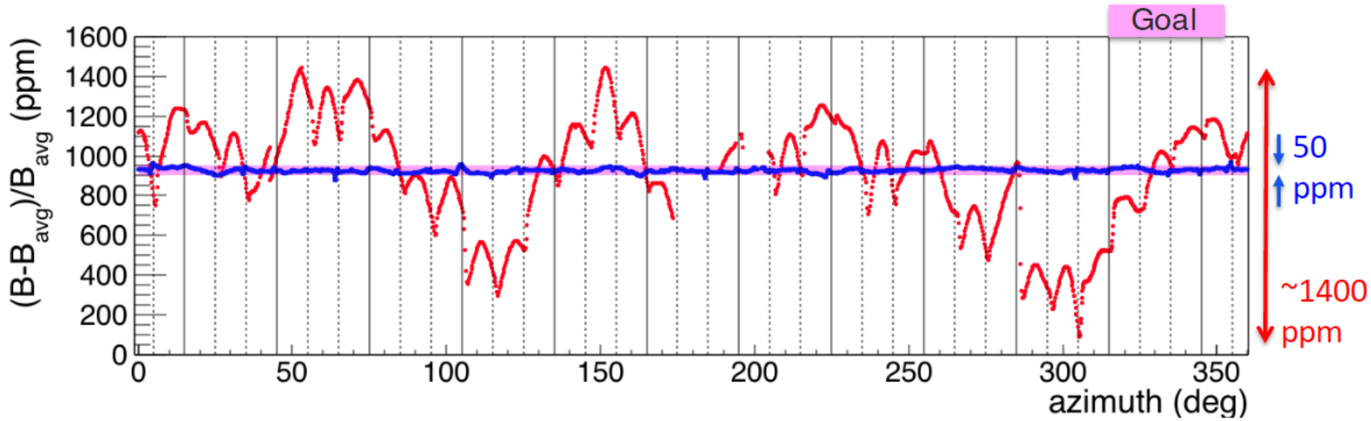


- October 2015: +/-700 ppm
- Goal: +/- 25 ppm

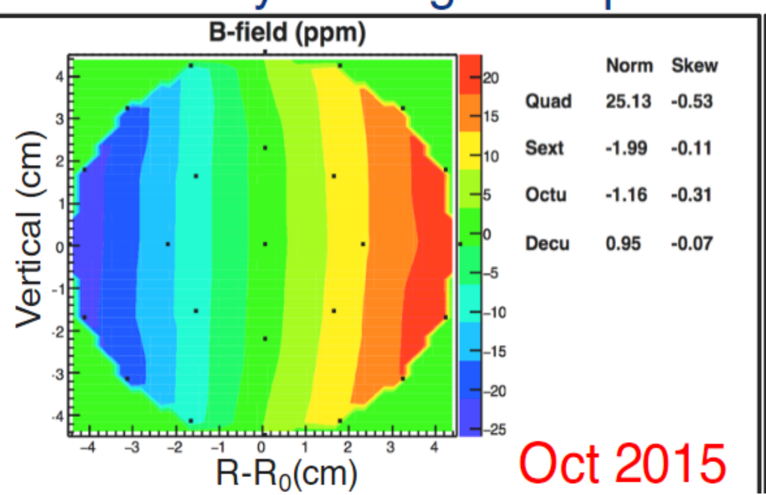
- October 2015: +/-25 ppm
- Goal: < 1 ppm

