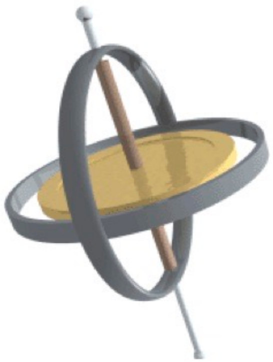
First Results of the Muon g-2 Experiment at Fermilab



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

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

Liang Li

Shanghai Jiao Tong University

Muon g-2 Collaboration

US Universities

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

US National Labs

- Argonne
- Brookhaven
- Fermilab

China

- Shanghai Jiao Tong

Germany

- Dresden

Italy

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

Korea

- CAPP/ISB
- KAIST

Russia

- Budker/Novosibirsk
- JINR Dubna

United Kingdom

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

May 27-31, 2019
Elba Collaboration Meeting

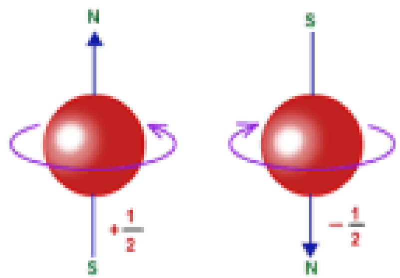
What is g-factor?

Spin, magnetic momentum, g-factor

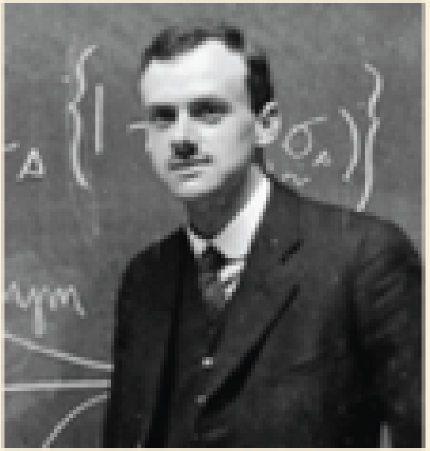
- **Intrinsic magnetic momentum for any (charge) particle with spin S**
- **g-factor dictates the relationship between momentum and spin, tells something fundamental about the particle itself (and those interacting with it)**
  - **Classical system → g = 1**
  - **Elementary particles such as electrons → g = 2**
  - **Composite particles such as protons → g != 2**
    - **proton g=5.6, neutron g=-3.8**
- **It provides a unique prospective to analyze the particle without 'breaking' it: observe and learn!**

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

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



Why g=2 or not?



Paul Dirac

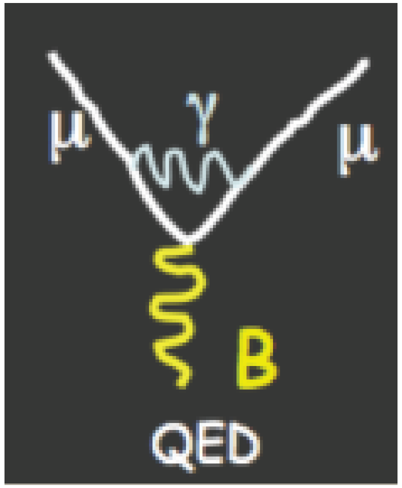
$$\left(\gamma^{\nu}(p_{\nu} - \frac{e}{c}A_{\nu}) - mc\right)\psi = 0$$

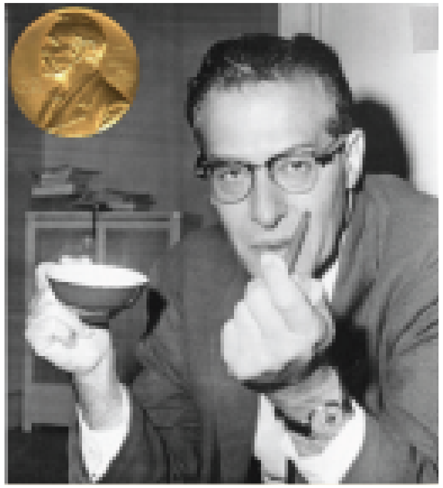
$$i\frac{\partial\psi}{\partial t} = \left[\frac{1}{2m}(\vec{p} - e\vec{A})^2 - 2\frac{e}{2m}\vec{S}\cdot\vec{B}\right]\psi$$

1928 Dirac predicted g=2 for electron

- **Do we really 'see' g=2 as predicted by Dirac?**
- **NO! [1948 Kush and Foley measured g_e = 2.00238(6)]**
  - **Where does this 0.1% deviation comes from?**
  - **Empty space ?!**
- **As it turns out, the space is never 'empty', virtual particles pop in and out within short period – radiative corrections**

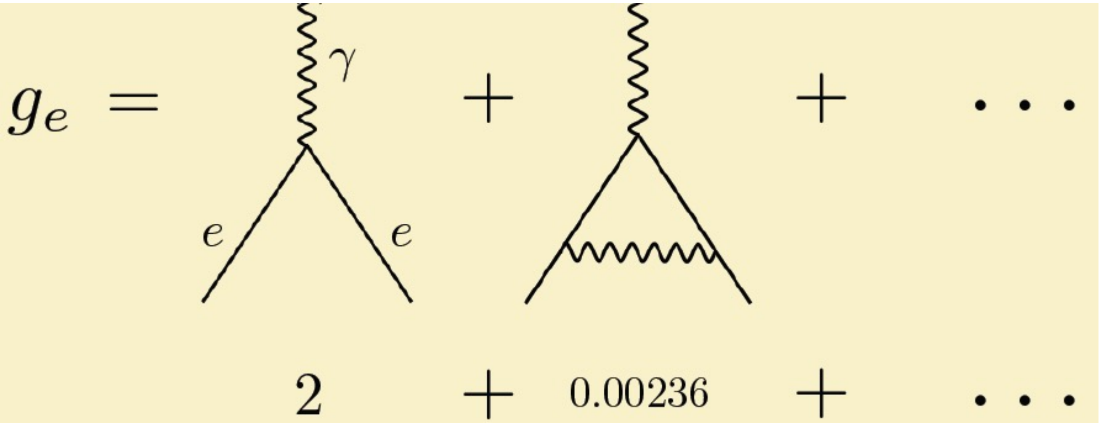
Quantum Corrections



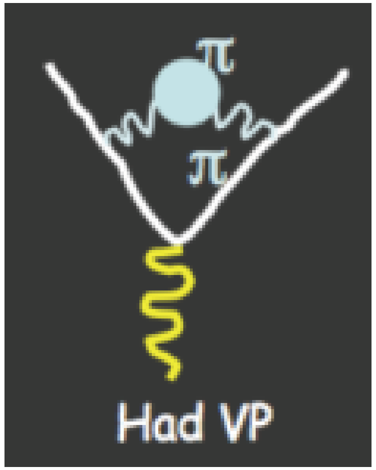


Soon in 1948 Schwinger calculated first order correction

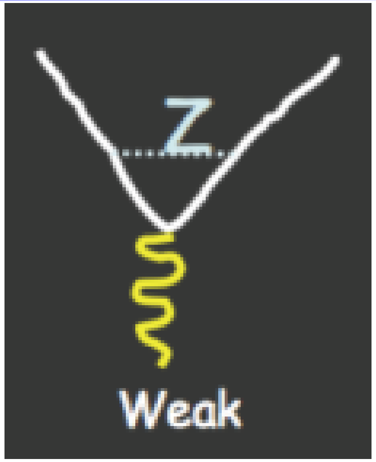
- $a_e = \alpha / 2\pi = 0.00118$
- Compared to experimental value $a_e = 0.00119(5)$
- First order QED: beginning of QED and the Standard Model



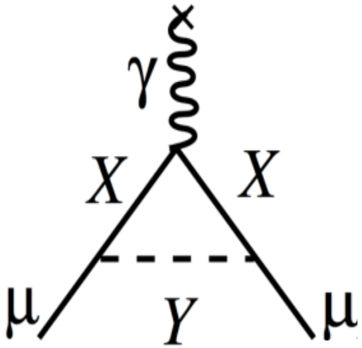
More Quantum Corrections



$$g_{exp} = 2.00233184$$
$$g_{theory} = 2.00233183$$



$$g_{exp} = 2.002331841$$
$$g_{theory} = 2.002331836$$



$$g_{exp} = 2.00233184178$$ (BNL result)
$$g_{theory} = 2.00233183630$$

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{had} + a_\mu^{EW} + \boldsymbol{a_\mu^{NP}}$$

Consider QCD (hadronic) and electroweak corrections

- **Difference seen in theory and experiment values**
- **New correction beyond EW scale? beginning of the Beyond Standard Model?**
- **g-2 is sensitive to new physics**

Muon g-2 Theory: Summary

$$a_\mu = a_\mu(\text{QED}) + a_\mu(\text{Weak}) + a_\mu(\text{Hadronic})$$

QED

+… $116\,584\,718.9\,(1) \times 10^{-11}$ 0.001 ppm

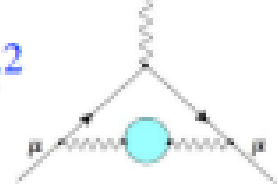
Weak

+… $153.6\,(1.0) \times 10^{-11}$ 0.01 ppm

Hadronic…

…Vacuum Polarization (HVP)

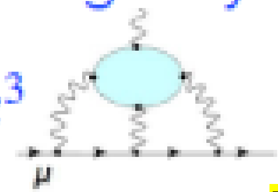
α^2



+… $6845\,(40) \times 10^{-11}$ [0.6%] 0.37 ppm

…Light-by-Light (HLbL)

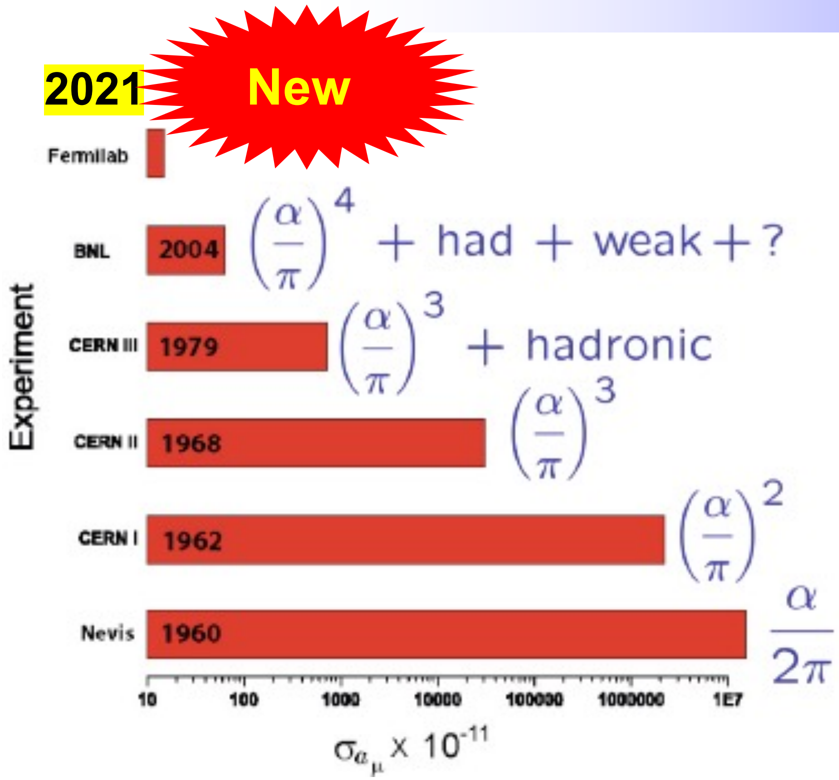
α^3

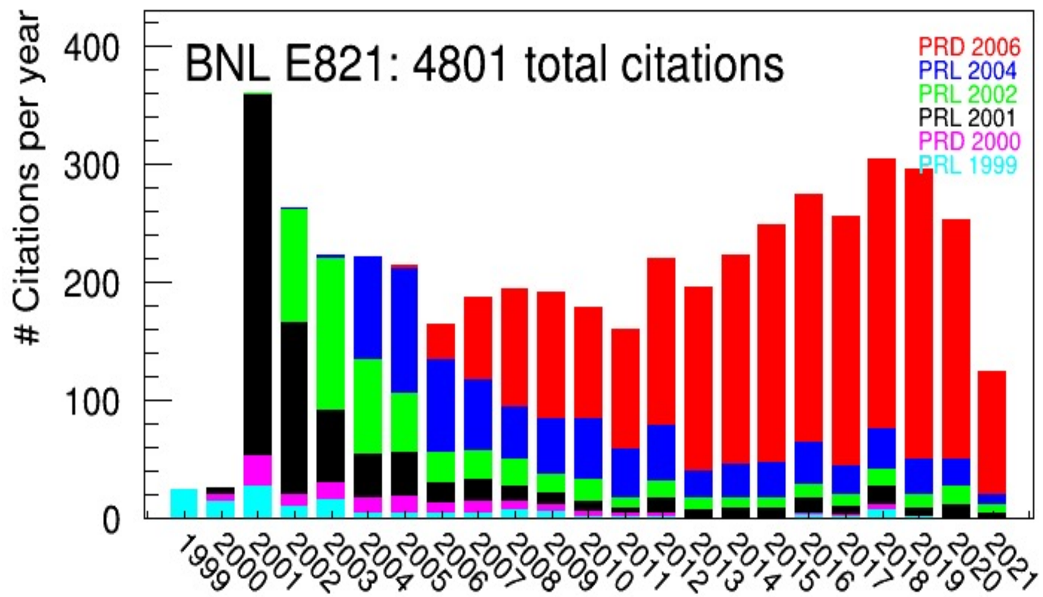


+… $92\,(18) \times 10^{-11}$ [20%] 0.15 ppm

Muon g-2 Theory Initiative: Phys. Rept. 887 (2020) 1-166

Muon g-2 Experiment

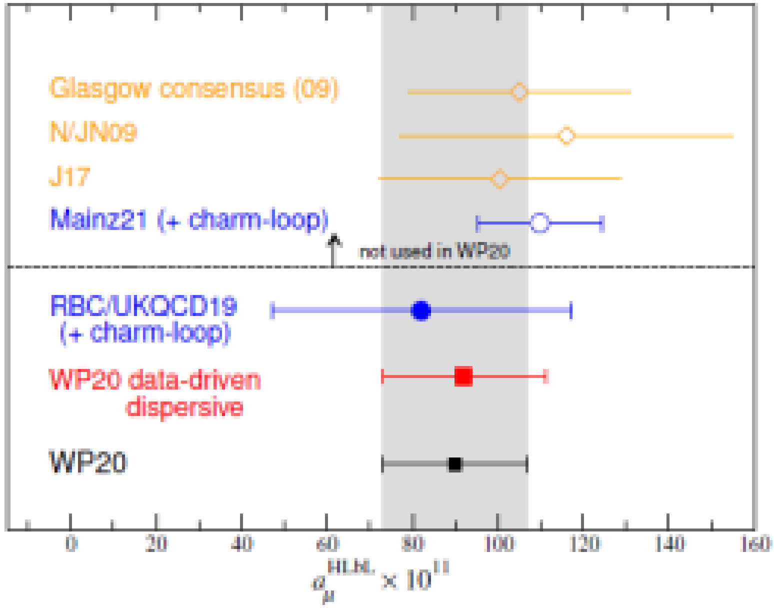


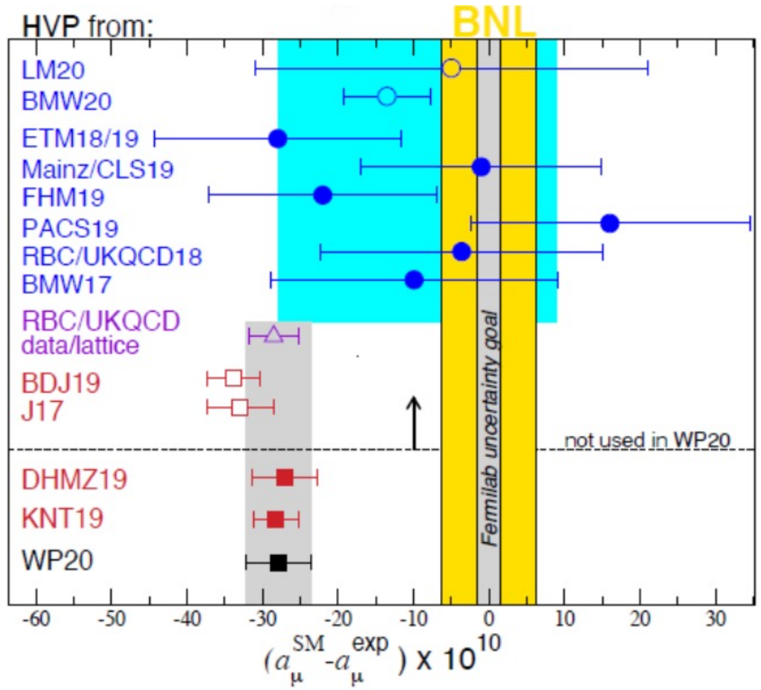


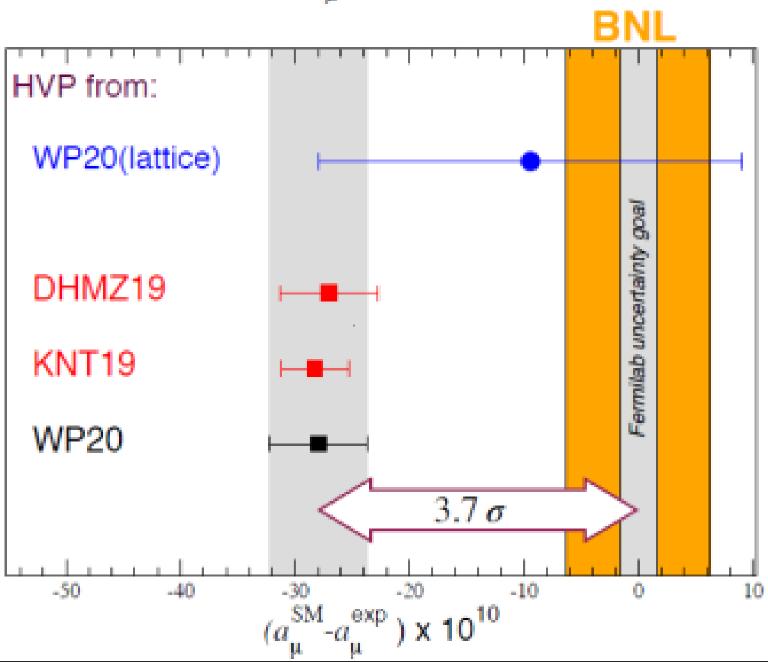
Over 50 years of non-stopping improvement on δa_μ

- **Pushing both theoretical and experimental frontend**
- **Last measurement from BNL E821 (2004) came with 0.54ppm**
- **New muon g-2 experiment at Fermilab aim at 0.14ppm**
- **Very exciting and highly expected measurement!**

Muon g-2 Experiment vs. Theory





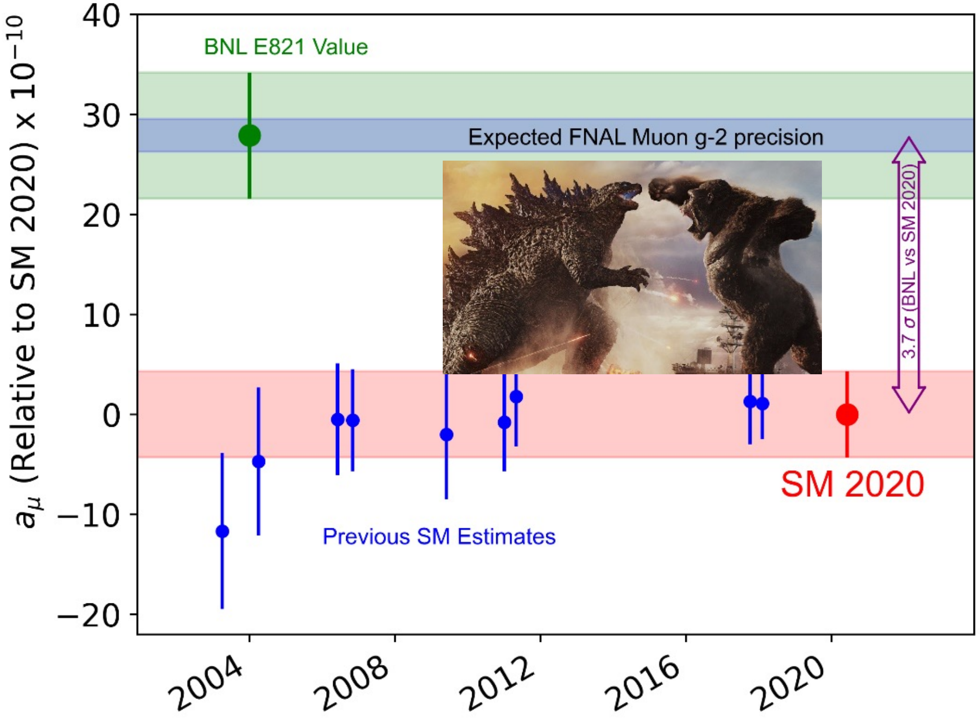


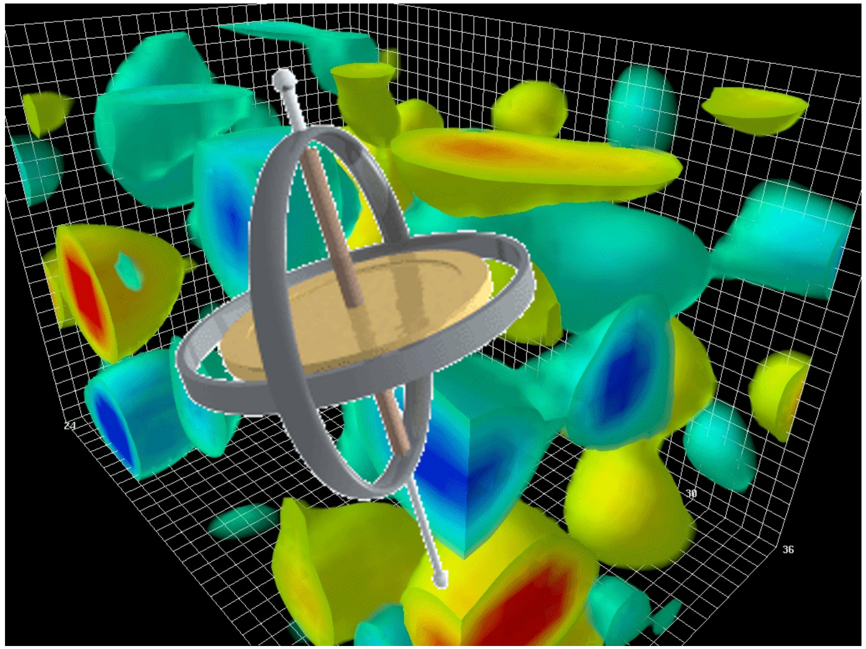
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Weak} + a_\mu^{HVP} + a_\mu^{HLbL} = 116591810\,(43) \times 10^{-11}$$

WP20: world average value of SM calc.

