Muon g-2 Experiment at Fermilab

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University of Illinois at Urbana-Champaign
On behalf of the Muon g-2 Collaboration

06/20/2017

The 26th International Workshop on Weak Interactions and Neutrinos

Outline

- **Motivation**
  - History of g-2
  - The big move
- **Muon storage**
- **Overview of the experimental technique**
  - Spin precession measurement
  - Determination of the magnetic field
- **Commissioning**
- **Project timeline**
- **Conclusion**

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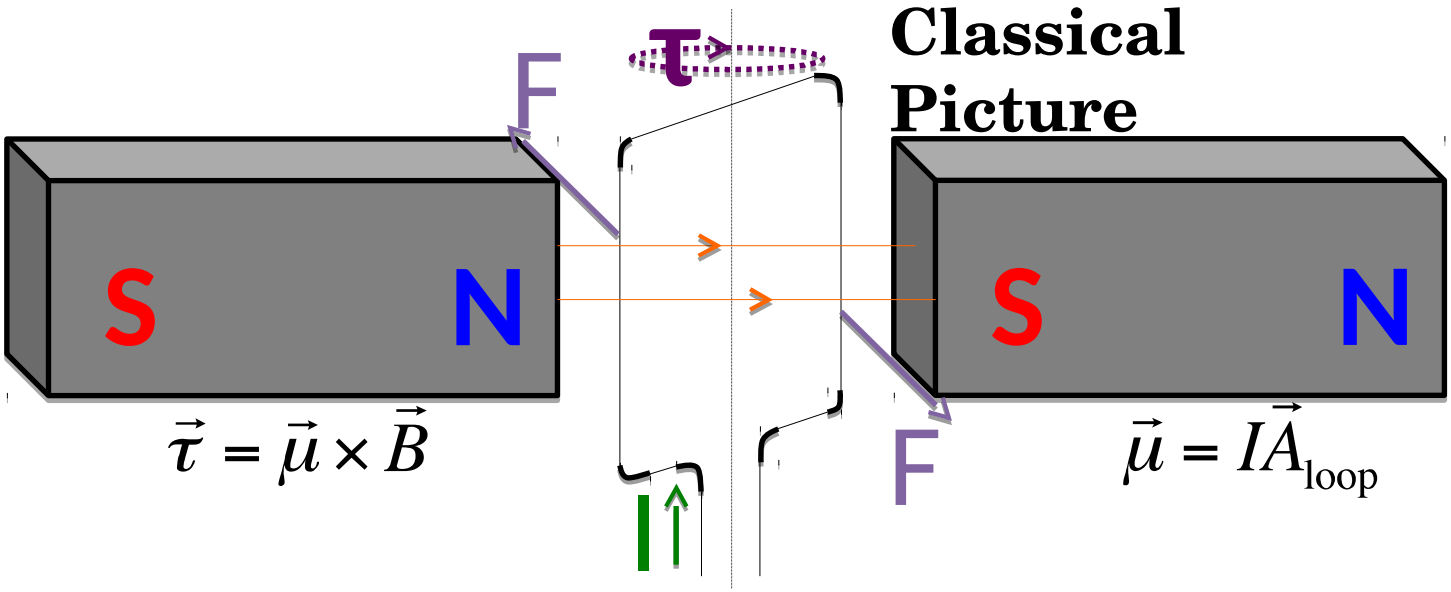
What is g-2?



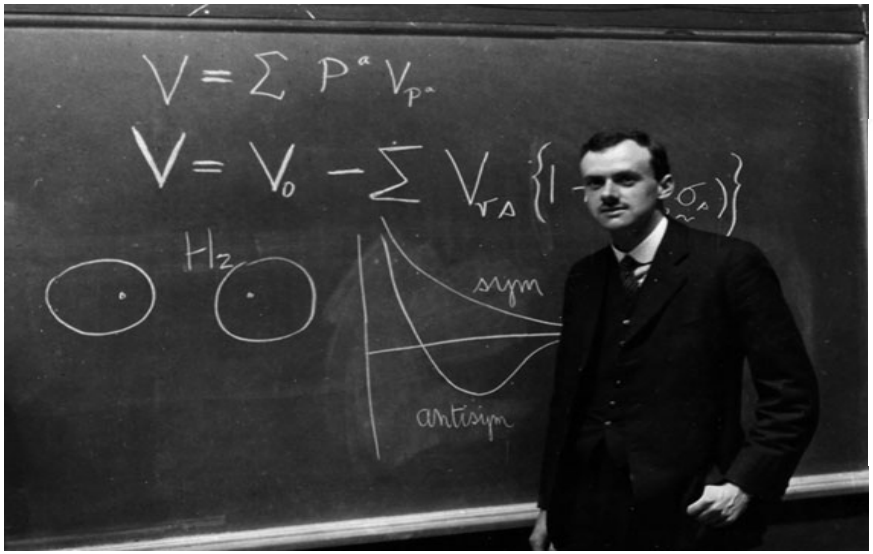
Quantum Picture

$$\vec{\mu} = g\frac{e}{2m_\mu c}\vec{S}$$

- **Muons have intrinsic spin**
- **"g" is a dimensionless proportionality constant relating spin to magnetic moment**
- **Muon's spin precesses in an external magnetic field**

History of g-2

- Dirac's relativistic theory predicted muon magnetic moment “g” = 2



The Nobel Prize in Physics 1933

Erwin Schrödinger, Paul A.M. Dirac

The Nobel Prize in Physics 1933 was awarded jointly to Erwin Schrödinger and Paul Adrien Maurice Dirac "for the discovery of new productive forms of atomic theory."

$$\left(\frac{1}{2m}(\vec{P} + e\vec{A})^2 + \frac{e}{2m}\vec{\sigma}.\vec{B}\right)\Psi_A = (E - m)\Psi_A$$

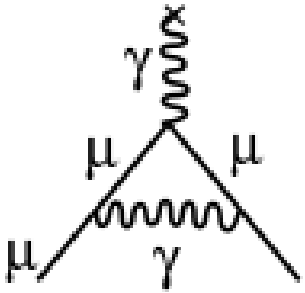
Dirac Equation

History of g-2

Experiment suggested that g-factor differs from the expected value of 2

$$\mu = (1 + a_\mu)\frac{e\hbar}{2m} \qquad a_\mu = \frac{g_\mu - 2}{2}$$

$g_\mu = 2.00\,2\,3$



The lowest-order (Schwinger) contribution to the lepton anomaly α/2π = 0.00232

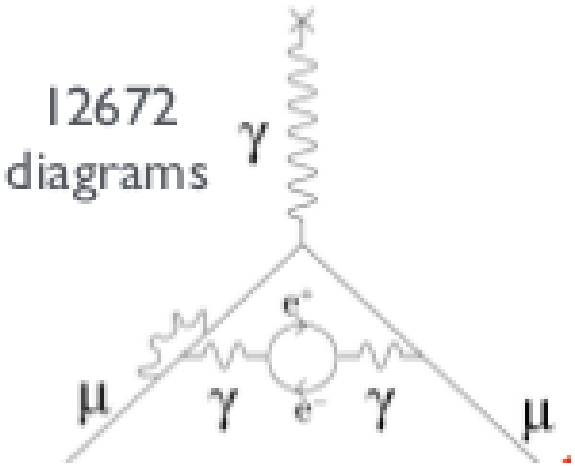
Nobel 1965

1st order QED

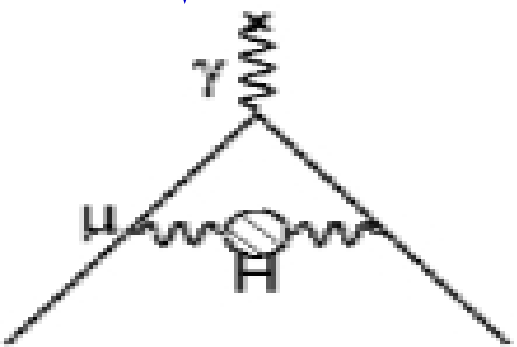
History of g-2

Standard Model prediction: $a^{SM} = a^{QED} + a^{Had} + a^{Weak}$

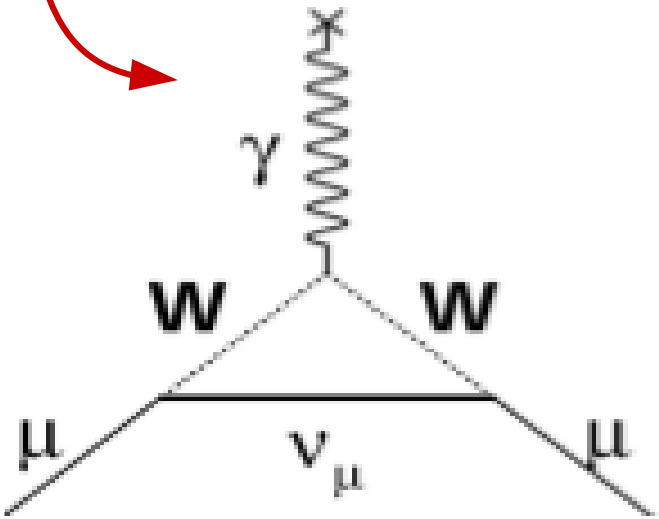
g_μ = **2.002 331 8417 8 (1 2 6)**



Aoyama, Hayakawa, Kinoshita and Nio calculated more than 12,000 diagrams to evaluate the 10th-order (5 loop) contributions



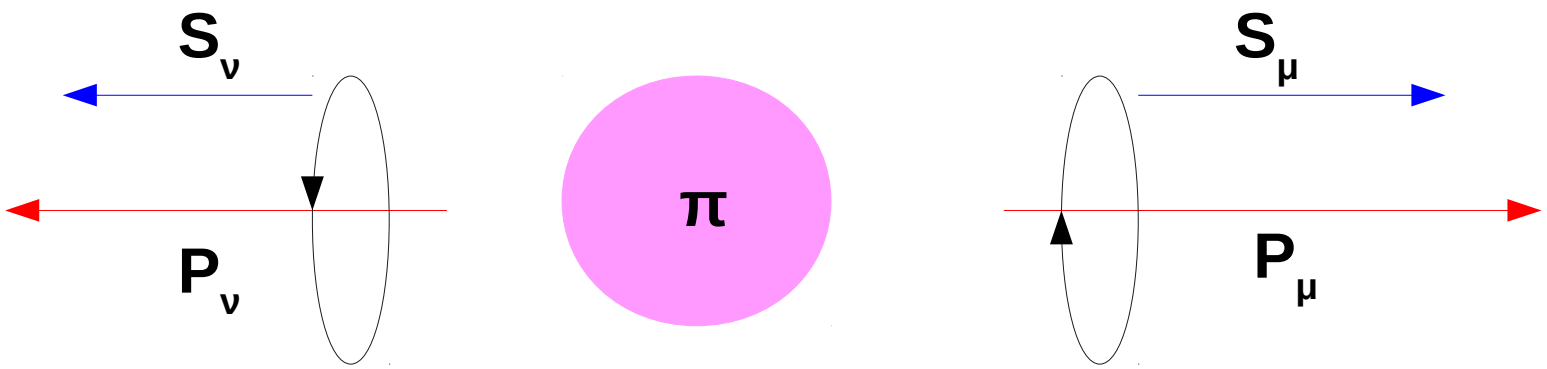
Hadronic contribution: dominant uncertainty in g



Electroweak

History of g-2

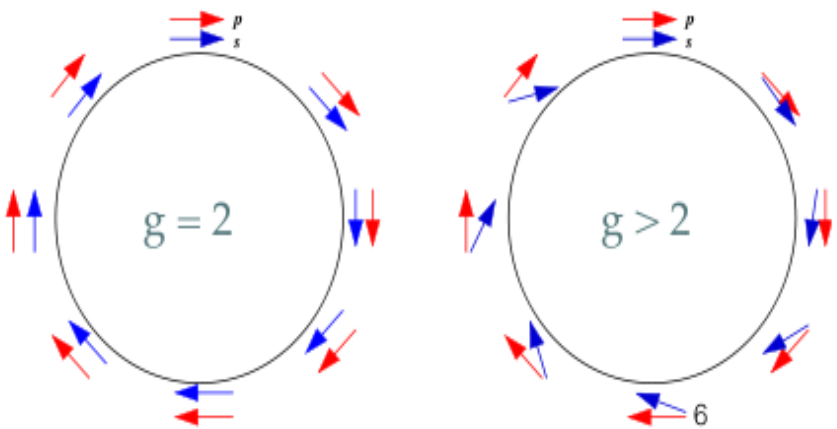
Spin Precession (ω_a) Measurement



[2]

h = 1

h = 1



[1]

- **The muon spin direction is correlated to the momentum of the emitted positrons**
- **Muon spin can be measured by measuring the decay positrons and analyzing their energies**

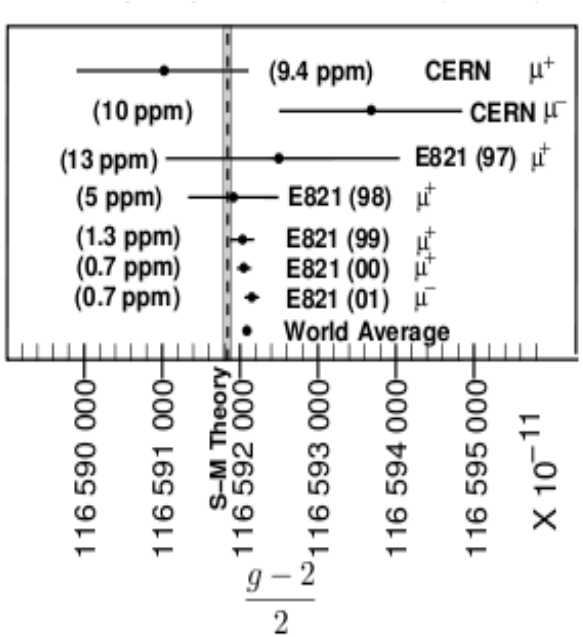
[1] J. Kasper, GM2-doc-4285

[2] J. Grange, GM2-doc-4869

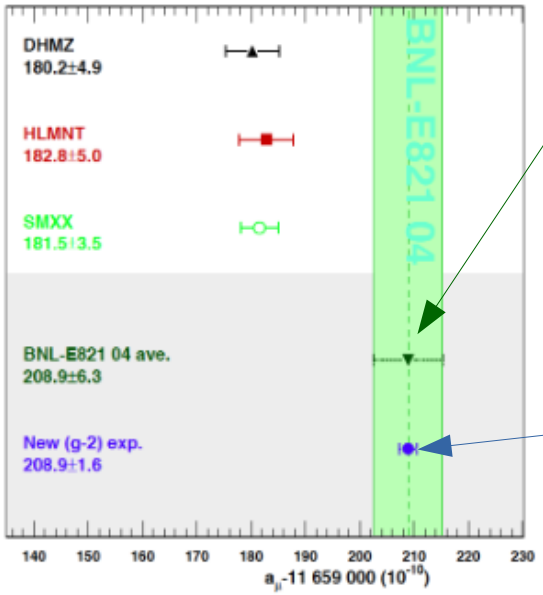
History of g-2

History of precession measurements

- Nevis cyclotron measured g_μ in 1957 for the first time
- Experimental techniques allow for more precise measurements
- Experimental measurements test the completeness of the Standard Model