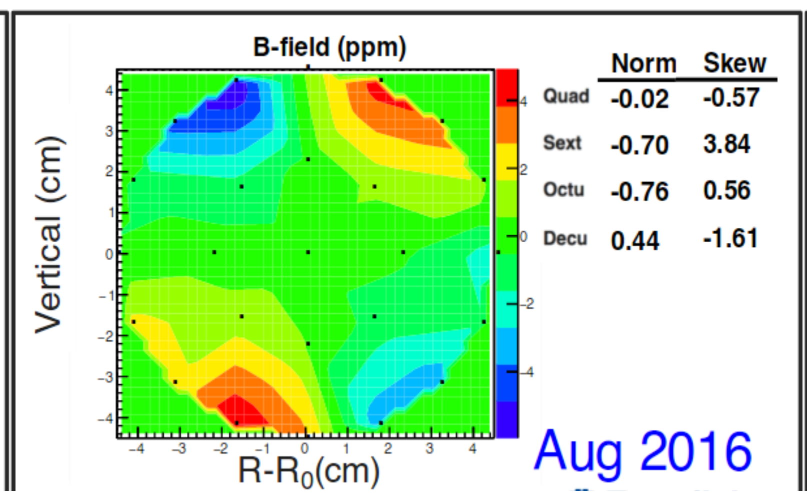
B Field Measurements from 2016 and 2017

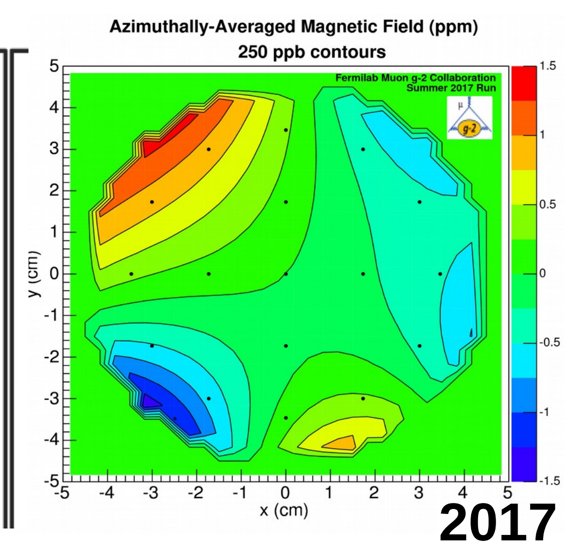
Rough Shimming Results



Azimuthally Averaged Map

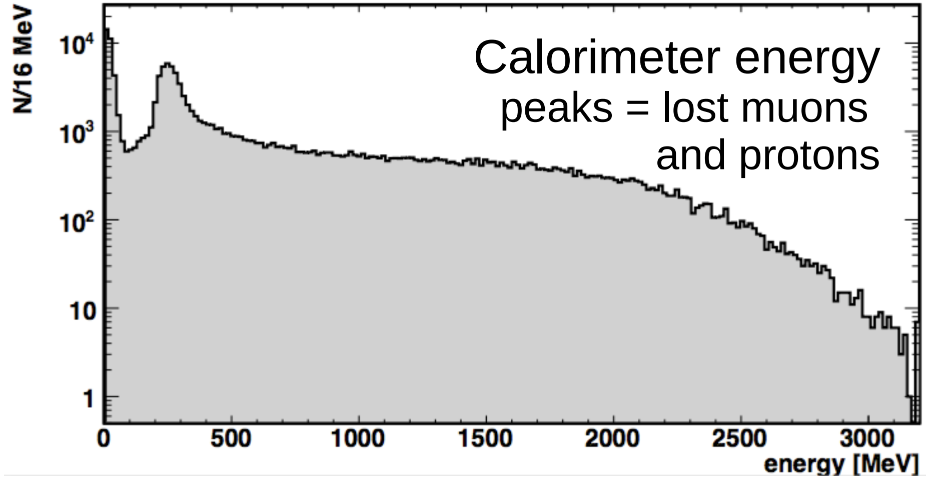




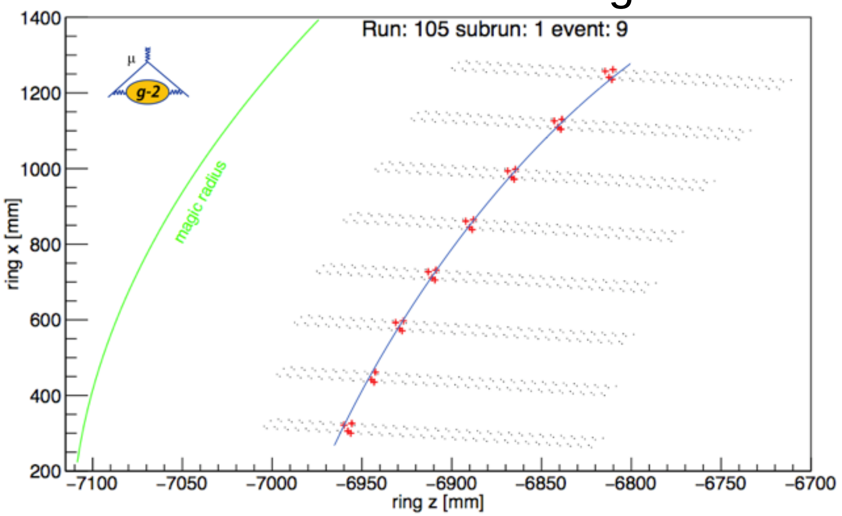


Engineering Run: Summer 2017

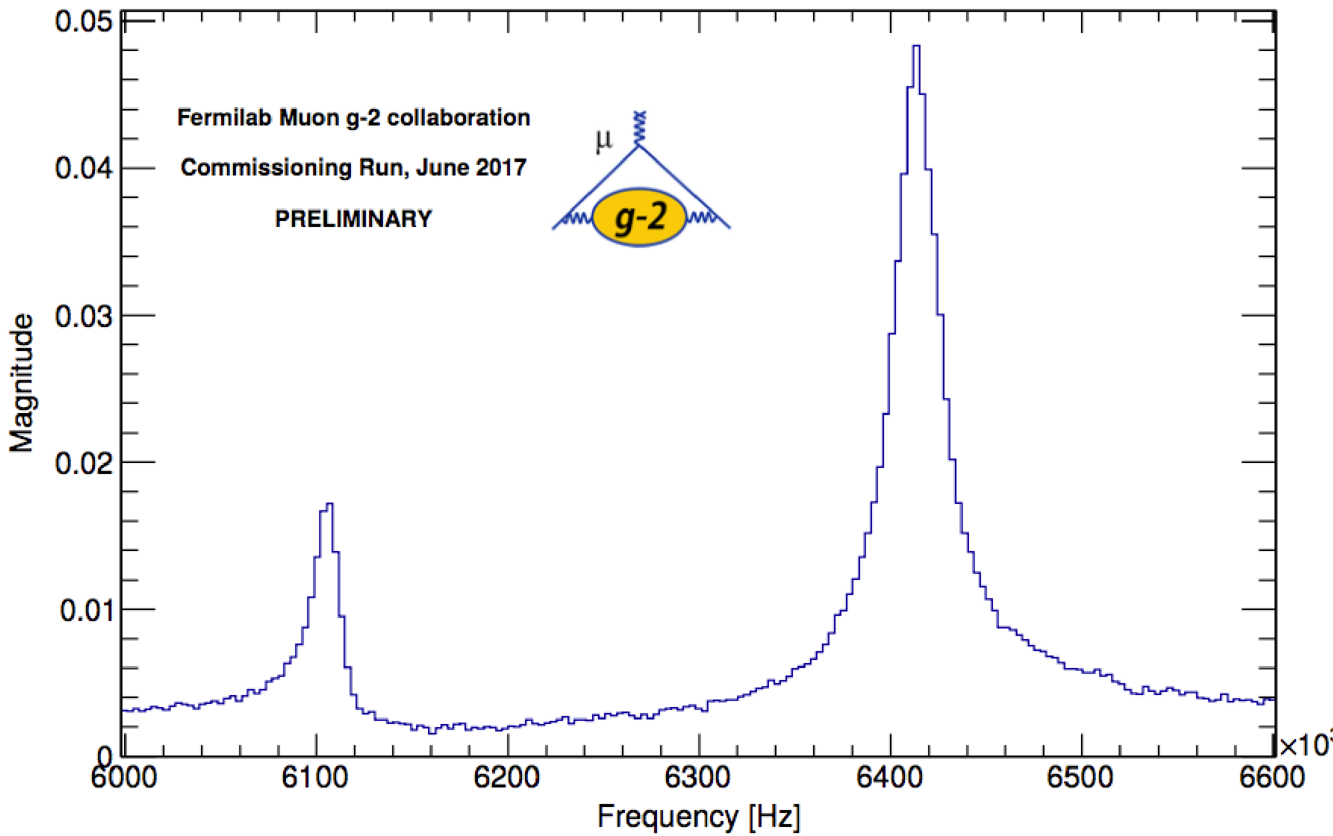
- This summer, an engineering run took place to test the system components
  - May 23 we had first particles delivered to ring and beam splash observed in calorimeters
  - Ran through July 7
  - Achieved particles circulating through the full storage ring and demonstrated the operation of the various systems!
- New run should start in November, physics data taking in winter



