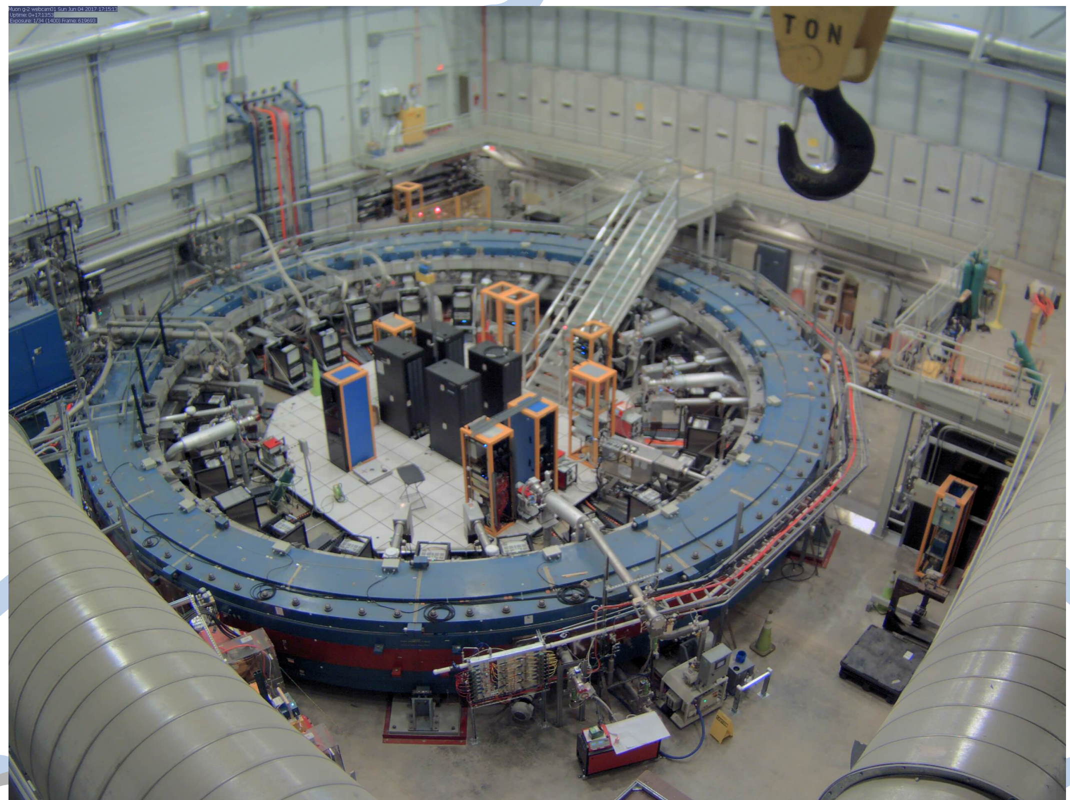
Current status and prospects of (g-2) measurements

Jason D. Crnkovic

on behalf of the Muon g-2 Collaboration

FPCP 2018, Hyderabad, India:
Monday, July 16th, 2018

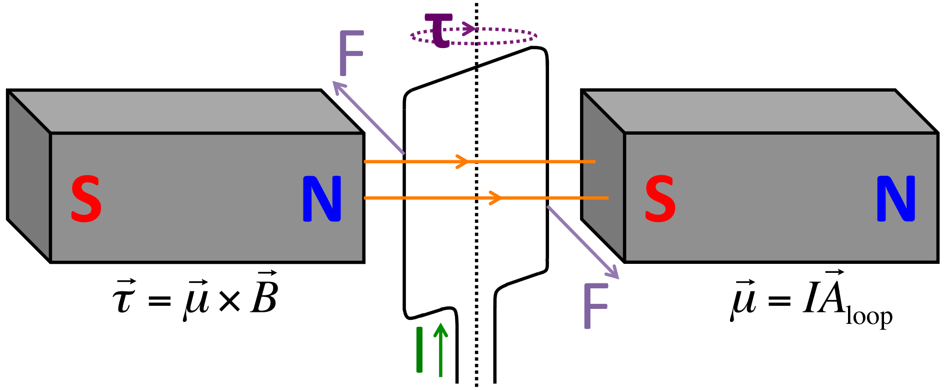


BROOKHAVEN NATIONAL LABORATORY

Fermilab

Magnetic dipole moments lead to spin precession.

Classical Picture



Quantum Picture

Dirac Equation for EM potential:

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

- **Spin-1/2 point particles**
- **Leads to Pauli Theory**
- **Predicts g = 2**

g-factor:

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

Larmor Precession (particle rest frame):

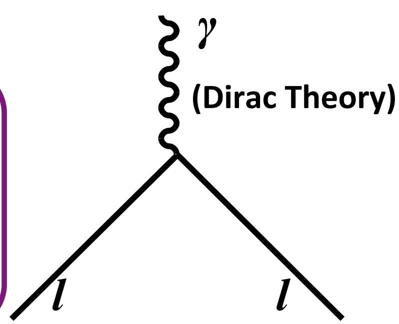
$$\frac{d\vec{s}}{dt} = \vec{\tau} = g\left(\frac{q}{2m}\right)\vec{s} \times \vec{B}$$

Quantum Field Theory Picture

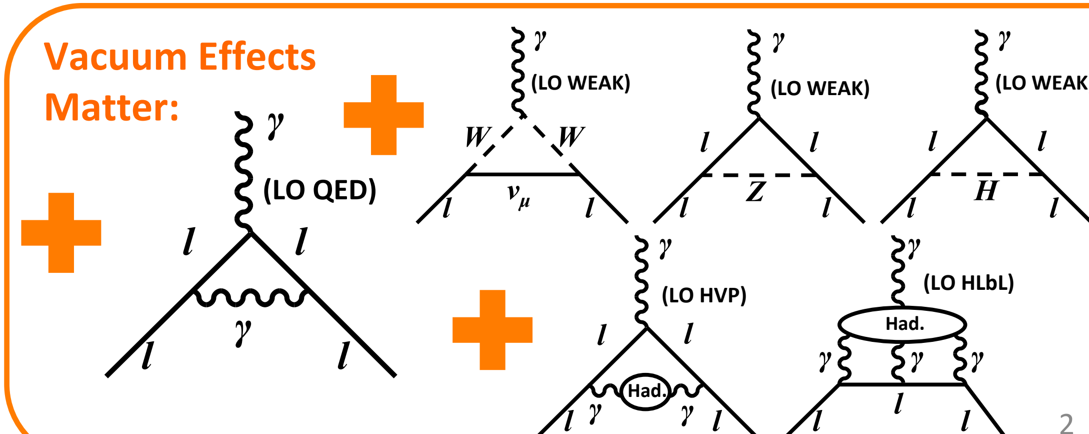
Anomaly:

$$a \equiv \frac{g-2}{2}$$

- **Predicts g ≠ 2**



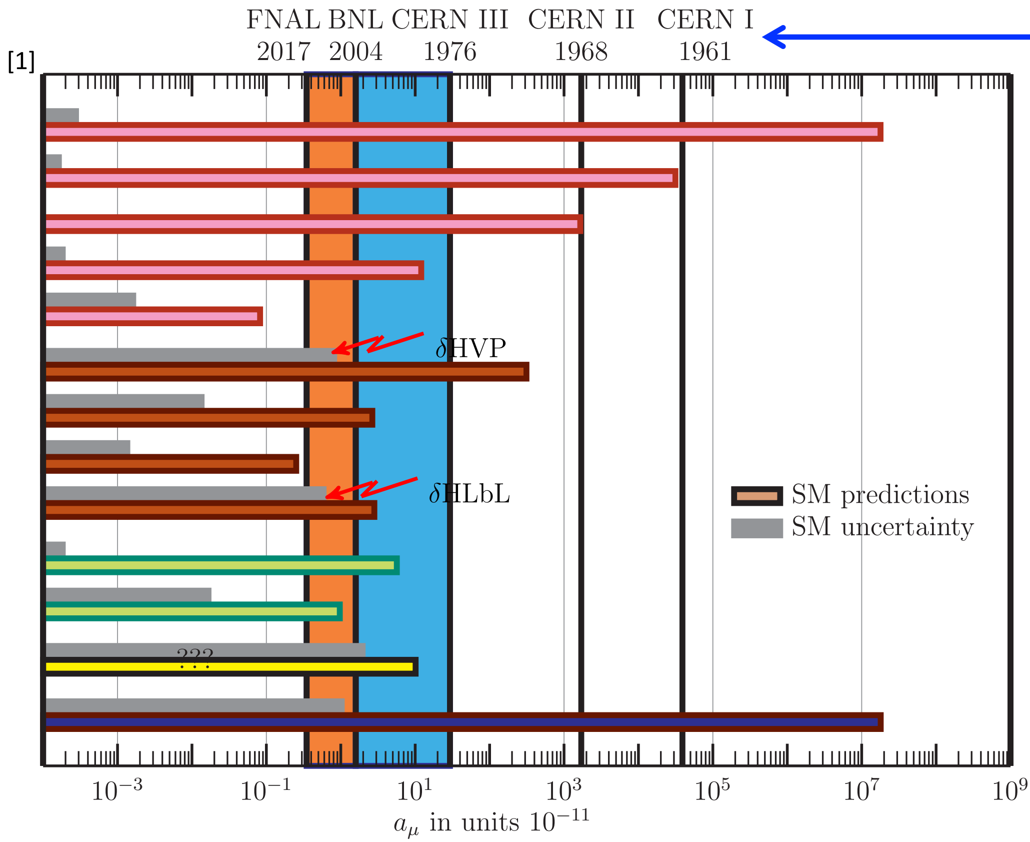
Vacuum Effects Matter:



Muons are useful for g-2 measurements.

- $\tau_\mu \approx 2.20\ \mu s$
  - Time-dilated μ-lifetime allows for μ-beams ($\gamma\tau_\mu \approx 64.4\ \mu s$ for "magic momentum" muons)
- $Br(\pi \rightarrow \mu\nu_\mu) \approx 100\%$
  - High intensity polarized μ-beams
- $Br(\mu \rightarrow e\nu_e\nu_\mu) \approx 100\%$
  - Parity violating Weak decay (correlation between e direction and μ spin)
- $m_\mu \approx 207 m_e$
  - $(m_\mu/m_e)^2 \approx 42{,}800$ times more sensitive to new physics than electron (good SM test)

Measurement precision achieved by different experiments



LO = Leading Order
QED = Quantum Electrodynamics
VP = Vacuum Polarization
NLO = Next To Leading Order
NNLO = Next To Next To Leading Order
LbL = Light-by-Light
HO = Higher Order
SM = Standard Model

[1] F. Jegerlehner, EPJ Web Conf. **166**, 00022 (2018) doi:10.1051/epjconf/201816600022 [arXiv:1705.00263 [hep-ph]].

Non-perturbative QCD dominates SM muon g-2 uncertainty.

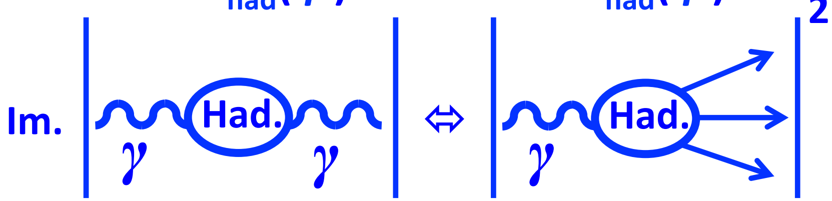
[1]

Contribution	a_μ [$\times 10^{-11}$]	δa_μ [$\times 10^{-11}$]
QED incl. 4-loops + 5-loops	116 584 718.86	0.03
hadronic LO VP	6 894.6	32.5
hadronic LbL	103.4	28.8
Hadronic HO VP	-87.0	0.6
Weak to 2-loops	153.6	1.1
Theory	116 591 783	43
Experiment	116 592 091	63
The. − Exp. (4.0σ difference)	-306	76

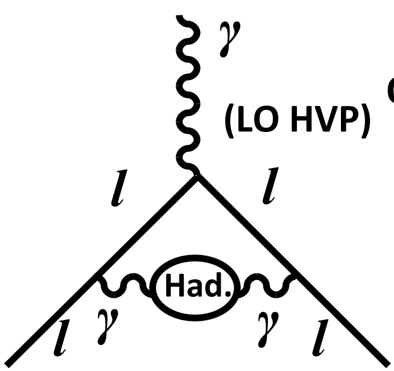
Largest source of SM error

Optical Theorem

$\mathrm{Im}\,\Pi_{\mathrm{had}}(q^2)$ $\sim \sigma_{\mathrm{had}}(q^2)$



Inclusive hadronic final state cross section



Analyticity & Optical Theorem ⇔

$$a_\mu^{\text{had. LO VP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} R(s)\hat{K}(s)$$

Can obtain from data for low energies

$$R(s) = \frac{\sigma\left(e^+e^- \to \text{hadrons}\right)}{\left(4\pi\alpha^2/3s\right)}$$

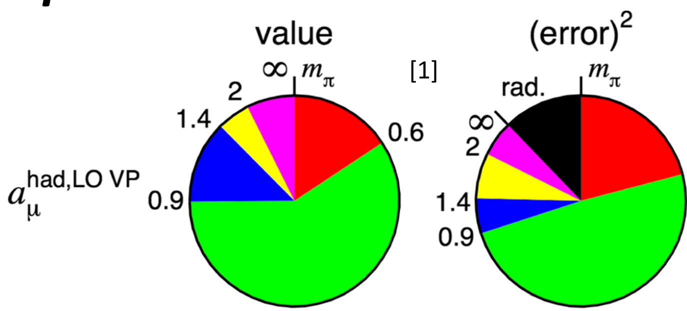
$\sigma(e^+e^- \to \mu^+\mu^-)$ at tree level

$$\hat{K}(s) = \frac{3s}{m_\mu^2}\int_0^1 dx \frac{x^2(1-x)}{x^2 + \left(s/m_\mu^2\right)(1-x)}$$

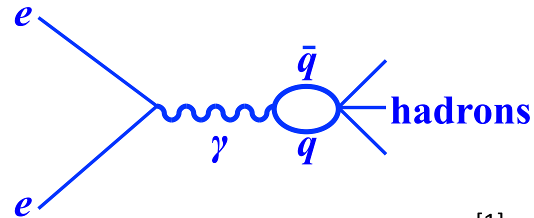
Amplifies low energy $\sigma(e^+e^- \to \text{hadrons})$

[1] F. Jegerlehner, arXiv:1804.07409 [hep-ph].

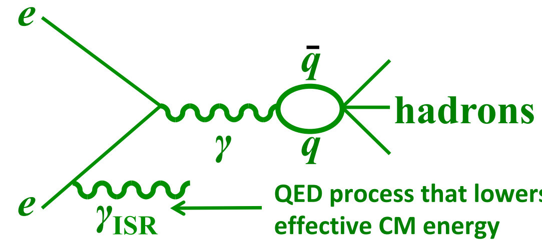
Work continues on improving the precision of $a_\mu^{\text{had. LO VP}}$.



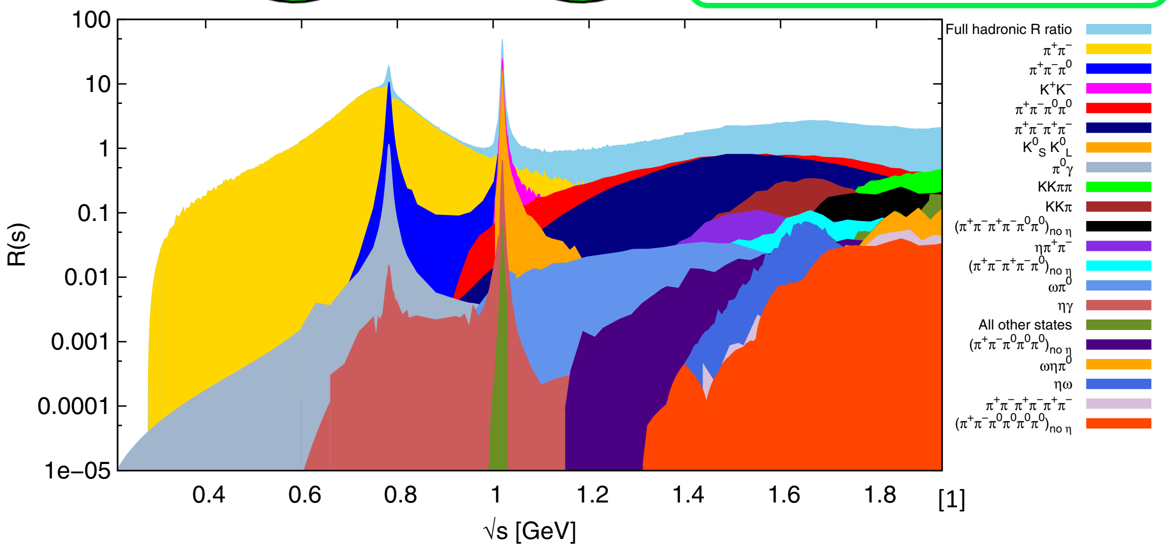
Direct Scan Method:

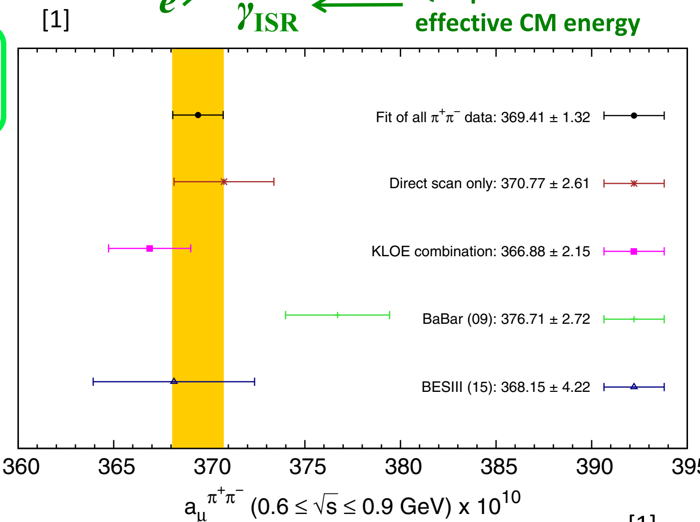


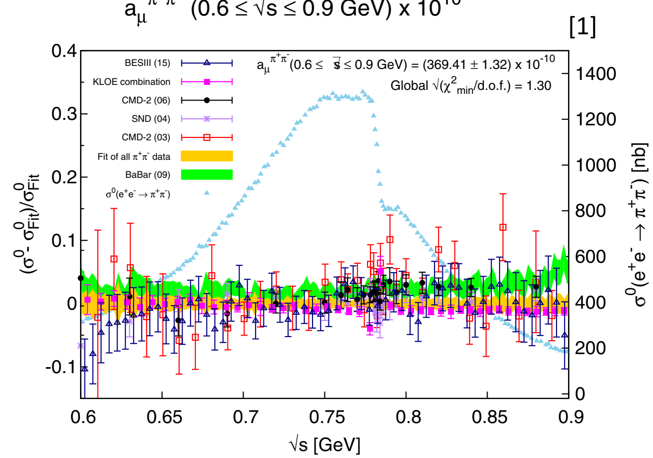
Initial State Radiation (ISR) method:
(suitable for Phi- and B-factories)