Measurement of $a_\mu = (g_\mu-2)/2$ from CERN and BNL E821.
The vertical band is the SM value using the hadronic contribution



- 2004 measurement by Brookhaven Muon g-2 collaboration found 3.6 standard deviation between these two values
- Fermilab aims to achieve a fourfold improvement in measurement of $a_\mu = (g_\mu-2)/2$

540 ppb (measured by BNL) → 140 ppb (FNAL goal)

The Big Move


Leaving BNL


Through the see


Closed down two Chicago highways
OVERSIZE LOAD

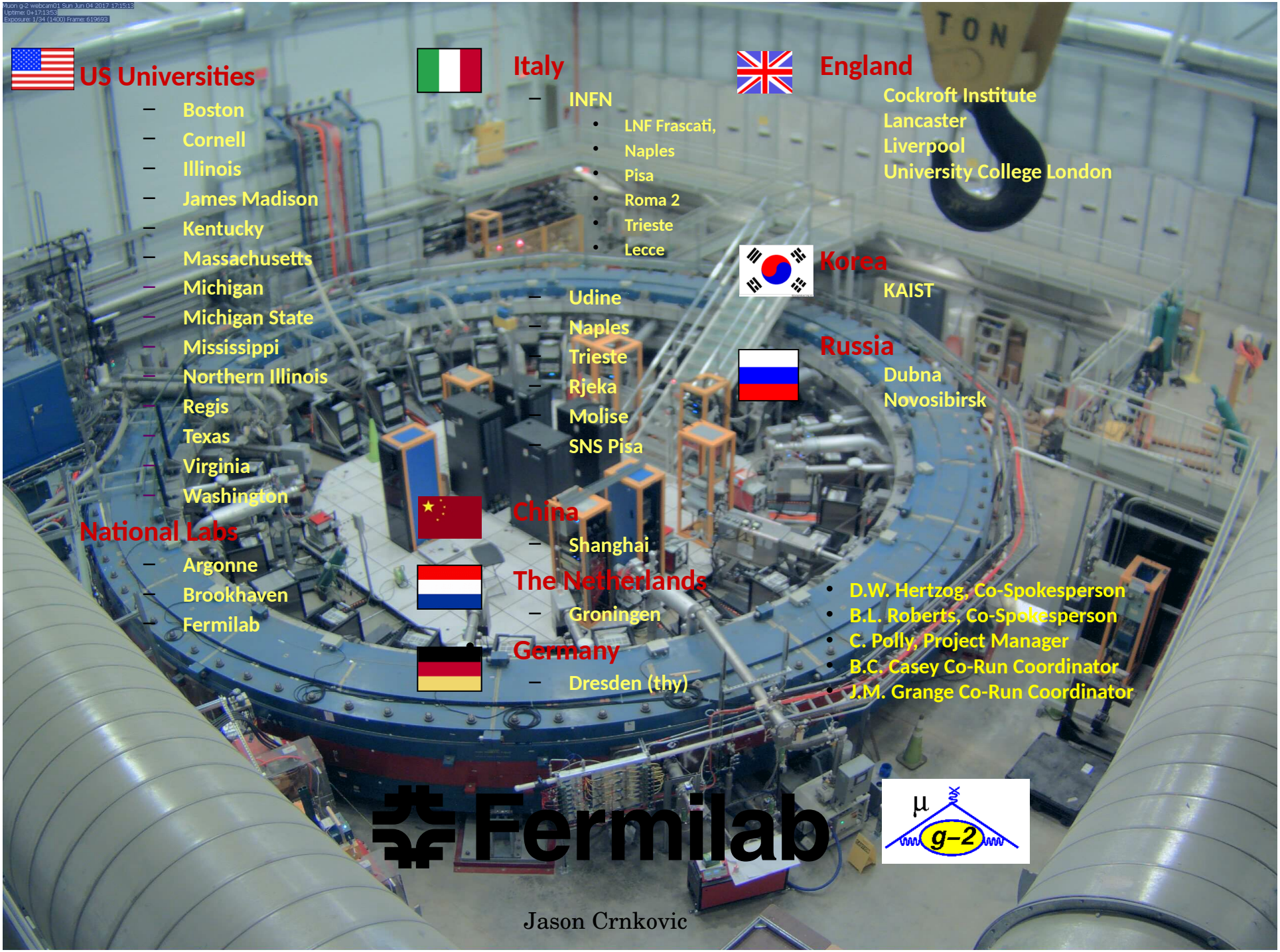

Reached Fermilab
Driving Discovery in Particle Physics


To MC1


Brendan Kiburg


New home for the ring

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
- Rjeka
- Molise
- SNS Pisa

China

- Shanghai

The Netherlands

- Groningen

Germany

- Dresden (thy)

England

Cockroft Institute
Lancaster
Liverpool
University College London

Korea

KAIST

Russia

Dubna
Novosibirsk

- 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

μ g–2

Jason Crnkovic

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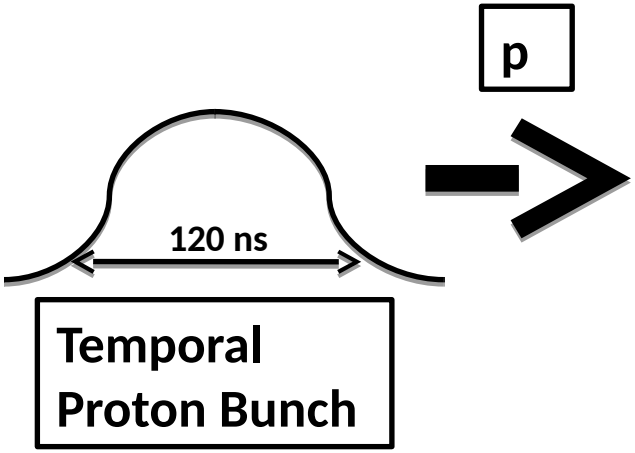
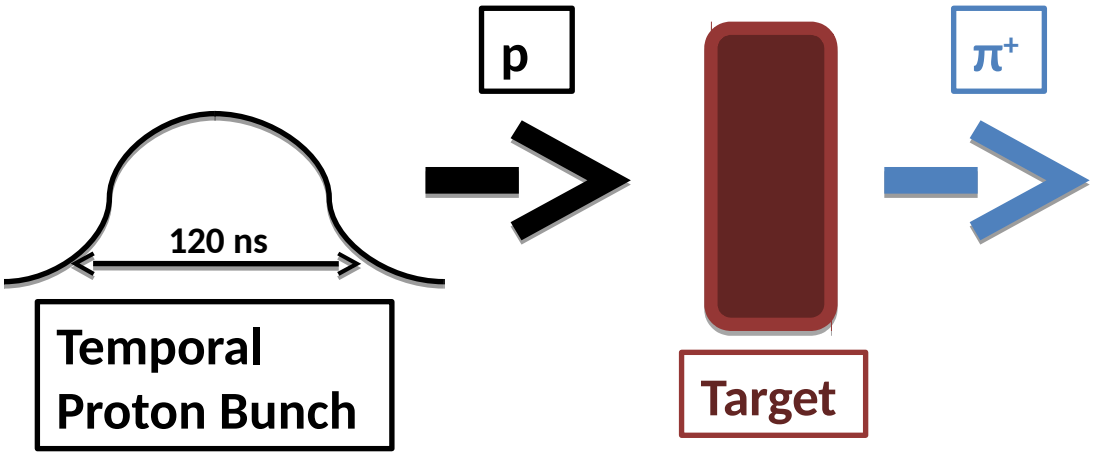
Muon Storage



- Start with a proton bunch

Not to scale

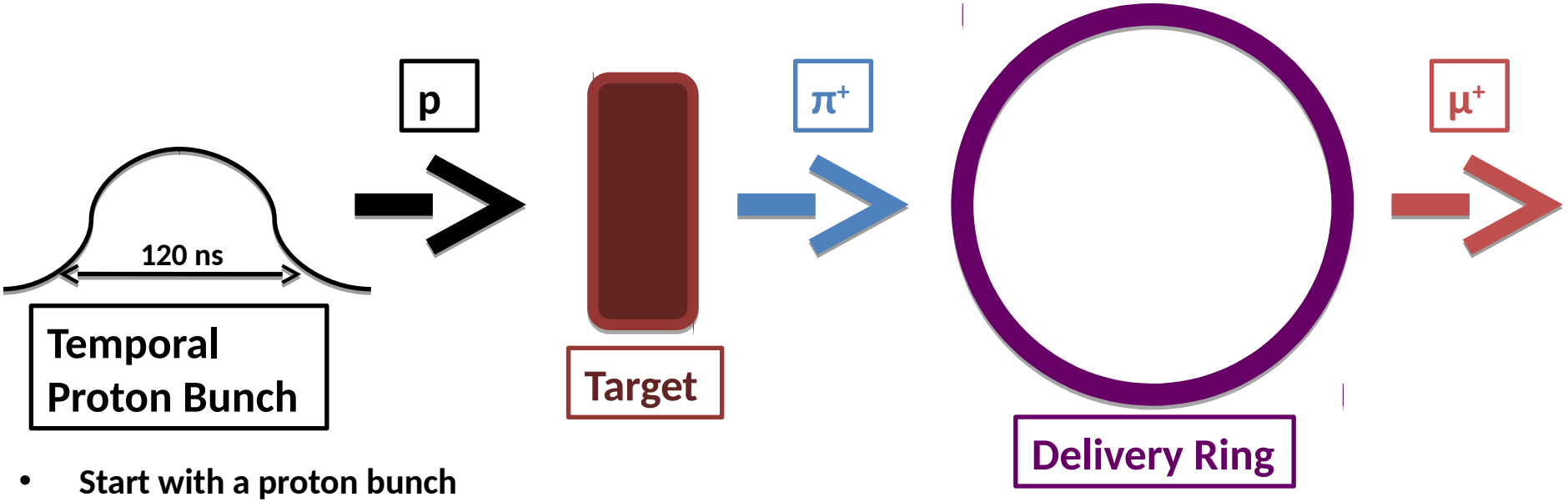
Muon Storage



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

Not to scale

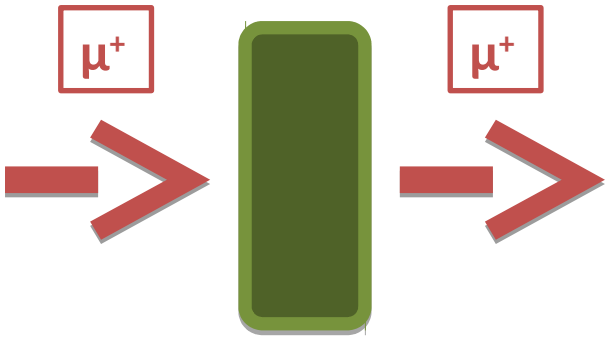
Muon Storage



- Start with a proton bunch
- Protons hit target to produce pions
- Pions decay to muons in Delivery Ring

Not to scale

Muon Storage



- M5 magnetic quads do final focusing before injection into ring

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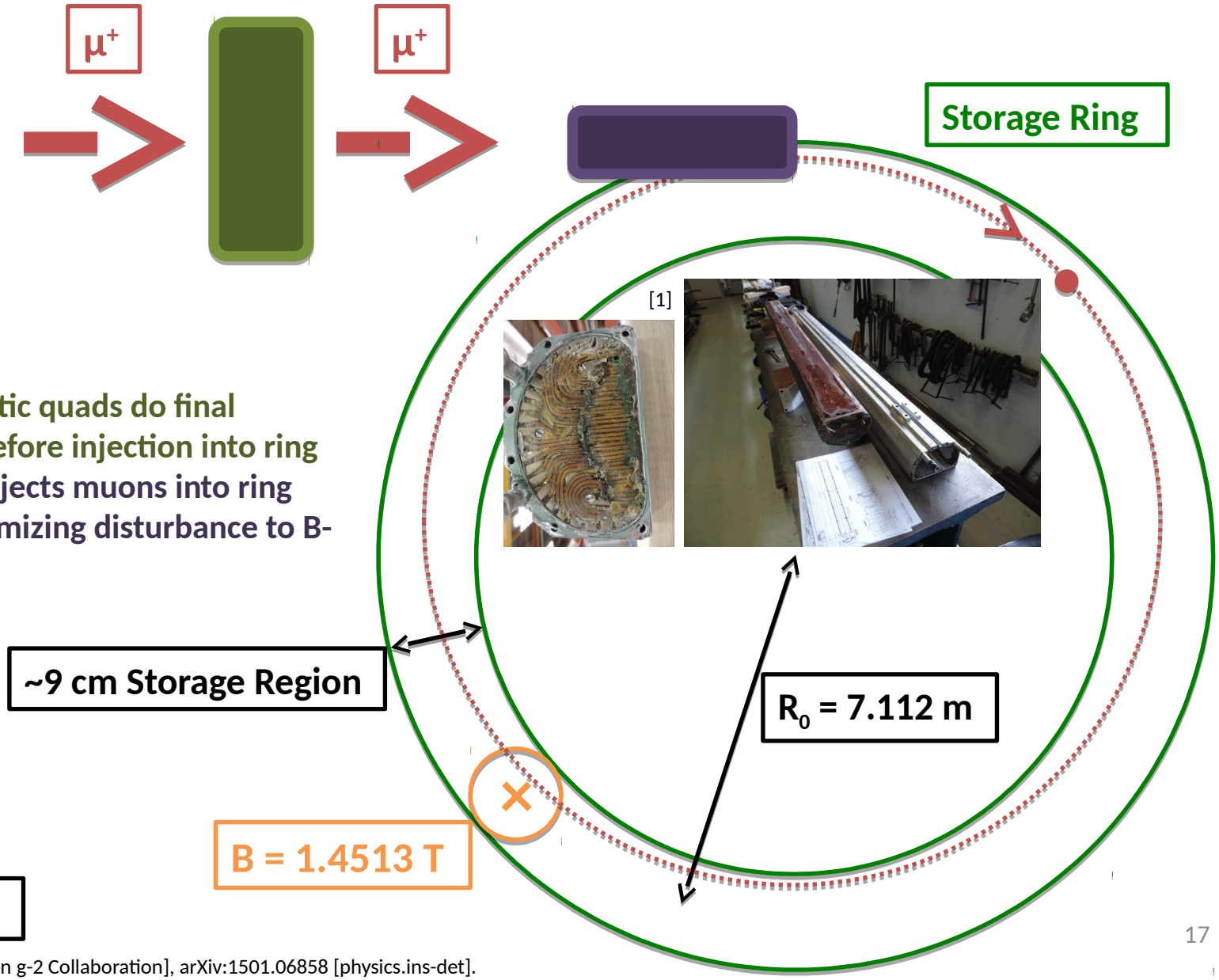
Muon Storage