Reconstructed track through tracker

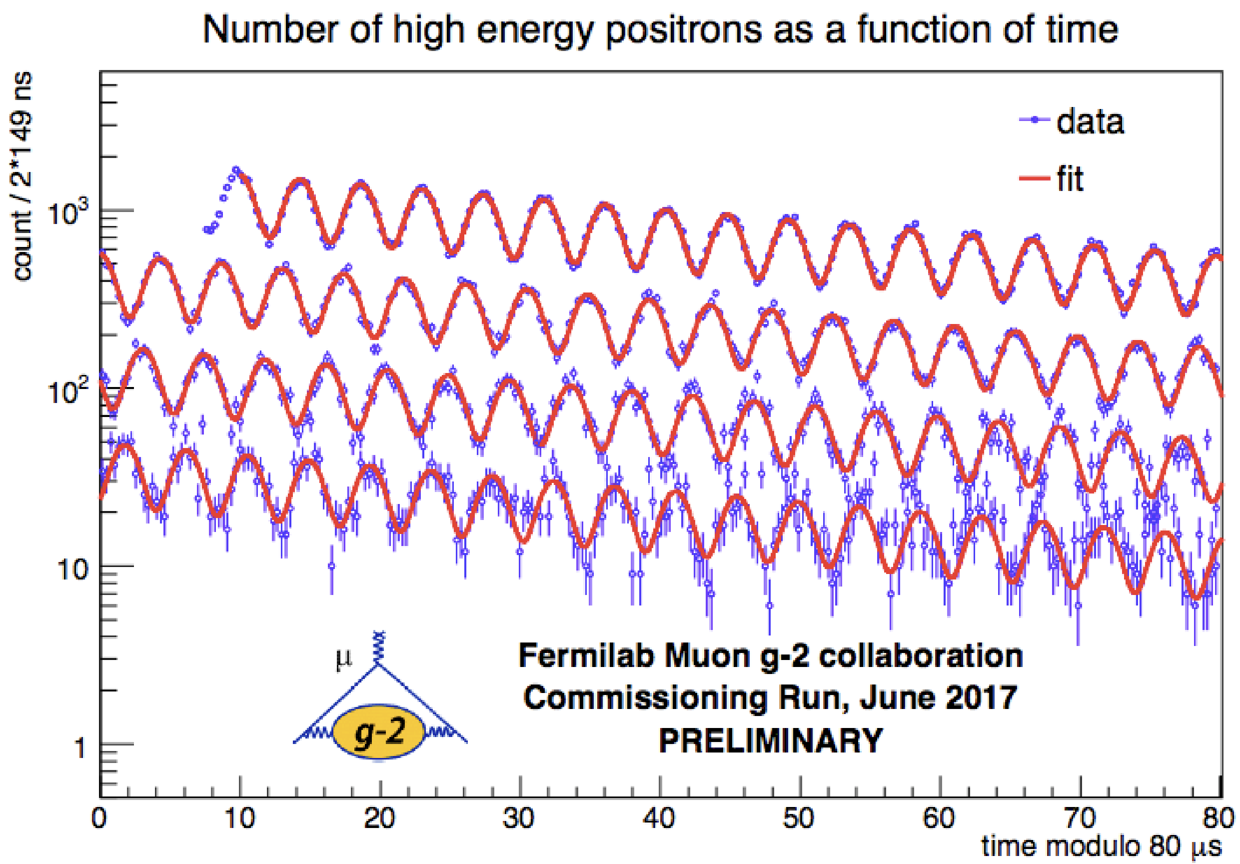


Beam Information from Fiber Harp



The plot shows the cyclotron revolution frequency for the proton on the right and the horizontal betatron oscillation of the proton on the left. The BO frequency arises from the beating of the cyclotron revolution frequency and the CBO frequency (that lives around 300 kHz).