σ(e⁺e⁻➔π⁺π⁻) contributes the most to the value and error





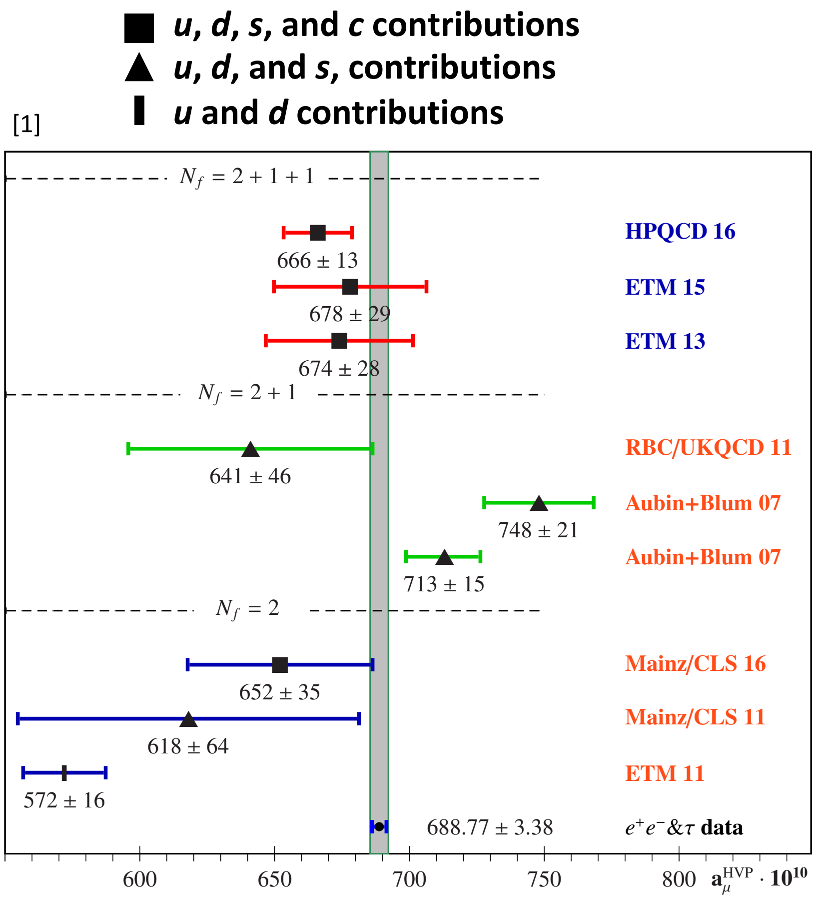


From a recent hadronic VP contributions to muon g-2 workshop[2]:

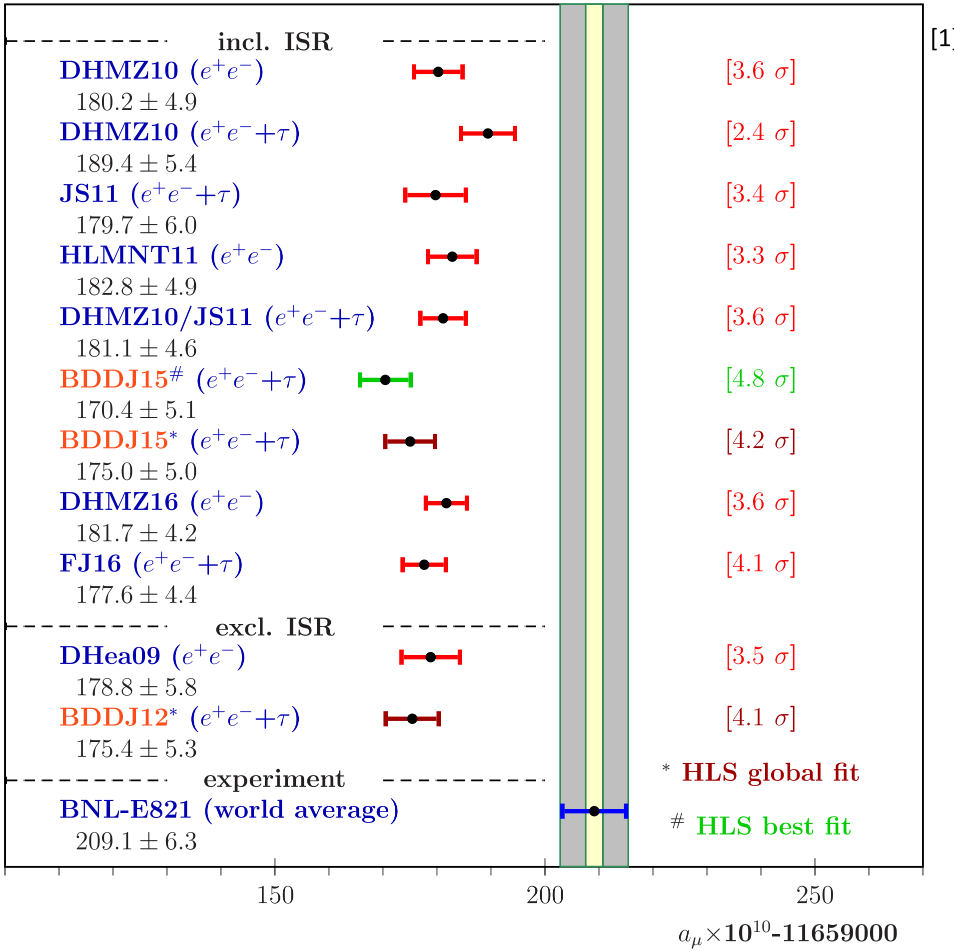
- Belle II studying an e^+e^-➔$\pi^+\pi^-$ measurement (Maeda Yosuke)
- BABAR working on e^+e^-➔$\pi^+\pi^-$ measurement using full BABAR data set (Michel Davier)
- BESIII preliminary e^+e^-➔$\pi^+\pi^-\pi^0$, $\pi^+\pi^-2\pi^0$, and $\pi^+\pi^-3\pi^0$ measurements (Christoph Florian Redmer)

[1] A. Keshavarzi, D. Nomura and T. Teubner, Phys. Rev. D **97**, no. 11, 114025 (2018) doi:10.1103/PhysRevD.97.114025 [arXiv:1802.02995 [hep-ph]].
[2] Workshop on hadronic vacuum polarization contributions to muon g-2, KEK, Tsukuba, Japan, Feb. 12th to 14th (2018):

BNL muon anomaly measurement and SM prediction differ by greater than 3σ.



Work continues with LQCD $a_\mu^{\text{had. LO VP}}$ calculations



- Historical e^+e^- and τ data discrepancy resolved by including effects such as $\rho-\gamma$ mixing (important isospin breaking effects): DHMZ10 (e^+e^- + τ) does not have $\rho-\gamma$ mixing correction
- BDDJ15# excludes while BDDJ15* includes BABAR $\pi^+\pi^-$ data
- If central values do not move, achieving Fermilab error goal will lead to a greater than 5σ difference

[1] F. Jegerlehner, EPJ Web Conf. **166**, 00022 (2018) doi:10.1051/epjconf/201816600022 [arXiv:1705.00263 [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
- Rjeka
- Molise
- SNS Pisa

China
- Shanghai

The Netherlands
- Groningen

Germany
- Dresden (thy)

England

Cockroft Institute
Lancaster
Liverpool
University College London

Korea

KAIST
CAPP

Russia

Dubna
Novosibirsk

Fermilab

Muon anomaly is obtained from 5 numbers.

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

Get from CODATA[1]:

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)

Fermilab Experiment a_μ total error goal is 140 ppb

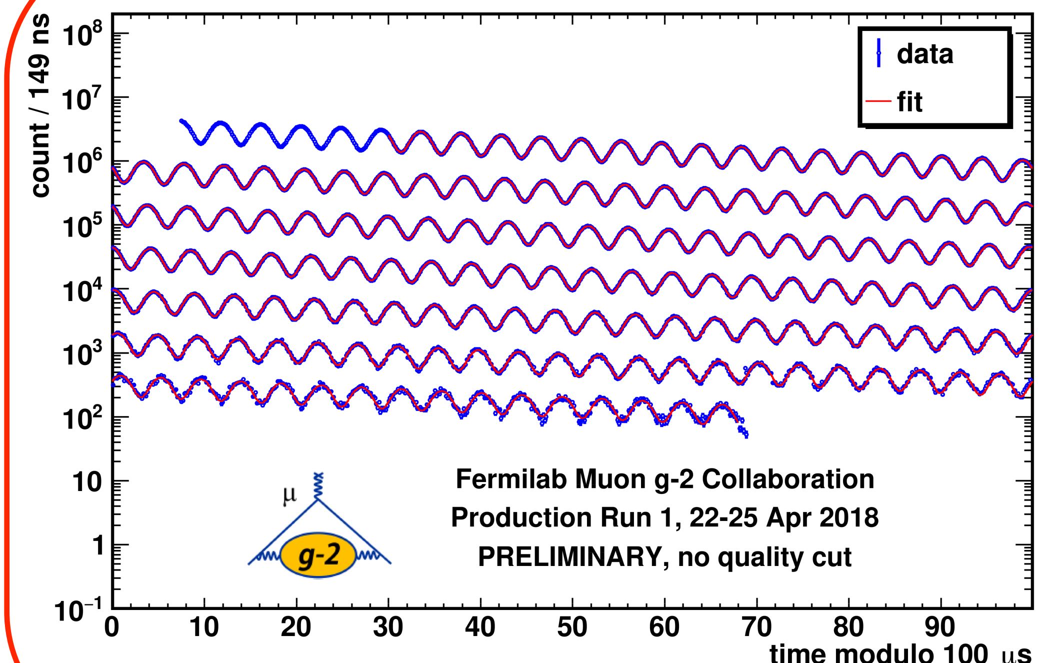
[1] P. J. Mohr, D. B. Newell and B. N. Taylor, Rev. Mod. Phys. **88**, no. 3, 035009 (2016) doi:10.1103/RevModPhys.88.035009 [arXiv:1507.07956 [physics.atom-ph]].

Muon anomaly is obtained from 5 numbers.

Anomalous spin precession frequency is extracted from decay positron time spectra

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

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



~60 hours of data yielding ~0.95 billion decay positrons

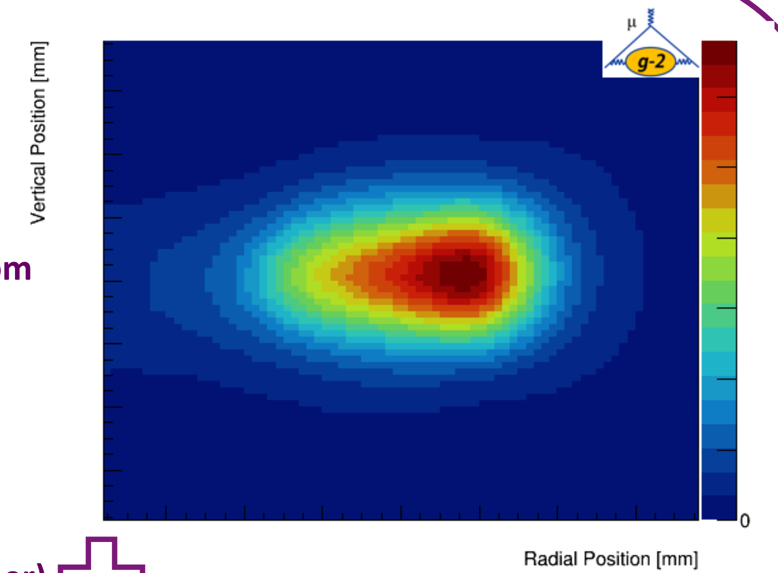
Muon anomaly is obtained from 5 numbers.

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

Average magnetic field seen by muons is measured with NMR

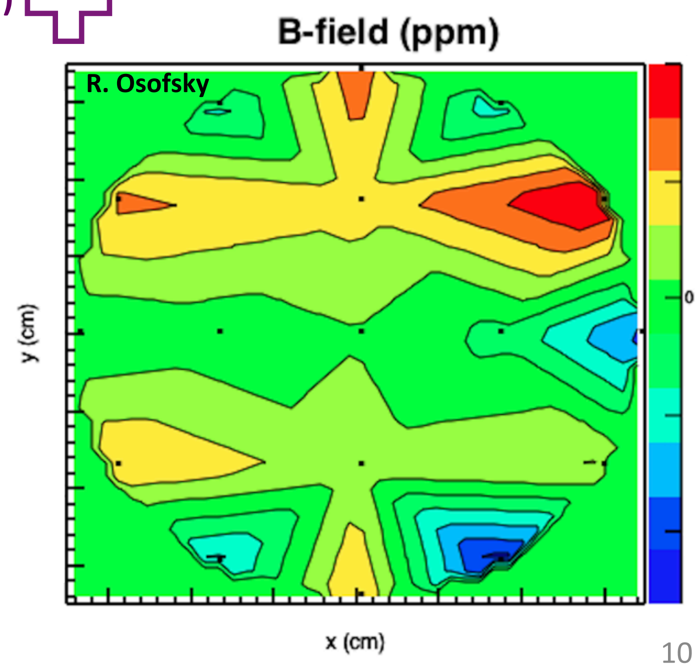
$$\hbar\omega_p = 2\mu_p \left|\vec{B}\right|$$

Obtain muon distribution from straw trackers

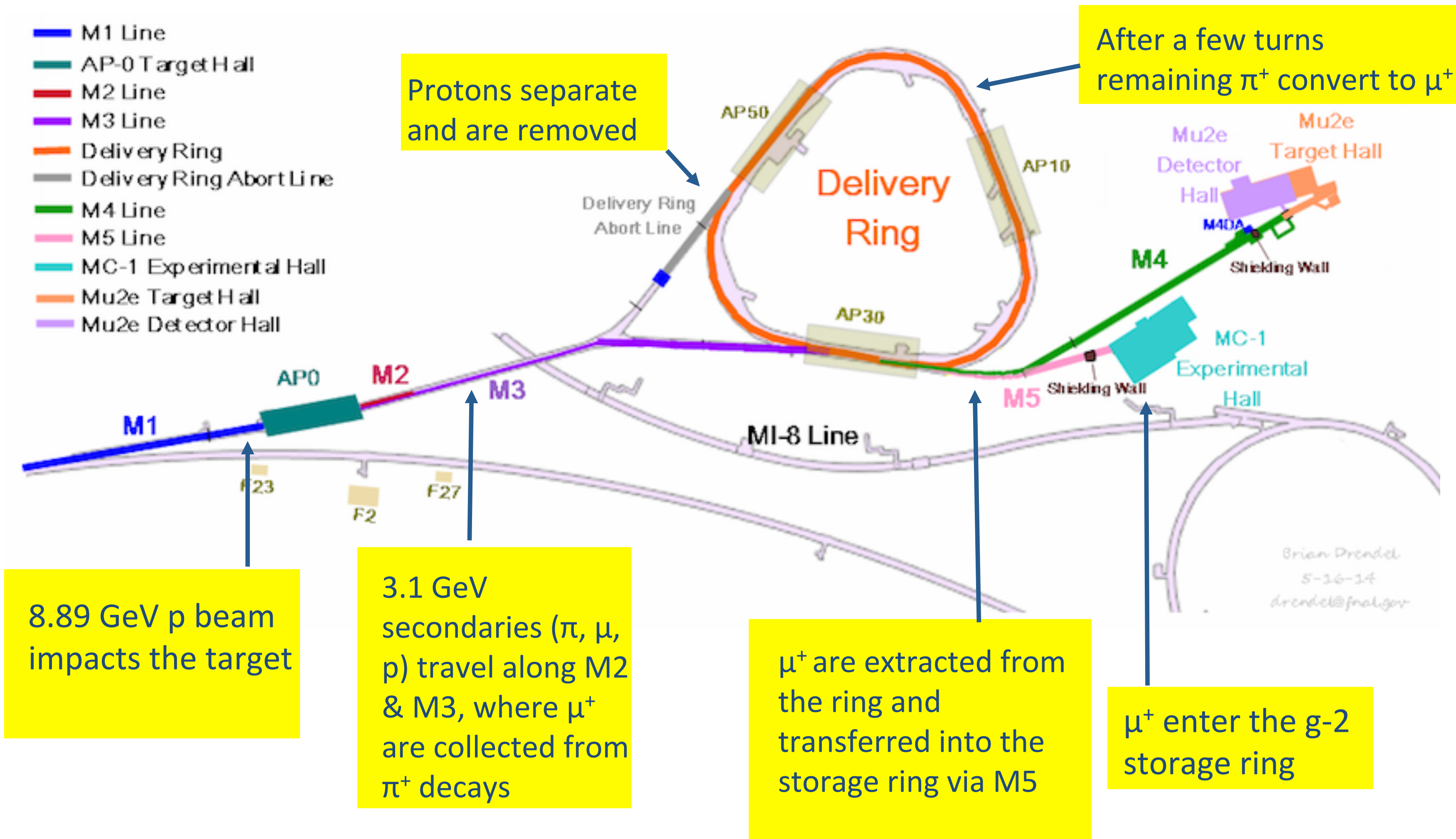


(Combine Together)

Obtain B-field from NMR probes

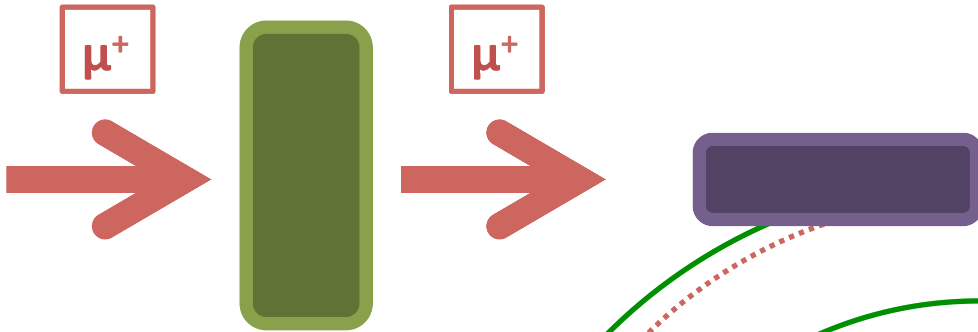


Fermilab beamline decays away most of the pions.