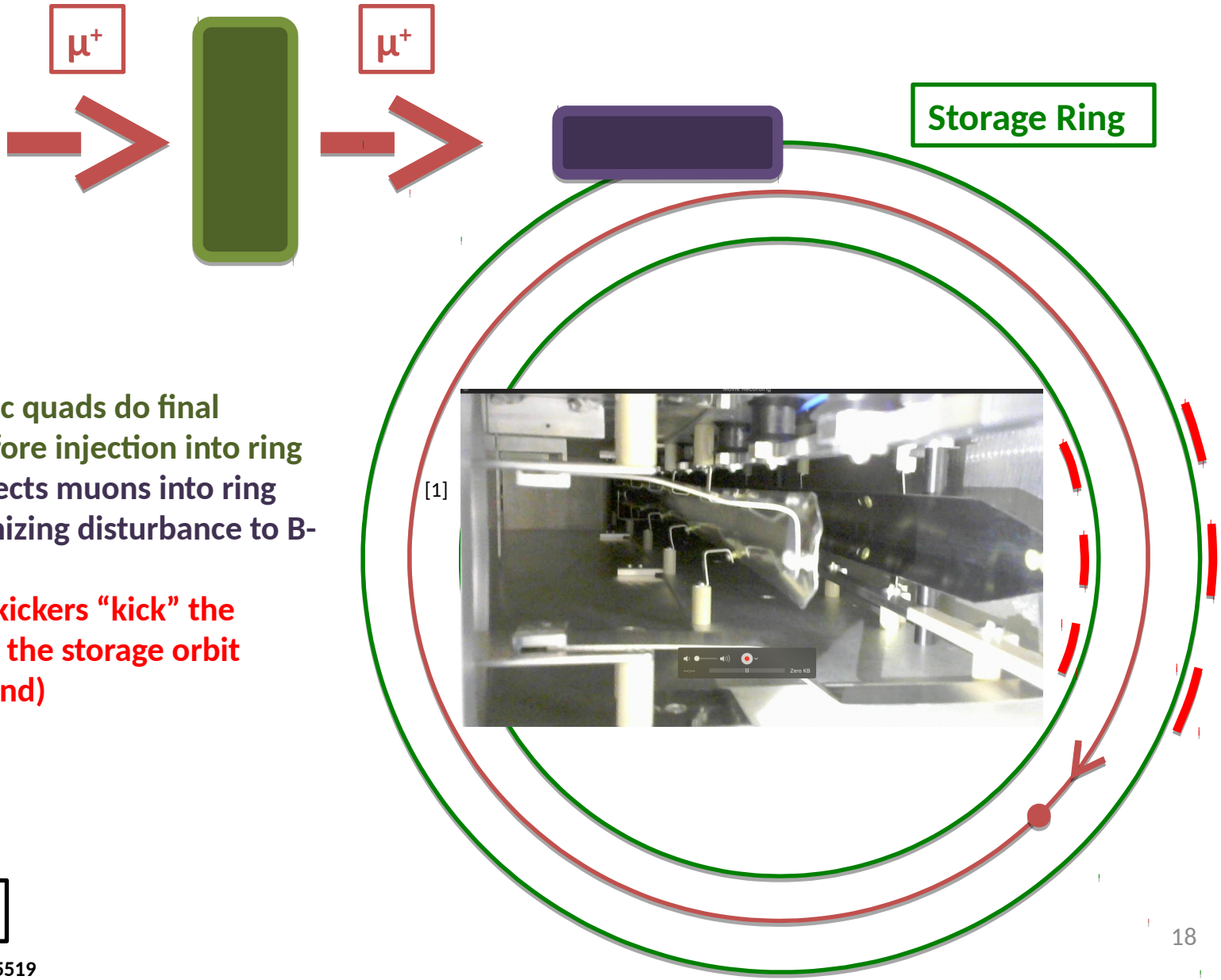


- M5 magnetic quads do final focusing before injection into ring
- Inflector injects muons into ring while minimizing disturbance to B-field

Not to scale

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

Muon Storage

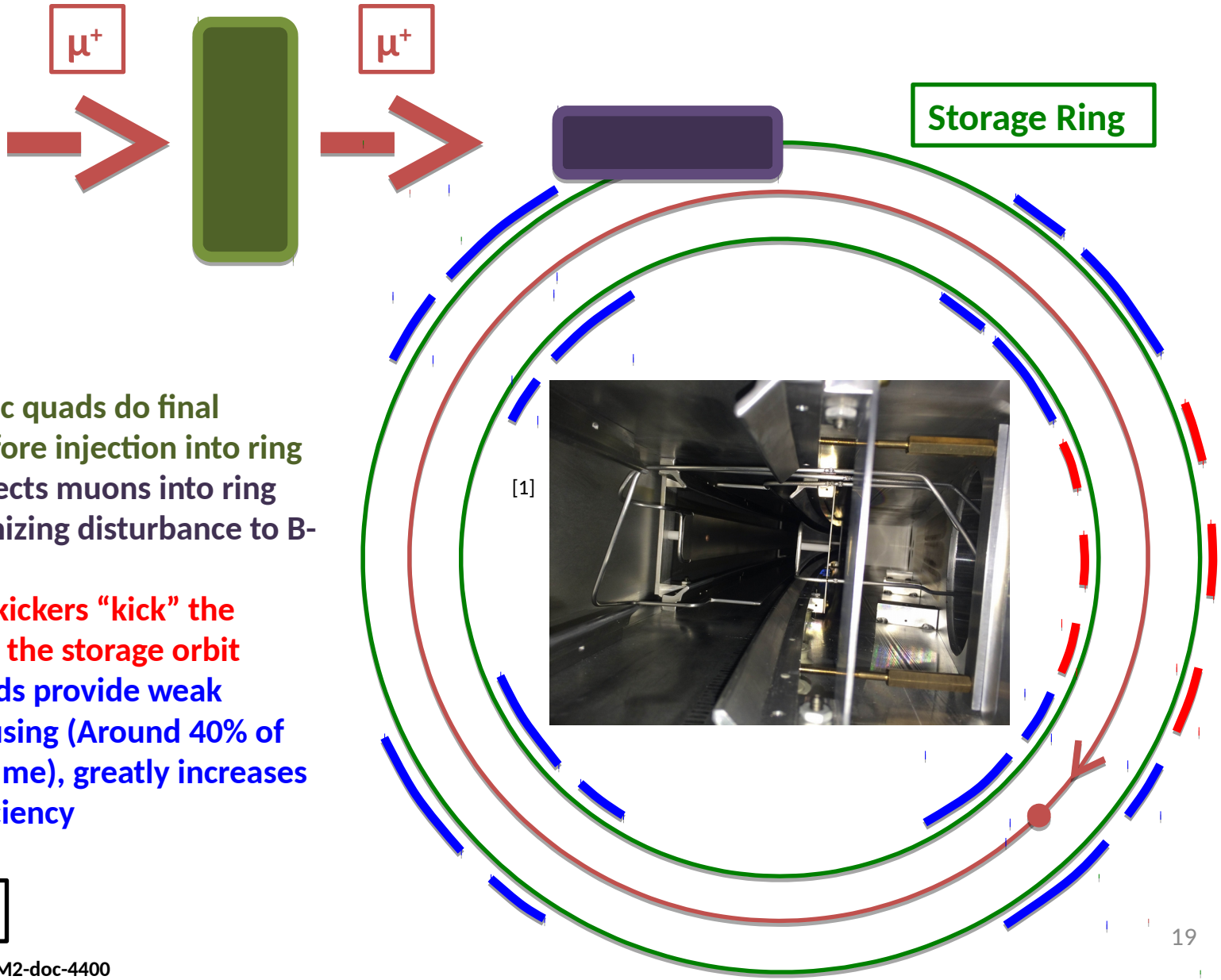


- M5 magnetic quads do final focusing before injection into ring
- Inflector injects muons into ring while minimizing disturbance to B-field
- 3 magnetic kickers "kick" the muons onto the storage orbit (10 mrad bend)

Not to scale

[1] H. Nguyen, GM2-doc-5519

Muon Storage

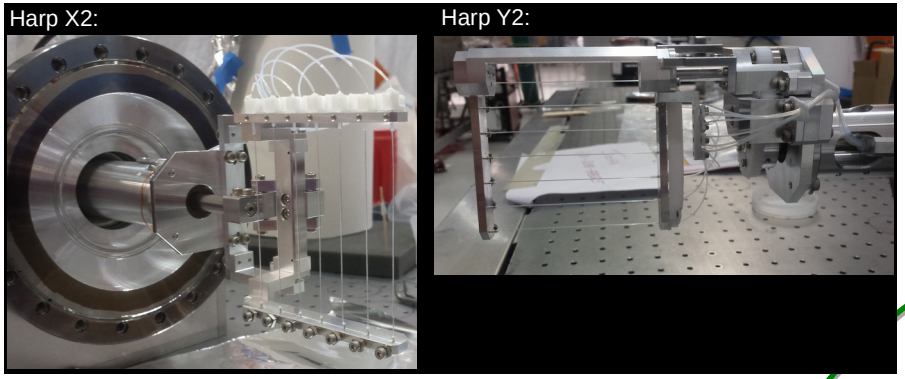


- M5 magnetic quads do final focusing before injection into ring
- Inflector injects muons into ring while minimizing disturbance to B-field
- 3 magnetic kickers "kick" the muons onto the storage orbit
- Electric quads provide weak vertical focusing (Around 40% of storage volume), greatly increases storage efficiency

Not to scale

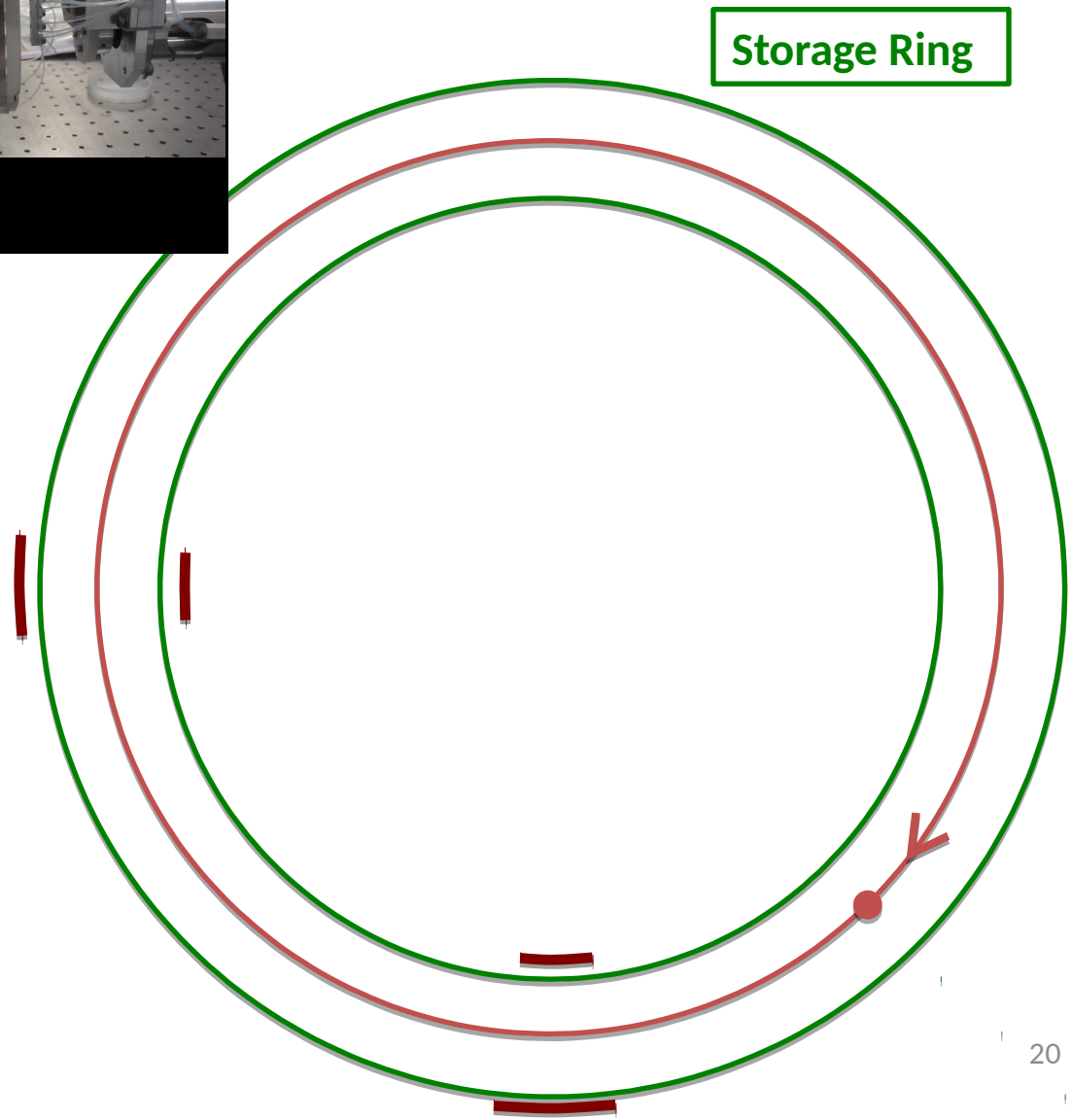
[1] J.D. Crnkovic *et. al.*, GM2-doc-4400