Analysis Demonstration

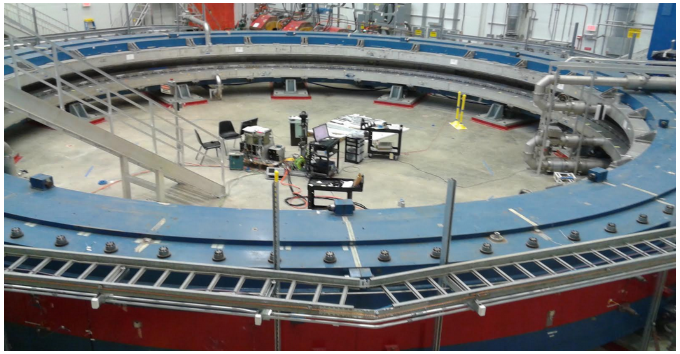


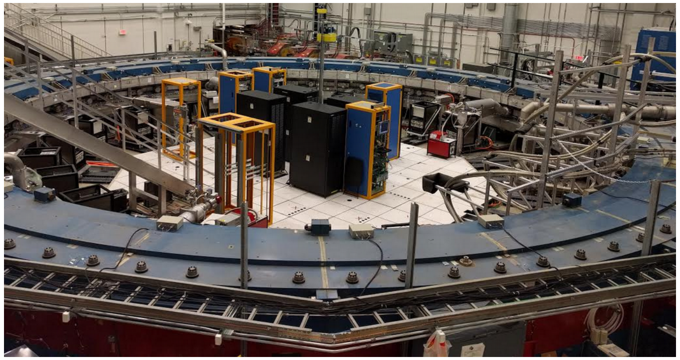
This figure was accumulated from two weeks of data accumulated in June 2017 and has approximately 700k positrons. The number of wiggles is somewhere between that achieved by CERN-II and CERN-III.

Summary and Plans

- Upcoming experiment will improve uncertainty by a factor of four versus the previous experiment's result
- Active collaboration with much work ongoing to ensure the operations of various sub-systems and data analysis
- Experiment installation and initial engineering run are completed
- Expect physics data this winter!

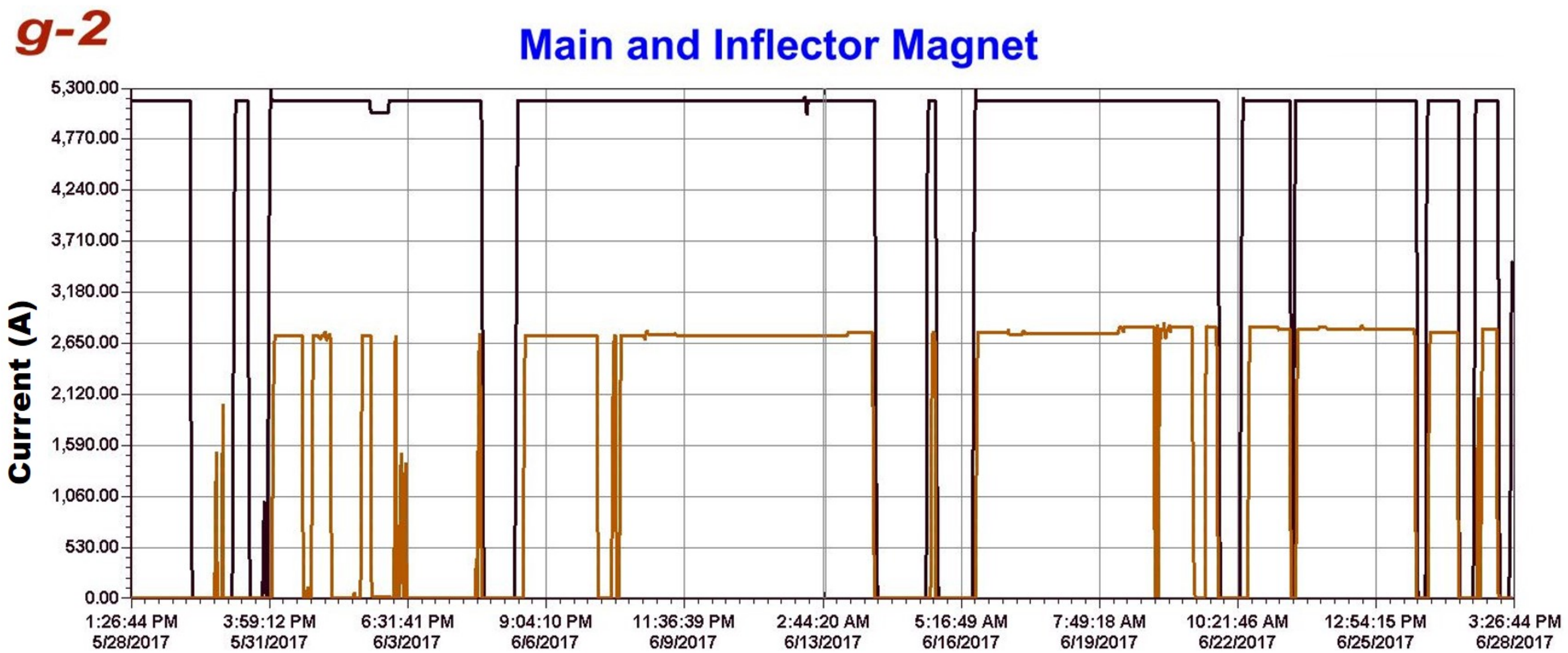
Installation work over the past year or so