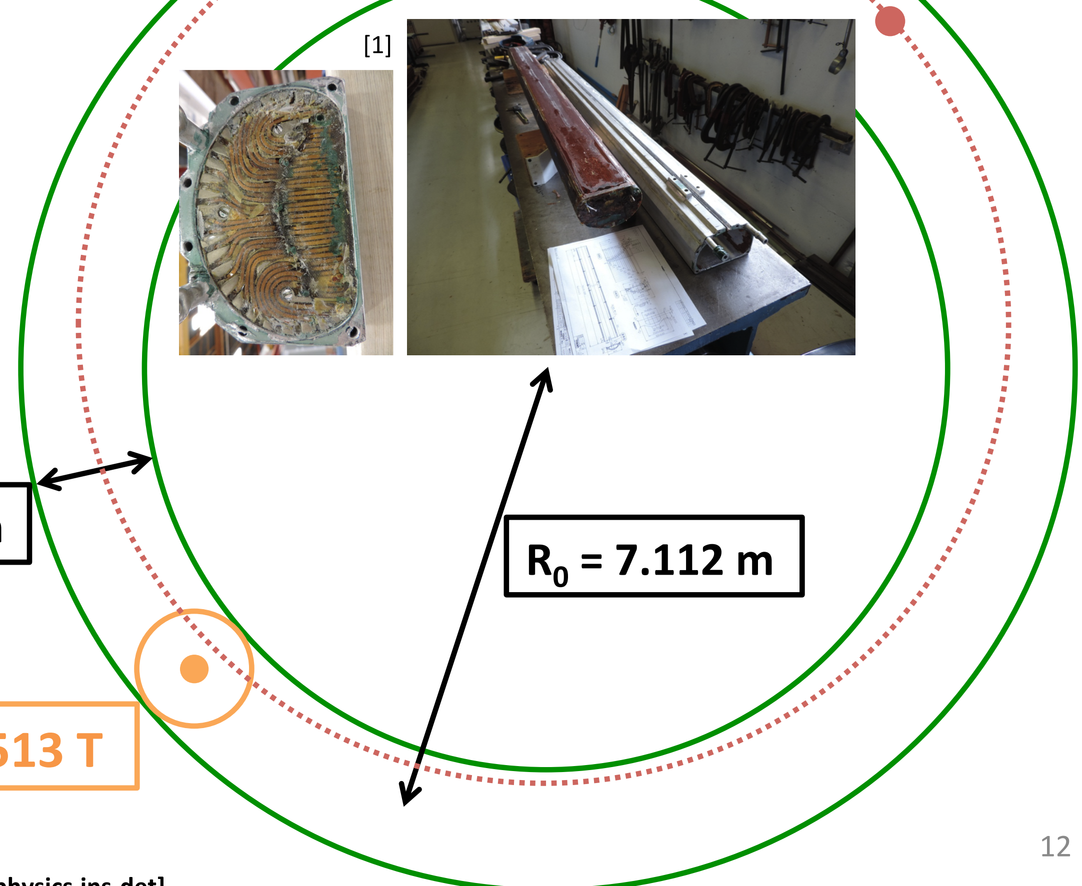


D. Stratakis

Fermilab Muon g-2 Experiment:

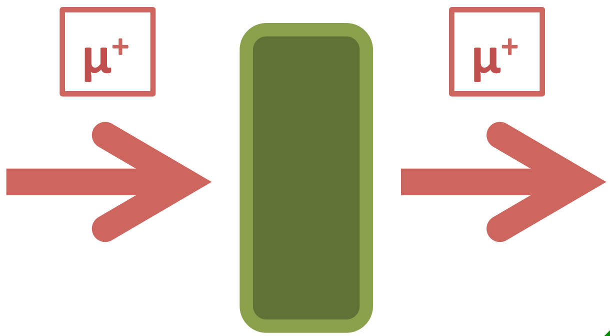


- M5 magnetic quads do final focusing before injection into ring
- Inflector injects muons into ring while minimizing disturbance to B-field

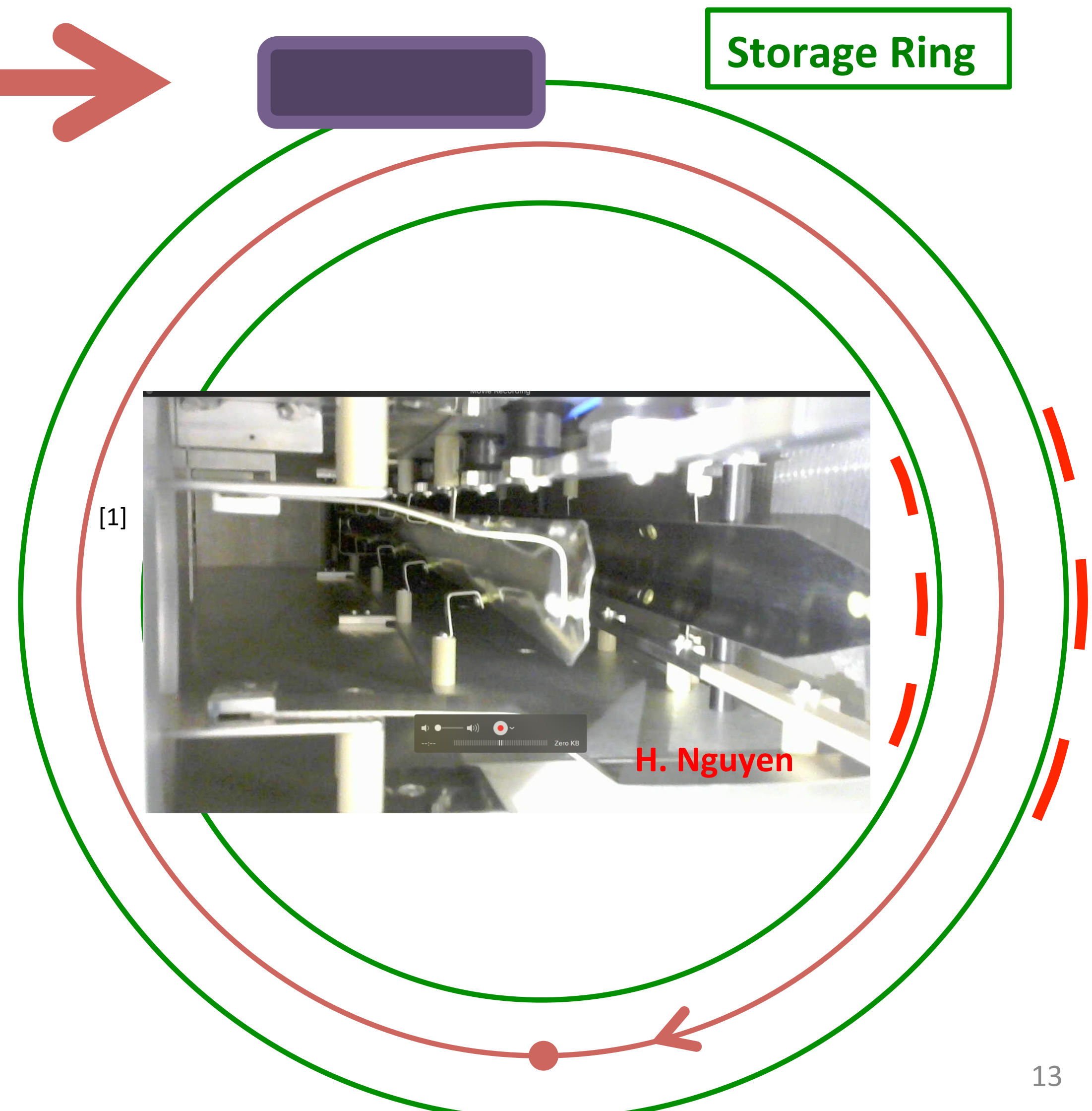


[1] J. Grange *et al.* [Muon g-2 Collaboration], arXiv:1501.06858 [physics.ins-det].

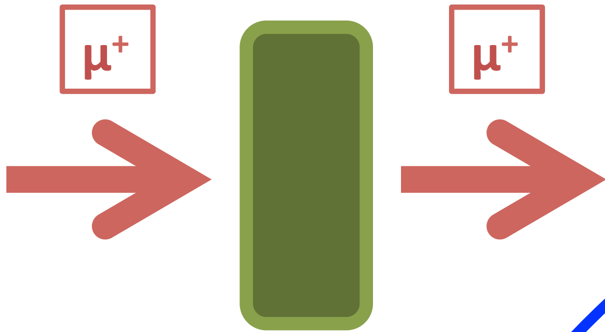
Fermilab Muon g-2 Experiment:

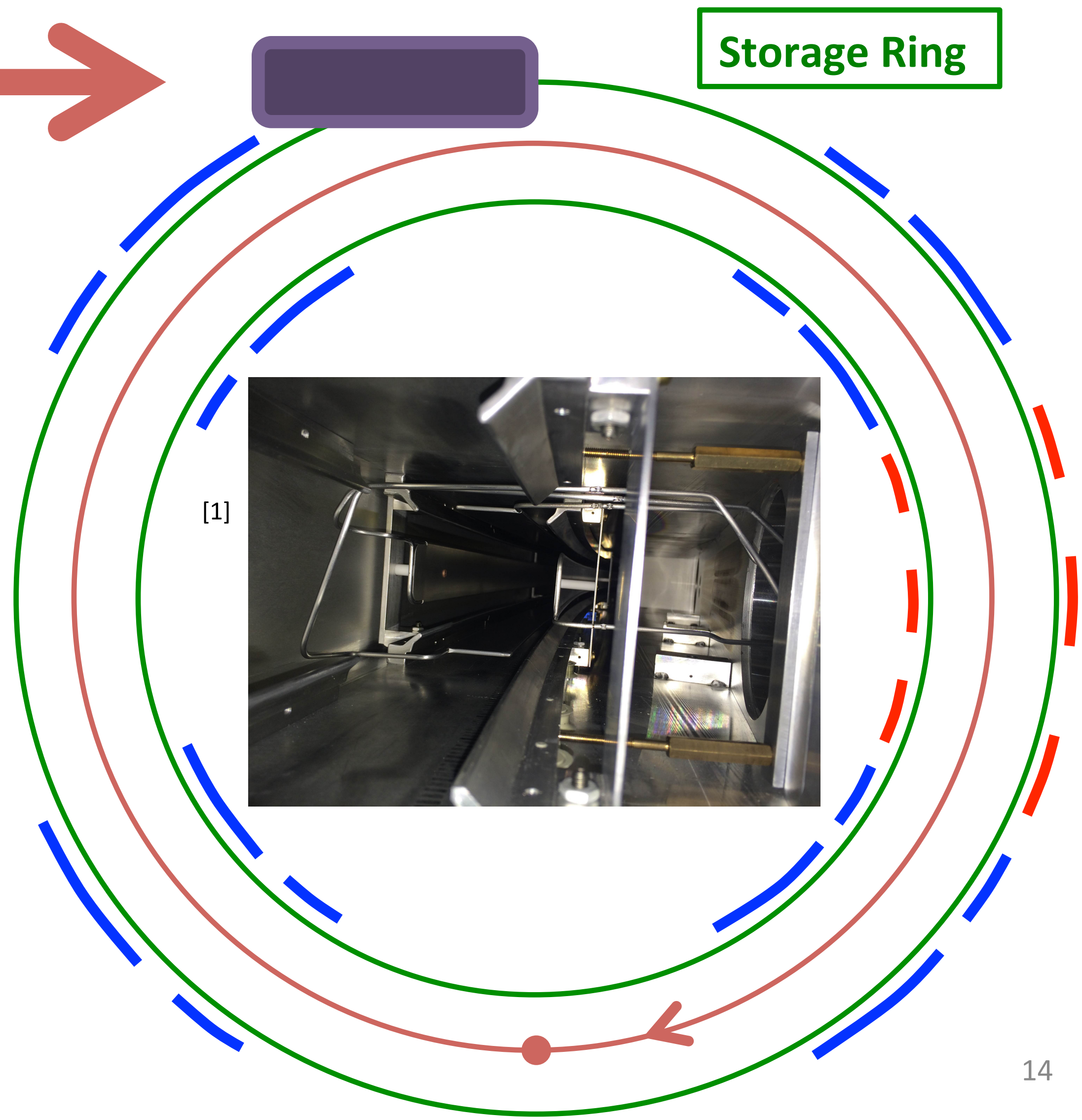


- M5 magnetic quads do final focusing before injection into ring
- Inflector injects muons into ring while minimizing disturbance to B-field
- 3 magnetic kickers “kick” the muons onto the storage orbit



Fermilab Muon g-2 Experiment:





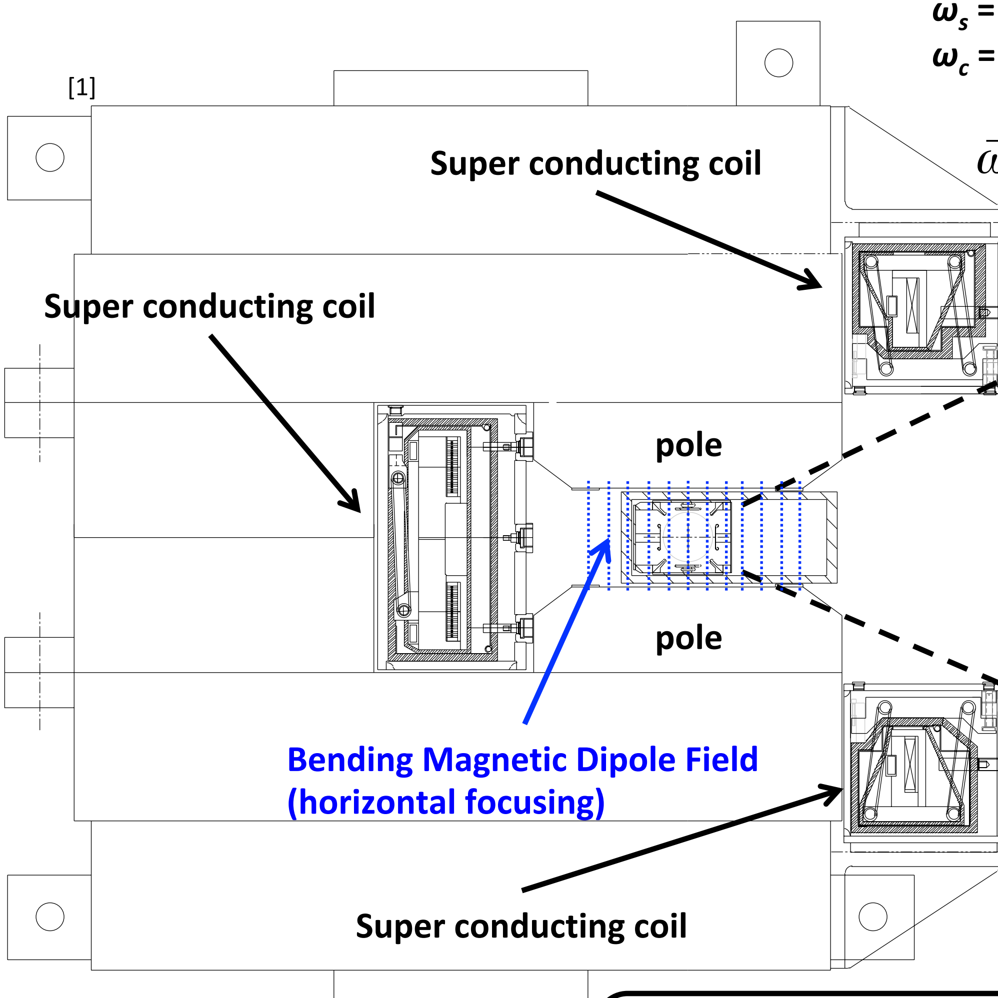
- M5 magnetic quads do final focusing before injection into ring
- Inflector injects muons into ring while minimizing disturbance to B-field
- 3 magnetic kickers “kick” the muons onto the storage orbit
- Electric quads provide weak vertical focusing

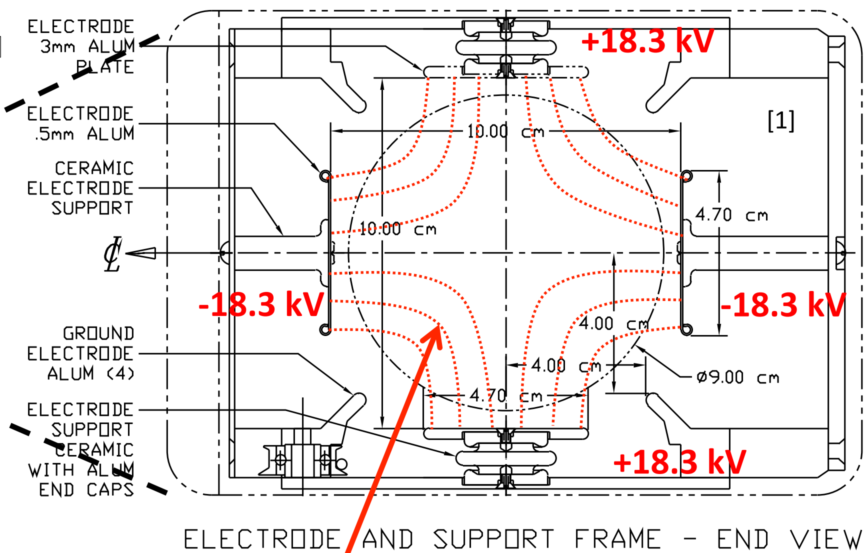
Experiment uses a weak focusing muon storage ring.

ω_a = anomalous precession frequency
ω_s = spin precession frequency
ω_c = cyclotron frequency

0 when γ = 29.3 =>
p_μ = 3.094 GeV/c

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





Scraping sets bottom, Q2 inner, and Q4 outer plates to ±13.1 kV.

