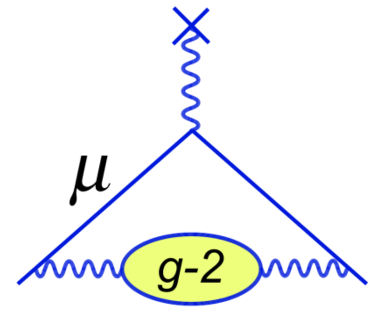
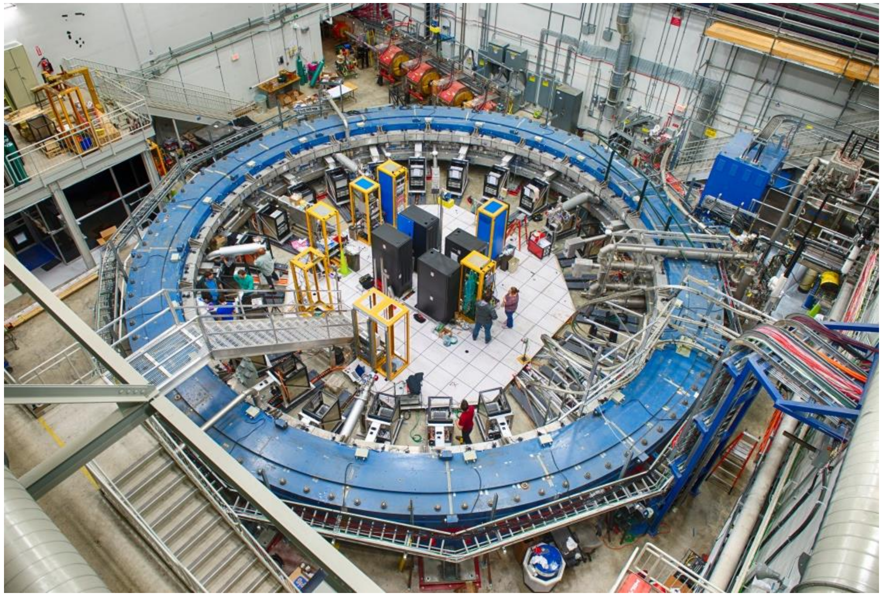


Status and outlook for Muon g-2 at Fermilab

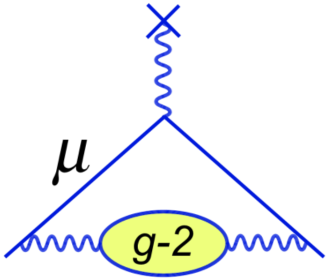
A.P. Schreckenberger on behalf of the Muon g-2 Collaboration
In Pursuit of New Particles and Paradigms

To Peek Beyond…

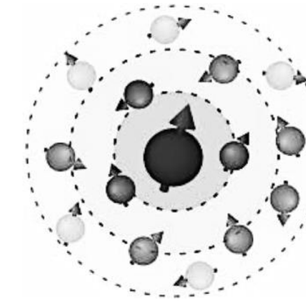
- Standard Model predicts and describes most particle experiment observations



- Exceptions to this include:
  - Matter-antimatter asymmetry
  - Presence of dark matter
  - Mass and strength hierarchy
- Muon g-2 indirectly searches for new physics by probing the impact of virtual particles on the behavior of muons



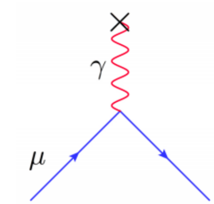
More than a Moment

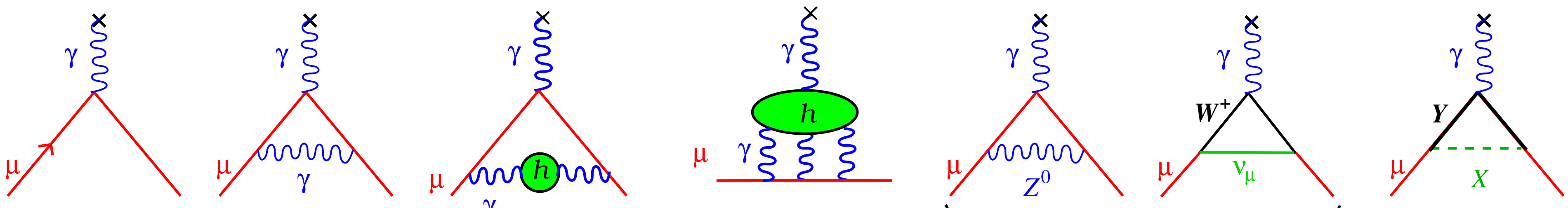


- Magnetic moment used as the handle
- Relation to particle spin and the dimensionless g-factor

$$\vec{\mu} = g\frac{q}{2m}\vec{S}$$

- For Dirac point-like particle, $g = 2$
  - Radiative corrections from fundamental forces increase value of g





$$g = 2(\,1 \quad + .00116\ldots \quad + .00000006951\ldots + .00000000105\ldots \quad + .000000001536 \quad +?\ )$$

Schwinger Term $\left(\frac{\alpha}{2\pi}\right)$ | **QCD** | **Electroweak** | **BSM?**

[1] A. Keshavarzi, D. Nomura, T. Teubner, Phys. Rev. D **97**, 114025 (2018)

Defining an Anomaly

- Consider these processes with respect to $a_\mu = \frac{g_\mu - 2}{2}$, where a_μ is the muon magnetic anomaly
  - $a_\mu^{SM} = 116591820.4(35.6) \times 10^{-11}$, [1]

QED processes contribute most to value of magnetic anomaly

QCD processes contribute most to uncertainty on a_μ
— Leading order vacuum polarization
— Light-by-light scattering

[1] A. Keshavarzi, D. Nomura, T. Teubner, Phys. Rev. D **97**, 114025 (2018)

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SM Contribution	$\delta a_\mu\ [\times 10^{-11}]$
Leading Order Hadronic Vacuum Polarization (HVP)	± 33.3
Hadronic Light-by-Light	± 26.0
Electroweak (2 loops)	± 1.0
Higher Order HVP	± 0.7
QED (to 5 loops)	± 0.08

