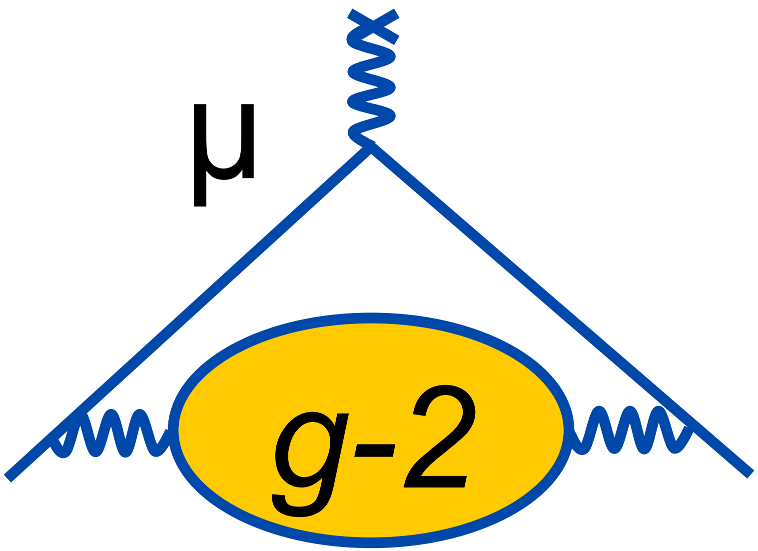
Flavor: Violation & Dipole Moments

DPF2019, Boston, MA, USA:
Monday, July 29th, 2019

Jason D. Crnkovic



BROOKHAVEN NATIONAL LABORATORY

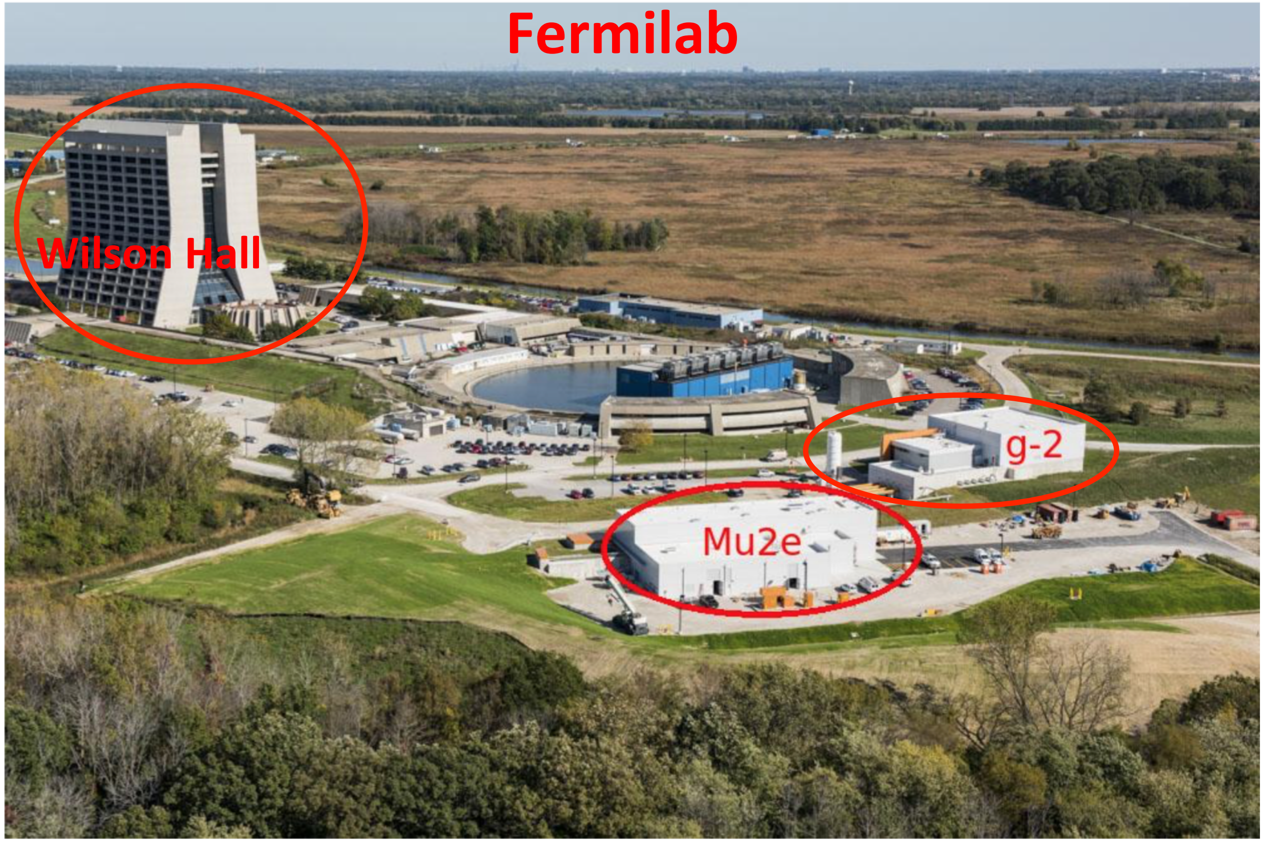
Fermilab

Scope of this talk:

What will not be discussed (*__lots of great work going on, but not enough time to discuss it__*):

- Fermilab muon EDM measurement (part of Muon g-2 Experiment)
- Muon g-2/EDM Experiment at J-PARC
- Electron dipole moments
- COMET at J-PARC
- Mu3e at PSI
- MEG II at PSI
- …

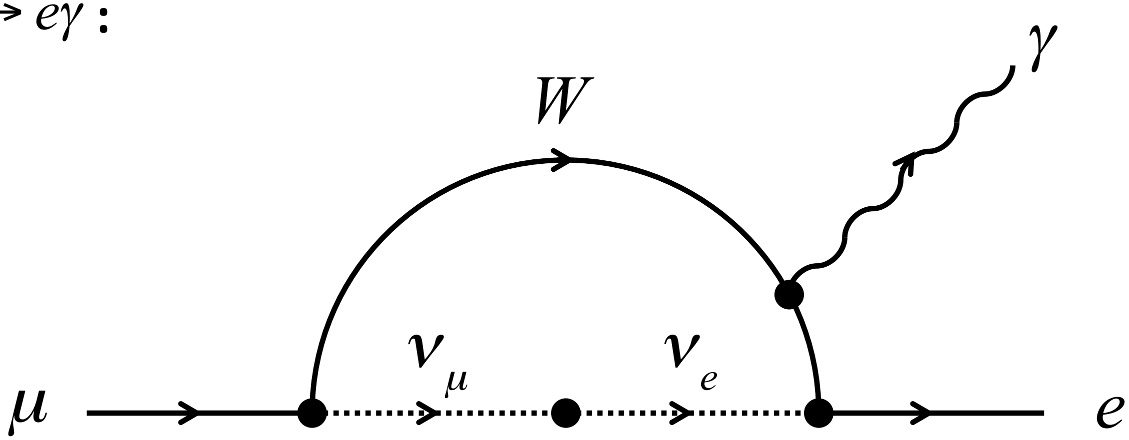
What will be discussed:



Why is charged lepton flavor violation interesting?

- Standard Model (SM) predicts charged lepton flavor violation (CLFV) at highly suppressed rates.
- An observation of CLFV would imply new physics.
- CLFV could potentially play a role in explaining the matter-antimatter asymmetry of the universe (leptogenesis).
- Quark and neutral lepton (neutrino) flavor violation has been observed.

For example $\mu \to e\gamma$:

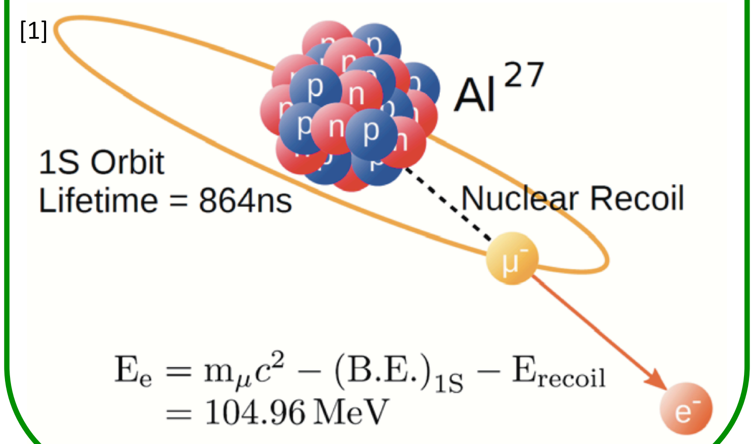


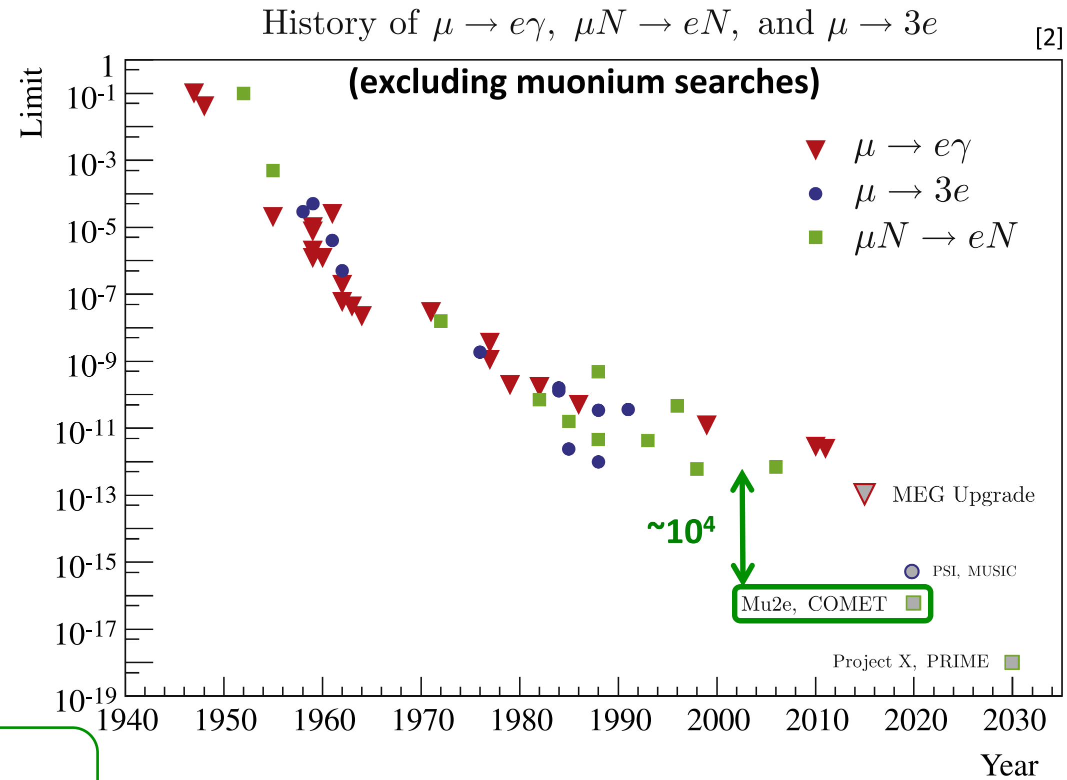
$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

Mu2e experiment will search for $\mu \to e$ conversion.

Mu2e physics signal:

$$\mu^- + A(Z,N) \to e^- + A(Z,N)$$





$$R_{\mu e} = \frac{\overbrace{\mu^- + A(Z,N) \to e^- + A(Z,N)}^{\text{Conversion Process}}}{\underbrace{\mu^- + A(Z,N) \to \nu_\mu + A(Z-1,N)}_{\text{Nuclear Muon Capture}}} < 7\times10^{-13}\,[\text{SINDRUM II}]$$

- **Mu2e goal is to probe $R_{\mu e}$ at the level of ~8×10^{-17} (90% CL).**
- **10^4 improvement with respect to SINDRUM II !!!**

[1] S. Giovannella, EPJ Web Conf. **179**, 01003 (2018). doi:10.1051/epjconf/201817901003
[2] R. H. Bernstein and P. S. Cooper, Phys. Rept. **532**, 27 (2013). doi:10.1016/j.physrep.2013.07.002 [arXiv:1307.5787 [hep-ex]]

Several potential mechanisms for enhancing $\mu \rightarrow e$ conversion.

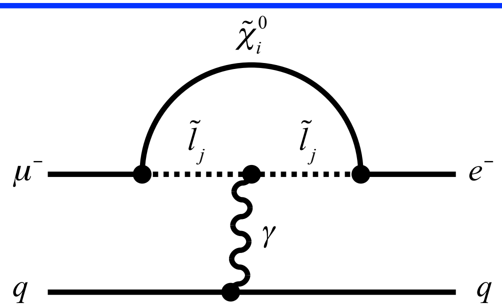
$\Lambda \rightarrow$ Effective mass scale.

$\kappa \rightarrow$ Relative size of the 2 types of terms.

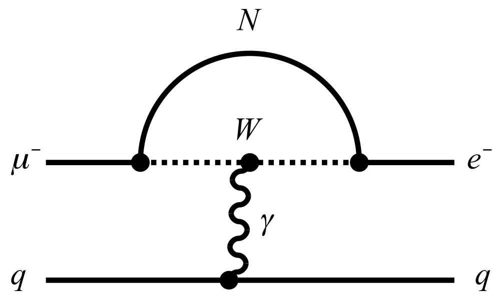
Effective Lagrangian:

$$L_{CLFV}^{[1]} = \underbrace{\frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \text{h.c.}}_{\text{Loop Terms}} + \underbrace{\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L \left(\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L\right) + \text{h.c.}}_{\text{Contact Terms}}$$

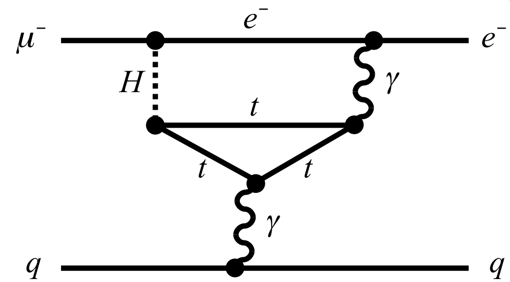
Loop Terms



Supersymmetry

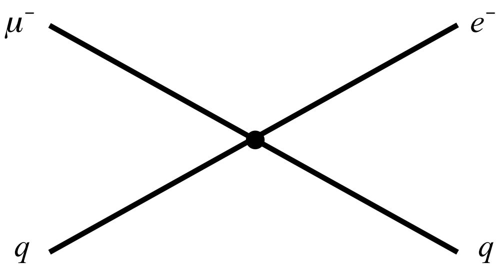


Heavy Neutrinos

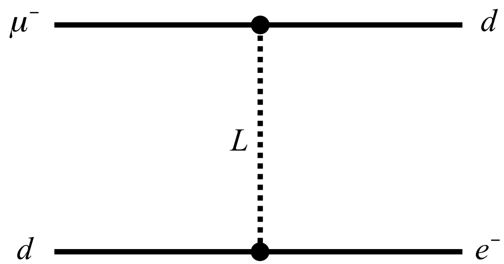


Two Higgs Doublets

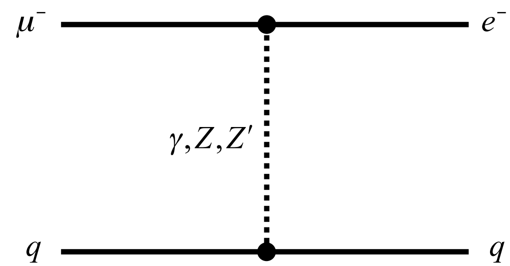
Contact Terms



Compositeness



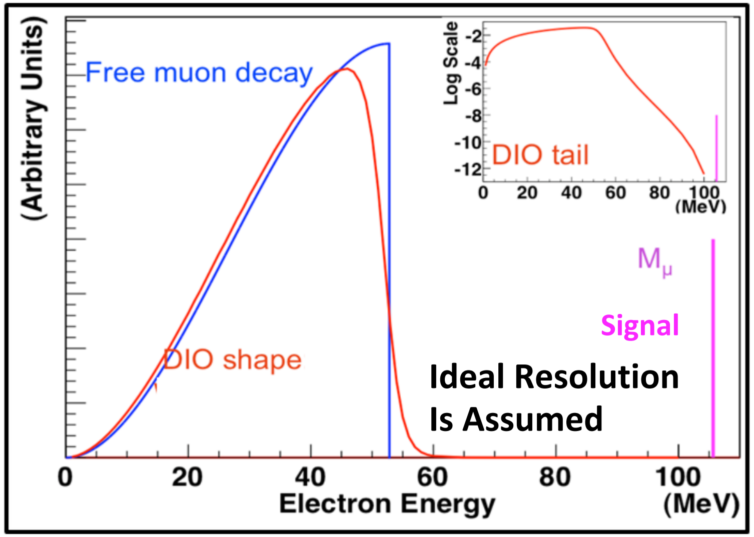
Leptoquarks



New Heavy Bosons / Anomalous Couplings

[1] A. de Gouvea and P. Vogel, Prog. Part. Nucl. Phys. **71**, 75 (2013). doi:10.1016/j.ppnp.2013.03.006 [arXiv:1303.4097 [hep-ph]]

Mu2e is a high precision experiment.

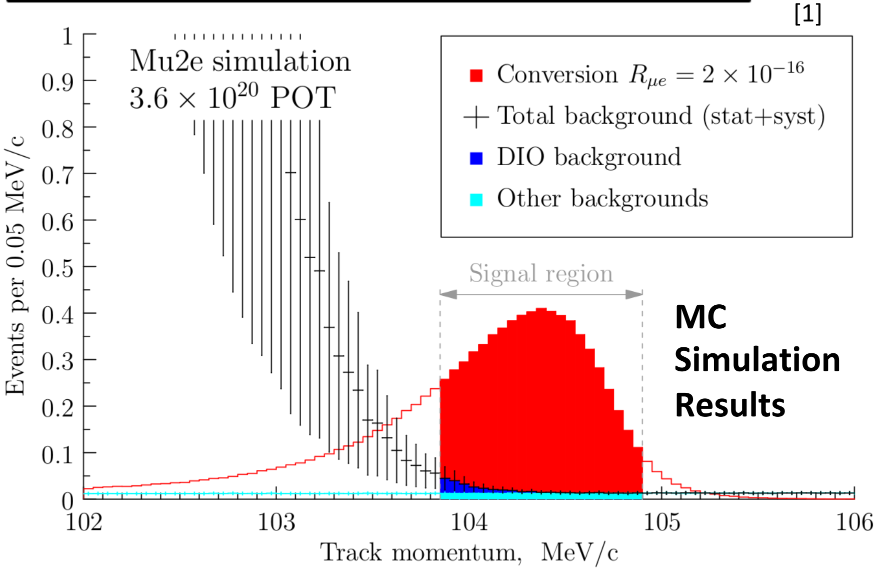


[1]

[1] Expected backgrounds in signal window for 3×10^{20} protons on target in a 3 year run.