Vertical Focusing Electric Quadrupole Field

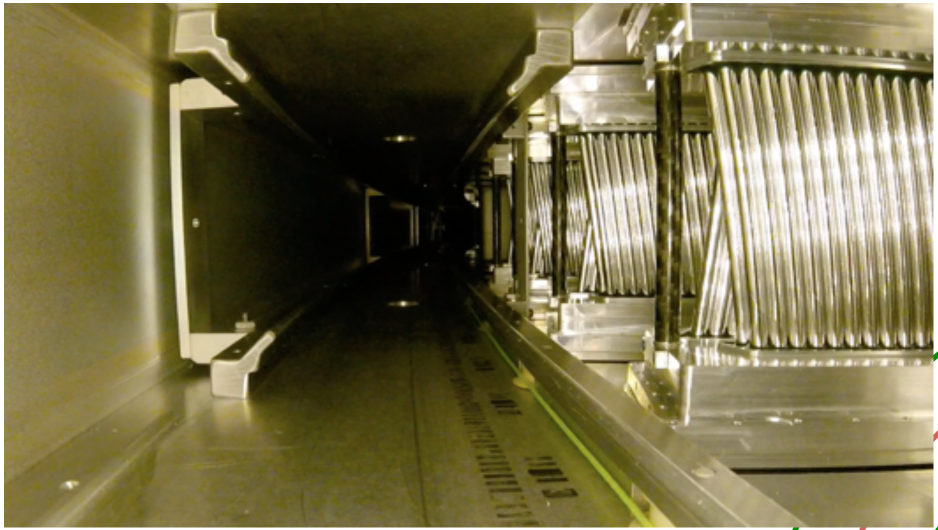
Horizontal And Vertical Tunes:

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

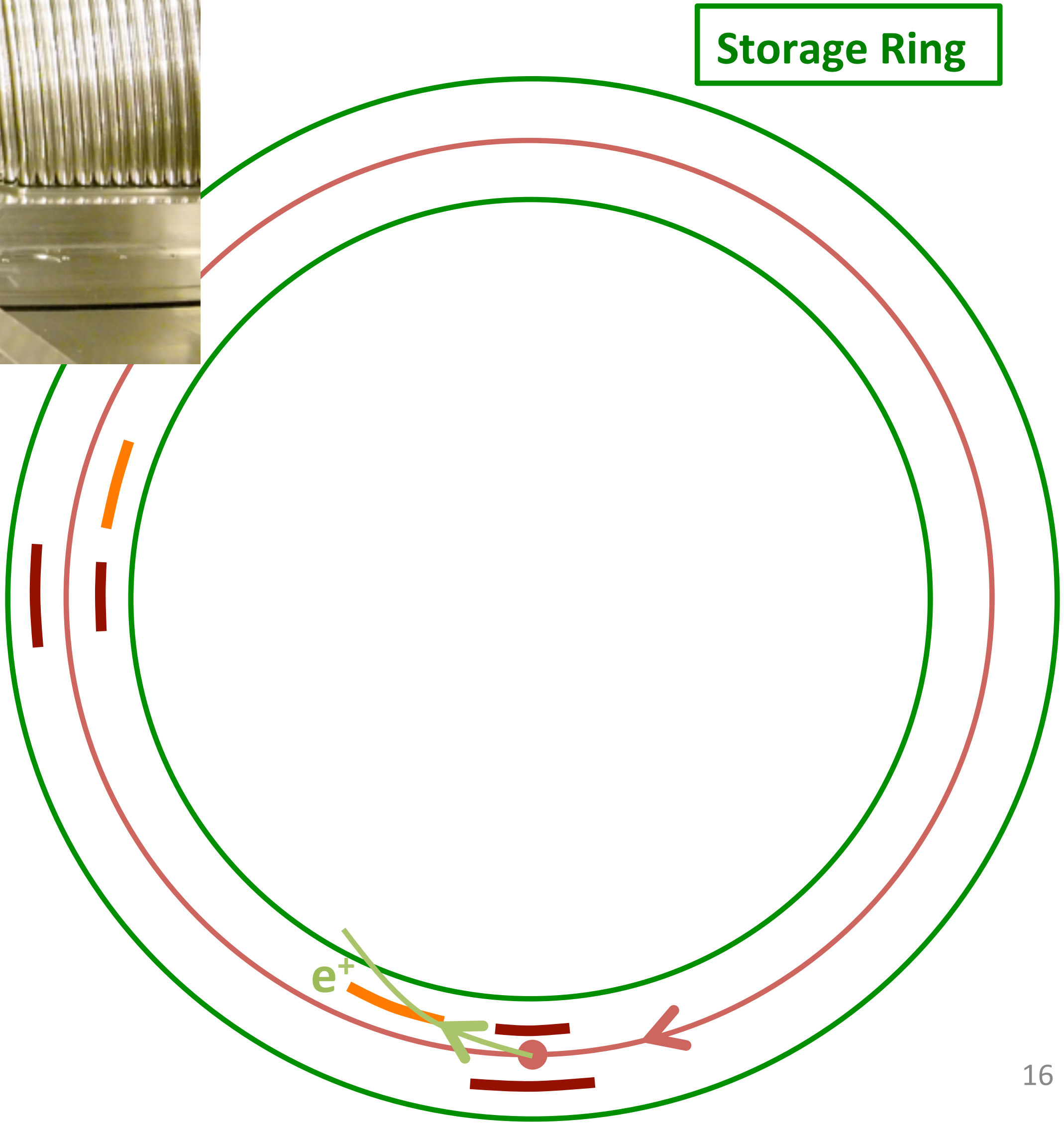
$$\nu_y \approx \sqrt{n}$$

[1] Y. K. Semertzidis *et al.*, Nucl. Instrum. Meth. A **503**, 458 (2003). doi:10.1016/S0168-9002(03)00999-9

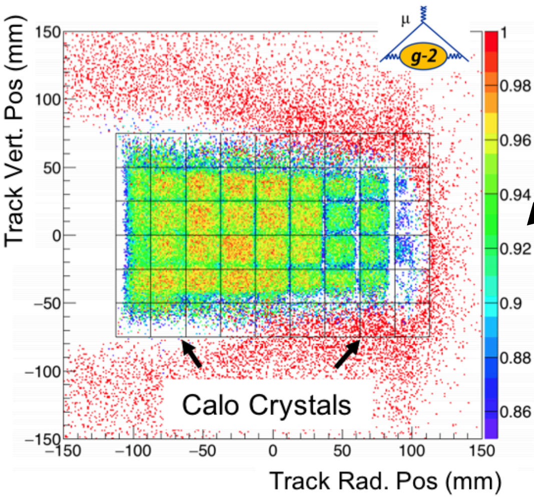
Fermilab Muon g-2 Experiment:



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

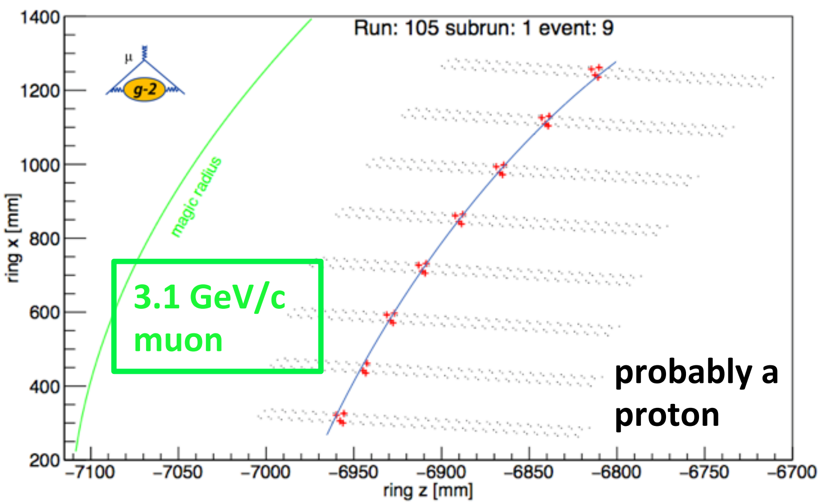


Straw tracker detectors measure the storage ring muon beam profile when taking physics data.

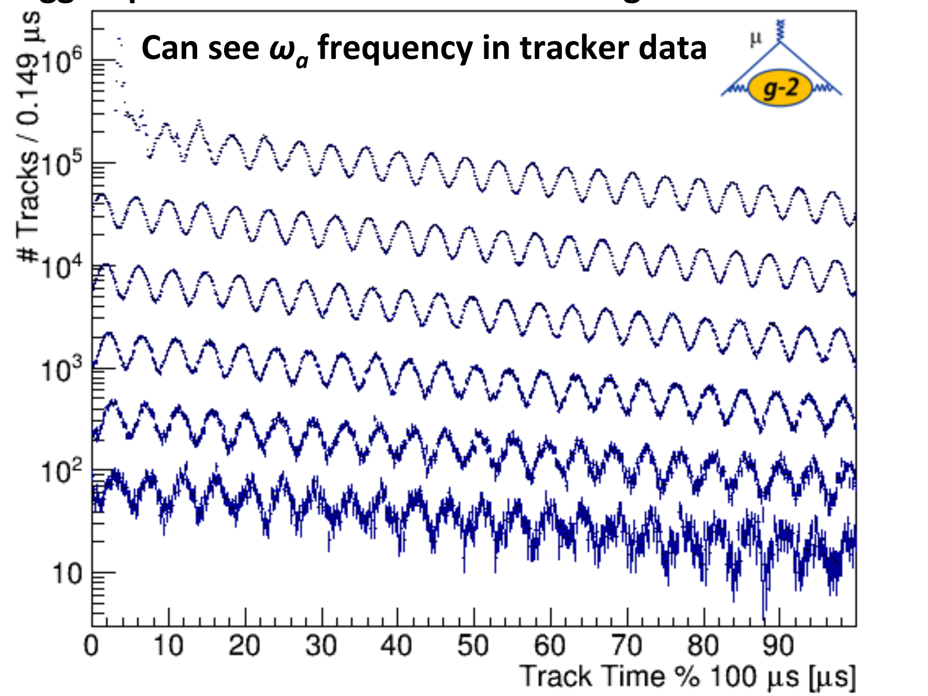


(calorimeter hits) / (total number of tracks) gives calo efficiency: nearly all the missing calo hits look like lost muons.

- Trackers used to extrapolate a decay positron trajectory back to muon decay position.
- Muon g-2 will also measure muon electric dipole moment by determining if there is any tilt in the muon precession plane away from vertical orientation.



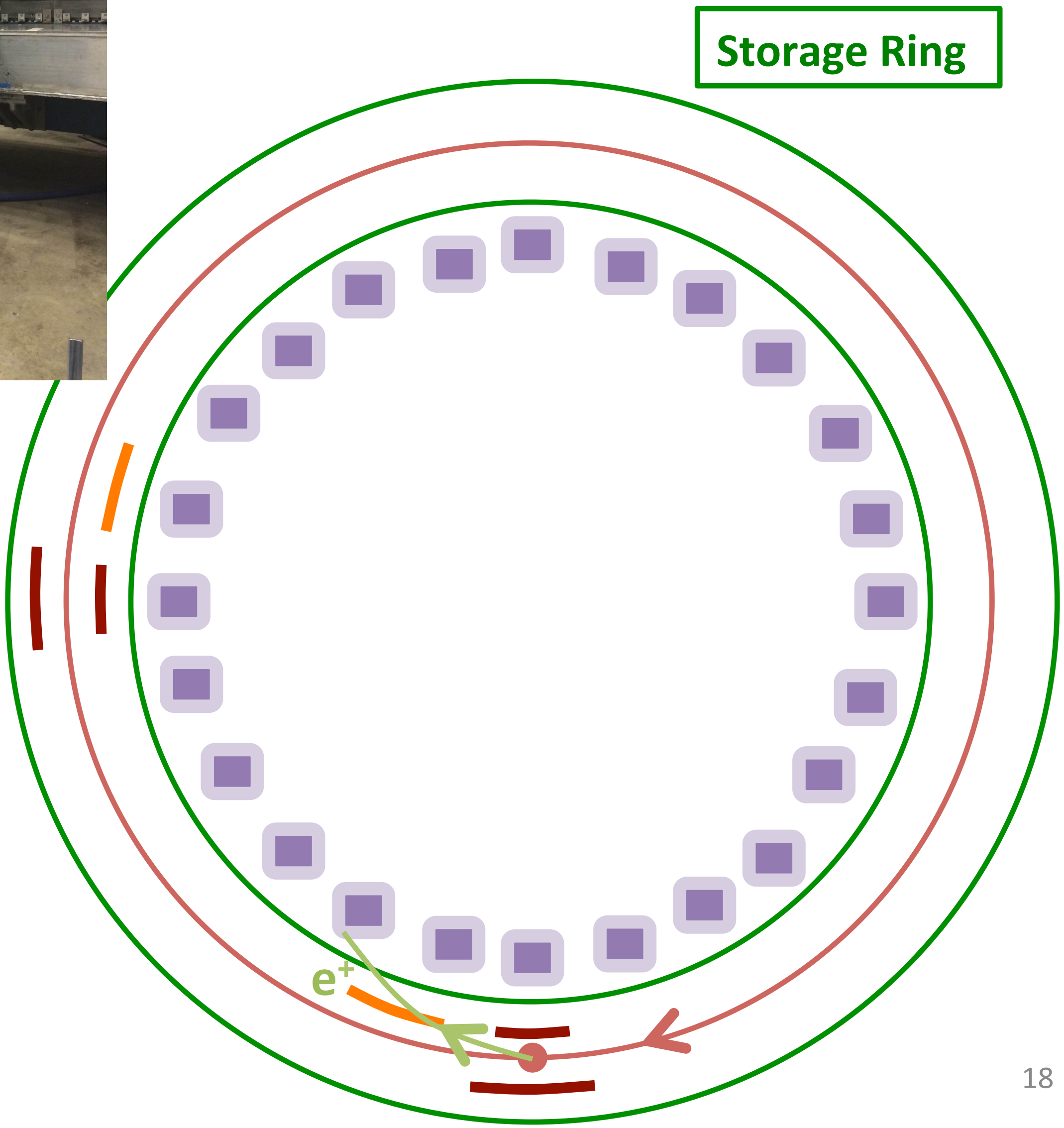
"Wiggle" plot for tracks with momentum greater than 1.8 GeV



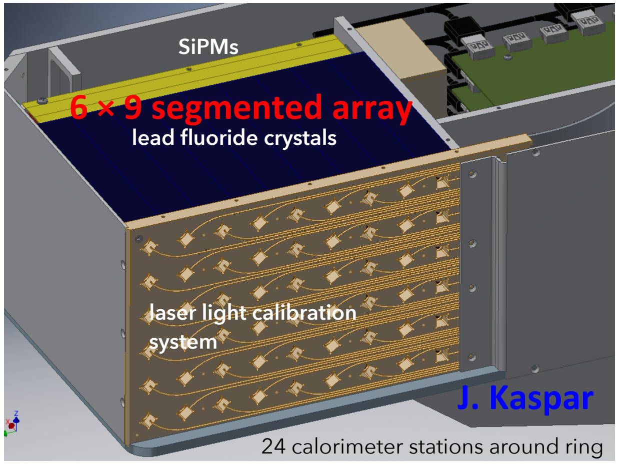
The above June 2017 commissioning data has large proton contamination: 60 p: 4 π: 1 µ

Fermilab Muon g-2 Experiment:

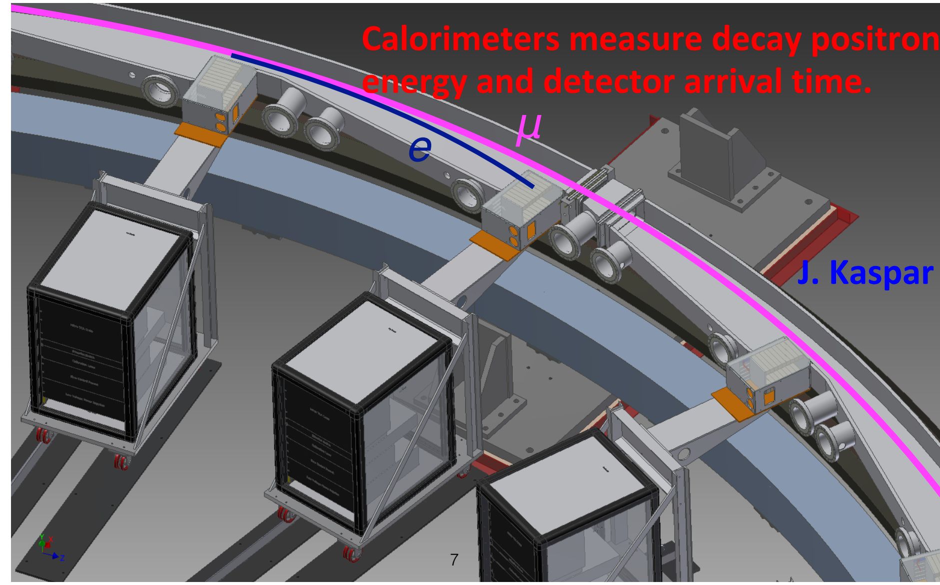
- 180° and 270° fiber profile beam monitors
- Straw tracker station provides decay positron trajectory reconstruction
- 24 calorimeters detect decay positron arrival time and energy



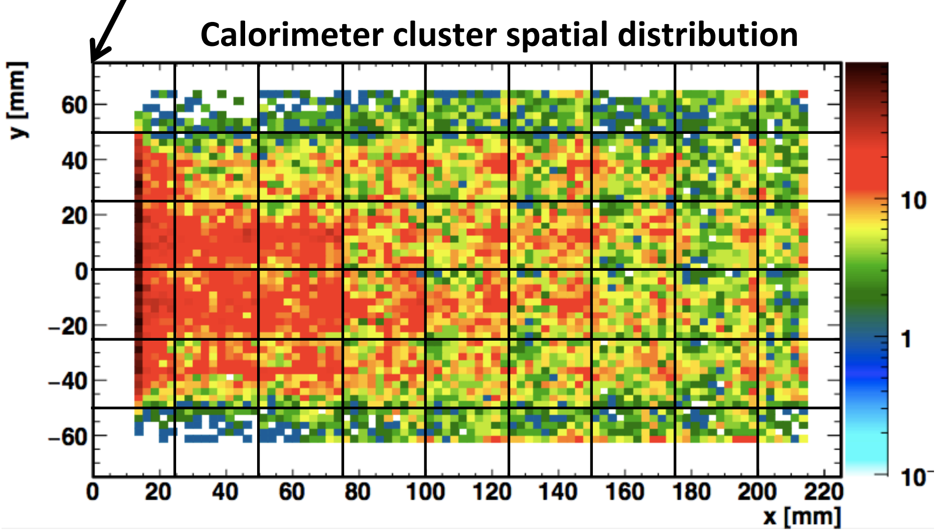
Segmented calorimeters provide spatial resolution that can be used to separate positron hits.