T. Aoyama et al., Phys. Rev. Lett. **109**, 111808 (2012)
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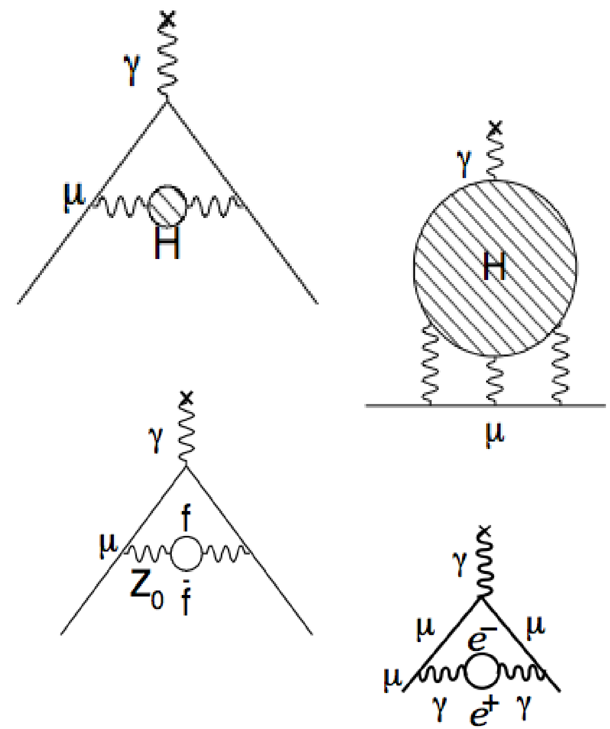

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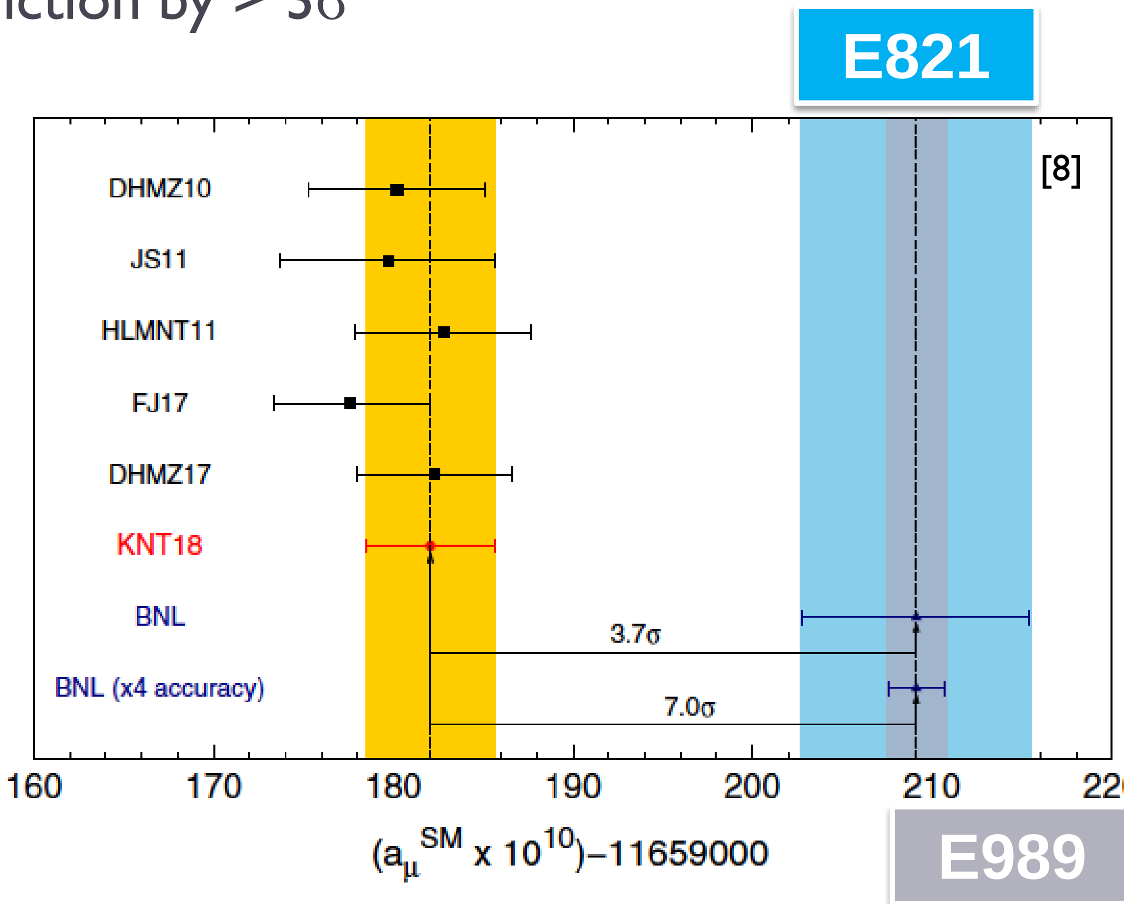
- Prologue: why muons?
  - Pion decay produces polarized beams
  - Parity violation → relation between muon spin and decay positron momentum
  - Heavier mass makes muons more sensitive to BSM physics
    - Driven by (m_e^2/m_μ^2)
  - Long lifetime permits the precision measurement

A Persisting Puzzle

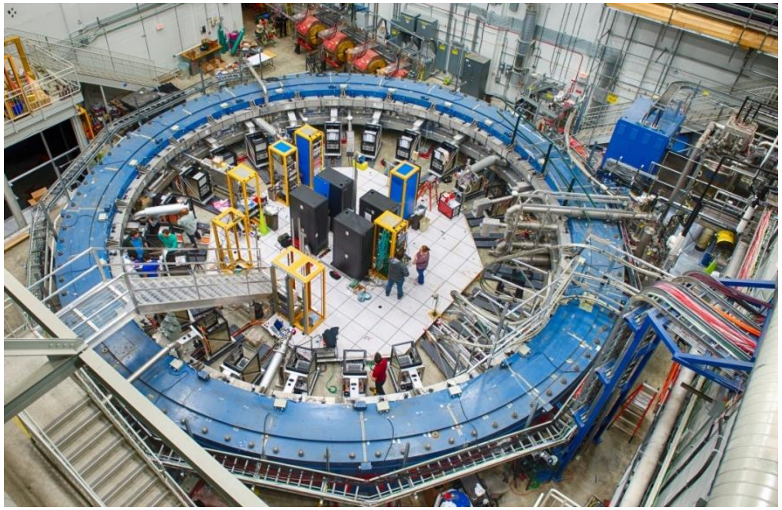
- BNL E821 measured a_μ to a precision of 540 ppb
  - Differs from SM prediction by > 3σ
- Motivated creation of FNAL-based experiment
- Precision goal of 140 ppb