- **Strong theory community consensus**
- **"Recent lattice result by BMW with 0.8% error needs further study"**
- **We (experiment) do not pick and choose theory value to compare**

Muon g-2 Experiment vs. Theory





Latest comparison gives 3.7 σ difference

- **Hint of BSM physics**
- **With improvements in theory calculation and experiment measurements, muon g-2 as a fundamental property can serve as a benchmark test for any new physics, such as dark matter, SUSY…**
- **Or even "Monsters"!**

E821(BNL) vs. E989(Fermilab)

E821 (BNL) : a_μ^{exp} = 116 592 089 (63) X 10^{-11}
Uncertainty: 0.46 ppm stat., 0.28 ppm syst.

Goal: reduce experimental uncertainty by a factor of 4

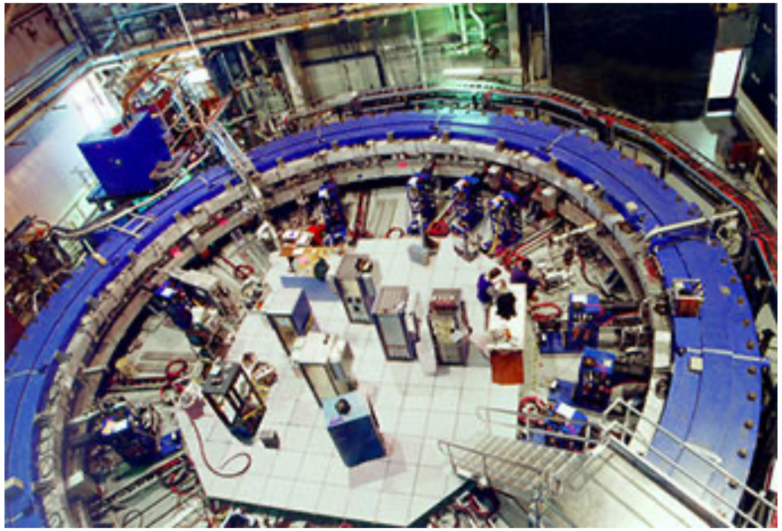
New team: >95% new people

New equipment: new beam + new detector + new monitor probes

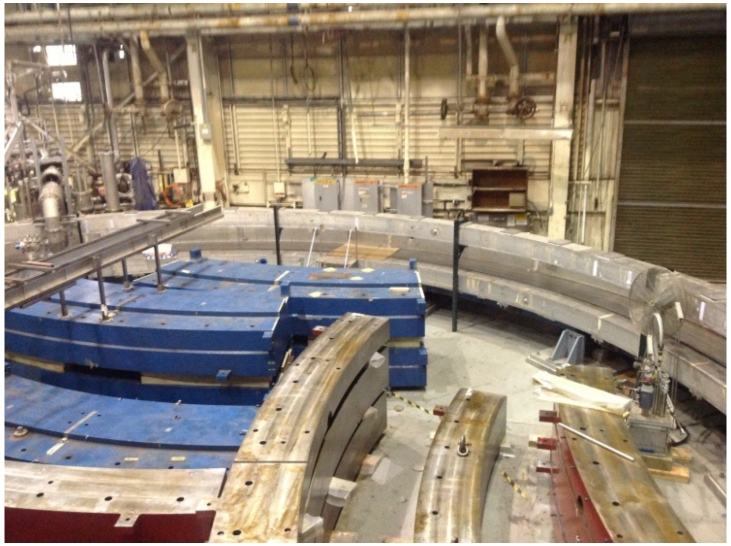
- 21 times more statistics: powerful Fermilab particle source
  - δ_{stat} = 0.46 ppm → 0.1 ppm
- New segmented calorimeters, straw wire tracker, fast muon kicker…
  - $\delta\omega_a$ = 0.21 ppm → 0.07 ppm
- Long shimming period, magnet temperature stability, more/better in-situ calibrations, more probes, modern instrumentation…
  - $\delta_{<B>(\omega_p)}$ = 0.17 ppm → 0.07 ppm

E989 (Fermilab) expected experimental uncertainty:
0.14ppm ~ 16 X 10^{-11}
> 5σ deviation with the same central value