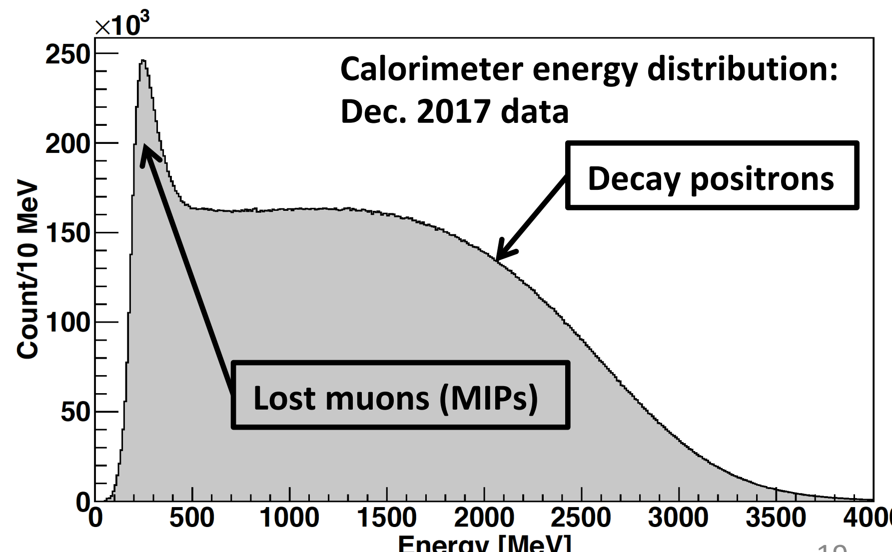
Crystals are 25×25×140 mm



Ring side of calorimeter

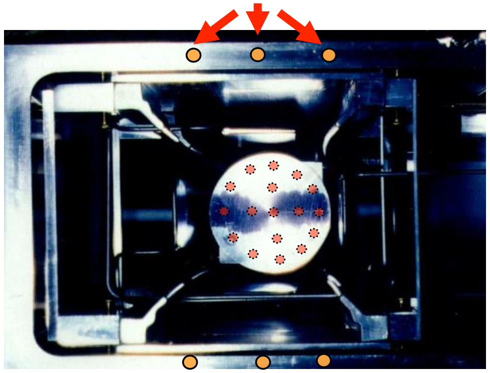


The above June 2017 commissioning data has large proton contamination: 60 p: 4 π: 1 μ

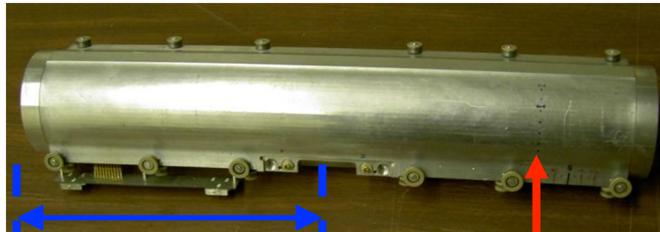


Fermilab Muon g-2 Experiment:

Fixed probes on vacuum chambers



Trolley with matrix of 17 NMR probes

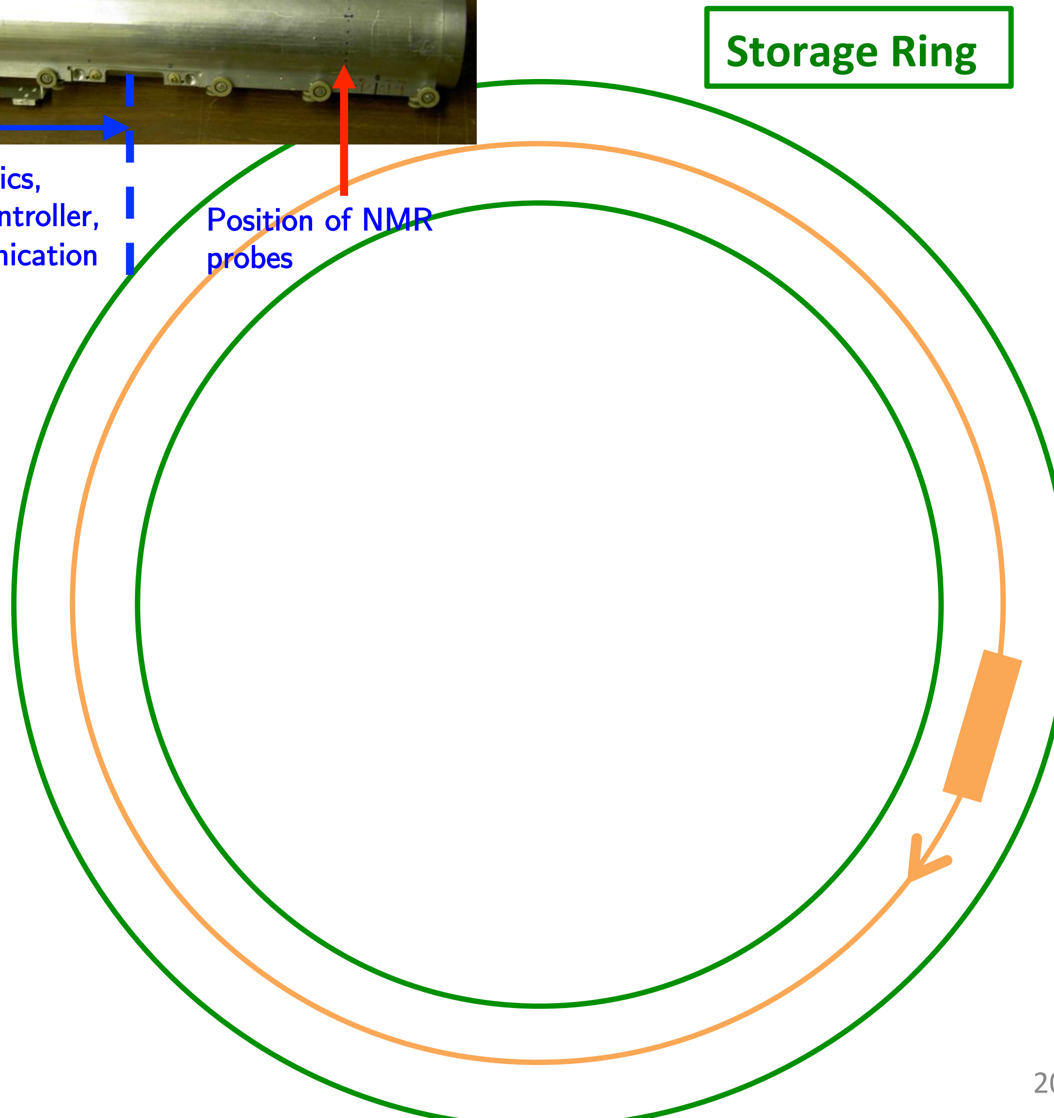


Electronics,
Microcontroller,
Communication

Position of NMR probes

R. Hong

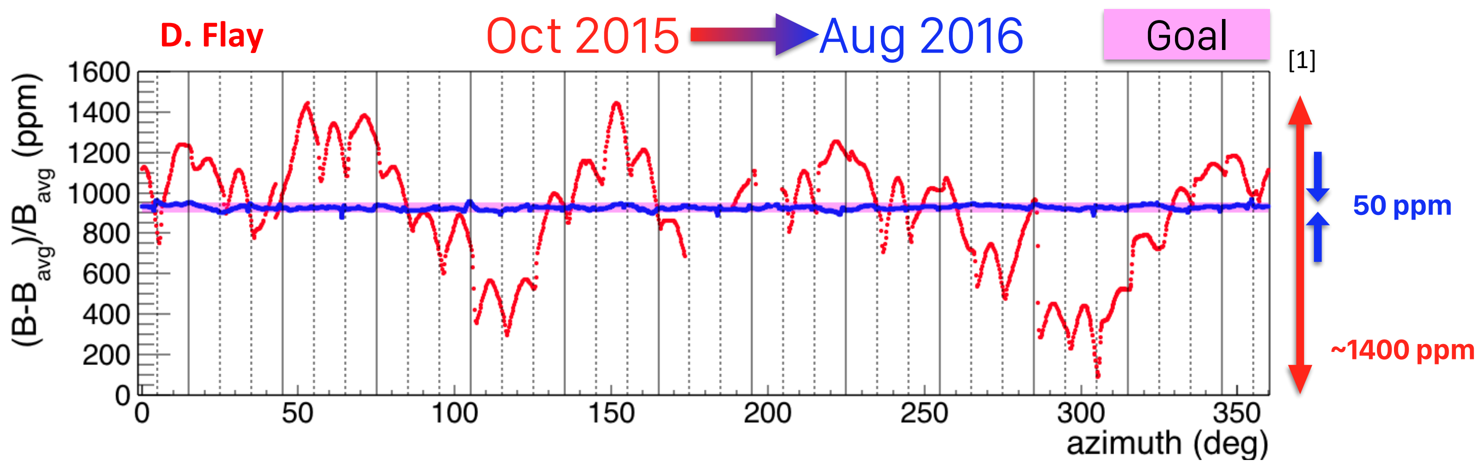
- Trolley periodically measures magnetic field seen by muons



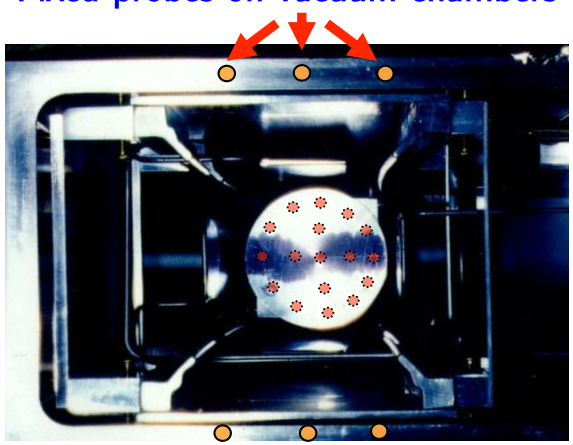
Trolley is used to measure muon storage region magnetic field during data collection.

Rough Shimming Results

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



Fixed probes on vacuum chambers [2]



Trolley with matrix of 17 NMR probes

Electronics, Microcontroller, Communication

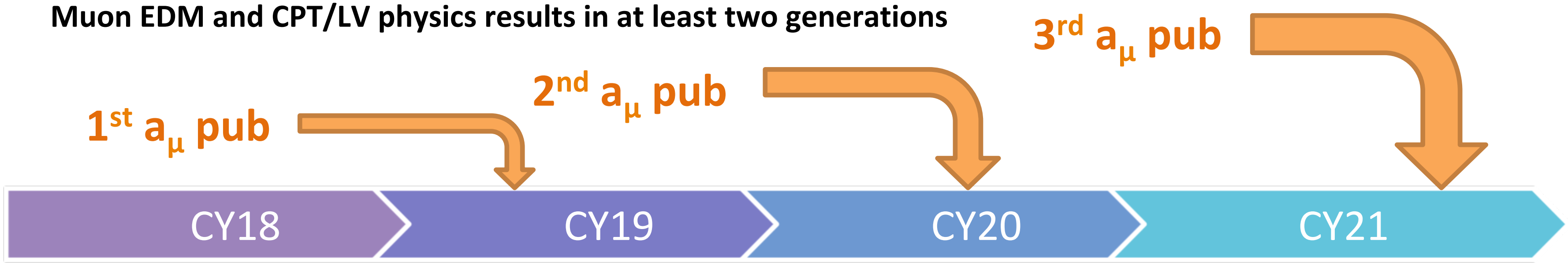
Position of NMR probes

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

R. Hong

Fermilab Muon g-2 Experiment publication plan:

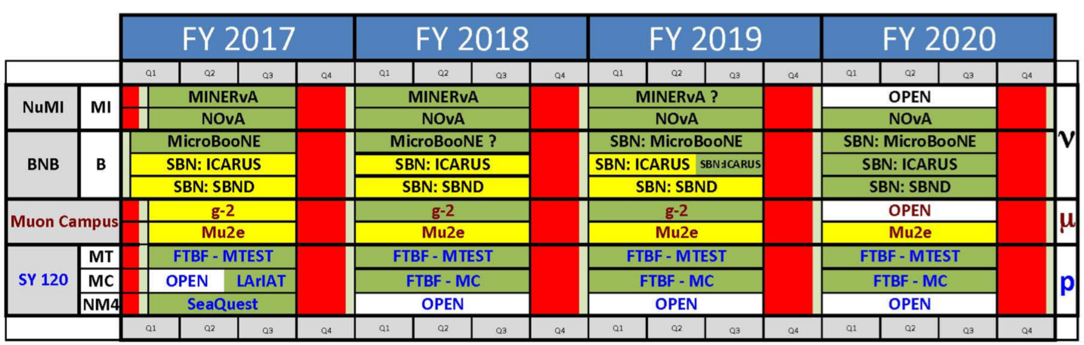
- 3 generations of a_μ publications
  - ~2 × BNL data (~400 ppb) collected in FY18 with 2019 publication goal
  - 5-10 × BNL data (~200 ppb) collected over FY18+FY19 with 2020 publication goal … caveat that we now enter unknown regime
  - 20+ × BNL data (~140 ppb) collected by end of FY20 with 2021 final publications goal
- Muon EDM and CPT/LV physics results in at least two generations



2 caveats to publications plan:

- BNL publications lagged 2-3 years behind acquiring data
  - Understanding systematics and fixing for next run take priority
  - However, we benefit from BNL experience and analysis tools much more advanced
- Likely 2020 running will be required to complete μ^+ statistics

Fermilab Accelerator Experiments' Run Schedule

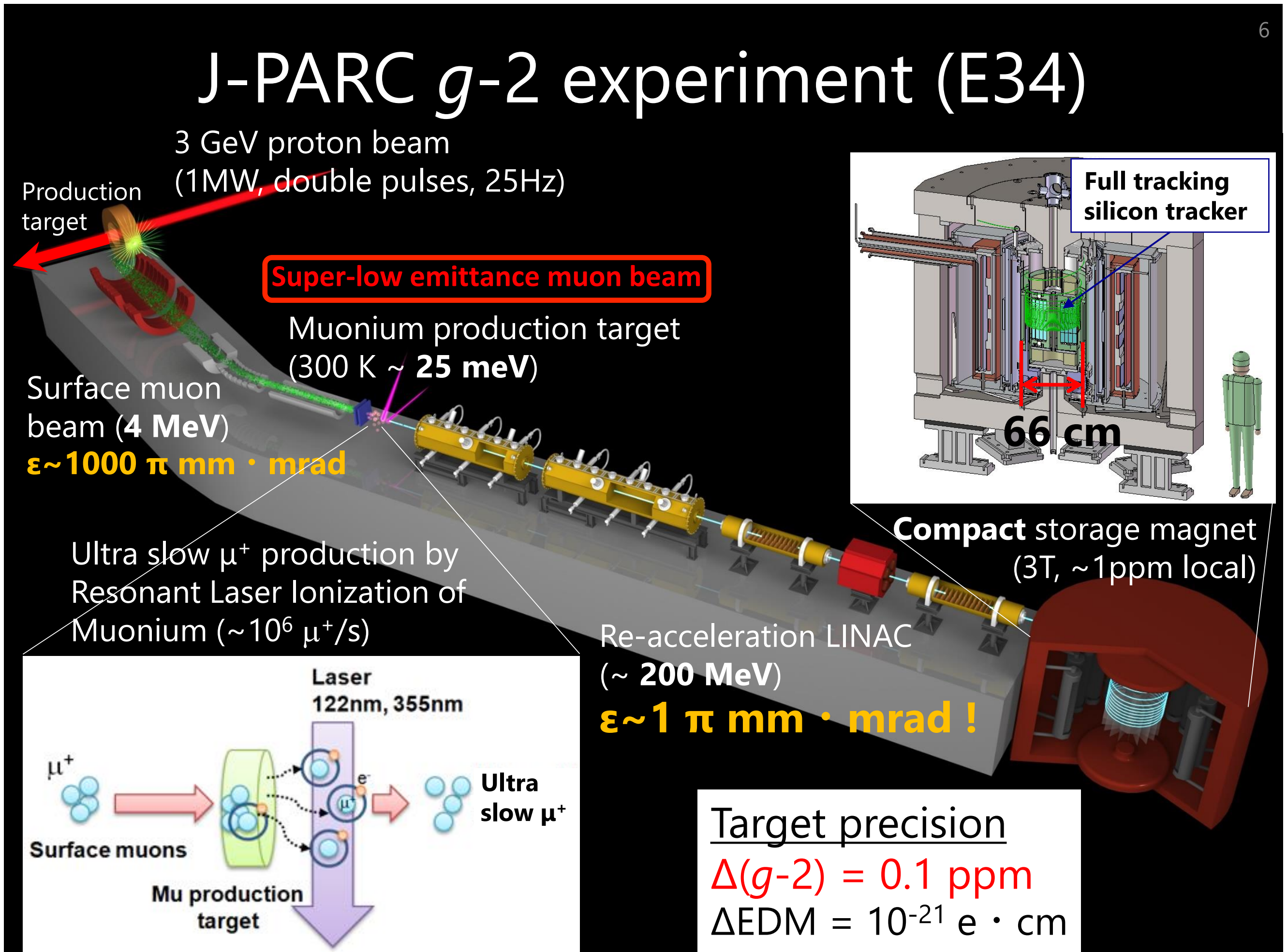


J-PARC g-2 experiment uses a very different experimental technique.

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

[1]

J-PARC experiment in a slide:



Fermilab sets to 0 by using 3.094 GeV/c magic momentum muons

J-PARC sets to 0 by not using electric focusing

[1] Takayuki Yamazaki, KEK Theory Meeting on Particle Physics Phenomenology (KEK-PH2018), Feb. 13th to 16th (2018).

J-PARC g-2 experiment is preparing for a measurement.

http://g-2.kek.jp/portal/publications.html

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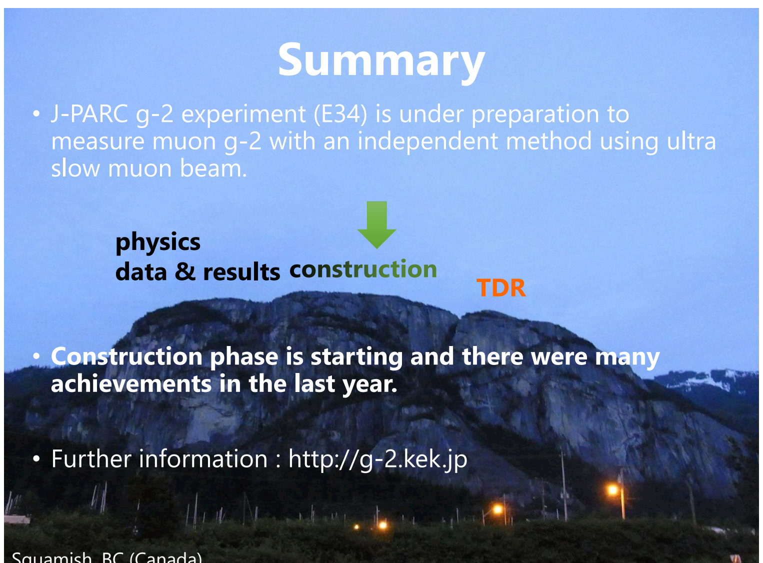
Technical Design Report (TDR) 2017

- We revised the TDR responding to focused review committee's recommendations and submitted to PAC in Dec. 2017.