Other Material

Magnet Up-time

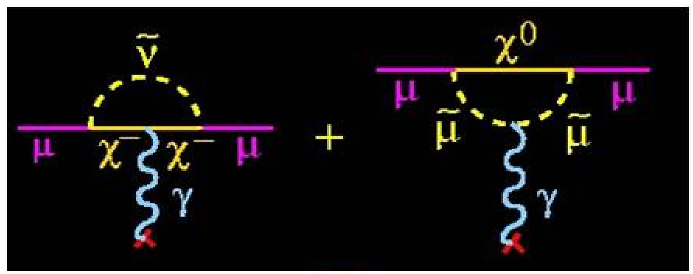


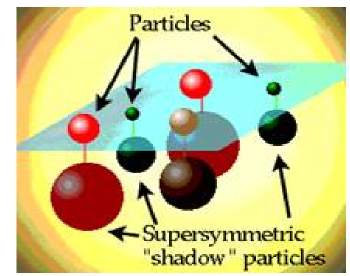
New Physics Example

What about the new physics?

NEXT

One example: SUSY



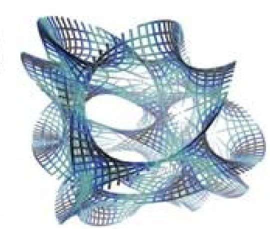


$$a_\mu(\text{SUSY}) \simeq (\text{sgn}\mu)\,130\times10^{-11}\,\tan\beta\left(\frac{100\ \text{GeV}}{\tilde{m}}\right)^2$$

difficult to measure at LHC

Another example: Universal Extra Dimensions (1 UED)

$$a_\mu(1\ \text{UED}) \approx -13 \times 10^{-11}$$



The new Muon g-2 experiment at Fermilab, APS April meeting 2016, Peter Winter

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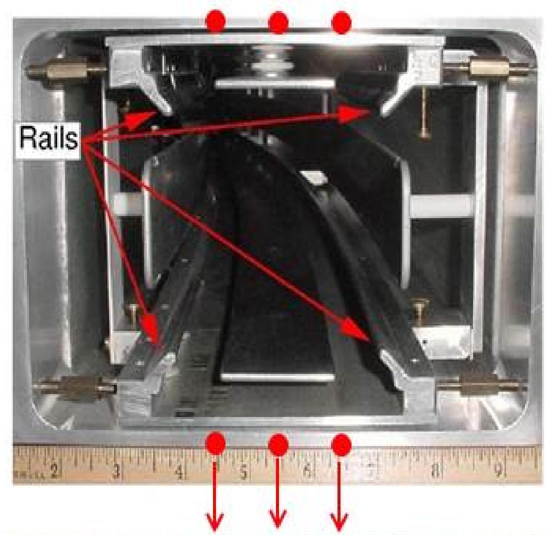
Measuring the Field (Pictures)

- Pulsed Nuclear Magnetic Resonance is extremely precise (<10 ppb)
- Monitor the field with 400 fixed NMR probes around the ring
- Map the storage field regularly during beam off periods with trolley
- Use a spherical water-based probe for absolute calibration (~30ppb accuracy)

Calibration probe



trolley

Fixed NMR probes

The new Muon g-2 experiment at Fermilab, APS April meeting 2016, Peter Winter