Muon Storage



[1]

- 180° and 270° fiber profile beam monitors



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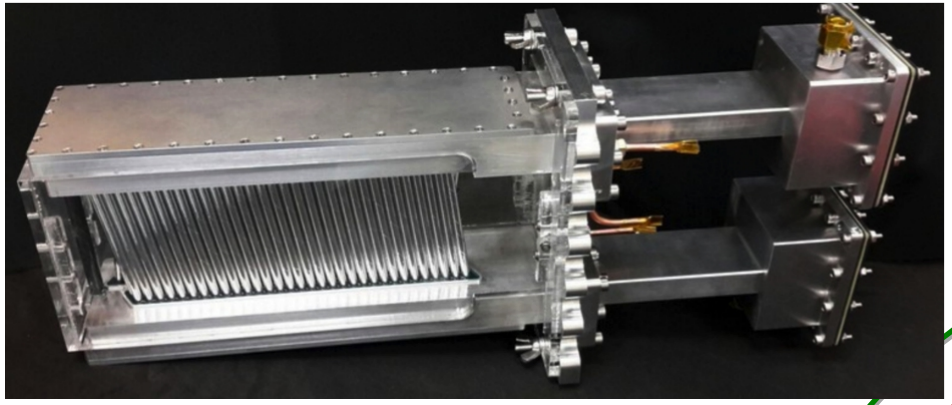
[1] R. Bjorkquist and F. Gray, GM2-doc-5218

Muon Storage



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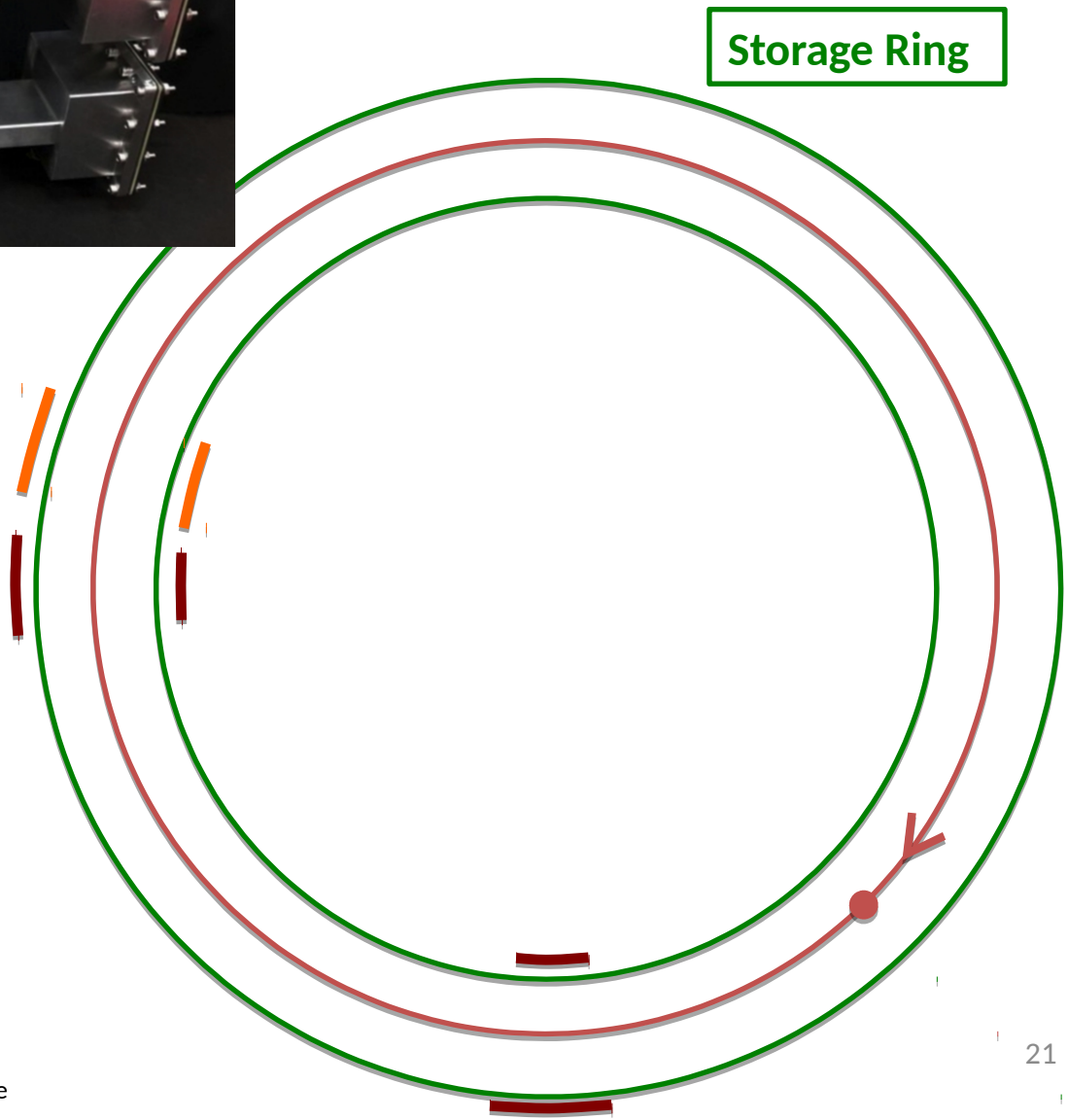


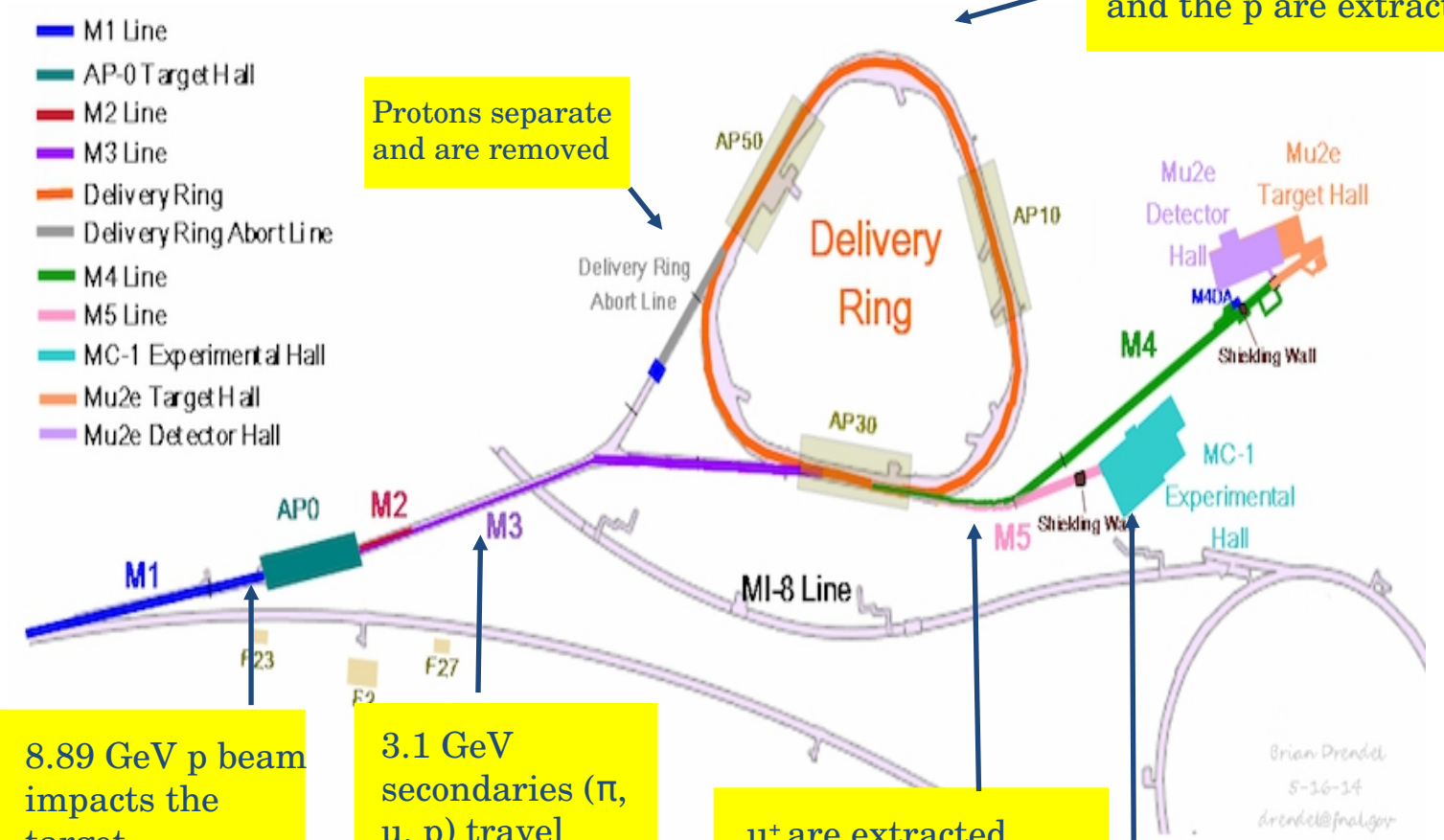
- 180° and 270° fiber profile beam monitors
- Straw tracker station provides decay positron trajectory reconstruction

Not to scale

[1] B. L. Roberts, First Workshop of the Muon g-2 Theory Initiative

Fermilab Beamline Optimal For This Experiment

After a few turns the remaining π^+ convert to μ^+ and the p are extracted



Protons separate and are removed

8.89 GeV p beam impacts the target

3.1 GeV secondaries (π, μ, p) travel along M2 & M3

μ^+ are extracted from the ring and transferred into the storage ring via M5

μ^+ enter the g-2 storage ring

D. Stratakis, GM2-doc-5664

Spin Precession (ω_a) Measurement

- Muon Cyclotron frequency : $\omega_c = \dfrac{eB}{\gamma mc}$
- Muon spin precesses frequency: $\omega_s = g_\mu \dfrac{eB}{2mc} + (1-\gamma)\dfrac{eB}{\gamma mc}$

Thomas precession

Larmor precession

- Measured experimentally:
  1) magnetic field $\hbar\omega_p = 2\mu_p |\vec{B}|$
  2) anomalous precession frequency $\omega_a = \omega_s - \omega_c$

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

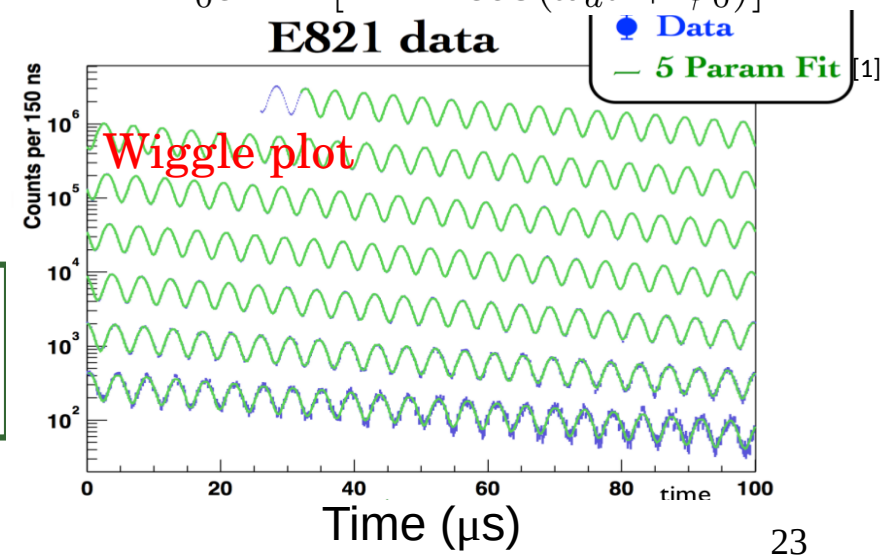
Anomalous spin precession obtained from decay positron time spectra

Free proton precession frequency. "how quickly would the spin of a free proton rotate in the g-2 ring?"