Date	Events
July, 2009	**LOI** submitted to PAC8
January, 2010	**Proposal** submitted to PAC9
January, 2012	**CDR** submitted to PAC13, Milestones defined.
July, 2012	Stage-1 status recommended by PAC15 Stage-1 status granted by the IPNS director
May, 2015	**TDR** submitted to PAC
Oct, 2016	**Revised TDR** submitted to PAC and FRC
Nov, 2016	**Focused review on technical design**
Dec 15, 2017	**Responses and Revised TDR submitted to PAC**

[1]



Muon g-2/EDM experiment at J-PARC

HOME INFORMATION COLLABORATION LINKS INTERNAL

- About this experiment
- Documents
- Publications
- Talks
- Press/Media
- Awards
- Funding and Support

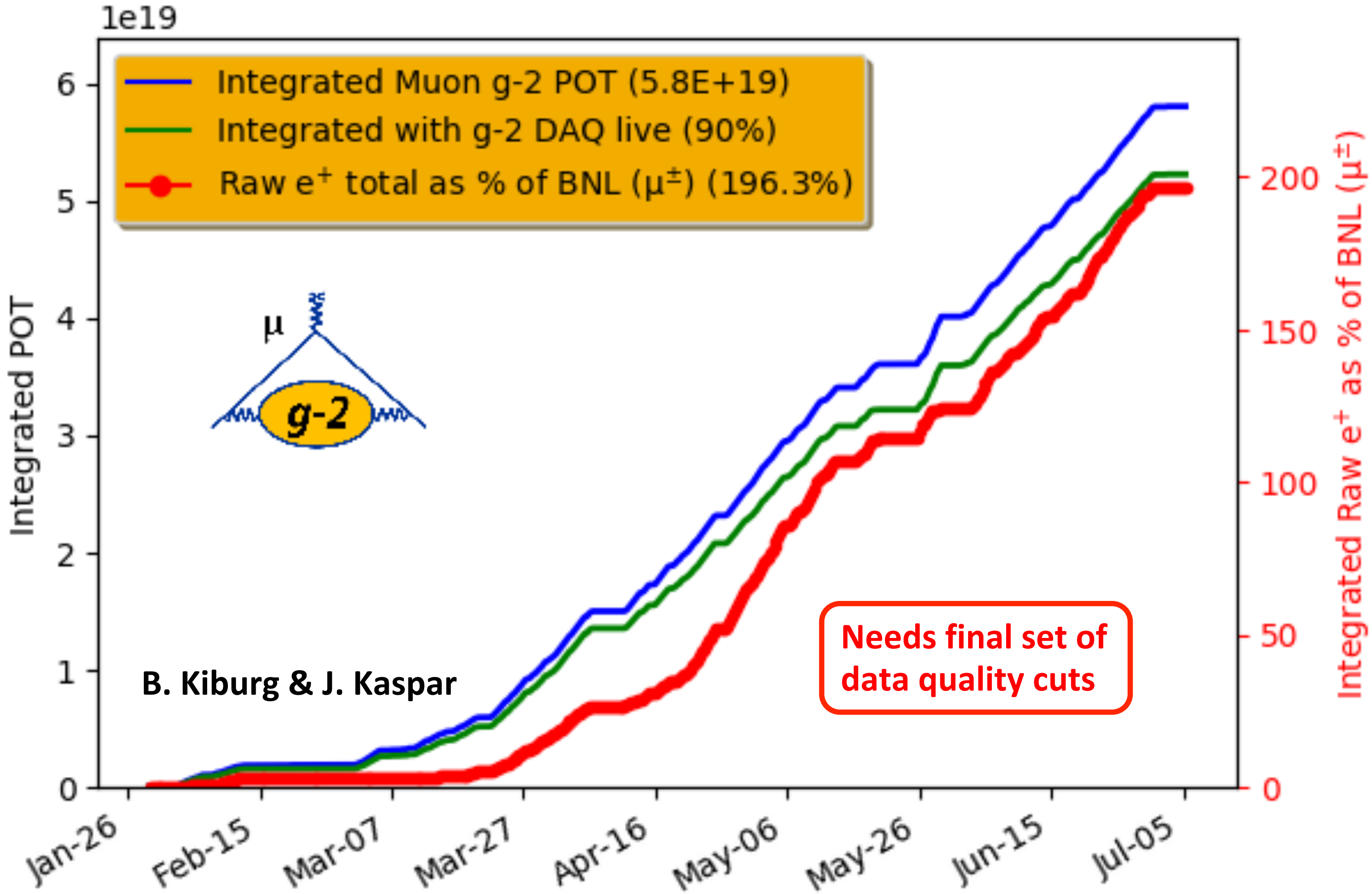
Papers in refereed journals

- **"Development of a microchannel plate based beam profile monitor for a re-accelerated muon beam"**, B. Kim, S. Bae, H. Choi, S. Choi, N. Kawamura, R. Kitamura, H. Ko, Y. Kondo, T. Mibe, M. Otani, G. P. Razuvaevef, E. Won, Nuclear Instruments and Methods in Physics Research Section A, 899, 22 (2018).
- **"First muon acceleration using a radio-frequency accelerator"**, S. Bae, H. Choi, S. Choi, Y. Fukao, K. Futatsukawa, K. Hasegawa, T. Iijima, H. Iinuma, K. Ishida, N. Kawamura, B. Kim, R. Kitamura, H. S. Ko, Y. Kondo, S. Li, T. Mibe, Y. Miyake, T. Morishita, Y. Nakazawa, M.Otani, G. P. Razuvaev, N. Saito, K. Shimomura, Y. Sue, E. Won, and T. Yamazaki, Phys. Rev. Accel. Beams 21, 050101 (2018).
- **"Magnetic design and method of a superconducting magnet for muon /EDM precise measurements in a cylindrical volume with homogeneous magnetic field"**, M. Abe, Y. Murata, H. Iinuma, T. Ogitsu, N. Saito, K. Sasaki, T. Mibe, H. Nakayama, Nuclear Instruments and Methods in Physics Research A 890 51–63 (2018).
- **"Three-dimensional spiral injection scheme for the g-2/EDM experiment at J-PARC"**, H. Iinuma, H. Nakayama, K. Oidea, K. Sasaki, N. Saito, T. Mibe, M. Abe, Nuclear Instruments and Methods in Physics Research A 832 51–62 (2016).
- **"Interdigital H-mode drift-tube linac design with alternative phase focusing for muon linac"**, M. Otani, T. Mibe, M. Yoshida, K. Hasegawa, Y. Kondo, N. Hayashizaki, Y. Iwashita, Y. Iwata, R. Kitamura, and N. Saito, Phys. Rev. Accel. Beams 19, 040101 (2016).
- **"Enhancement of muonium emission rate from silica aerogel with a laser ablated surface"**, G.A. Beer, Y. Fujiwara, S. Hirota, K. Ishida, M. Iwasaki, S. Kanda, H. Kawai, N.Kawamura, R.Kitamura, S. Lee, W. Lee, G.M. Marshall,T. Mibe, Y. Miyake, S. Okada, K. Olchanski, A.Olin, Y. Oishi, H. Onishi,M. Otani, N. Saito, K. Shimomura, P. Strasser, M. Tabata, D.Tomono, K.Ueno, K. Yokoyama, and E. Won, Prog. Theor. Exp. Phys. 091C01 (2014).
- **"Measurement of muonium emission from silica aerogel"**, P. Bakule, G.A. Beer, D.Contreras, M. Esashi, Y. Fujiwara, Y. Fukao, S. Hirota, H. Iinuma, K. Ishida, M. Iwasaki, T. Kakurai, S.Kanda, H. Kawai, N. Kawamura, G.M. Marshall, H. Masuda, Y. Matsuda, T. Mibe, Y.Miyake, S. Okada, K. Olchanski, A. Olin, H. Onishi, N. Saito, K. Shimomura, P. Strasser, M. Tabata, D.Tomono, K. Ueno, K. Yokoyama, and S. Yoshida, Prog. Theor. Exp. Phys. 103C01 (2013).

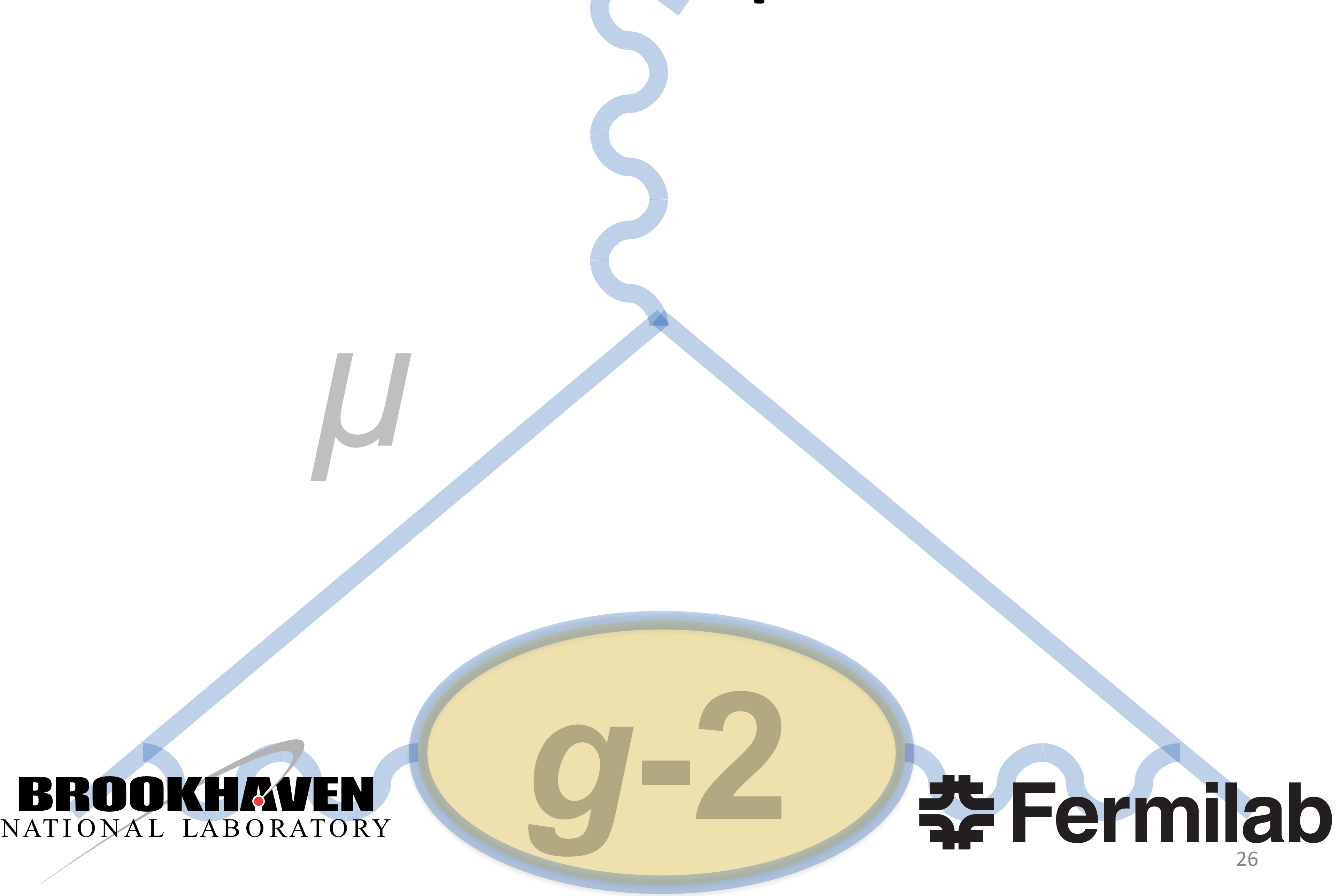
[1] Takayuki Yamazaki, KEK Theory Meeting on Particle Physics Phenomenology (KEK-PH2018), Feb. 13th to 16th (2018).

Conclusions

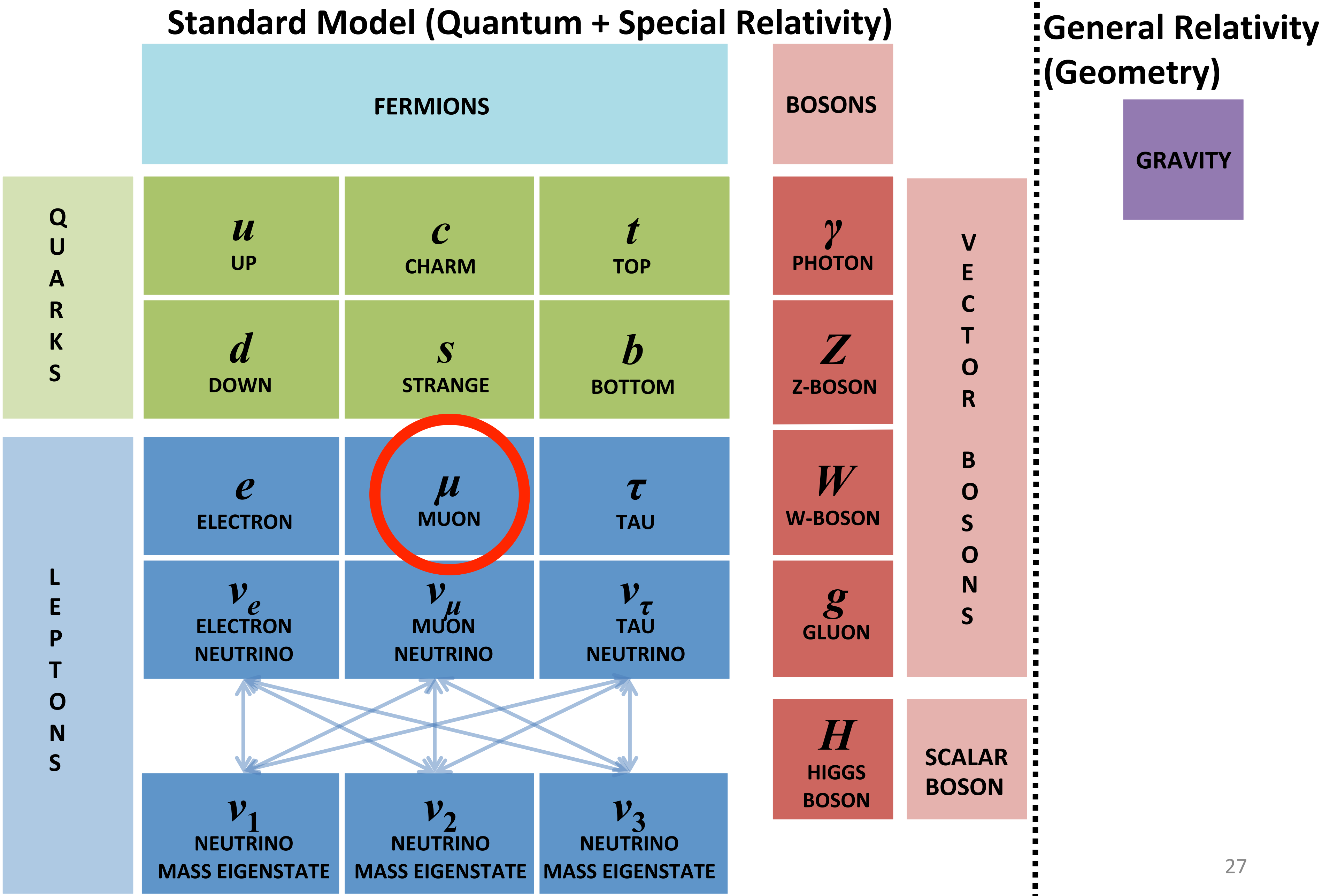
- Fermilab experiment finished 1st physics data run July 7th.
- Fermilab 1st physics data set is ~2 × BNL data set with a goal of publishing in 2019.
- Fermilab experiment has the ultimate goal of measuring muon g-2 ~4 times more precisely than the BNL experiment.
- J-PARC experiment is preparing for a measurement.
- Work continues on improving the precision of the SM muon g-2 prediction.



Backup



Standard Model zoo of particles:



The Muon was discovered from cosmic rays.

[1]

Seth Neddermeyer

[2]

Carl D. Anderson

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)

1940: First cloud chamber photograph of muon decay. [3]

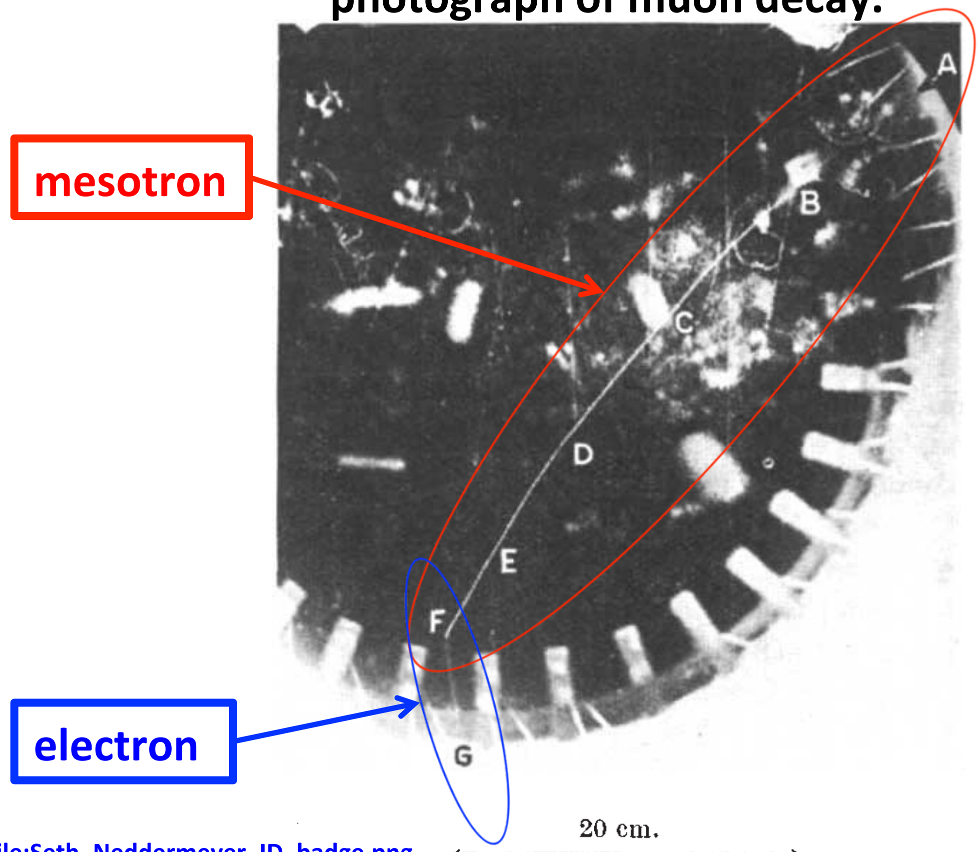


Fig. 1.

[1] 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
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.