Process	Expected event yield
Cosmic ray muons	$0.21 \pm 0.02(\text{stat}) \pm 0.06(\text{syst})$
DIO	$0.14 \pm 0.03(\text{stat}) \pm 0.11(\text{syst})$
Antiprotons	$0.040 \pm 0.001(\text{stat}) \pm 0.020(\text{syst})$
Pion capture	$0.021 \pm 0.001(\text{stat}) \pm 0.002(\text{syst})$
Muon decay-in-flight	< 0.003
Pion decay-in-flight	0.001 ± 0.001
Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
Radiative muon capture	$0.000^{+0.004}_{-0.000}$
Total	$0.41 \pm 0.13(\text{stat} + \text{syst})$

[1]



Muon Processes:

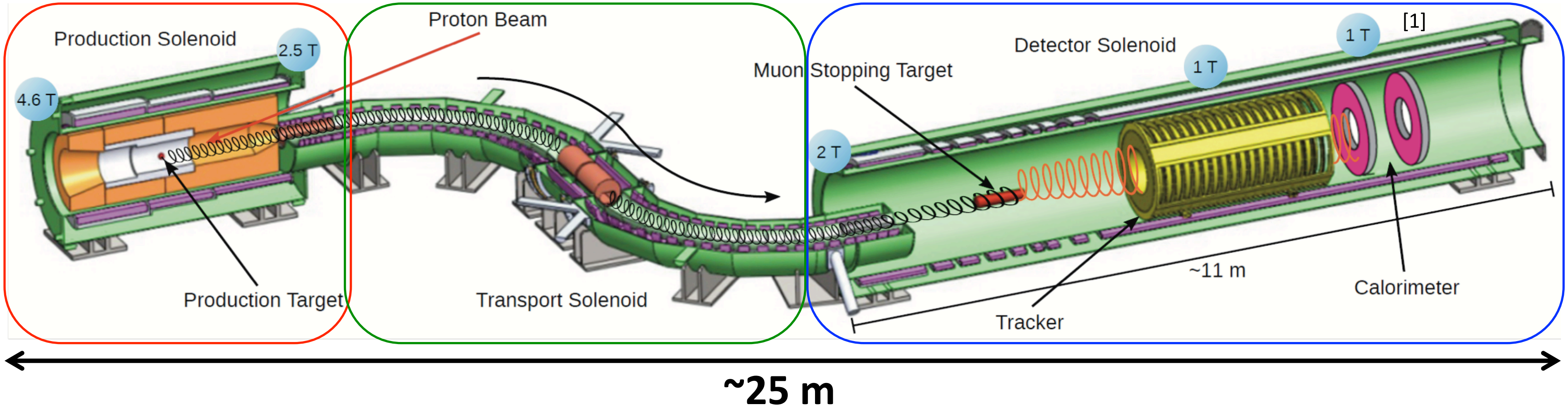
- **5σ discover reach of $R_{\mu e} \geq 2 \times 10^{-16}$**
- **Nuclear Capture ~61% ($\mu^- + {}^{27}Al \rightarrow \nu_\mu + {}^{27}Mg^*$)**
- **DIO ~39% (Michel spectrum distorted by nucleus)**

DIO = Decay In Orbit
POT = Protons On Target

[1] R. Bonventre [Mu2e Collaboration], SciPost Phys. Proc. **1**, 038 (2019). doi:10.21468/SciPostPhysProc.1.038

Mu2e Experiment is composed of 3 superconducting solenoid systems.

The graded magnetic fields suppress backgrounds, increase muon yield, and improve geometric acceptance of signal electrons.



Production Solenoid (PS):
- **Pulsed 8 GeV proton beam strikes a tungsten pion production target.**
- **Pions are captured by the graded magnetic field.**

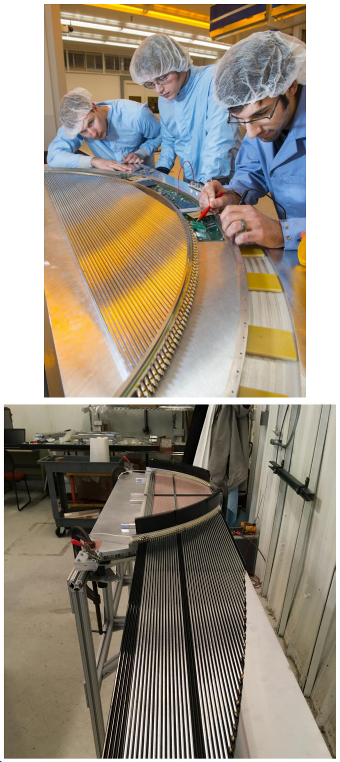
Transport Solenoid (TS):
- **Select low momentum negative muons (pions decay into muons).**
- **Reject high momentum negative particles & positive particles (absorber foils and collimators), as well as line-of-sight neutral particles (S-shape).**

Detector Solenoid (DS):
- **Create muonic atoms with an aluminum stopping target.**
- **Straw tracker detectors measure electron momenta and trajectories.**
- **Calorimeters measure energy, time, and particle ID.**
- **Cosmic ray veto detectors surround the detector solenoid.**

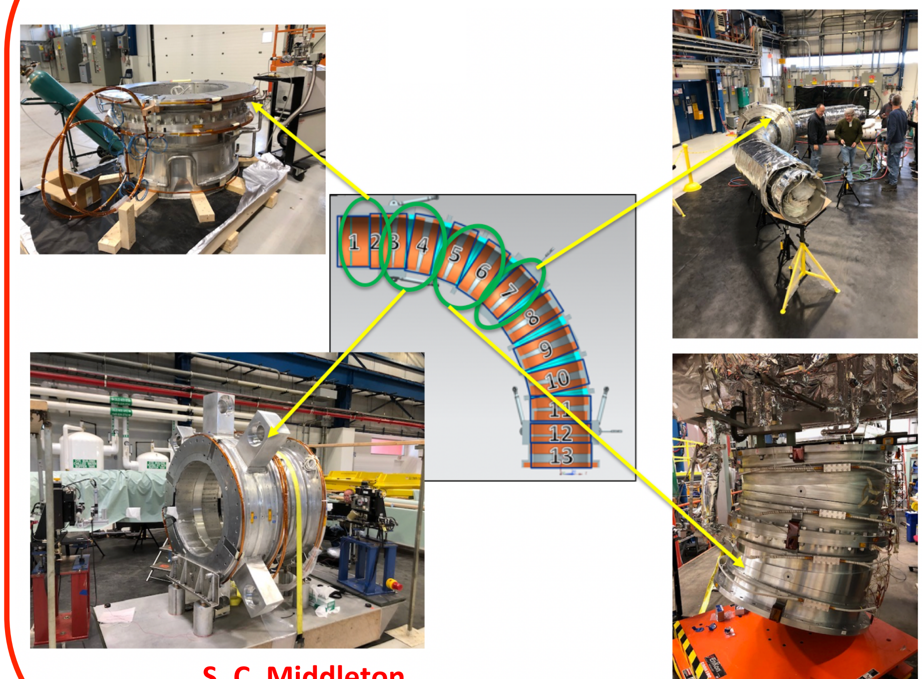
[1] S. Giovannella, EPJ Web Conf. **179**, 01003 (2018). doi:10.1051/epjconf/201817901003

Construction of the Mu2e Experiment is underway!

Tracker Construction

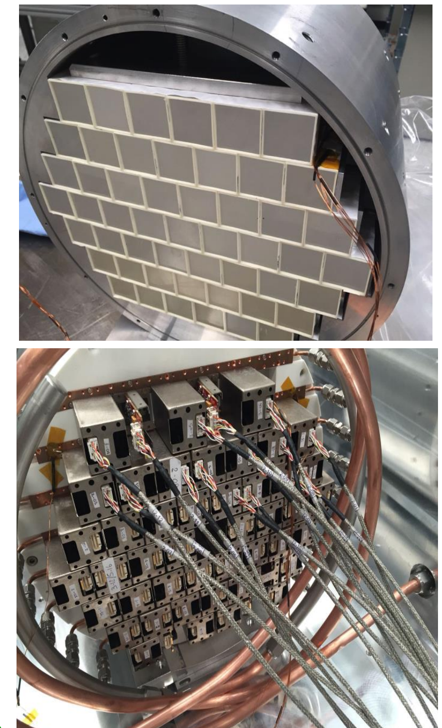


Transport Solenoid

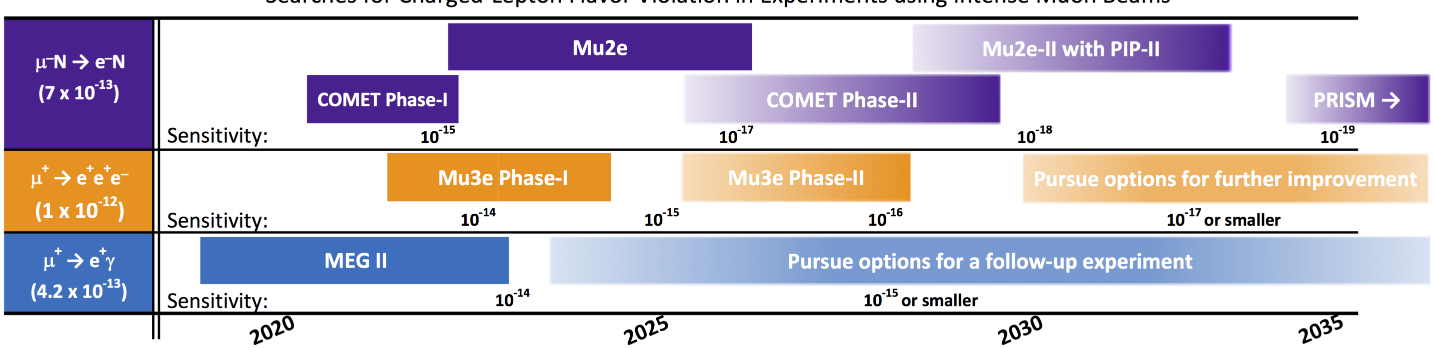


S. C. Middleton

Calorimeter Prototype



Searches for Charged-Lepton Flavor Violation in Experiments using Intense Muon Beams

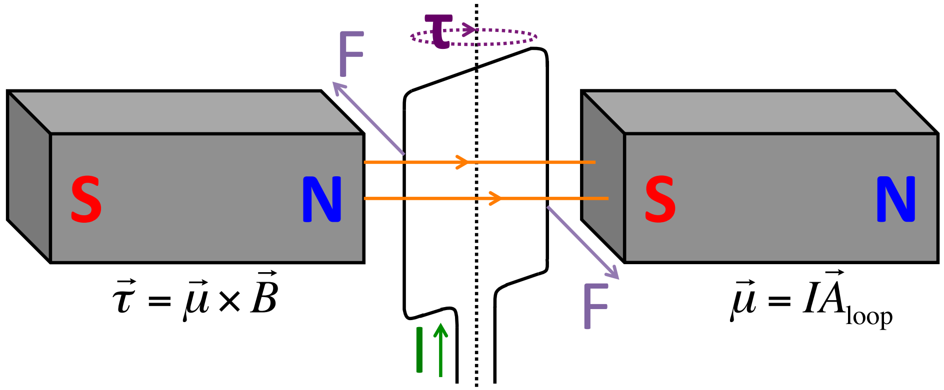


[1]

[1] A. Baldini *et al.*, arXiv:1812.06540 [hep-ex] (2018).

Different ways of thinking about magnetic dipole moments:

Classical Picture:



Quantum Picture:

g-factor:

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

Dirac Equation for EM potential:

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

- Spin-1/2 point particles
- Predicts g = 2

Larmor Precession (particle rest frame):

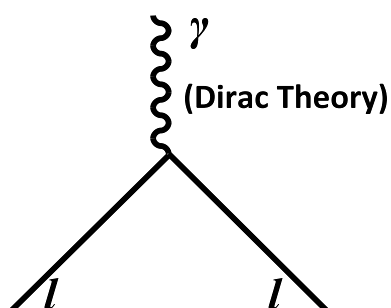
$$\frac{d\vec{s}}{dt} = \vec{\tau} = \vec{\mu} \times \vec{B} = g\left(\frac{q}{2m}\right)\vec{s} \times \vec{B}$$

Quantum Field Theory: Picture

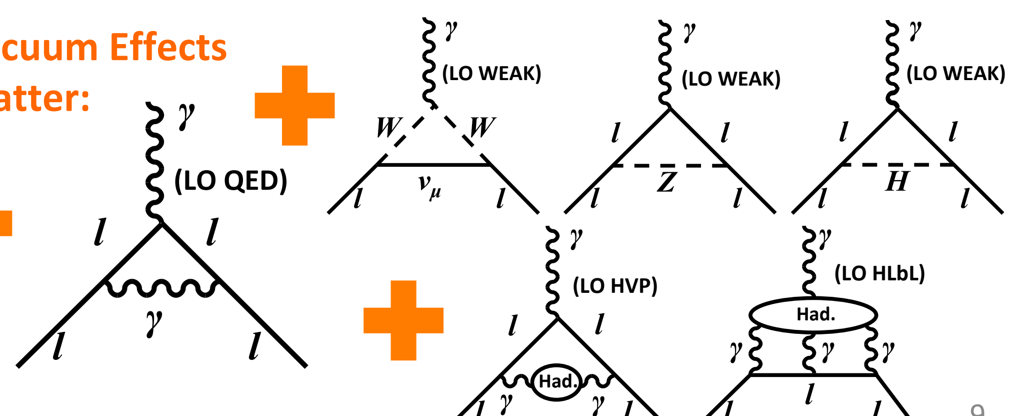
Anomaly:

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

- Predicts g ≠ 2

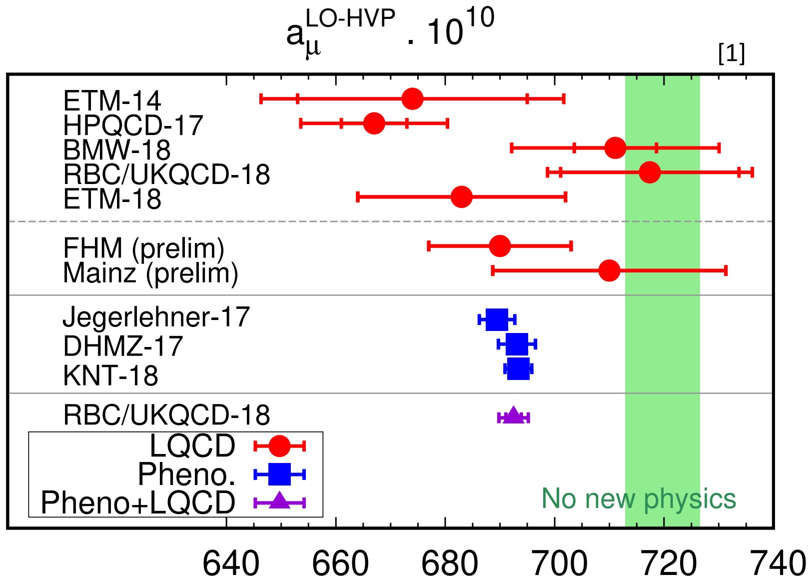


Vacuum Effects Matter:



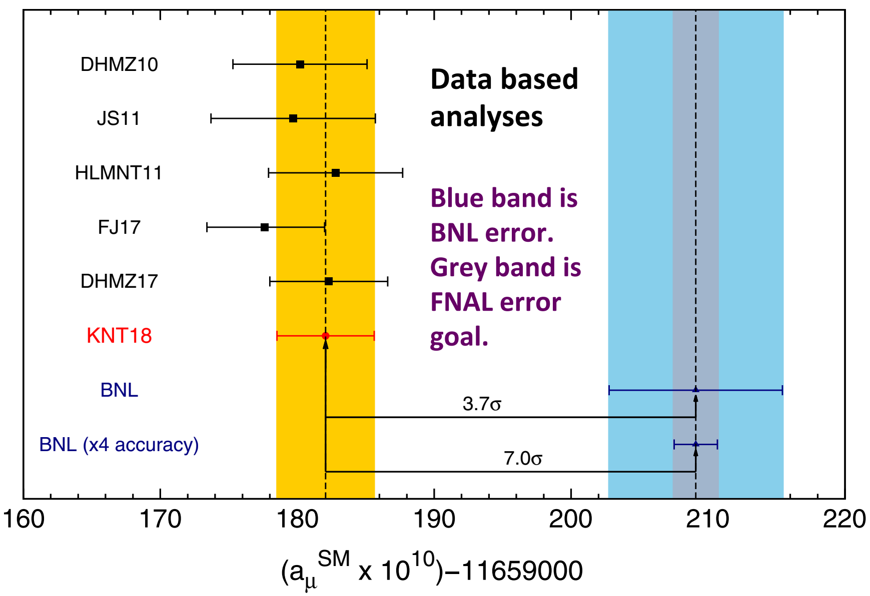
Muon anomaly provides an important test of the Standard Model.

[1]



Ongoing effort in calculating low energy QCD contributions using data and Lattice QCD.

[2]



- SM error driven by LO HVP and LbL (low energy QCD)
- Can get LO HVP from electron-positron cross sections (data)

[1] K. Miura, PoS LATTICE **2018**, 010 (2019). doi:10.22323/1.334.0010

[2] 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]]

Muon g-2 Experiment measures the anomalous spin precession frequency.

$$\vec{\omega}_s = -g_\mu \frac{q}{2m}\vec{B} - (1-\gamma)\frac{q}{\gamma m}\vec{B}$$

$\vec{\omega}_s$ = spin precession frequency

$\vec{\omega}_c$ = cyclotron frequency

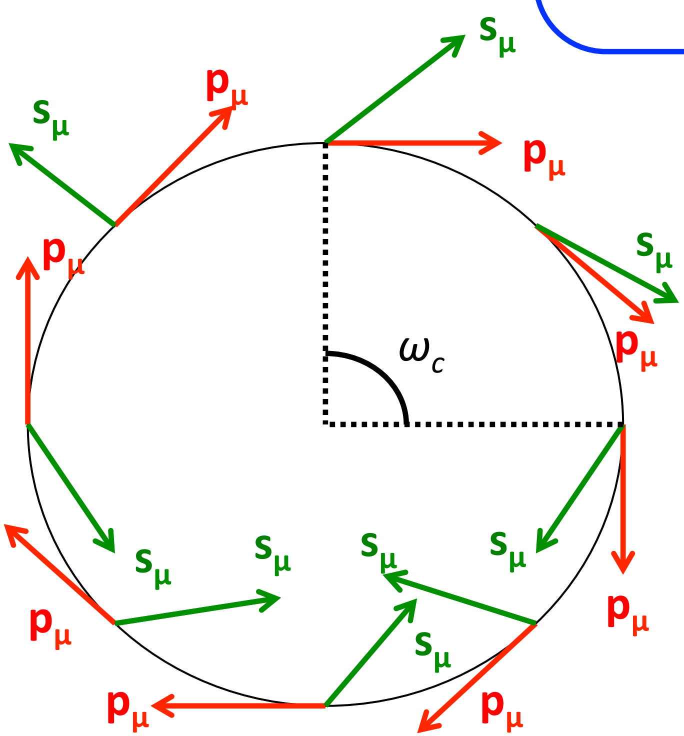
$$\vec{\omega}_c = -\frac{q}{m\gamma}\vec{B}$$

$\vec{\omega}_a$ = anomalous precession frequency

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{g_\mu - 2}{2}\right)\frac{q}{m}\vec{B} = -a_\mu \frac{q}{m}\vec{B}$$

Simple case of no E-field, constant B-field, and momentum perpendicular to B-field.

Experiment is sensitive to spin precession relative to momentum.



$$0 \text{ if } p = p_{\text{magic}} = mc/\sqrt{a_\mu} = 3.094 \text{ GeV}/c$$

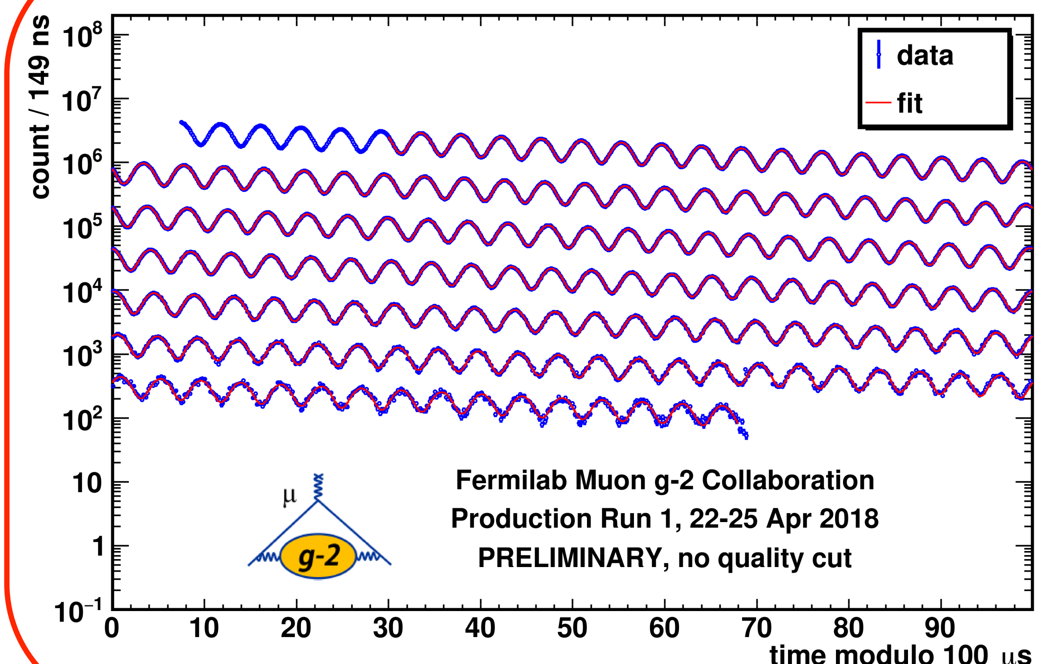
$$\vec{\omega}_a \approx -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

Muon anomaly is obtained from 5 numbers.

Anomalous spin precession frequency is extracted from decay positron time spectra

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

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



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]].

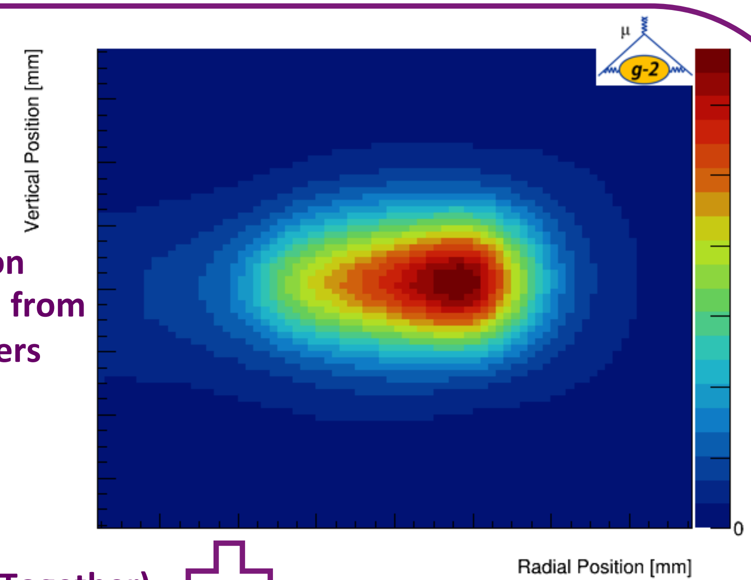
Muon anomaly is obtained from 5 numbers.

Average magnetic field seen by muons is measured with NMR

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

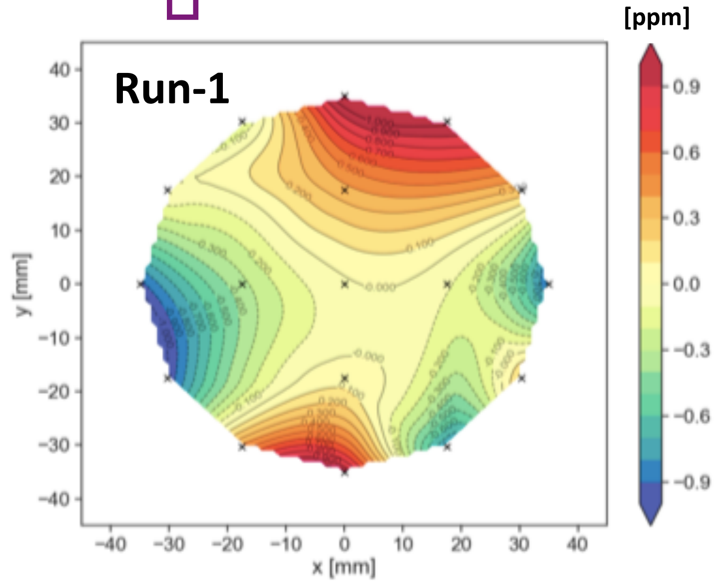
$$a_\mu = \frac{\dfrac{g_e}{2}\,\dfrac{m_\mu}{m_e}\,\dfrac{\omega_a}{\langle\omega_p\rangle}}{\dfrac{\mu_e}{\mu_p}}$$

Obtain muon distribution from straw trackers



(Combine Together)

Obtain B-field from NMR probes



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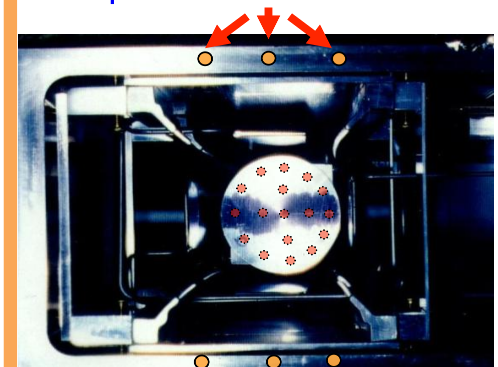
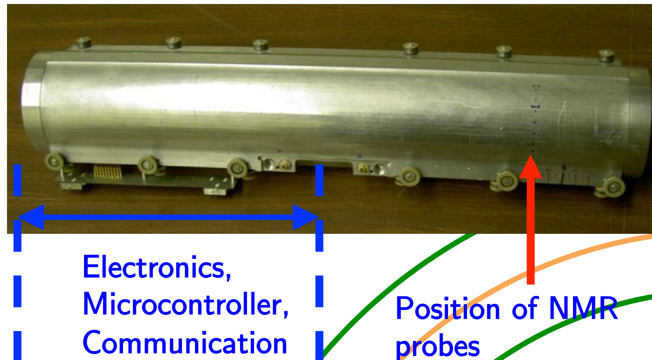
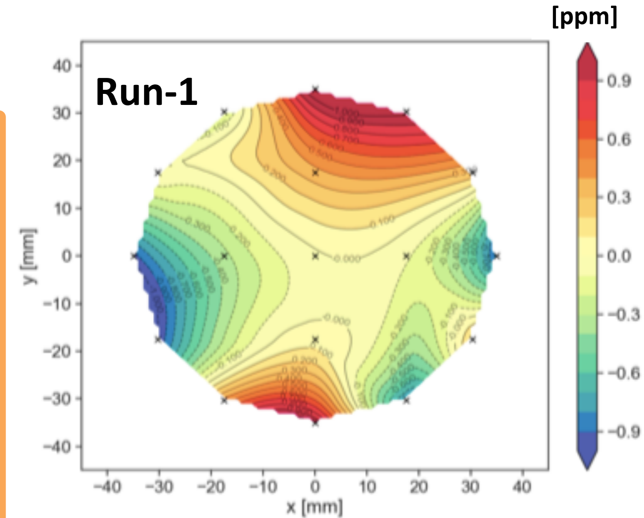
Fermilab Muon g-2 Experiment:

Fixed probes on vacuum chambers

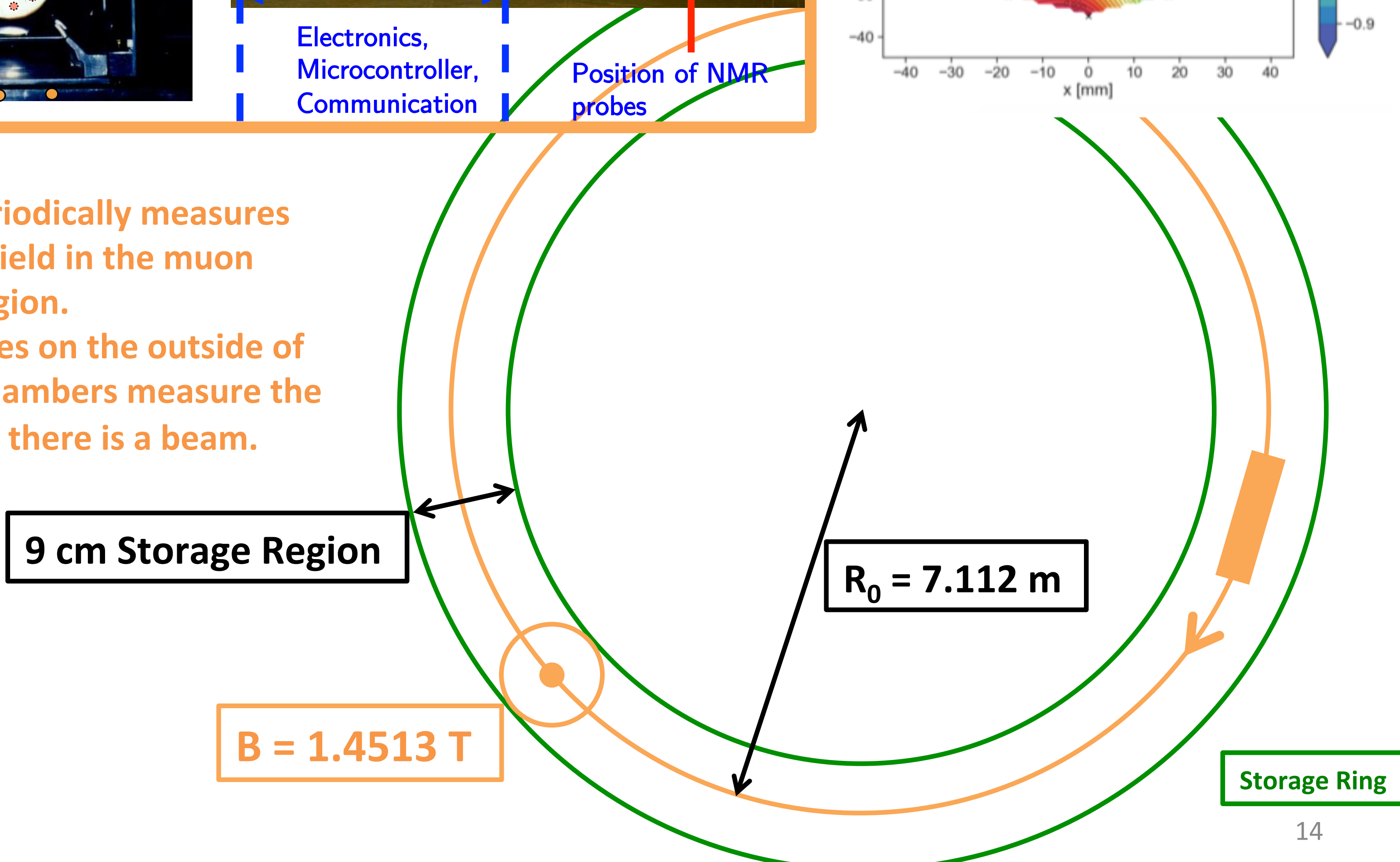


Trolley with matrix of 17 NMR probes





- Trolley periodically measures magnetic field in the muon storage region.
- NMR probes on the outside of vacuum chambers measure the field when there is a beam.



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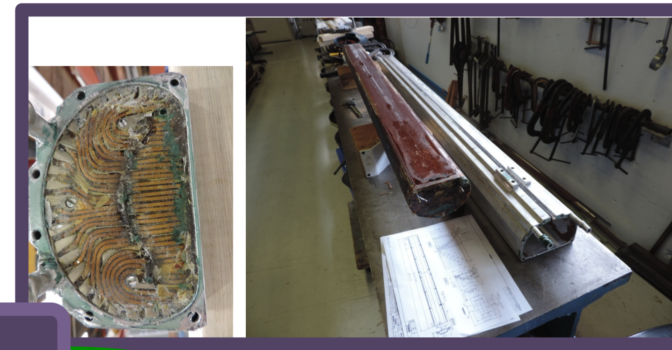
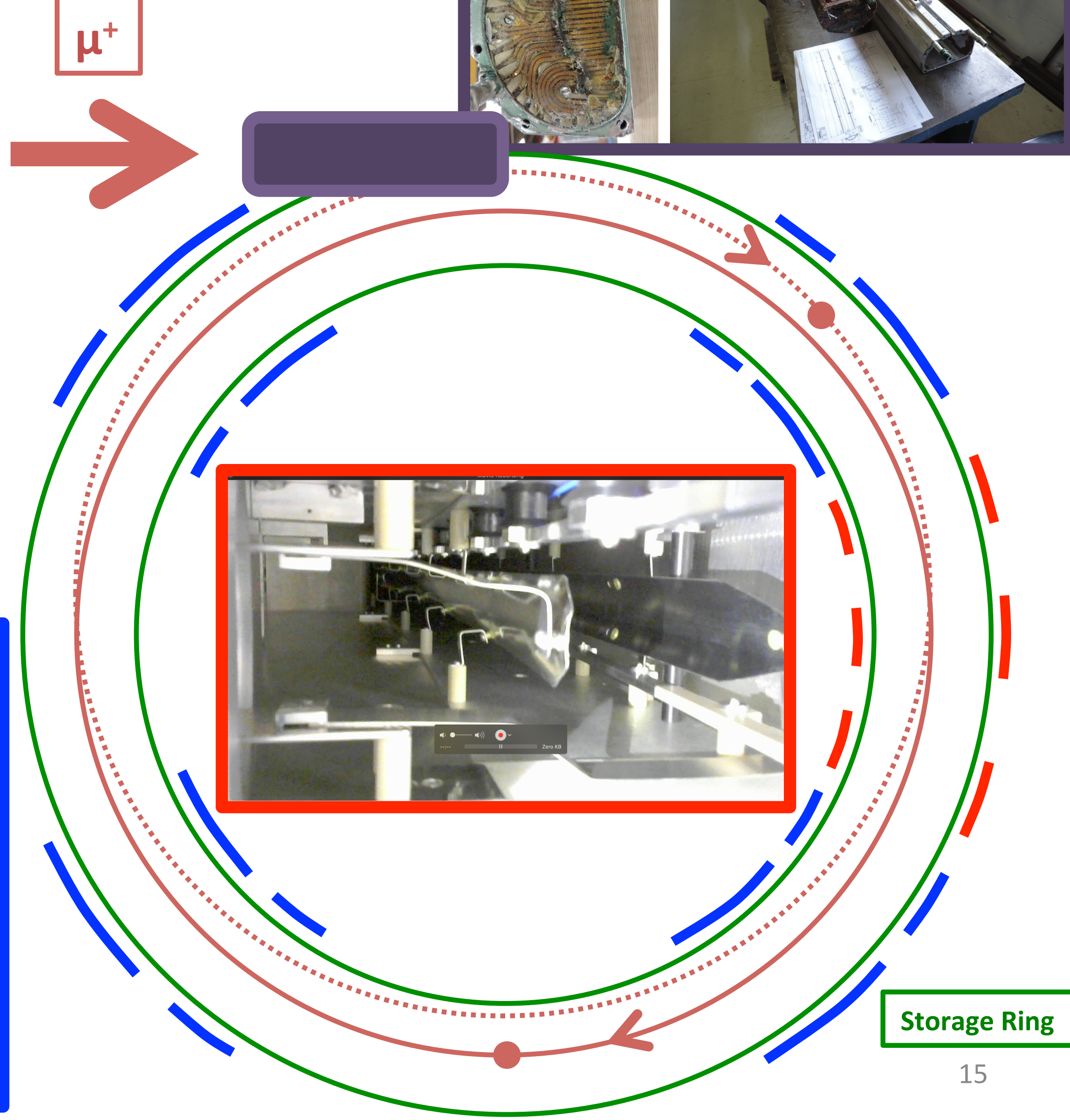
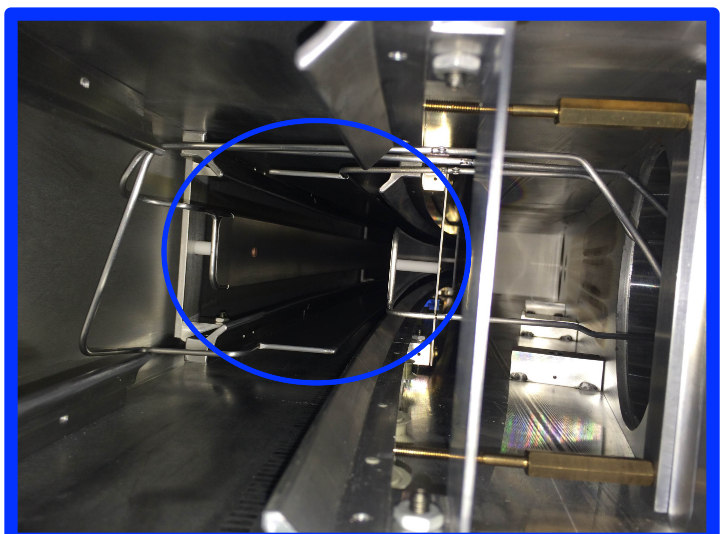
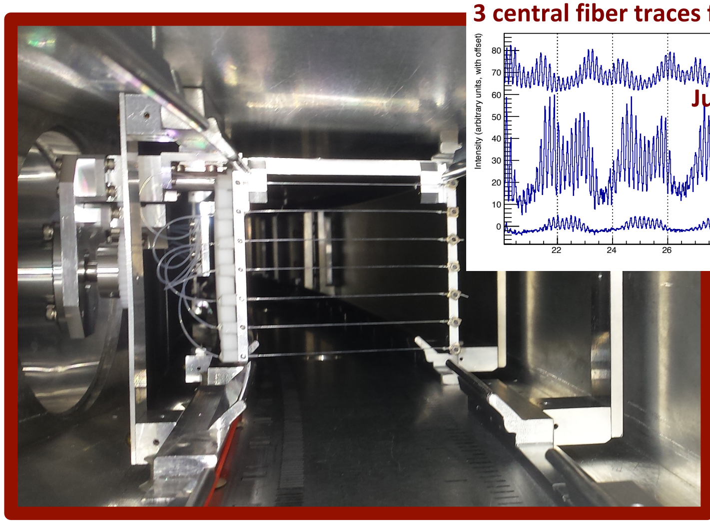




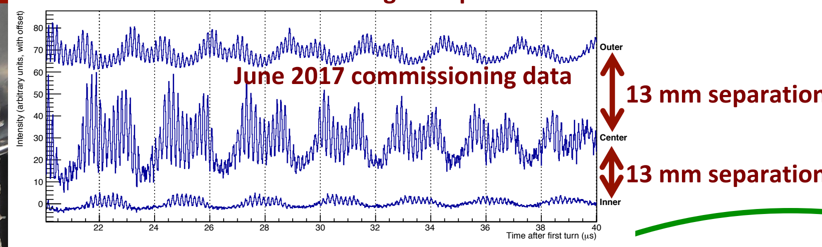
- Inflector injects muons into ring while minimizing disturbance to B-field
- 3 magnetic kickers “kick” the muons onto the storage orbit
- 4 pairs of electric quads provide vertical focusing

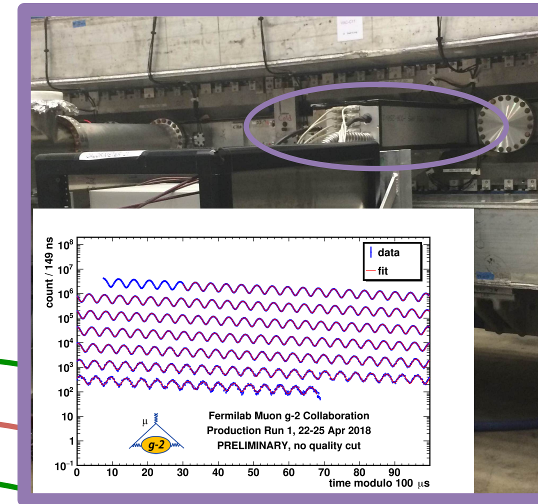


Fermilab Muon g-2 Experiment:

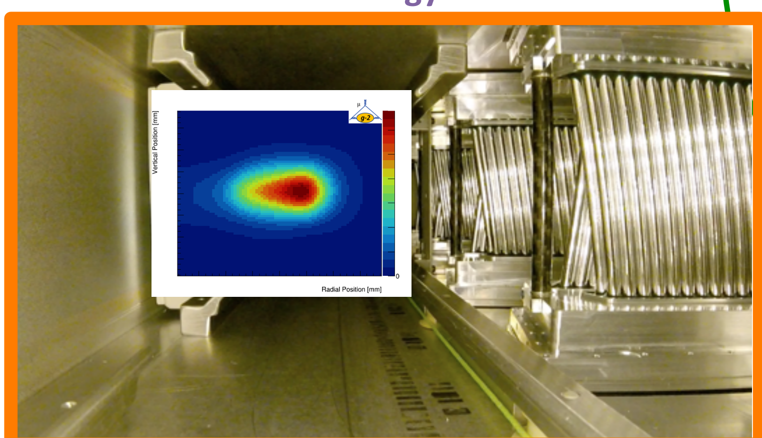


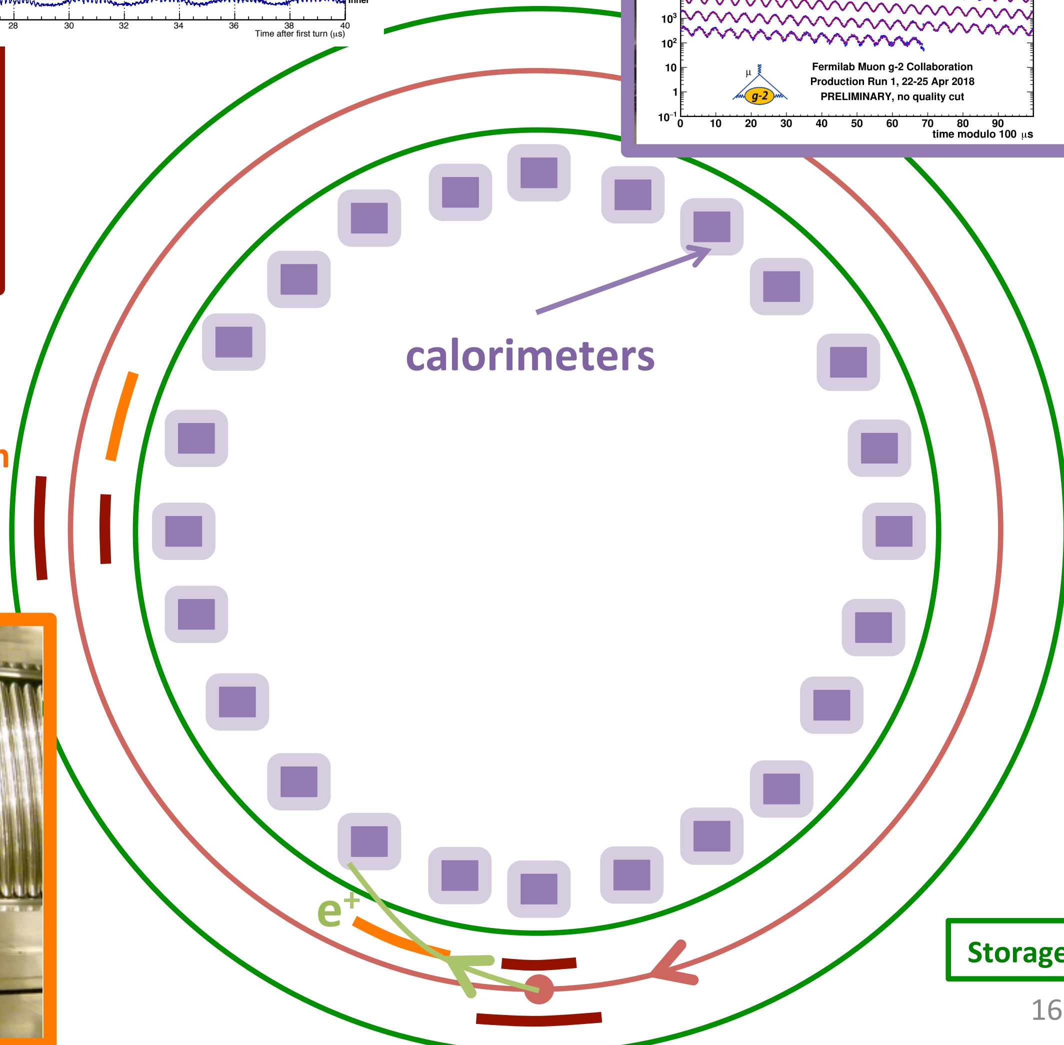
3 central fiber traces from 180 degree x-profile monitor





- 180° and 270° fiber profile beam monitors (special runs; degrades beam)
- 2 straw tracker stations measure decay positron trajectory, which provides beam profile reconstruction
- 24 calorimeters detect decay positron arrival time and energy



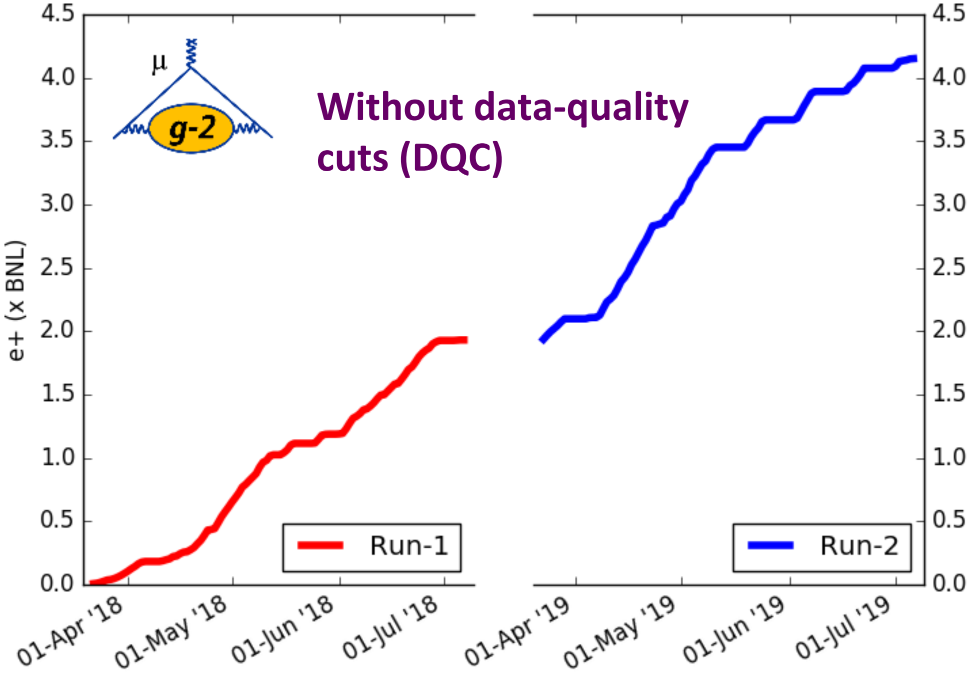


Storage Ring

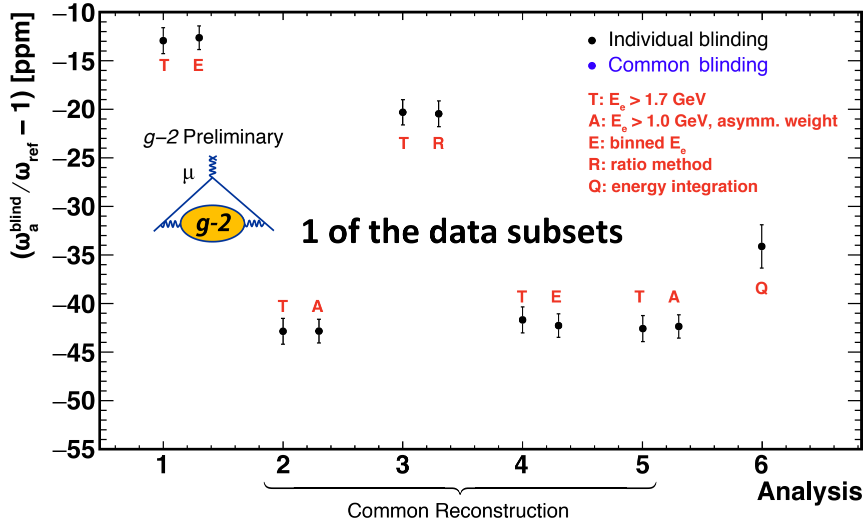
Status of the Fermilab Muon g-2 Experiment:

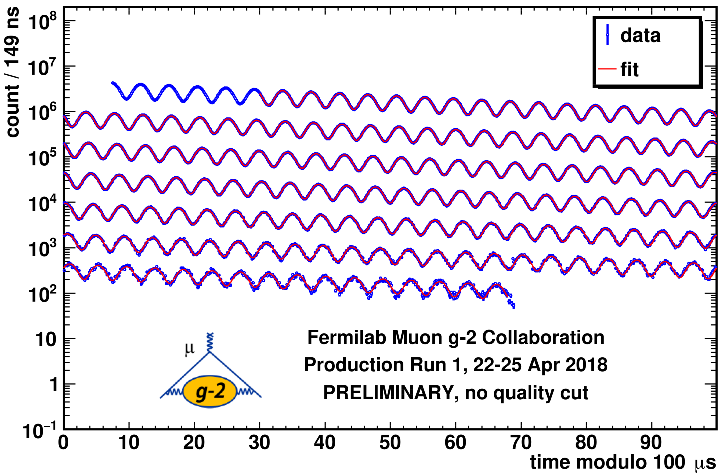
- Finished Run-1 & Run-2; looking at data!
- Currently in a Summer shutdown preparing for Run-3.
- Goal of publishing Run-1 results by the end of the year!

Expect ~1.8×BNL Run-2 dataset vs. ~1.4×BNL Run-1 dataset after Data Quality Cuts.



Run-1 ω_a analysis:





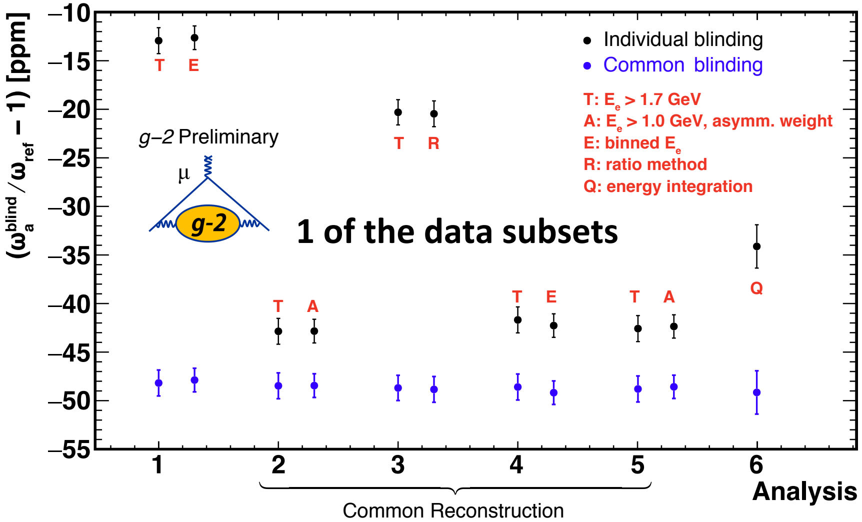
Example fit function:

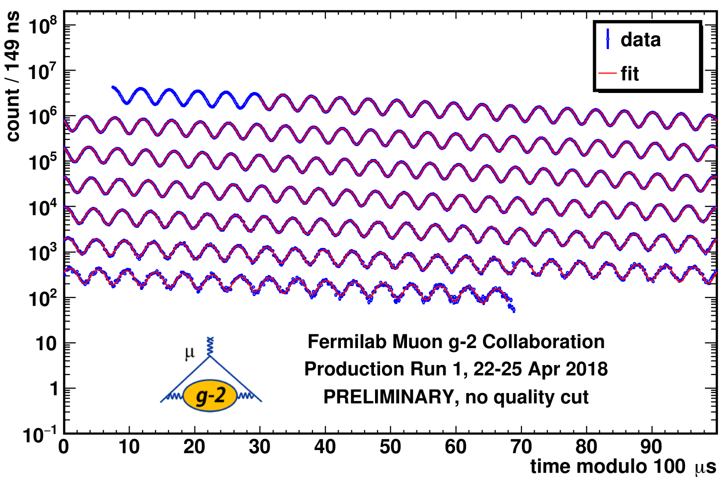
$$N(t) = N_0 \Lambda(t) N_{cbo}(t) N_{vw}(t) e^{-t/\tau}$$

$$\cdot\left\{1 + A_0 \cdot A_{cbo}(t) \cdot \cos\left[\omega_a(R) \cdot t + \phi_0 + \phi_{cbo}(t)\right]\right\}$$

- **Data are hardware blinded.**
  - No collaborator knows the clock tick frequencies (2 external people know).
- **Each analyzer has their own private software frequency offset.**

Run-1 ω_a analysis:





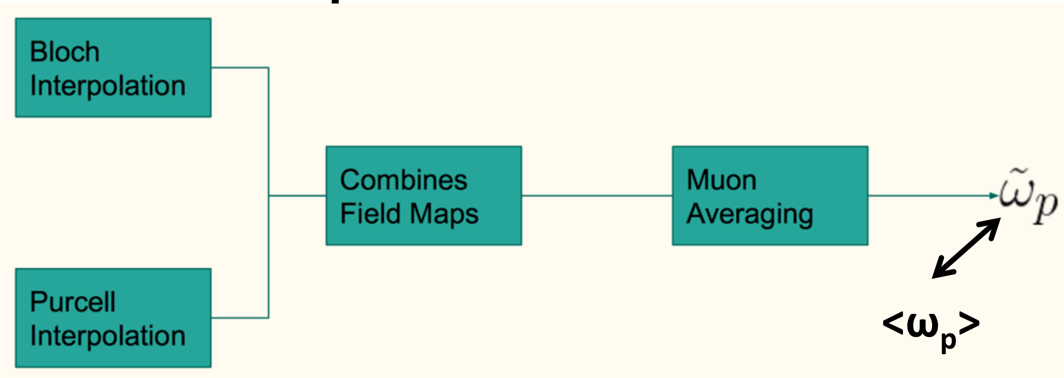
Example fit function:

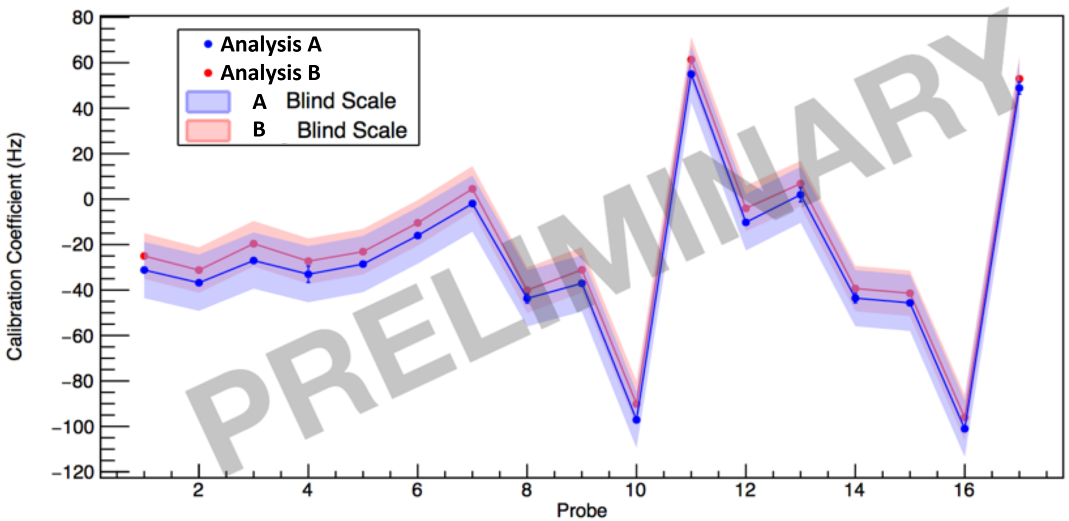
$$N(t) = N_0 \Lambda(t) N_{cbo}(t) N_{vw}(t) e^{-t/\tau}$$

$$\cdot \left\{ 1 + A_0 \cdot A_{cbo}(t) \cdot \cos\left[\omega_a(R) \cdot t + \phi_0 + \phi_{cbo}(t)\right] \right\}$$

- **Data are hardware blinded.**
  - No collaborator knows the clock tick frequencies (2 external people know).
- **Each analyzer has their own private software frequency offset.**
  - Private software offsets removed for 1 of the data subsets (practice exercise & early verification).
- **Run-1 has 4 primary data subsets with different Kicker & Electrostatic Quadrupole settings.**
- **6 groups fitting the frequency with multiple methods.**
- **3 independent event reconstruction efforts.**
  - 2 methods fit individual (E,t), but with very different approaches for how the spatial information is used.
  - Q-method is a new charge integrating technique (unique to FNAL Experiment).
- **Data is gain & pileup corrected, binned, and randomized with respect to the cyclotron frequency.**
- **Full fit functional forms are producing excellent χ^2 and clean residuals.**

Run-1 $\langle\omega_p\rangle$ (B-field) analysis:





Use 400 fixed probes (outside of the vacuum chambers) to interpolate between trolley runs.

- 2 independent teams making good progress.
  - Data are hardware blinded.
  - Results are still software blinded, except for 1 of the data subsets.
- Preliminary Run-1 estimate.

B-field the trolley measures is not the B-field free protons experience.

- B-field perturbations due to trolley probe materials, electronics, enclosures (need a calibration)
  - Compare trolley probes to the plunging probe: plunging probe B-field perturbations are well measured.
- 2 independent analyses have produced preliminary results.
  - Presently examining field gradients, alignment of trolley/plunging probe active volumes, and impact of field oscillations.

Compare plunging and absolute calibration probes.

- 2 types of absolute calibration probes
  - Spherical shaped H_2O based
  - Polarized ^3He based
- BNL Experiment only used H_2O based absolute calibration probe.

Muon g-2 Experiment final error goals:

ω_a systematic uncertainty summary[1].

Category	BNL [ppb]	FNAL Goal [ppb]
Gain Changes	120	20
Pileup	80	40
Lost Muons	90	20
CBO	70	< 30
E-field & Pitch Corrections	50	30
Total (Quadrature Sum)	190	70

a_μ uncertainty summary[1,2].

Category	BNL [ppb]	FNAL Goal [ppb]
Total Statistical Uncertainty	460	100
Total Systematic Uncertainty	280*	100
Total (Quadrature Sum)	540*	140

* The net systematic is across 3 running periods.

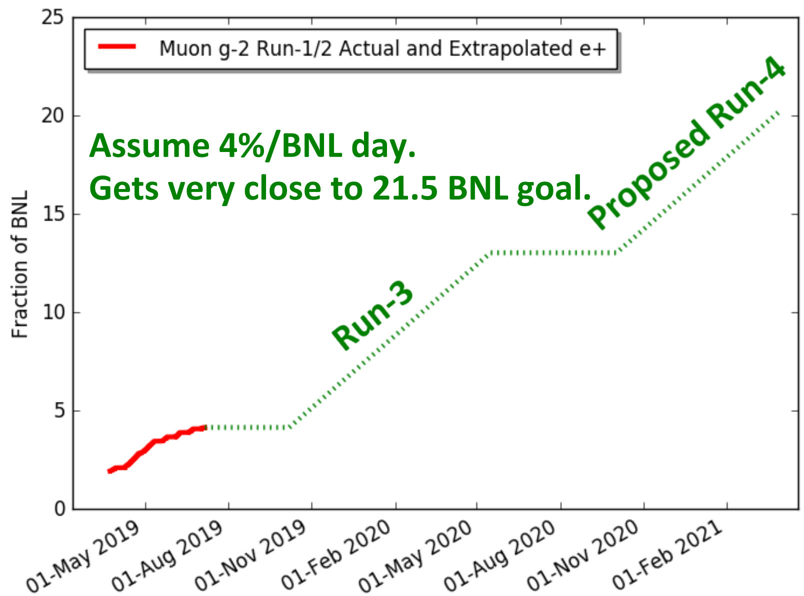
$\langle\omega_p\rangle$ (B-field) systematic uncertainty summary[1].

Category	BNL [ppb]	FNAL Goal [ppb]
Absolute Field Calibration	50	35
Trolley Probe Calibrations	90	30
Trolley Measurements Of B_0	50	30
Fixed Probe Interpolation	70	30
Muon Distribution	30	10
Time-dependent External Magnetic Fields	-	5
Others (Collective Smaller Effects)	100	30
Total (Quadrature Sum)	170	70

[1] J. Grange *et al.* [Muon g-2 Collaboration], arXiv:1501.06858 [physics.ins-det].
[2] M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D 98, 030001 (2018).

Stay tuned …

- **Mu2e Experiment is currently under construction.**
- **Mu2e expects to start taking data in 2023.**
- **Muon g-2 Experiment has finished Run-1 and Run-2 data collection.**
- **Muon g-2 is in a summer shutdown and preparing for Run-3.**
- **Muon g-2 has the goal of publishing a Run-1 physics result by the end of 2019.**



Run-3 starts Oct-7 and ends May-15.

The proposed Run-4 would share beam time with Mu2e commissioning.
Muon g-2: 6 months
Mu2e: 3 months

1st publication (>1 x BNL statistics)

2nd publication (3 x BNL statistics)

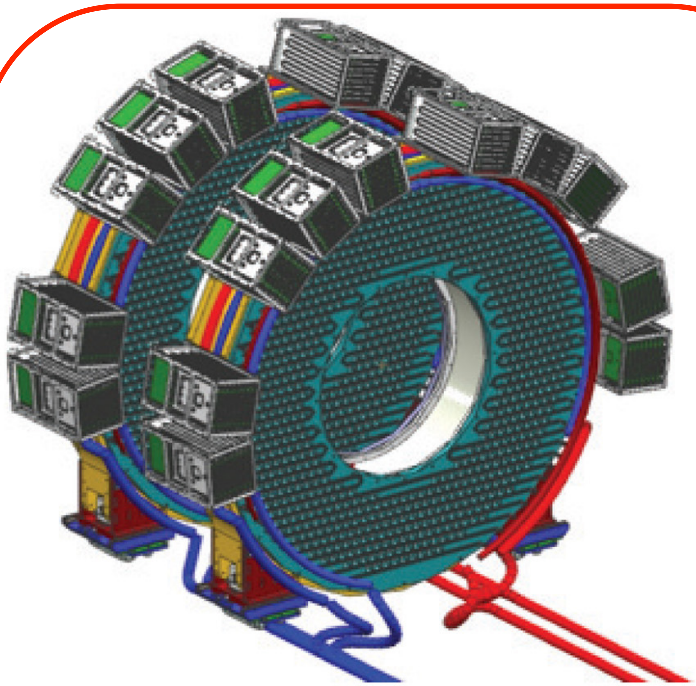
3rd publication (10 x BNL statistics)

Final publication

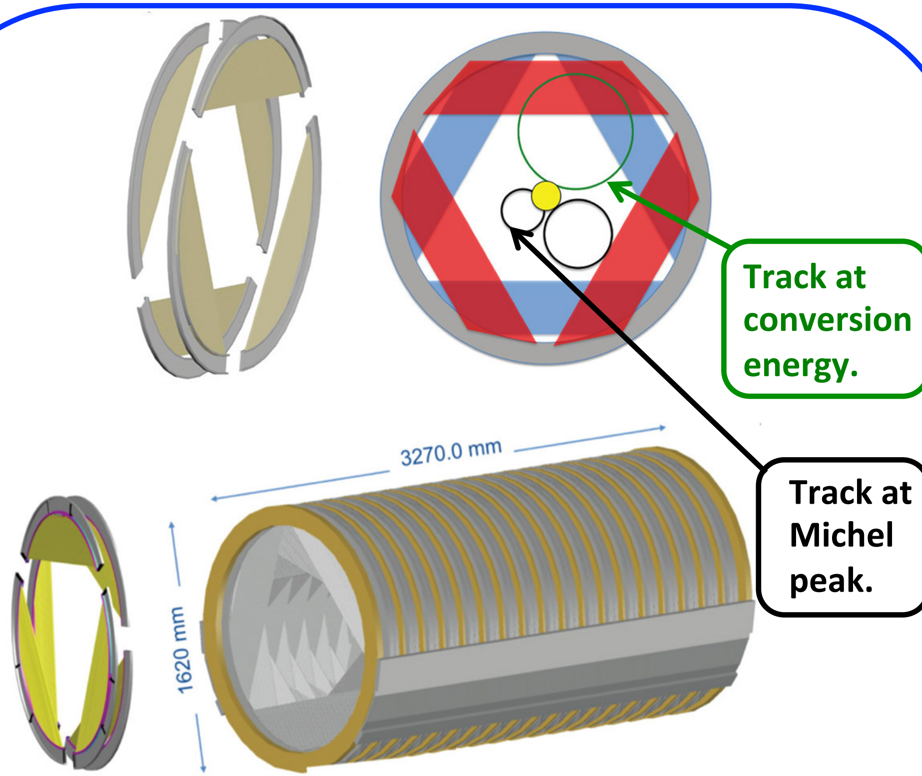
CY18 | CY19 | CY20 | CY21 | CY22

Backup

Trackers and calorimeters are used to reconstruct electron kinematics.



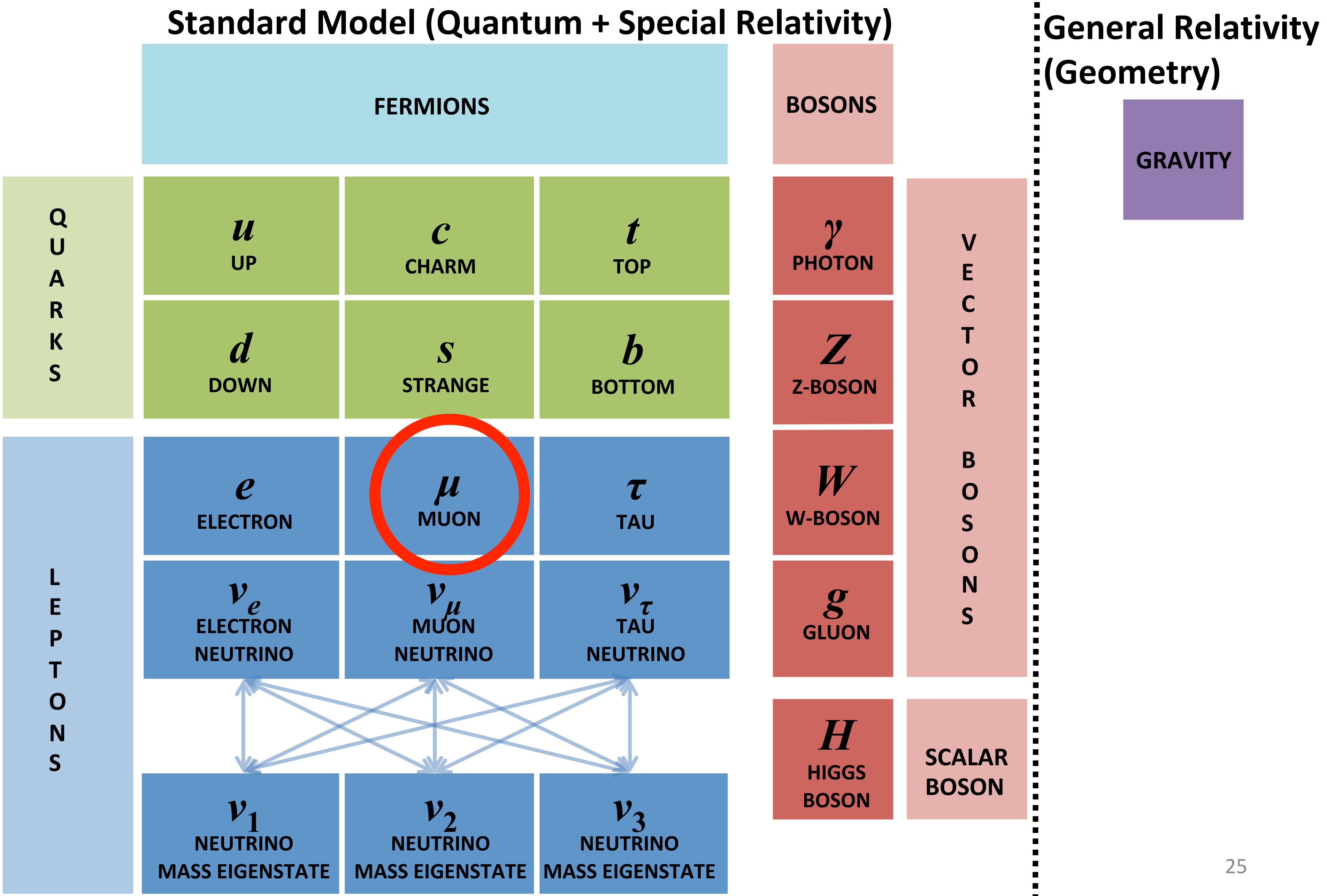
- 2 annular disks separated by half a track wavelength gives ~90% acceptance.
- Each disk contains ~674 scintillating CsI crystals readout with SiPMs
- Resolution ~5% at 105 MeV and ~1 ns.



- 5mm diameter straw drift tubes made with mylar-epoxy-Au-Al walls and Au-plated W wire.
- Operates in a vacuum with Ar/CO2 gas at ~1.45 kV.
- Ultra low mass system to minimize multiple scattering.
- Highly segmented to handle high rates.
- Resolution less than 200 keV/c at 105 MeV.
- 18 stations each having 12 × 120° panels = 216 panels ➔ ~21,000 straws.
- Nearly blind to all DIO background (only electrons greater than 90MeV get reconstructed).

[1] R. H. Bernstein [Mu2e Collaboration], Front. in Phys. **7**, 1 (2019). doi:10.3389/fphy.2019.00001 [arXiv:1901.11099 [physics.ins-det]].

Standard Model zoo of particles:



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.

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

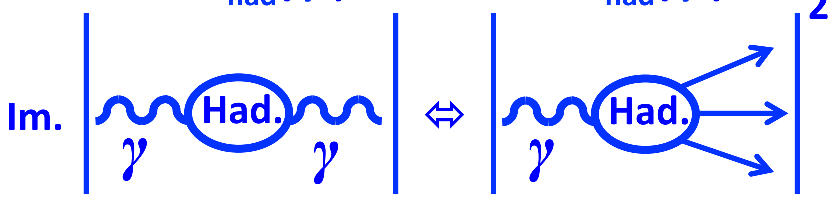
[1]

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

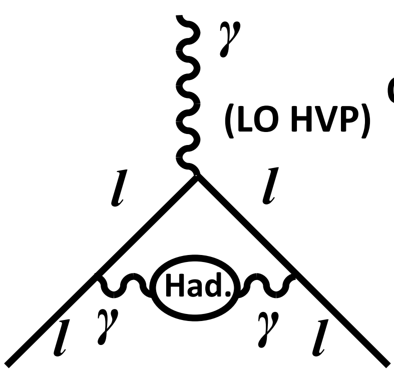
Largest source of SM error → hadronic LO VP

Optical Theorem

$\text{Im}\,\Pi_{had}(q^2)$ ~ $\sigma_{had}(q^2)$



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 → $R(s)$

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

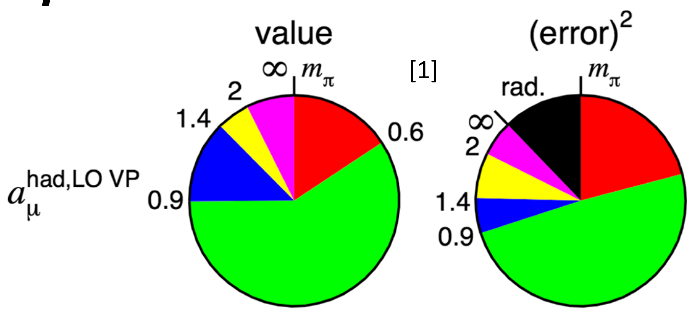
$\sigma(e^+e^- \to \mu^+\mu^-)$ at tree level → $(4\pi\alpha^2/3s)$

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

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

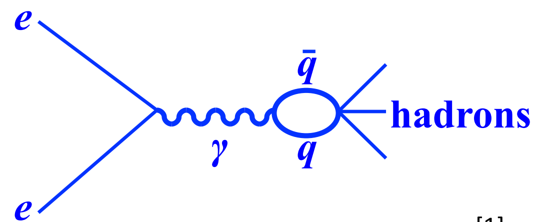
[1] F. Jegerlehner, arXiv:1804.07409 [hep-ph].

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

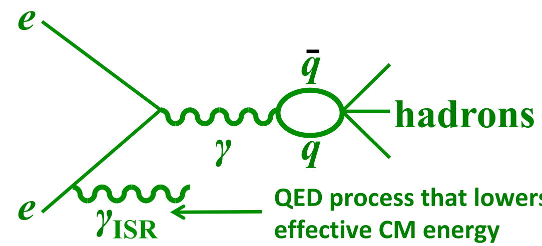


[1]

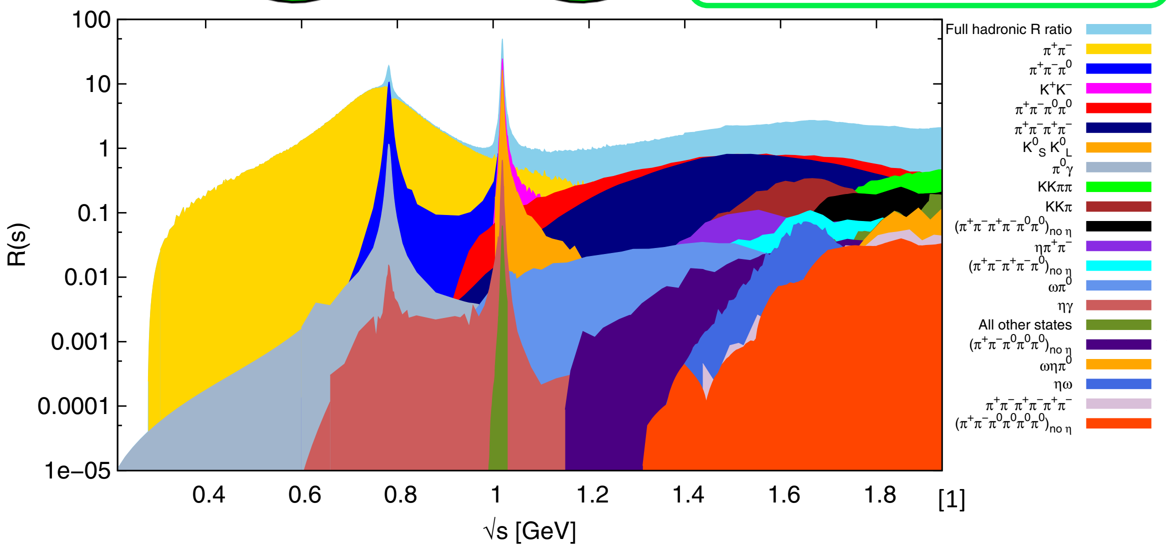
Direct Scan Method:



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

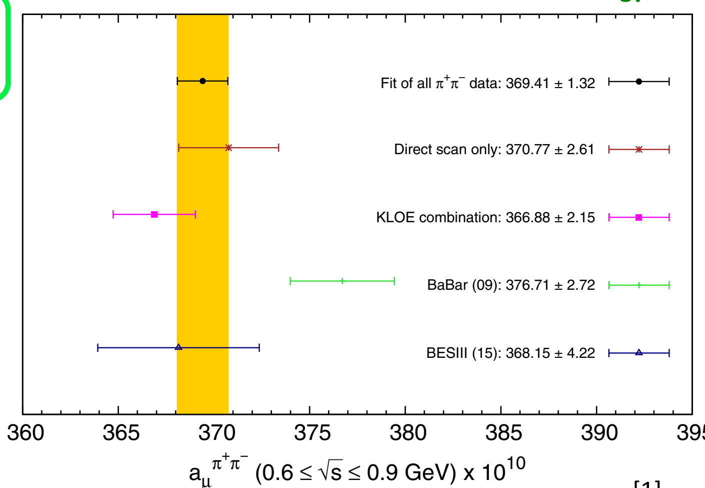


σ(e+e-➔π+π-) contributes the most to the value and error

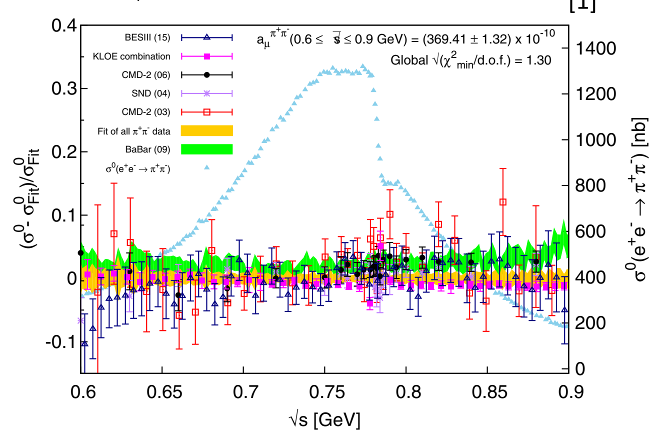


[1]

[1]



[1]

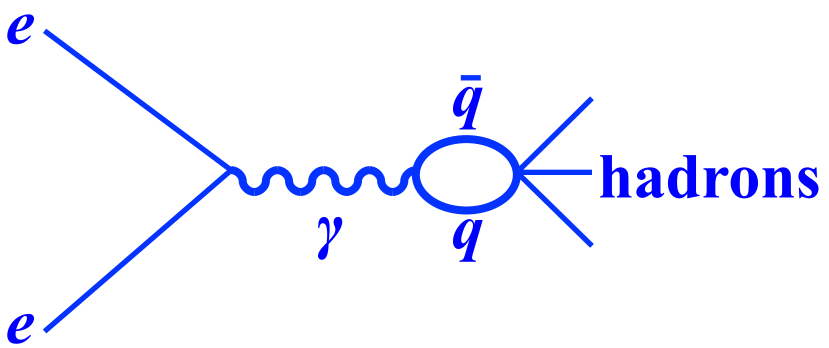


From a recent hadronic VP contributions to muon g-2 workshop[2]:

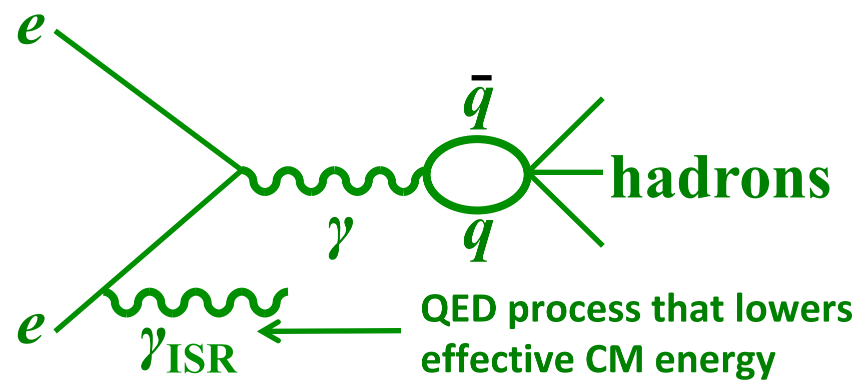
- Belle II studying an e^+e^-➔$\pi^+\pi^-$ measurement (Maeda Yosuke)
- BABAR working on e^+e^-➔$\pi^+\pi^-$ measurement using full BABAR data set (Michel Davier)
- BESIII preliminary e^+e^-➔$\pi^+\pi^-\pi^0$, $\pi^+\pi^-2\pi^0$, and $\pi^+\pi^-3\pi^0$ measurements (Christoph Florian Redmer)

[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):

Direct Scan Method:

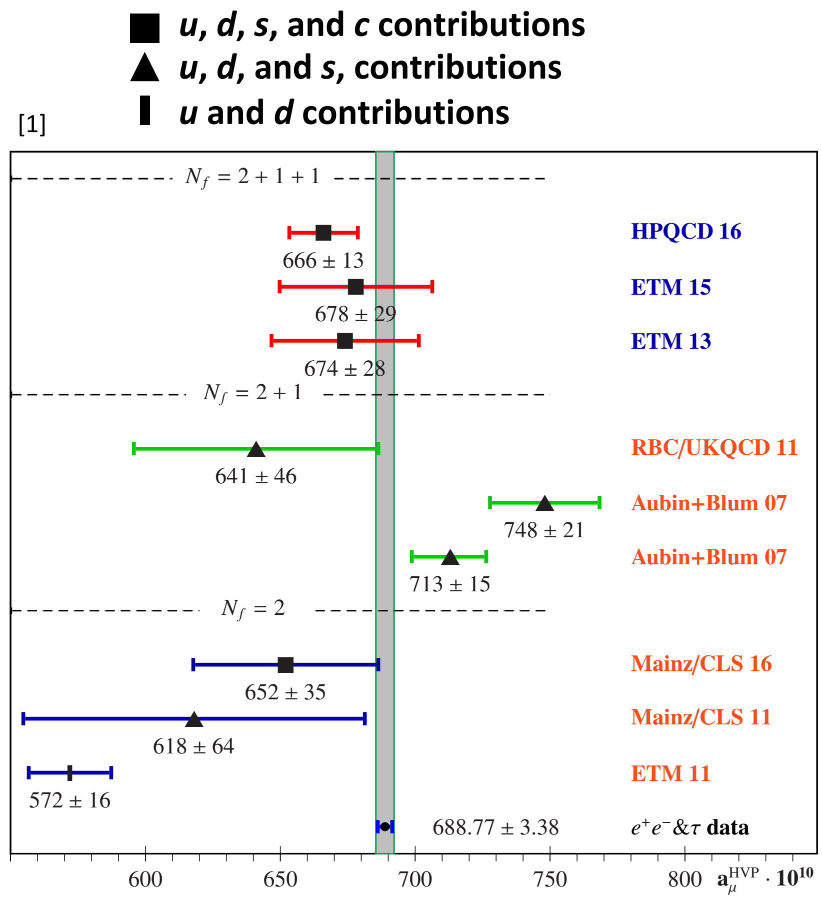


Initial State Radiation (ISR) method:
(suitable for Phi- and B-factories)

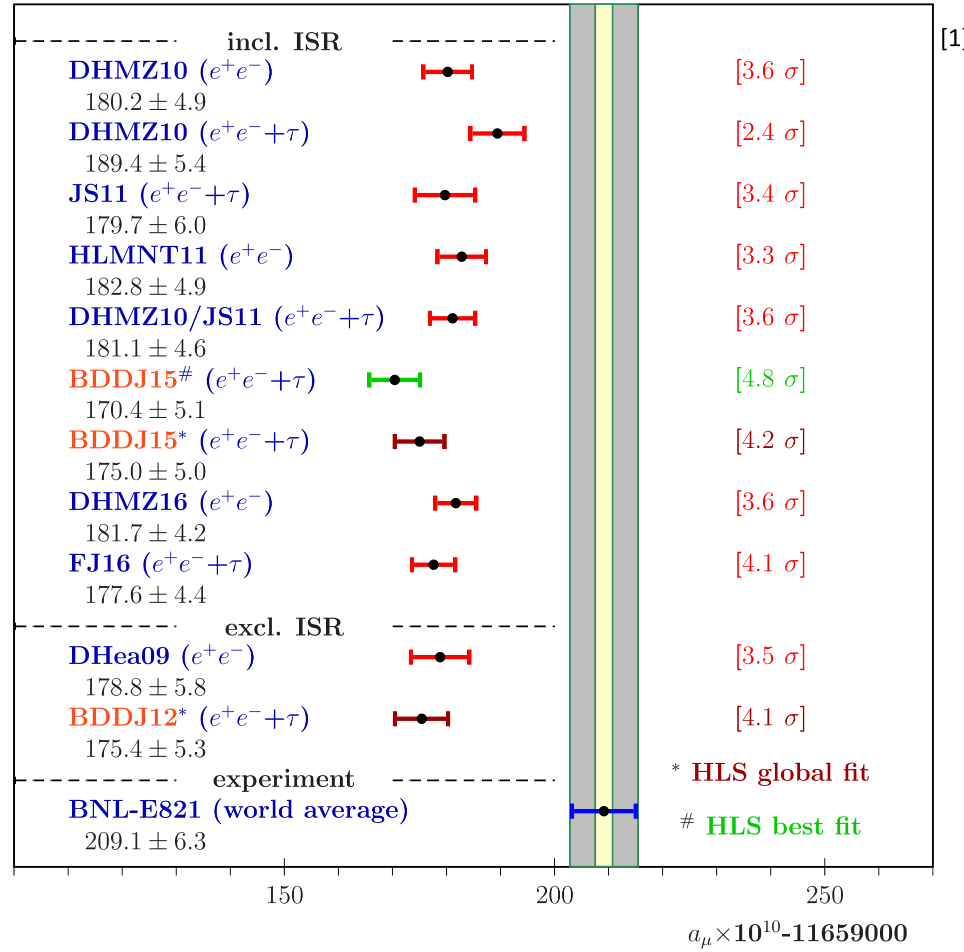


BNL muon anomaly measurement and SM prediction differ by greater than 3σ.

[1]



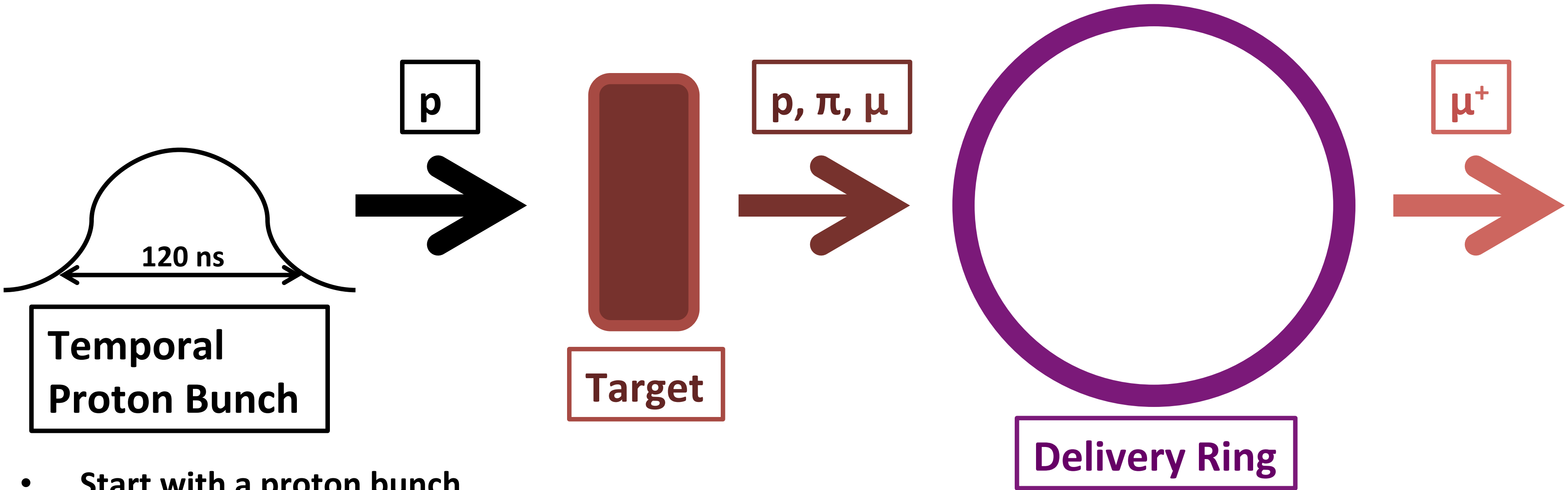
Work continues with LQCD $a_\mu^{\text{had. LO VP}}$ calculations



- **Historical e^+e^- and τ data discrepancy resolved by including effects such as $\rho-\gamma$ mixing (important isospin breaking effects): DHMZ10 ($e^+e^- + \tau$) 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 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 Collaboration …

Domestic Universities

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

National Labs

- Argonne
- Brookhaven
- Fermilab

China

- Shanghai

Germany

- Dresden

Italy

- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

Korea

- CAPP/IBS
- KAIST

Russia

- Budker/Novosibirsk
- JINR Dubna

United Kingdom

- Lancaster/Cockcroft
- Liverpool
- University College London
- Manchester

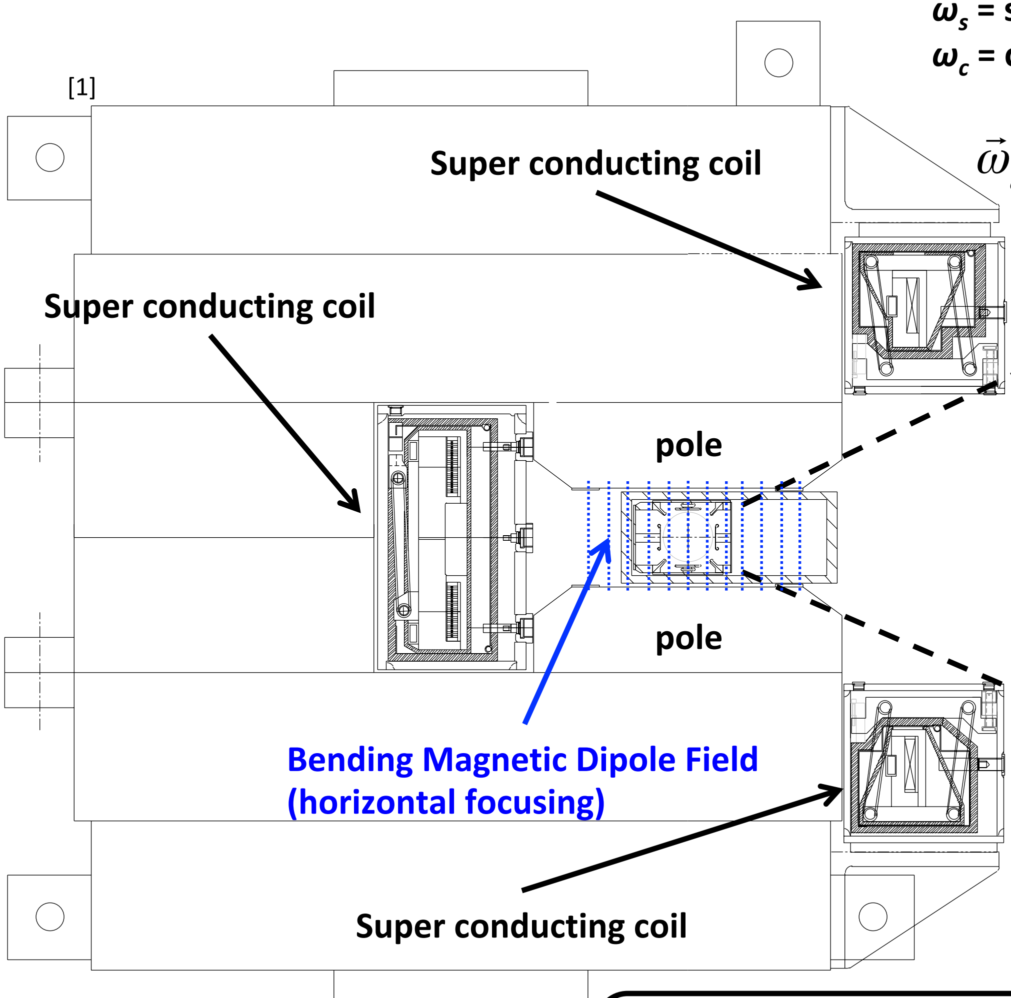
Fermilab

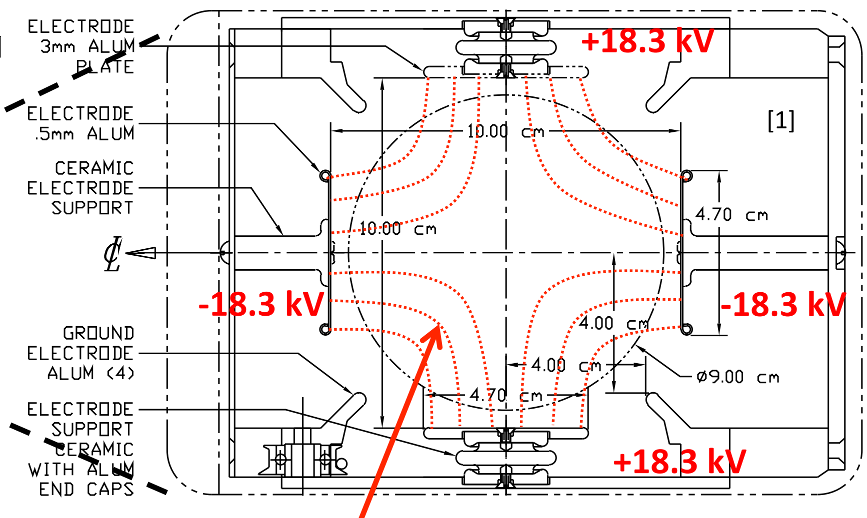
Experiment uses a weak focusing muon storage ring.

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

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





ELECTRODE AND SUPPORT FRAME - END VIEW

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

Vertical Focusing Electric Quadrupole Field

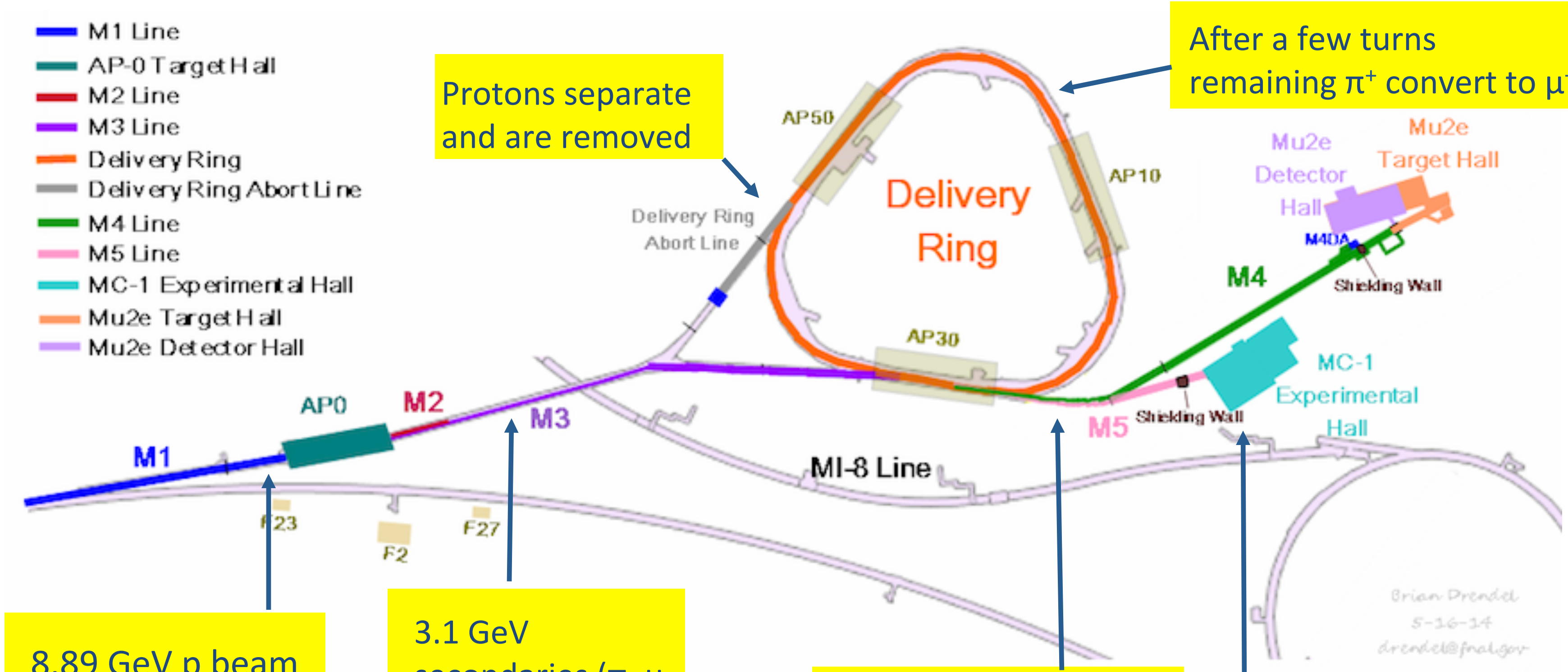
Horizontal And Vertical Tunes:

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

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

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

Fermilab beamline decays away most of the pions.



Protons separate and are removed

After a few turns remaining π^+ convert to μ^+

8.89 GeV p beam impacts the target

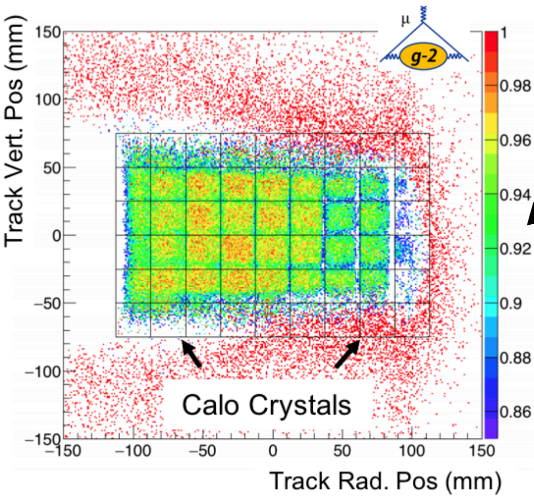
3.1 GeV secondaries (π, μ, p) travel along M2 & M3, where μ^+ are collected from π^+ decays

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

μ^+ enter the g-2 storage ring

D. Stratakis

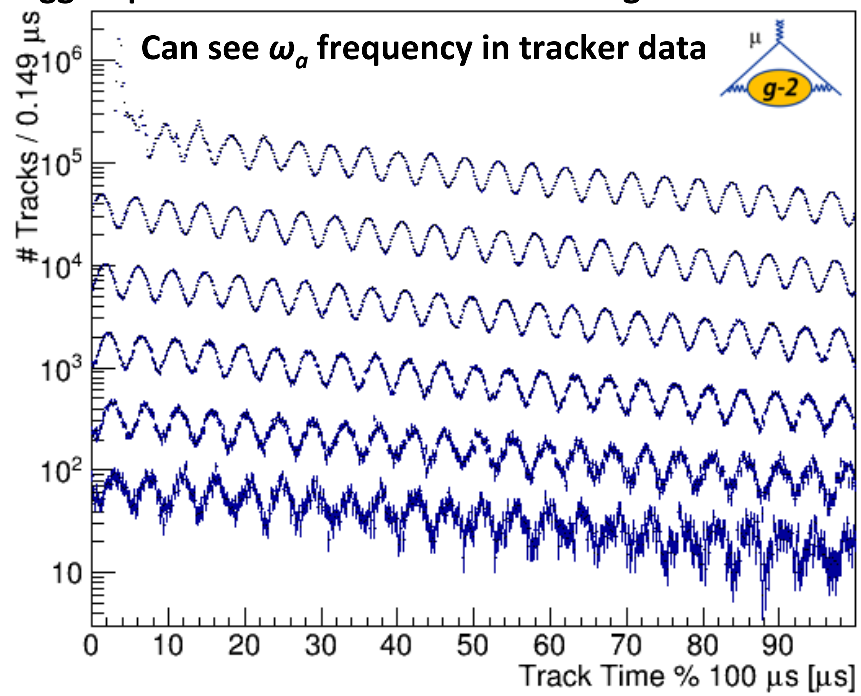
Straw tracker detectors measure the storage ring muon beam profile when taking physics data.

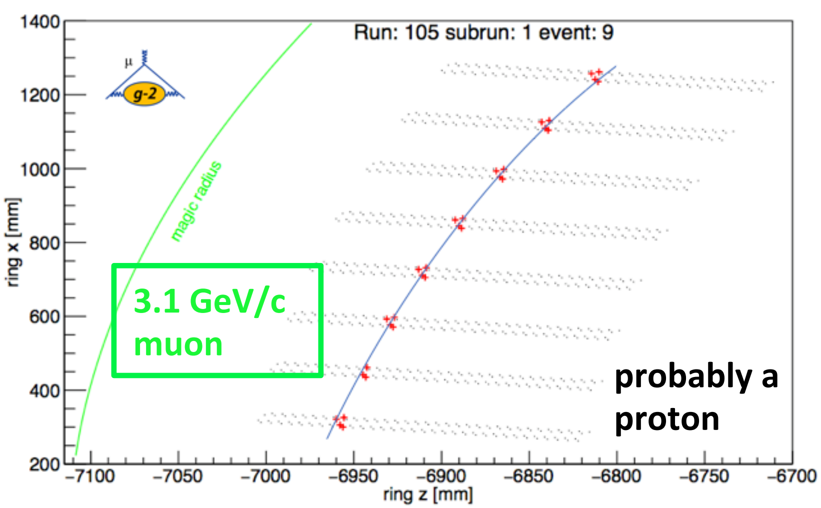


(calorimeter hits) / (total number of tracks) gives calo efficiency: nearly all the missing calo hits look like lost muons.

- **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.**

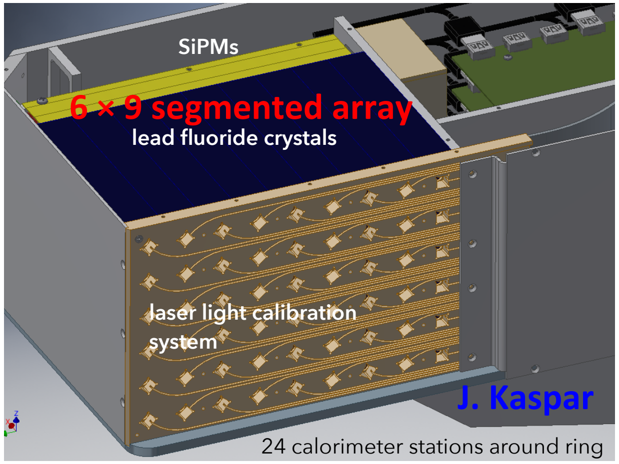
"Wiggle" plot for tracks with momentum greater than 1.8 GeV



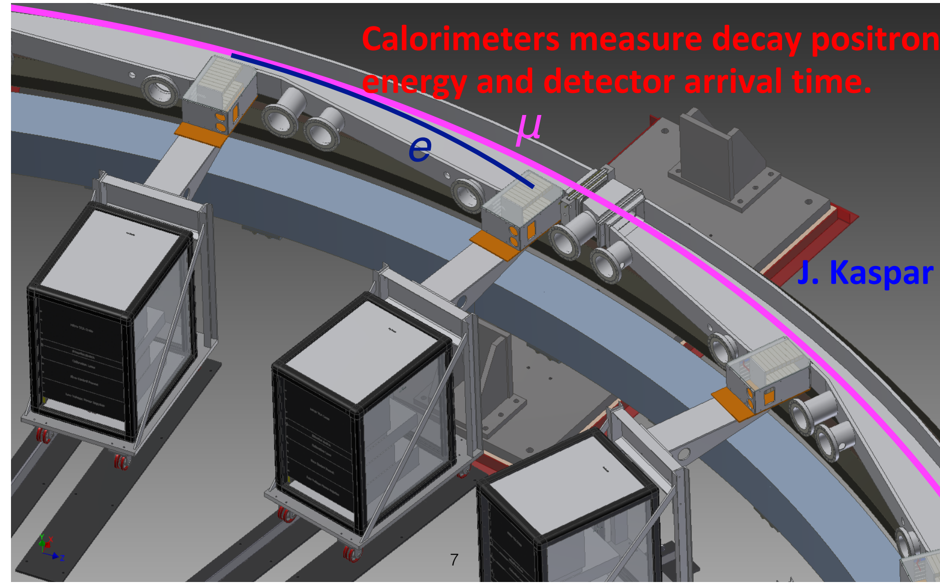


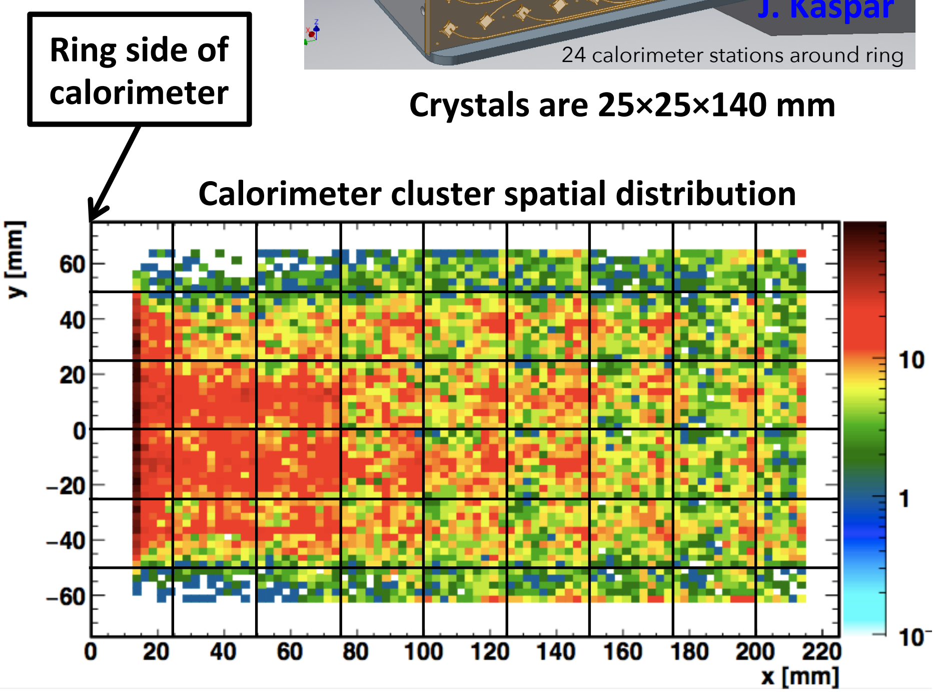
The above June 2017 commissioning data has large proton contamination: 60 p: 4 π: 1 μ

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

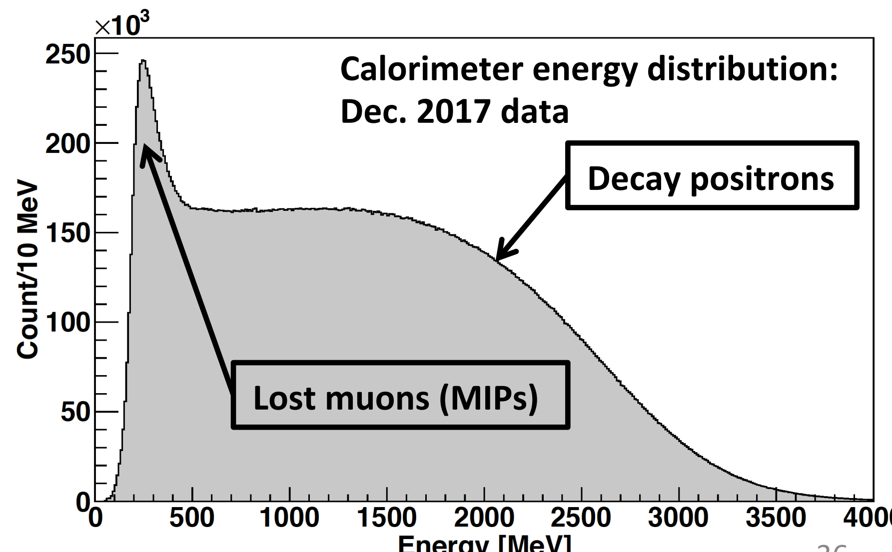


Crystals are 25×25×140 mm





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

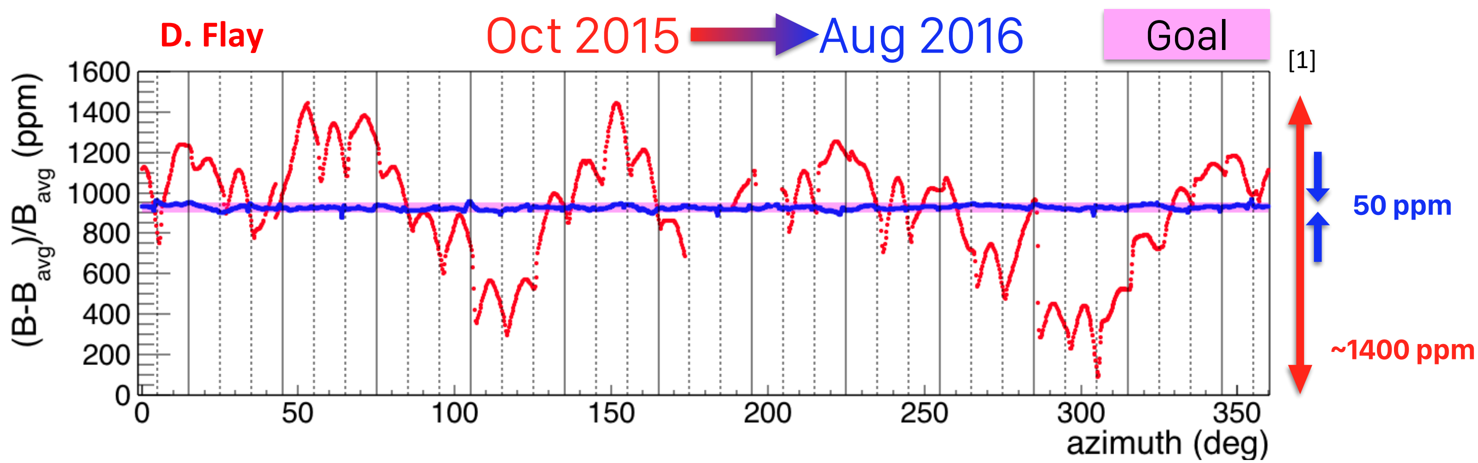


Trolley is used to measure muon storage region magnetic field during data collection.

Rough Shimming Results

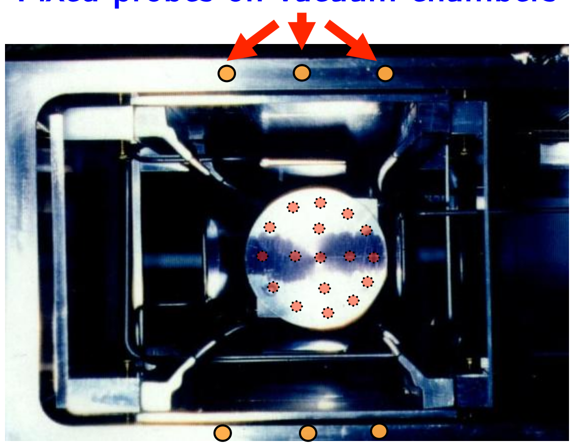
Storage ring field is shimmed to be highly uniform to reduce systematic errors

D. Flay



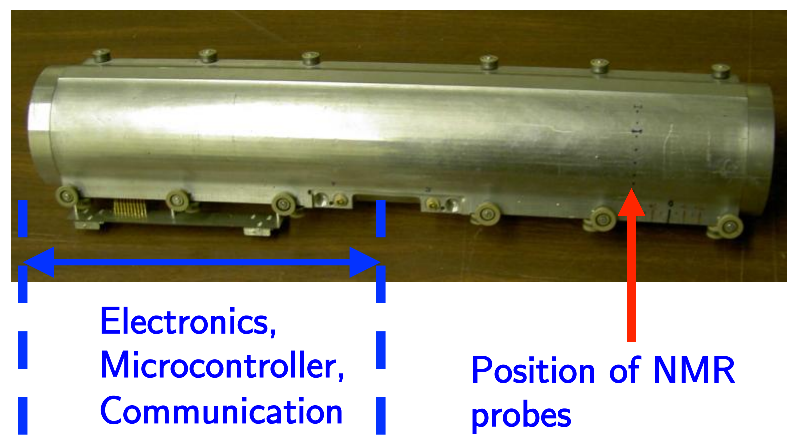
Trolley can be pulled around storage ring when beam is not being delivered.

Fixed probes on vacuum chambers



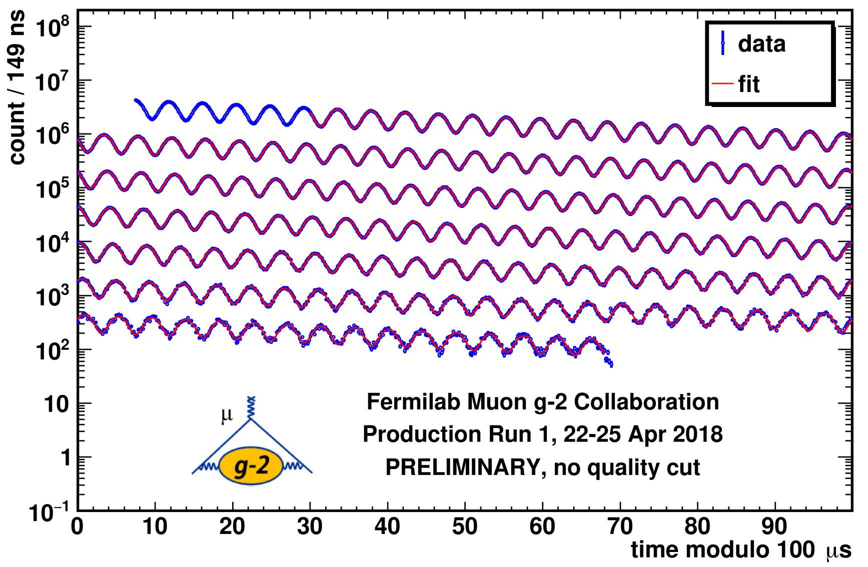
[2]

Trolley with matrix of 17 NMR probes



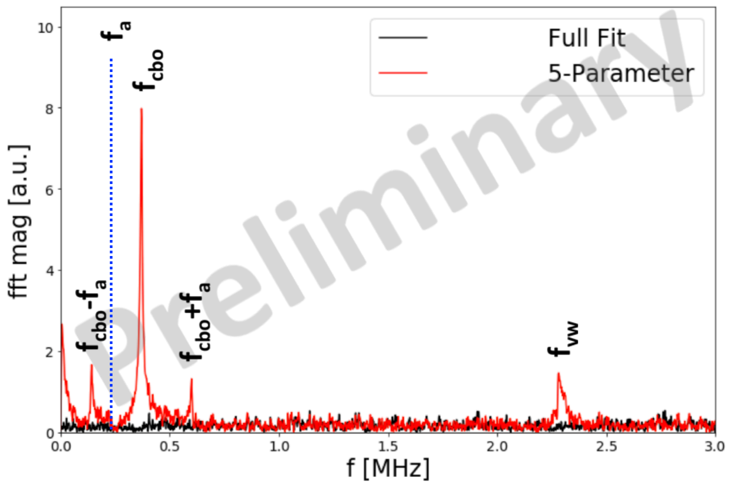
R. Hong

Run-1 ω_a analysis:



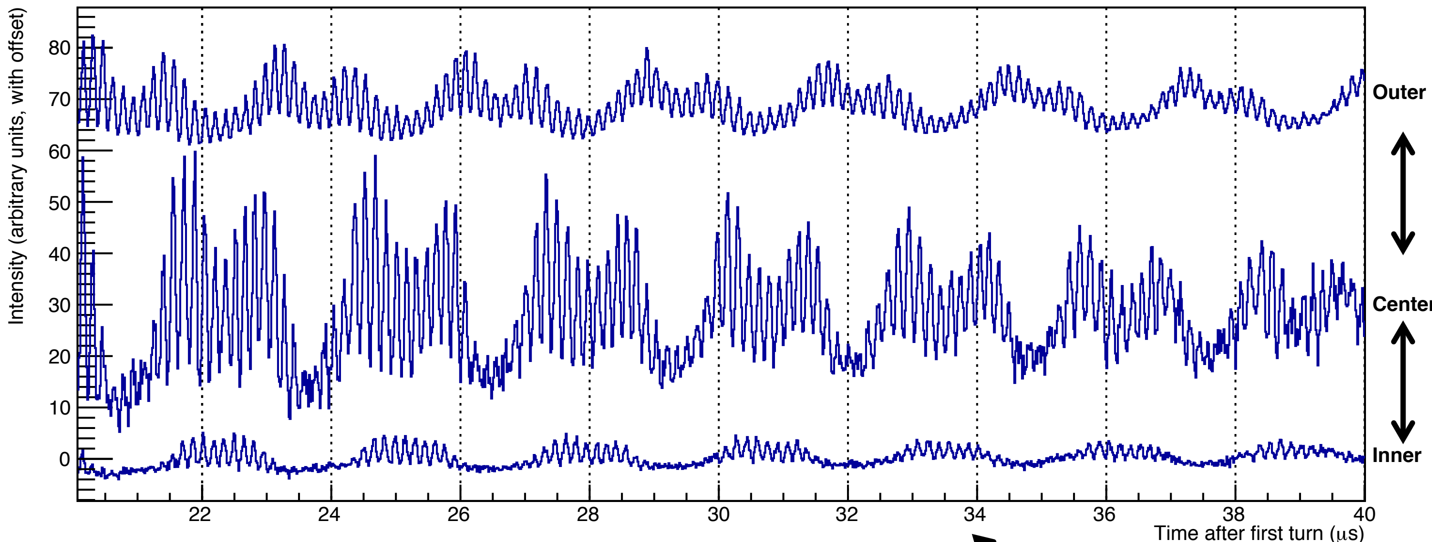
Example fit function:

$$N(t) = N_0 \Lambda(t) N_{cbo}(t) N_{vw}(t) e^{-t/\tau}$$
$$\cdot \left\{ 1 + A_0 \cdot A_{cbo}(t) \cdot \cos\left[\omega_a(R) \cdot t + \phi_0 + \phi_{cbo}(t) \right] \right\}$$



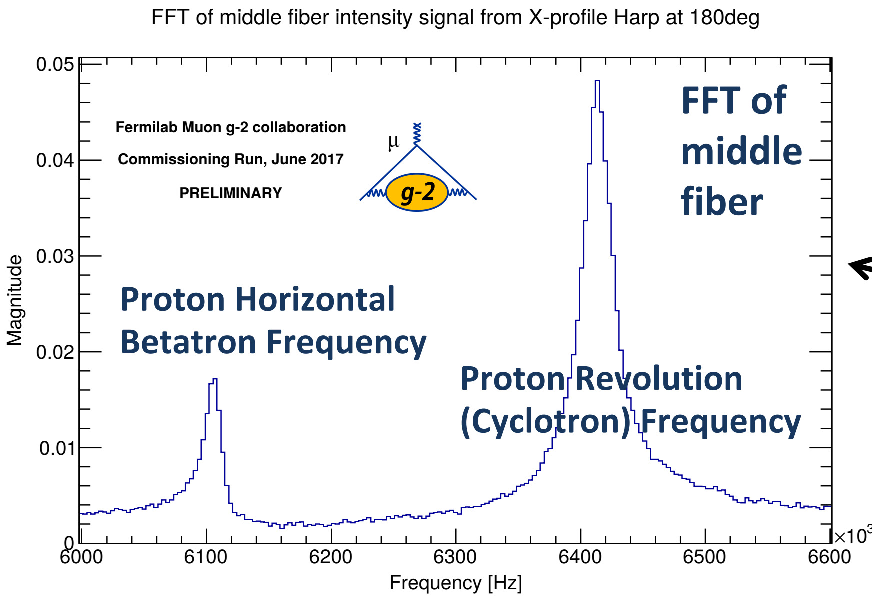
Fiber profile beam monitors (fiber harps) study the storage ring beam dynamics.

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



13 mm spatial separation

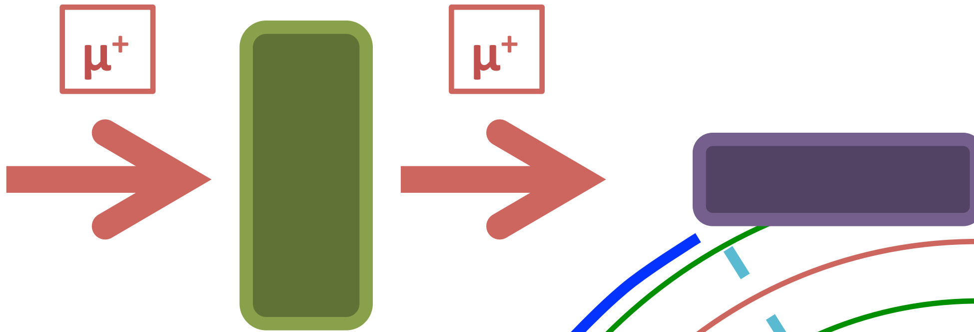
13 mm spatial separation

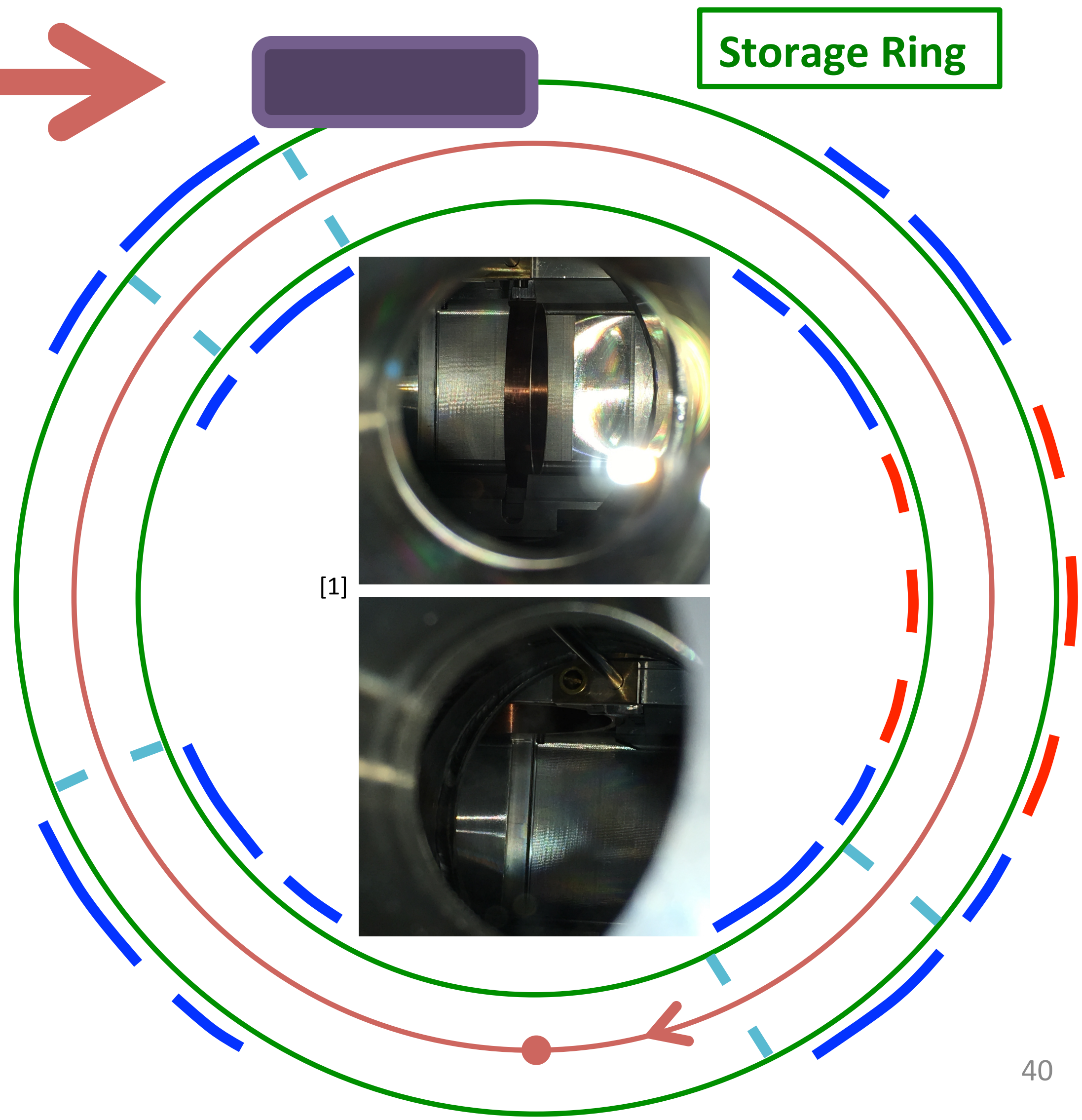


Fiber harps degrade beam, not used when taking physics data.

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

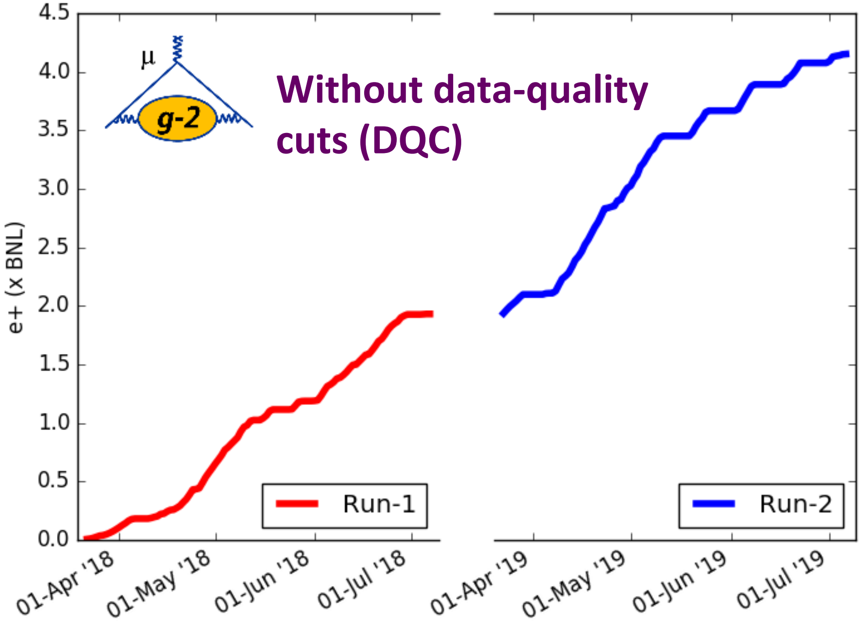
Not to scale

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

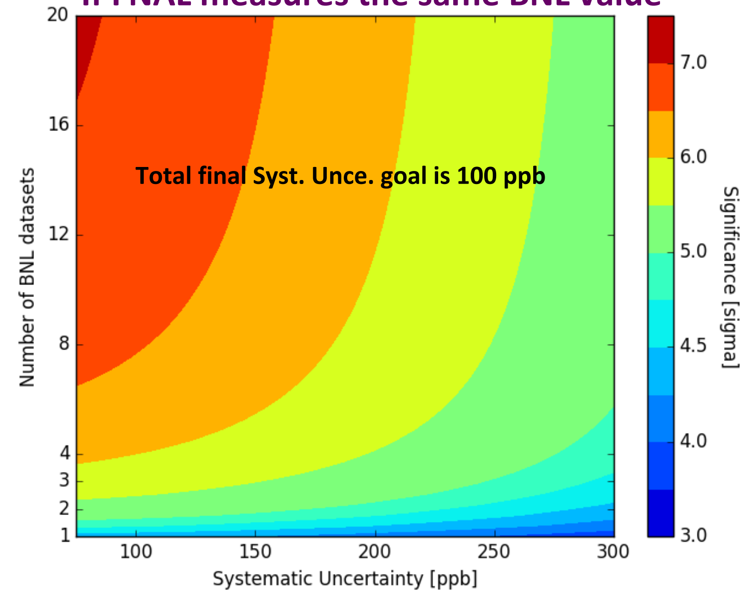
Status of the Fermilab Muon g-2 Experiment:

- Finished Run-1 & Run-2; looking at data!
- Currently in a Summer shutdown preparing for Run-3.
- Goal of publishing Run-1 results by the end of the year!

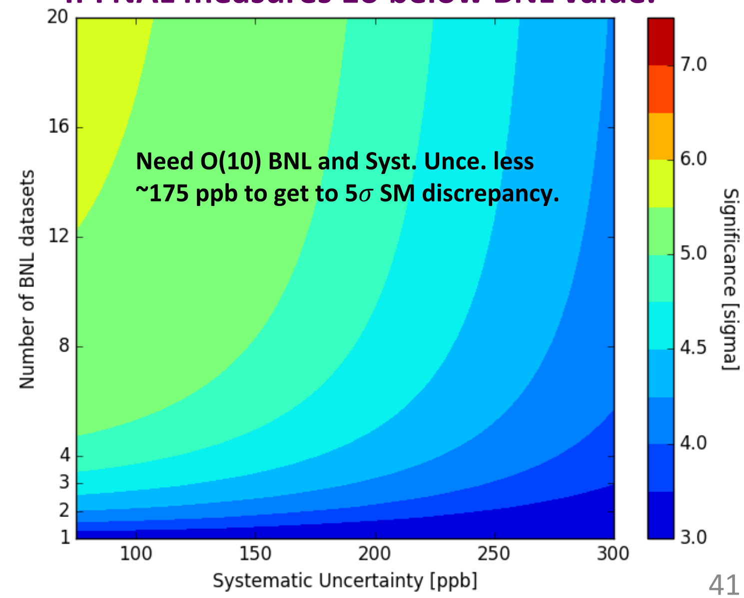
Expect ~1.8×BNL Run-2 dataset vs. ~1.4×BNL Run-1 dataset after Data Quality Cuts.



If FNAL measures the same BNL value



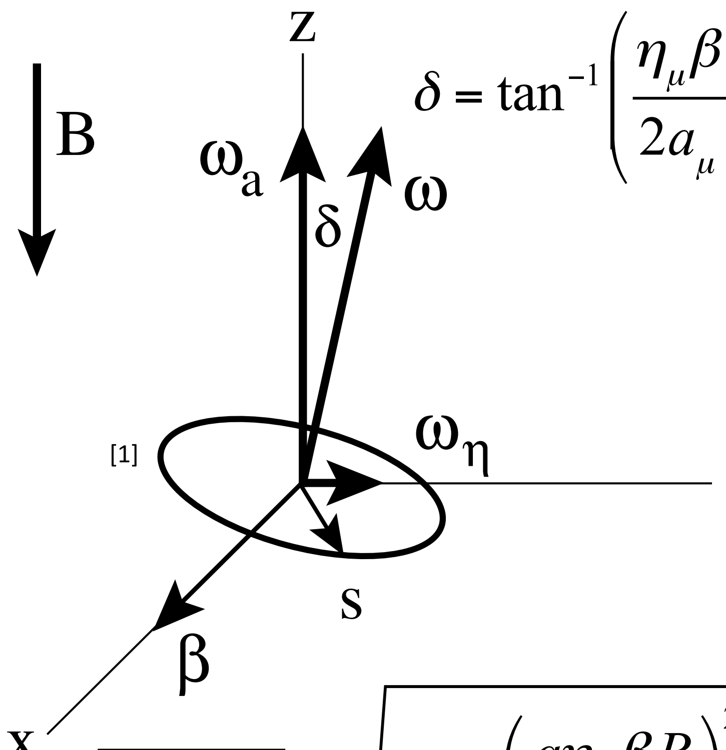
If FNAL measures 1σ below BNL value.



Muon electric dipole moment (EDM) will tilt the spin precession plane.

[1]

- Muon EDM will violate P, T, and CP symmetries.
- Experiment only measures one precession frequency!
- To a good approximation, $\vec{\omega}_a$ is parallel to $\vec{B}$ and $\vec{\omega}_\eta$ points radially in the storage ring.
- Straw Tracker Detectors can measure a tilt in the spin precession plane.
  - From a radial or longitudinal magnetic field component.
  - From a muon EDM.
  - A tilt in the precession plane leads to an up-down asymmetry in the positron angle.



$$\delta = \tan^{-1}\left(\frac{\eta_\mu \beta}{2a_\mu}\right)$$

$$\omega = \sqrt{\omega_a^2 + \omega_\eta^2} \approx \sqrt{\omega_a^2 + \left(\frac{q\eta_\mu \beta B}{2m}\right)^2}$$

B-field contribution dominates over E-field contribution in storage ring.

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

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