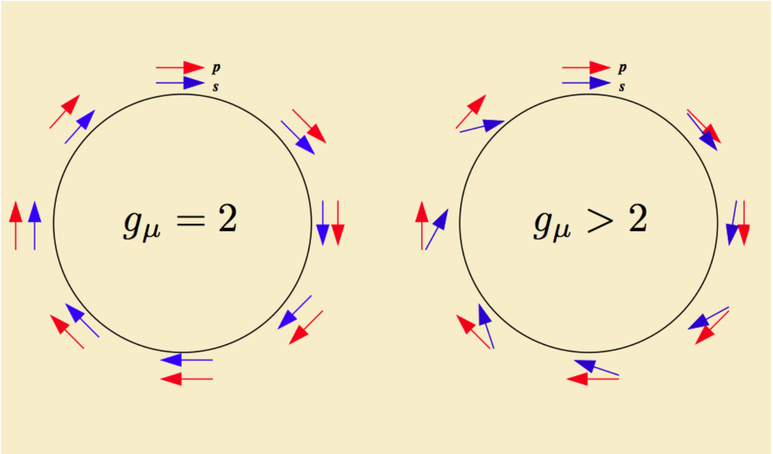


[8] A. Keshavarzi, D. Nomura, T. Teubner, Phys. Rev. D **97**, 114025 (2018)

Building an Experiment

- Muon g-2 ring provides 1.45T field in storage vacuum region
- Polarized muons injected from Fermilab accelerator complex
- Mismatch between cyclotron frequency and spin precession frequency provide handle on a_μ
  - $\vec{\omega}_C = -\frac{q}{\gamma m}\vec{B}$
  - $\vec{\omega}_S = -\frac{q}{\gamma m}\vec{B}(1 + \gamma a_\mu)$
  - $\vec{\omega}_a \equiv \vec{\omega}_S - \vec{\omega}_C = -\frac{q}{m} a_\mu \vec{B}$



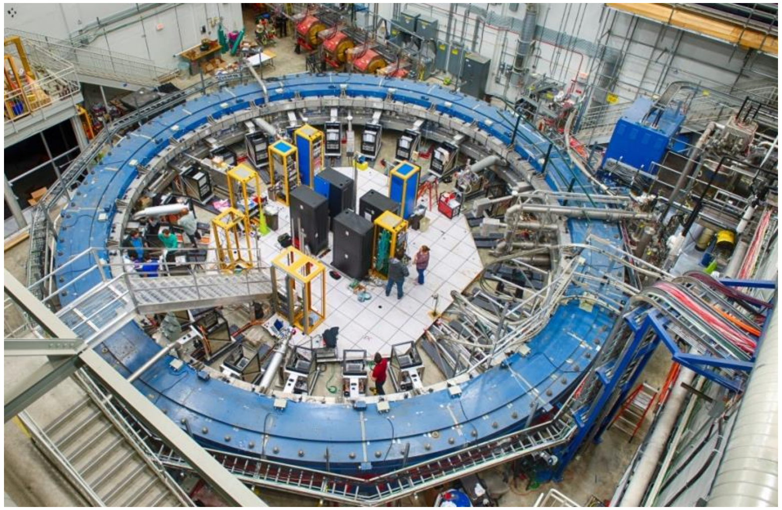


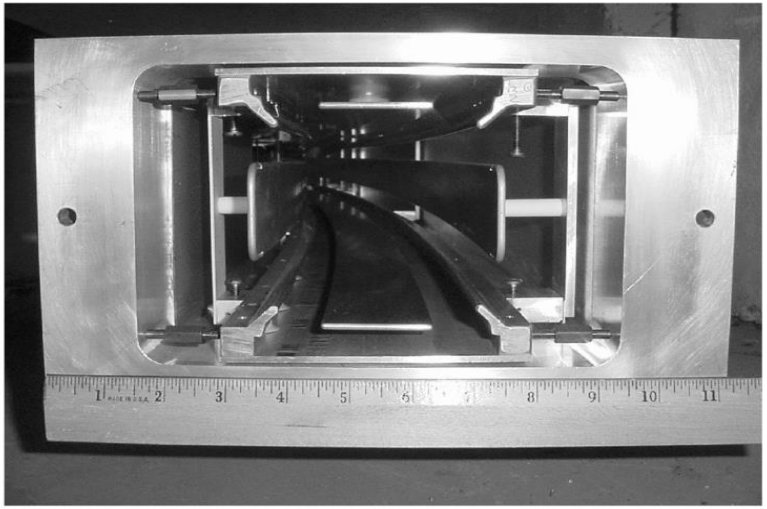
Building an Experiment – Some Expansion

- Uniform storage ring field only provides horizontal focusing
- Vertical focusing provided by electrostatic quadrupoles
  - Muons observe magnetic field

$$\vec{\omega}_a \equiv -\frac{q}{m}\left(a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right)$$

  - Quadrupole term vanishes when $p_\mu = 3.094$ GeV/c, $\gamma = 29.3$
    - Tune beam to exploit the "magic momentum"





Building an Experiment

$$a_\mu(expt) = \frac{g_e}{2}\frac{m_\mu \mu_p}{m_e \mu_e}\frac{\boldsymbol{\omega_a}}{\langle \boldsymbol{\omega_p} \rangle}$$

Building an Experiment

m_μ / m_e known to 22 ppb

μ_e / μ_p known to 3 ppb

g_e known to 0.26 ppt

$$a_\mu(expt) = \frac{g_e}{2} \frac{m_\mu \mu_p}{m_e \mu_e} \frac{\omega_a}{\langle \omega_p \rangle}$$

Get from CODATA[9]:

g_e = -2.00231930436182(52)

m_μ/m_e = 206.7682826(46)

μ_e/μ_p = -658.2106866(20)

[9] P. J. Mohr, D. B. Newell and B. N.Q Taylor, Rev. Mod. Phys. **88**, no. 3, 035009 (2016)

Building an Experiment

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$$a_\mu(expt) = \frac{g_e}{2}\frac{m_\mu \mu_p}{m_e \mu_e}\frac{\omega_a}{\langle \omega_p \rangle}$$

- $\langle \omega_p \rangle$ assessed via NMR probes to find average field seen by muons
- ω_a measured via muon decay products
  - Exploiting the nature of weak decay
- Frequency standard for clocks blinded to ppm level

Get from CODATA[9]:

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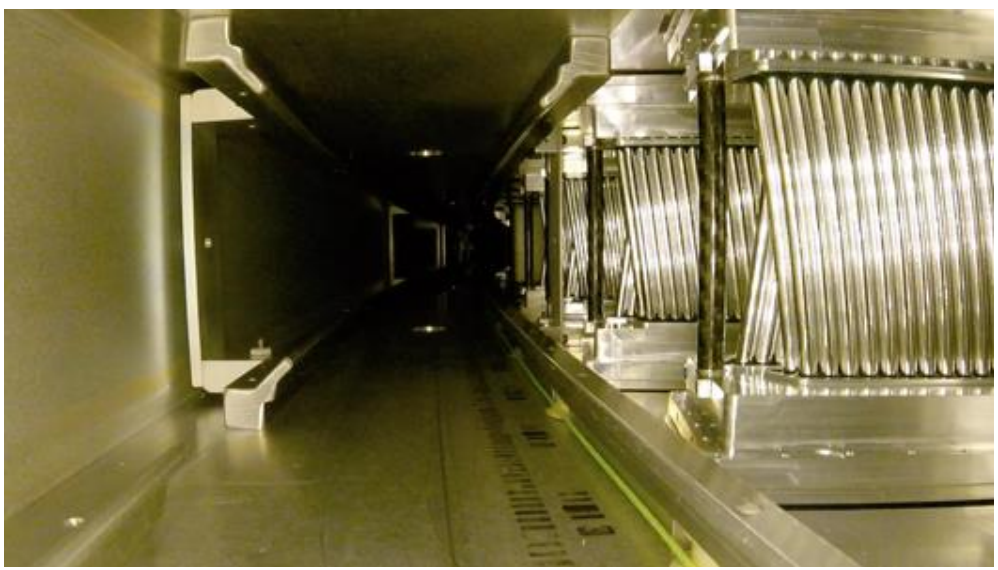
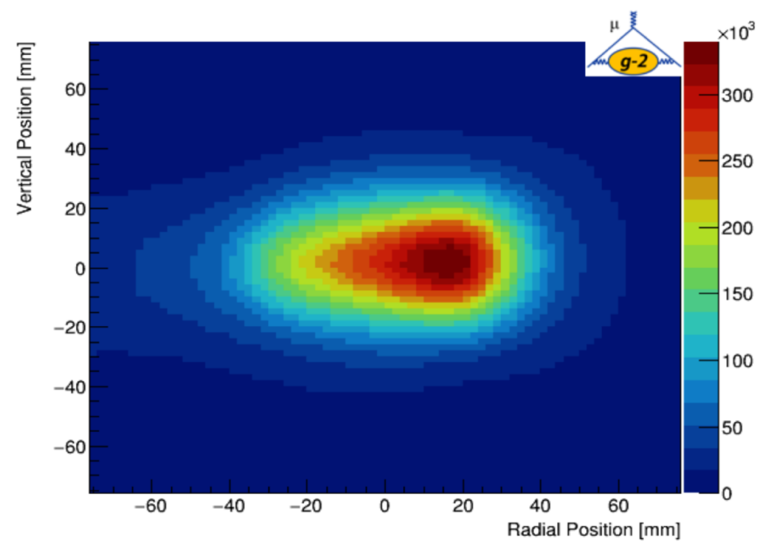
Building an Experiment: The Field

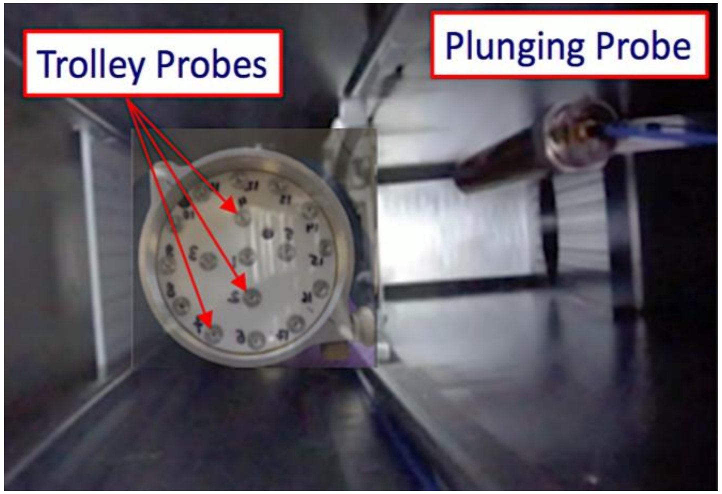
- Understanding $\langle \omega_p \rangle$ component requires knowledge of the *magnetic field* and *muon beam*
  - Muon beam profile extrapolated from decay positrons observed in straw trackers

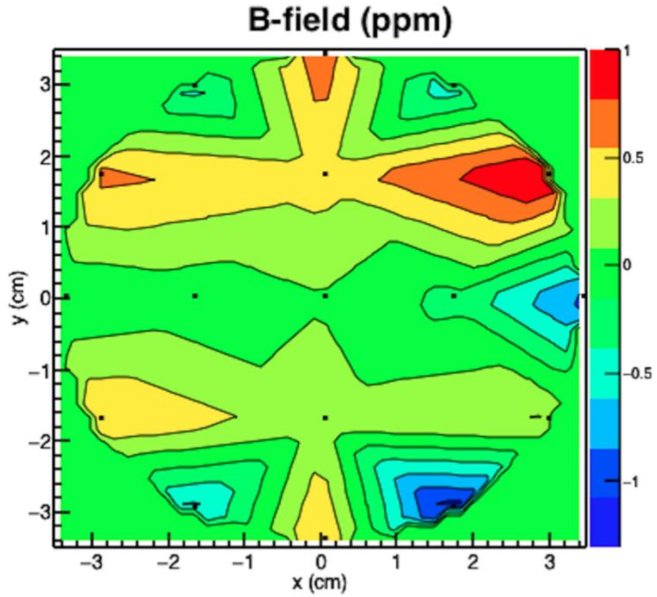




Building an Experiment: The Field

- Understanding $\langle \omega_p \rangle$ component requires knowledge of the *magnetic field* and *muon beam*
  - Muon beam profile extrapolated from decay positrons observed in straw trackers
  - Proton NMR probes pulled on trolley to measure field along the azimuth