Comparison of the charged leptons:

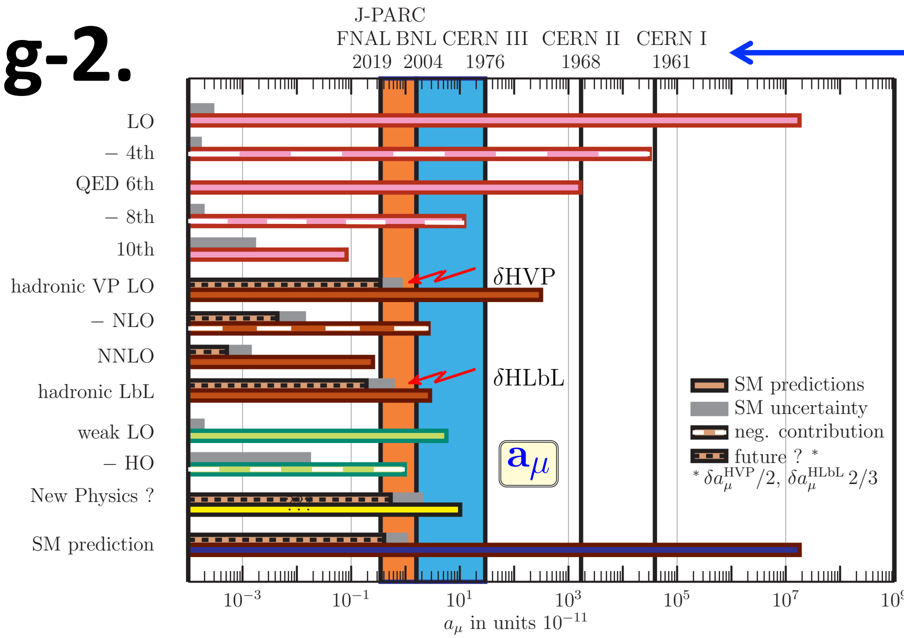
τ_e	∞	-
τ_μ	2.1969811 ± 0.0000022 μs	1.0 ppm
τ_τ	(2.903 ± 0.005) × 10^{-7} μs	0.17 %
m_e	0.5109989461 ± 0.0000000031 MeV	6.1 ppb
m_μ	105.6583745 ± 0.0000024 MeV	23 ppb
m_τ	1776.86 ± 0.12 MeV	68 ppm
a_e	0.00115965218091 ± 0.00000000000026	0.22 ppb
a_μ	0.0011659209 ± 0.0000000006	0.51 ppm
a_τ	> -0.052 and < 0.013 CL=95.0%	-

Mode	Fraction (Γ_i / Γ)
$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$	≈ 1
$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \gamma$	(6.0 ± 0.5) × 10^{-8}
$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu e^+ e^-$	(3.4 ± 0.4) × 10^{-5}

Mode	Fraction (Γ_i / Γ)
$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$	17.39 ± 0.04 %
$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$	17.82 ± 0.04 %
$\tau^- \rightarrow \pi^- \nu_\tau$	10.82 ± 0.05 %
$\tau^- \rightarrow K^- \nu_\tau$	0.696 ± 0.010 %

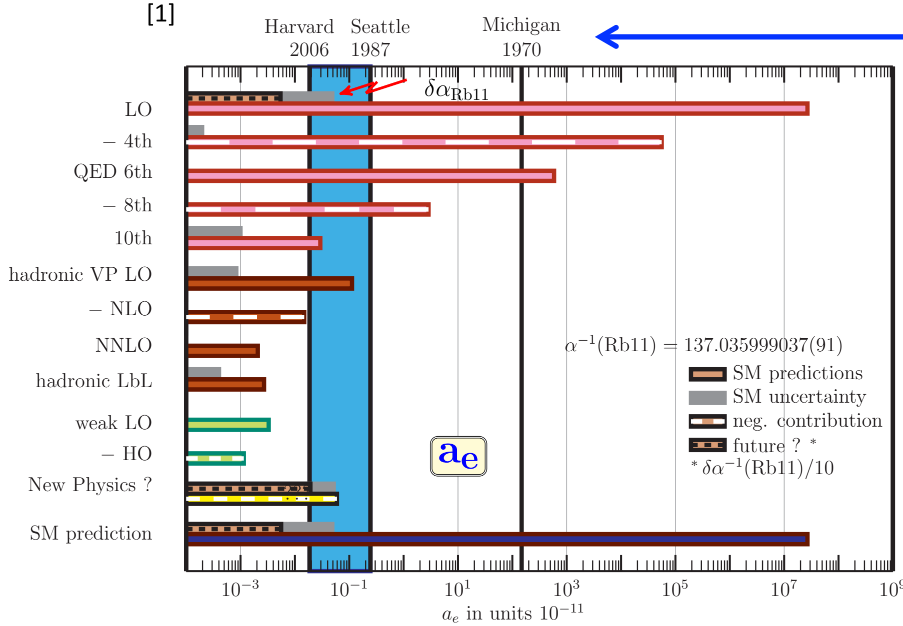
C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, 40, 100001 (2016) and 2017 update.

Muon g-2 is more sensitive to new physics than electron g-2.



Measurement precision achieved by different experiments

[1]



Measurement precision achieved by different experiments

LO = Leading Order
NLO = Next To Leading Order
NNLO = Next To Next To Leading Order
HO = Higher Order
LbL = Light-by-Light
VP = Vacuum Polarization
QED = Quantum Electrodynamics

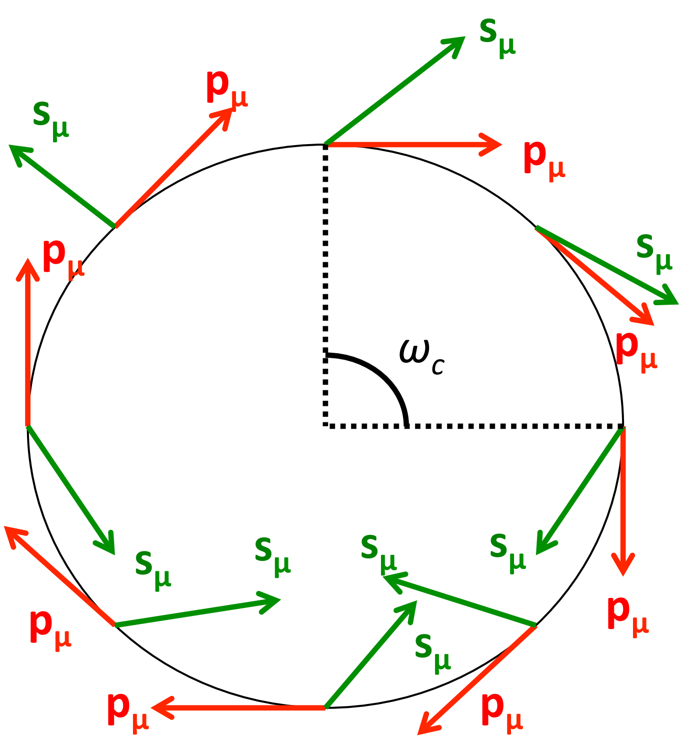
[1] F. Jegerlehner, arXiv:1804.07409 [hep-ph].

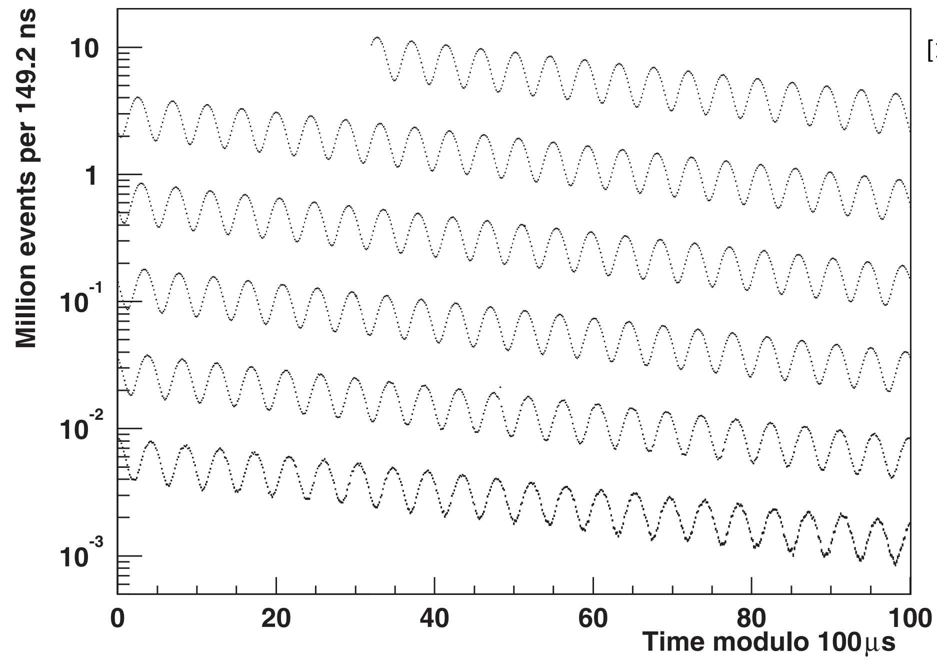
Experiment measures muon spin precession relative to momentum.

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

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

0 for p_μ = 3.094 GeV/c when γ = 29.3





[1]

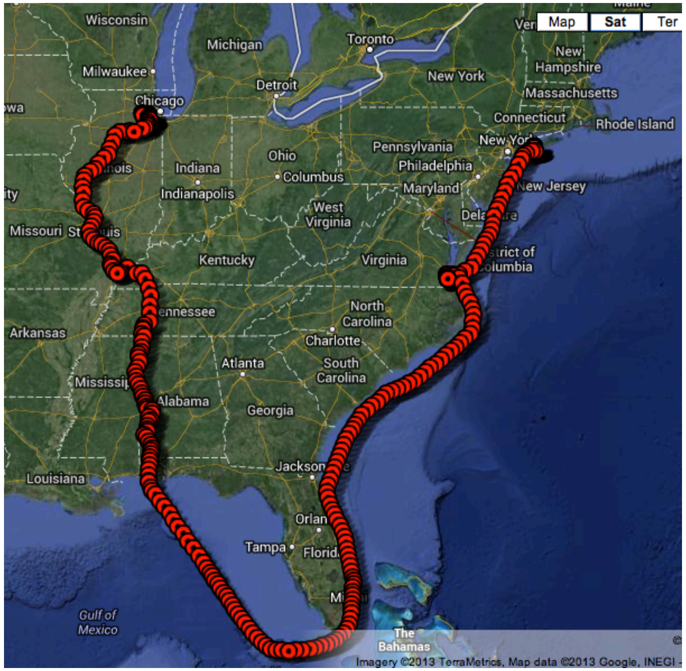
- μ parity-violating Weak decays => in μ^+ rest frame, high energy decay e^+ want to be | | to μ^+ spin and low energy decay e^+ want to be anti | | to μ^+ spin

- Lab frame high energy decay e^+ correspond to μ^+ rest frame high energy decay e^+ that point close to the direction of lab frame μ^+ (forward decays) => modulation on top of exponential decay for lab frame high energy e^+

[1] G. W. Bennett *et al.* [Muon G-2 Collaboration], Phys. Rev. D **73**, 072003 (2006) [hep-ex/0602035].

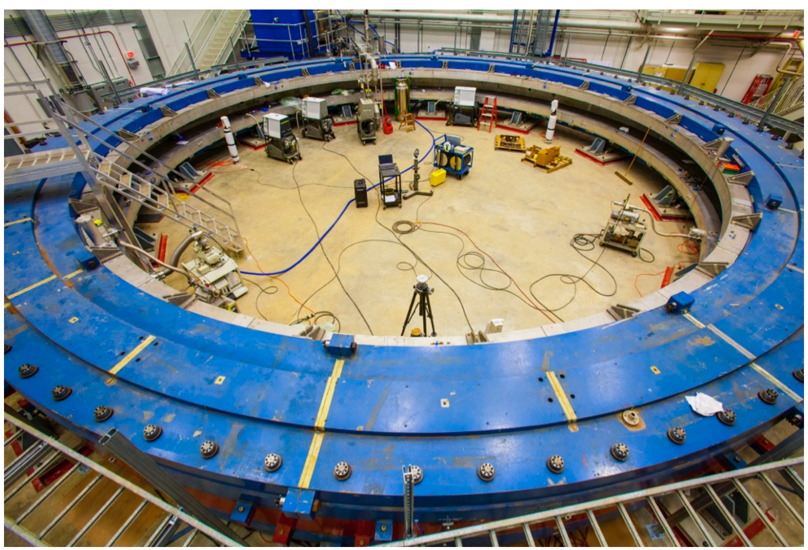
BNL muon storage ring was moved to Fermilab.

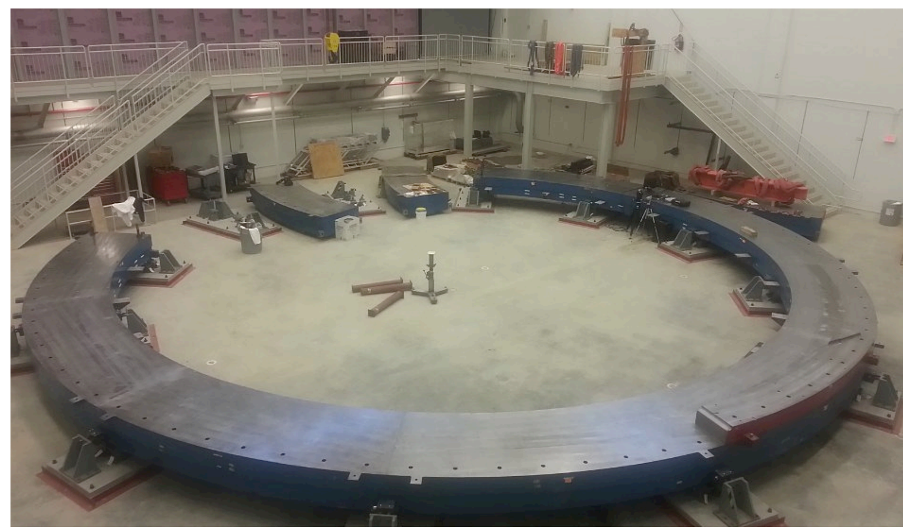
[1]



[2]

[2]



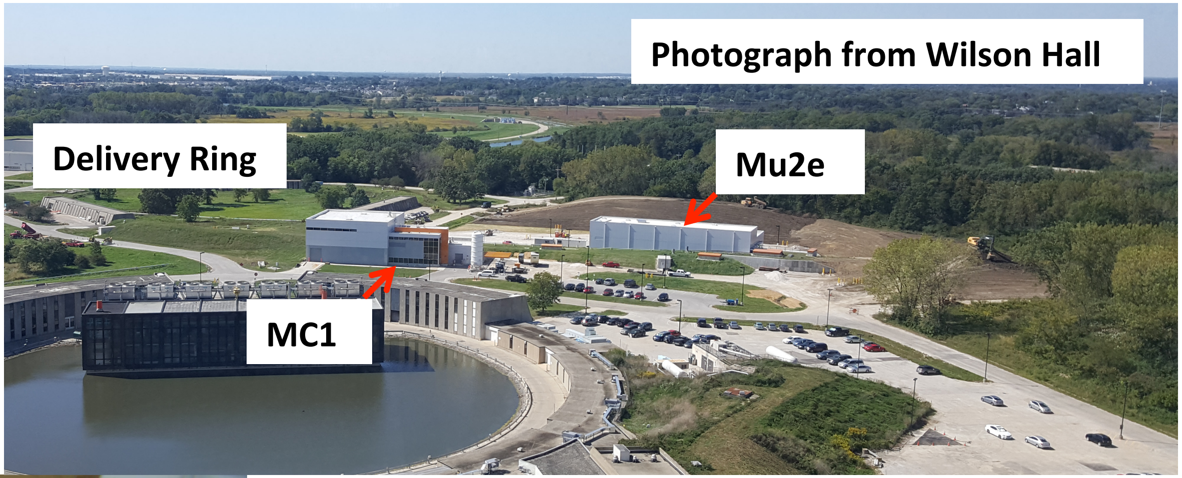


[2]

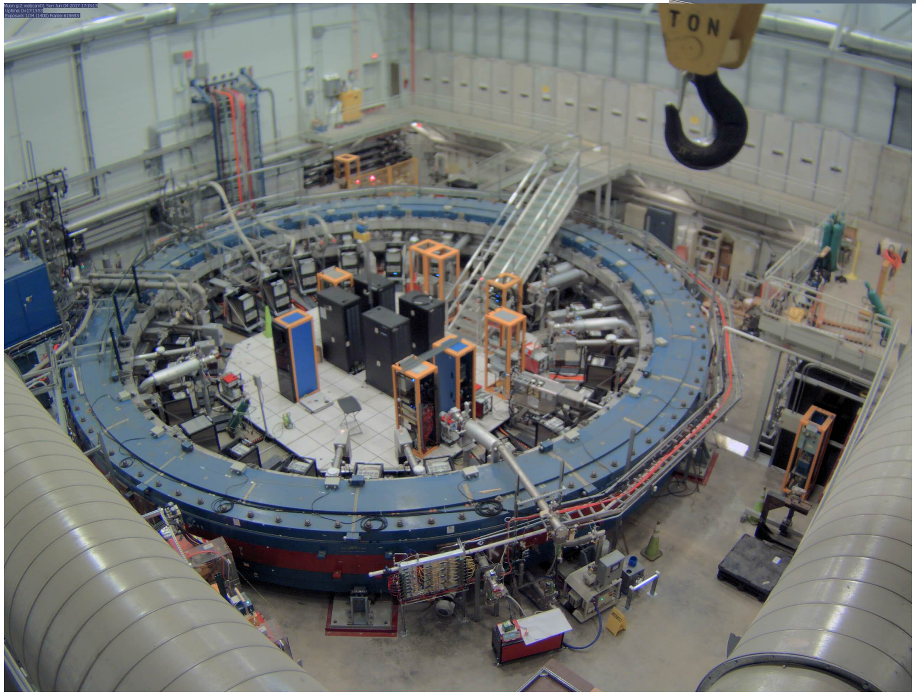
[1] C. Polly, GM2-doc-4096

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

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

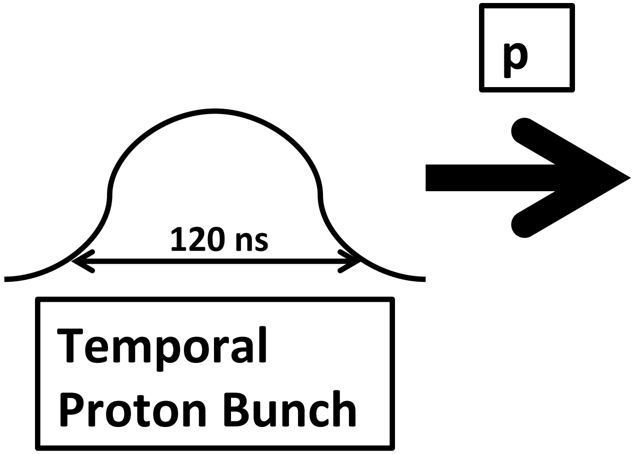


[1]