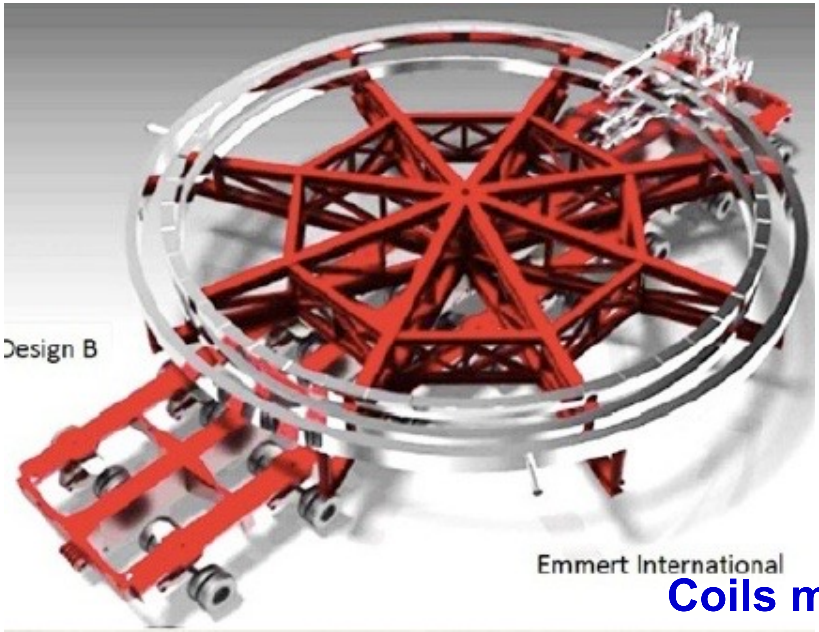
The Big Move of The Big Ring



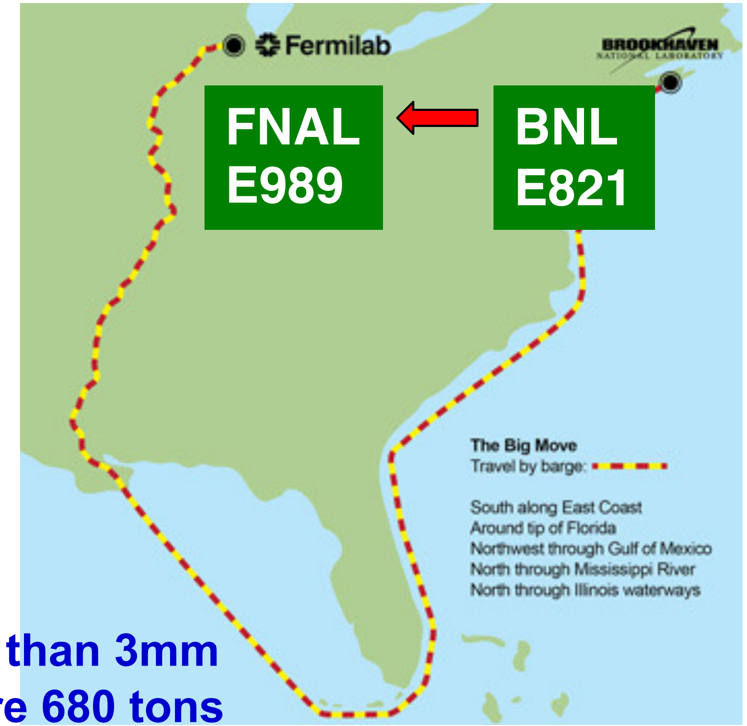
Disassembly



- $2-3M to move
- >10x more to rebuild
- Time & effort

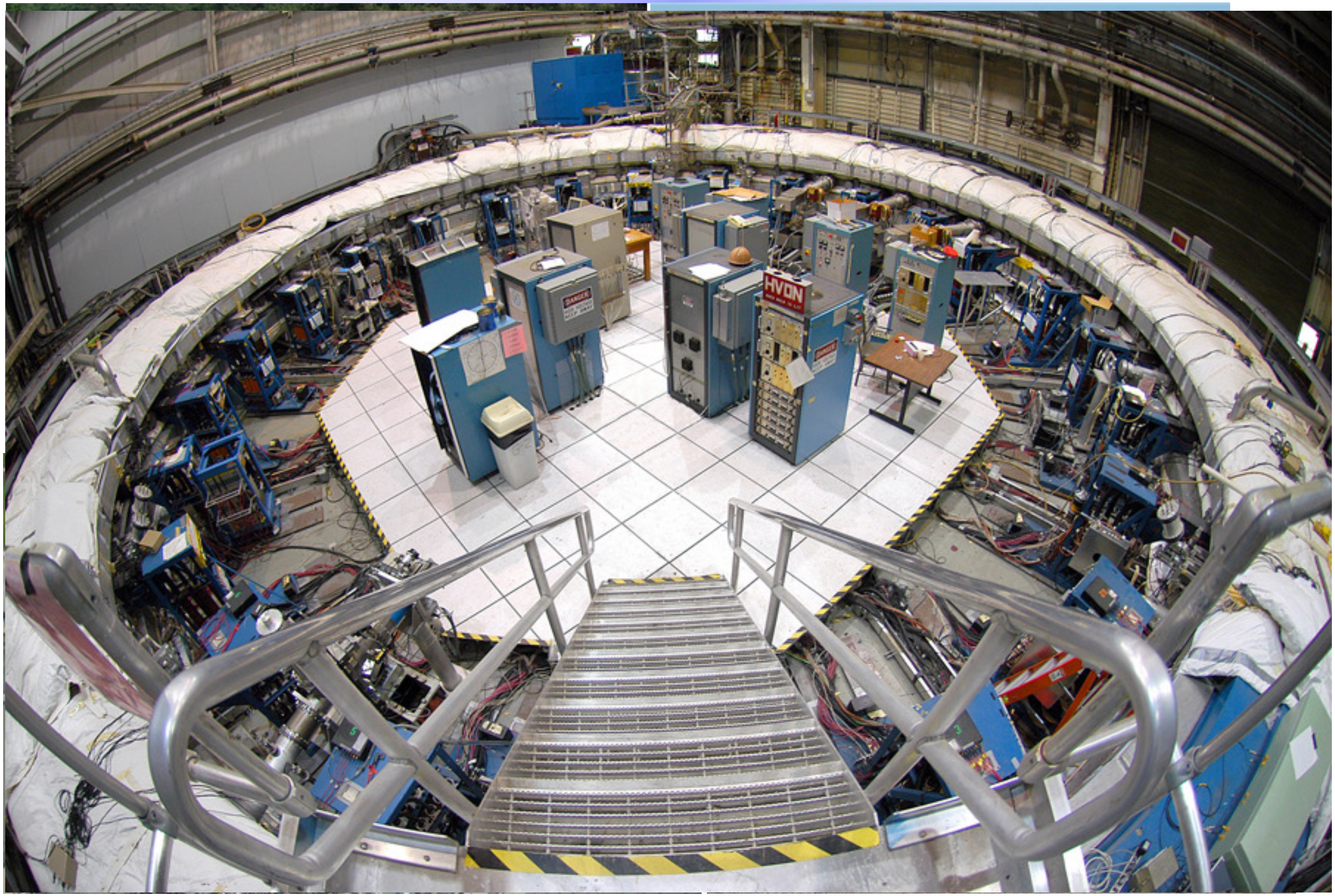


The Big Move

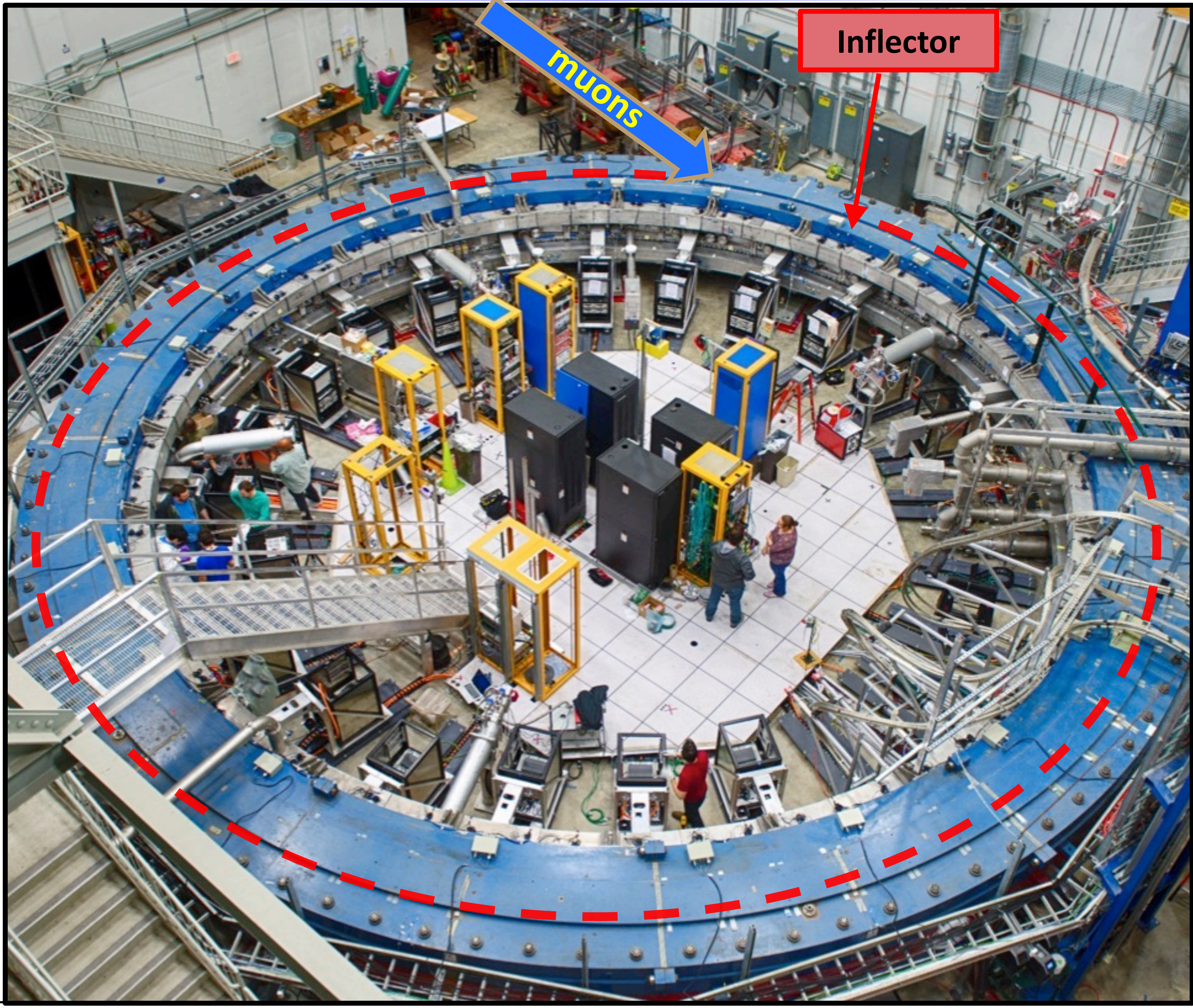


Coils must not flex more than 3mm
Ring 570 tons, with fixture 680 tons

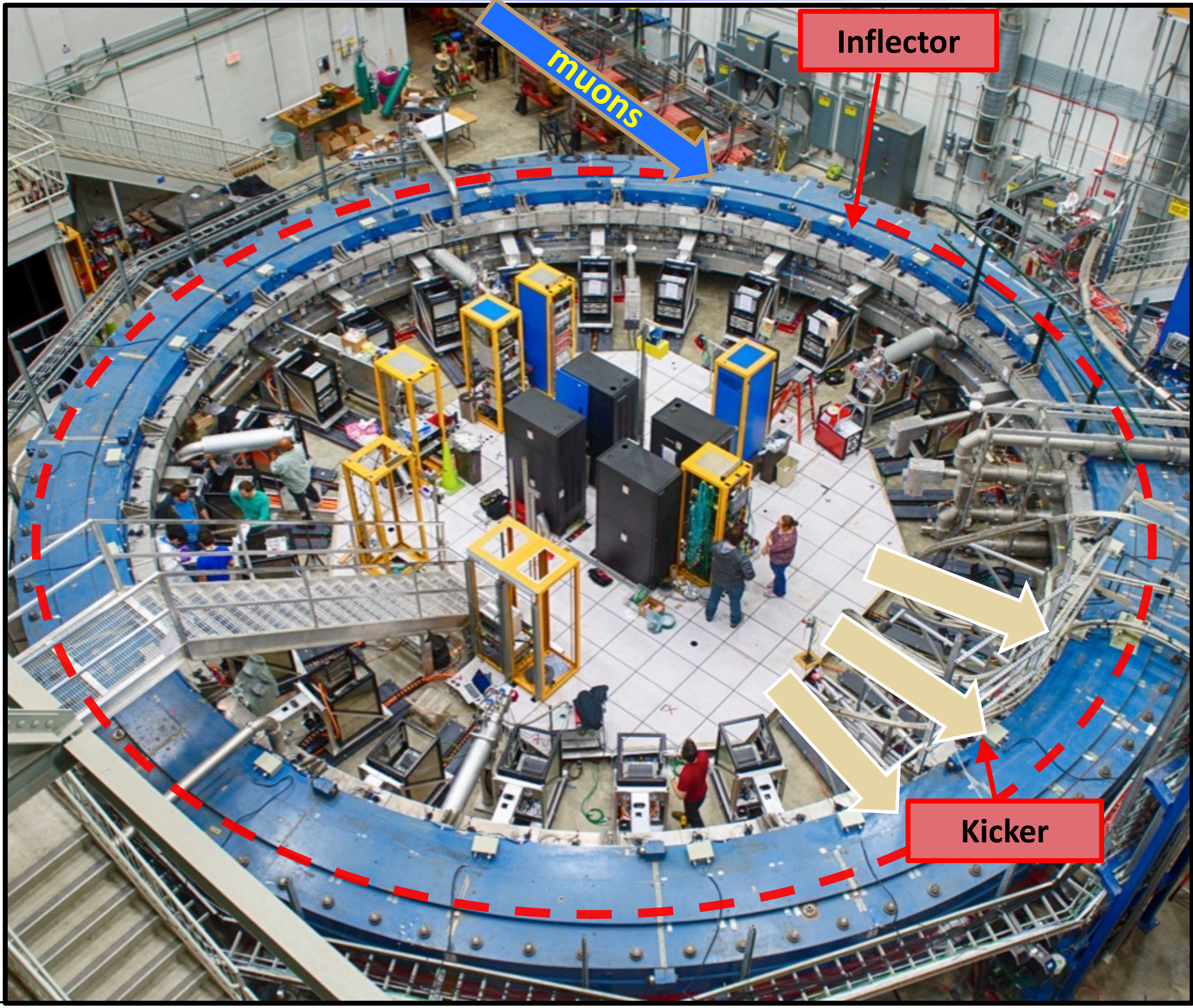
Arriving at Fermilab



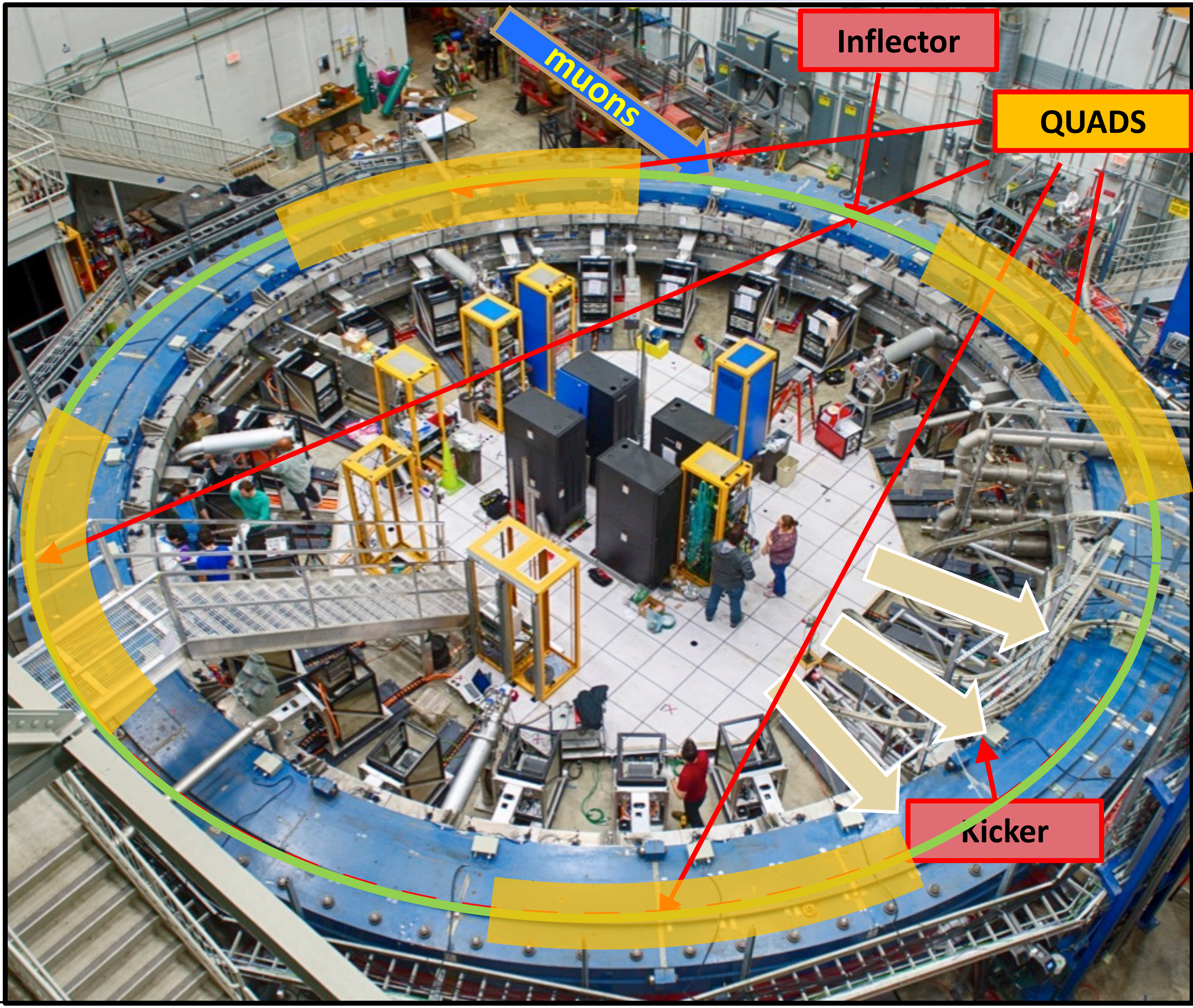
Injection into muon storage ring



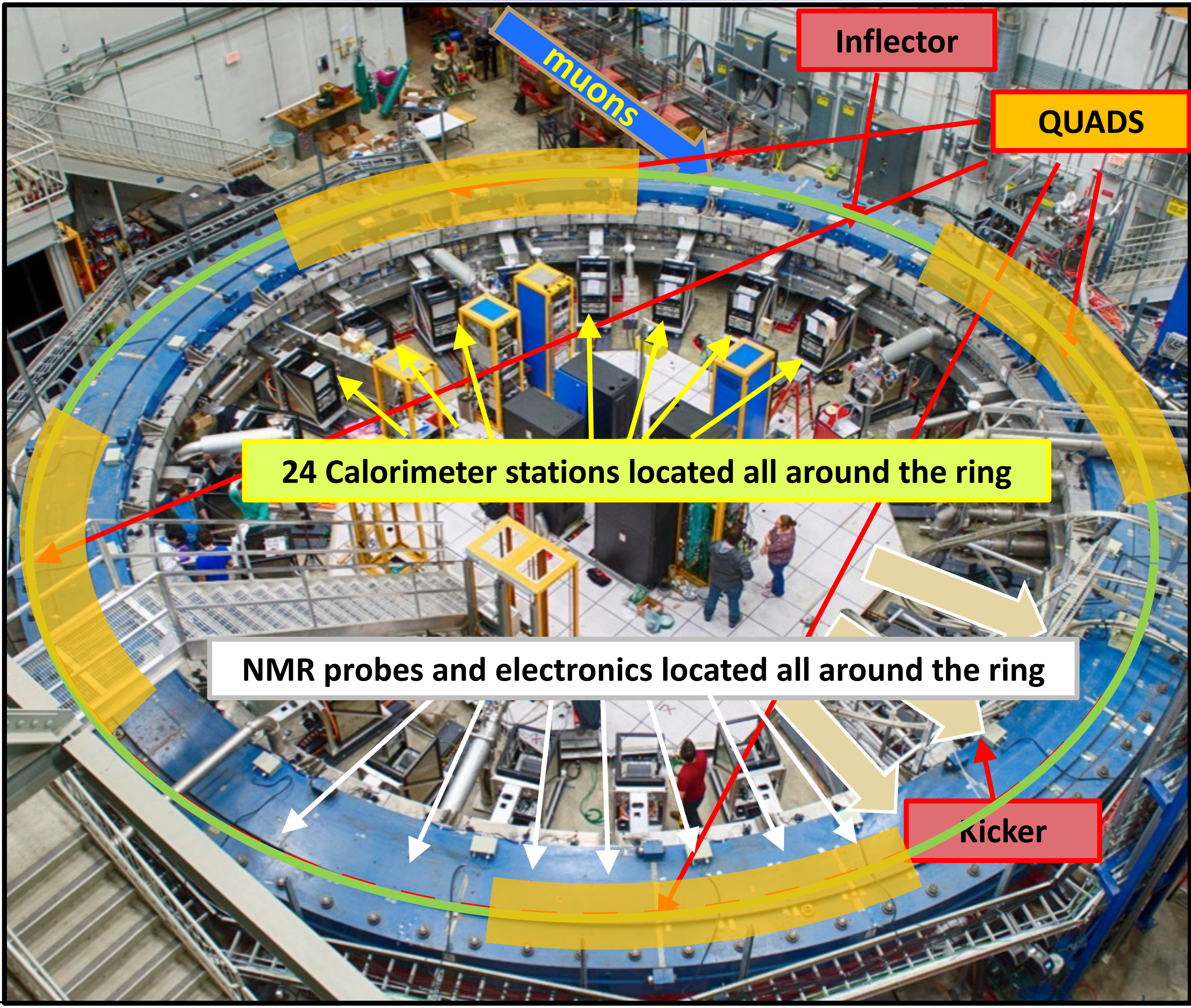
Injection into muon storage ring



Injection into muon storage ring



Injection into muon storage ring

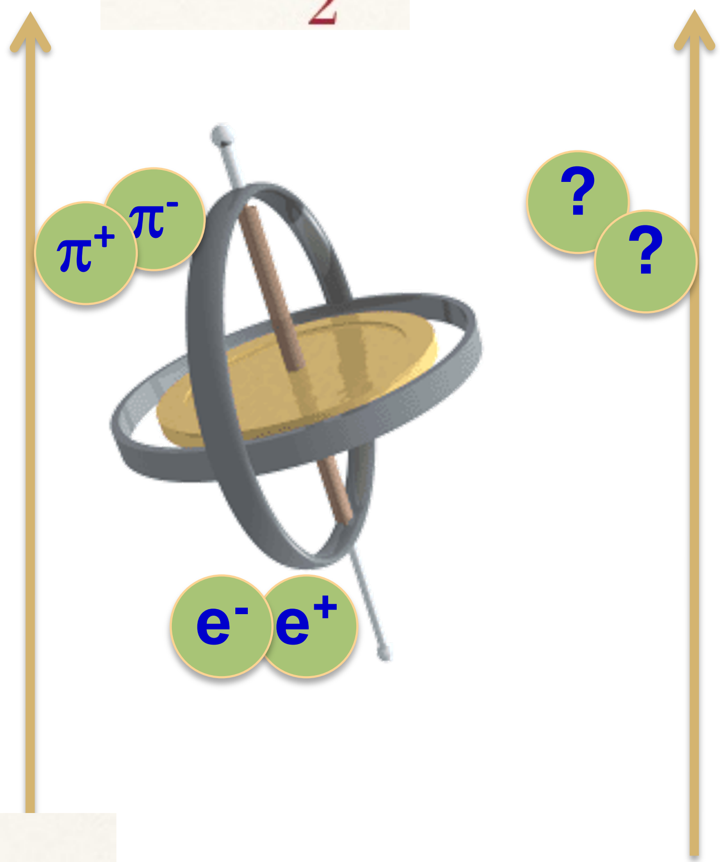


Experimental: How to Measure?

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

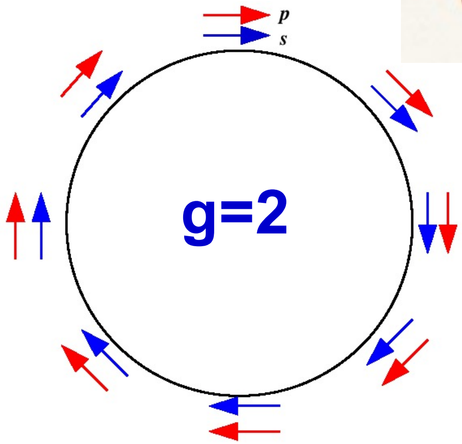
The name of game changes: a → ω

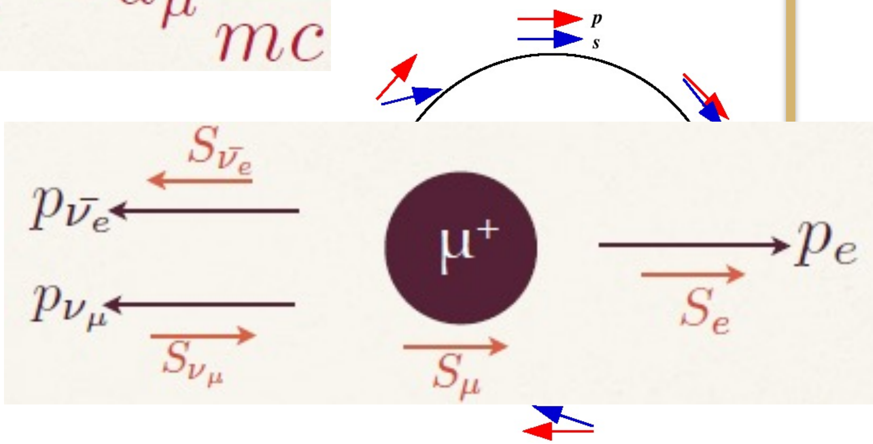
- **Put (polarized) muons in a magnetic field and measure precession f.q.**
- **Get muon spin direction from decayed electrons**
- **a_μ ~ difference between precession frequency and cyclotron frequency**



$$\omega_a = \omega_s - \omega_c$$

$$\omega_a = a_\mu \frac{eB}{mc}$$





$$\omega_s = g\frac{eB}{2mc}$$

Frequency Measurements

Never measure anything but frequency!

Arthur Schawlow
1981 Nobel Laureate

Frequency Measurements

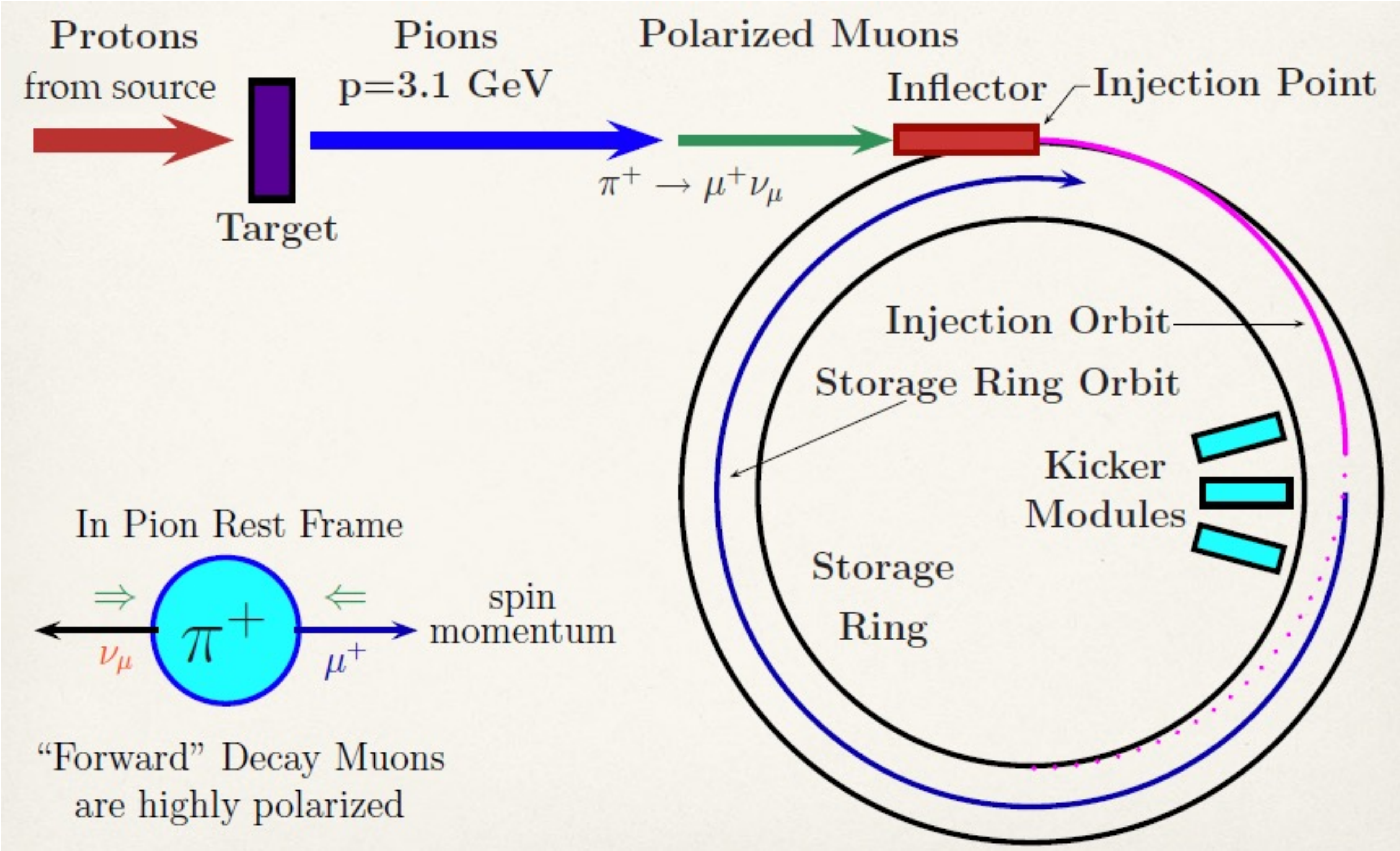
Frequency measurements can be done in very high precision

- **Measure frequency ratio and extract from several measurements**

$$a_\mu \sim \frac{\omega_a}{<B>} = \frac{g_e}{2}\frac{\omega_a}{\varpi_p}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}$$

  - ω_p is the proton precession frequency ($\omega_p \sim |B|$)
  - ϖ_p is the weighted magnetic field folded with muon distribution
  - All other values from Committee on Data for Science and Technology (CODATA), uncertainty < 25 ppb
    - E.g. muon-to-electron mass ratio by muonium hyperfine structure experiment
- **Final measurements done in three steps**
  - Inject muons into a ring with uniform magnetic field
  - Measure muon frequency difference ω_a
  - Measure proton precession frequency ω_p and muon distribution
  - Blind analyses: measurements and correction factors done *before* simultaneously and independently *before* final answer

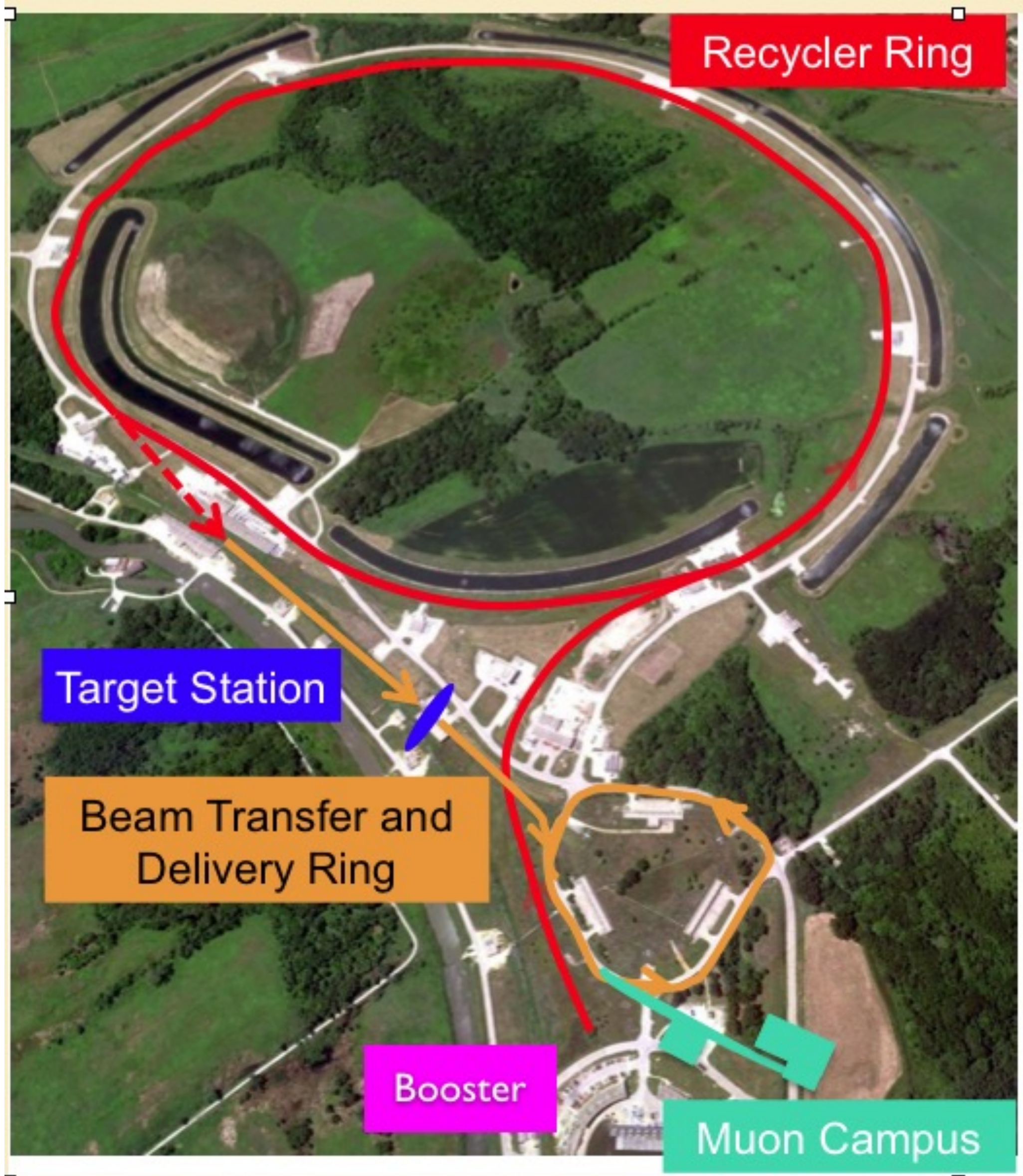
Experiment Setup



Muon Campus Plan

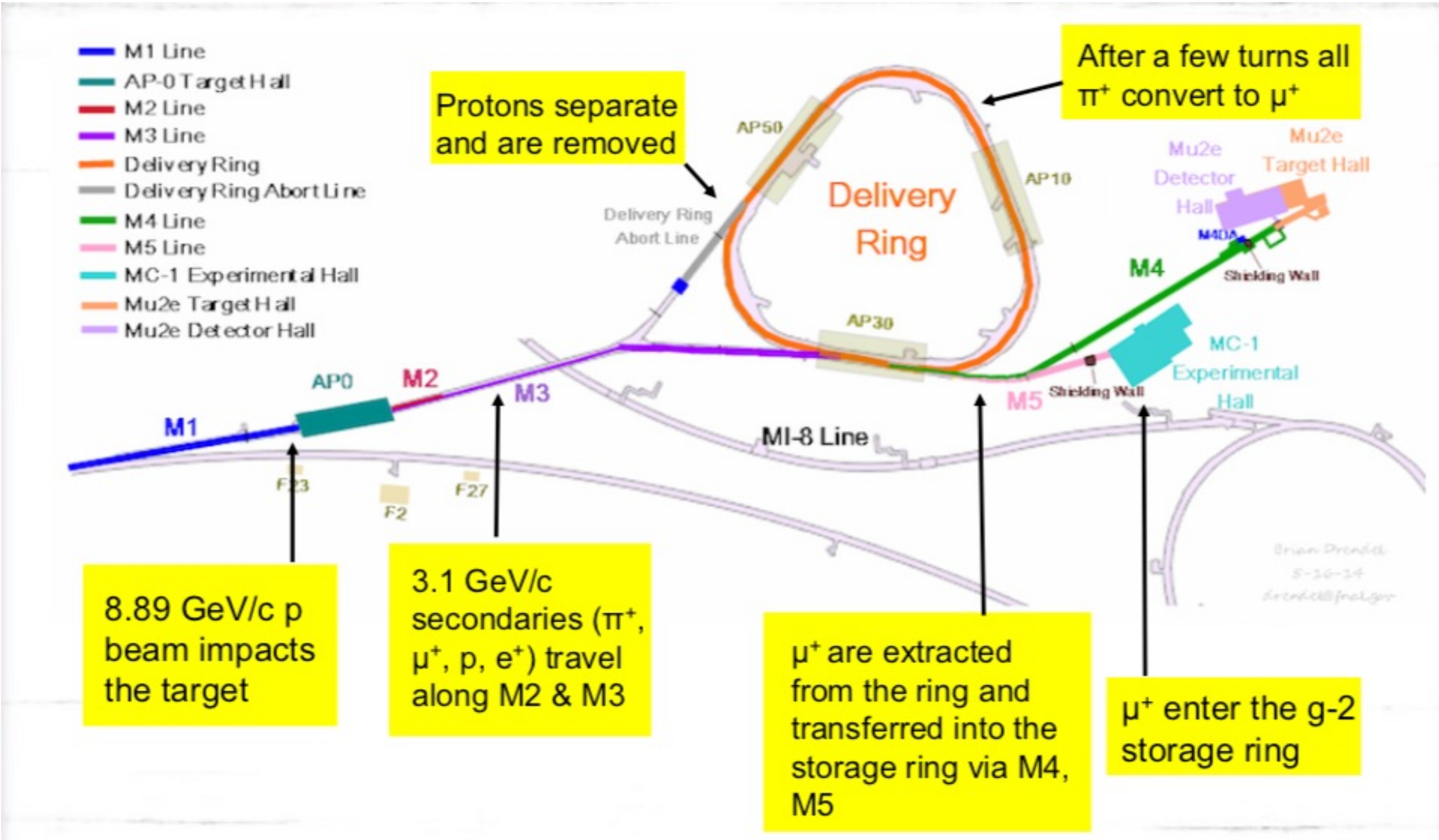
Muon Campus and MC1

Muon Campus

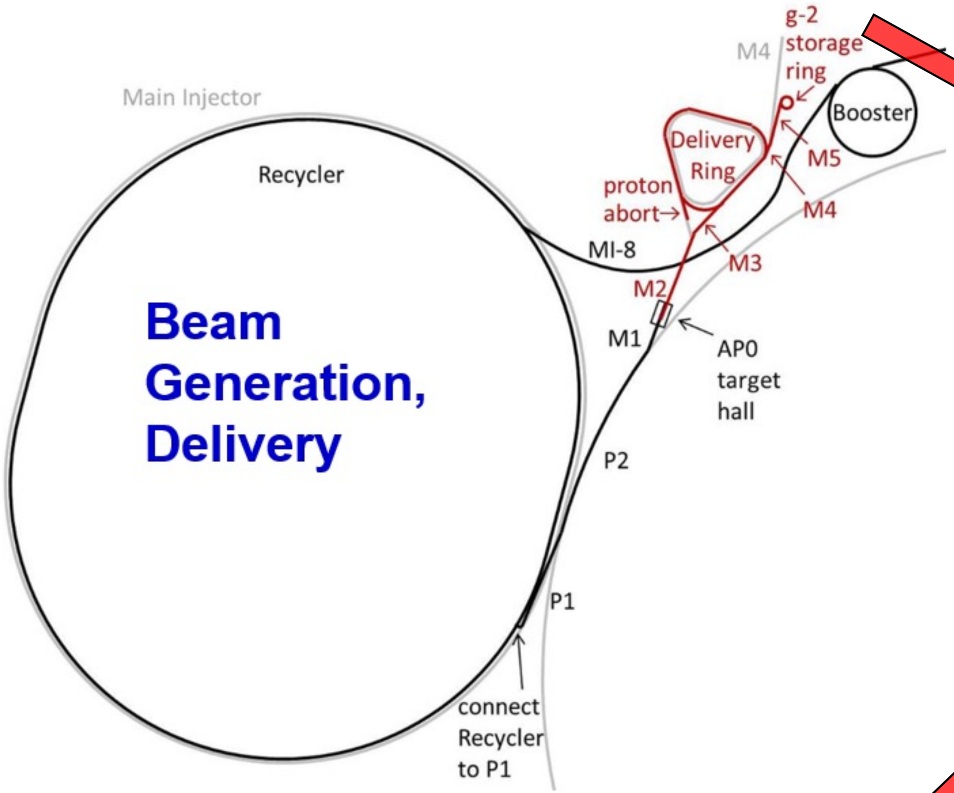


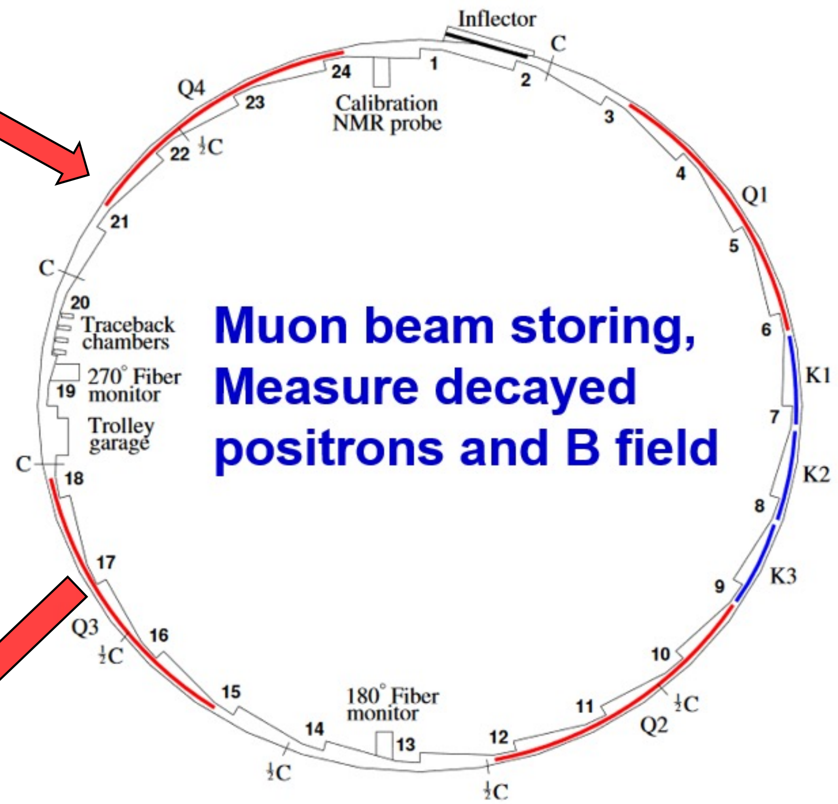
- **Source** generates 35 keV H^- ion beam.
- **Linac** accelerates H^- ion beam to 400 MeV and strips e-
- **Booster** accelerates protons from 400 MeV to 8GeV
- MI-8 Line takes the beam from the booster to the Recycler
- **Recycler** splits a batch from the booster into 4 bunches small enough to fit in the storage ring
- Beam strikes **target** to create pions
- M2/M3 lines take the pion/muon/proton beam from **target** to **delivery ring**
- Pions decay in the **delivery ring** - protons are kicked out
- M4/M5 lines then take the muon beam to **MC1**