Averaged over azimuth

Building an Experiment: The Field

- Understanding $\langle \omega_p \rangle$ component requires knowledge of the *magnetic field* and *muon beam*
  - Muon beam profile extrapolated from decay positrons observed in straw trackers
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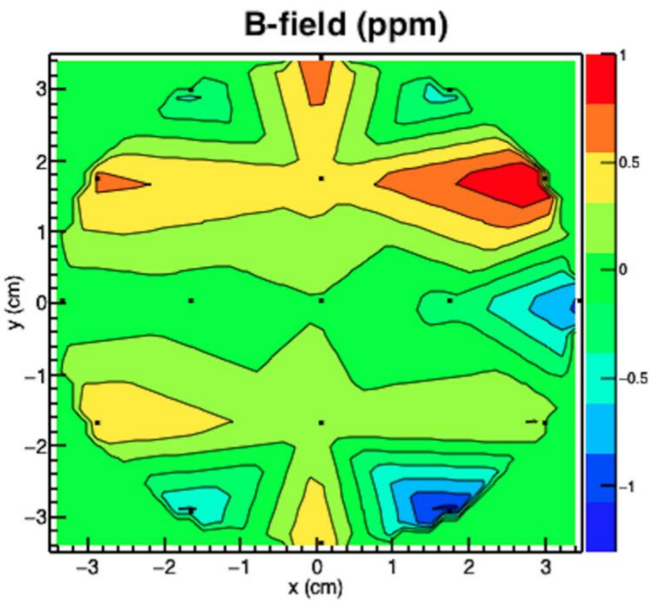
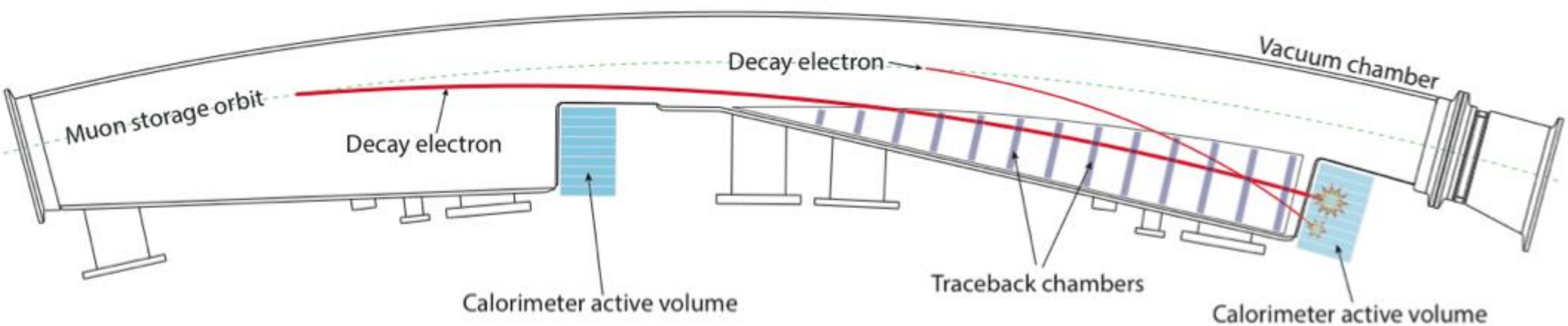


- Magnetic field uniformity efforts reduced systematic uncertainty
  - 170 ppb (BNL)
  - 70 ppb (FNAL)

Building an Experiment: Muons

- ω_a assessed using 24 calorimeters that are spaced around the storage ring
- Muons in beam weakly decay $[\mu^+ \rightarrow \bar{\nu}_\mu \nu_e e^+]$
  - Positrons preferentially emitted along muon spin vector
  - With high energy cut, selected positrons had initial momenta aligned to muon spins

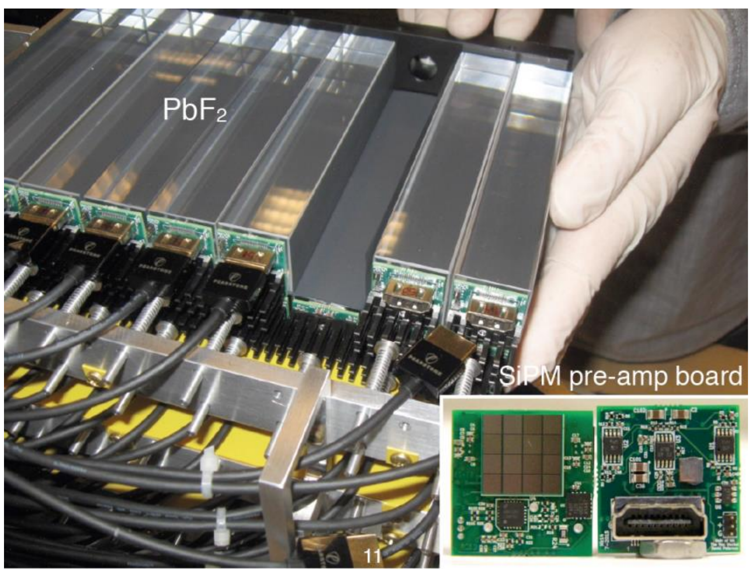


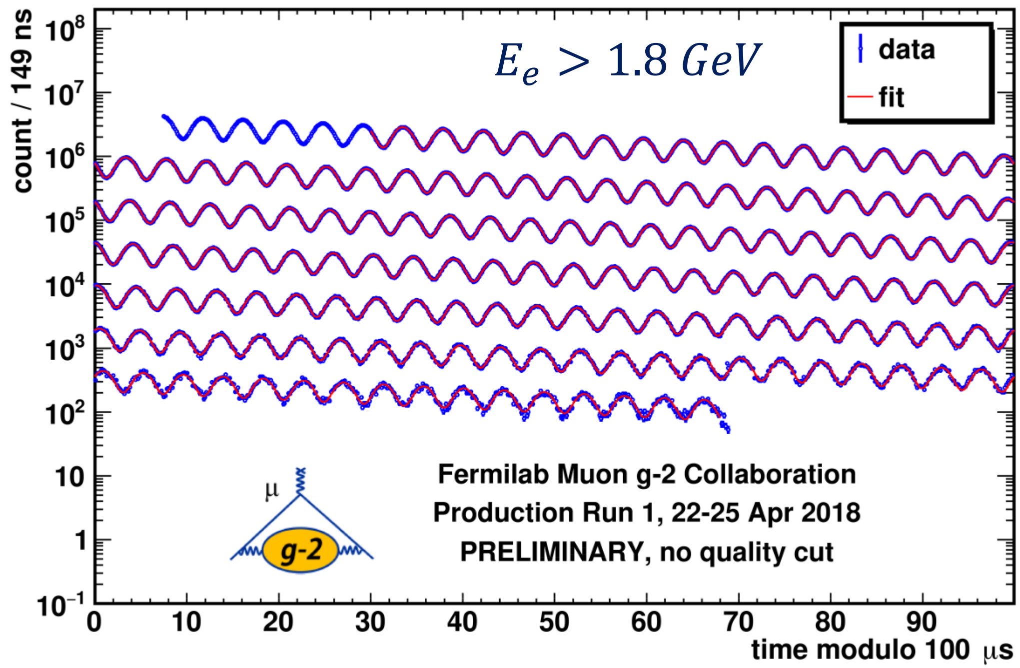
Building an Experiment: Muons

- Energy cut results in sinusoidally-oscillating function for deposition in calorimeters:

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

- Fit data to extract ω_a

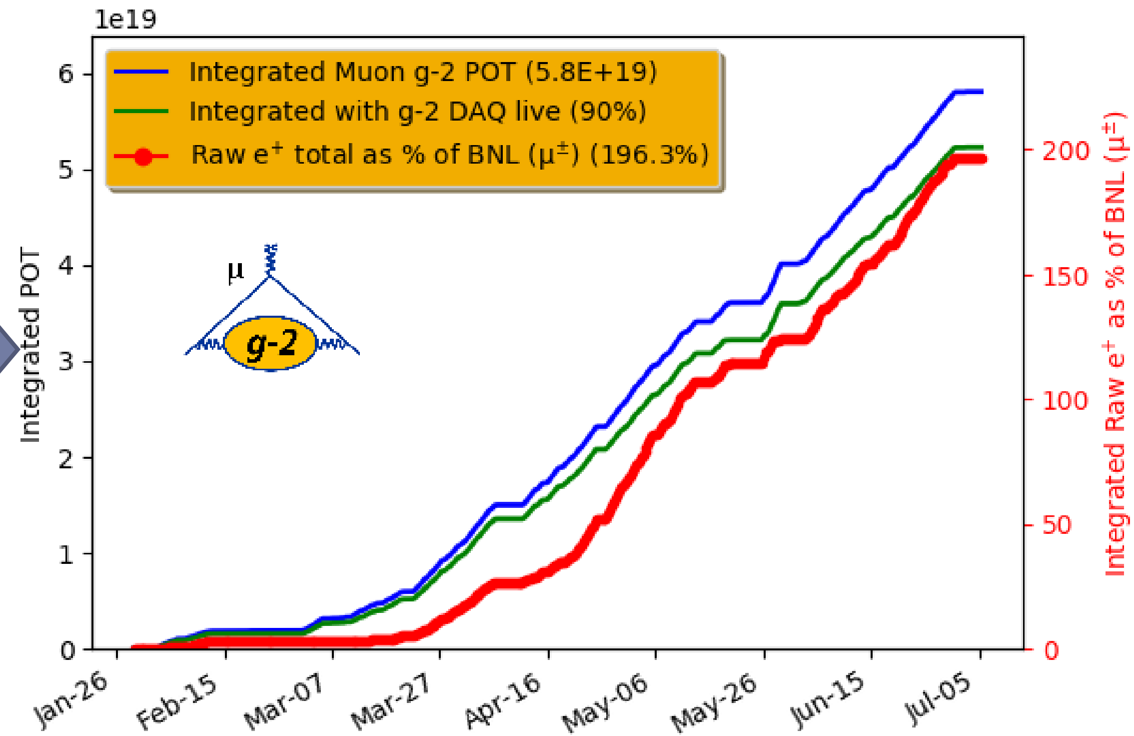




Run 1 Data Taking

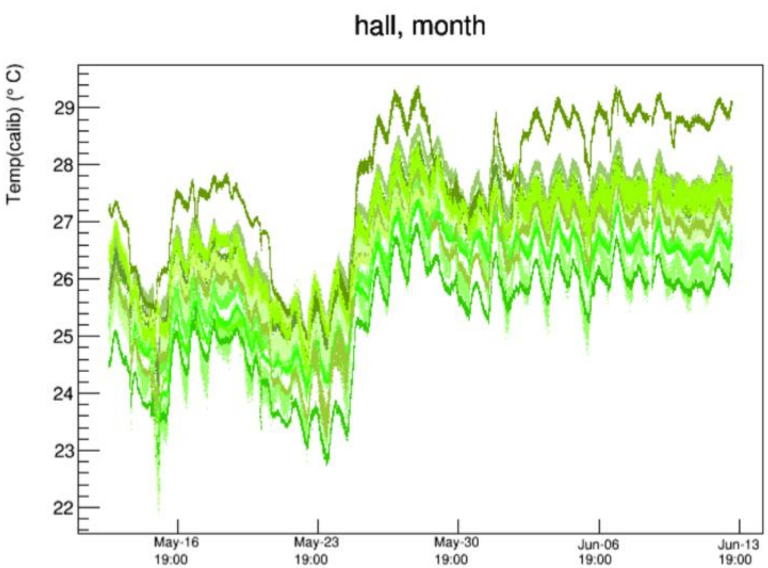
- First data run finished on July 7, 2018
  - Acquired almost 2X the BNL dataset in a few months
  - Data quality cuts still need to be applied
  - In 3 months, 17.5TB e^+ events recorded (BNL total was 9.4TB e^+/ e^-)

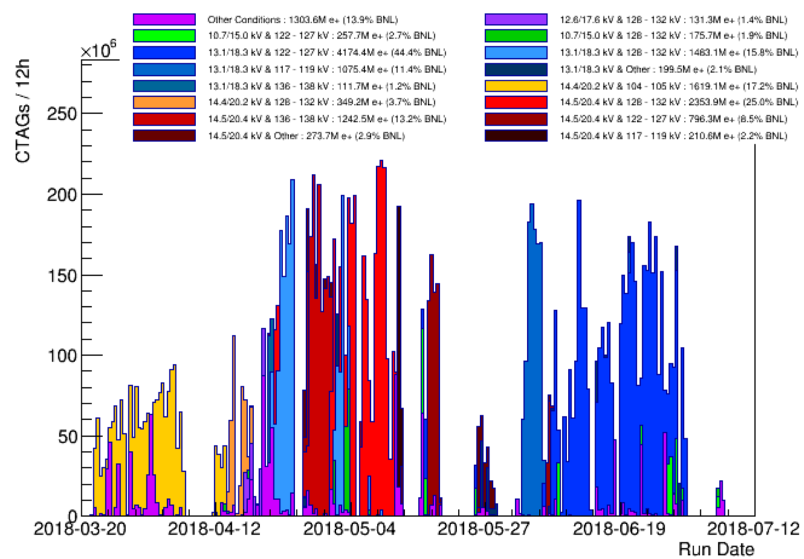
Achieved 50% of design flux



Run 1 Learning Points

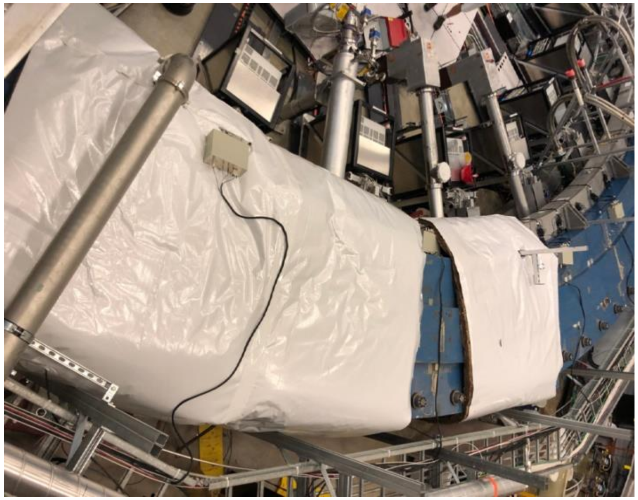
- Analysis underway on the Run 1 dataset with aim to unblind Summer 2019
- Several challenges uncovered during this time:
  - Temperature fluctuations in the experimental hall
  - Stability issues with electrostatic quadrupole system
  - Stability issues with the kicker system

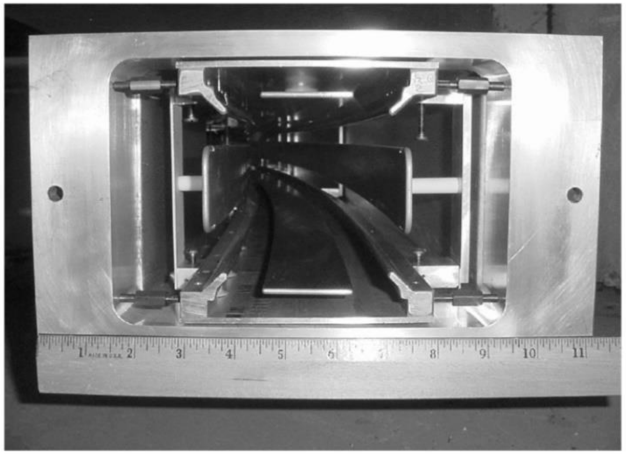




Upgrades for Run 2

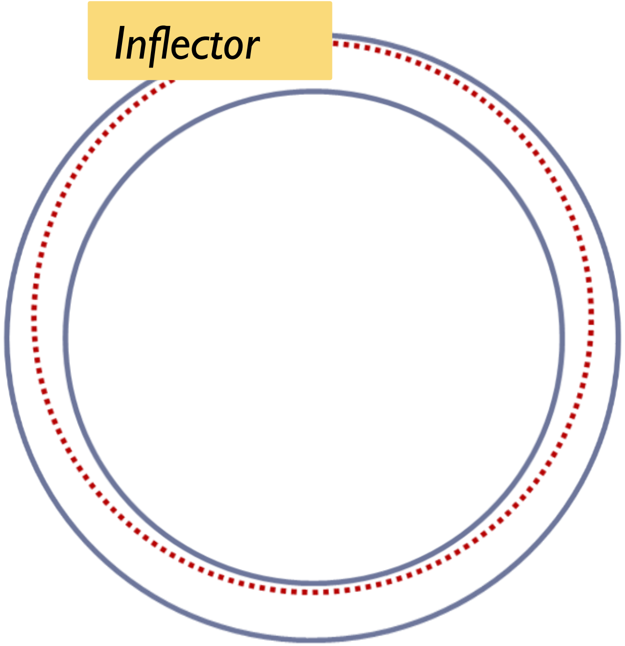
- Magnet covered in insulation to address effect of temperature fluctuations
- Electrostatic quadrupole stability improved by adding mechanical supports to HV leads
  - Vibrations caused breakdowns
  - Latest round of conditioning shows improvement
- Additional upgrades to magnet system protections and beamline monitors
- Kicker system underwent largest overhaul