[1] J. Mott, GM2-doc-4380

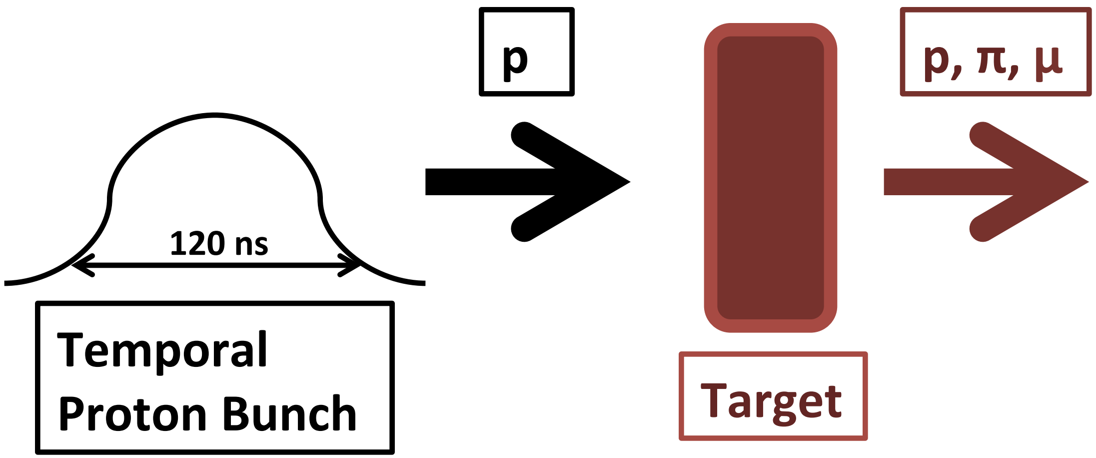
Fermilab Muon g-2 Experiment:



- **Start with a proton bunch**

Not to scale

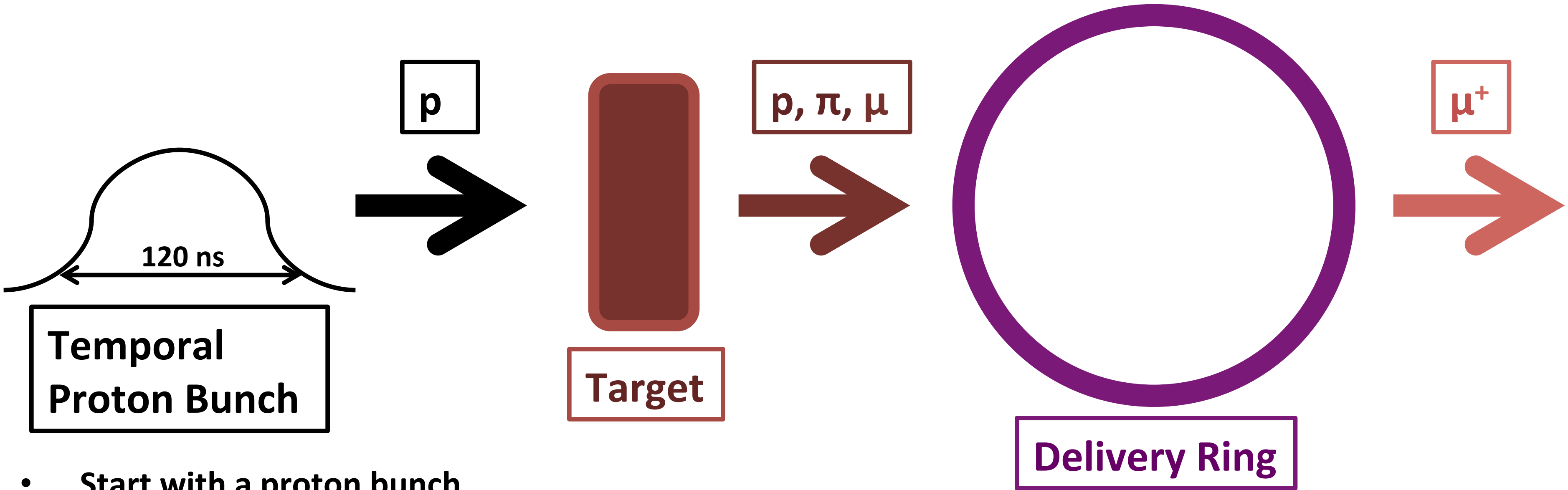
Fermilab Muon g-2 Experiment:



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

Not to scale

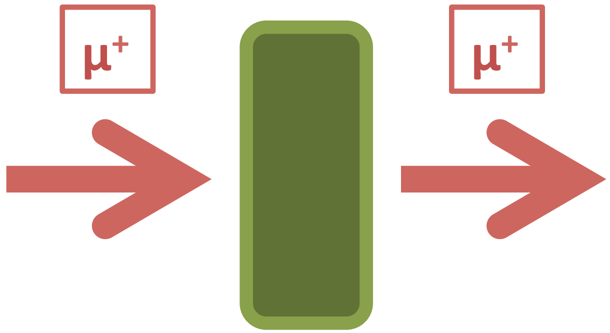
Fermilab Muon g-2 Experiment:



- Start with a proton bunch
- Protons hit target to produce pions
- Delivery Ring extracts protons and allows for remaining pions to decay to muons

Not to scale

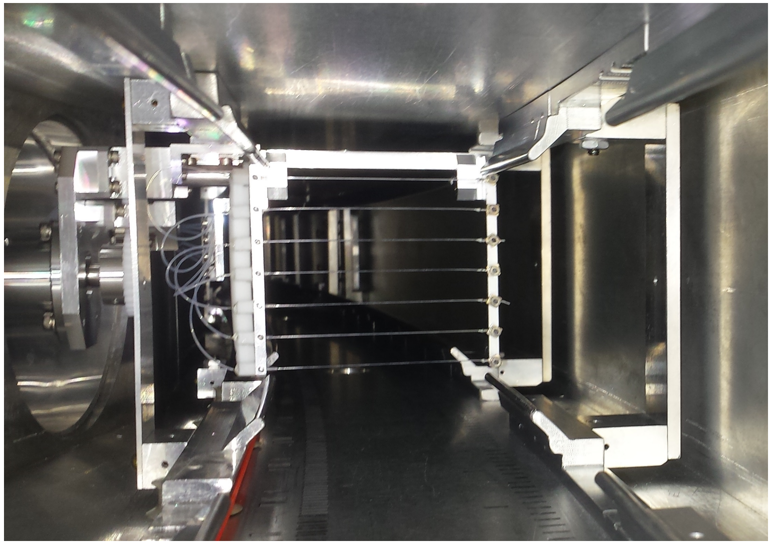
Fermilab Muon g-2 Experiment:



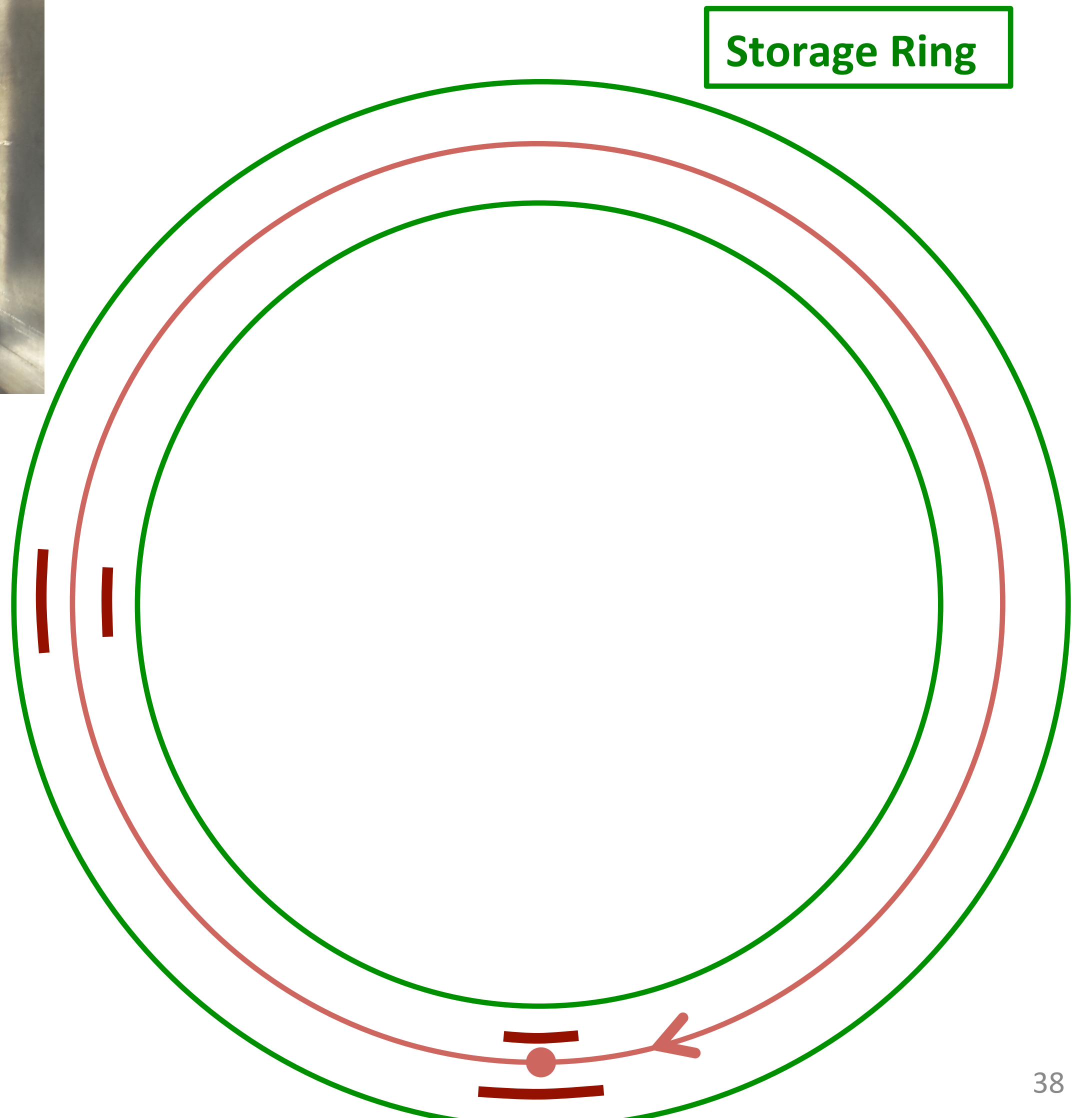
- M5 magnetic quads do final focusing before injection into ring

Not to scale

Fermilab Muon g-2 Experiment:

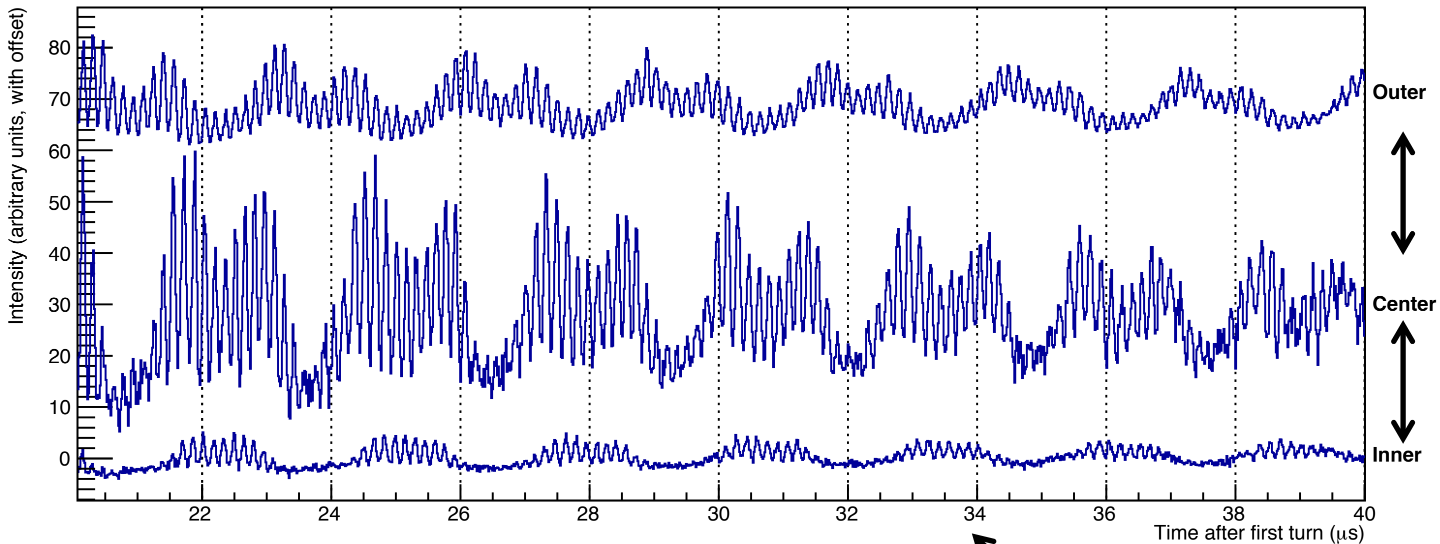


- **180° and 270° fiber profile beam monitors**



Fiber profile beam monitors (fiber harps) study the storage ring beam dynamics.

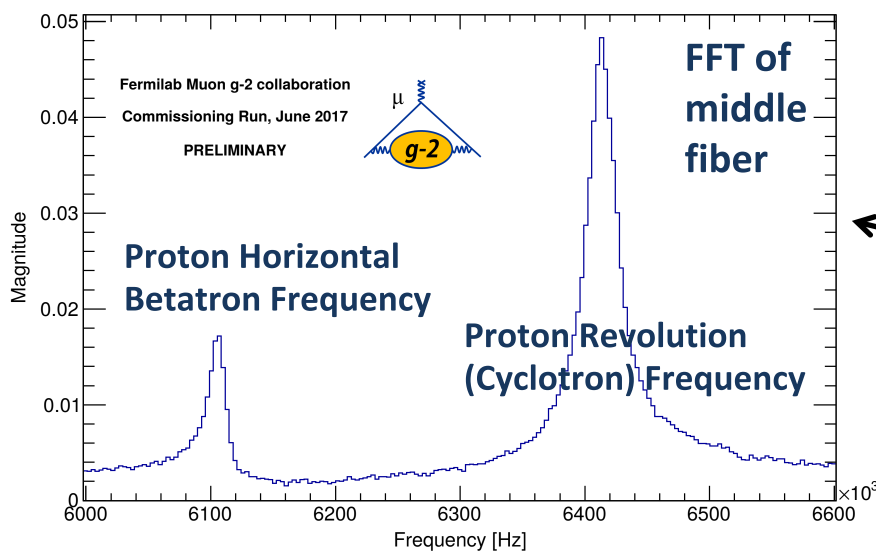
3 central fiber traces from x-profile monitor at 180 degree position.



13 mm spatial separation

13 mm spatial separation

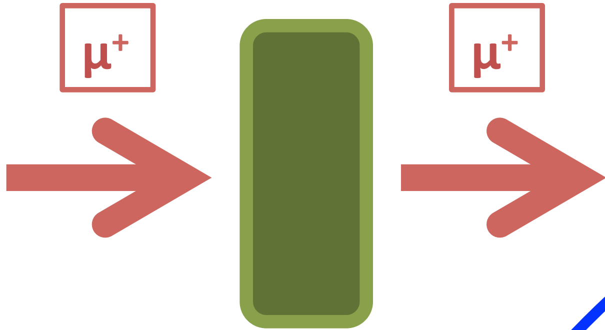
FFT of middle fiber intensity signal from X-profile Harp at 180deg

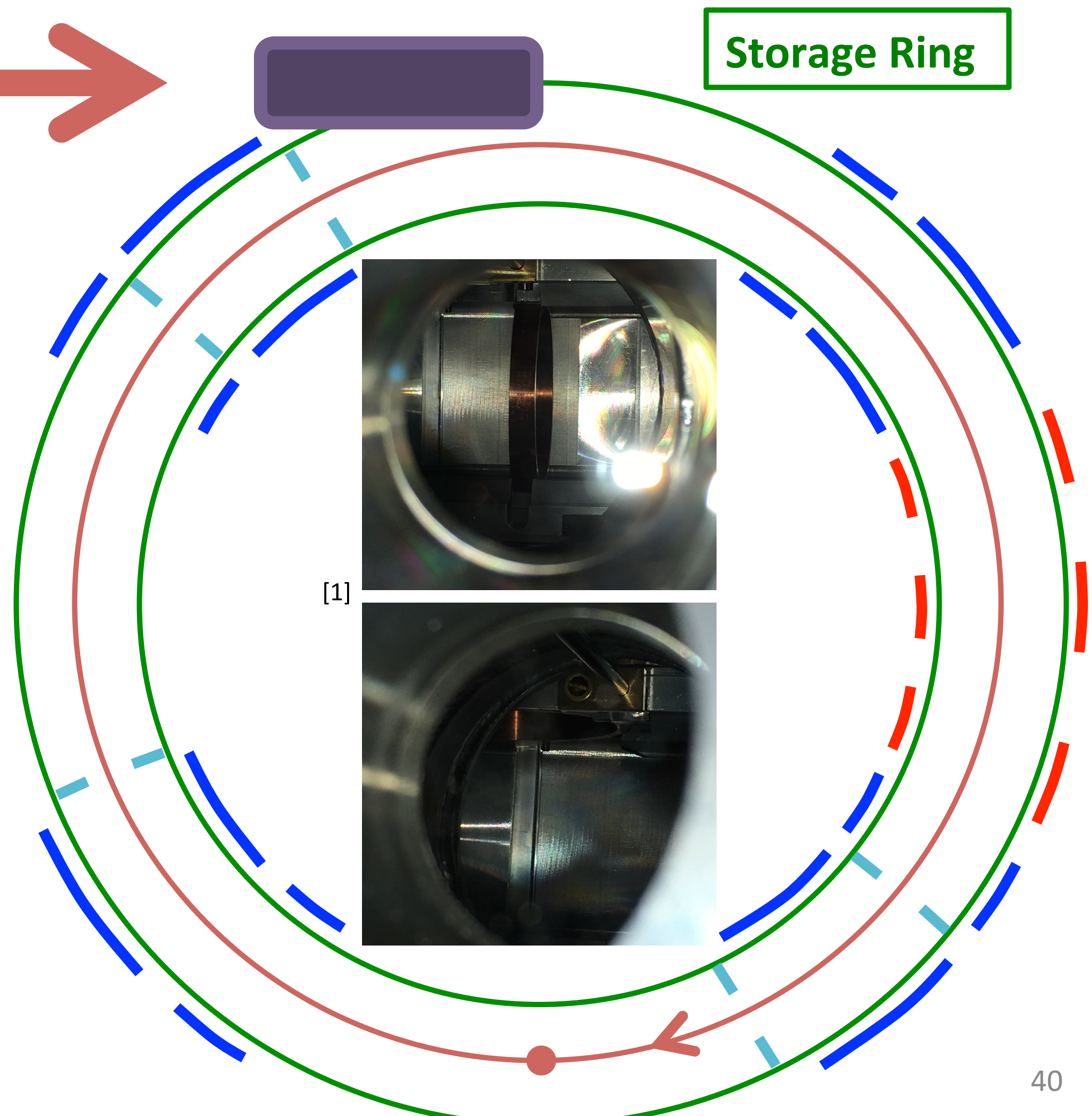


Fiber harps degrade beam, not used when taking physics data.

June 2017 commissioning data has large proton contamination: 60 p: 4 π: 1 μ

Fermilab Muon g-2 Experiment:





- 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
- Quads scrape beam against collimators at early times

Not to scale

[1] J.M. Grange, GM2-doc-8765

Current ring configuration: