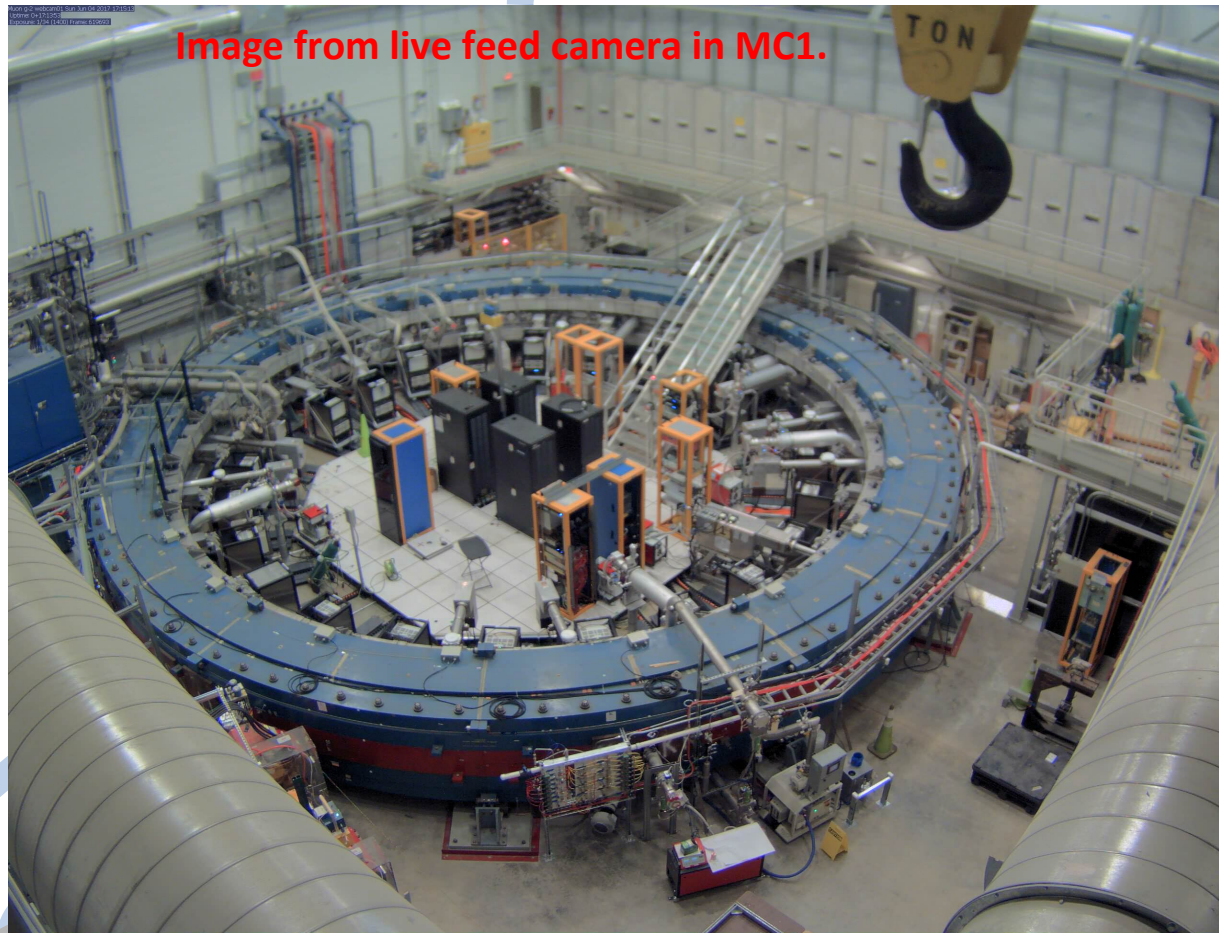


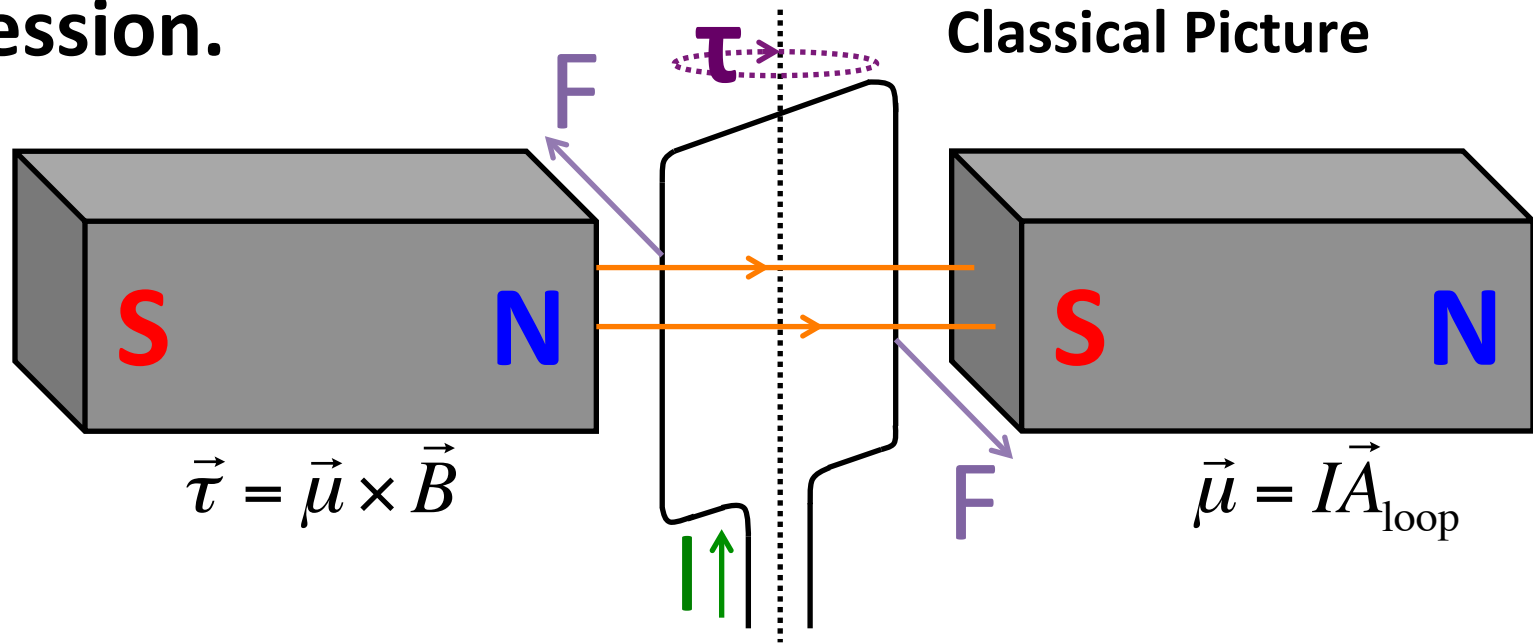
# Muon g-2 Experiment

Jason D. Crnkovic on behalf of the Muon g-2 Collaboration

Fermilab 50<sup>th</sup> Anniversary Users Meeting:  
Thursday, June 8<sup>th</sup>, 2017



# Intrinsic magnetic dipole moments leads to spin precession.



## Quantum Picture

Charged leptons and quark have intrinsic spin.

$$\vec{\mu} = g \left( \frac{q}{2m} \right) \vec{s}$$

Larmor Precession (particle rest frame):

$$\frac{d\vec{s}}{dt} = \vec{\tau} = g \left( \frac{q}{2m} \right) \vec{s} \times \vec{B}$$

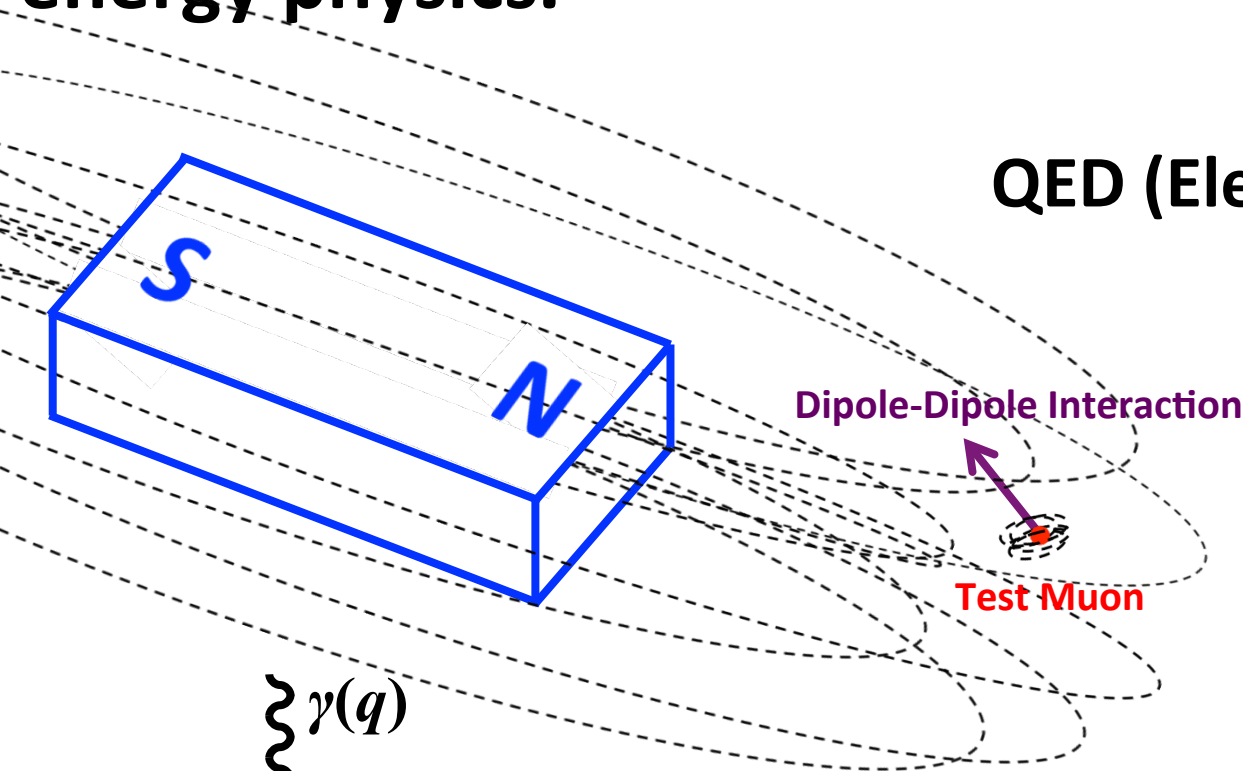
Dirac Equation for EM potential:

$$\left[ i\gamma^\mu (\partial_\mu + ieA_\mu) - m \right] \psi = 0$$

- Spin-1/2 point particles
- Leads to Pauli Theory
- Naturally predicts  $g = 2$

# Muon g-2 uses a low energy parameter to probe high energy physics.

## QED (Electromagnetism)



A Feynman diagram showing a muon vertex. A circle with a cross inside represents the vertex. A wavy line labeled  $\gamma(q)$  enters from the top. Two solid lines labeled  $\mu(p_1)$  and  $\mu(p_2)$  enter from the bottom left and bottom right, respectively.

$$= (-ie) \bar{u}(p_2) \left[ \gamma^\mu \boxed{F_E(q^2)} + i \frac{\sigma^{\mu\nu} q_\nu}{2m_\mu} \boxed{F_M(q^2)} \right] u(p_1)$$

Dirac (electric) Form Factor:  $F_E(q^2)$

$F_E(0) = 1$

(Charge Renormalization)

Pauli (Magnetic) Form Factor:  $F_M(q^2)$

$F_M(0) = a = (g - 2) / 2$

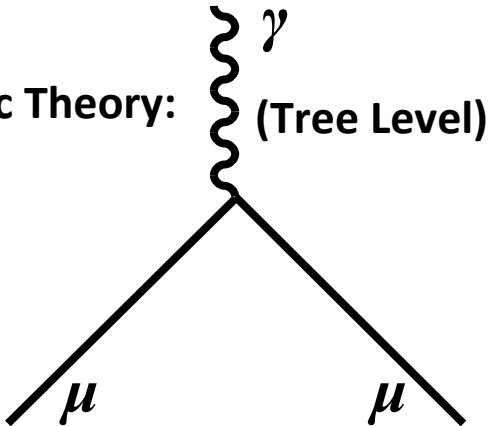
(Finite Prediction For a)

# Vacuum effects matter ....

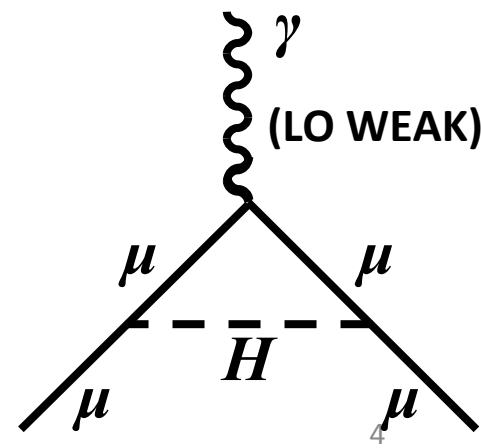
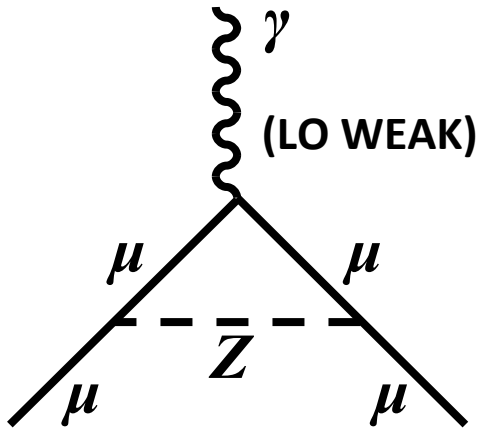
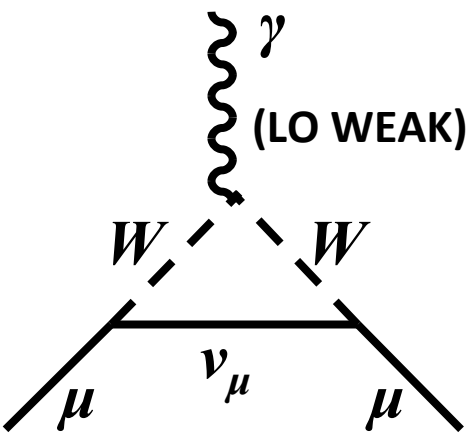
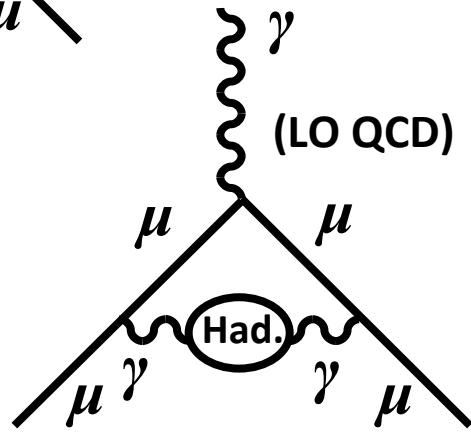
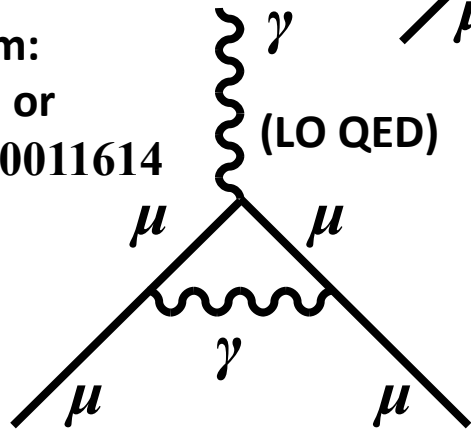
Brookhaven Measurement  
(updated  $\lambda$ )