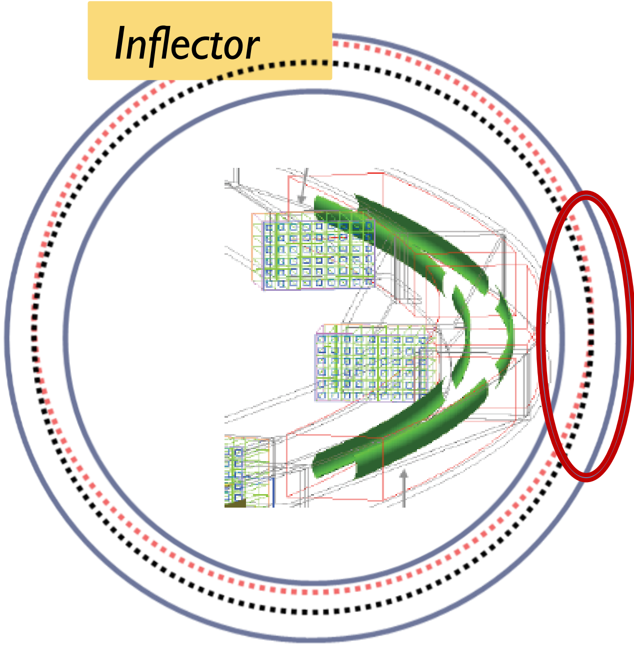
Kicker Upgrade – Overview

- When beam enters ring, not on the correct trajectory for storage



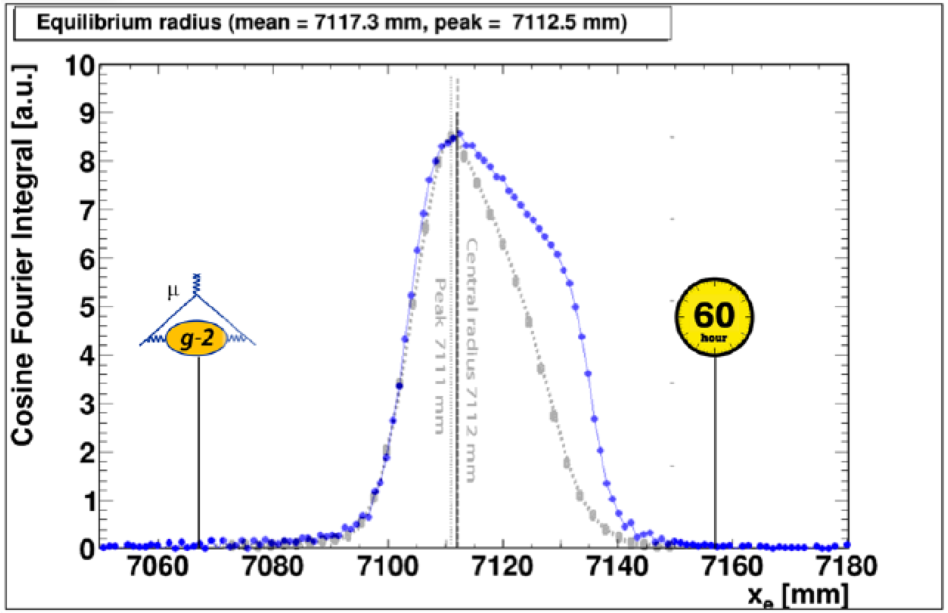
Kicker Upgrade – Overview

- When beam enters ring, not on the correct trajectory for storage
  - Correction comes from three magnets placed ¼ turn from the injection point
  - Reduces field strength by 280G
- Desired pulse time ~120ns
- Put muons onto closed orbit paths



Kicker Upgrade – Run 1 Findings

- Kicker upgrade driven by several observations
  - Aim to improve the muon flux from 50% design mark
  - Analysis revealed radial distribution that suggested under-kicking
    - Additionally generates stronger betatron oscillations
  - Resistive loads were repeatedly damaged
  - PFN measurements showed breakdowns



Kicker Upgrade

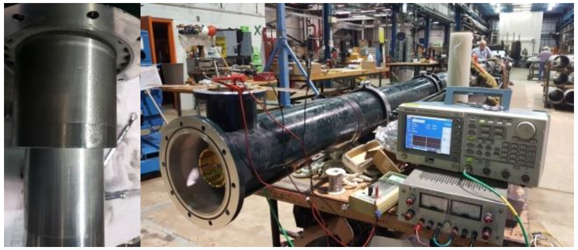
- ***Robust system essential for meeting design goals!***
  - Kicker performance, muon storage, beam systematics

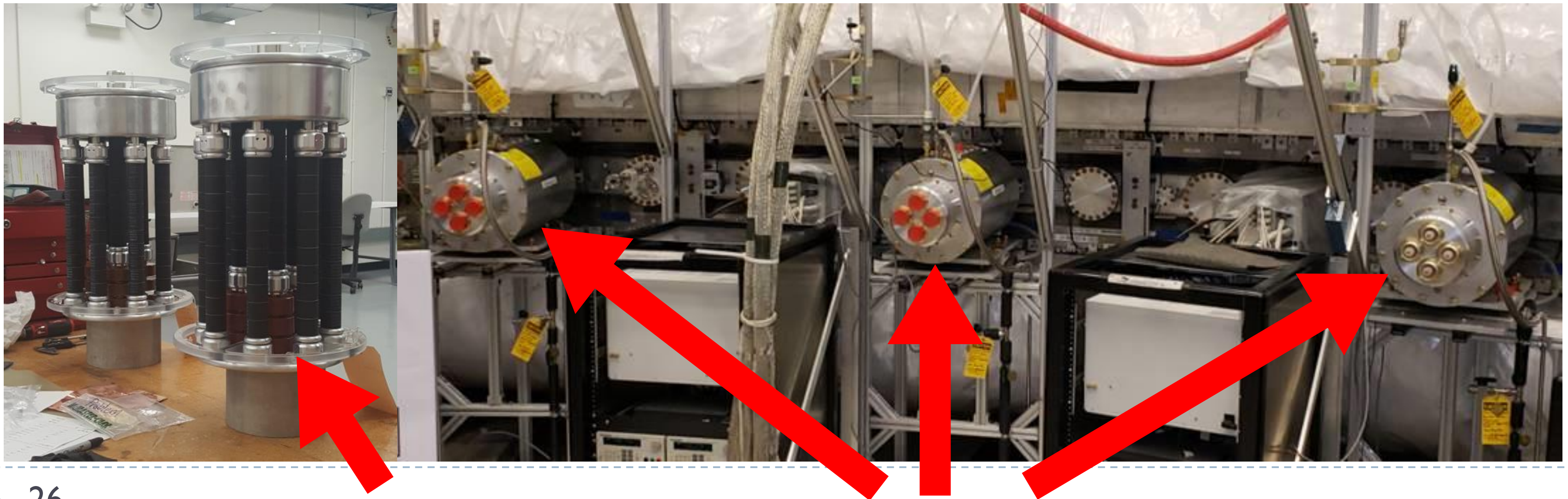
Kicker Upgrade

- <u>*Robust system essential for meeting design goals!*</u>
  - Kicker performance, muon storage, beam systematics
- Blumlein pulsers refurbished
  - Surfaces pitted by sparking were polished
  - New mechanical supports were installed

Kicker Upgrade

- *Robust system essential for meeting design goals!*
  - Kicker performance, muon storage, beam systematics
- Blumlein pulsers refurbished
- New resistive loads (bazookas) were designed and constructed
  - More robust equipment, capacitive 'speed-up' network

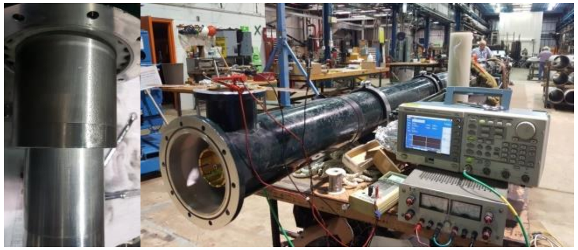




Bazooka Interior **Bazookas Installed**

Kicker Upgrade

- ***Robust system essential for meeting design goals!***
  - Kicker performance, muon storage, beam systematics
- Blumlein pulsers refurbished
- New resistive loads (bazookas) were designed and constructed



- Superior plumbing for cooling and dielectric fluids installed

- New power supply racks designed, built, and installed at Fermilab
- Trigger controls and data acquisition system also improved

Outlook

- The muon magnetic anomaly provides insight into potential BSM physics

- Muon g-2 Run 1 data is currently being analyzed
  - Collected roughly 2X the BNL dataset in three months
  - *Expected result coming later this year, so stay tuned!*

- Significant upgrades were implemented prior to Run 2 that will make the ring systems more robust
  - Kicker system improvements, in particular, will have large impact on muon storage
  - Essential for push to acquiring >20X BNL dataset

Back-Up

The Beam Profile

- Coherent betatron oscillations generated shape of snapshot on Slide 13
  - Consequence of betatron oscillations and detector sampling
  - Understanding behavior critical for measurement