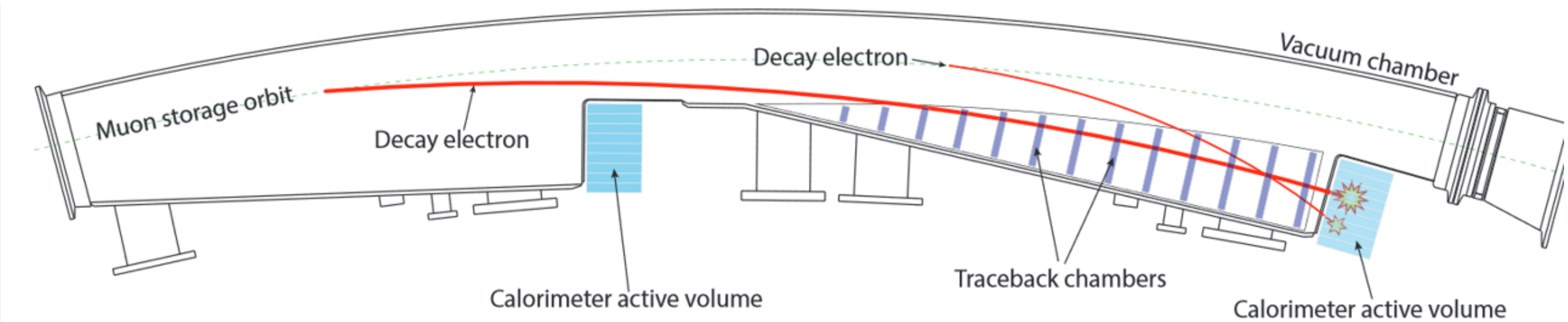
Muon Storage



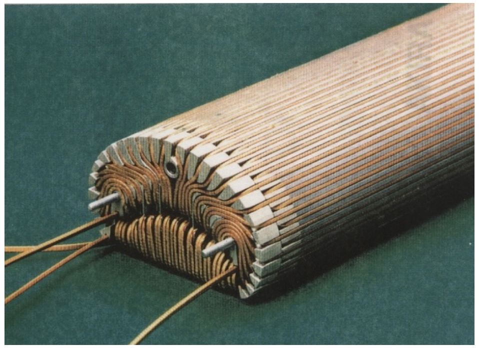
Muon Storage



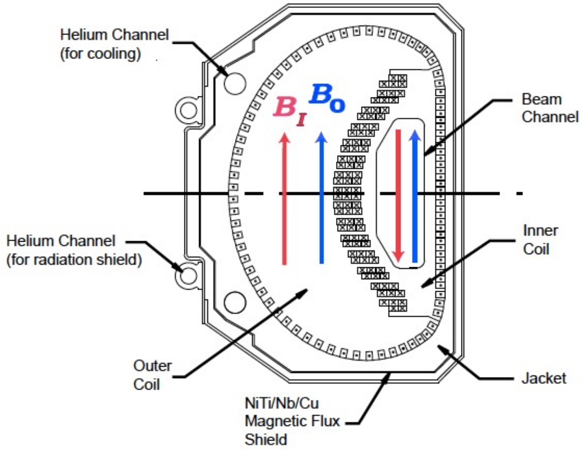


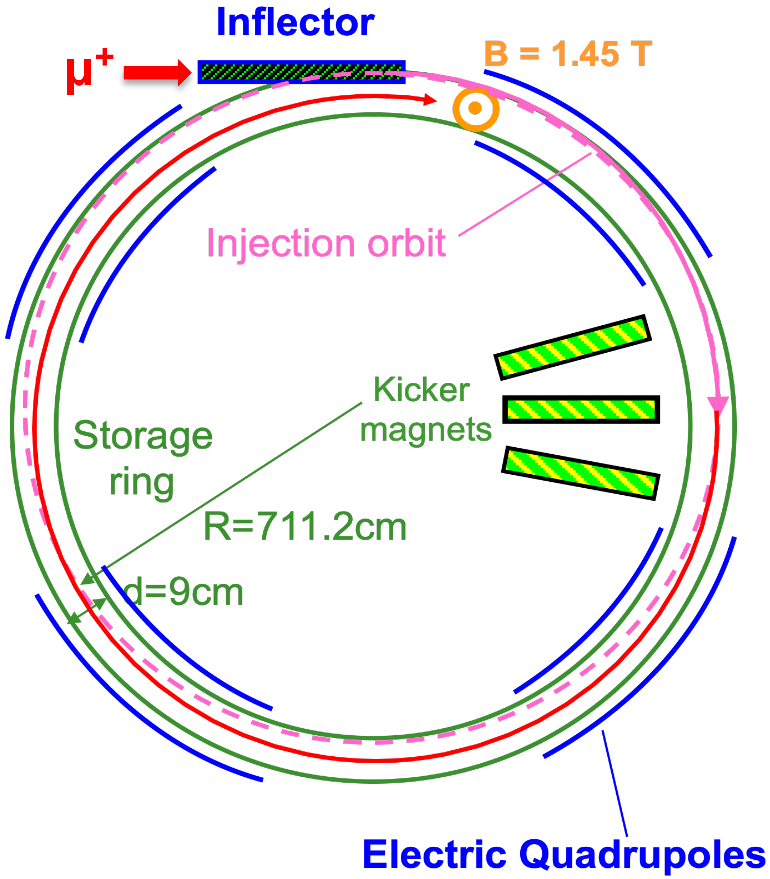


Muon Injection and Storage System



Truncated double cosine theta superconducting septum magnet

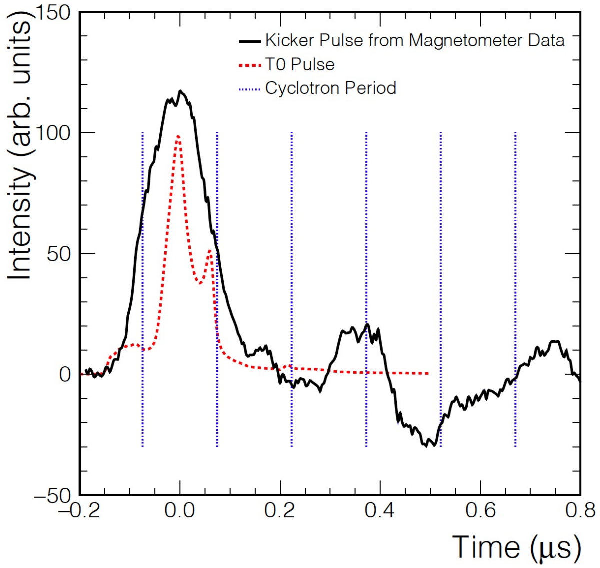


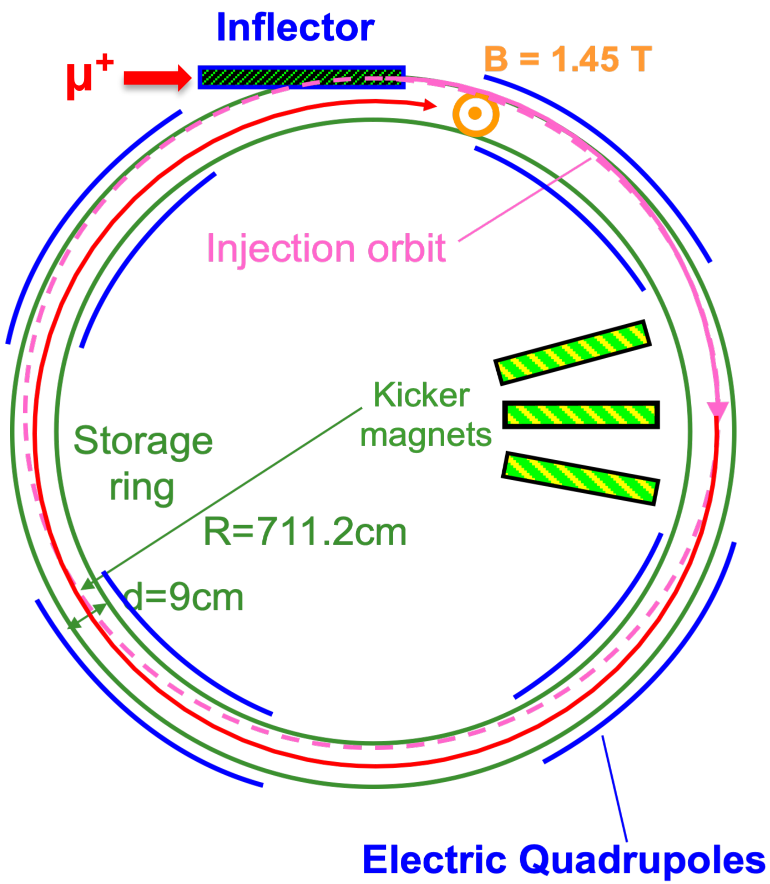


Superconducting inflector

- Provides nearly field free region for muons to enter the ring
- Beam injected through magnet windings
- Does NOT perturb main precision field

Muon Injection and Storage System

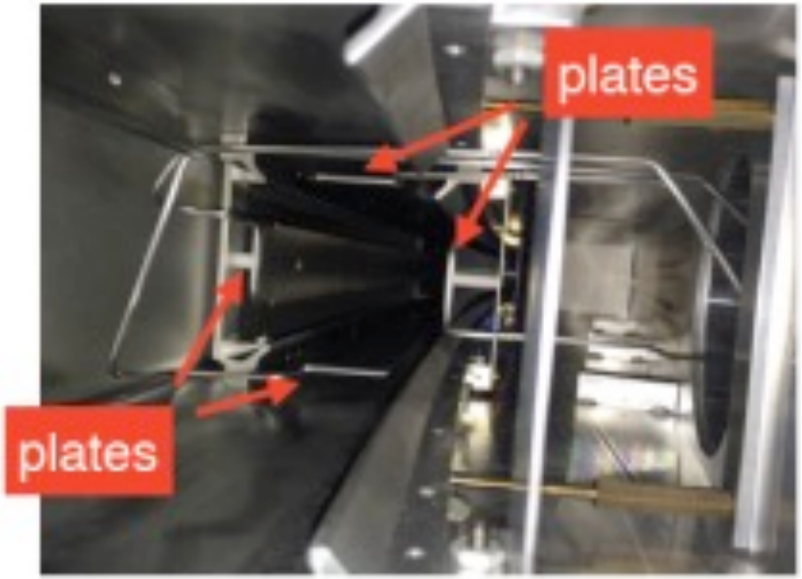


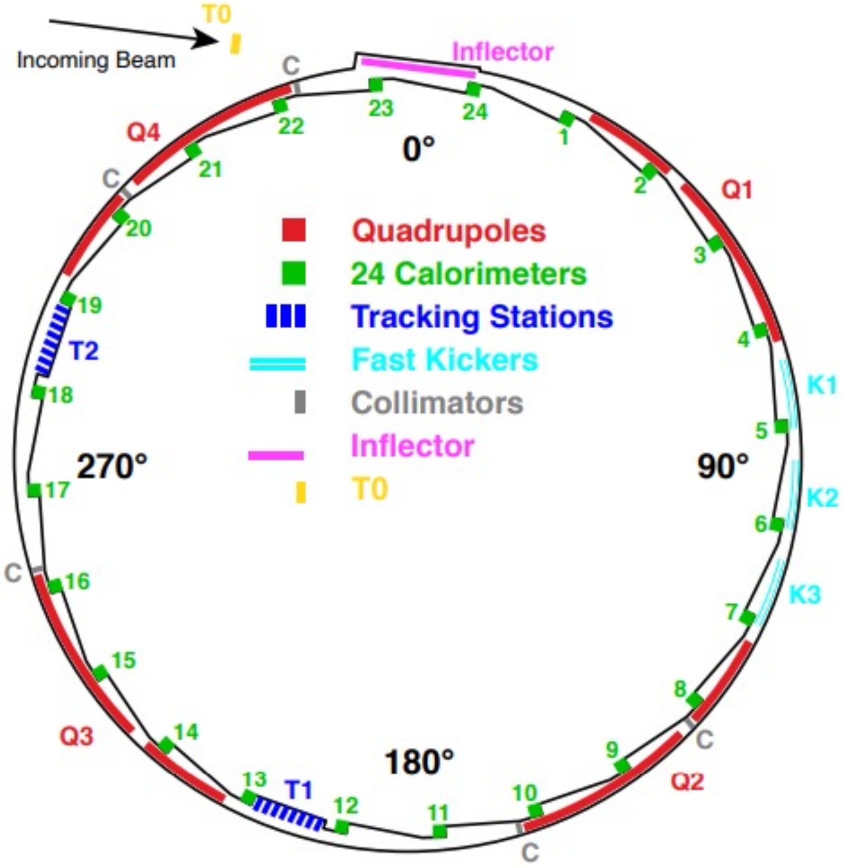


Pulsed fast magnetic kickers

- Direct muons onto storage orbit (~10 mrad)
- 1-turn pulsed magnet (~200 G)

Muon Injection and Storage System





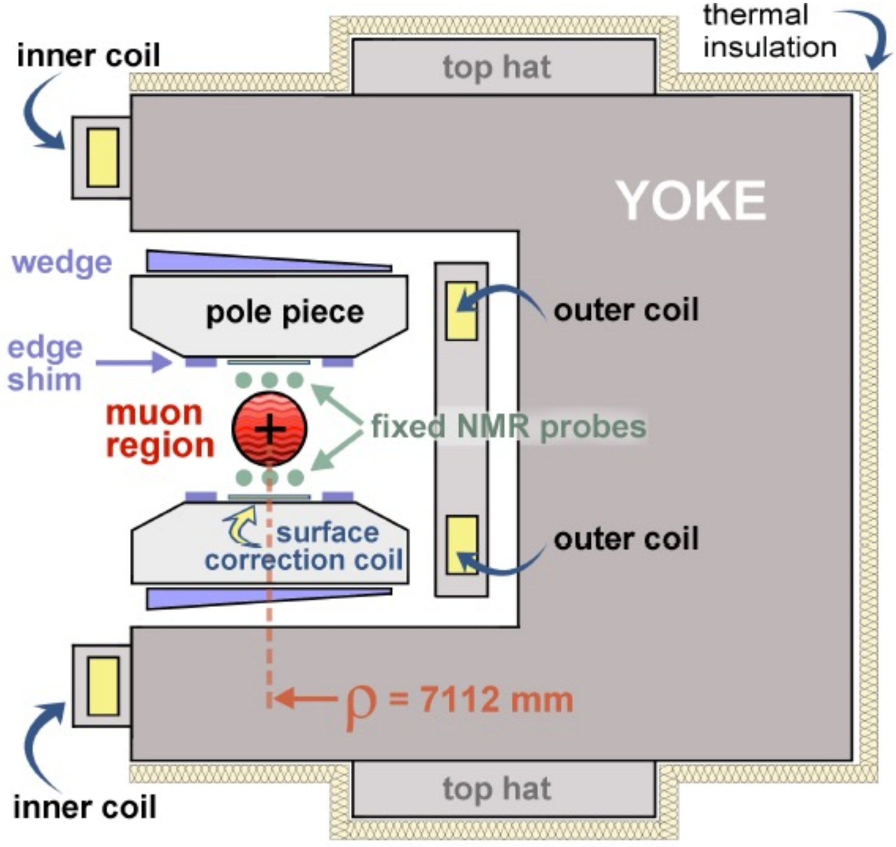
Pulsed electric quadrupoles

- Vertical beam confinement
- Pulsed HV power source
- Operates at ± 18-20 ***KV***

Magnetic Shimming

Magnetic field need to be uniform to ±1 ppm level averaged over azimuth

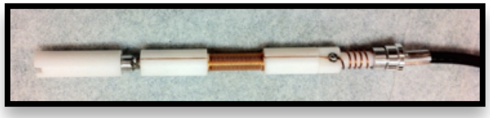
- 1 B field ~ 1.45T
- 12 C shape flux return yokes
- 72 poles
  - Minimizing higher-order multipoles
  - Dipole moment ~ 1.45T
- Field Shimming
  - Passive shim method (geometry)
    - 24 iron top hats
    - 864 wedges: angle quadrupole
    - >1000 edge shims: sextapole
    - >8000 surface iron foils
  - Active shim method (current)
    - Surface correction coil
    - Power supply feedback

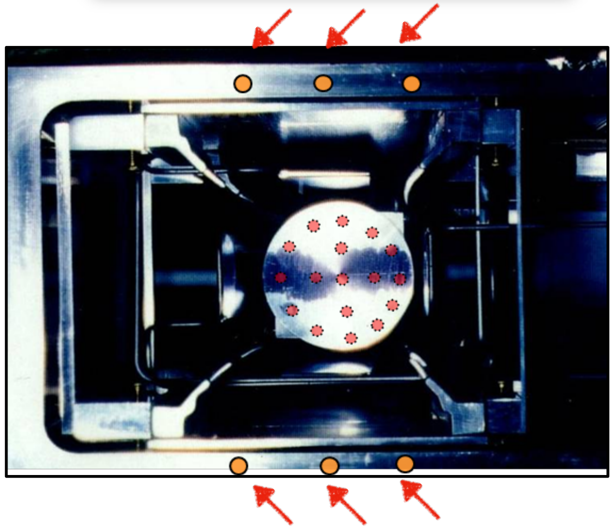


g-2 Magnet in Cross Section

Measuring ω_p, the B field

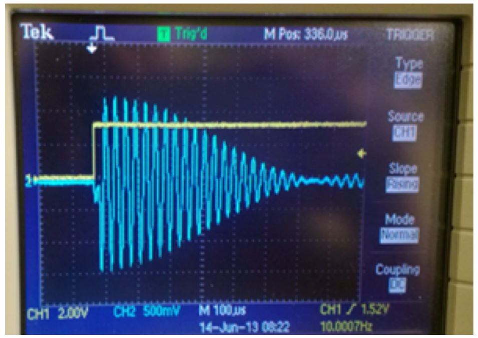
- 378 **Fixed Probes** above and below the vacuum chamber measure the field continuously throughout the experiment





- A 17-element **NMR Trolley** maps the field where muons live every 2-3 days: beam off

- Digitizing **Free Induction Decay (FID)** signals for more precise frequency determination

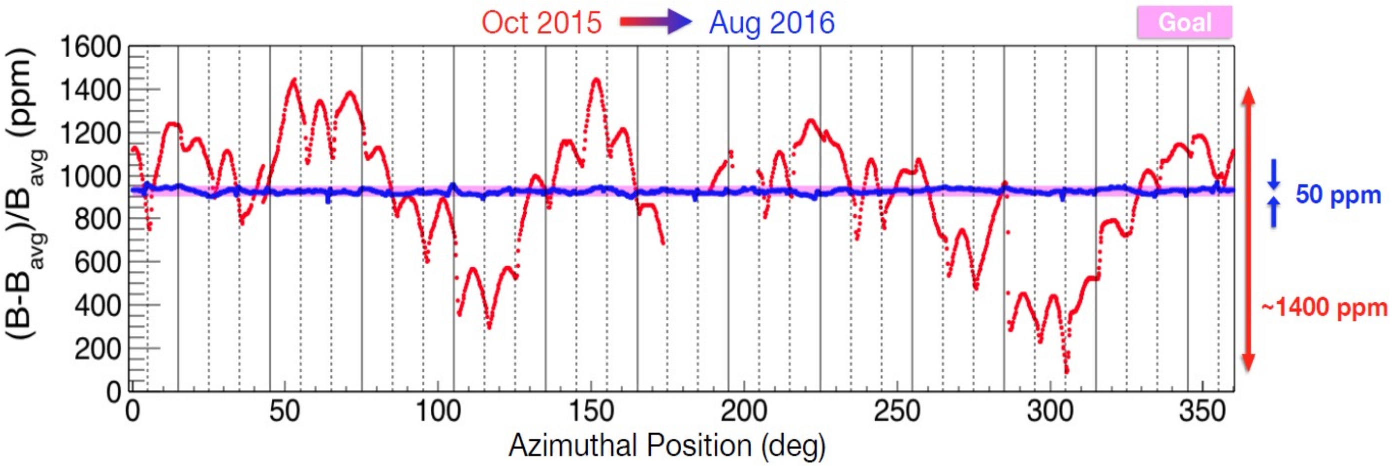


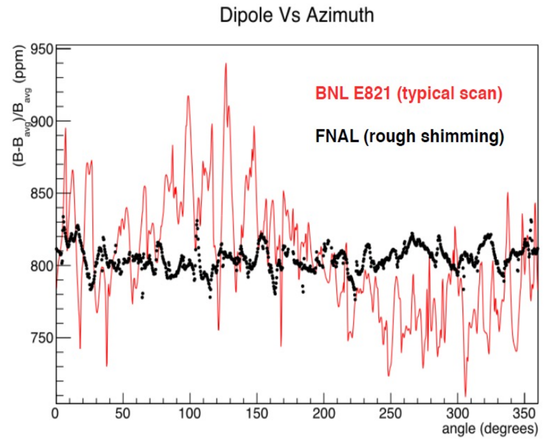
(FID) Waveforms with ~10 ppb resolution

- Monitoring the field and provide feedback to the storage ring power supply during data taking