$g_\mu = 2.00233184182$  or  
 $a_\mu = 0.00116592091$

Corresponds to Dirac Theory:  
 $g_\mu = 2$  or  
 $a_\mu = 0$



Schwinger Term:  
 $g_\mu \sim 2.0023228$  or  
 $a_\mu = \alpha / 2\pi \sim 0.0011614$





# Vacuum effects matter ....

Brookhaven Measurement  
(updated  $\lambda$ )

$$g_\mu = 2.00233184182 \text{ or}$$

$$a_\mu = 0.00116592091$$

Corresponds to Dirac Theory:

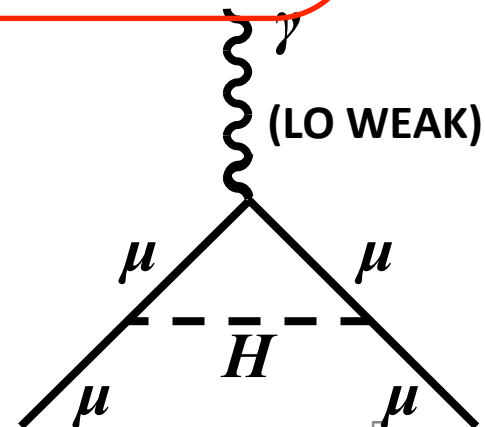
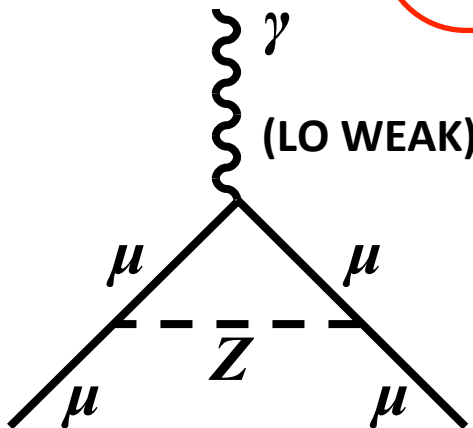
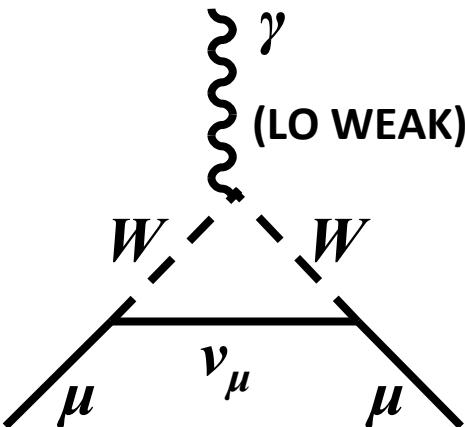
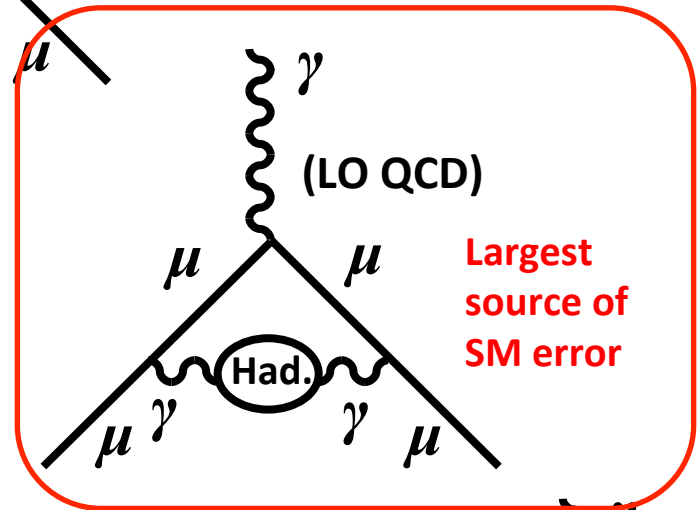
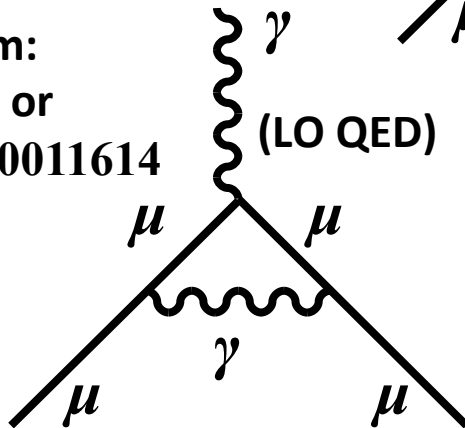
$$g_\mu = 2 \text{ or}$$

$$a_\mu = 0$$

Schwinger Term:

$$g_\mu \sim 2.0023228 \text{ or}$$

$$a_\mu = \alpha / 2\pi \sim 0.0011614$$



# BNL has a long love affair with Muon g-2.

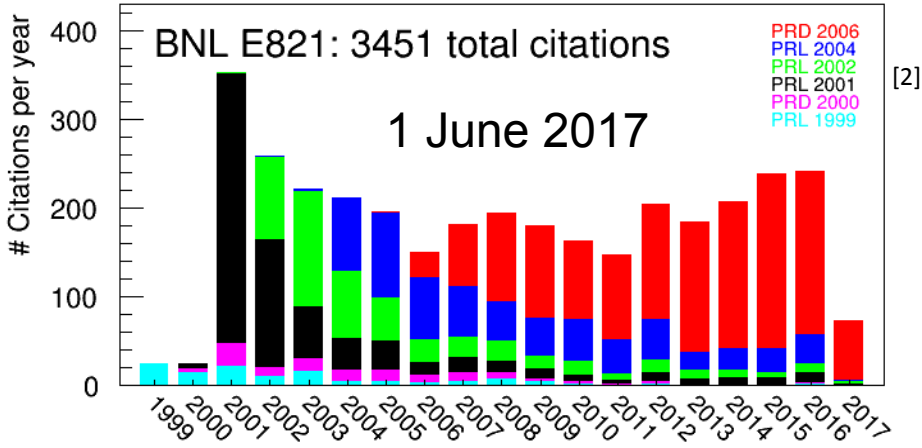
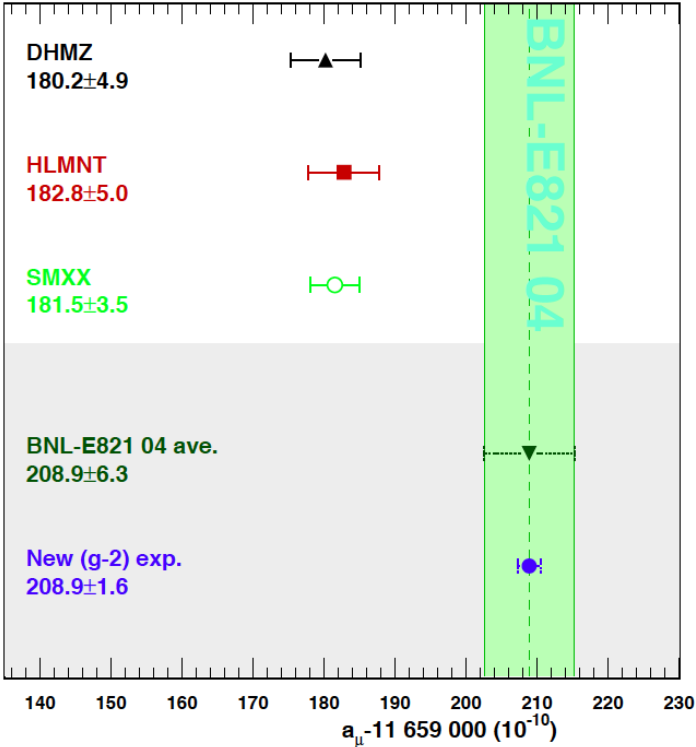
[1]



**Figure 2** Photograph from 1984 workshop at Brookhaven National Laboratory. Standing, from left: G. Danby, J. Field, F. Farley, E. Picasso, and F. Krienen; kneeling, from left: J. Bailey, V. Hughes, and F. Combley.

**Last data run period was 2001.**  
**BNL Experiment review article published 2006.**

[3]



[1] D. W. Hertzog and W. M. Morse, Ann. Rev. Nucl. Part. Sci. **54**, 141 (2004).  
[2] B. L. Roberts, First Workshop of the Muon g-2 Theory Initiative  
[3] T. Blum, A. Denig, I. Logashenko, E. de Rafael, B. Lee Roberts, T. Teubner and G. Venanzoni, arXiv:1311.2198 [hep-ph].

# Fermilab Muon g-2 Collaboration ...



## US Universities

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois
- Regis
- Texas
- Virginia
- Washington

## National Labs

- Argonne
- Brookhaven
- Fermilab



## Italy

- INFN
  - LNF Frascati,
  - Naples
  - Pisa
  - Roma 2
  - Trieste
  - Lecce
- Udine
- Naples
- Trieste
- Rijeka
- Molise
- SNS Pisa



## England

Cockcroft Institute  
Lancaster  
Liverpool  
University College London



## Korea

KAIST



## Russia

Dubna  
Novosibirsk



## China

- Shanghai



## The Netherlands

- Groningen



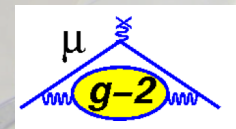
## Germany

- Dresden (thy)

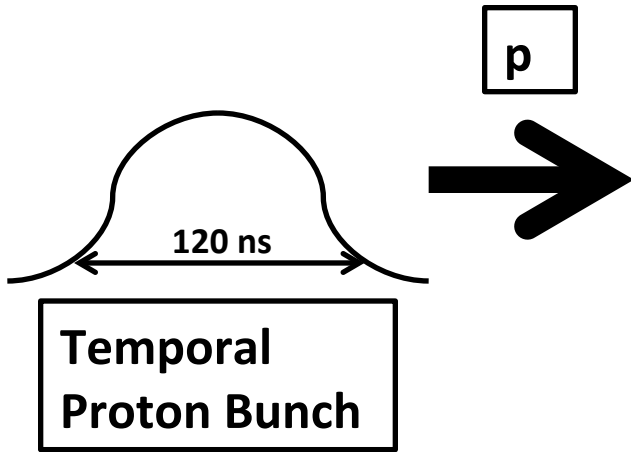
- D.W. Hertzog, Co-Spokesperson
- B.L. Roberts, Co-Spokesperson
- C. Polly, Project Manager
- B.C. Casey Co-Run Coordinator
- J.M. Grange Co-Run Coordinator



Fermilab



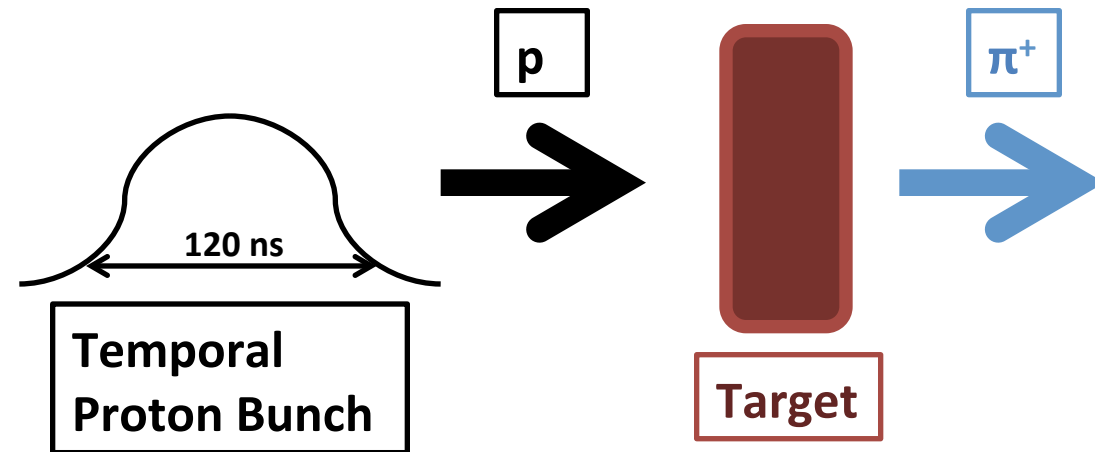
# Fermilab Muon g-2 Experiment, the flip book:



- Start with a proton bunch

Not to scale

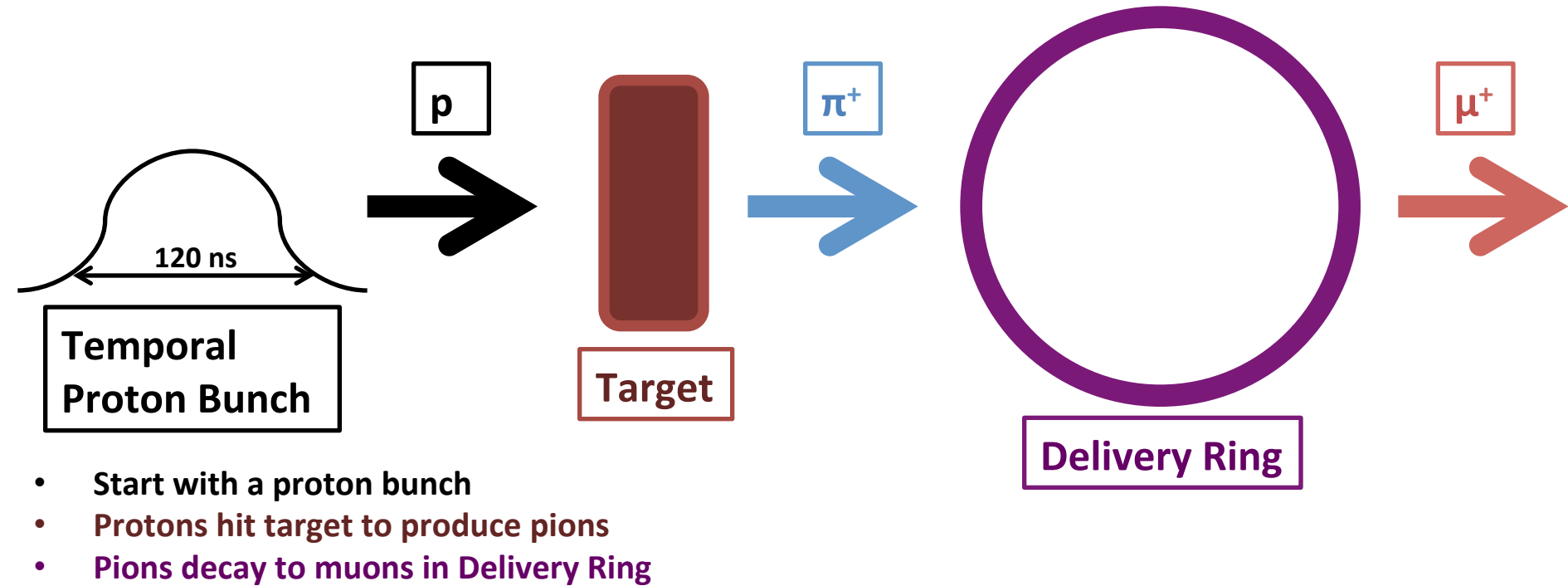
# Fermilab Muon g-2 Experiment, the flip book:



- Start with a proton bunch
- Protons hit target to produce pions

Not to scale

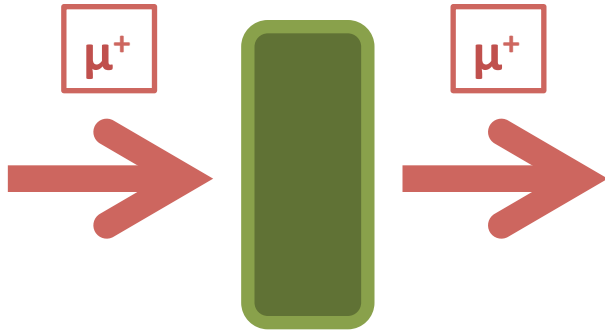
# Fermilab Muon g-2 Experiment, the flip book:



Not to scale



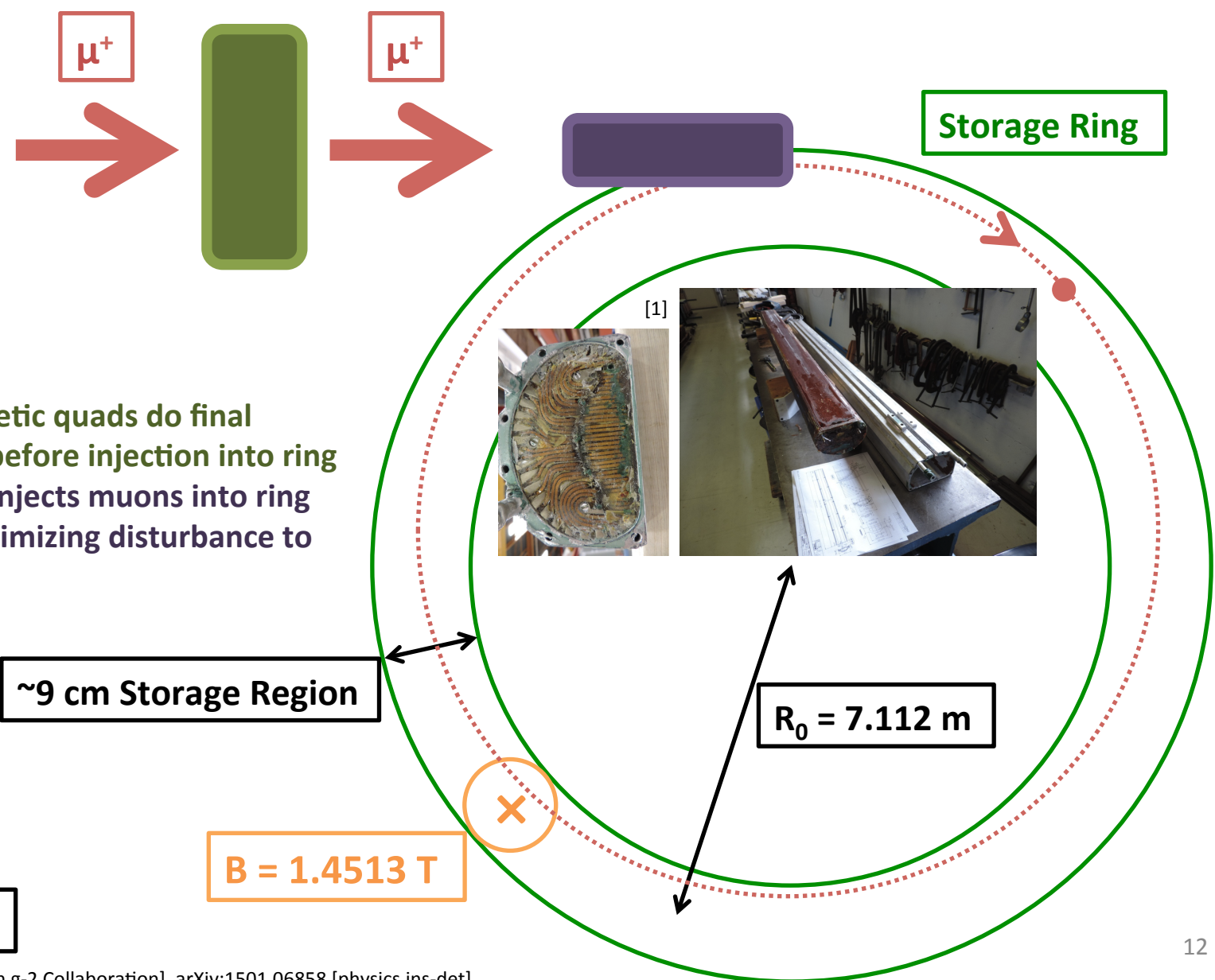
# Fermilab Muon g-2 Experiment, the flip book:



- M5 magnetic quads do final focusing before injection into ring

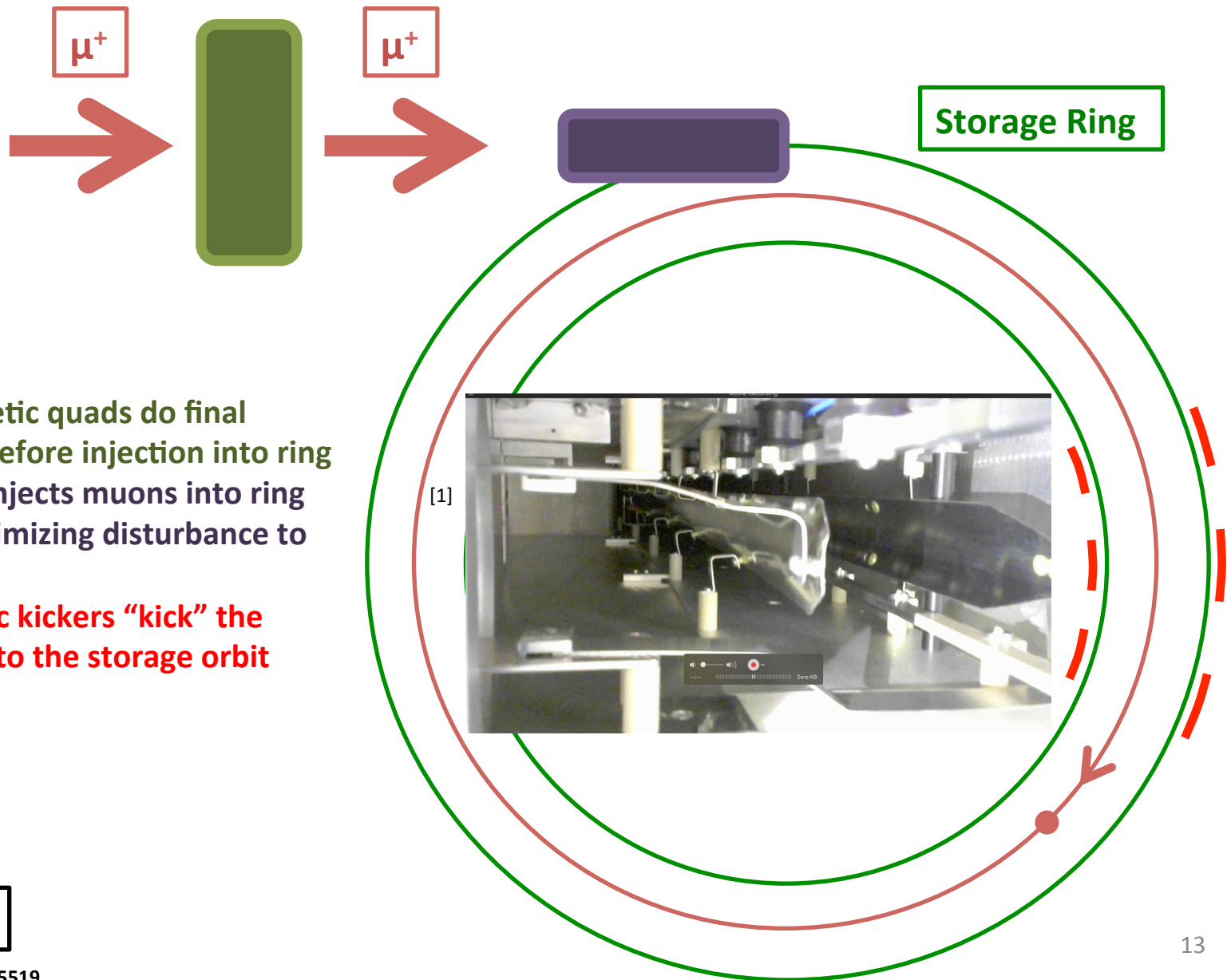
Not to scale

# Fermilab Muon g-2 Experiment, the flip book:



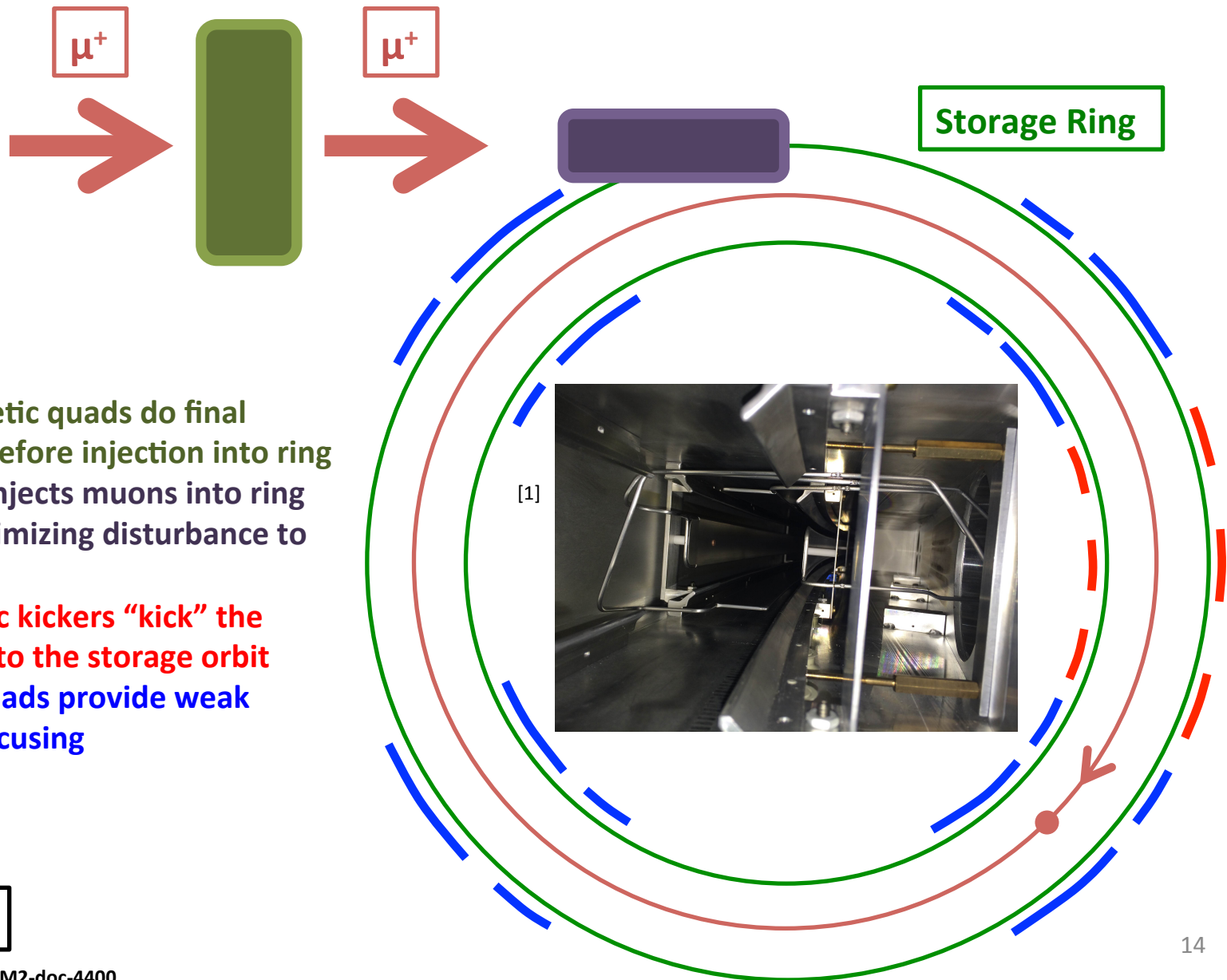
[1] J. Grange *et al.* [Muon g-2 Collaboration], arXiv:1501.06858 [physics.ins-det].

# Fermilab Muon g-2 Experiment, the flip book:

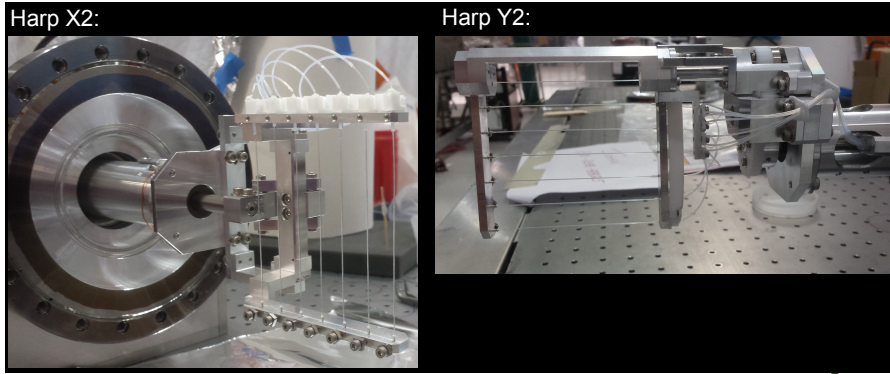


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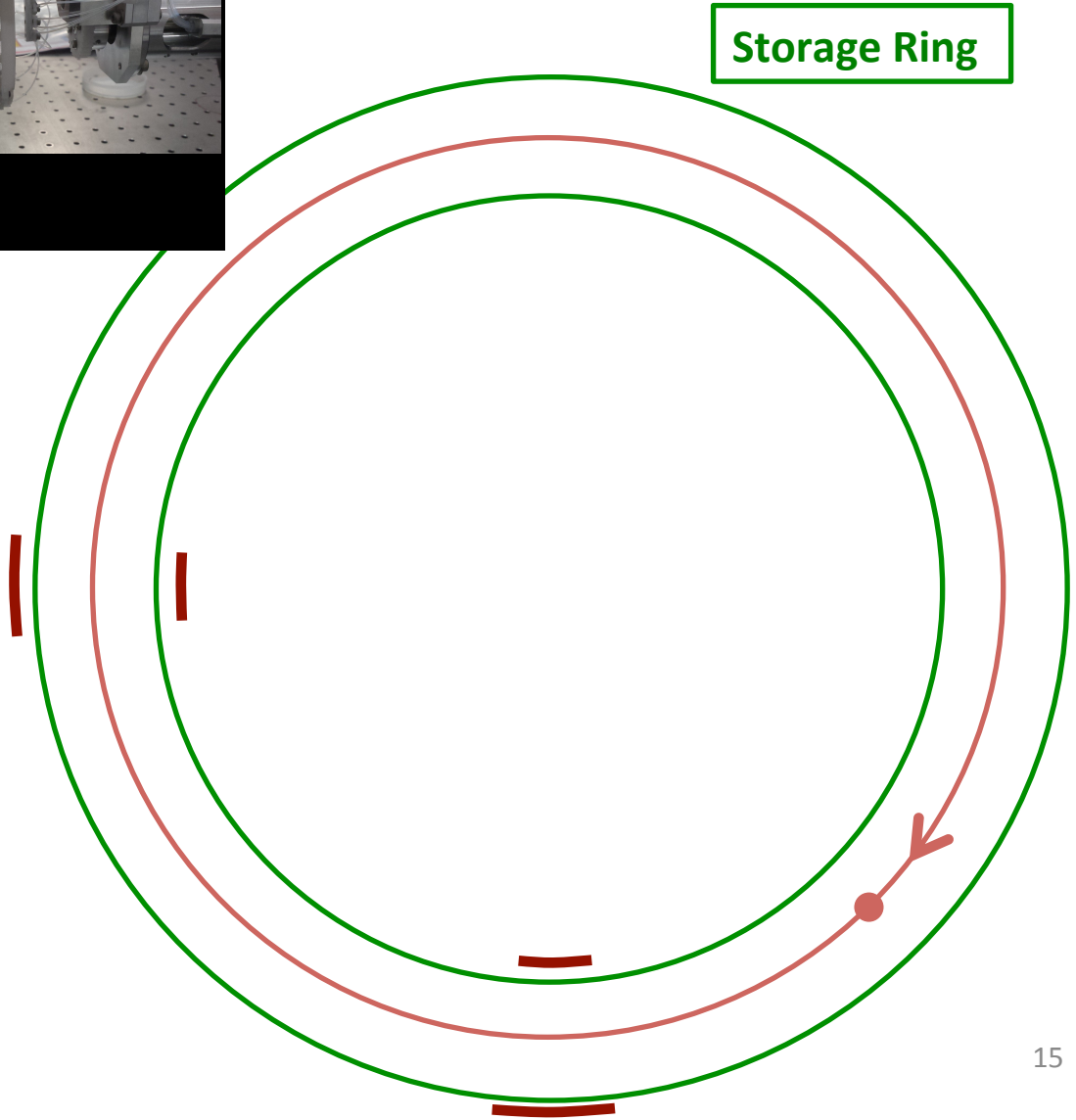
# Fermilab Muon g-2 Experiment, the flip book:



# Fermilab Muon g-2 Experiment, the flip book:

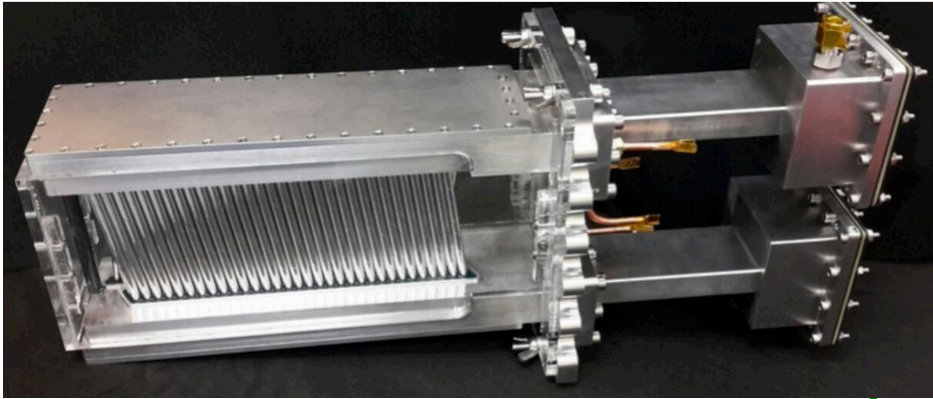


- 180° and 270° fiber profile beam monitors



Not to scale

# Fermilab Muon g-2 Experiment, the flip book:

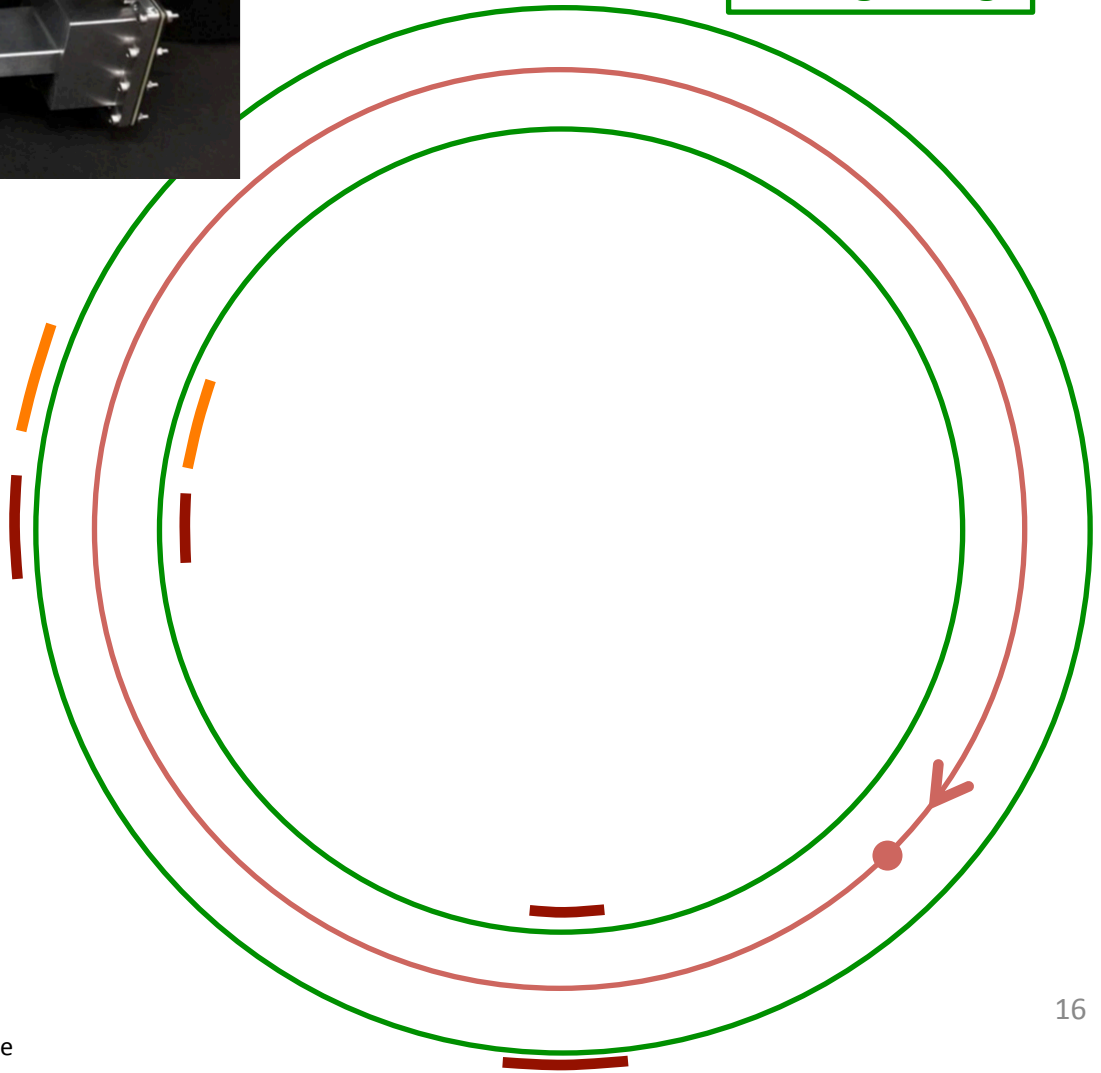


[1]

Storage Ring

- 180° and 270° fiber profile beam monitors
- Straw tracker station provides decay positron trajectory reconstruction

Not to scale

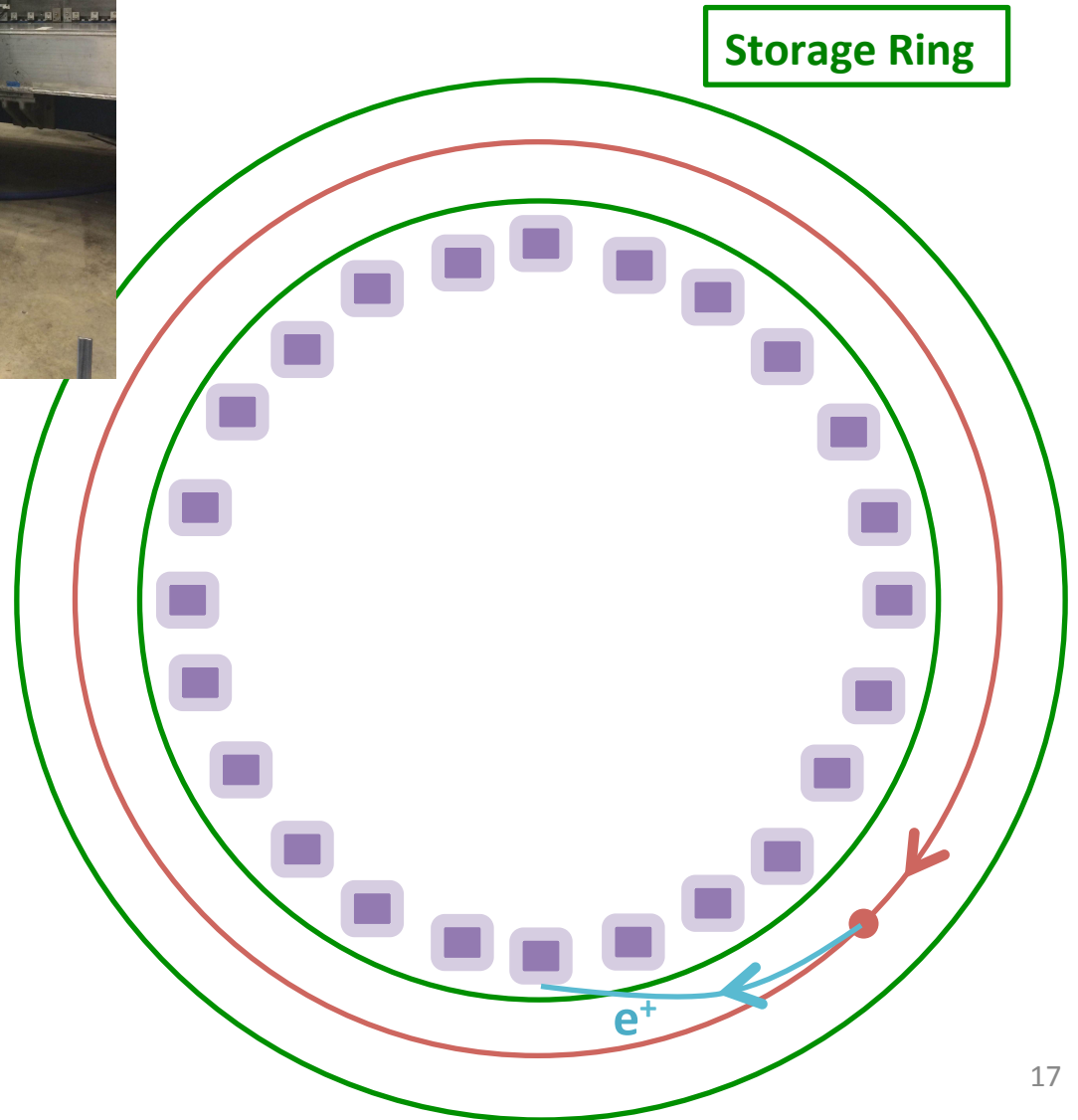




# Fermilab Muon g-2 Experiment, the flip book:

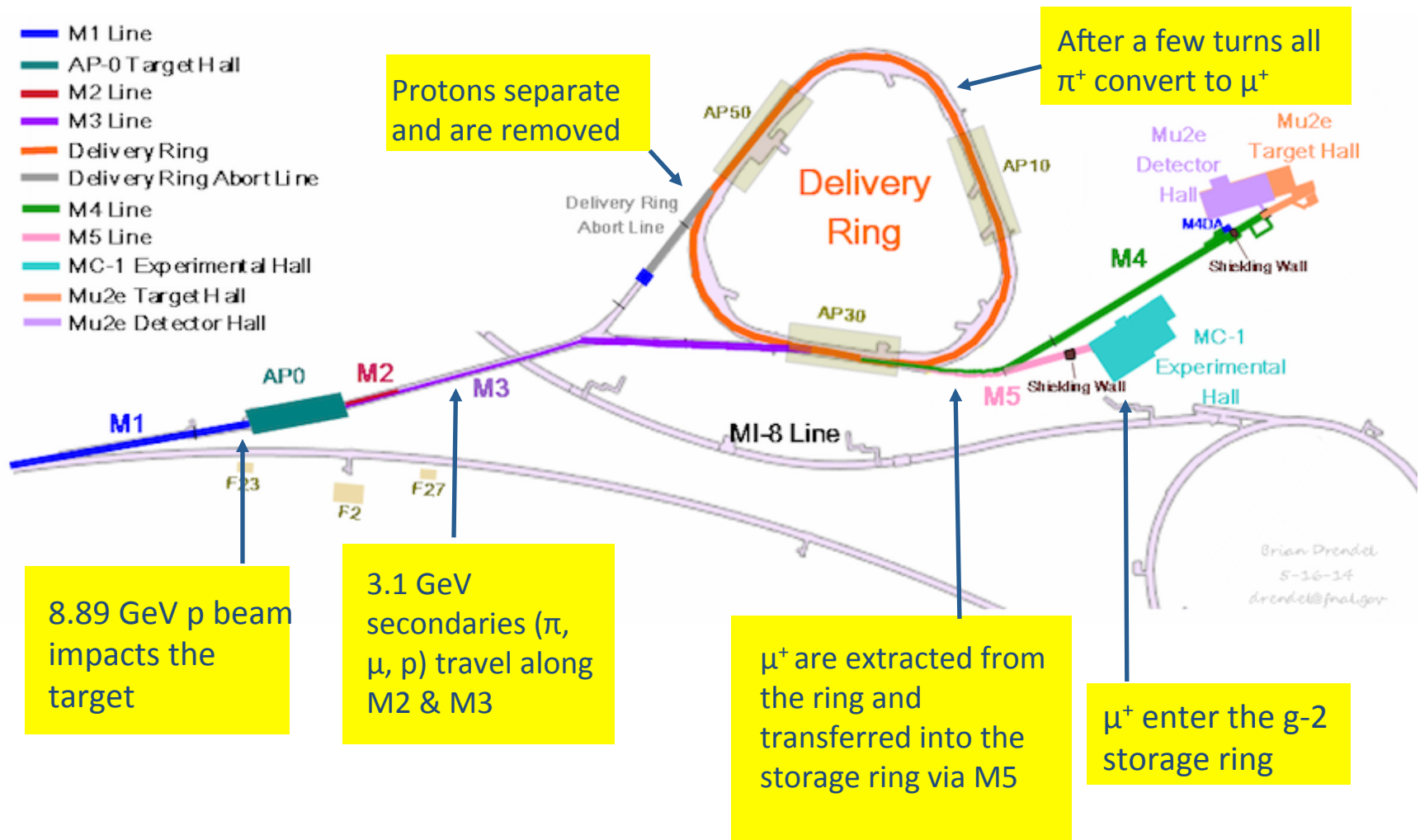


- 24 calorimeters detect decay positron arrival time and energy



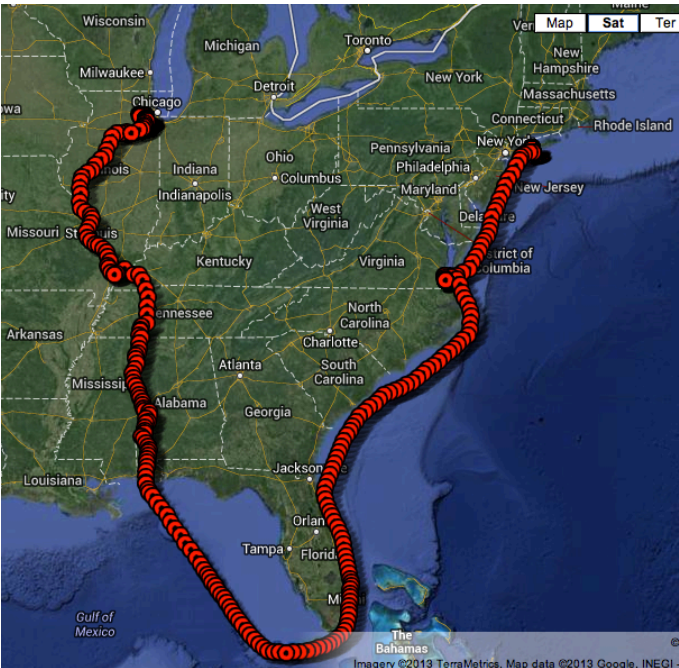
Not to scale

# Fermilab beamline decays away most of the pions.



# BNL muon storage ring was moved to Fermilab.

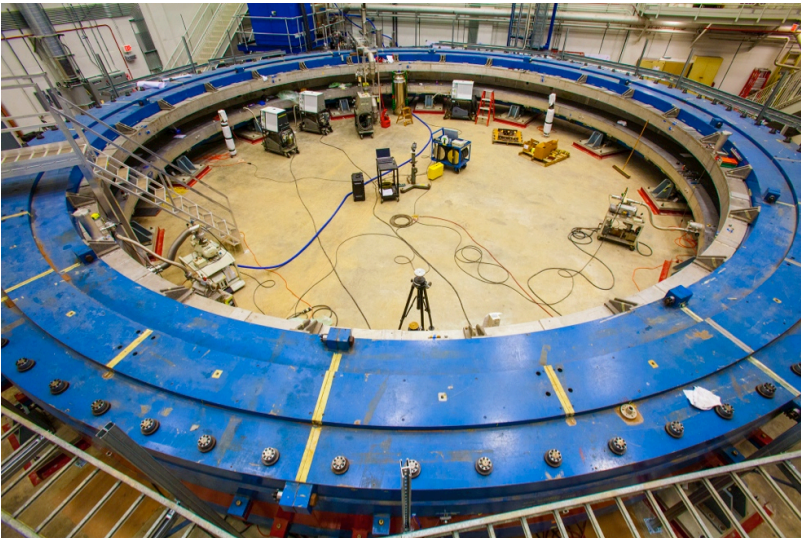
[1]