Get from CODATA [2]
g_e = -2.002 319 304 361 82(52) (0.00026 ppb)
m_μ/m_e = 206.768 2826(46) (22 ppb)
μ_e/μ_p = -658.210 6866(20) (3.0 ppb)

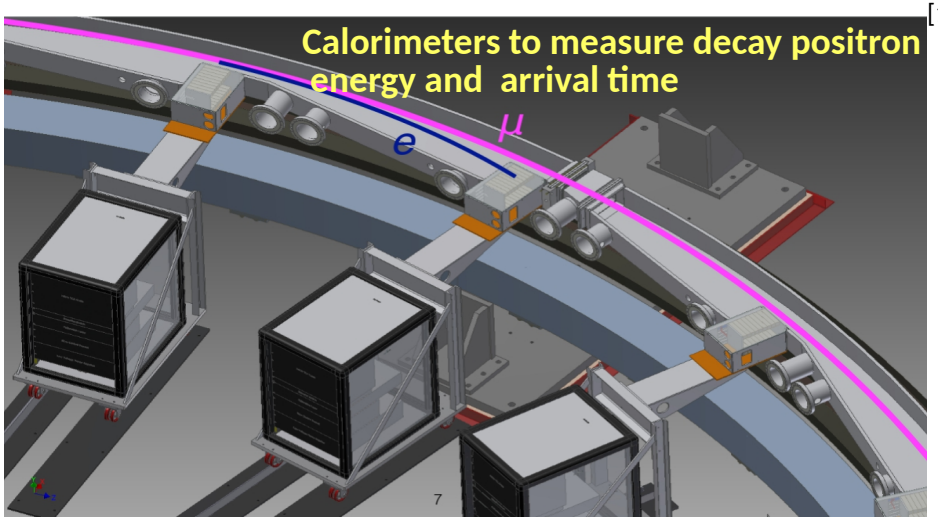
5-parameter fit function

$$N = N_0 e^{-\frac{t}{\gamma\tau_\mu}}[1 - A\cos(\omega_a t + \phi_0)]$$



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

Spin Precession (ω_a) Measurement



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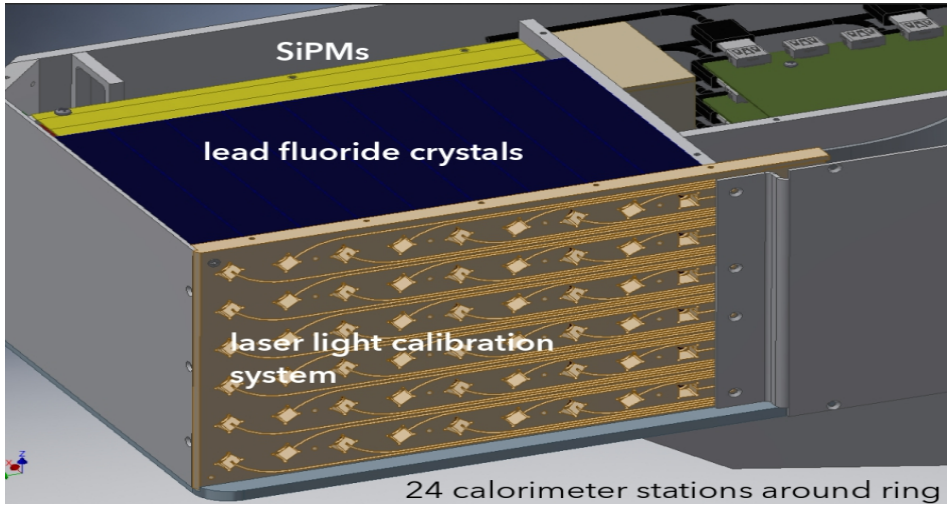

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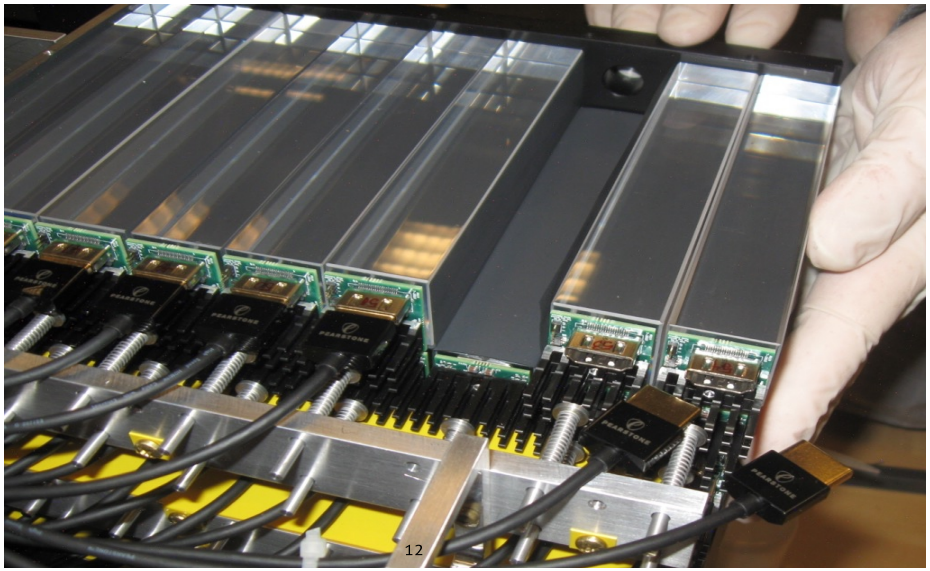
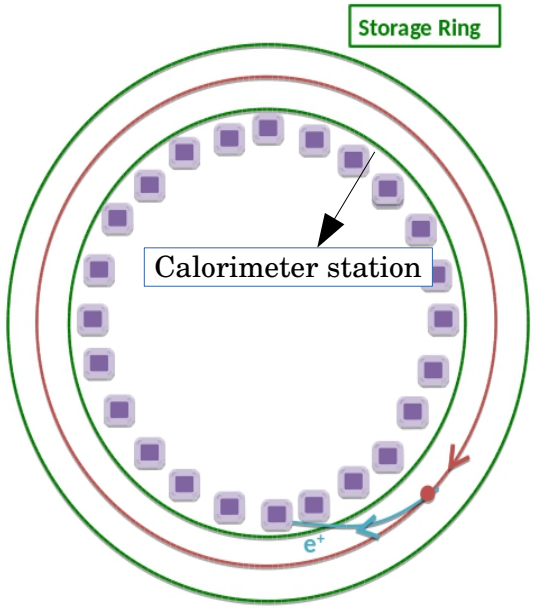


[1]

24 calorimeters detect decay positron arrival time and energy

[2]



Not to scale

S. Ganguly

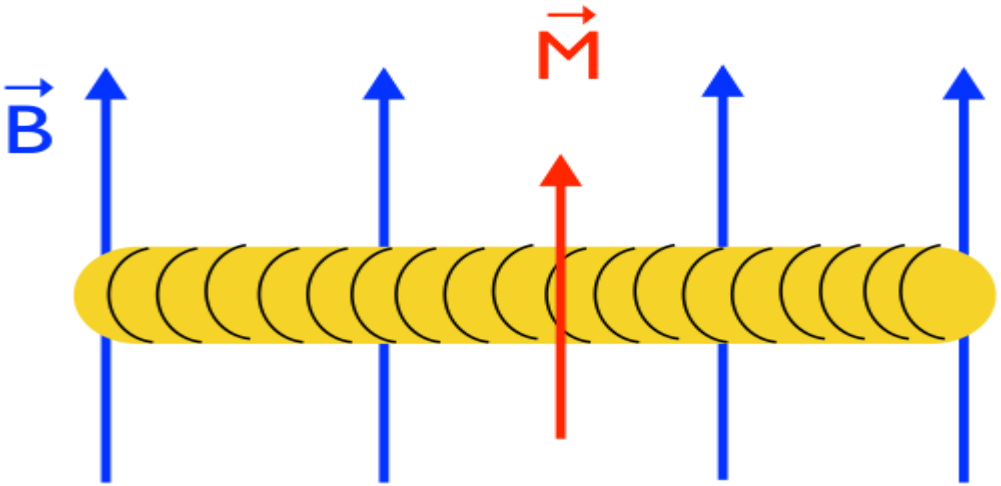
[1] J. Kasper, GM2-doc-4285
[2] J. Crnkovic, GM2-doc-6569

Determination of the magnetic field

- **Pulsed nuclear magnetic resonance (NMR) measures the B-field to the tens of ppb**
- **A π/2 RF pulse is used to rotate the proton spin**

$$\hbar\omega_p = 2\mu_p \left|\vec{B}\right|$$

Sample with bulk magnetization M surrounded by RF coils



[1]

[1] J. Grange, GM2-doc-4869

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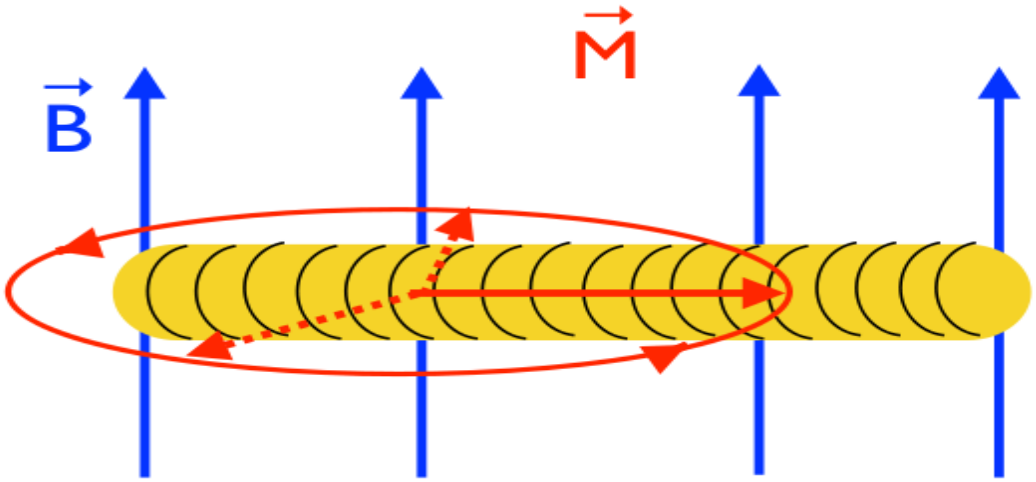
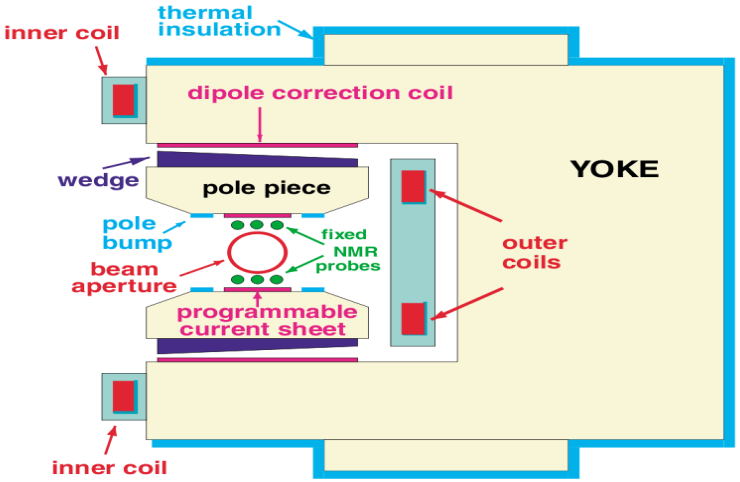


[1] J. Grange, GM2-doc-4869

Shimming The Magnet

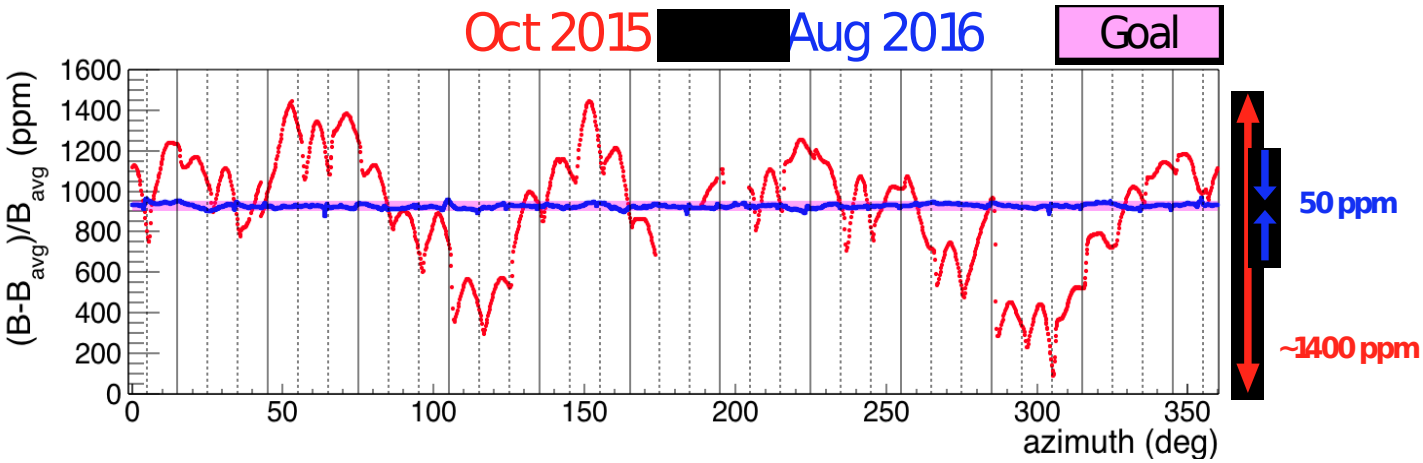
- Various shimming tools used to shim the large field volume to high precision



[1]

Rough Shimming Results

[2]



High uniformity of the storage ring field after shimming; reduces systematic errors

[1] J. Grange, GM2-doc-4869

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

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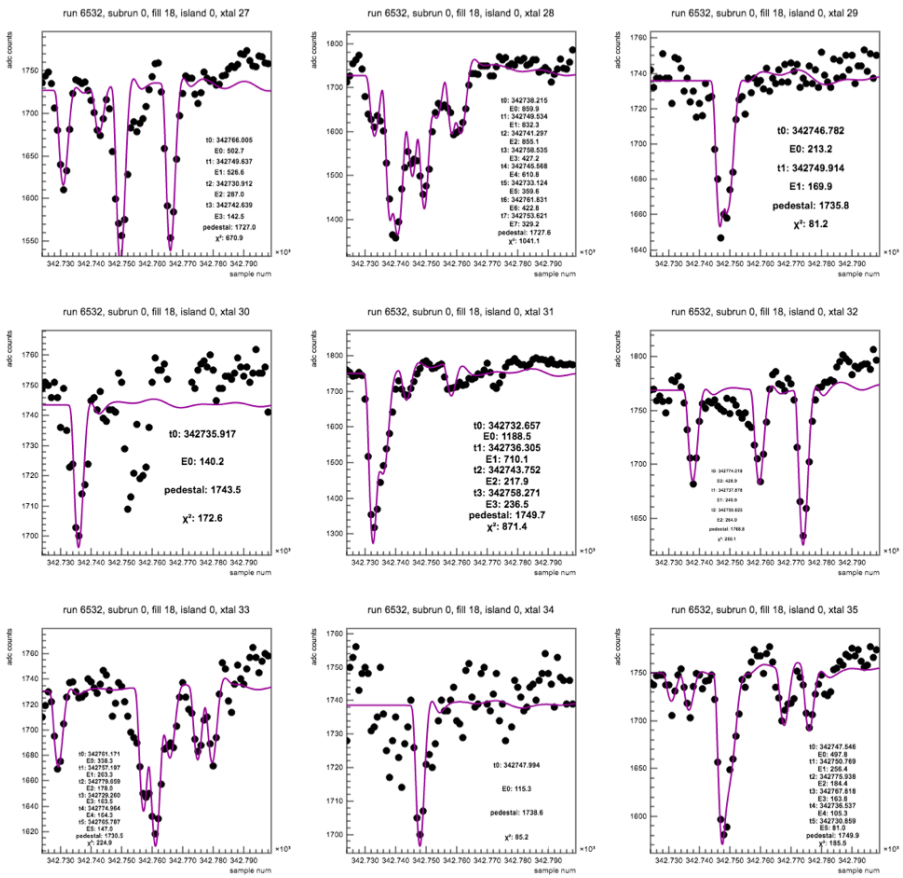
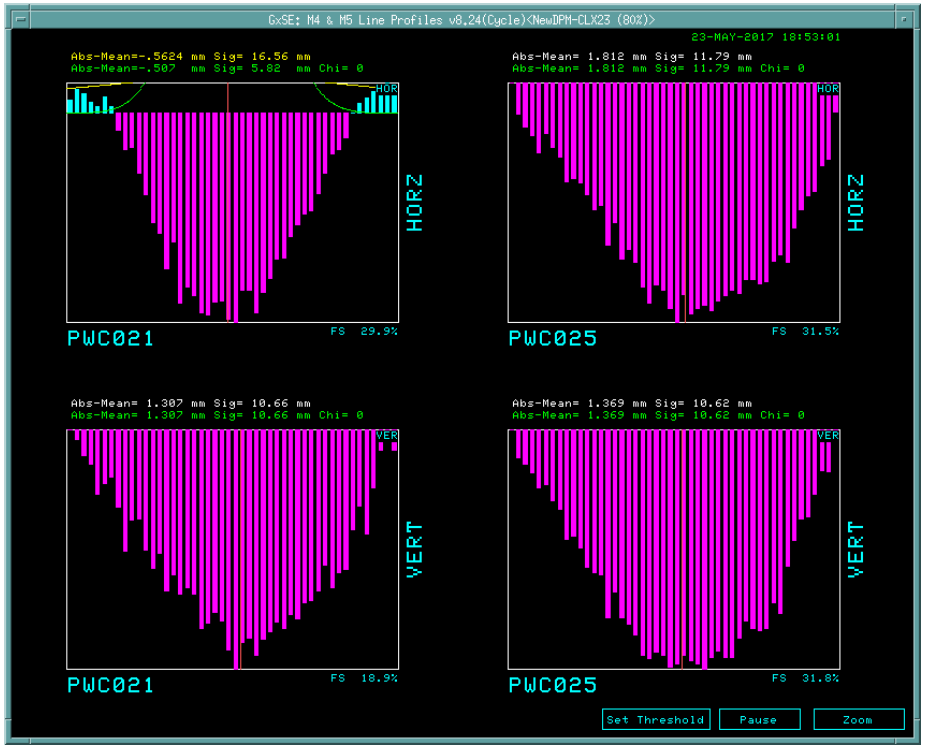
Commissioning

Fermilab Muon g-2 experiment is currently in the commissioning phase – beam arrived on May 24th

Splash of beam hitting calorimeter 24.

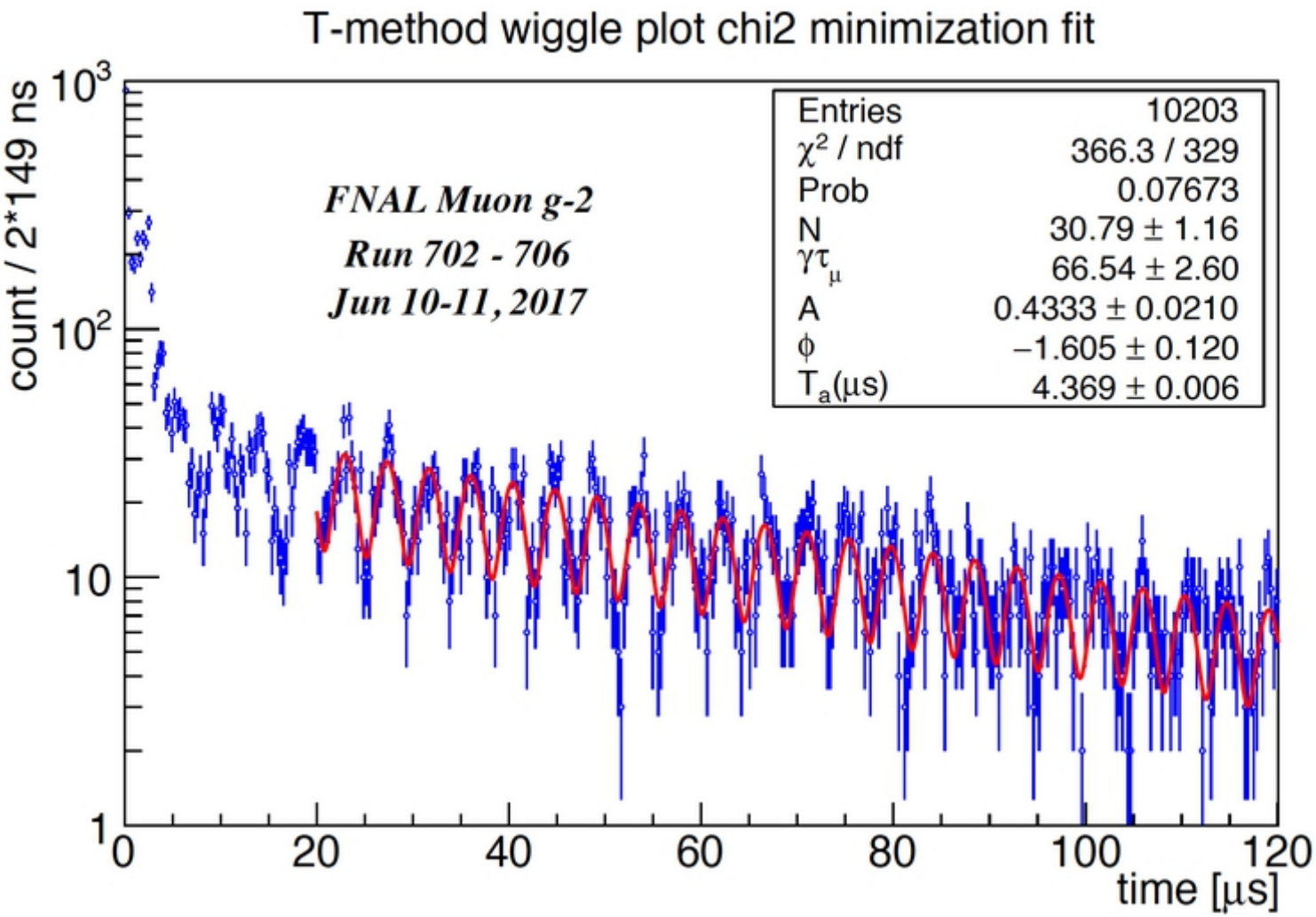




Beam profile on last PWC just before the storage ring entrance

Commissioning

1st evidence of precessing muons!!!!!



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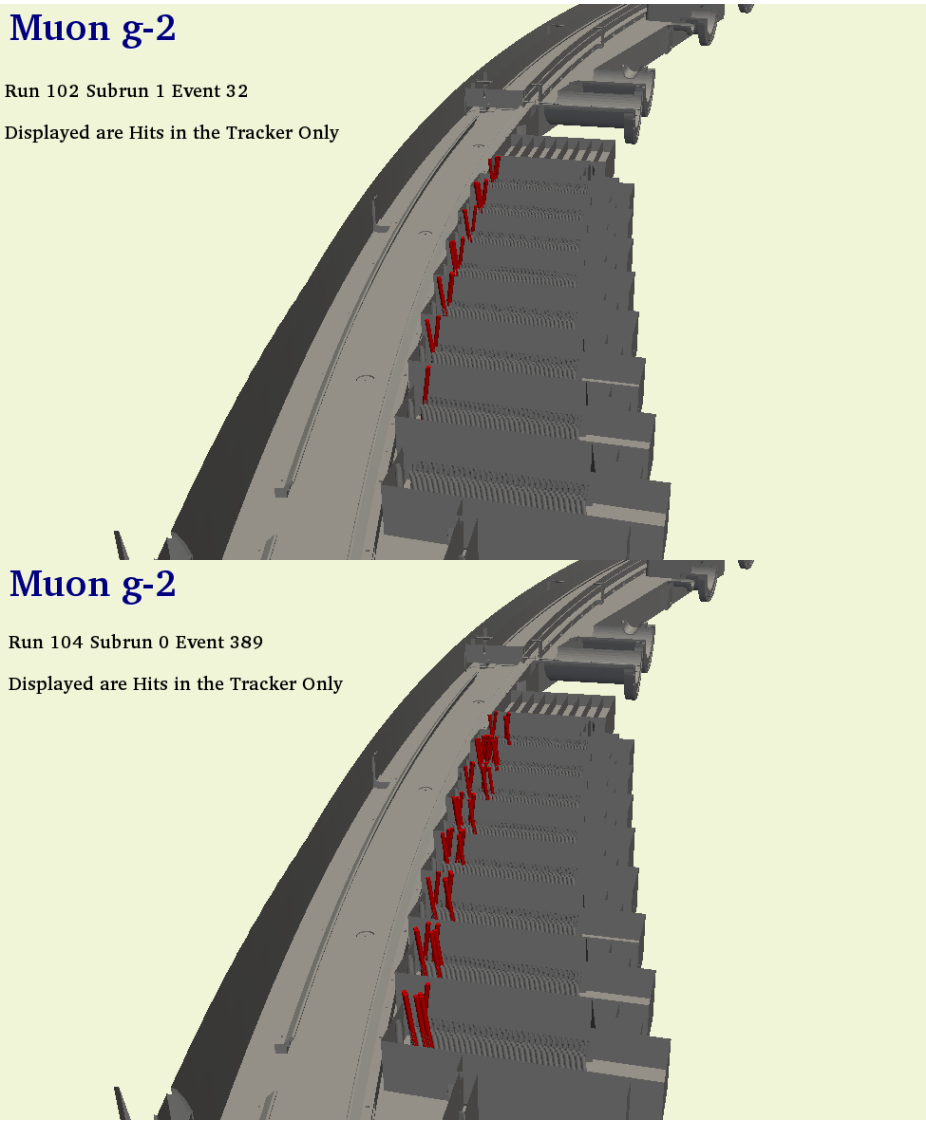
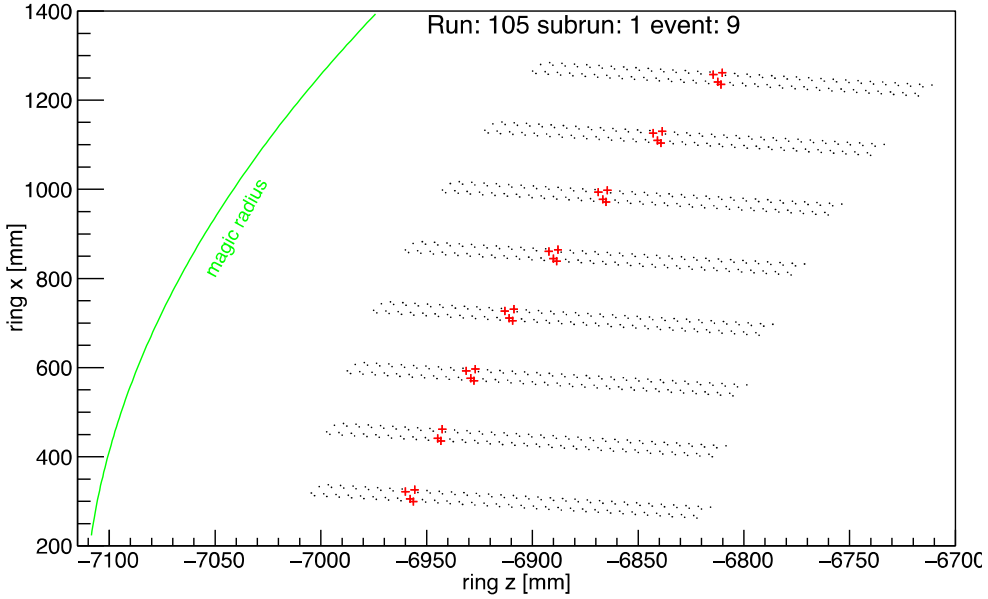


Example tracker straw hits from commissioning data



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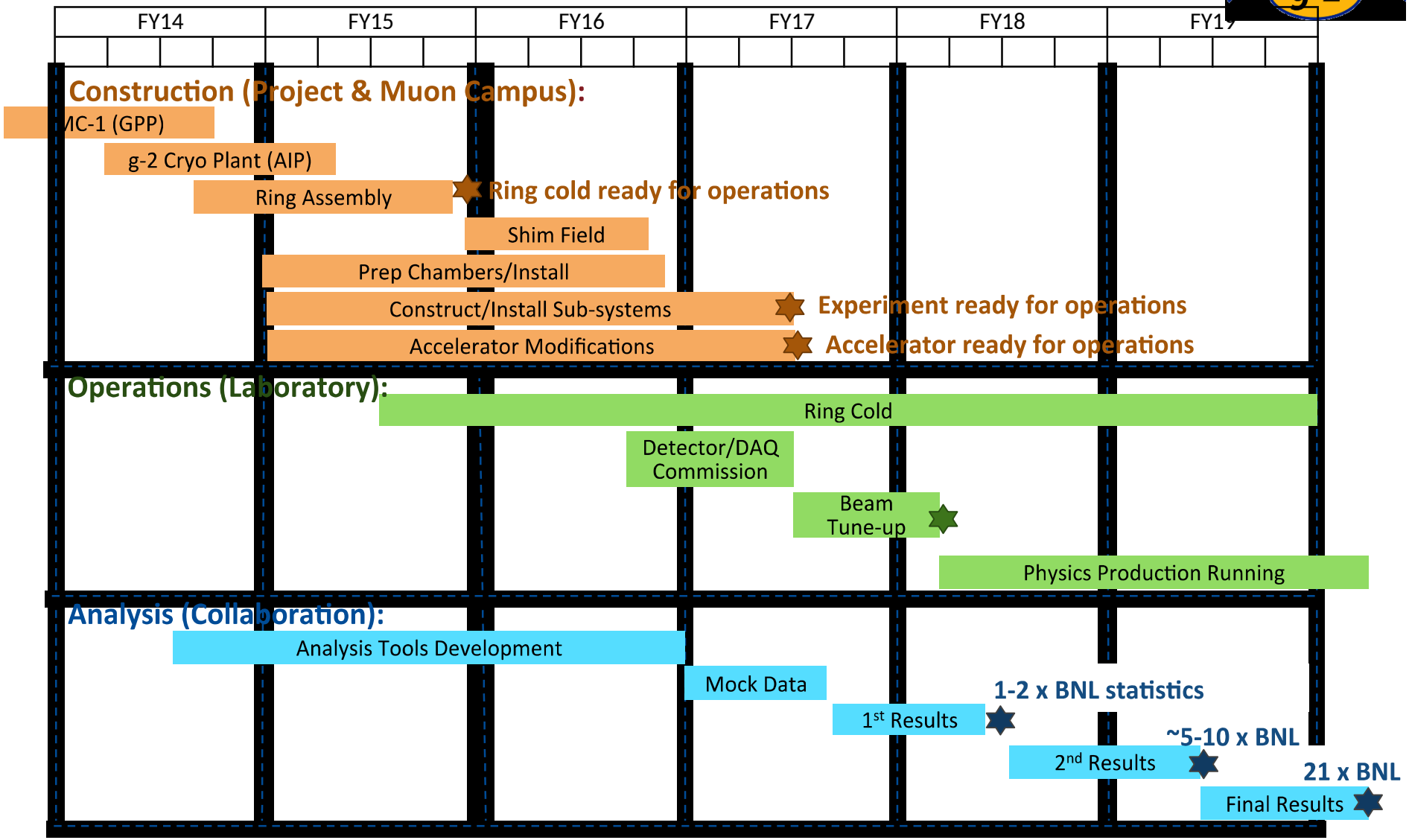
Project Timeline



Fermilab

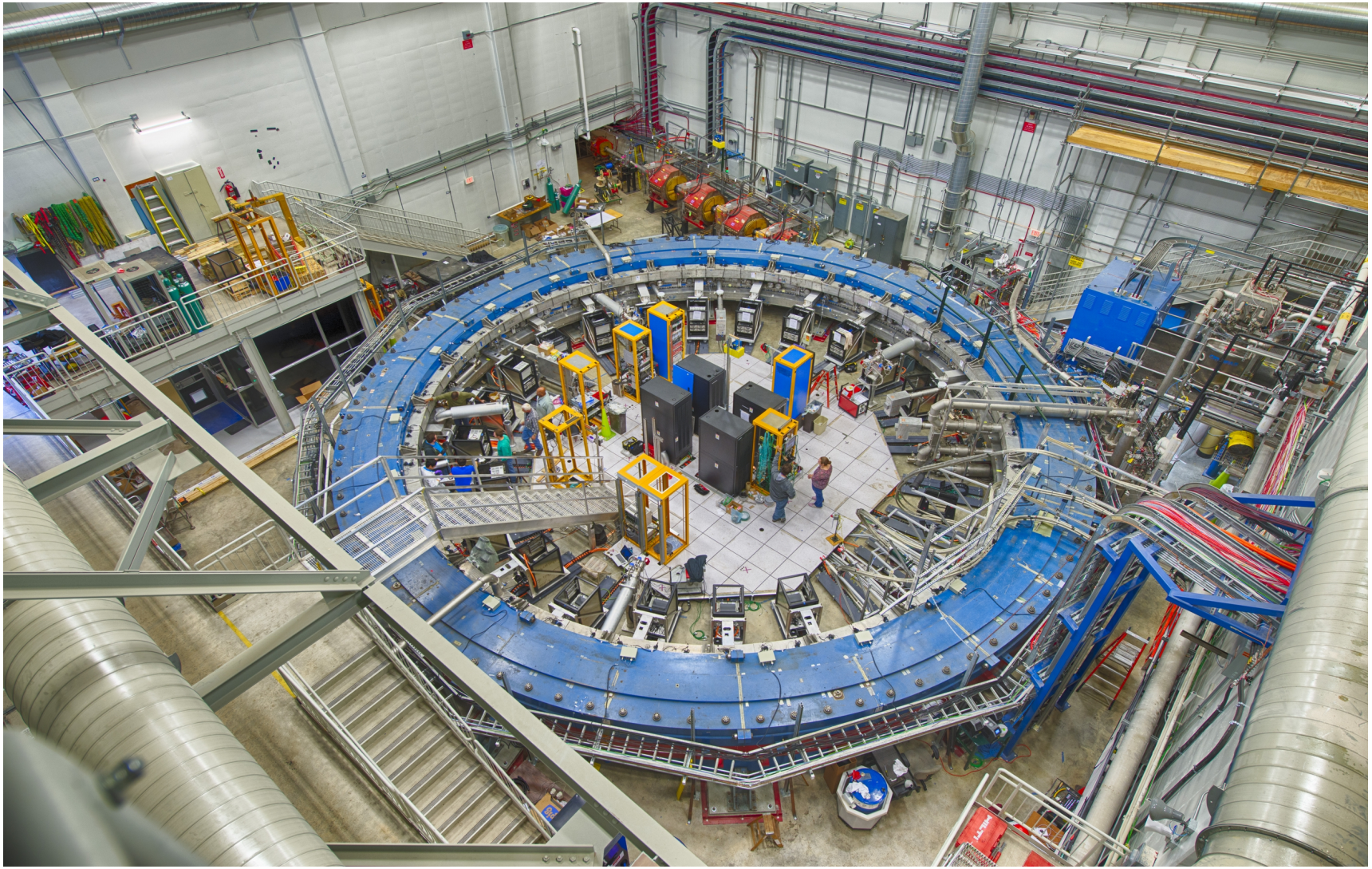
C. Polly and E. Swanson, GM2-doc-4284

Conclusion

Fermilab Muon g-2 experiment:

- **Currently undergoing the commissioning phase**
- **Aims to increase statistics by factor of >20 and reduce systematics by factor of ~3 w.r.t BNL experiment**
- **Goal is to measure anomalous magnetic moment 4-times more precisely than the BNL measurement**

Thank You!



Backup

Properties of Muon

$m_\mu \approx 207 m_e$ [1]

- $(m_\mu / m_e)^2 \approx 42{,}800$ times more sensitive to new physics than electron

$\tau_\mu \approx 2.20\ \mu s$ [1]

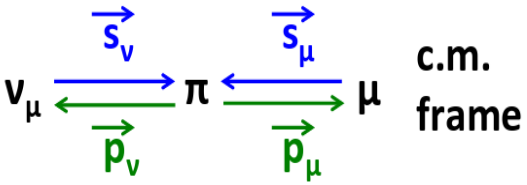
- Time-dilated μ-lifetime allows for μ-beams (BNL (g-2) $_\mu$ $\gamma\tau_\mu \approx 64.4\ \mu s$)

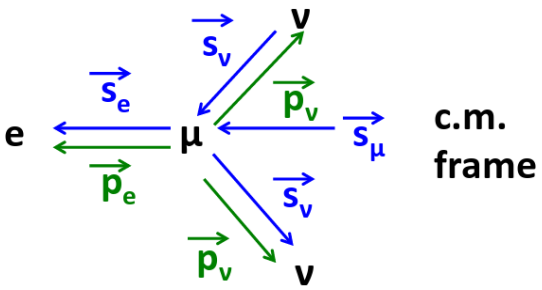
$Br(\pi \to \mu\nu_\mu) \approx 100\%$ [1]

- High intensity μ-beams; polarized μ

$Br(\mu \to e\nu_e\nu_\mu) \approx 100\%$ [1]

- Parity violating Weak decay



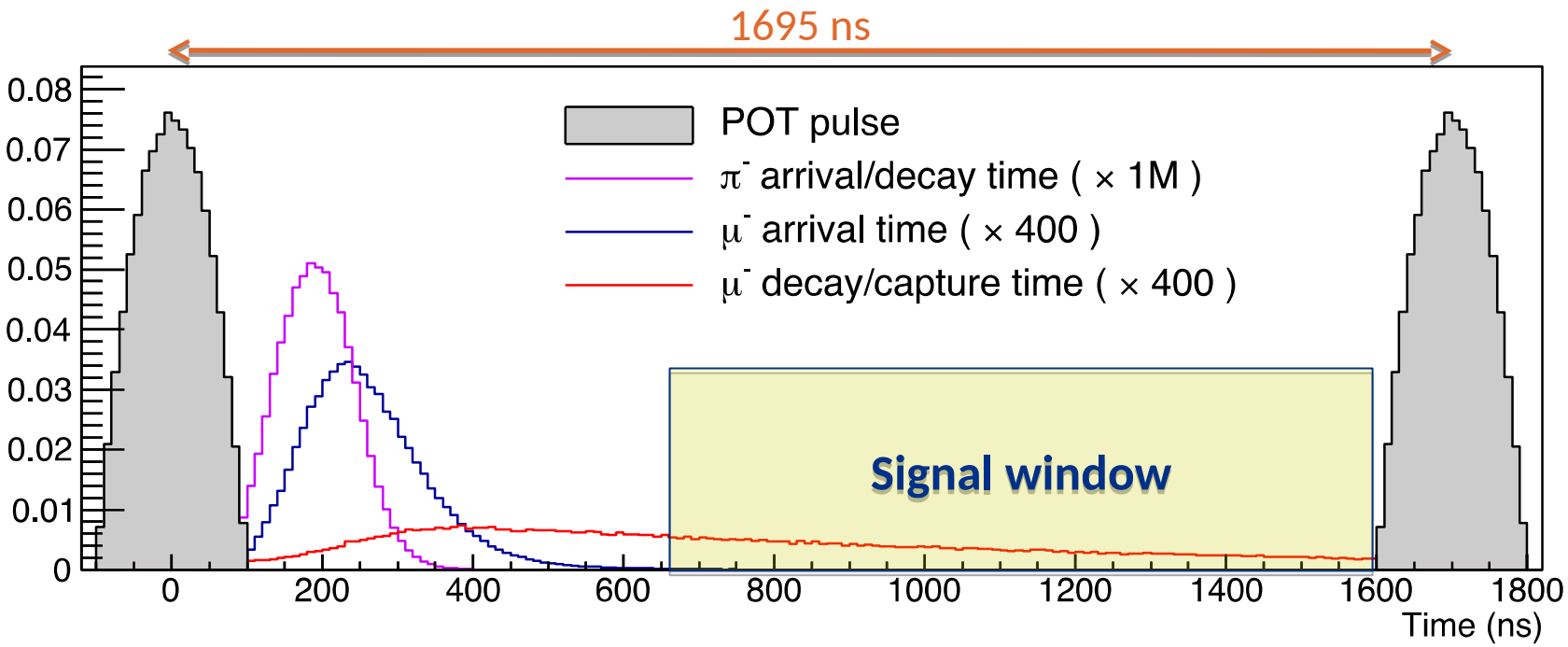


[1] K.A. Olive et al. (Particle Data Group), Chin. Phys. C38, 090001 (2014)

(URL: hjp://pdg.lbl.gov)

Novel Beamline Design

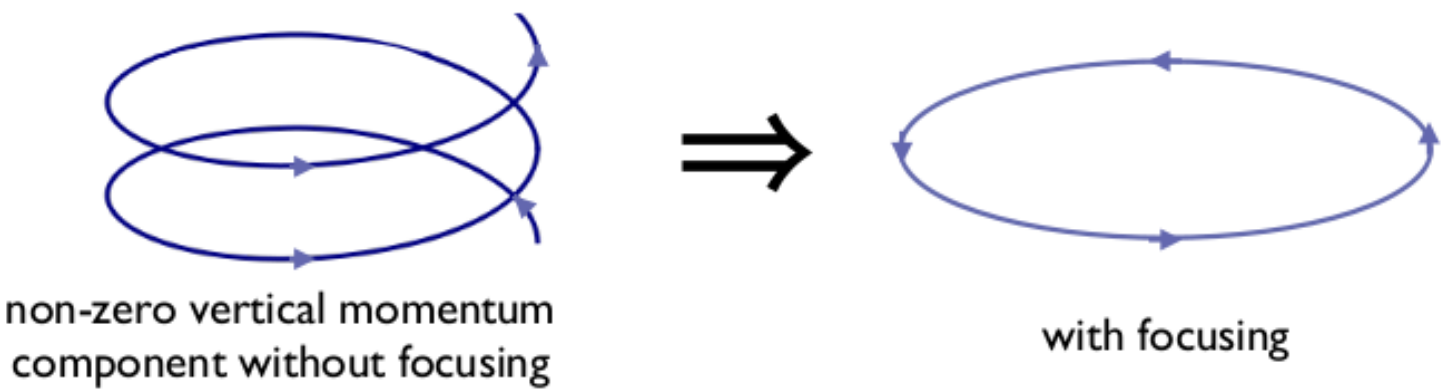
- Pulsed proton beam, ~250 ns wide , ~1695 ns apart
- Delay live gate ~700 ns
- Suppress prompt backgrounds (beam electrons and pion interactions)



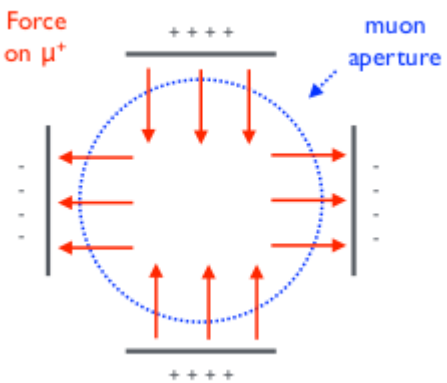
Quadrupoles

- The storage ring acts as a weak-focusing betatron, with the vertical focusing provided by electrostatic quadrupoles

[1]



[1]



[1] J. Grange, GM2-doc-4869

Magic Momentum

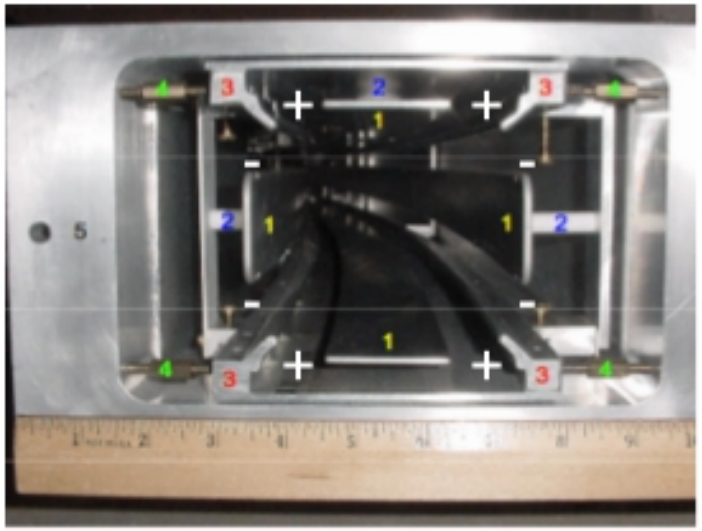
- Fortunate trick: judicious choice of muon energy
  - pioneered by CERN III (1979)

$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right]$$ [1]

$\emptyset$ $\emptyset$

for γ = 29.3
finite γ spread
leads to small
correction

Aside:
JPARC g-2 plans
to use
300 MeV muons,
low dispersion;
no E-field req'd



(1) plates, (2) HV standoffs, (3) trolley rails, (4) adjustment screws, (5) vacuum chamber

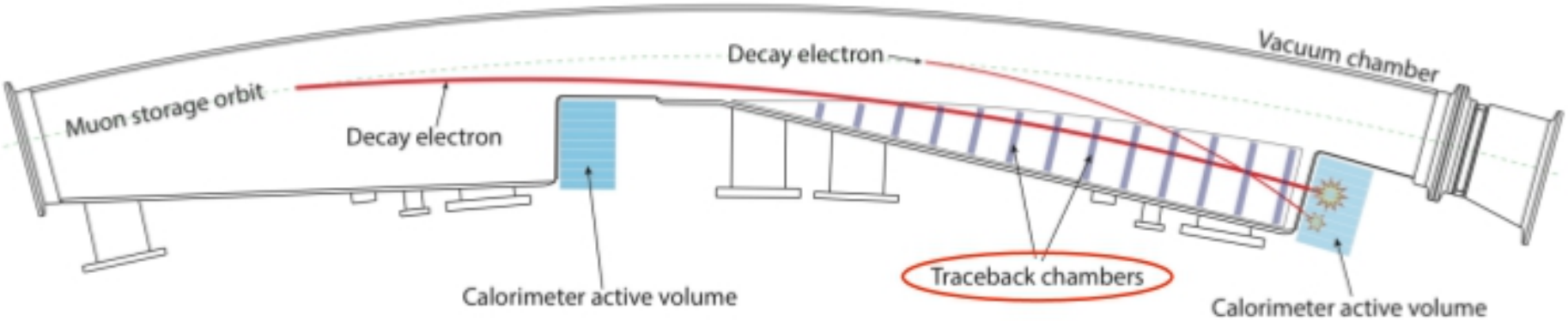
Electrostatic vertical focusing in the ring ⟶ Electric field term

A pure quadrupole electric field provides a linear restoring force in the vertical direction,

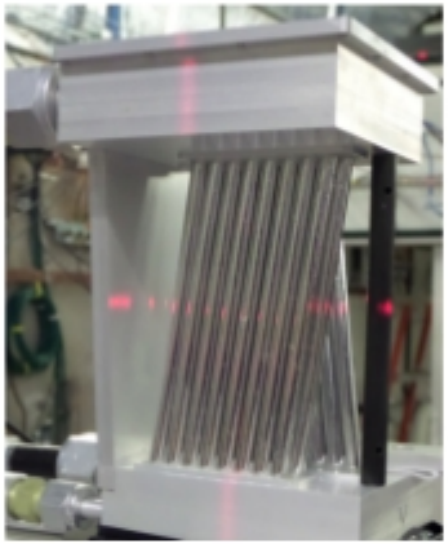
Combination of the (defocusing) electric field and the central (dipole) magnetic field provides a net linear restoring force in the radial direction

[1] J. Grange, GM2-doc-4869

Straw tracker



- Nearly massless (~10^{-3} X_0) detectors measure full beam profile at three locations in ring. Beam profile monitors:
  - betatron motion
  - momentum spread
  - magnetic field variations (indirect)
- Few mm resolution for pileup detection
- Better energy resolution than calorimeter allows verification of gain measurements



Prototype at FNAL test beam

Joe Grange

Straw tracker

- Also affords sensitivity to additional physics: muon electric dipole moment (EDM)

size of μ EDM

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\mathrm{EDM}} = \vec{\omega}_a - \frac{q\eta}{2m}(\vec{\beta} \times \vec{B}) \qquad \vec{d}_\mu = \eta \frac{e}{4mc}\vec{S}$$

"radial"
spin precession

- Non-zero EDM observable in up-down asymmetry in spin precession

- BNL: $|\vec{d}_\mu| < 1.8 \times 10^{-19} e \text{ cm}$

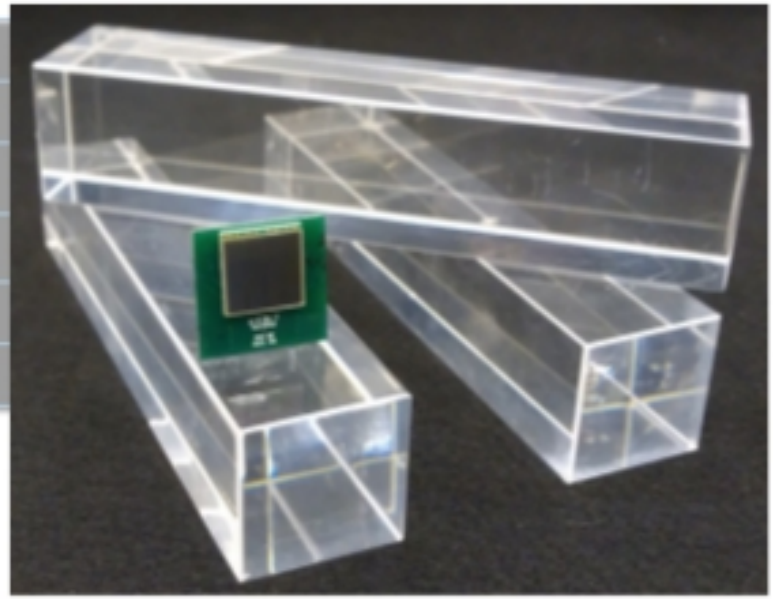
  Phys. Rev. D 80, 052008 (2009)

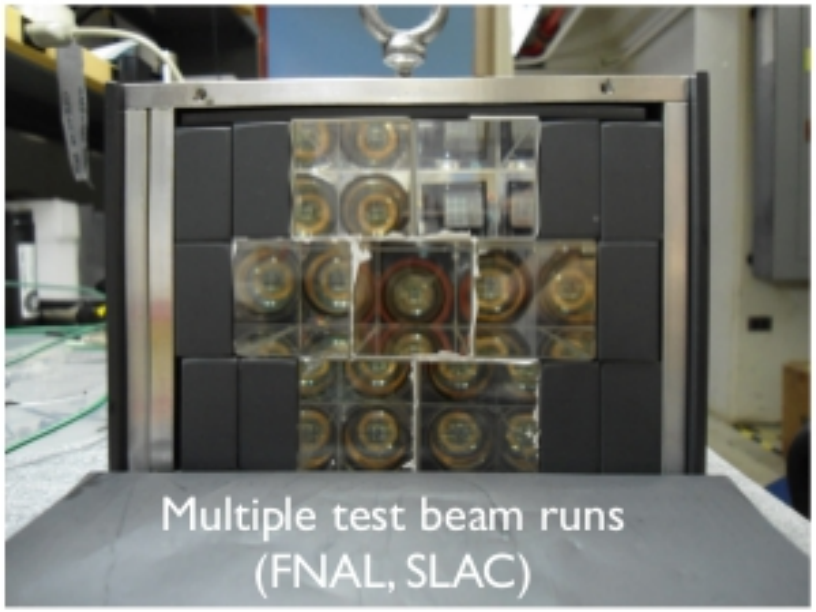
- Goal is order of magnitude improvement

NIU g-2 group heavily involved. Future colloquium by Prof. Eads with more on straw trackers.

Calorimeter improvements

Size	2.5 x 2.5 cm
Thickness	14 cm (> 15 X_0)
Segmentation	6 x 9
Radiation length	0.93 cm
Moliere radius R_M	2.2 cm
Moliere radius R_M (Cerenkov)	1.8 cm

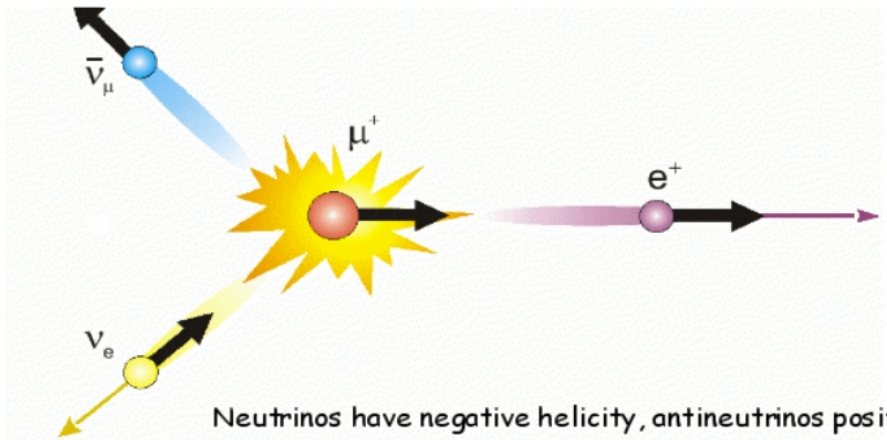




- Much greater segmentation
- Dense medium (PbF_2)
- SiPM readout operates in fringe field
  - waveform fully digitized
- Needs stable bias voltage

Pileup

Muon Decay



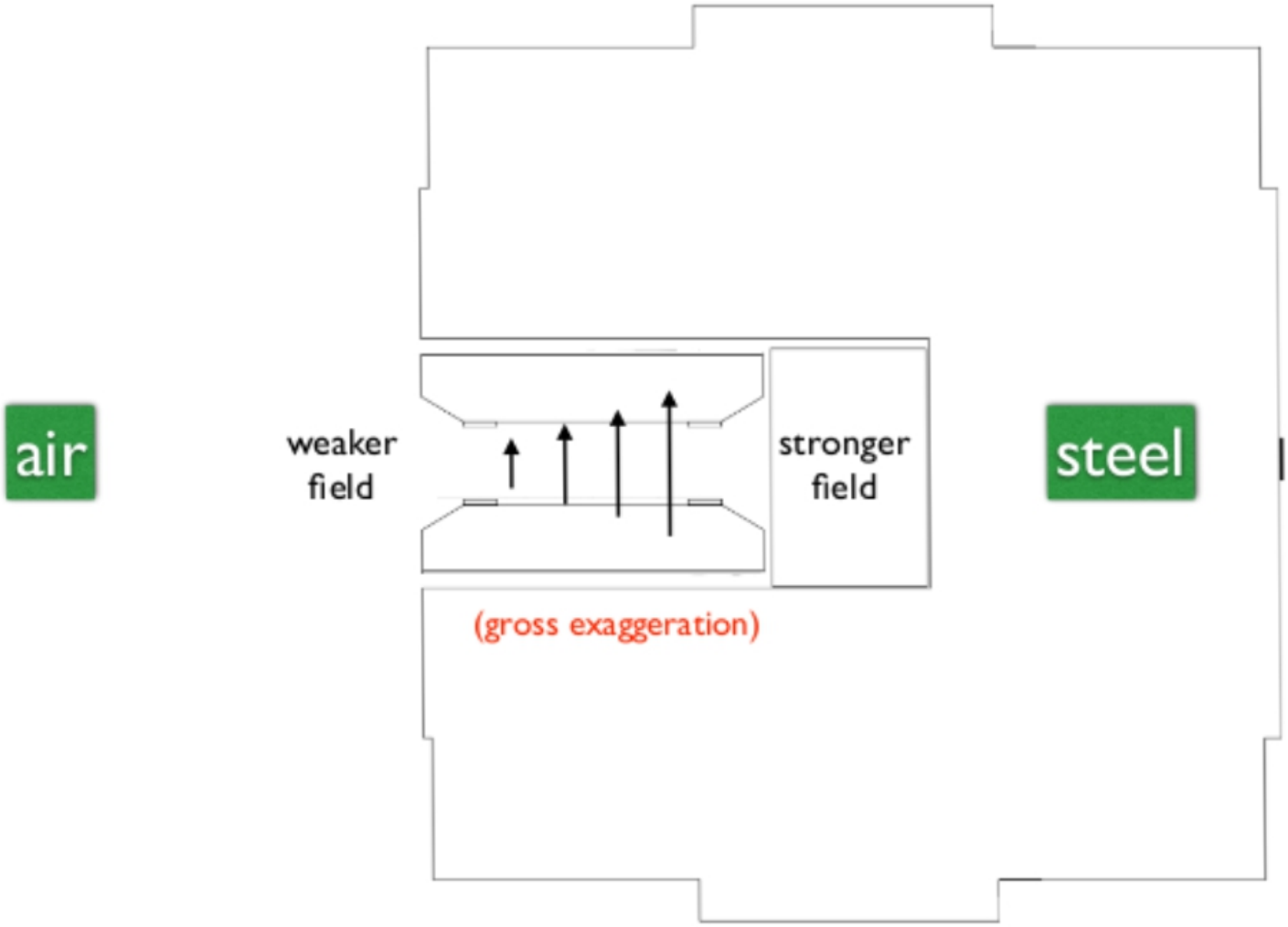
Neutrinos have negative helicity, antineutrinos positive. An ultrarelativistic positron behaves like an antineutrino. Thus the positron tends to be emitted along the muon spin when ν_e and $\bar{\nu}_\mu$ go off together (highest energy e^+).

- **A high E e^+ has a larger radius of curvature ⟶ a longer time-of-flight to the calorimeter**
- **Carries phase of a muon that decayed earlier than one that produced a low E e^+**
- **2 low E pulses are lost and an apparent high E pulse is gained**
- **HighE pulse still has the phase of the low E pulses**

- The muon spin direction is correlated to the momentum of the emitted positrons
- Correlation between muon and decay positron spin strongest at high momentum.
- Pileup of two low E e+ may fake high E e+.

Strategy: calorimeters with higher segmentation, Moreover straw trackers to rectify uncernities

Passive shimming



Passive shimming