- Absolute and cross calibration of all probes

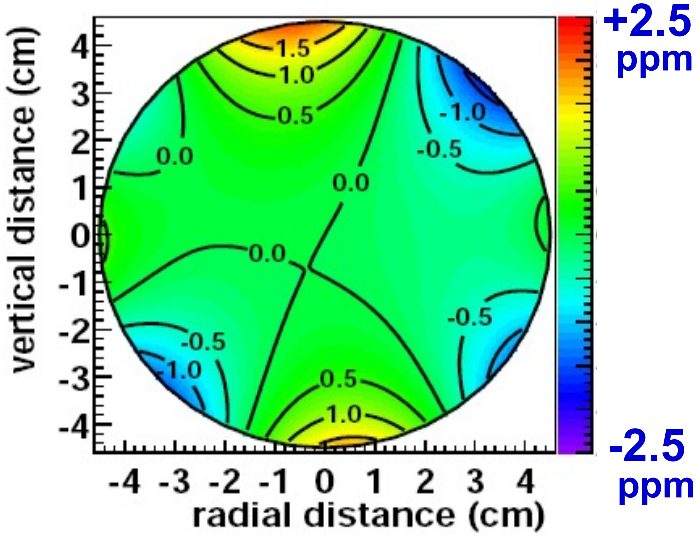
B Field Measurements





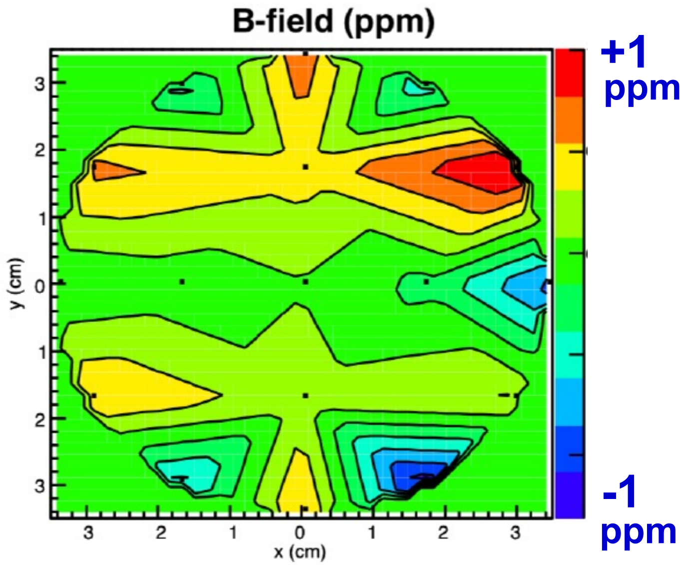
Shim 1.45 T field to high uniformity and measure it vs time

BNL Field Map

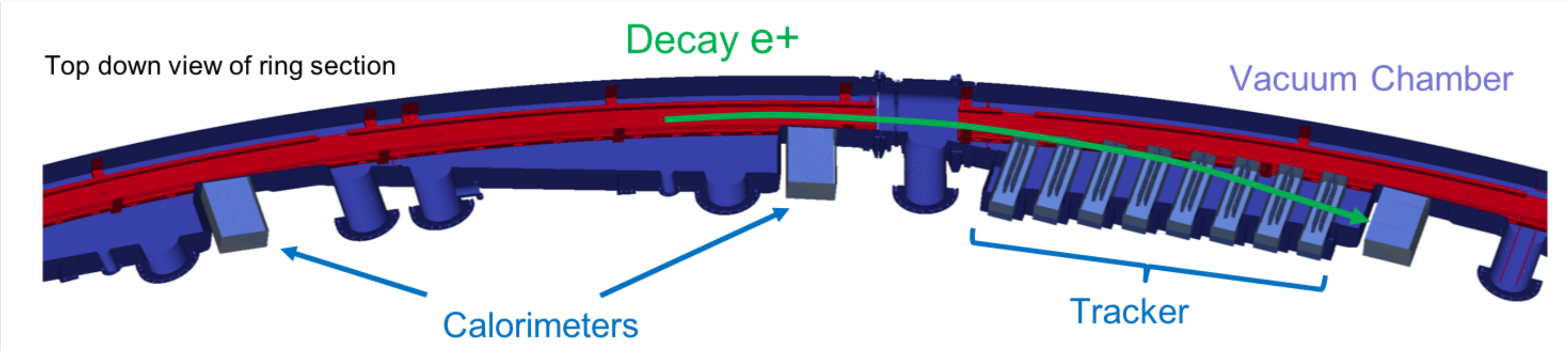


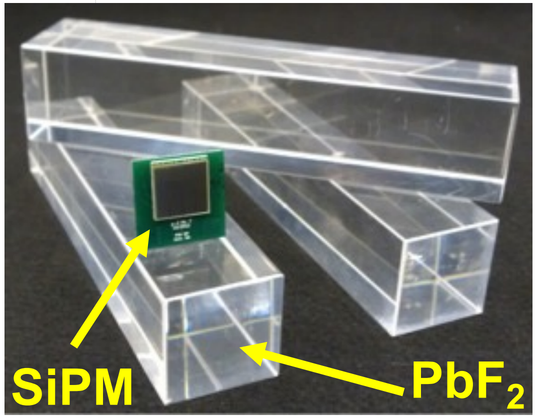
Averaged over azimuth: Shimmed to ±1 ppm level

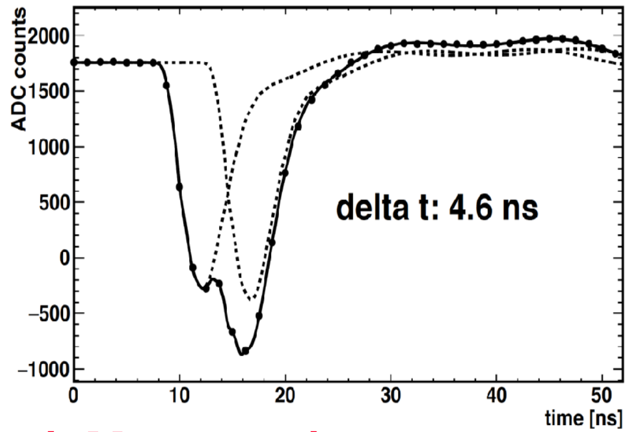
Field Map on 03/17/2018



Detector Performance: Calorimeter



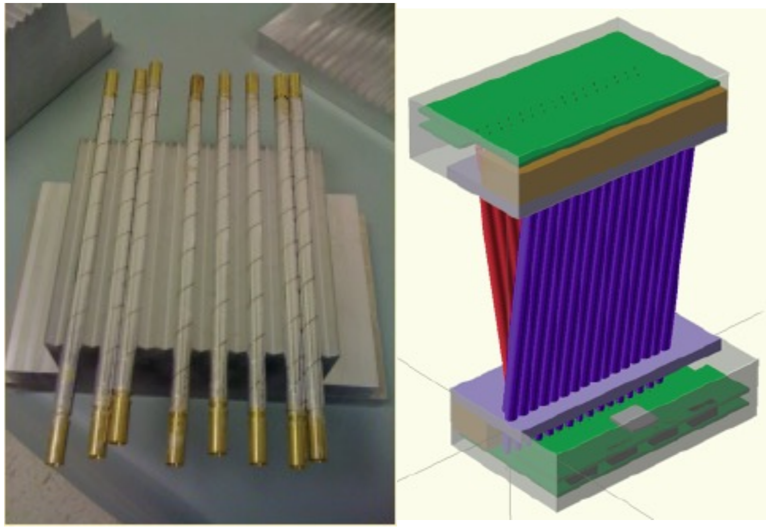


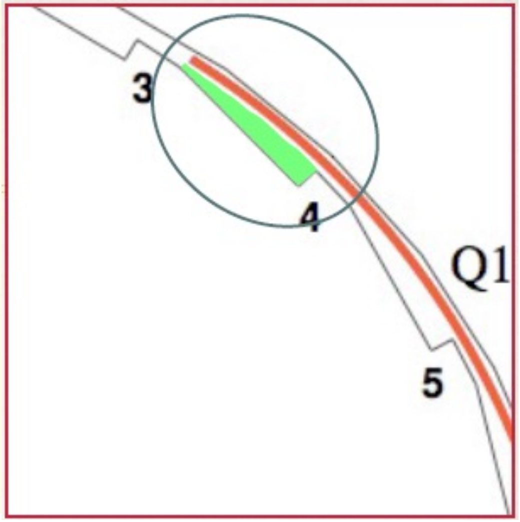


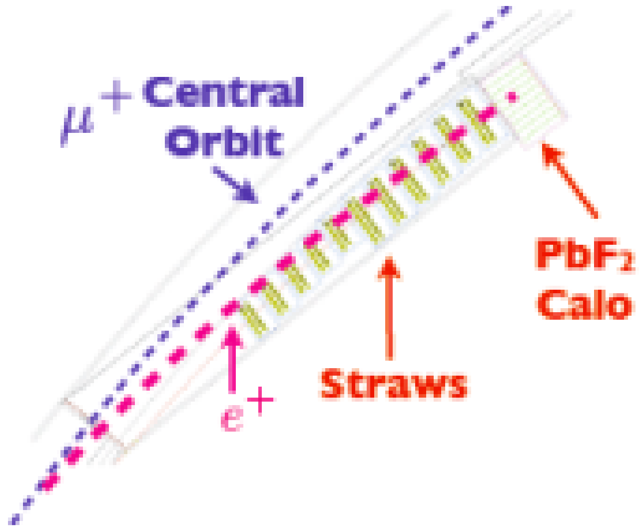
Segmented, fast response, PbF_2 crystal calorimeter (9X6 array)

- **Lead-floride Cherenkov crystal reduces pileup: SICCAS-SJTU-Washington**
  - **Fast separation for pileup backgrounds (>2.5 ns, 100%)**
  - **Resolution (2.3% at 3 GeV) better than requirement (5%)**
- **Silicon photomultiplier (SiPM) directly on back of PbF_2**
  - **No disturbing magnetic field, avoid long light guides**

Detector Performance: Tracker



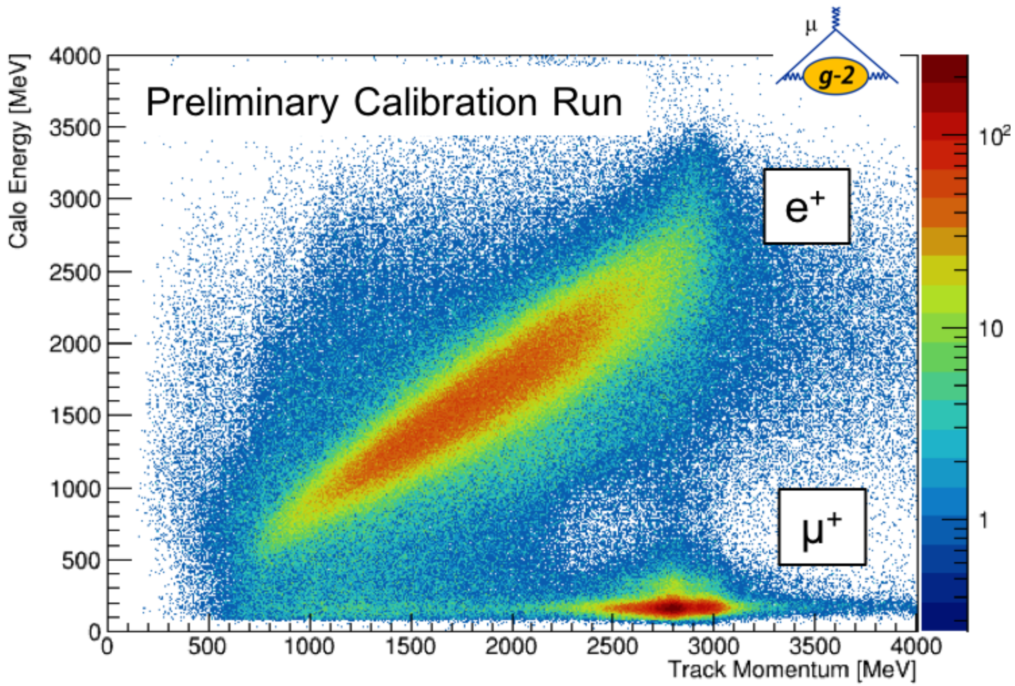




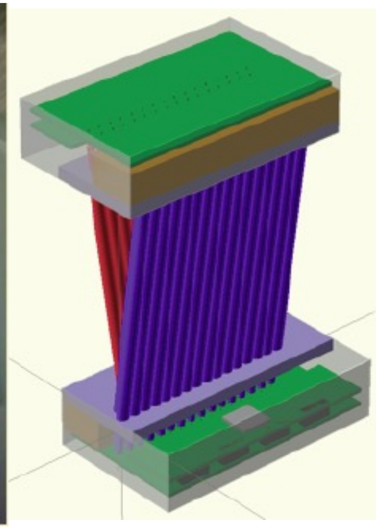
Doublet of UV straw chambers

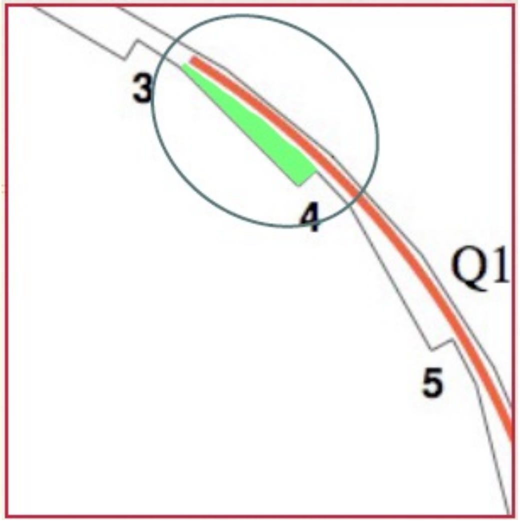
New straw tracking detector

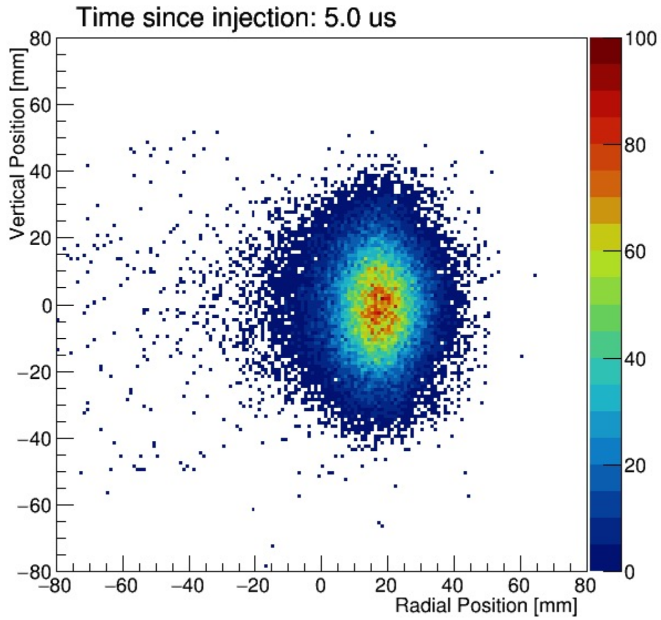
- Two stations installed, 1024 straws
- Measure muon decay vertex and momentum



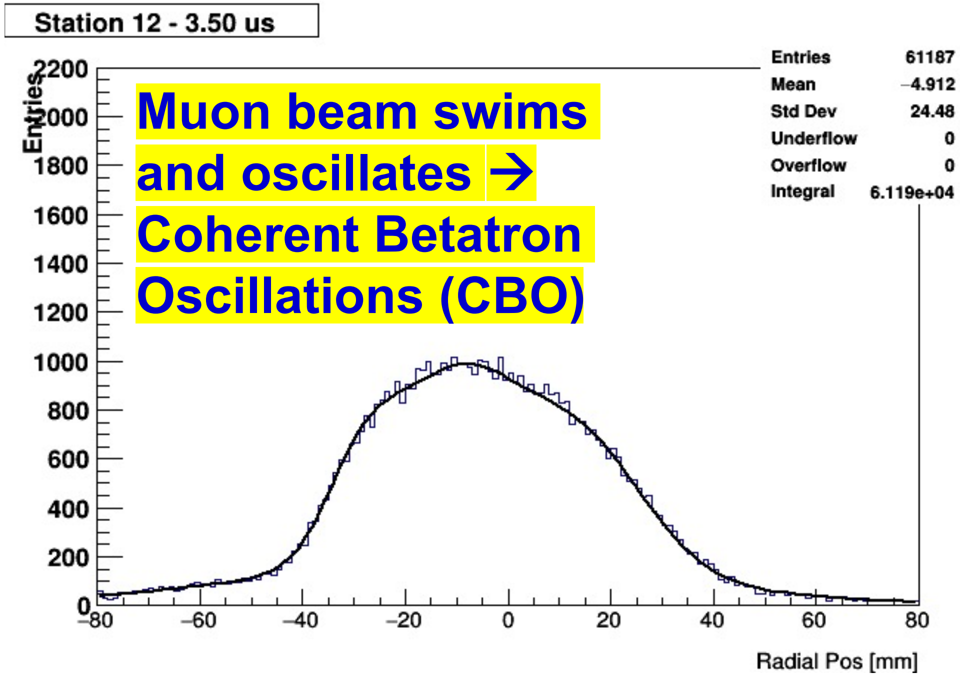
Detector Performance: Tracker



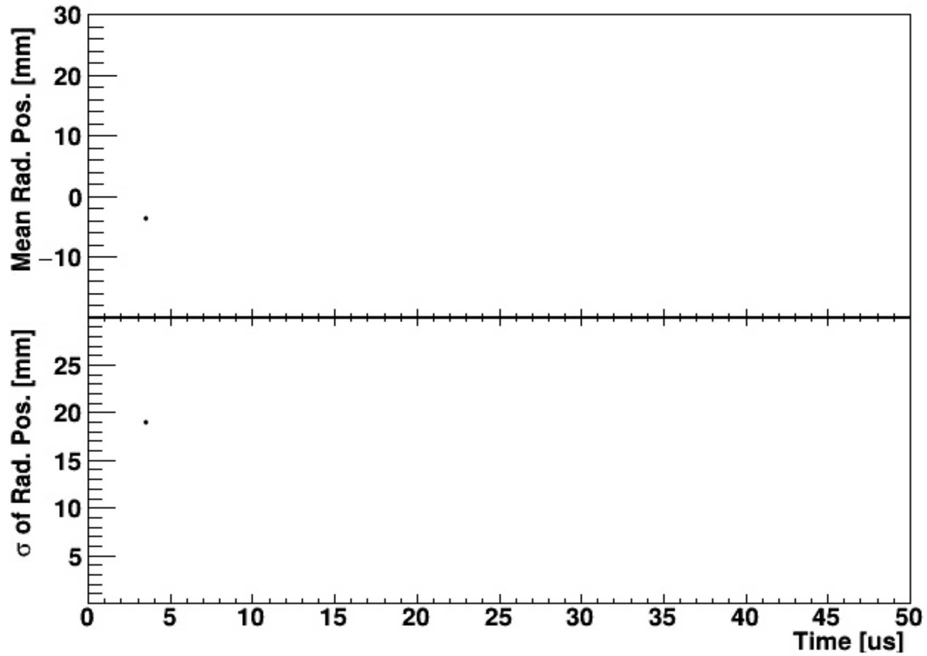




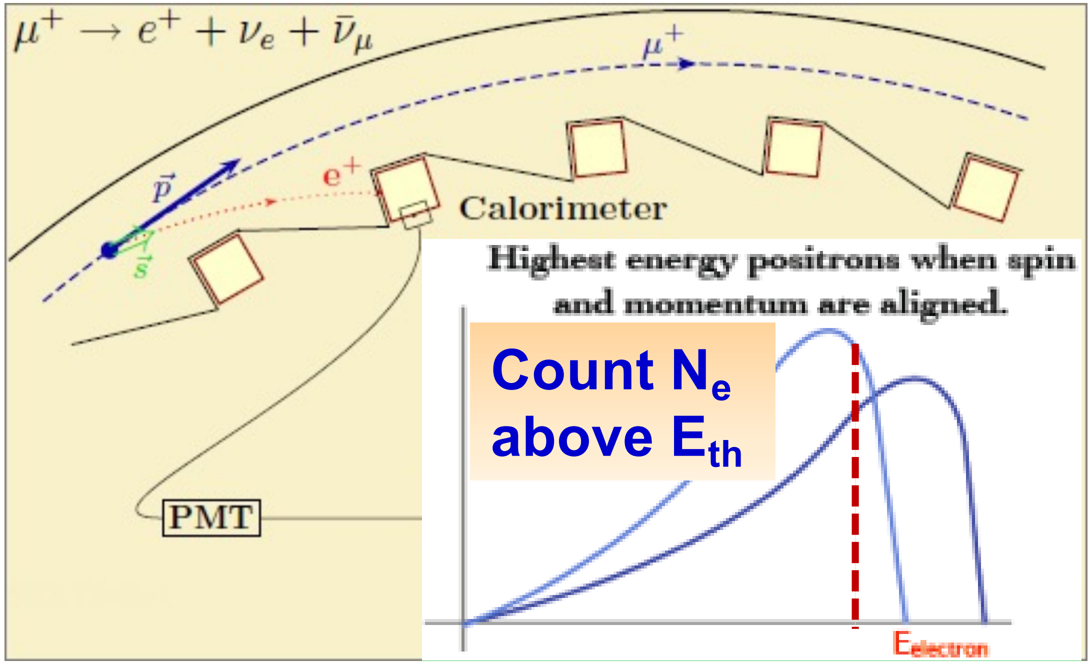
Doublet of UV straw chambers

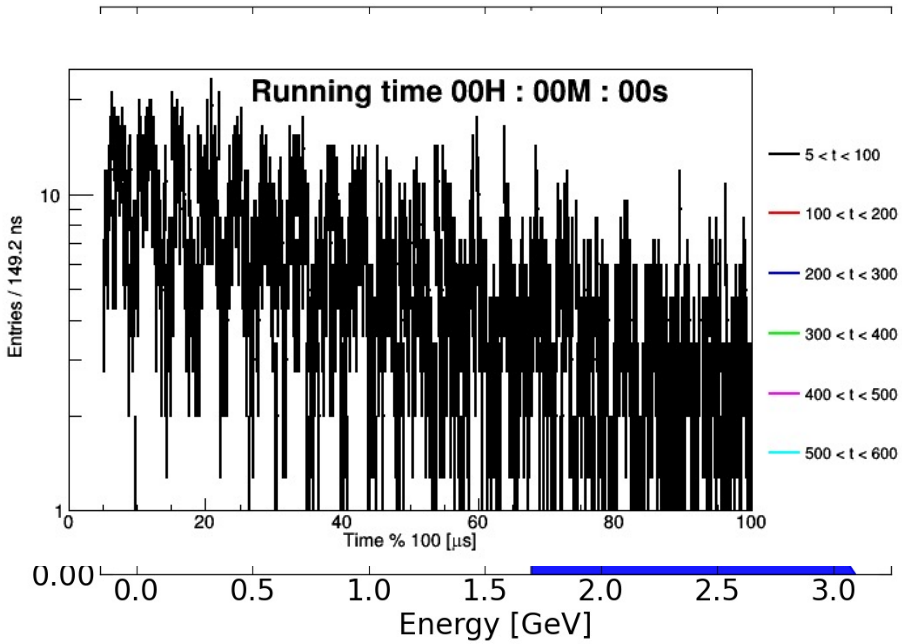


Muon beam swims and oscillates → Coherent Betatron Oscillations (CBO)



Measuring ω_a





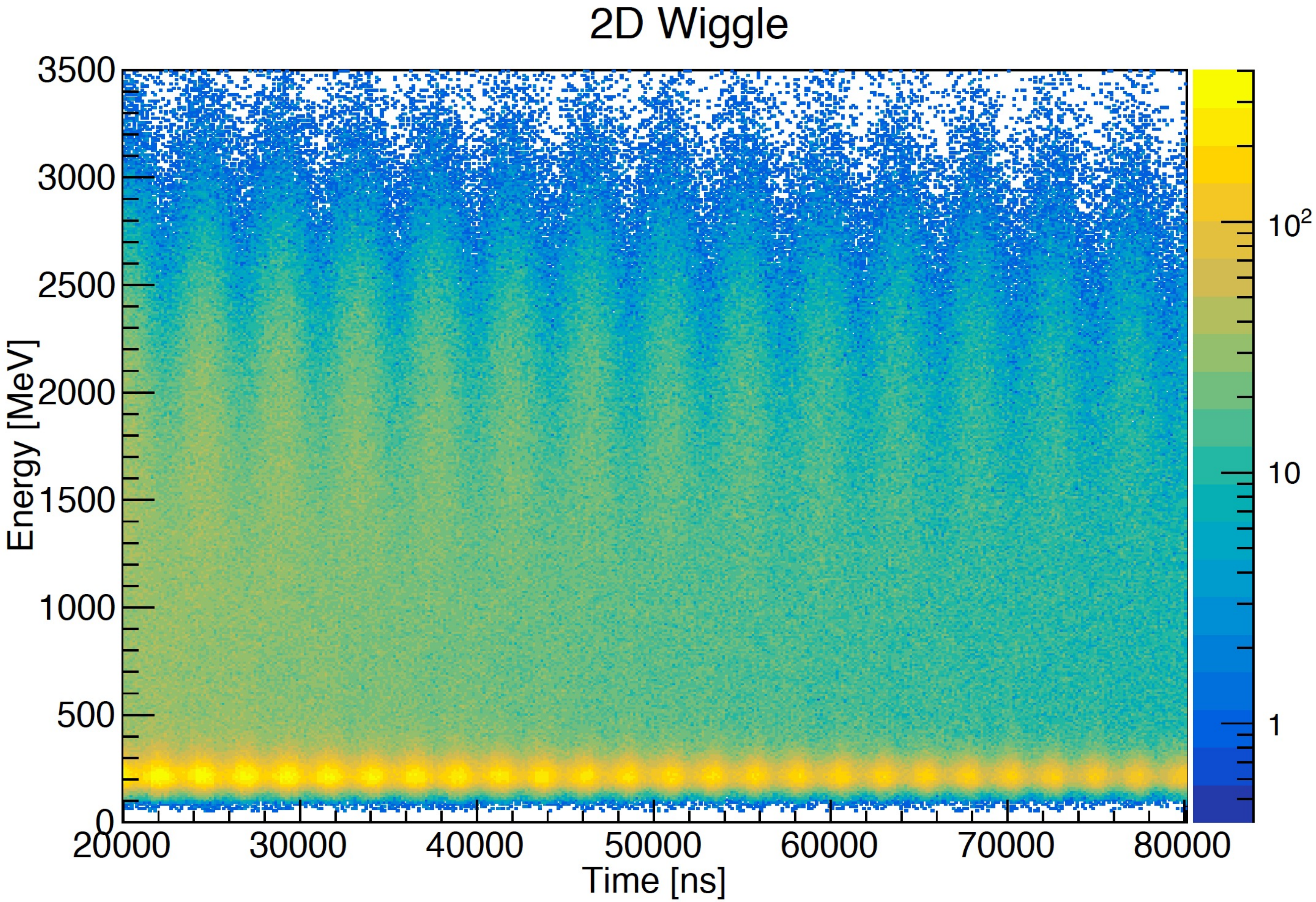
The integrated number of electrons (above E_{th}) modulated at ω_a

- **Angular distribution of decayed electrons correlated to muon spin**
- **Five parameter fit to extract ω_a**

$$N_{\text{ideal}}(t) = N_0 \exp(-t/\gamma\tau_\mu)[1 - A\cos(\omega_a t + \phi)]$$

- **Pileup**
- **Gain (energy scale) changes**
- **Coherent Betatron Oscillations**
- **Muon Losses**
- **E-field and pitch corrections**

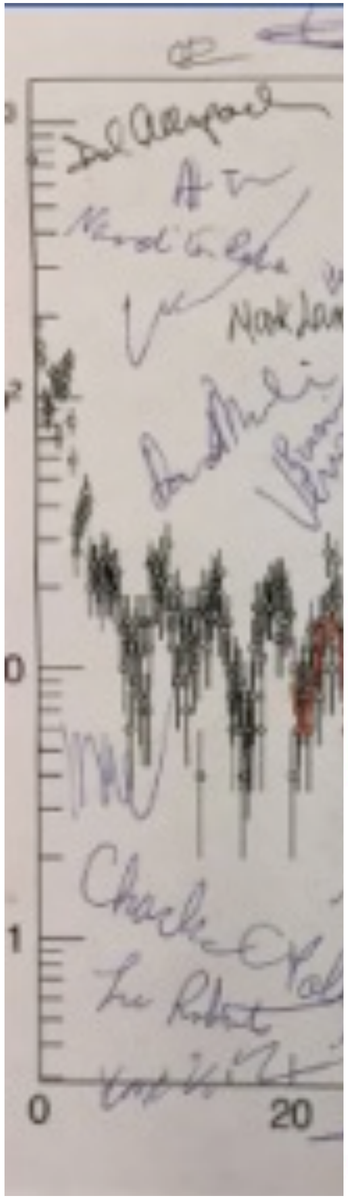
Wiggle, Wiggle, Wiggle…

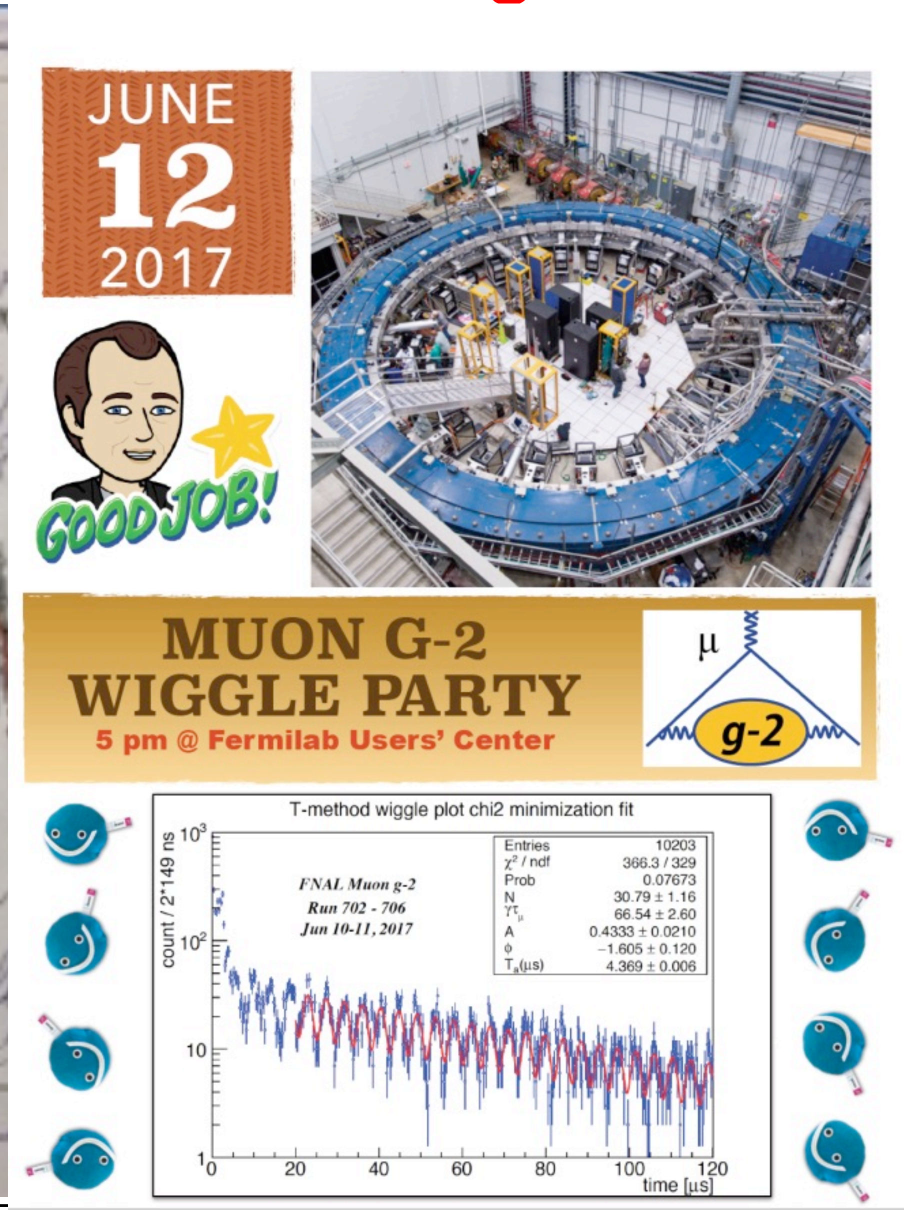


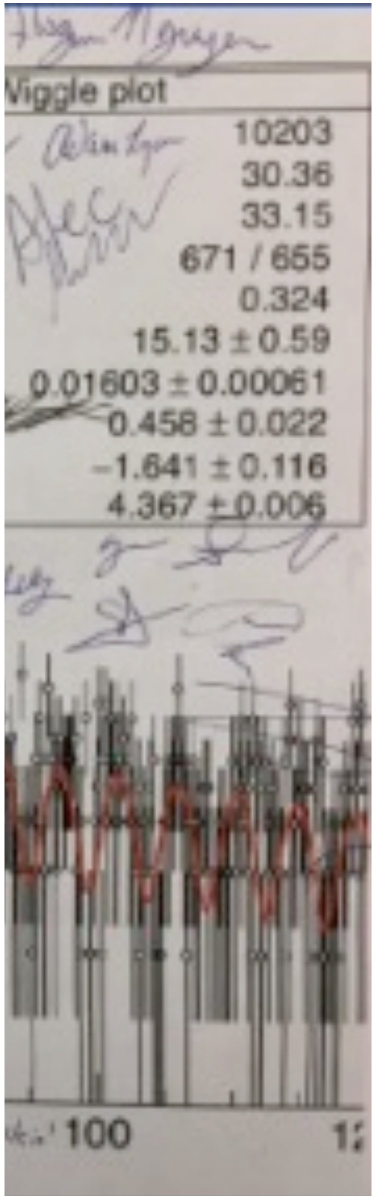
Energy vs. Time seen by calorimeters

Wiggle, Wiggle, Wiggle…

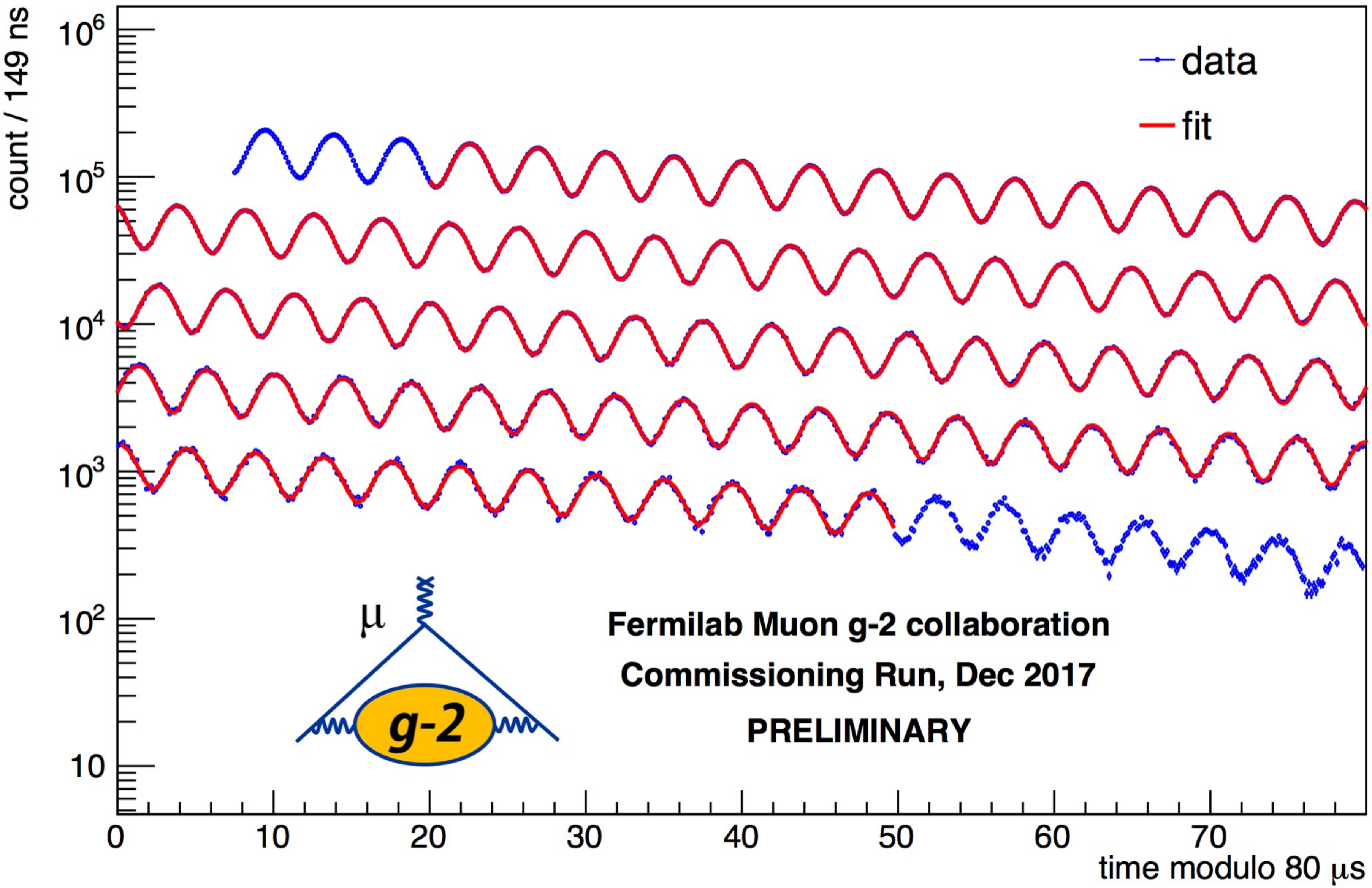
First commissioning run: June 2017



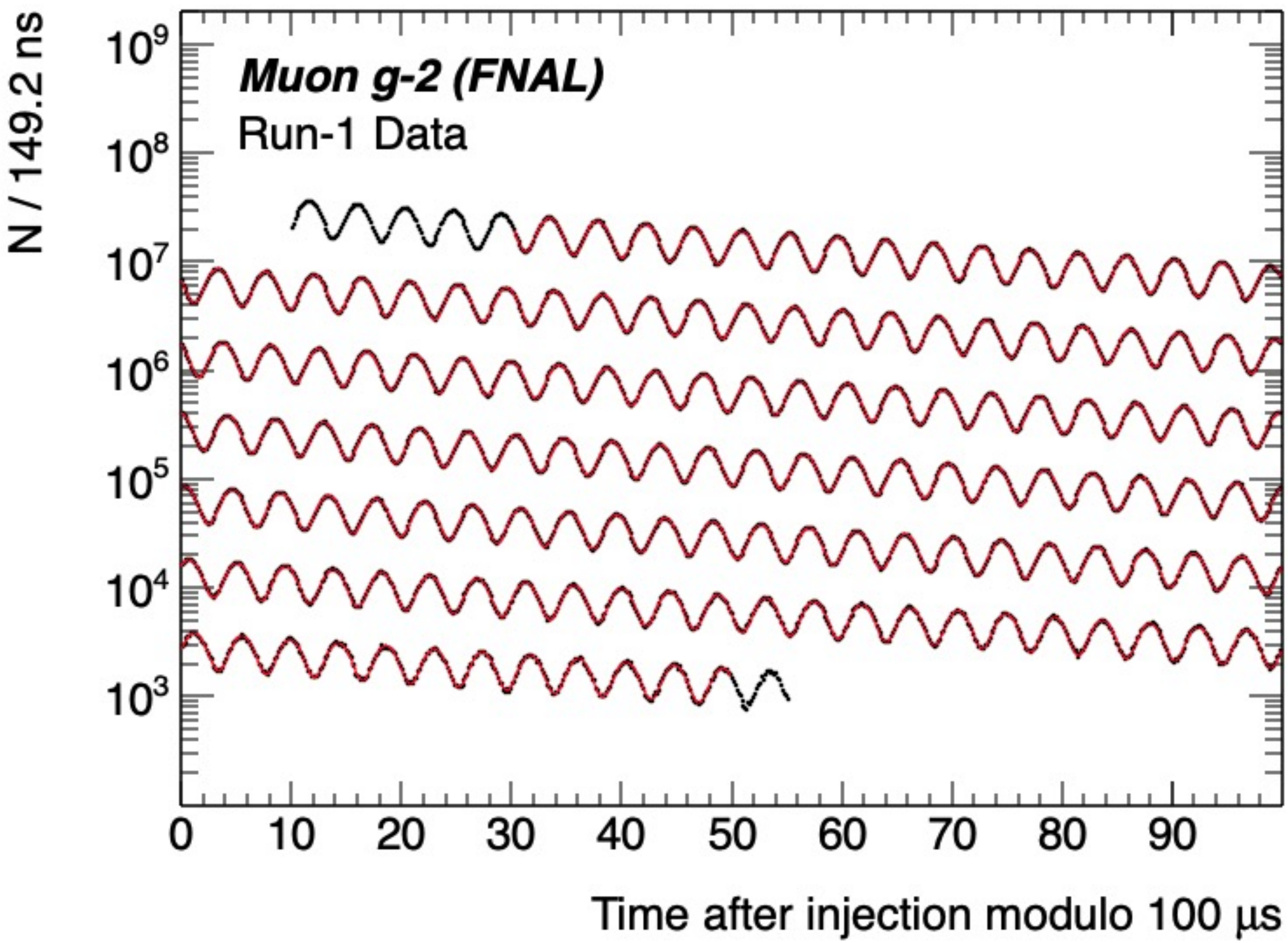




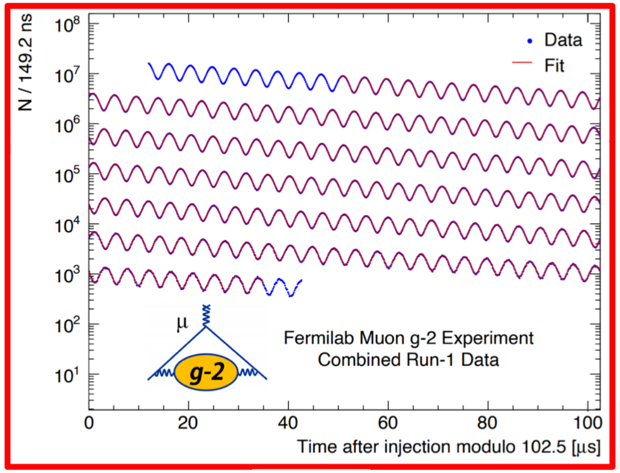
Wiggle, Wiggle, Wiggle…



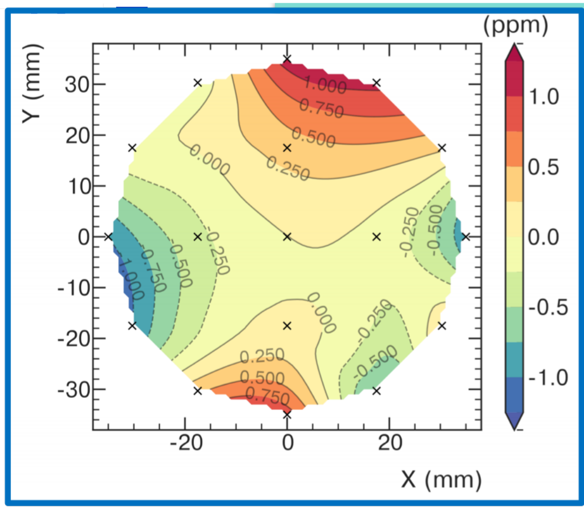
Wiggle, Wiggle, Wiggle…



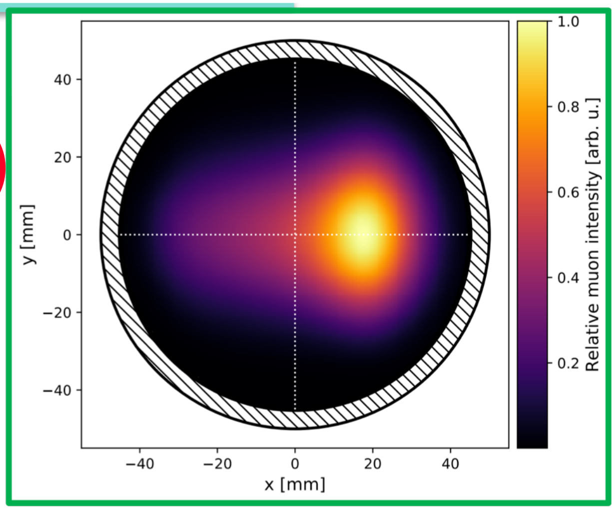
Data Analyses



$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\mathrm{clock}}\ \omega_a^m\ (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\mathrm{calib}}\ \langle\ \omega_p(x,y,\phi) \times M(x,y,\phi)\ \rangle (1 + B_k + B_q)}$$



⊗



Data Analyses

The glory details

- **Muons make horizontal circular movement under influence of magnetic field B, what about vertical movement?**
  - **Need to use electrostatic quadruples to confine muons vertically, this brings additional complication**

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

Pitch correction

minimized if $\gamma = 29.3$

Electric field correction

- **How to measure this?**
  - **Choose $\gamma = 29.3$, $p_\mu = 3.09$ GeV (magic momentum)**
  - **Residual electric field correction**
  - **Muon beam swims and breathes vertically and horizontally**
    - **Coherent betatron oscillations (CBO)**
    - **Betatron motion leads to a pitch correction since muons don't always travel perpendicular to the magnetic field**

E-field Correction, C_e

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\ (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$

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

Not all muons are at magic momentum!

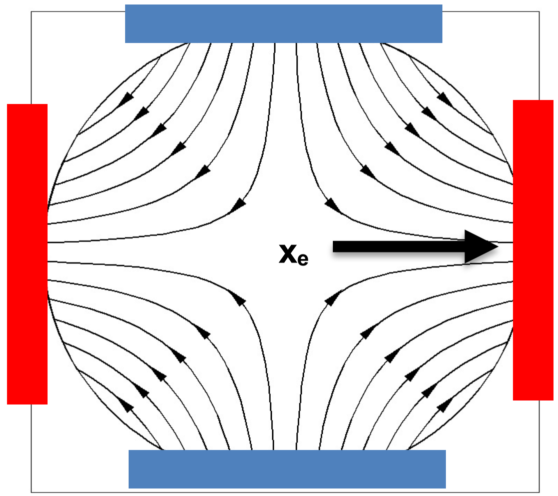
$$C_e = 2n(1-n)\beta_0^2 \frac{\langle x_e^2 \rangle}{R_0^2}$$

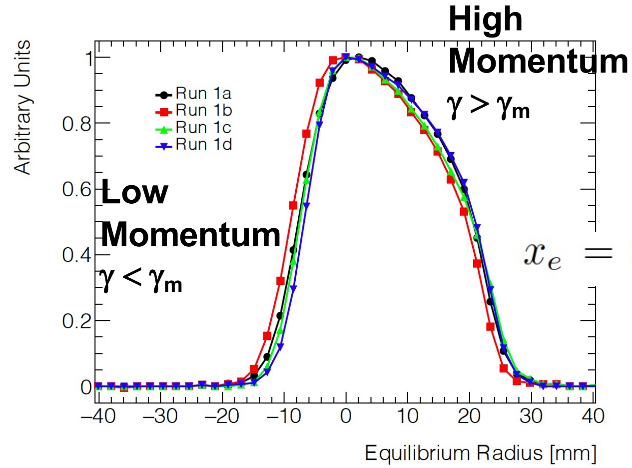
$$\langle x_e^2 \rangle = \sigma_{x_e}^2 + \langle x_e \rangle^2$$

Correction depends on width and mean

$$C_e \sim 450\ ppb,\ \delta_{C_e} \sim 50 ppb$$

Phys. Rev. Accel. Beams 24, 044002 (2021)





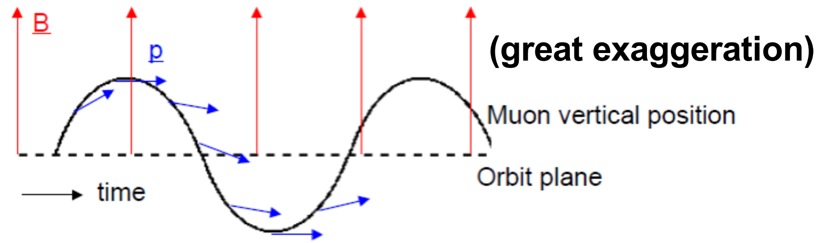
$$x_e = x - R_0$$

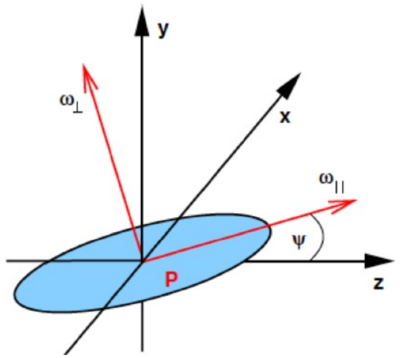
Fourier analysis of early time spectrum

Pitch Correction, C_p

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$

$$\vec{\omega}_a = -\frac{e}{mc}\left[a_\mu \vec{B} - a_\mu \left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta}\right]$$

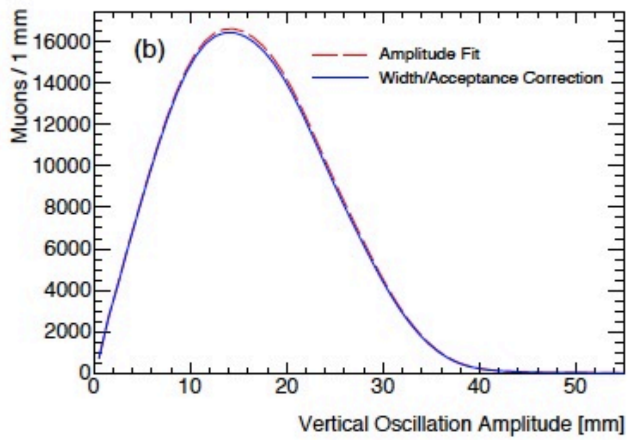




$$C_p = \frac{\psi_0^2}{4} = \frac{n}{4R_0^2}\langle A^2\rangle$$

Correction depends on amplitude of vertical oscillation

$$C_p \sim 200\ ppb,\ \delta_{C_p} \sim 10 ppb$$



Phys. Rev. Accel. Beams 24, 044002 (2021)

Muon Loss Correction, C_{ml}

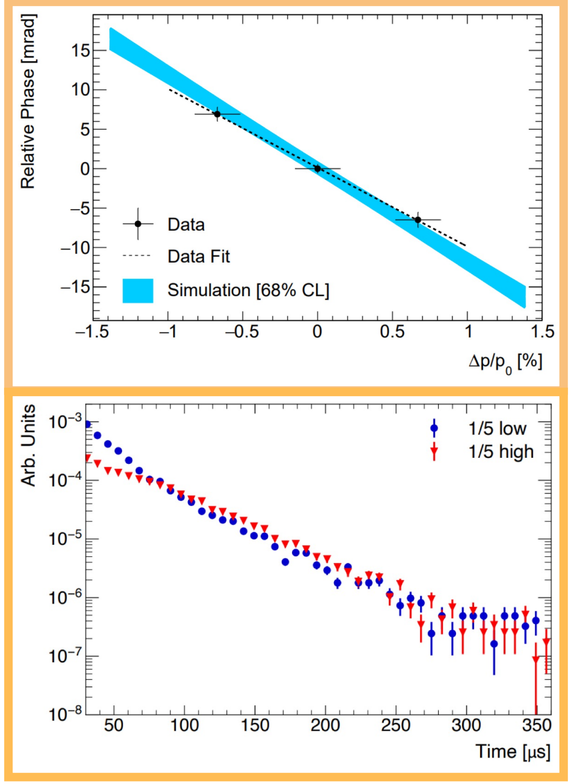
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\mathrm{clock}}\ \omega_a^m\,(1 + C_e + C_p + \boxed{C_{ml}} + C_{pa})}{f_{\mathrm{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$

Phase-momentum correlation due to dipole bending magnets in upstream beamline

Momentum-dependent muon losses mean different average phase early to late

$$\Delta\omega_a = \frac{d\phi}{dt} = \boxed{\frac{d\langle\phi\rangle}{d\langle p\rangle}} \cdot \boxed{\frac{d\langle p\rangle}{dt}} \neq 0$$

$$\boxed{C_{ml} < 20\ ppb, \delta_{C_{ml}} \sim 5\ ppb}$$



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Phase-acceptance Correction, C_{pa}

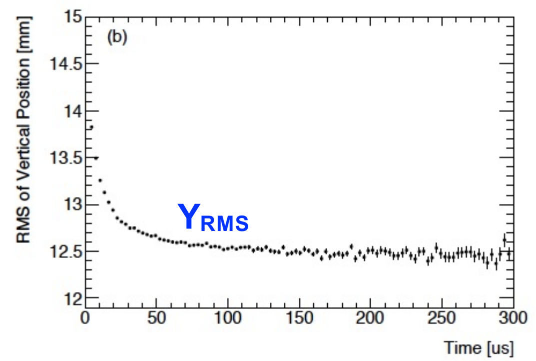
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$

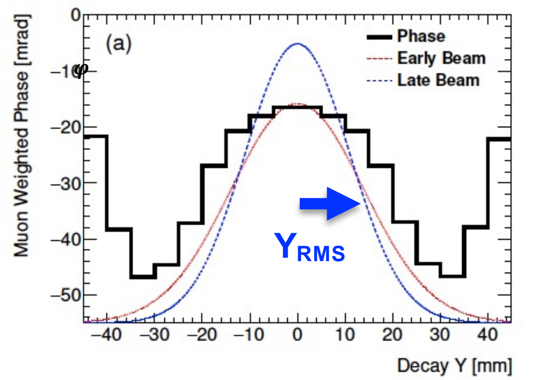
Beam shifting from early-to-late time due to storage ring conditions

Decay-position-dependent phase means different average phase early to late

$$\Delta\omega_a = \frac{d\phi}{dt} = \frac{d\langle Y_{RMS}\rangle}{dt} \cdot \frac{d\langle \phi \rangle}{d\langle Y_{RMS}\rangle} \neq 0$$

$$C_{pa} \sim 200\ ppb,\ \delta_{C_{pa}} \sim 80\ ppb$$





Phys. Rev. Accel. Beams 24, 044002 (2021)
Phys. Rev. D 103, 072002 (2021)

Magnetic Field Measurement, ω_p

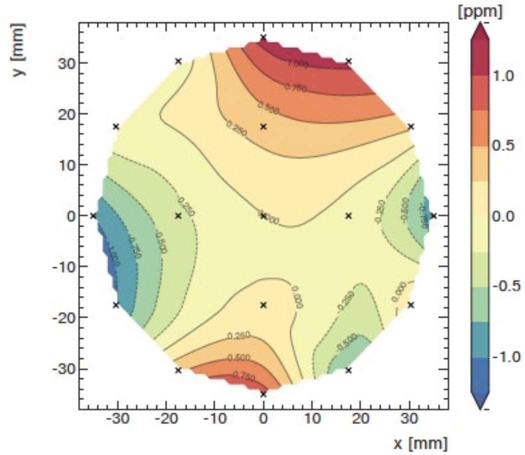
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\ (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle\omega_p(x,y,\phi) \times M(x,y,\phi)\rangle(1 + B_k + B_q)}$$

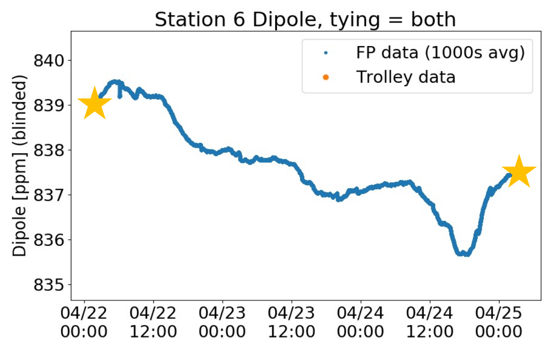
NMR trolley maps magnetic fields at about 9000 locations in azimuth in the storage region every 2-3 days

Fixed NMR probes interpolate the field between the trolley runs

Dedicated Plunging Probe to calibrate the NMR trolley probes to the water sample

$\delta_{\omega_p} \sim 48ppb$





Phys. Rev. A 103, 042208 (2021)

Muon-weighted Average Field, $\tilde{\omega}_p$

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$

The actual field experienced by the muon in the storage region

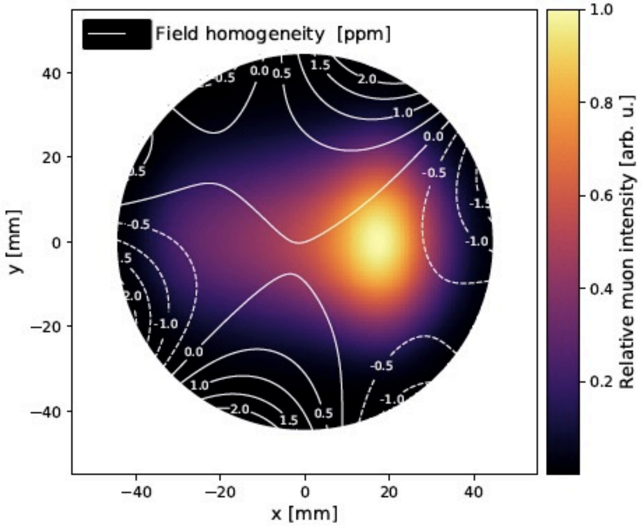
Measure muon beam distribution with straw trackers by extrapolating positron tracks back to the storage region

Use beam dynamics simulations, tuned to the tracker data, to get the muon beam distribution around the ring

$$\delta_{\tilde{\omega}_p} \sim 56ppb$$

Phys. Rev. A 103, 042208 (2021)

Muon's view



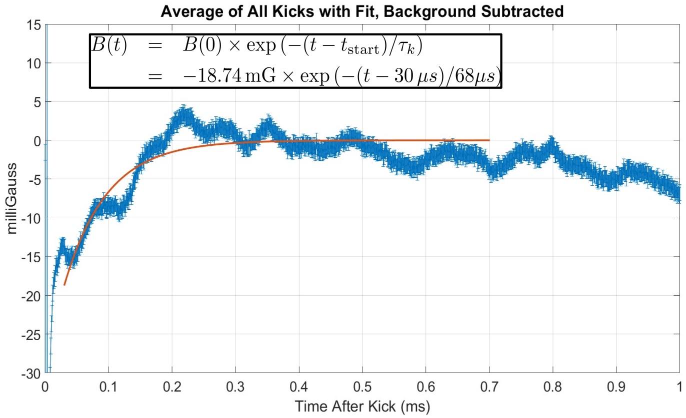
Kicker Transient Field, B_k

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\ (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

When kicker produces pulsed magnetic field (~ 200G) for 150 ns, eddy currents generated in kicker plates

Magnetometer between kicker plates

Faraday magnetometer installed between the plates to measure the rotation of polarized light in a crystal due to the transient field



Signal is fitted with an exponentially decaying function: $\Delta B(t) = \Delta B(0) \exp(-t/\tau_k)$

$$B_k \sim 30\ ppb,\ \delta_{C_{pa}} \sim 40\ ppb$$

Phys. Rev. A 103, 042208 (2021)

Electrostatic Quadrupole Transient Field, B_q

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$

ESQs are (dis-)charged every muon fill ($700\mu s$)

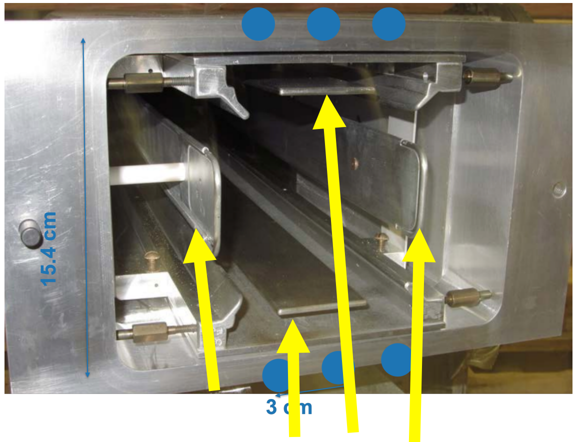
Electric pulse induces mechanical vibrations in ESQ plates and then generates magnetic perturbations

Customized NMR probes measured B_q at several positions in the storage region

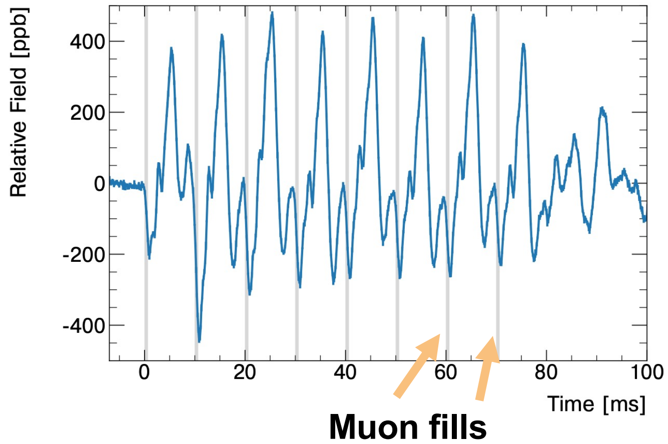
Uncertainty determined by the full width of the measured effect due to limited measurements in Run1 → expect improvement in Run2

$$B_q \sim 20\ ppb,\ \delta_{B_q} \sim 90\ ppb$$

Phys. Rev. A 103, 042208 (2021)



Quad plates inside vacuum chamber



ω_a^m Measurement

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\rm clock}\, \omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\rm calib}\, \langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$

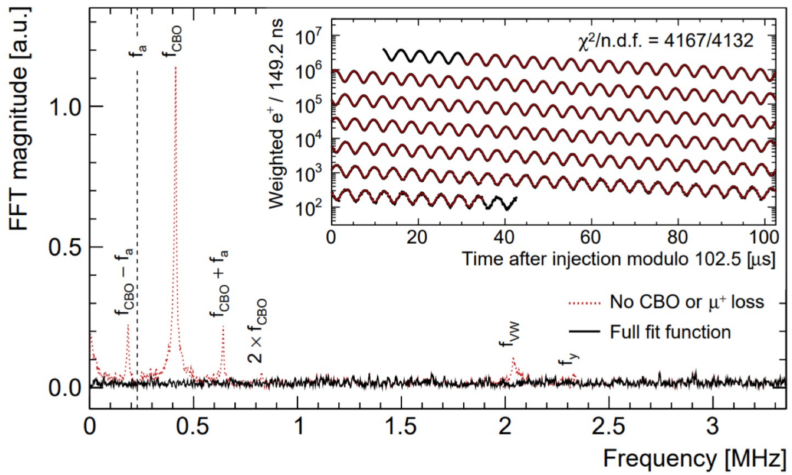
The ideal and naïve case, 5-parameter function:

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

- **Pileup**
- **Gain (energy scale) changes**
- **Coherent Betatron Oscillations**
- **Muon Losses**
- **E-field and pitch corrections**

$$F(t) = N_0 \cdot N_x(t) \cdot N_y(t) \cdot \Lambda(t) \cdot e^{-t/\gamma\tau_\mu} \cdot [1 + A_0 \cdot A_x(t) \cdot \cos(\omega_a^m t + \phi_0 \cdot \phi_x(t))]$$

Phys. Rev. D 103, 072002 (2021)



$$N_x(t) = 1 + e^{-t/\tau_{\rm CBO}} A_{N,x,1} \cos(\omega_{\rm CBO} t + \phi_{N,x,1}) + e^{-2t/\tau_{\rm CBO}} A_{N,x,2} \cos(2\omega_{\rm CBO} t + \phi_{N,x,2})$$

$$N_y(t) = 1 + e^{-t/\tau_y} A_{N,y,1} \cos(\omega_y t + \phi_{N,y,1}) + e^{-2t/\tau_y} A_{N,y,2} \cos(\omega_{VW} t + \phi_{N,y,2})$$

$$\Lambda(t) = 1 - K_{\rm loss} \int_0^t e^{t'/\gamma\tau_\mu} L(t')\, dt'$$

$$A_x(t) = 1 + e^{-t/\tau_{\rm CBO}} A_{A,x,1} \cos(\omega_{\rm CBO} t + \phi_{A,x,1})$$

$$\phi_x(t) = 1 + e^{-t/\tau_{\rm CBO}} A_{\phi,x,1} \cos(\omega_{\rm CBO} t + \phi_{\phi,x,1})$$

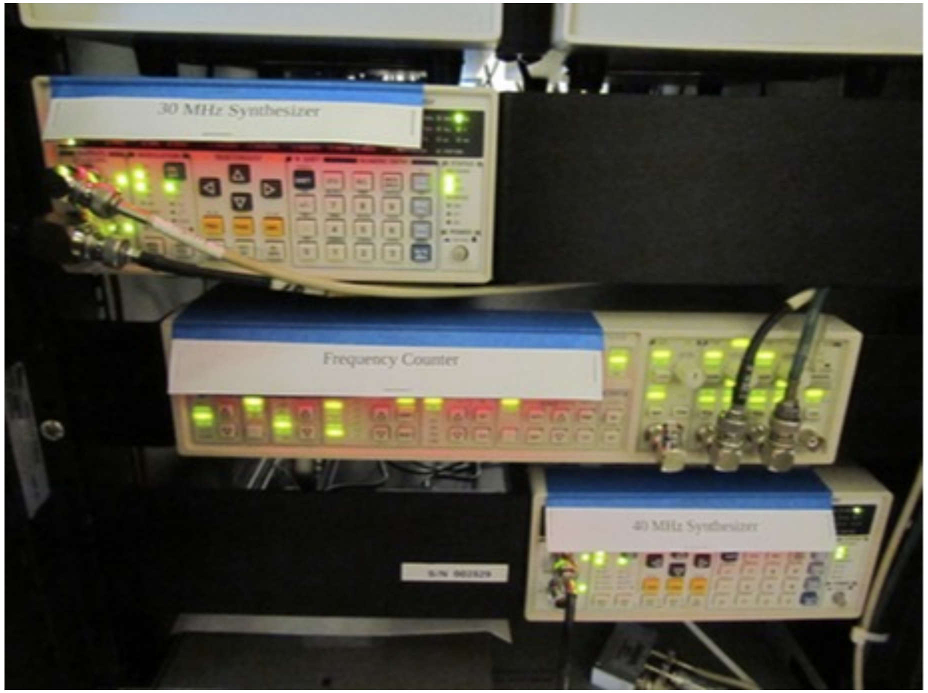
Blinded Analysis

Avoid possible bias during analysis

- **Credibility is the key**

Hardware Blinding

- **Perturb the clocks from the nominal frequency of 40 MHz → 39.XX MHz**



Blinded Analysis

Avoid possible bias during analysis

- Credibility is the key

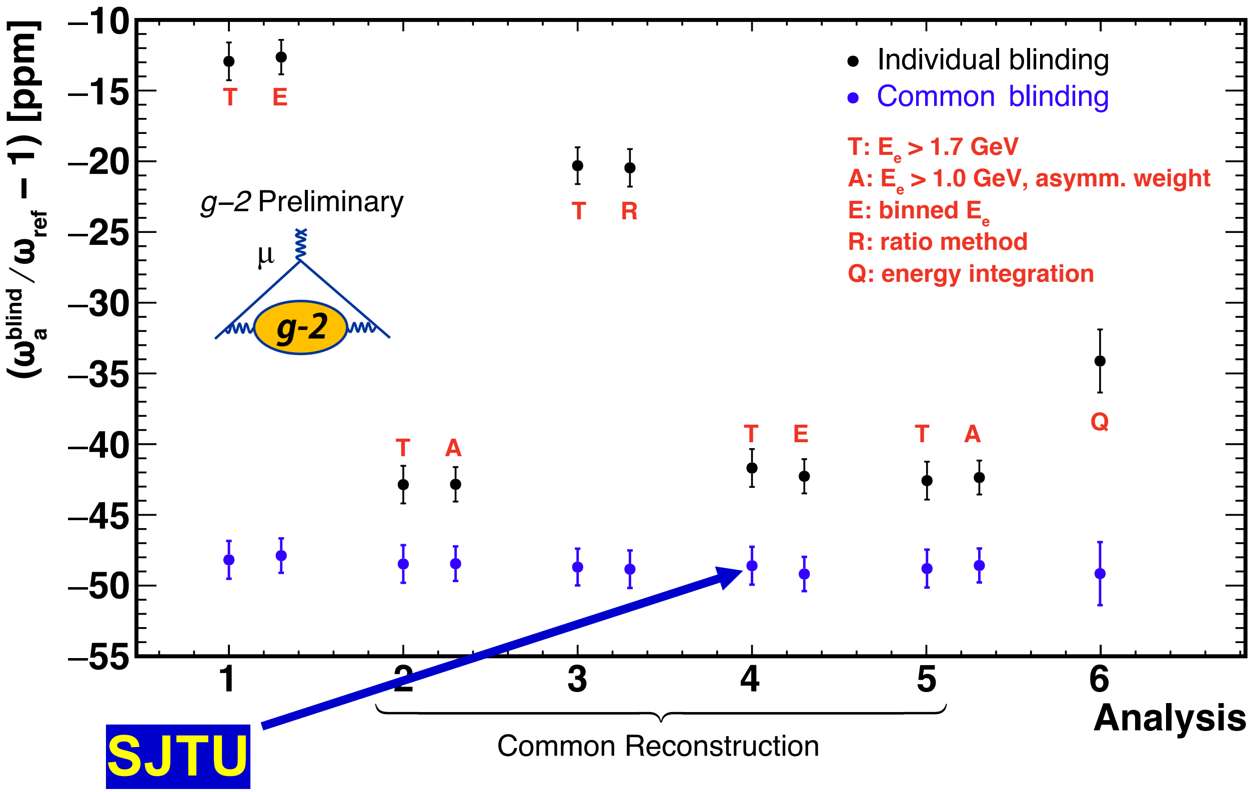
Hardware Blinding

- Perturb the clocks from the nominal frequency of 40 MHz → 39.XX MHz

Software Blinding

- Software package to apply individual offsets to fit results to ensure independence of analyses
- $\omega_a \rightarrow \omega_a \pm \Delta$ ppm
- Unblinding can be done in different stages and cross check

Relative Unblinding



- 6 independent ω_a analysis groups with multiple methods blinded from each other
- Relative unblinding performed for analysis consistency check
- A-weighted method extract more information from high energy positrons
- Statistics uncertainty: δ_{stat} = 0.43 ppm < 0.46 ppm (BNL)

Systematics: Numerator

Source	Uncertainty
Frequency Standard	1 ppt
Frequency Synthesizers	0.1 ppb
Digitization Frequency	2 ppb
Total Systematic	2 ppb

Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_{pa}	-184	-165	-117	-164
Stat. uncertainty	23	20	15	14
Tracker & CBO	73	43	41	44
Phase maps	52	49	35	46
Beam dynamics	27	30	22	45
Total uncertainty	96	74	60	80

$R(\omega_a)$ with detailed systematics categories [ppb]				
Total systematic uncertainty	65.2	70.5	54.0	48.8
Time randomization	14.8	11.7	9.2	6.9
Time correction	3.9	1.2	1.1	1.0
Gain	12.4	9.4	8.9	4.8
Pileup	39.1	41.7	35.2	30.9
Pileup artificial dead time	3.0	3.0	3.0	3.0
Muon loss	2.2	1.9	5.2	2.4
CBO	42.0	49.5	31.5	35.2
Ad-hoc correction	21.1	21.1	22.1	10.3

***Run 1 ω_a data analyzed in four subsets**

	1a	1b	1c	1d
C_p (ppb)	**176**	**199**	**191**	**166**
Statistical uncertainty	<0.1	<0.1	<0.1	<0.1
Tracker alignment/reco.	11.0	12.3	12.0	10.7
Tracker res. & acc. removal	3.3	3.9	3.7	3.0
Azimuthal avg. & calo. acc.	1.0	1.3	2.2	1.1
Amplitude fit	1.2	0.4	1.0	2.9
Quad alignment/voltage	4.4	4.4	4.4	4.4
Systematic uncertainty	**12.4**	**13.7**	**13.6**	**12.3**

Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_{ml}	-14	-3	-7	-17
Phase-momentum	2	0	1	3
Form of $l(t)$	2	0	1	1
f_{loss} function	2	1	2	2
Linear sum ($\sigma_{C_{ml}}$)	6	2	4	6

	1a	1b	1c	1d
C_e (ppb)	**471**	**464**	**534**	**475**
Statistical uncertainty	0.4	0.5	0.4	0.2
Fourier method	8.4	13.4	14.4	3.9
Momentum-time correlation	52	52	52	52
Quad alignment/voltage	6.4	6.4	6.4	6.4
Field index	1.7	1.5	1.7	4.0
Systematic uncertainty	**53**	**54**	**54**	**53**

Systematics: Denominator

run-1 (substructure)	77.4 ppb
azimuthal shape*	7.6 ppb
skin depth	12.6 ppb
frequency extraction (0.4/1ms)	4.6 ppb
Q3L: fit, position	1.5 ppb
repeatability	13.3 ppb
drift	10.2 ppb
radial dependency	4.4 ppb
2^{nd} 8-pulses	14.0 ppb
total −15.0 ppb	81.7 ppb

Source	Uncertainty (ppb)
Temperature	**15 – 28**
Configuration	**22**
Trolley	**25**
Fixed Probe Production	**<1**
Fixed Probe Baseline	**8**
Tracking Drift	**22 – 43**
Total	**43 – 62**

PROBE	Calibration Coefficients		
	Value (Hz)	Stat (Hz)	Syst (Hz)
1	90.81	0.38	2.02
2	84.21	0.65	1.18
3	95.02	0.53	2.19
4	86.03	0.25	1.28
5	92.96	0.51	1.10
6	106.24	0.46	1.35
7	116.64	0.96	1.61
8	76.39	0.60	1.21
9	83.52	0.23	1.64
10	24.06	1.39	1.26
11	177.55	0.22	1.99
12	110.85	0.44	1.73
13	122.89	2.08	1.93
14	77.11	0.53	1.88
15	74.82	1.06	1.59
16	20.35	0.44	2.94
17	172.12	1.23	1.96
AVG		**0.70**	**1.70**

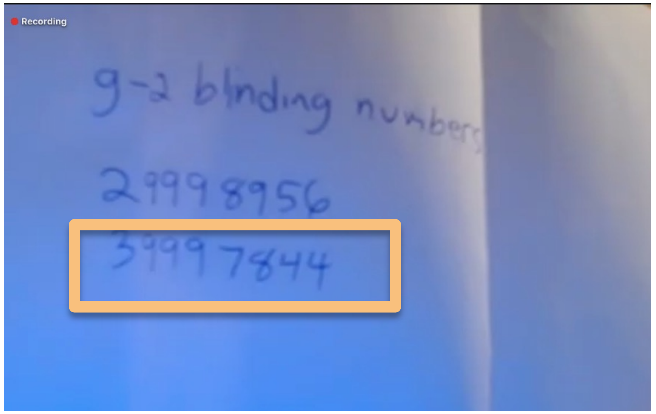
Run-1 Estimate:
B_k = -27.4 ± 37 ppb

Quantity	Symbol	Value	Unit
Diamagnetic Shielding T dep	$(1/\sigma)d\sigma/dT$	-10.36(30)	ppb/℃
Bulk Susceptibility	δ_b	-1504.6 ± 4.9	ppb
Material Perturbation	δ_s	15.2 ± 13.3	ppb
Paramagnetic Impurities	δ_p	0 ± 2	ppb
Radiation Damping	δ_{RD}	0 ± 3	ppb
Proton Dipolar Fields	δ_d	0 ± 2.3	ppb

	correction [ppb]				uncertainty [ppb]			
Dataset	1a	1b	1c	1d	1a	1b	1c	1d
1. Tracker and calo effects	-	-	-	-	9.2	13.3	15.6	19.7
2. COD effects	1.6	1.5	1.7	1.4	5.2	4.7	5.2	4.9
3. In-fill time effects	-1.9	-2.3	-1.2	-4.1	-	-	-	-
Total	**-0.3**	**-0.8**	**0.5**	**-2.7**	**10.6**	**14.1**	**16.5**	**20.3**

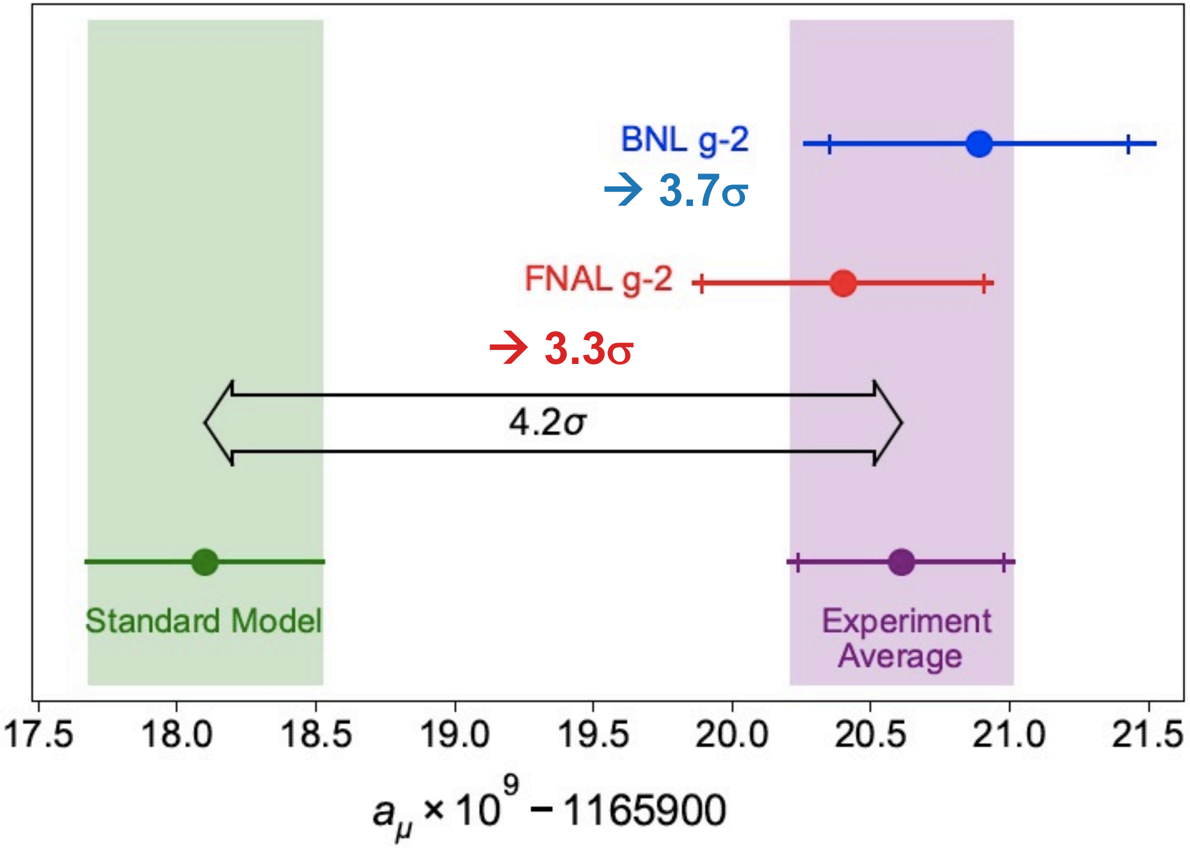
The Unblinding Ceremony!

Feb 25, 2021



Secret frequency of 39.XX MHz

Unblinded result



- 15% smaller error than BNL
- Both experiments dominated by statistical error
- Good agreement
- Increased significance after combination

a_μ(Exp) - a_μ(SM) = 0.00000000251(59) → 4.2σ

Correction Factors and Uncertainties

Quantity	Correction terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	⋯	434
ω_a^m (systematic)	⋯	56
C_e	489	53
C_p	180	13
C_{ml}	−11	5
C_{pa}	−158	75
$f_{\mathrm{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle$	⋯	56
B_k	−27	37
B_q	−17	92
$\mu_p'(34.7°)/\mu_e$	⋯	10
m_μ/m_e	⋯	22
$g_e/2$	⋯	0
Total systematic	⋯	157
Total fundamental factors	⋯	25
Totals	544	462

$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54)\times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

Phys. Rev. Lett. 126, 141801 (2021)

Four Papers in a Roll

PHYSICAL REVIEW A 103, 0

Featured in Physics

Magnetic-field measurement and analysis for the Mu

(The Muon g − 2 Collaborat

PHYSICAL REVIEW LETTERS 126, 141801 (2021)

Editors' Suggestion | Featured in Physics

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

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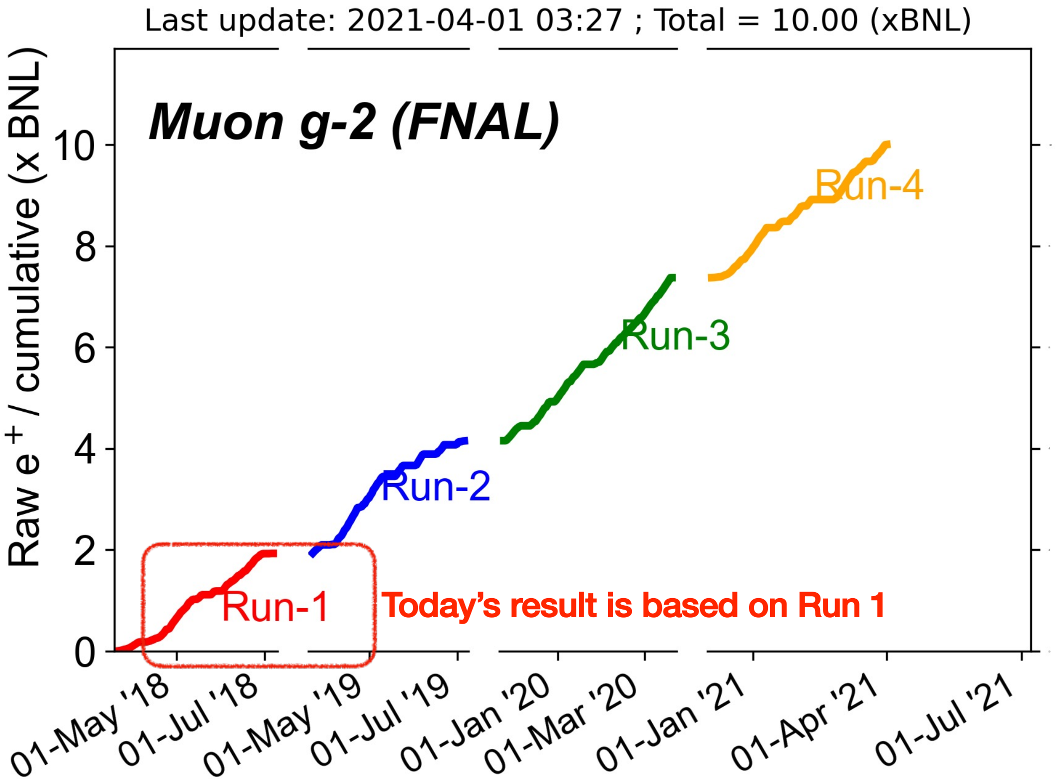
... to the Run-1 measurement of the muon anomalous ... gnetic moment at Fermilab

... The Muon $g-2$ Collaboration)

Unprecedented: Physical Review Series publish four papers at once for one measurement!

Data Collection

We have collected plenty of data over the past 3 years



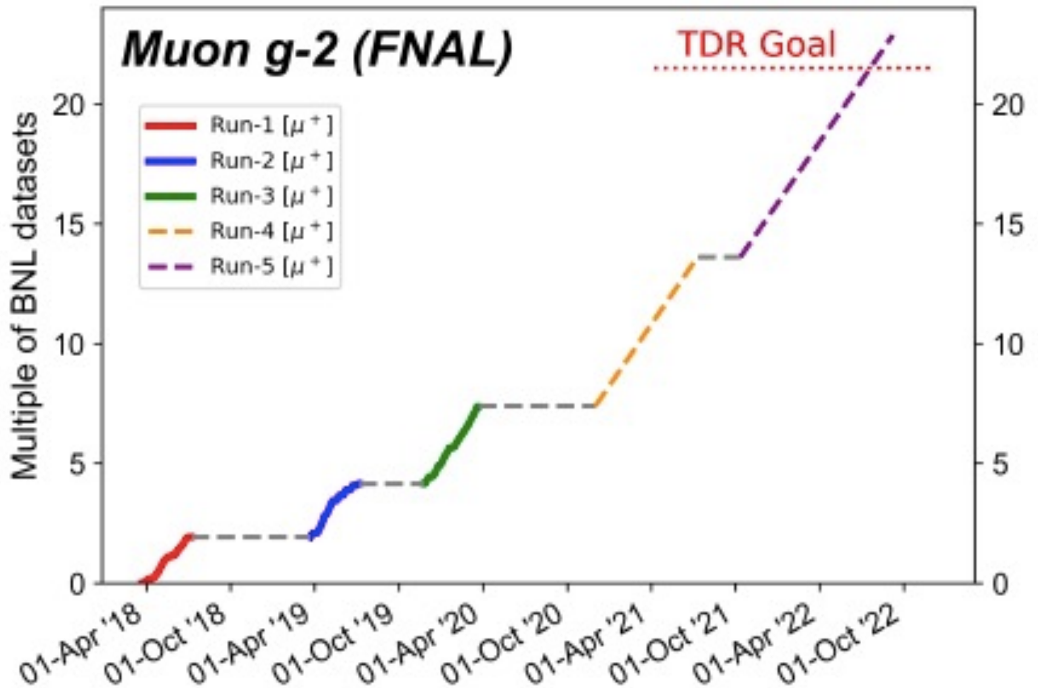
Run 1 results ~6% of full stats:
434 ppb stat ⊕ 157 ppb syst errors

Outlook

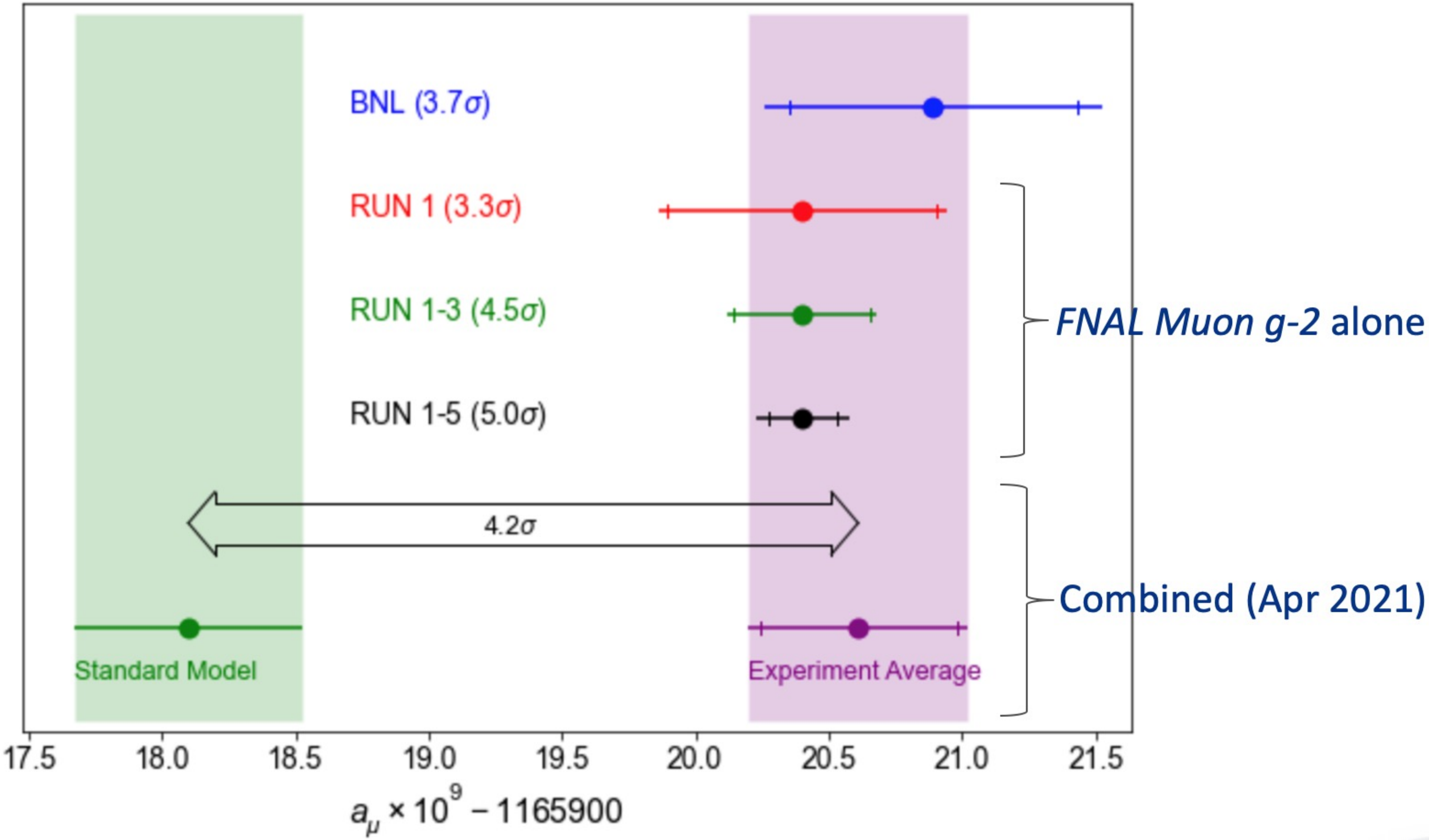
- Analysis of Run2/3 ongoing, expect a factor of two improvement in precision

- Run 4 data taking now is expected to bring the statistics to 13x BNL

- Run 5 in 2021-2022 should bring us to the TDR goal of ~ 21x BNL



Outlook



BNL (3.7σ)
RUN 1 (3.3σ)
RUN 1-3 (4.5σ)
RUN 1-5 (5.0σ)
4.2σ
Standard Model
Experiment Average
FNAL Muon g-2 alone
Combined (Apr 2021)
17.5
18.0
18.5
19.0
19.5
20.0
20.5
21.0
21.5
$a_\mu \times 10^9 - 1165900$

Conclusions

- The first results of Muon g-2 measurement at 0.46 ppm
- Result consistent with BNL result (within one sigma) with improved precision

$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

- Combining BNL's result, it strengthens the significance of the discrepancy to 4.2 sigma!
- We expect a factor of two improvement in precision from Run2/3 data and more from Run4/5.

Stay tuned!