[2]



[2]



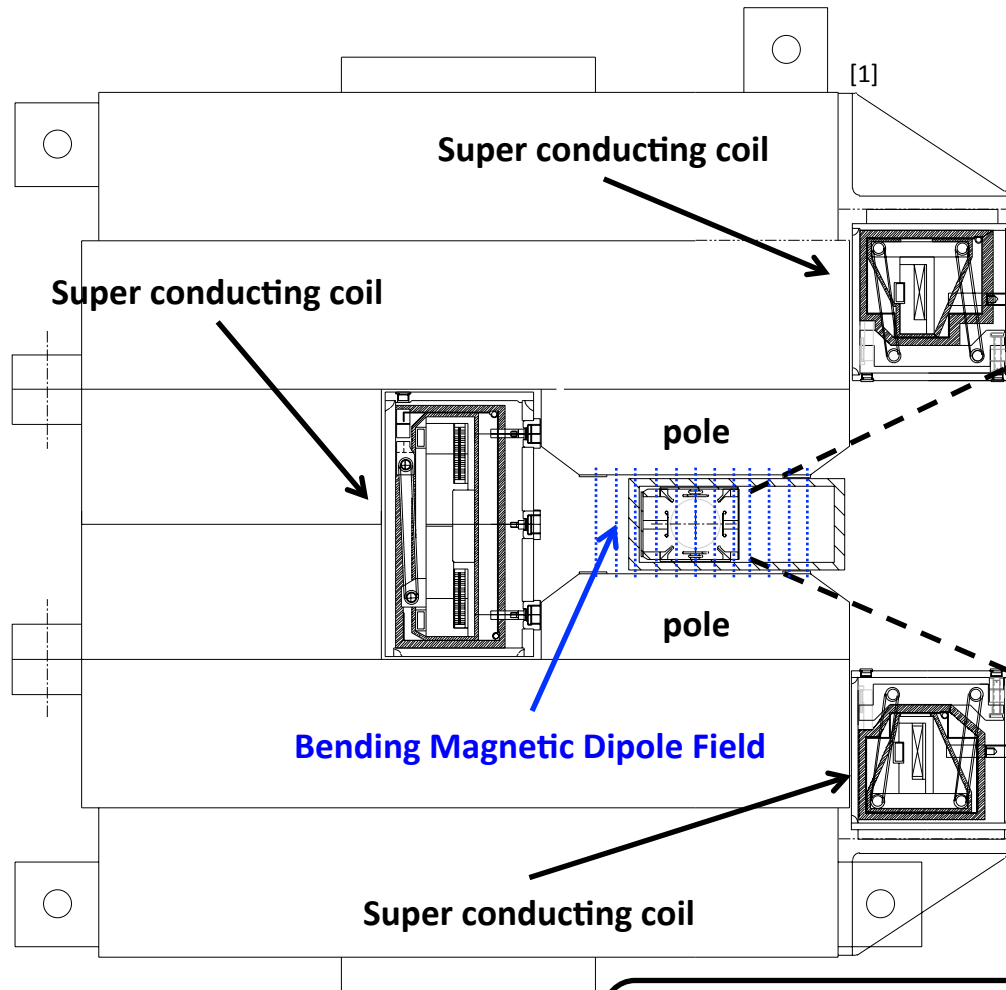
[2]



[1] C. Polly, GM2-doc-4096  
[2] C. Polly and E. Swanson, GM2-doc-4284



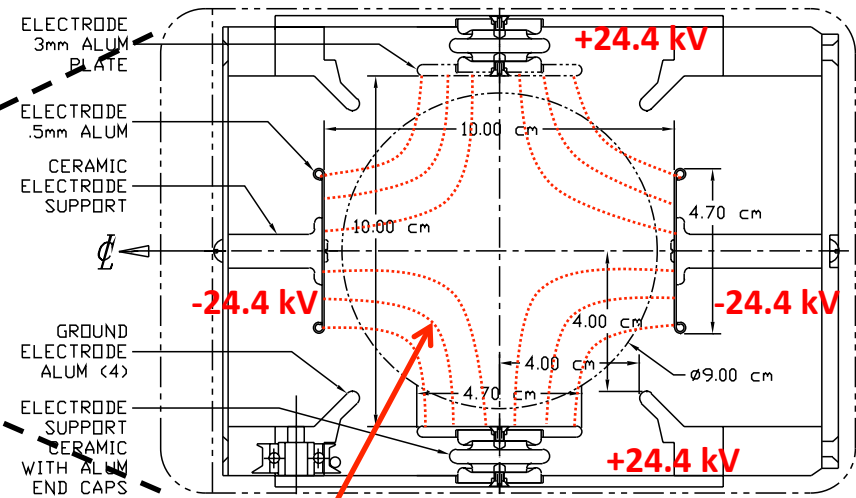
# BNL and Fermilab experiments use a weak focusing muon storage ring.



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

0 when  $\gamma = 29.3$

[1]



ELECTRODE AND SUPPORT FRAME - END VIEW

E821  $\mu^+$  plate voltages  
Scraping sets bottom, Q2 inner,  
and Q4 outer plates to  $\pm 17$  kV.

Horizontal And Vertical Tunes:

$$\nu_x \approx \sqrt{1-n}$$

$$\nu_y \approx \sqrt{n}$$

Focusing Electric  
Quadrupole  
Field

# The muon anomalous magnetic moment is obtained from 5 numbers.

Anomalous spin precession frequency is extracted from decay positron time spectra

$$a_\mu = \frac{\frac{g_e}{2} \frac{m_\mu}{m_e} \omega_a}{\frac{\mu_e}{\mu_p}}$$

Diagram illustrating the components of the muon anomalous magnetic moment  $a_\mu$ . The numerator consists of three terms:  $g_e$  (blue box),  $m_\mu/m_e$  (orange box), and  $\omega_a$  (red box). The denominator consists of two terms:  $\mu_e$  (green box) and  $\mu_p$  (green box). A red arrow points from the text "Anomalous spin precession frequency is extracted from decay positron time spectra" to  $\omega_a$ . A purple arrow points from the text "Average magnetic field seen by muons is measured with NMR" to the denominator.

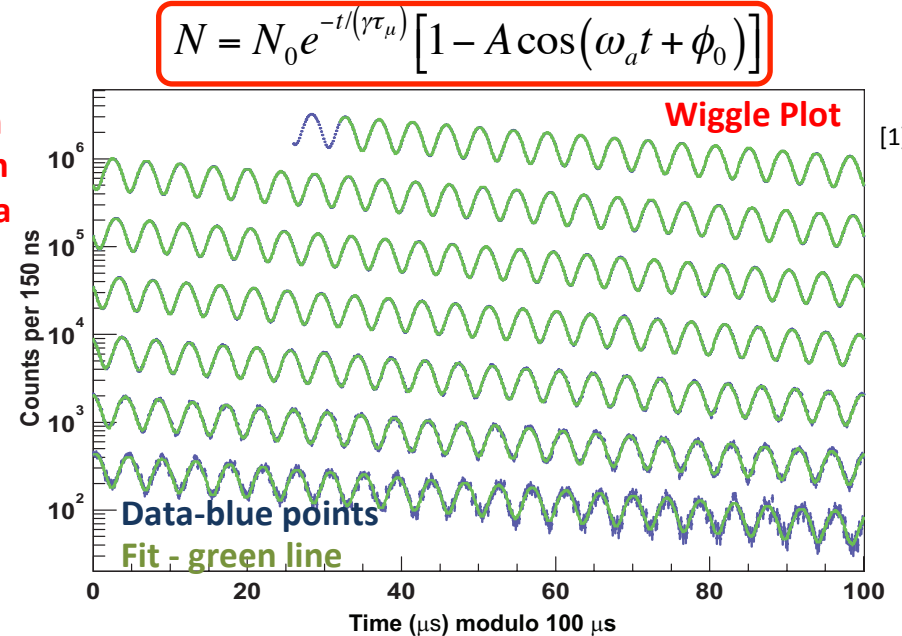
Get from CODATA<sup>[3]</sup>:

$g_e = -2.002\,319\,304\,361\,82(52)$  (0.00026 ppb)

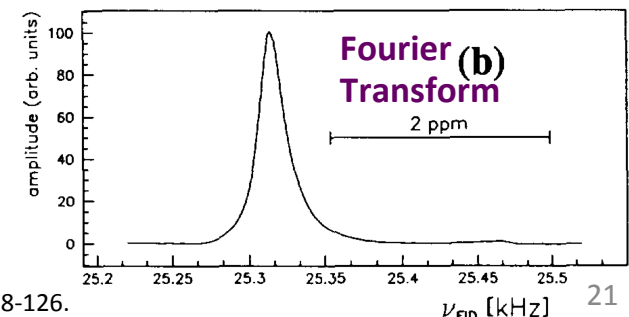
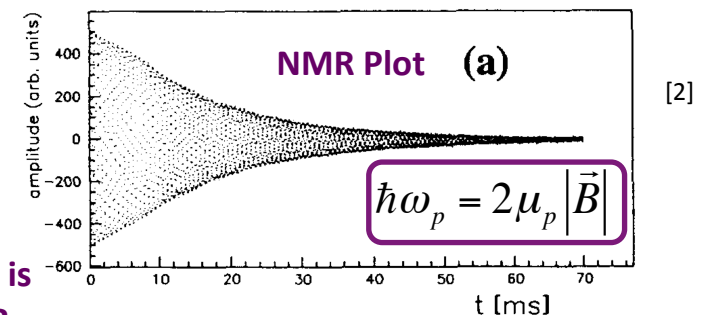
$m_\mu/m_e = 206.768\,2826(46)$  (22 ppb)

$\mu_e/\mu_p = -658.210\,6866(20)$  (3.0 ppb)

Fermilab Experiment  $a_\mu$  total error goal is 140 ppb



Average magnetic field seen by muons is measured with NMR

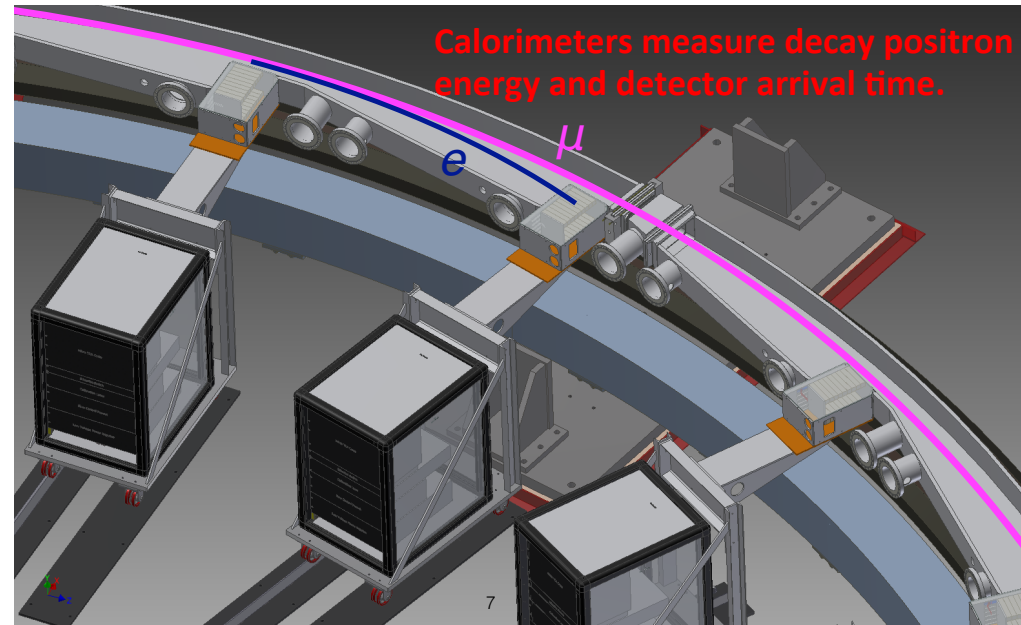
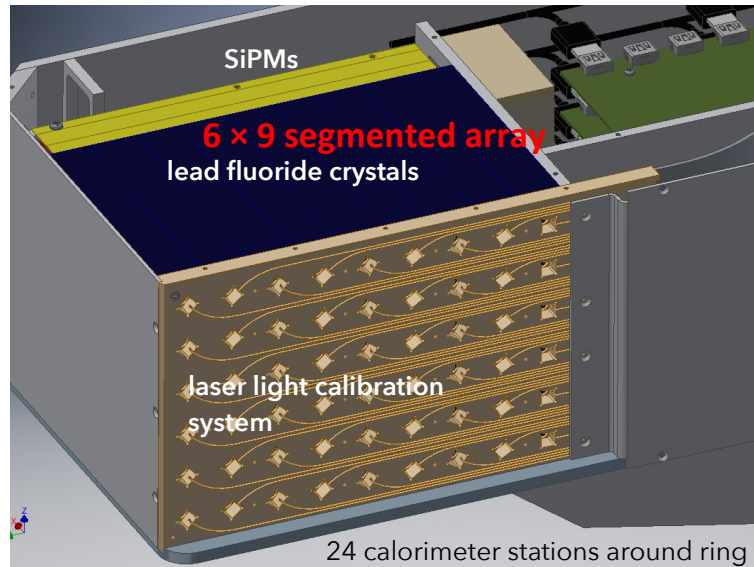


[1] J. Grange *et al.* [Muon g-2 Collaboration], arXiv:1501.06858 [physics.ins-det].

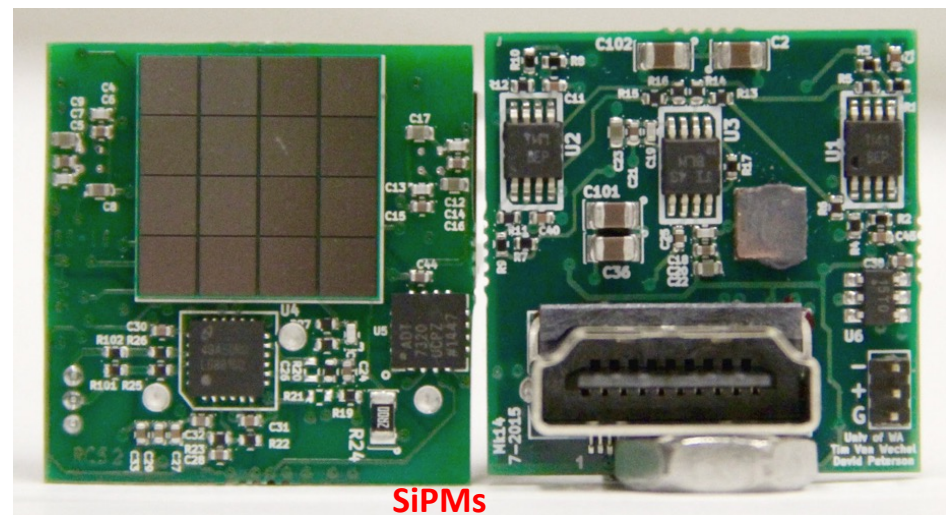
[2] R. Prigl, U. Haeberlen, K. Jungmann, G. zu Putlitz and P. von Walter, Nucl. Instr. Methods A 374 (1996) 118-126.

[3] P. J. Mohr, D. B. Newell and B. N. Taylor, Rev. Mod. Phys. **88**, no. 3, 035009 (2016) doi:10.1103/RevModPhys.88.035009 [arXiv:1507.07956 [physics.atom-ph]].

# Wiggle plots are created by applying a suitable energy threshold cut to the decay positron data.



[1]

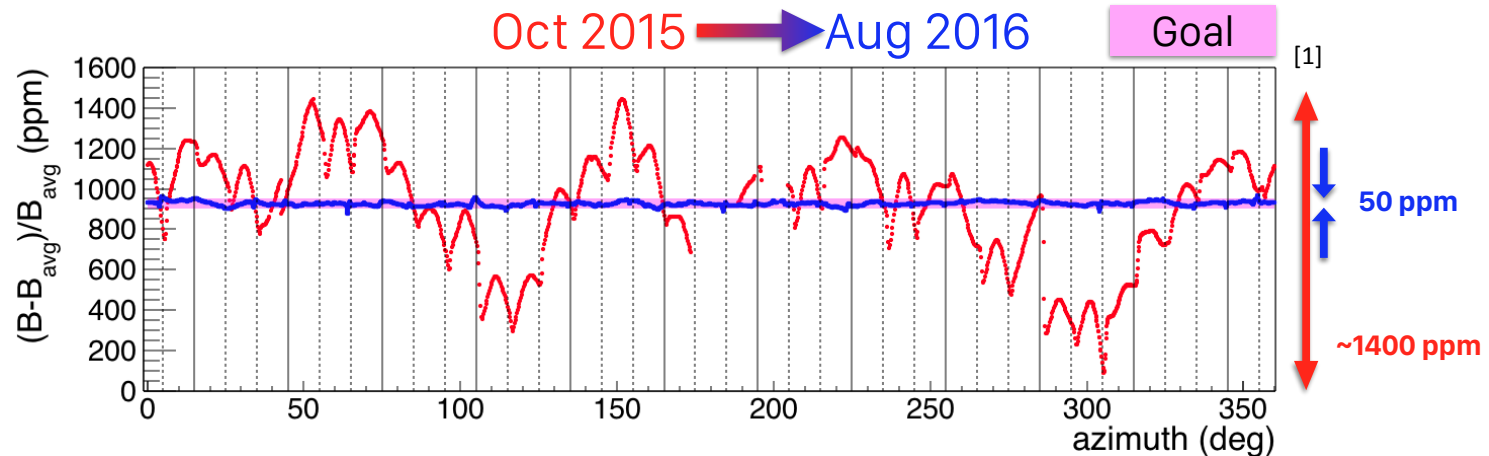




**Trolley is used to measure muon storage region magnetic field during data collection.**

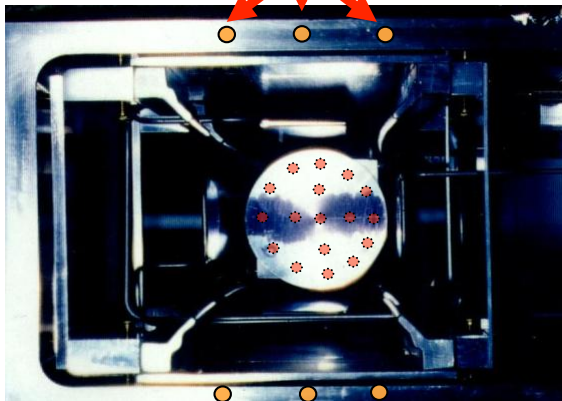
## Rough Shimming Results

**Storage ring field is shimmed to be highly uniform to reduce systematic errors**

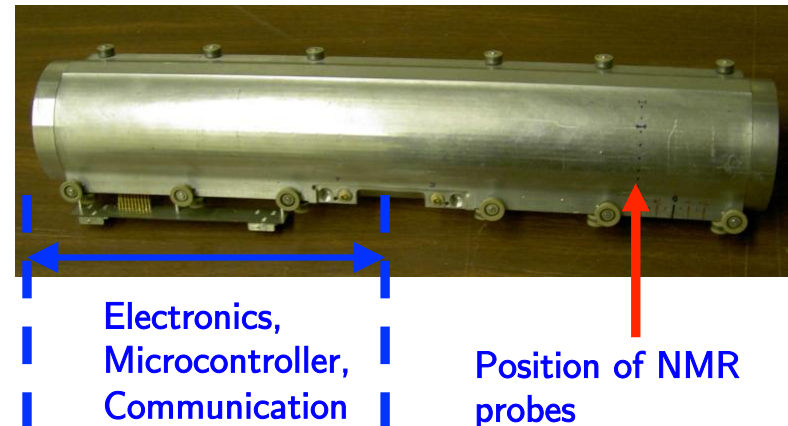


**Trolley can be pulled around storage ring when beam is not being delivered.**

Fixed probes on vacuum chambers



Trolley with matrix of 17 NMR probes

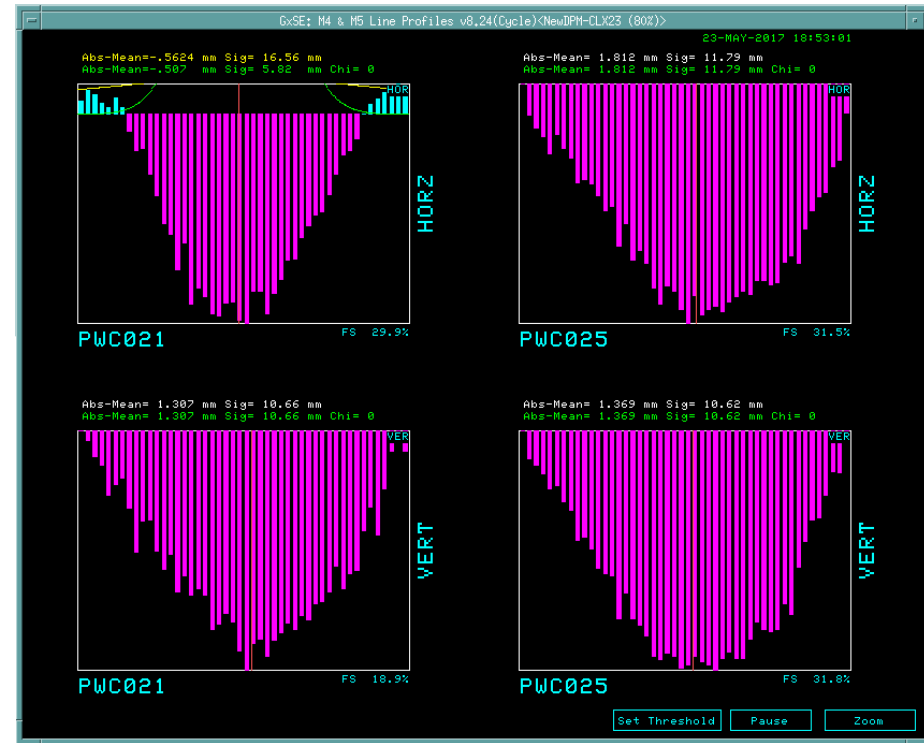
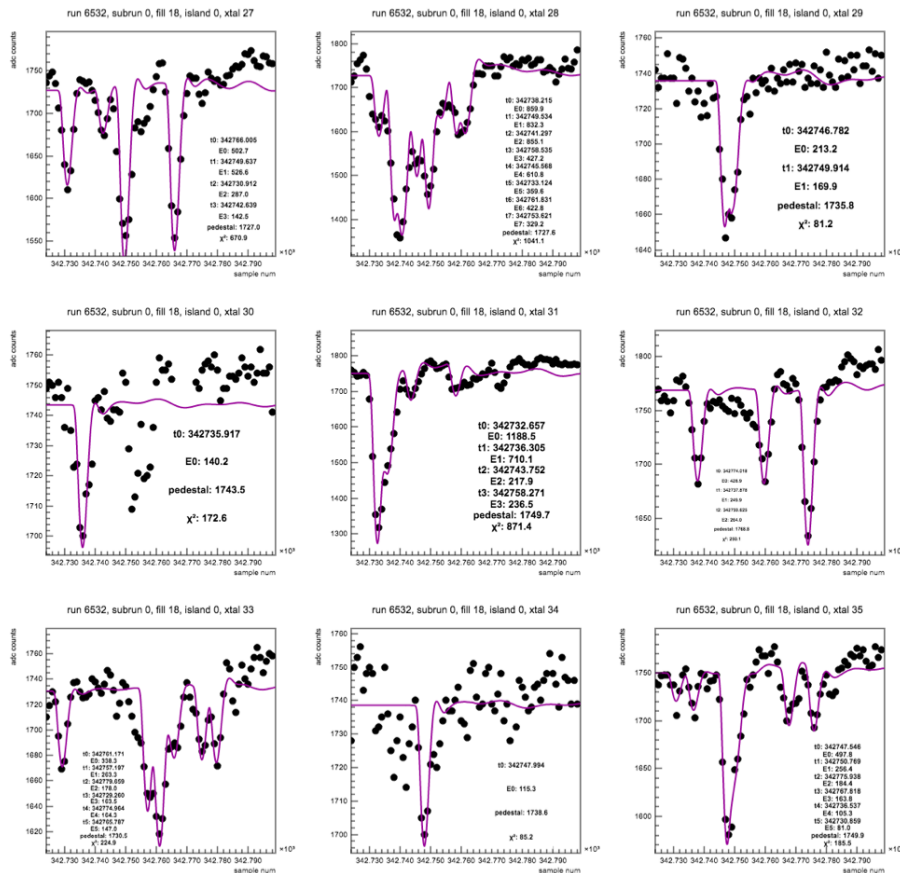


[1] D. Flay, GM2-doc-4410

[2] R. Hong, GM2-doc-4872

# Fermilab Muon g-2 experiment is currently in the commissioning phase.

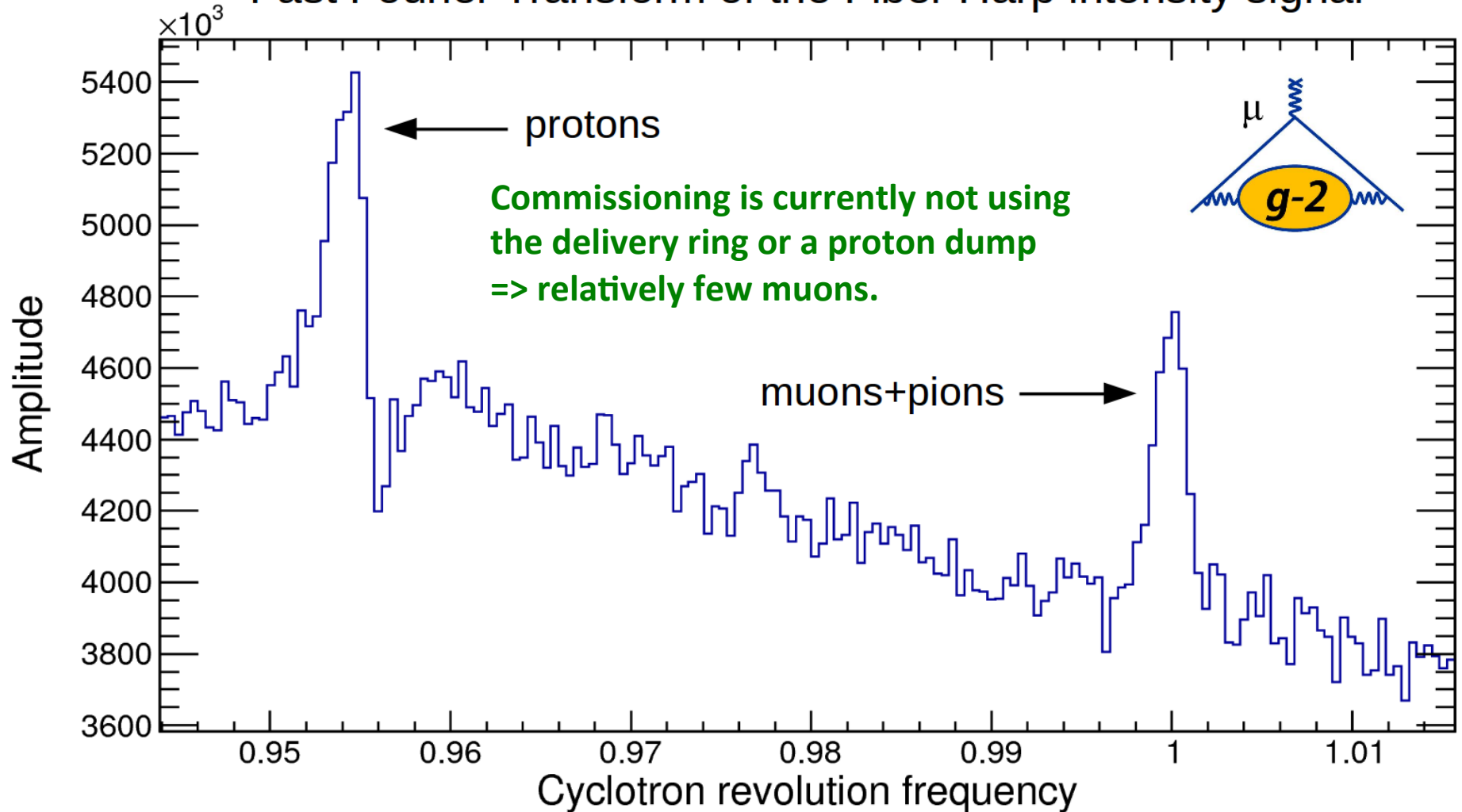
Splash of beam hitting calorimeter 24.



Beam profile on last PWC just before the storage ring entrance

# Fermilab Muon g-2 experiment is currently in the commissioning phase.

Fast Fourier Transform of the Fiber Harp intensity signal

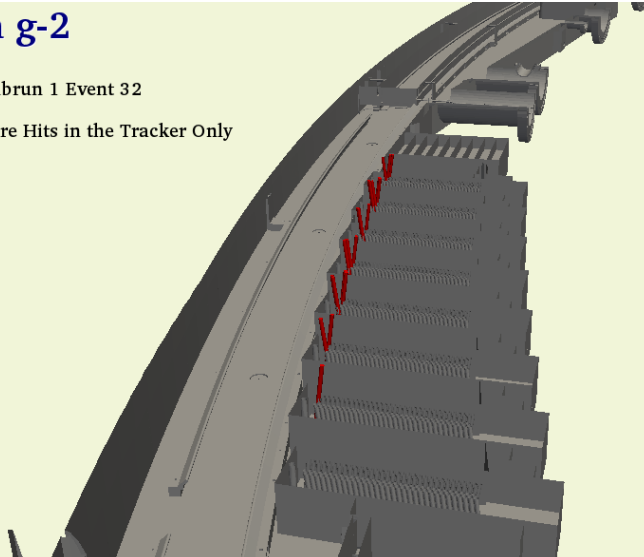


# Fermilab Muon g-2 experiment is currently in the commissioning phase.

## Muon g-2

Run 102 Subrun 1 Event 32

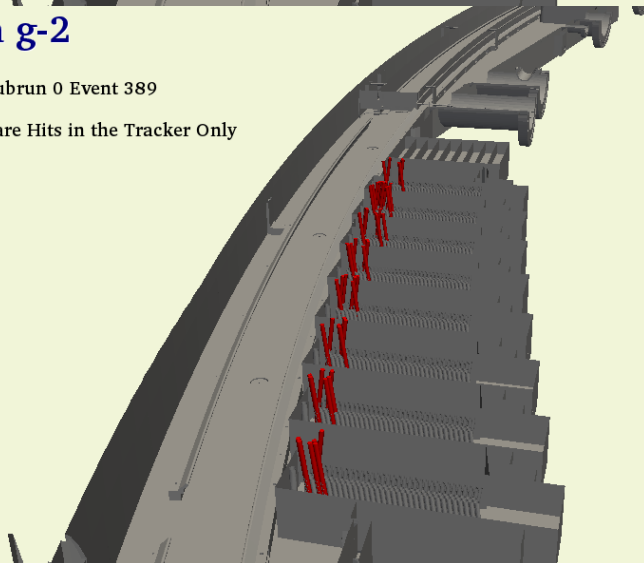
Displayed are Hits in the Tracker Only



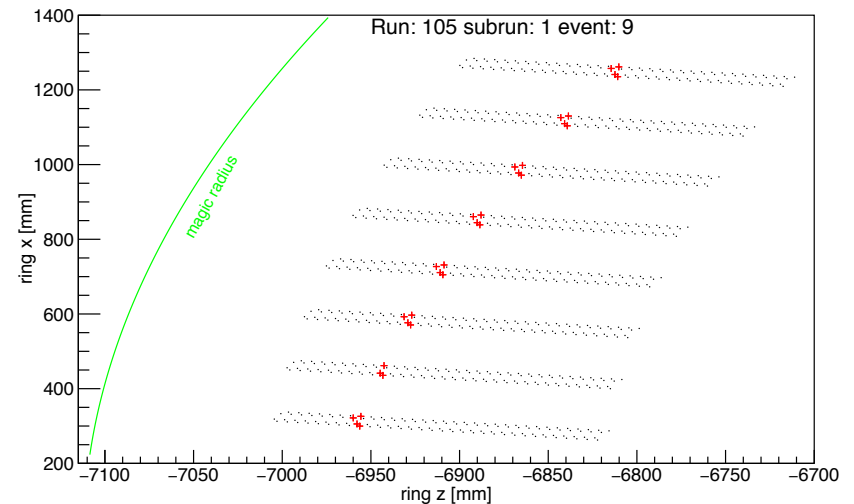
## Muon g-2

Run 104 Subrun 0 Event 389

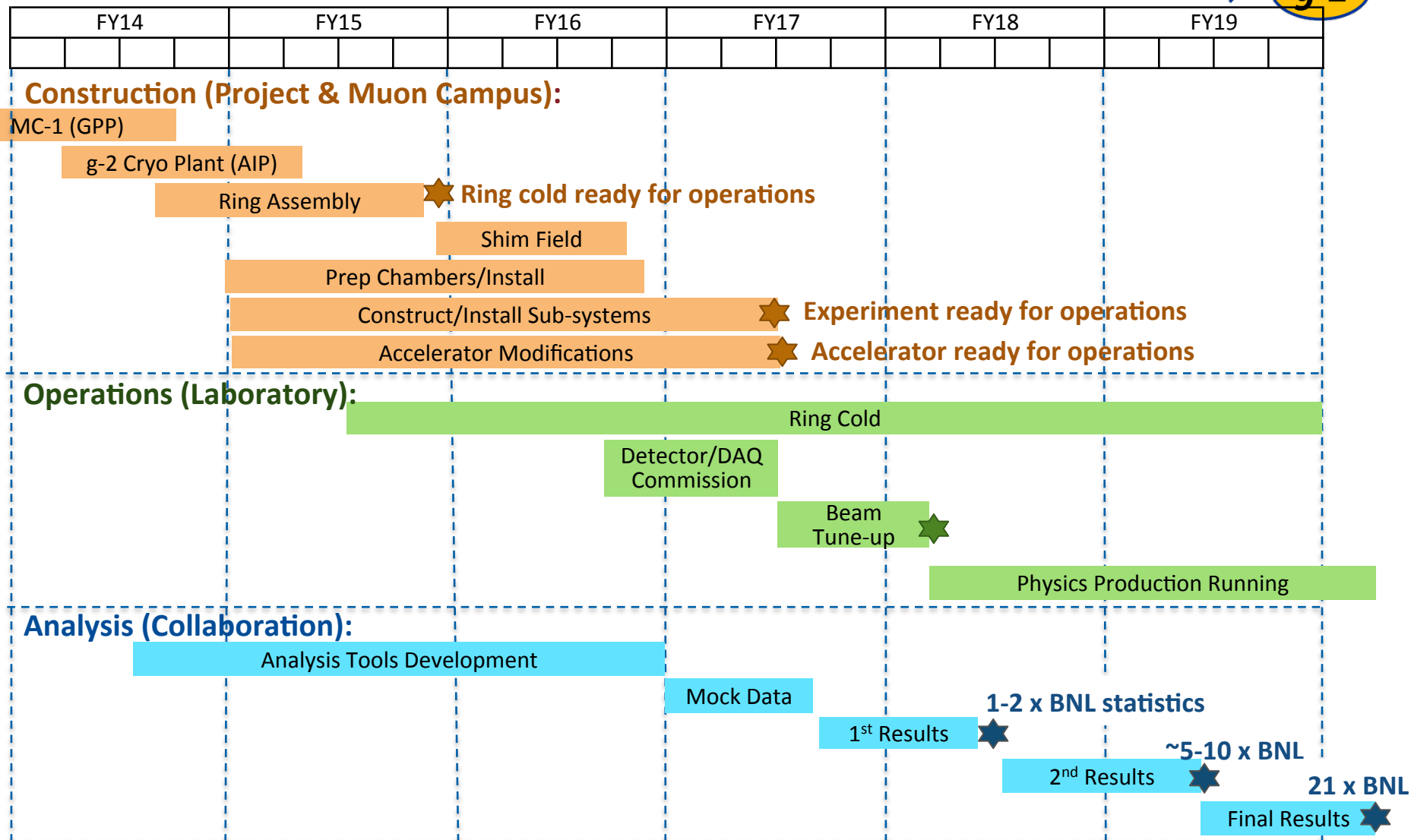
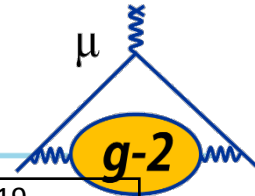
Displayed are Hits in the Tracker Only



Example tracker straw hits from commissioning data.



# Project Timeline





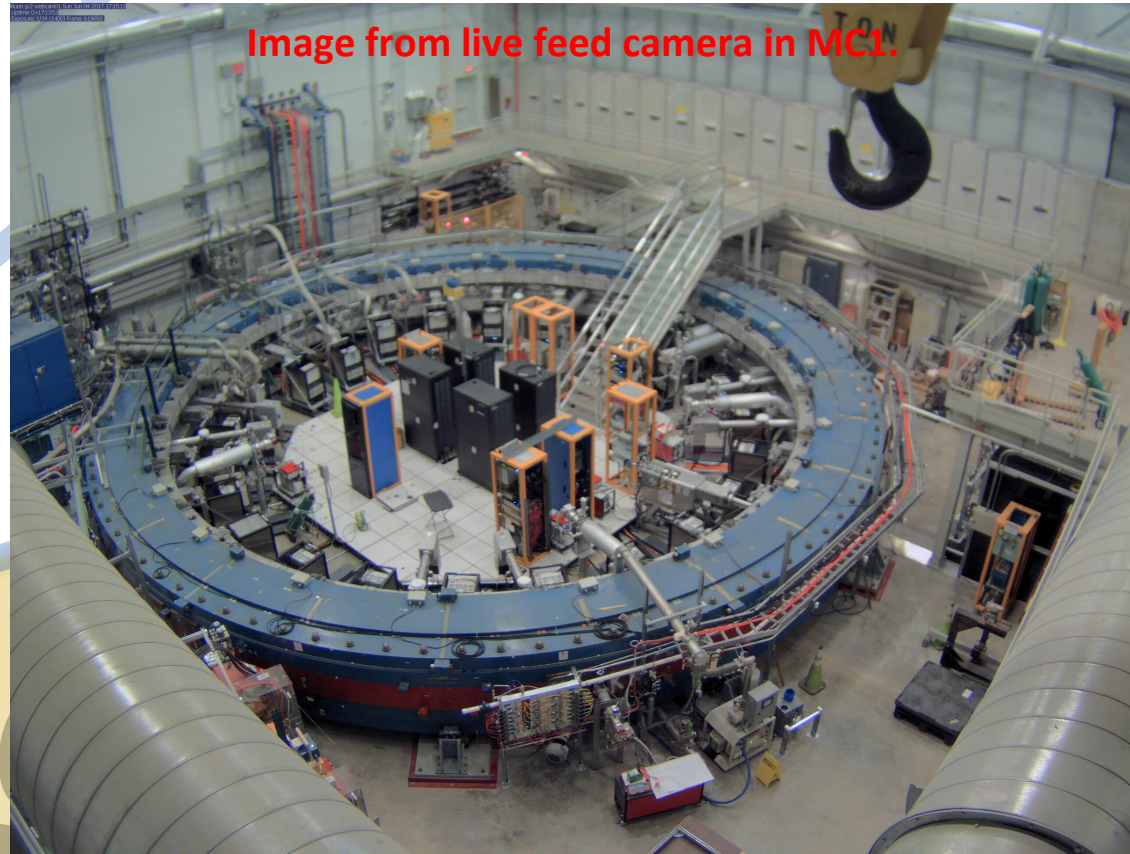
# Conclusions

- Fermilab Experiment is currently performing the commissioning run.
- Fermilab Experiment's goal is to measure  $a_\mu$  around 4 times more precisely than the BNL Experiment .
- Deeper understanding needed for Fermilab Experiment's total systematic error goal (considering higher order-systematic effects).

MC1 Control Room on May 31<sup>st</sup>, 2017 during data taking



Image from live feed camera in MC1.



# Backup

$\mu$

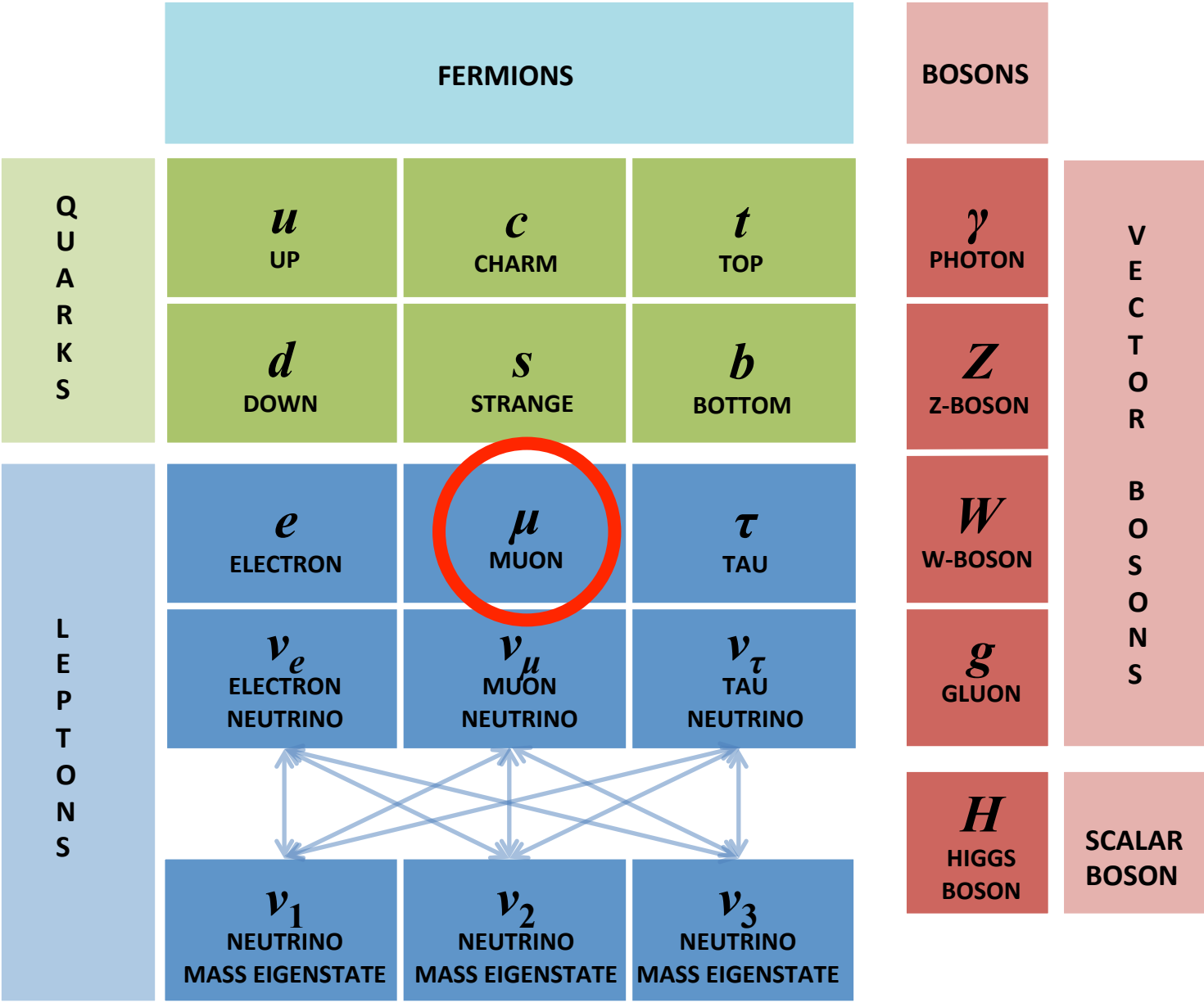
$g-2$

**BROOKHAVEN**  
NATIONAL LABORATORY

 **Fermilab**

# Standard Model zoo of particles:

Standard Model (Quantum + Special Relativity)



General Relativity  
(Geometry)

GRAVITY

# The Muon was discovered from cosmic rays.



Seth Neddermeyer

[1]

Discovered in 1936 by Carl D. Anderson and Seth Neddermeyer:

- Cosmic radiation determined not to be an electron or proton.
- Originally thought to be the Yukawa pion (called the mu-meson or mesotron)



Carl D. Anderson

[2]

1940: First cloud chamber photograph of muon decay.

[3]

mesotron

electron

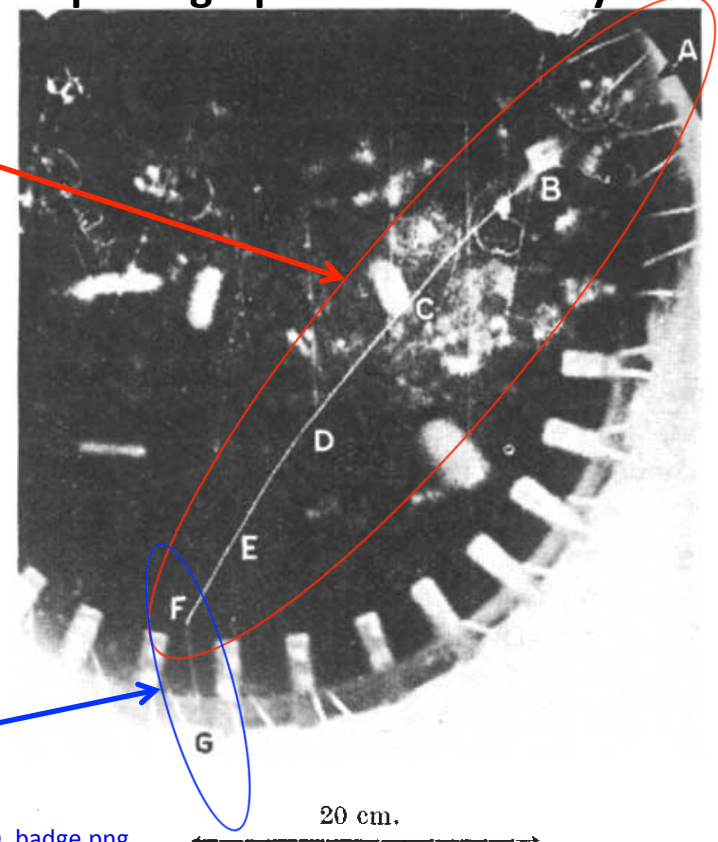


Fig. 1.

[1] [https://en.wikipedia.org/wiki/File:Seth\\_Neddermeyer\\_ID\\_badge.png](https://en.wikipedia.org/wiki/File:Seth_Neddermeyer_ID_badge.png)  
<http://www.lanl.gov/history/wartime/staff.shtml>

[2] [https://en.wikipedia.org/wiki/File:Carl\\_Anderson.jpg](https://en.wikipedia.org/wiki/File:Carl_Anderson.jpg)  
[http://nobelprize.org/nobel\\_prizes/physics/laureates/1936/anderson-bio.html](http://nobelprize.org/nobel_prizes/physics/laureates/1936/anderson-bio.html)

[3] E. Williams, G. Roberts, Evidence for transformation of mesotrons into electrons, Nature 145 (1940) 102–103.

# What is the Muon thingy you speak of?

Recent review on the arXiv:

T. P. Gorringe and D. W. Hertzog, “Precision Muon Physics,” arXiv:1506.01465 [hep-ex] (2015).

|                                            |                                                        |     |
|--------------------------------------------|--------------------------------------------------------|-----|
| $m_\mu$                                    | $105.6583715 \pm 0.0000035 \text{ MeV}$                | [1] |
| $m_e$                                      | $0.510998928 \pm 0.000000011 \text{ MeV}$              |     |
| $m_\tau$                                   | $1776.82 \pm 0.16 \text{ MeV}$                         |     |
| $\tau_\mu$                                 | $2.1969811 \pm 0.0000022 \text{ }\mu\text{s}$          |     |
| $\tau_e$                                   | $\infty$                                               |     |
| $\tau_\tau$                                | $(2.903 \pm 0.005) \times 10^{-7} \text{ }\mu\text{s}$ |     |
| $\lambda$ ( $\mu/p$ magnetic moment ratio) | $3.18334514 \pm 0.00000009$                            |     |
| $a_\mu$                                    | $0.0011659209 \pm 0.0000000006$                        |     |
| $a_e$                                      | $0.00115965218076 \pm 0.00000000000027$                |     |
| $a_\tau$                                   | $> -0.052 \text{ and } < 0.013$                        |     |
| $d_\mu$                                    | $(-1 \pm 9) \times 10^{-20} \text{ ecm}$               |     |

| Mode                                          | Fraction ( $\Gamma_i / \Gamma$ ) |
|-----------------------------------------------|----------------------------------|
| $\mu^- \rightarrow e^- \nu_e \nu_\mu$         | $\approx 1$                      |
| $\mu^- \rightarrow e^- \nu_e \nu_\mu \gamma$  | $0.014 \pm 0.004$                |
| $\mu^- \rightarrow e^- \nu_e \nu_\mu e^+ e^-$ | $(3.4 \pm 0.4) \times 10^{-5}$   |

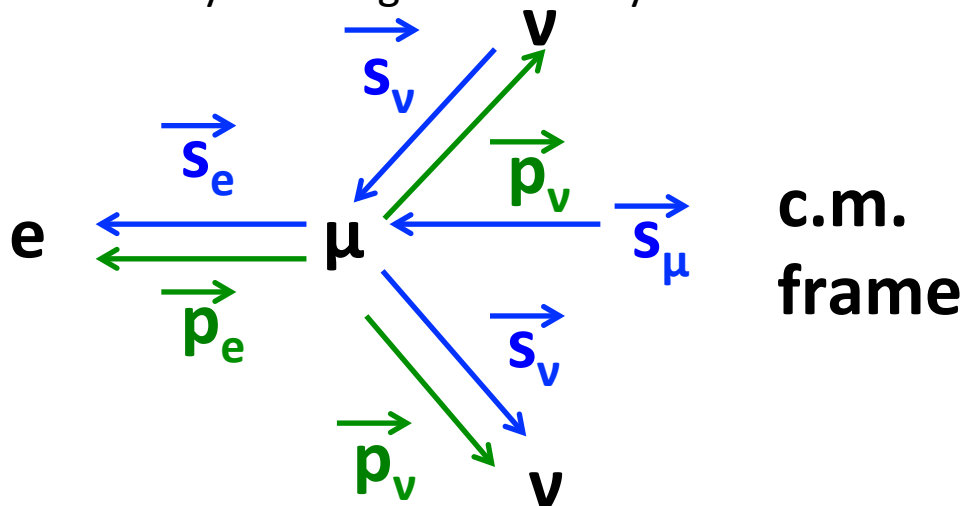
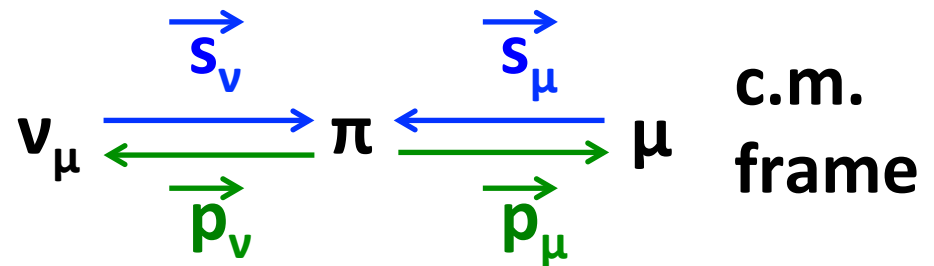
[1]

[1] K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014).



# The muon has useful properties for a g-2 measurement

- $m_\mu \approx 207 m_e$ <sup>[1]</sup>
  - $(m_\mu / m_e)^2 \approx 42,800$  times more sensitive to new physics than electron
- $\tau_\mu \approx 2.20 \mu s$ <sup>[1]</sup>
  - Time-dilated  $\mu$ -lifetime allows for  $\mu$ -beams (BNL  $(g-2)_\mu \gamma \tau_\mu \approx 64.4 \mu s$ )
- $Br(\pi \rightarrow \mu \nu_\mu) \approx 100\%$ <sup>[1]</sup>
  - High intensity  $\mu$ -beams; polarized  $\mu$
- $Br(\mu \rightarrow e \nu_e \nu_\mu) \approx 100\%$ <sup>[1]</sup>
  - Parity violating Weak decay



# There is a history of Muon g-2 testing the Standard Model.

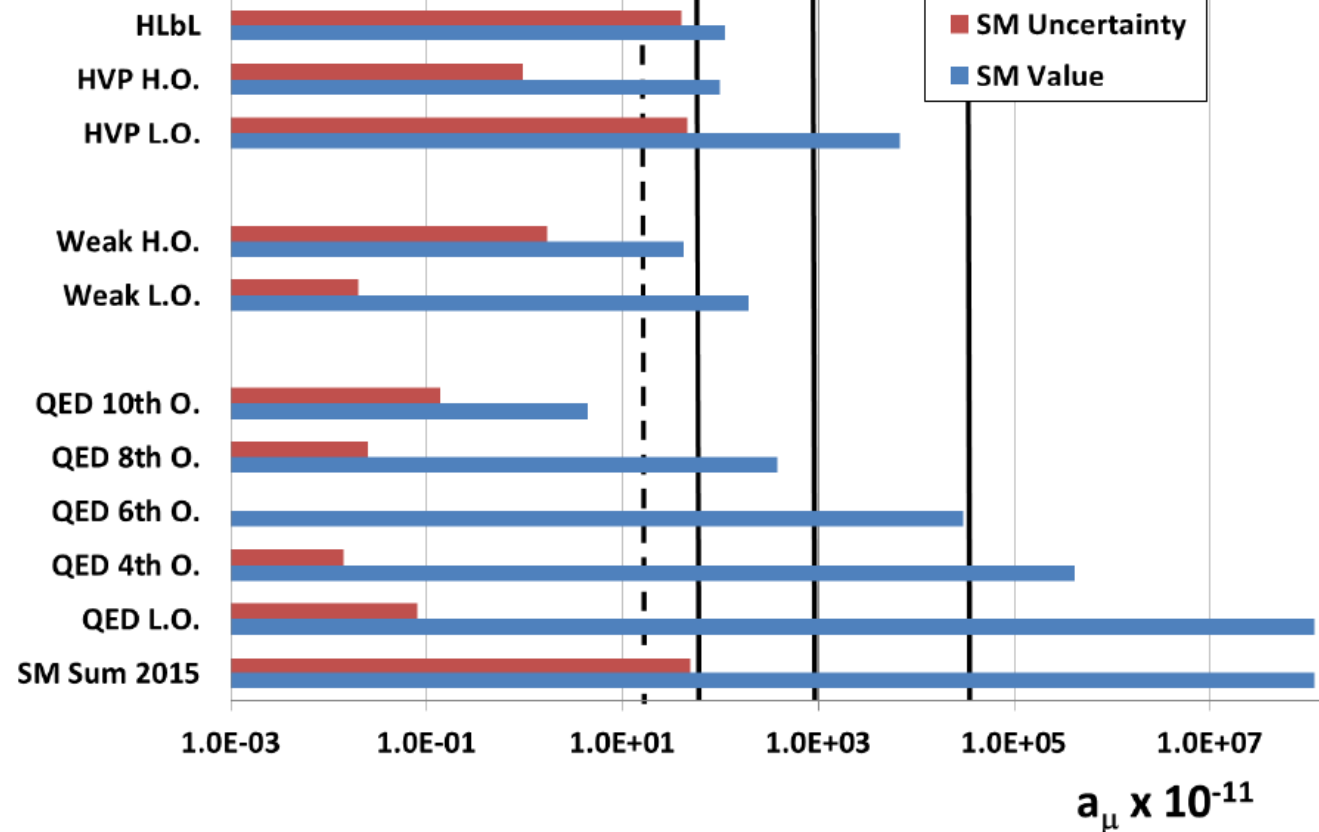
Quantum Chromodynamics (QCD)

HLbL = Hadronic Light-by-Light  
HVP = Hadronic Vacuum Polarization  
Weak = Weak Interaction  
QED = Quantum Electrodynamics

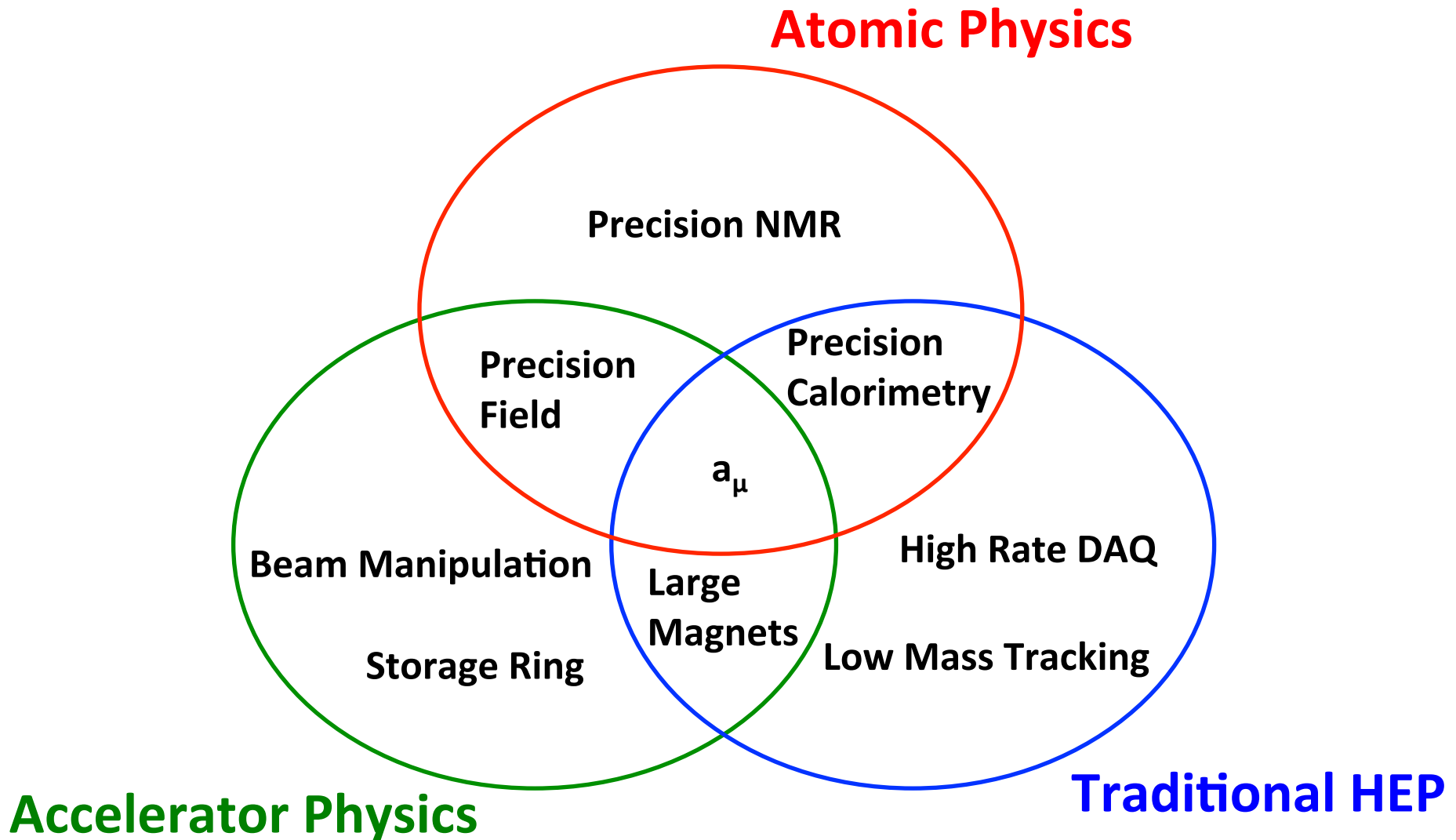
Measured values from experiments

Precision Goals or Measured  
FNAL E821 CERN III CERN II

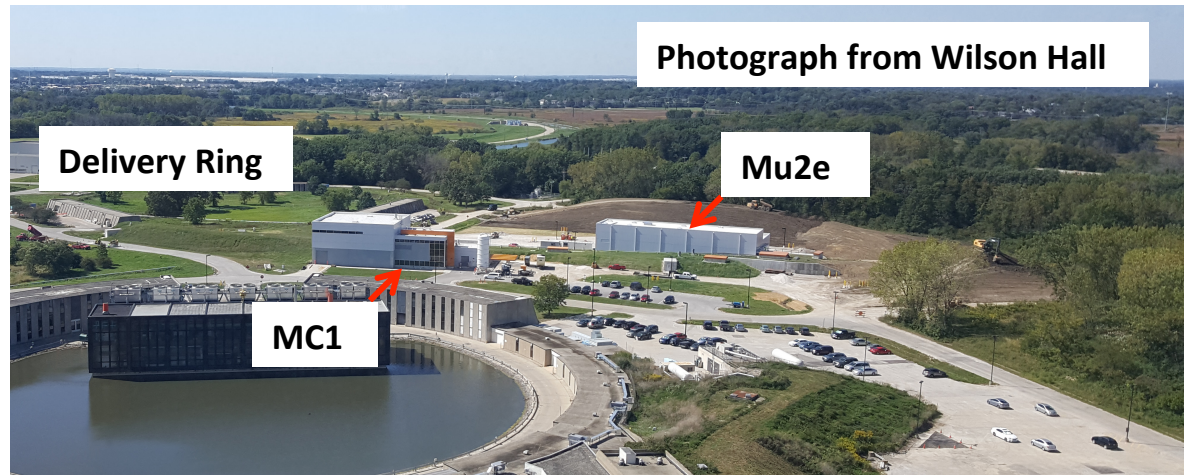
SM predicted values and errors



# Storage ring based muon g-2 experiments are not typical HEP experiments.



# Muon storage ring is now installed and operating in the Muon campus.



[1]

Image from live feed camera in MC1.



# Commissioning beam will have a large proton and pion background.

## Muon Campus



## Muon Campus without DR (g-2 commissioning)

