The g-2 experiment at Fermilab

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Israeli Joint Particle Physics Seminar

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Introduction

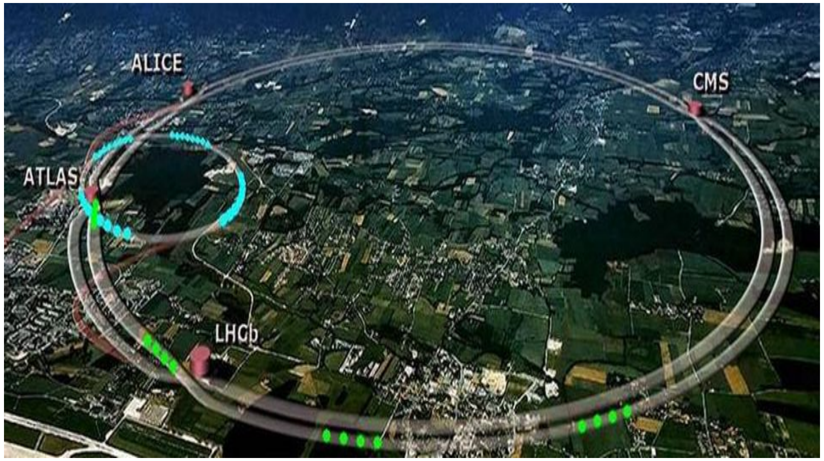
The Standard Model provides an excellent explanation of most experimental data currently available but still leaves many unanswered questions

What is dark matter?

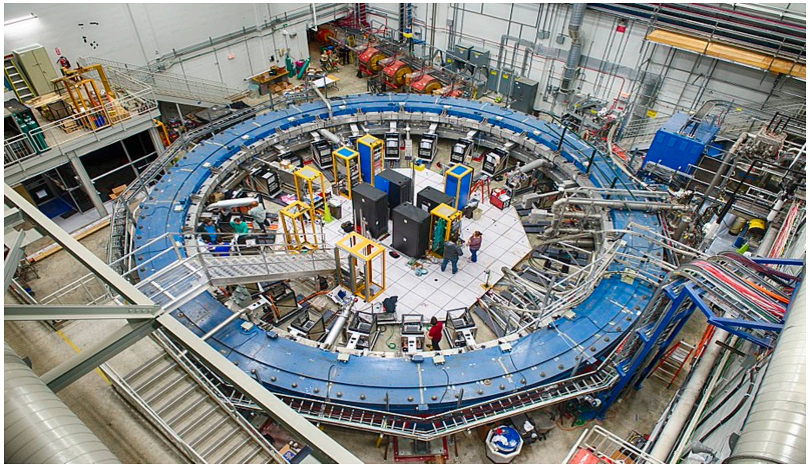
What is the cause of the matter anti-matter asymmetry?

Gravity?

High energy frontier



High intensity frontier



$$E = mc^2$$

$$\Delta E \Delta t \geq \frac{1}{2}\hbar$$

Magnetic Moments

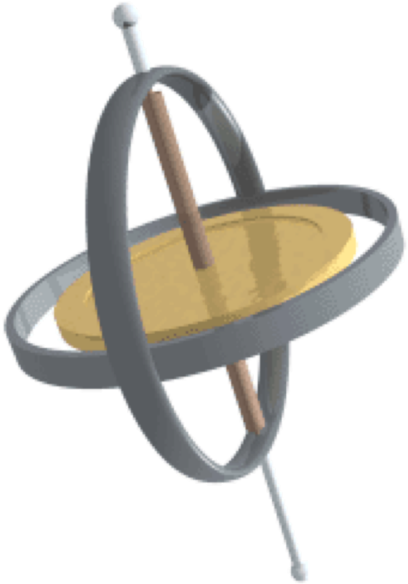
The magnetic moment determines how something interacts with a magnetic field

The muon has an intrinsic magnetic moment that is coupled to its spin via the gyromagnetic ratio *g*:

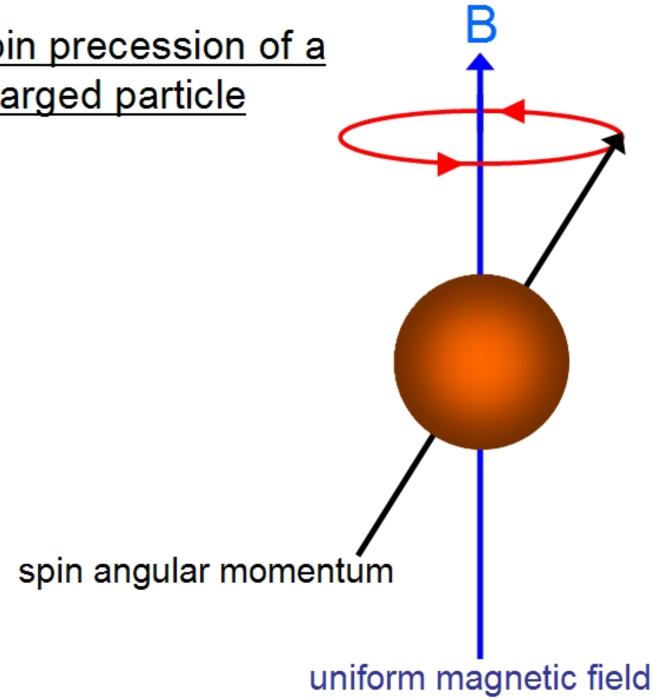
$$\vec{\mu} = g\frac{e}{2m_\mu}\vec{S}$$

When placed in a magnetic field this causes the spin to precess at a frequency determined by g

$$a_\mu = \frac{g-2}{2}$$

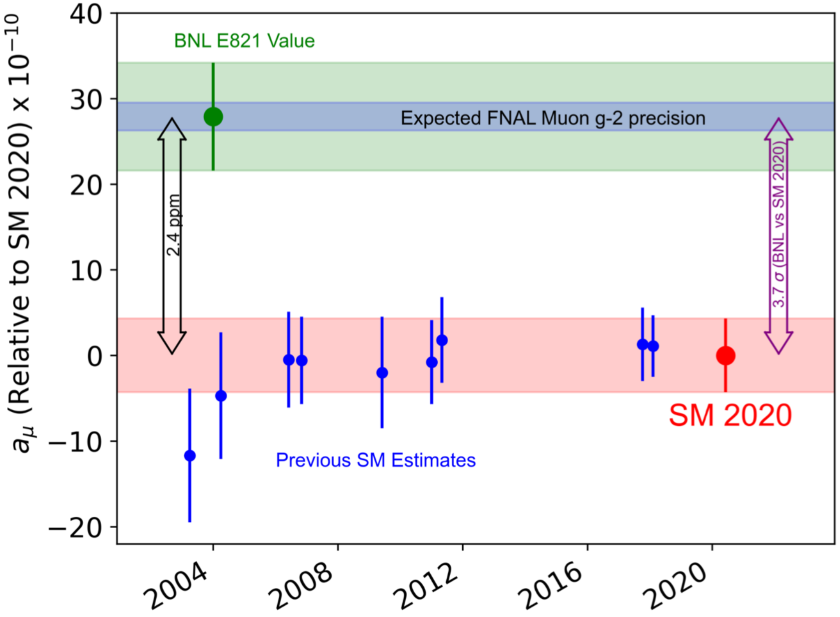


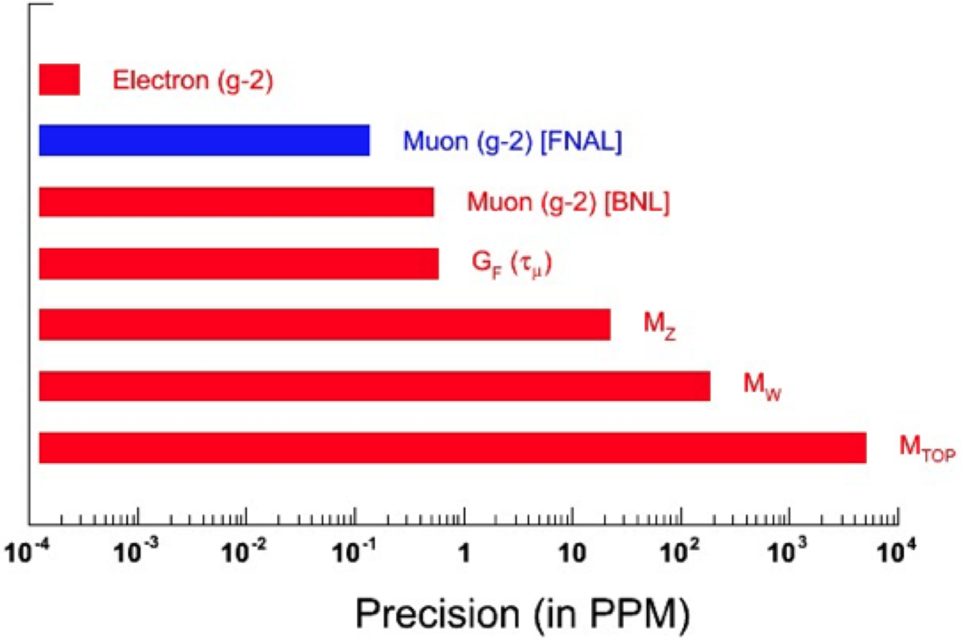
Spin precession of a charged particle



Precision

The g-2 experiment at Fermilab aims to measure the anomalous magnetic moment of the muon to a precision of 140 ppb



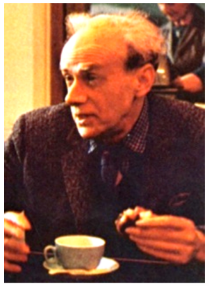


The BNL E821 measurement had an uncertainty of 540 ppb or 2.4ppm

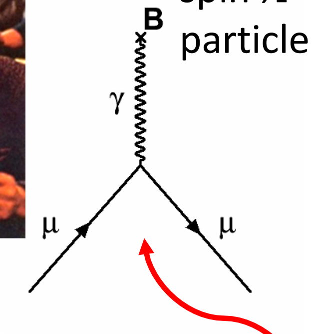
The first result from the Fermilab experiment is on a dataset of a similar size ~10 billion μ^+

The Standard Model Contributions

Dirac



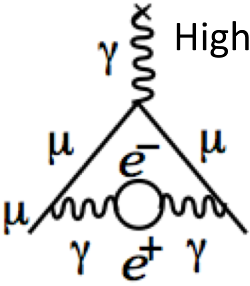
Charged,
spin ½
particle



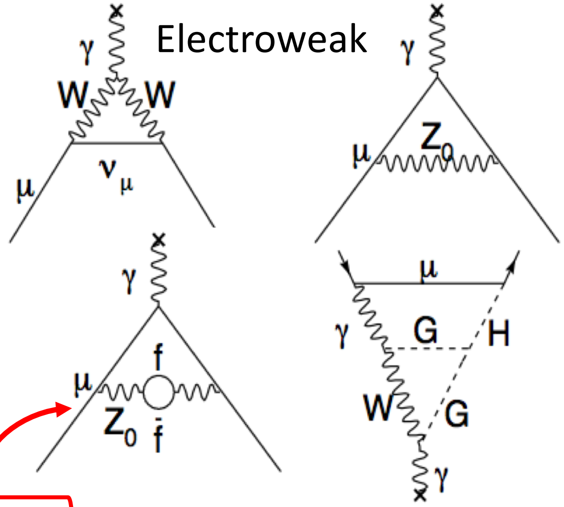
Kinoshita

12672
diagrams

Higher Order
QED

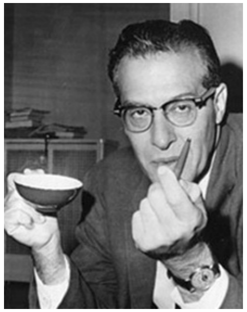


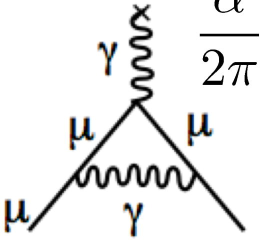
Electroweak



$$g_\mu = 2.002\,331\,841\,78(126)$$

Schwinger

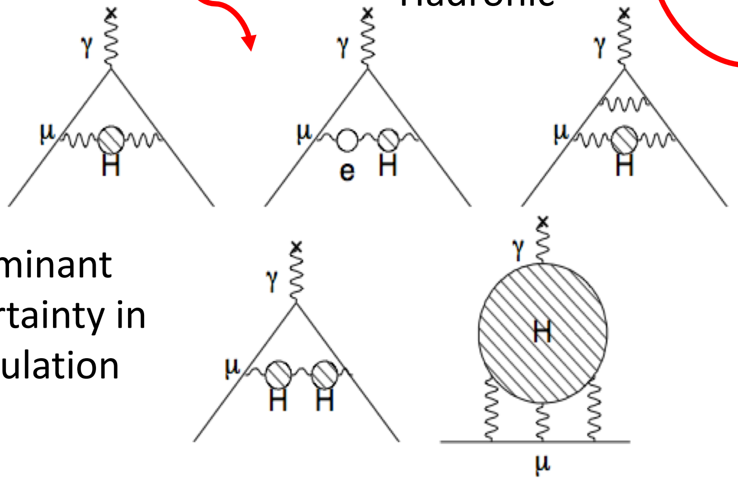




$$\frac{\alpha}{2\pi} = 0.00232$$

1st Order QED

Hadronic



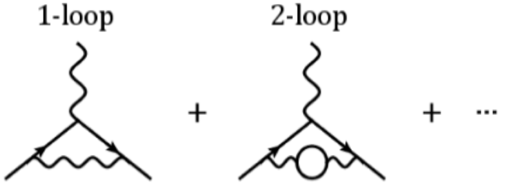
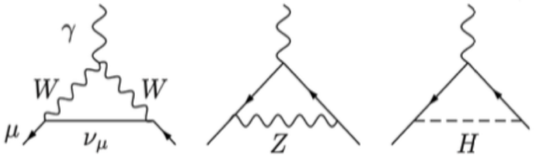
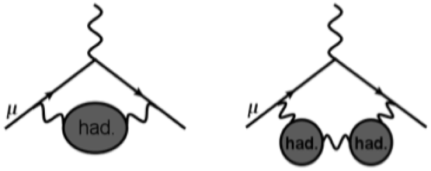
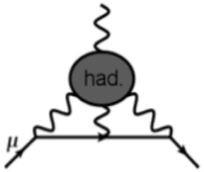
Dominant
uncertainty in
calculation

?

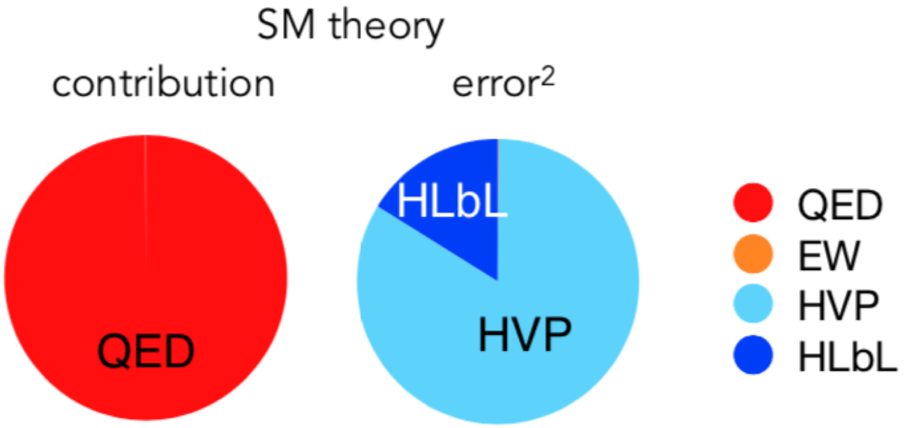
Theoretical Contributions

All Standard model particles contribute to the theoretical prediction

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{HVP}} + a_\mu^{\text{HLbL}}$$

			a_μ^{SM} portion	δa_μ^{SM} portion
QED		Perturbative (Known to five-loop)	$\sim$ 99.99%	$\sim$0.001%
EW		Perturbative (Known to two-loop)	$\sim$ 1 ppm	$\sim$0.2%
HVP		Non-perturbative (Data-driven & lattice)	$\sim$ 59 ppm	**$\sim$84%**
HLbL		Non-perturbative (Data-driven & lattice)	$\sim$ 1 ppm	**$\sim$16%**

Theory Summary



Muon g-2 theory initiative recommended result:

$$\Delta a_\mu = 279(76) \times 10^{-11} \rightarrow 2.39(0.65)\ \text{ppm}$$

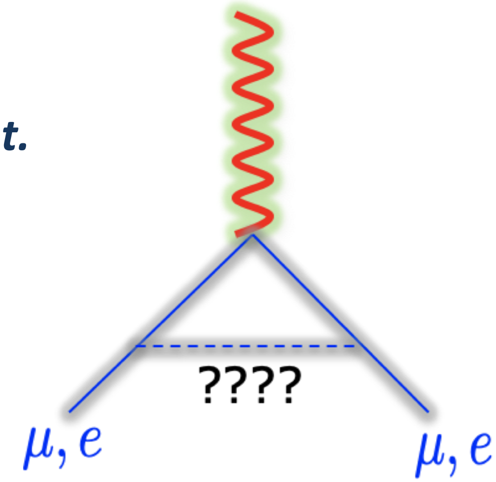
Results in 3.7σ discrepancy when compared to BNL measurement.

New physics contributes as:

$$\left(\frac{m_\ell}{M_{\text{NEW}}}\right)^2$$

The muon has a mass advantage

$$\left(\frac{m_\mu}{m_e}\right)^2 \approx 44{,}000$$



Muons at Fermilab

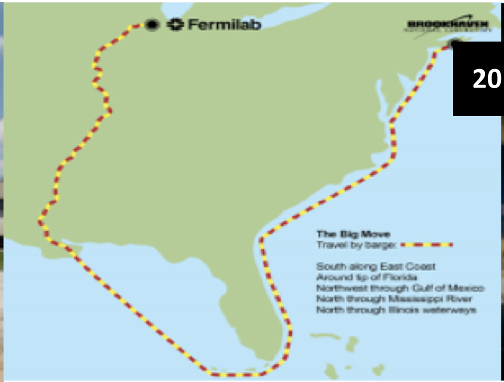
Lower instantaneous rate but larger integrated rate than BNL

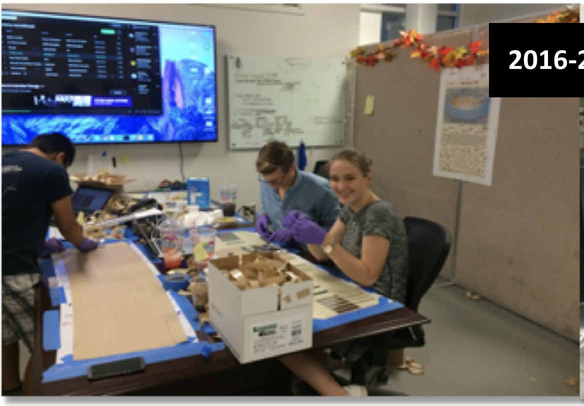
~ 10,000μ^+ (from 10^{12} p) at 3.1 GeV every 10 ms

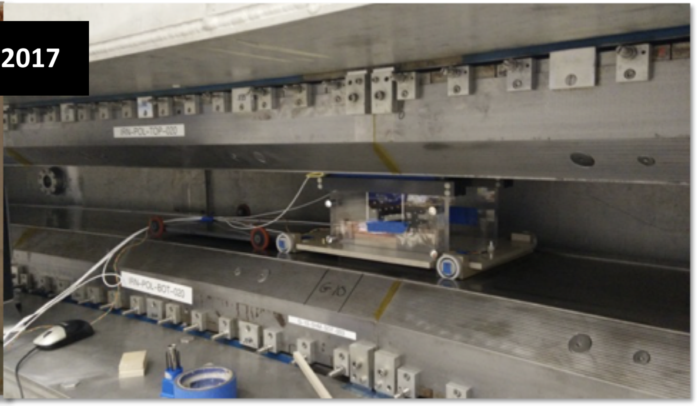
(g-2): ⅓ of proton cycles, neutrino expts: ⅔

Extra 900m of instrumented beamlines

The Road to Data Taking

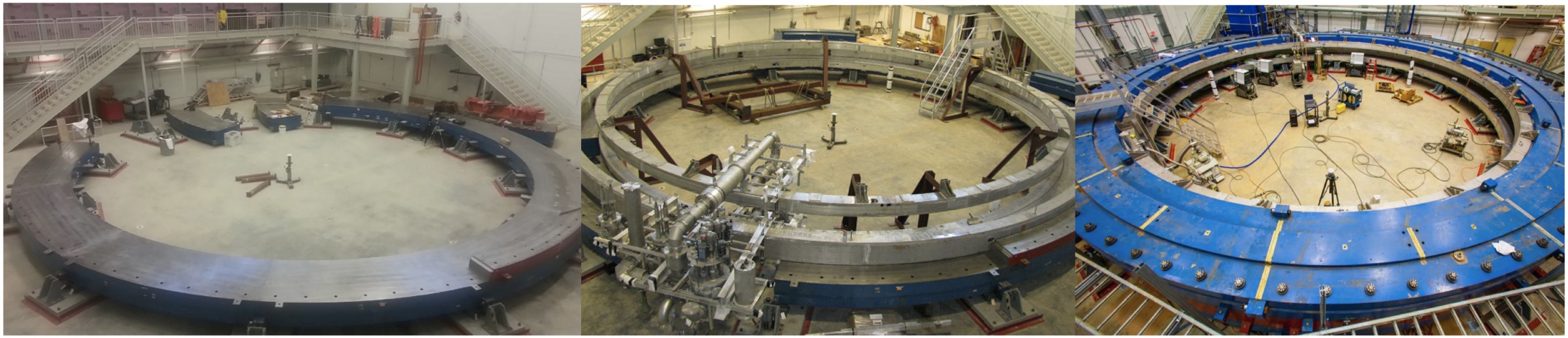




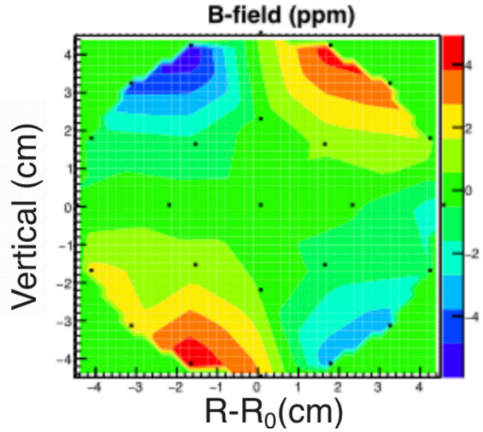


Run-1 data taking started Feb. 2018

Magnet Shimming



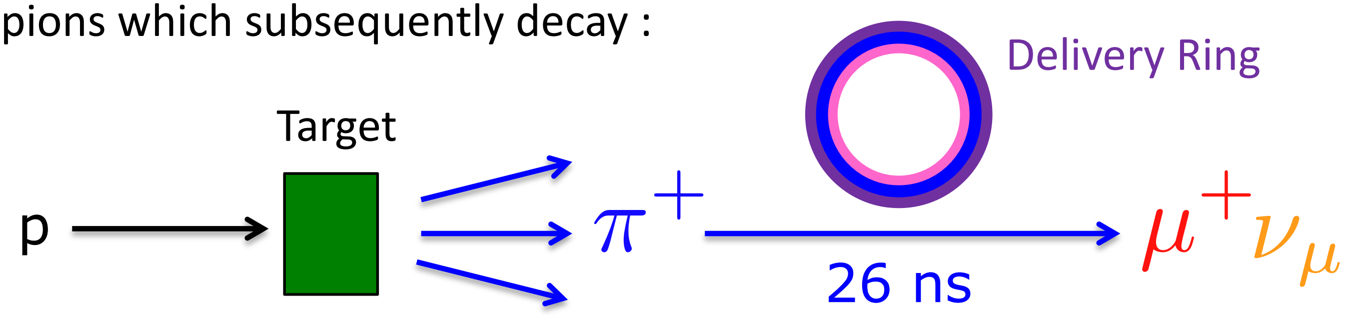
Magnetic field uniformity 3 times better than the goal (BNL)



Muon Production

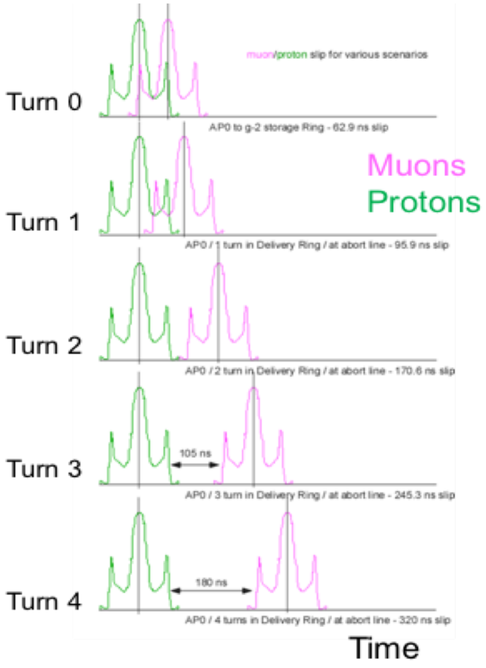
A proton beam is hit into a pion production target and the muons from the pion decays are collected

Protons hit a pion target to produce pions which subsequently decay :



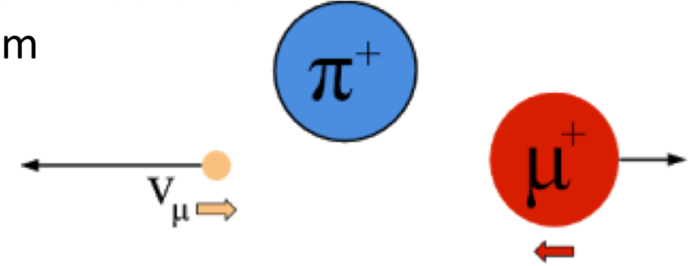
3.11 GeV pions selected using a lithium lens

The muons and protons separate as they go around the delivery ring



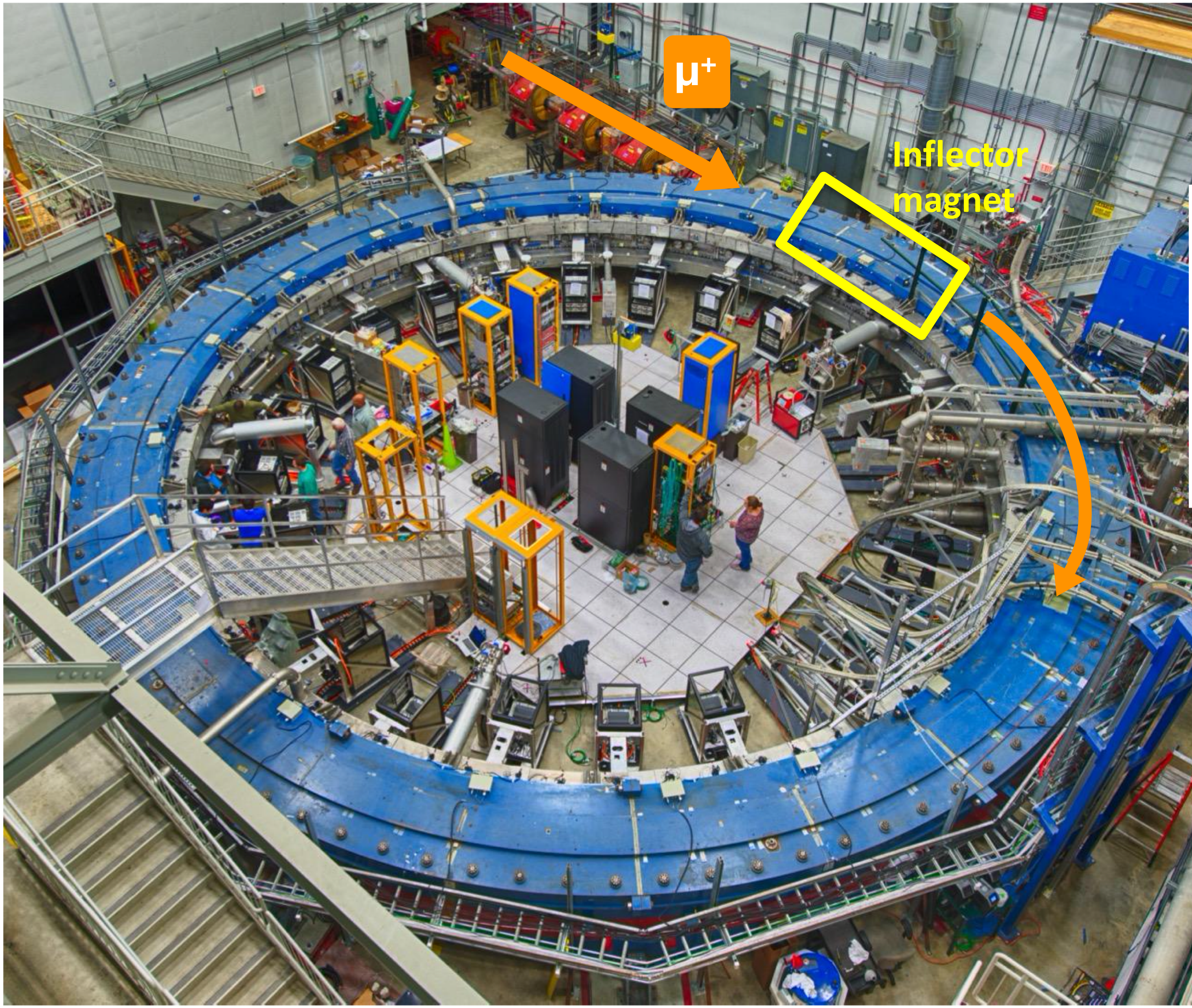
In the pion decay the neutrino must have spin opposite to the momentum

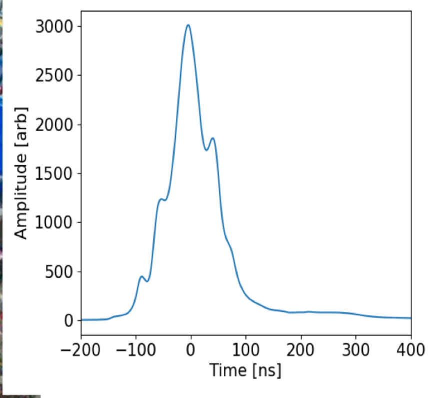
→ To conserve spin the muon spin must also be opposite to the momentum



We get a naturally polarised muon beam from the physics of the pion decays

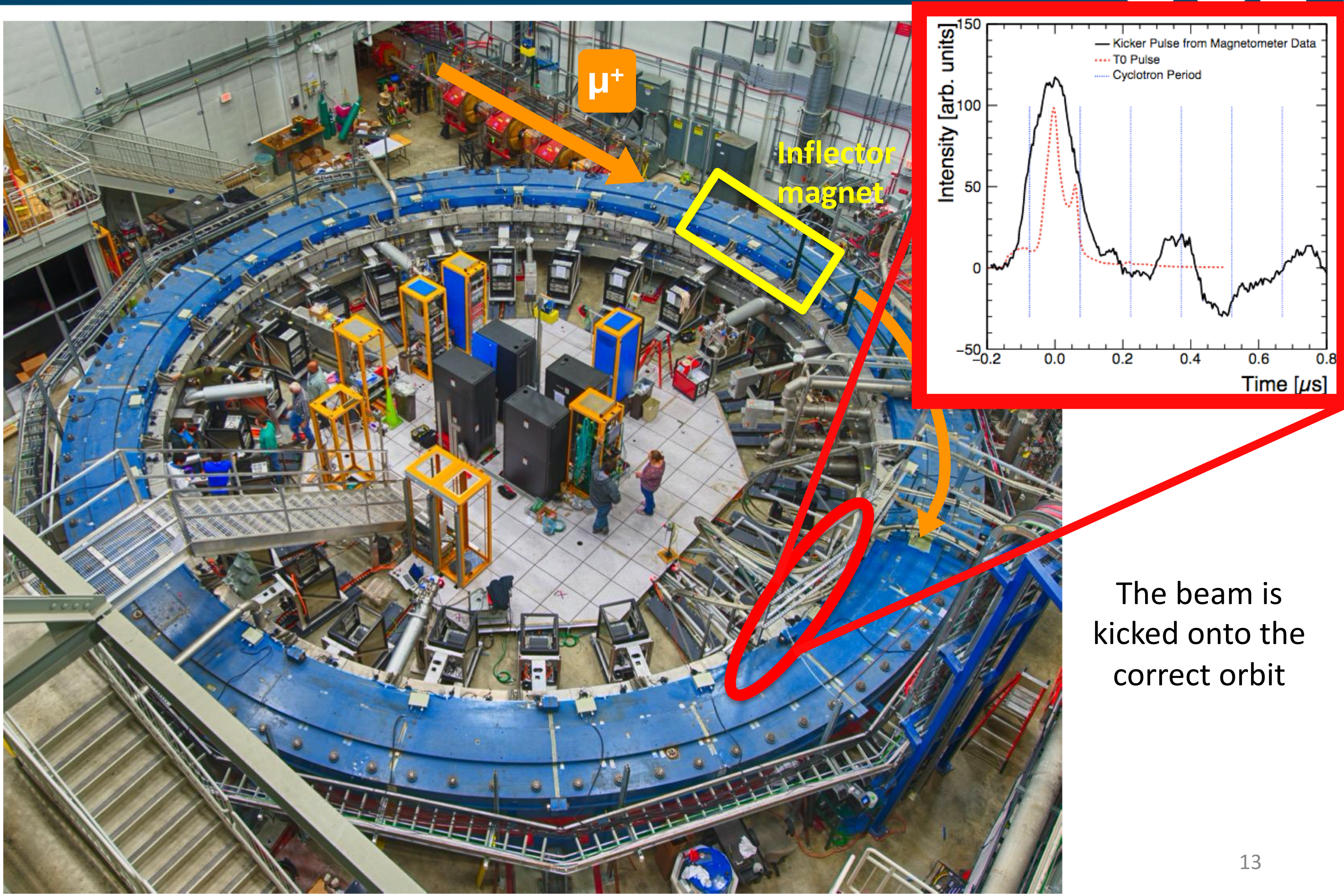
Beam Injection





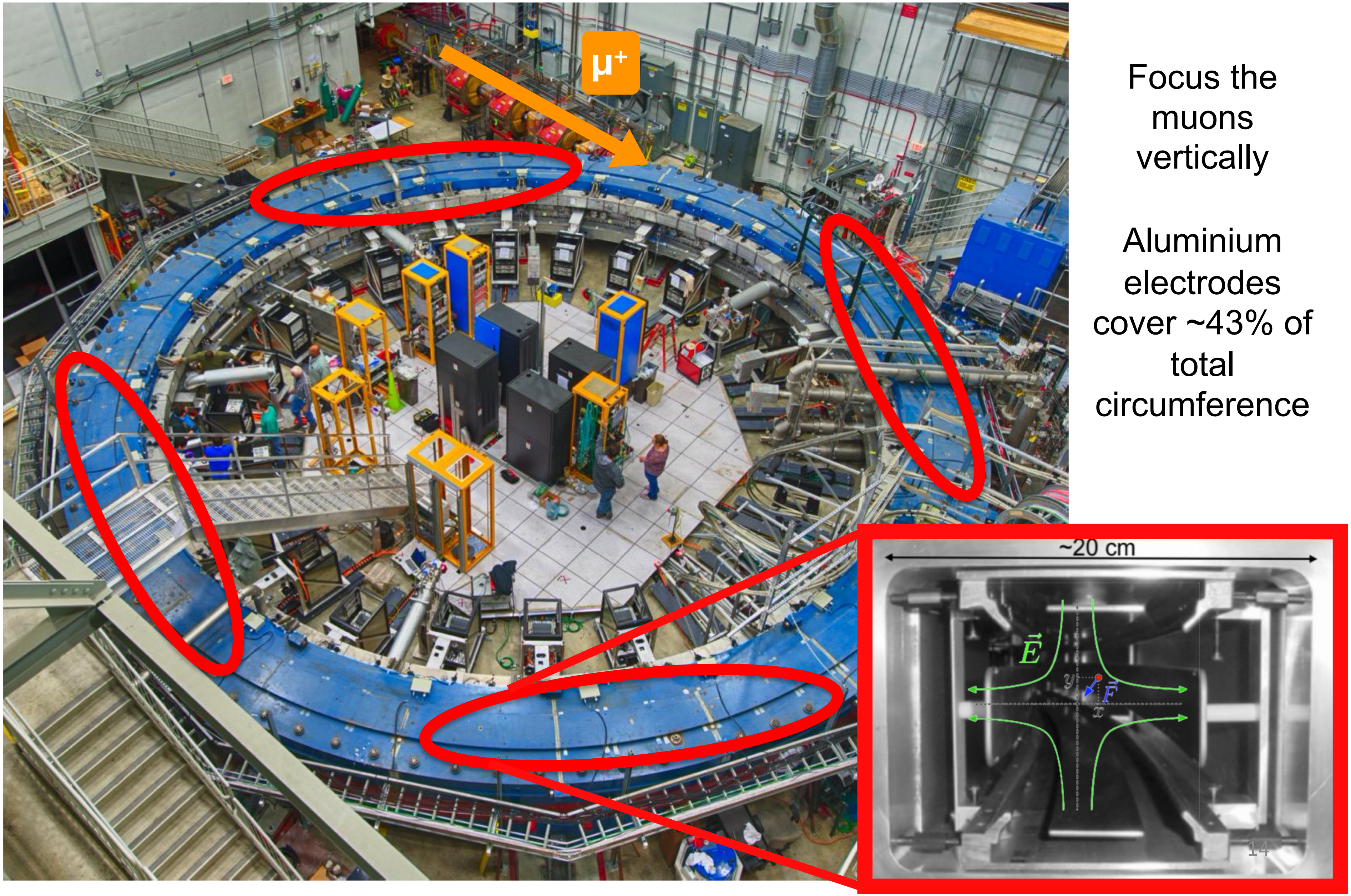
The time and spatial distribution of the beam is monitored at injection

Kicker Magnets



The beam is kicked onto the correct orbit

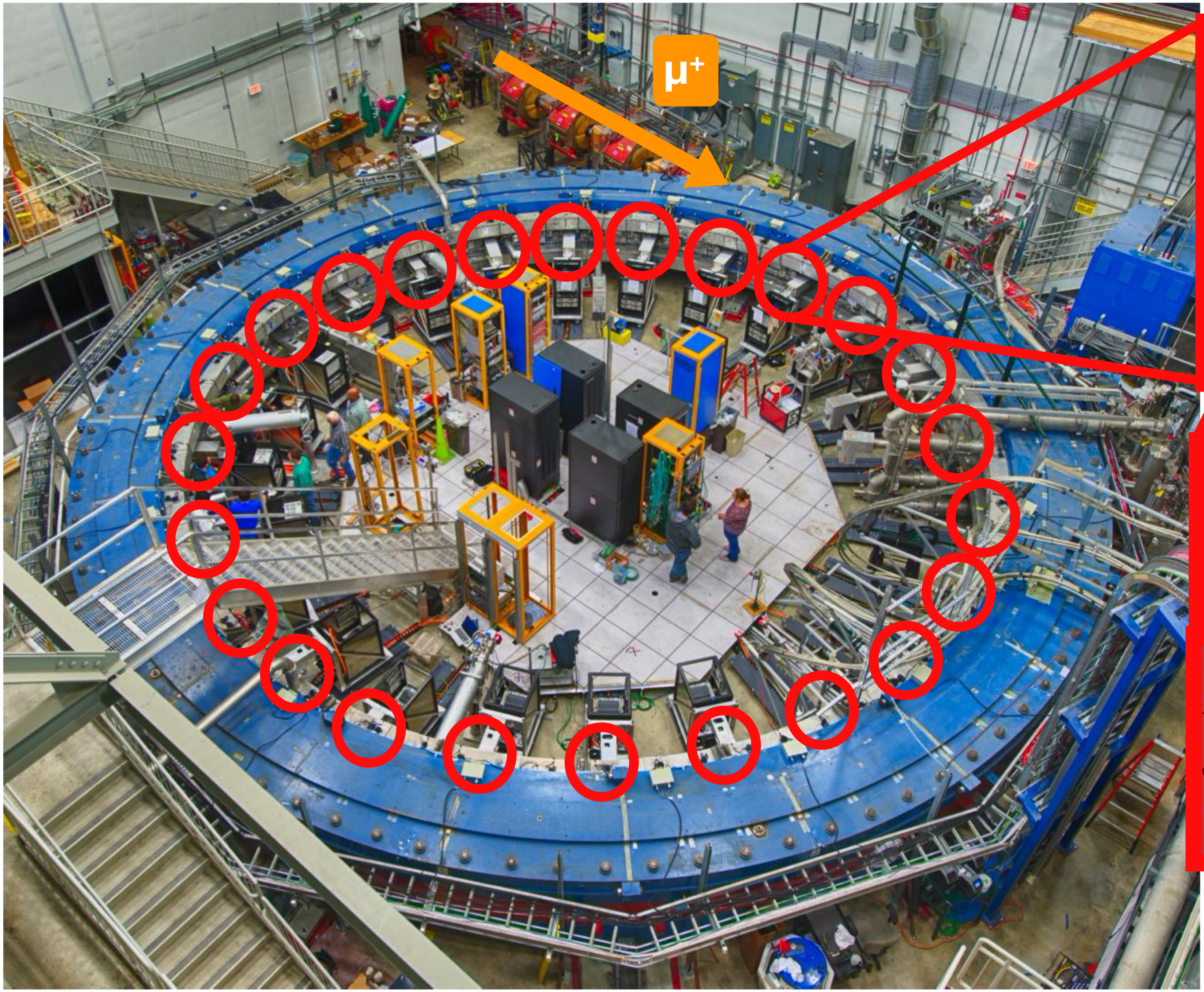
Beam Focussing



Focus the muons vertically

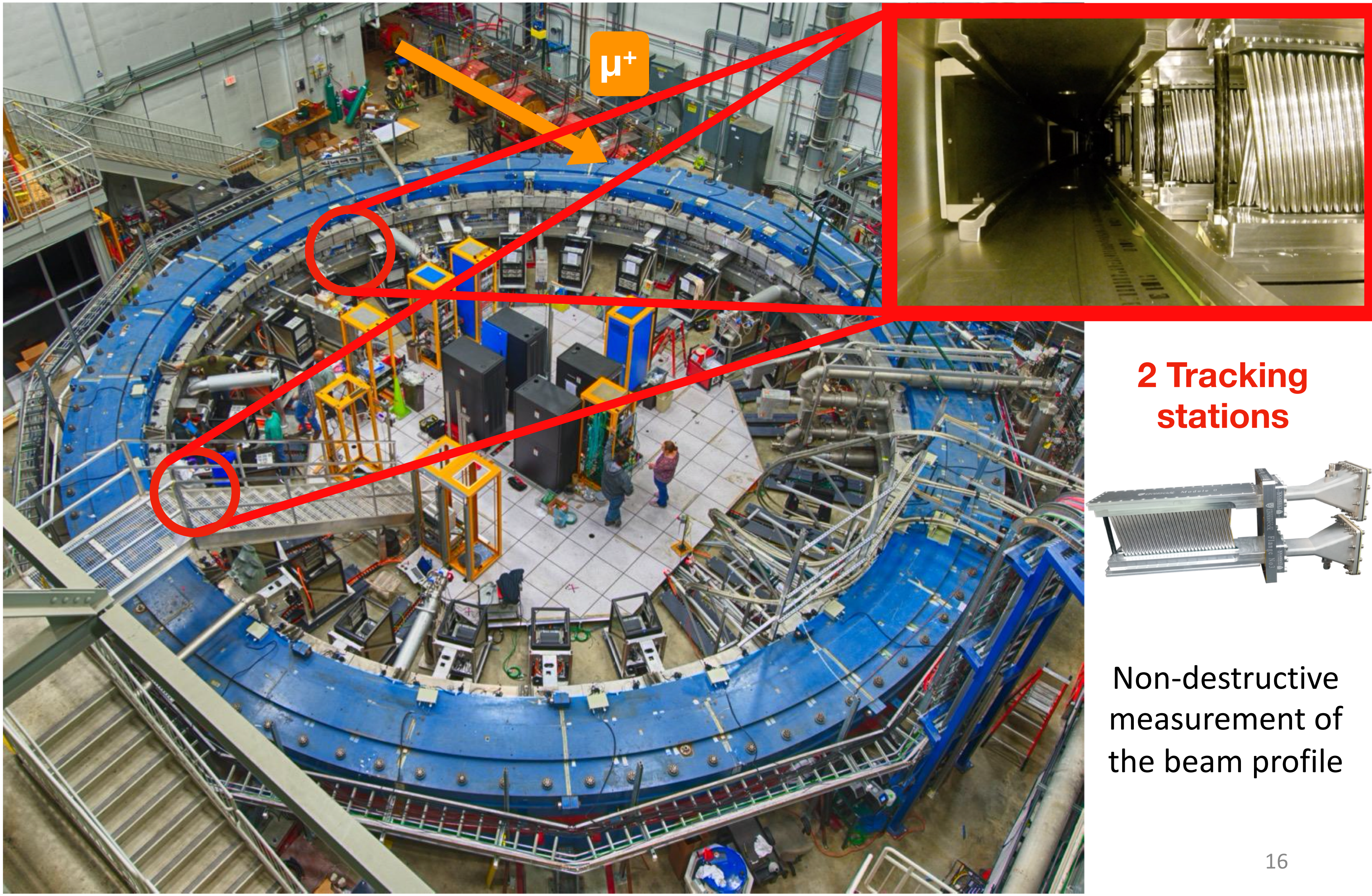
Aluminium electrodes cover ~43% of total circumference

Calorimeters



24 Calorimeters

Tracking Detectors



2 Tracking stations

Non-destructive measurement of the beam profile

Measurement Principle

- Inject polarised muon beam into magnetic storage ring
- Measure difference between spin precession and cyclotron frequencies

$$g = 2,\ \omega_a = 0$$

$$g \neq 2,\ \omega_a \propto a_\mu$$

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{mc}$$

Spin precession freq.

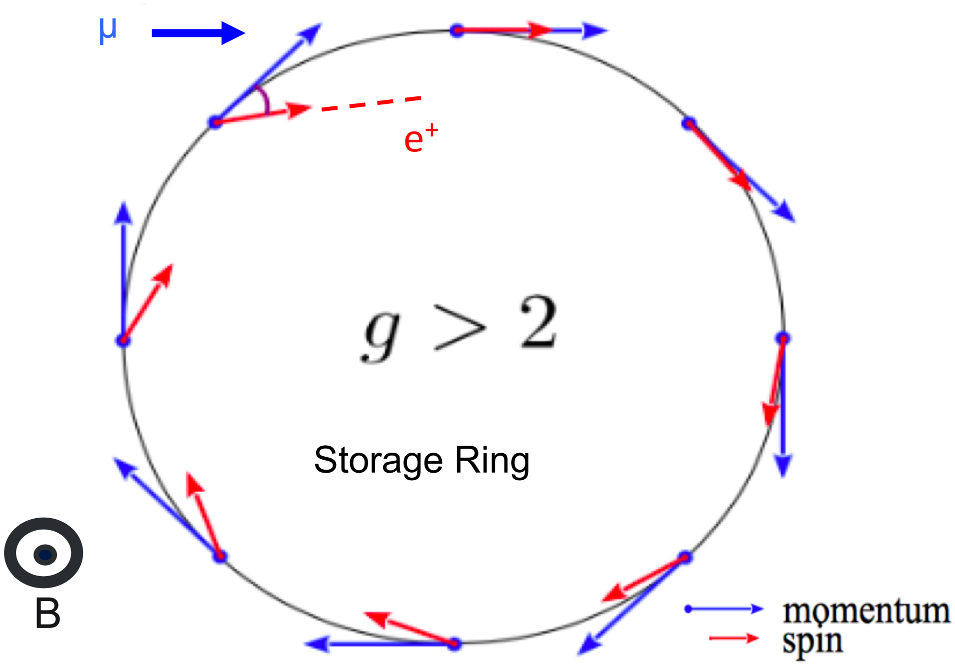
$$\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

Larmor precession

Thomas precession

Cyclotron freq.

$$\omega_c = \frac{eB}{\gamma mc}$$



Measurement Details

The experiment actually measures two frequencies

$$a_\mu = \underset{\text{What we measure}}{\boxed{\frac{\omega_a}{\tilde{\omega}_p}}} \overset{\text{3ppb}}{\frac{\mu_p}{\mu_e}} \underset{\text{22ppb}}{\frac{m_\mu}{m_e}} \overset{\text{0.0003ppb}}{\frac{g_e}{2}}$$

Unblinding conversion factor

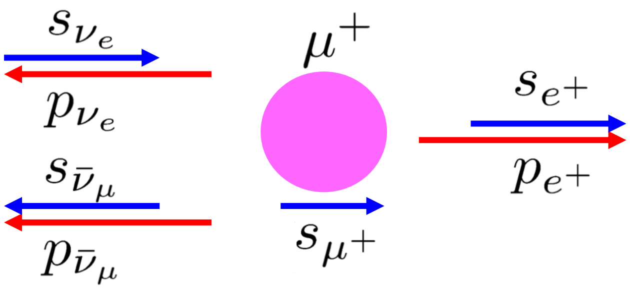
Measured $g-2$ frequency

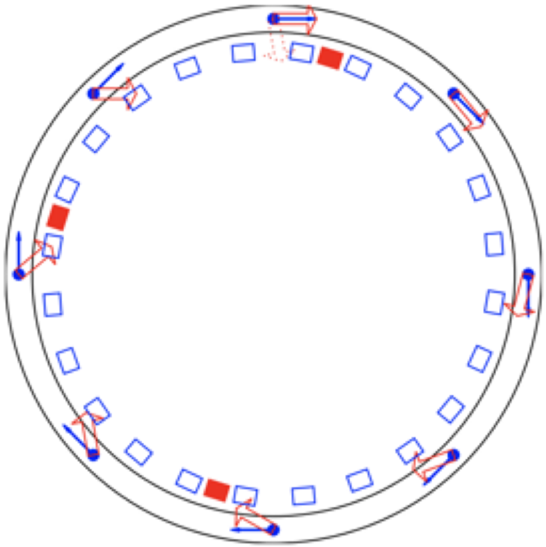
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\,(1 + \overbrace{C_e + C_p + C_{ml} + C_{pa}}^{\text{Corrections from the beam dynamics systematic effects}})}{f_{\text{calib}}\ \underbrace{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle}_{\text{Magnetic field weighted over the muon distribution and azimuthally averaged}}(1 + \underbrace{B_k + B_q}_{\text{Corrections from the transient magnetic field}})}$$

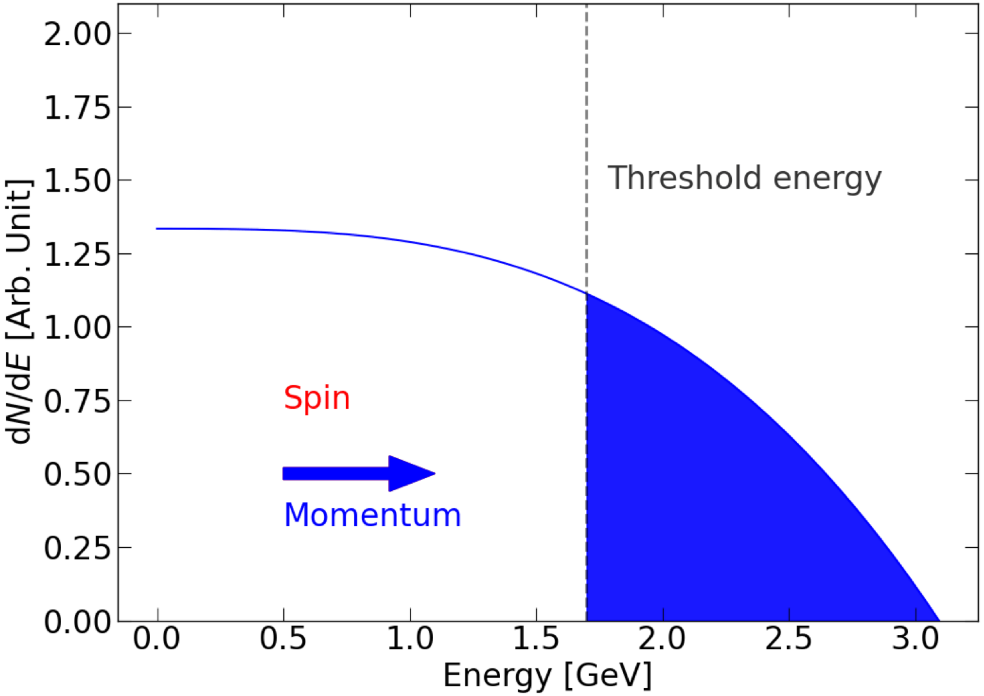
NMR probe calibration factor

Measuring ω_a

High energy e^+ preferentially emitted in direction of muon spin

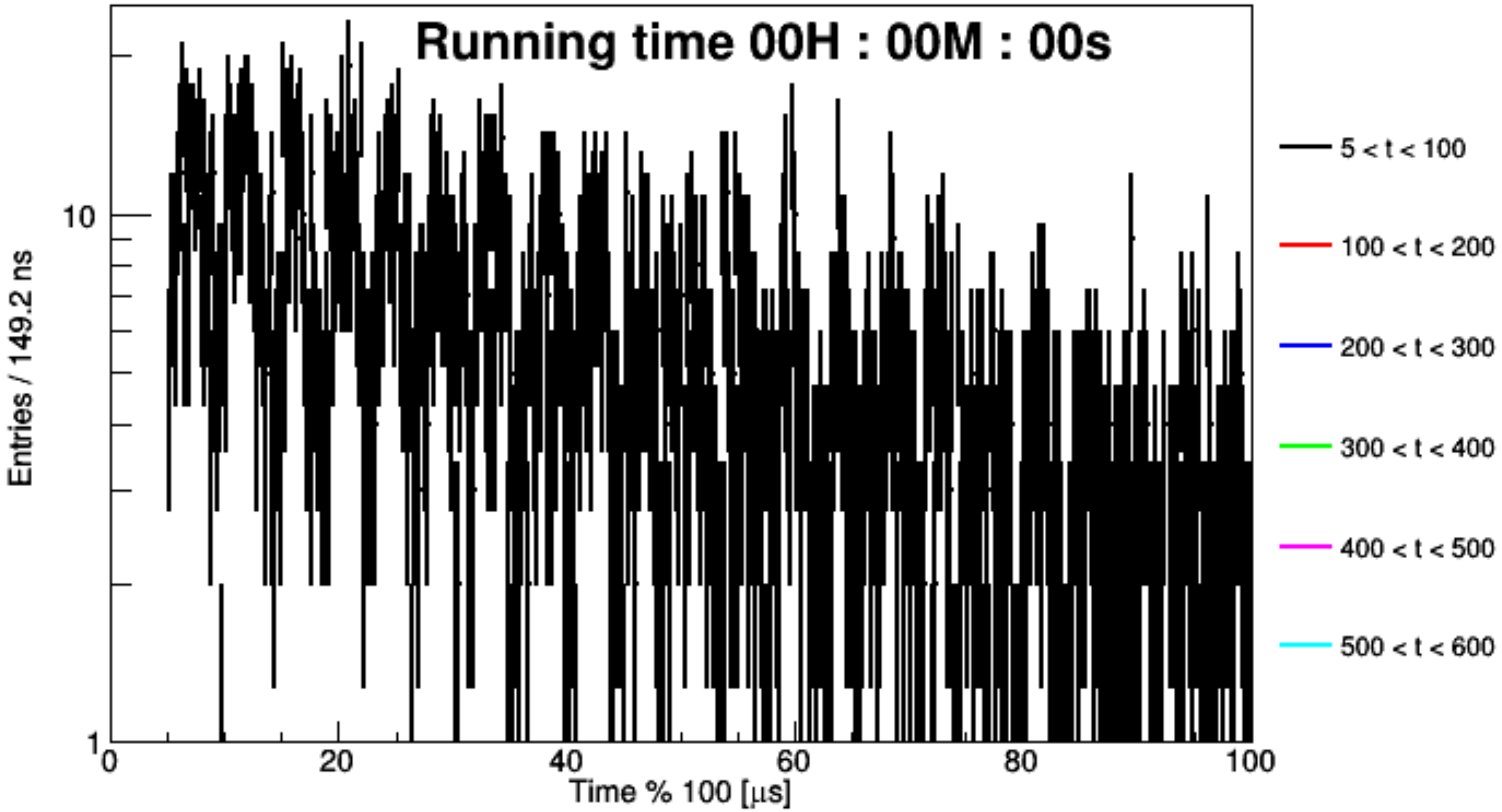






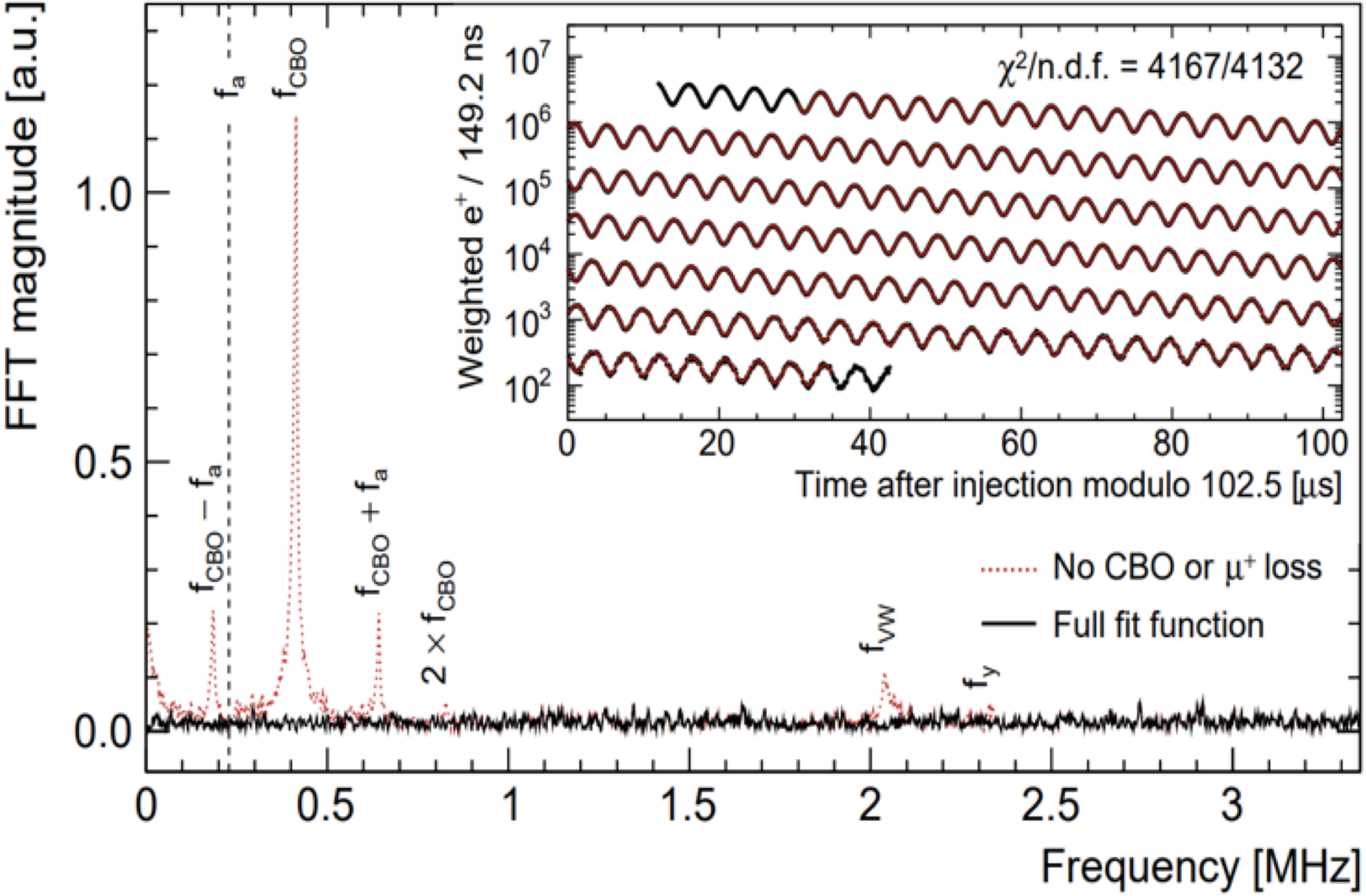
Simply count the number above an energy threshold vs time

Wiggle Plot



$$N_e(t) \simeq N_0 e^{-\frac{t}{\gamma\tau}}[1 - A\cos(\omega_a t + \phi_a)]$$

Fitting for ω_a



Beam Corrections

The beam has a small vertical component which is focused using electrostatic quadrulpoles, but this introduces extra terms

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

We can minimise the first by choosing γ = 29.3 to give p_μ = 3.1GeV, the magic momentum

For a 1.45T field, this sets the radius of the ring to 7.11m

However we now have 2 corrections to make to a_μ because:

Not all muons are at the 'magic' momentum of 3.1GeV

E-field correction

$$C_E = \frac{\Delta\omega_a}{\omega_a}$$

Vertical momentum component aligned with B field

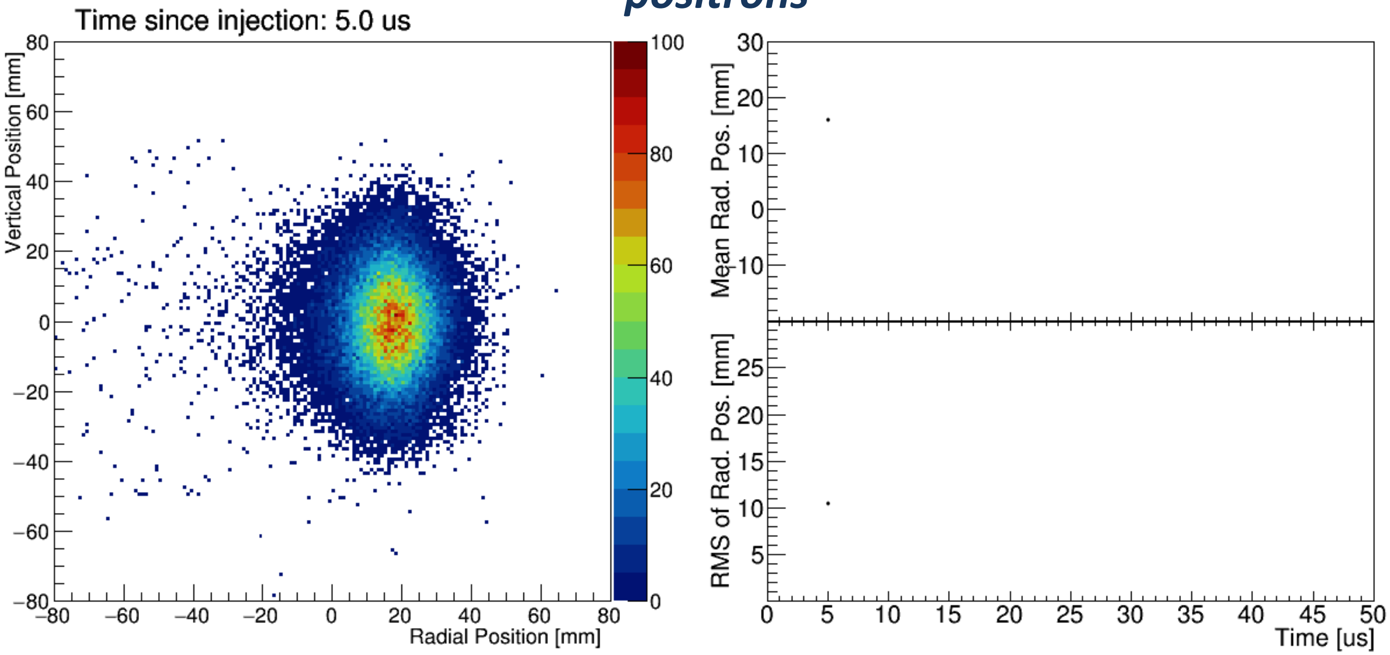
Pitch correction

$$C_p = \frac{\Delta\omega_a}{\omega_a}$$

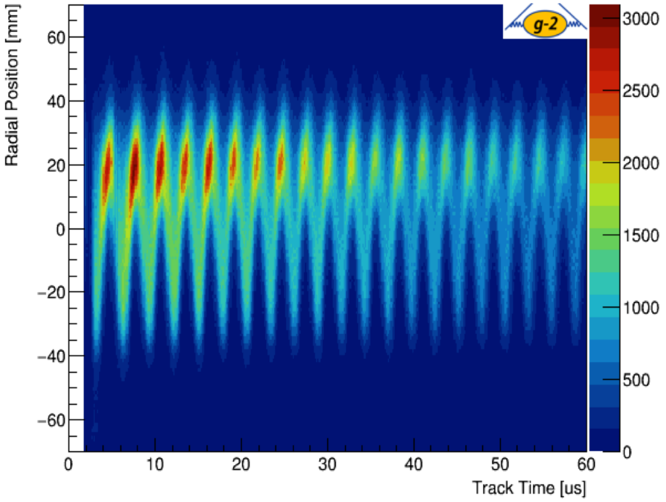
- Both corrections depend on the quadrupole field strength, and are < 0.5ppm

Beam Measurements

The tracking detectors measure the movements of the beam over time from the decay positrons

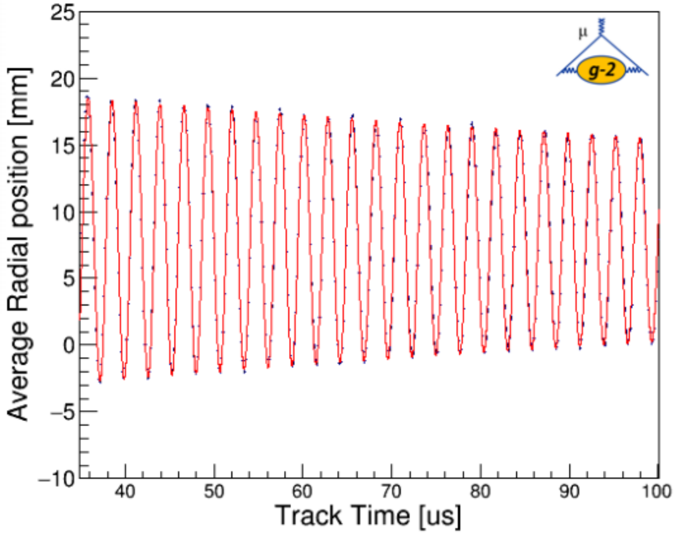


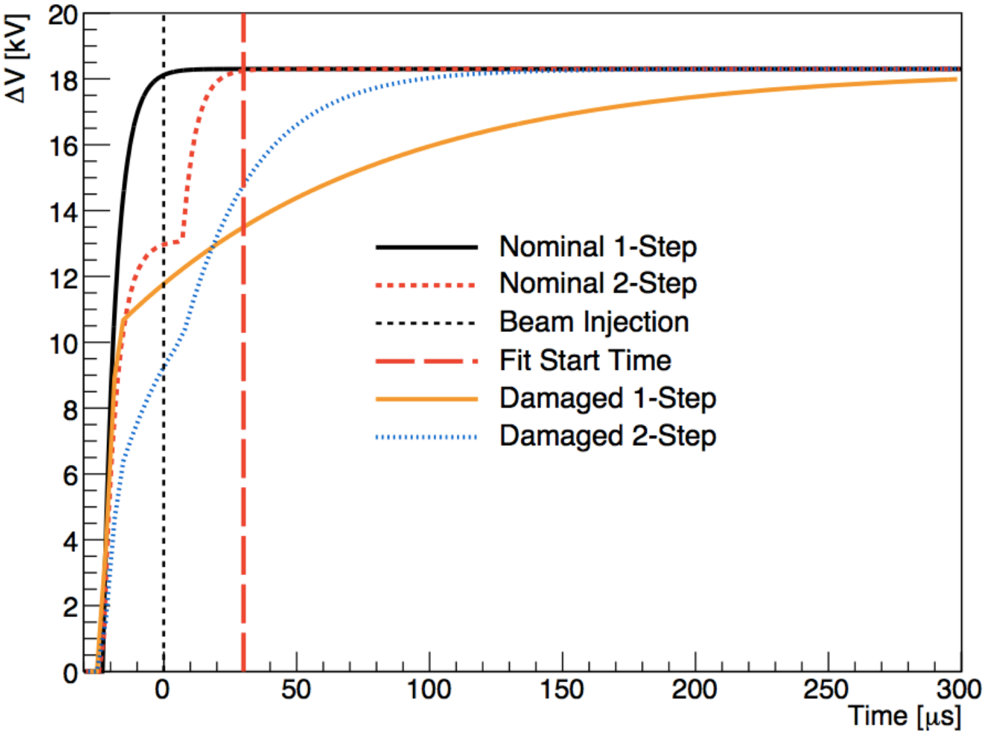
Muons oscillate radially and vertically at different frequencies, according to the quadrupole strength

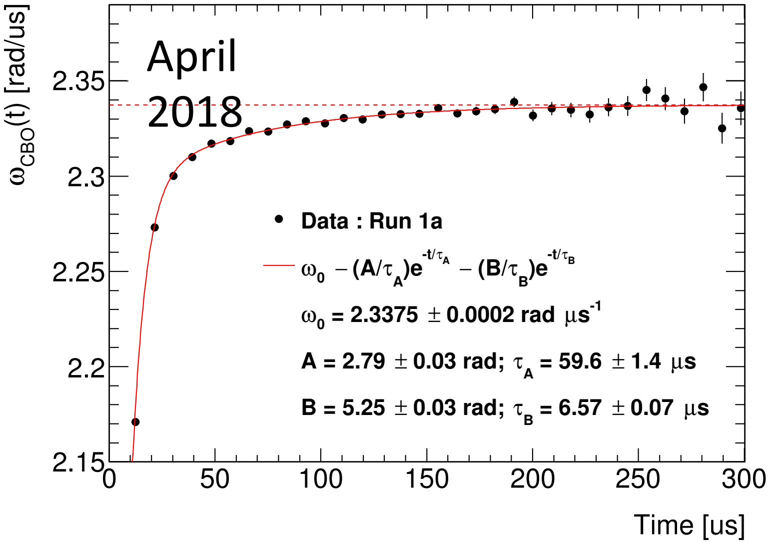


Run-1 Specific Issue

- The beam oscillations were observed to change frequency over time in the fill
- Found to be due to 2/32 faulty resistors in the quads







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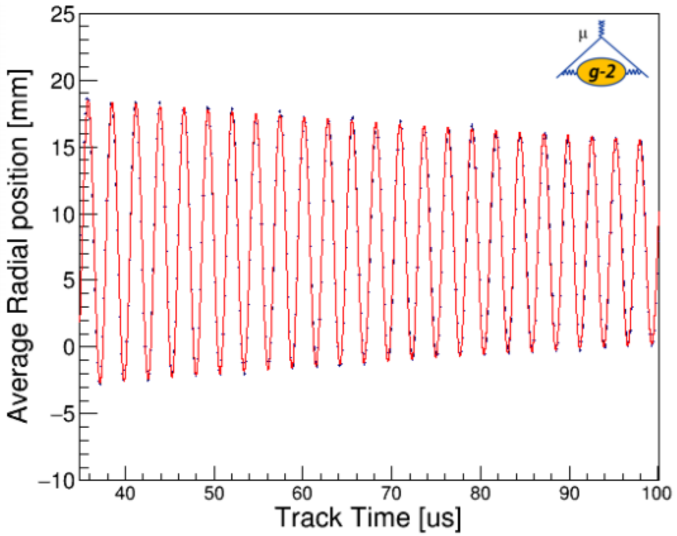
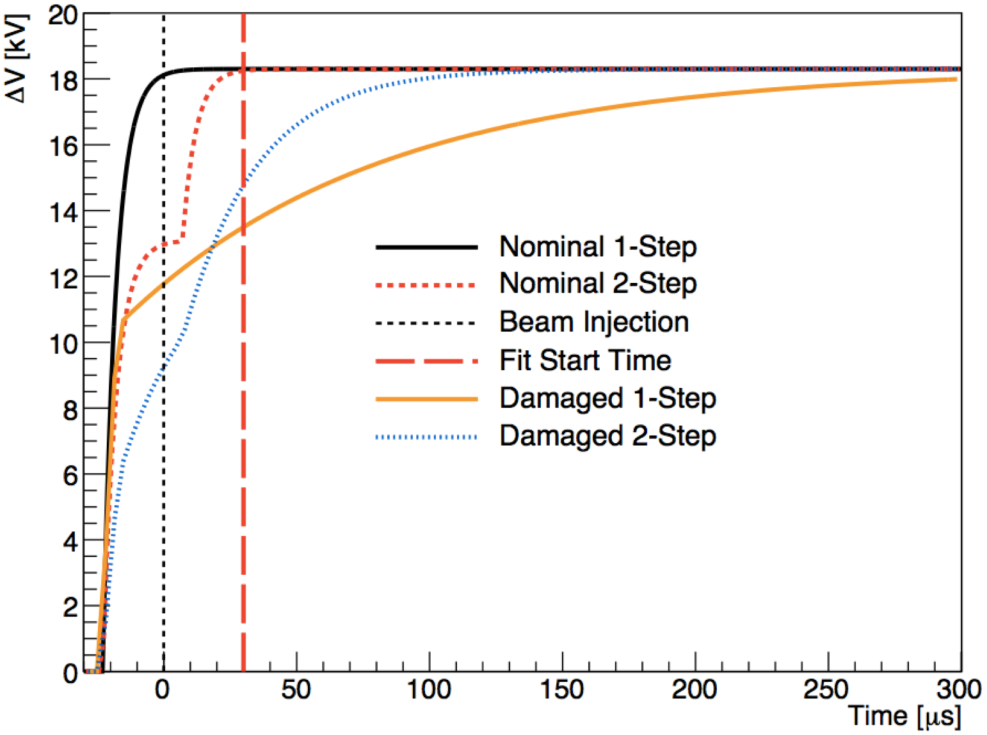
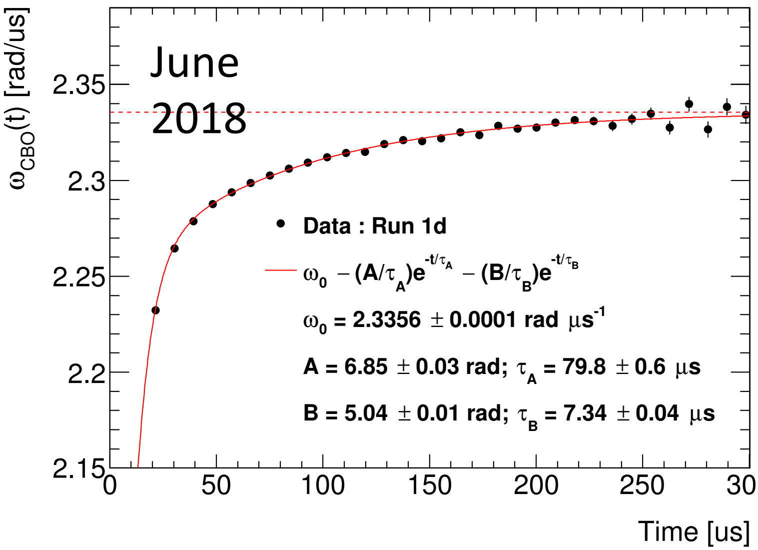
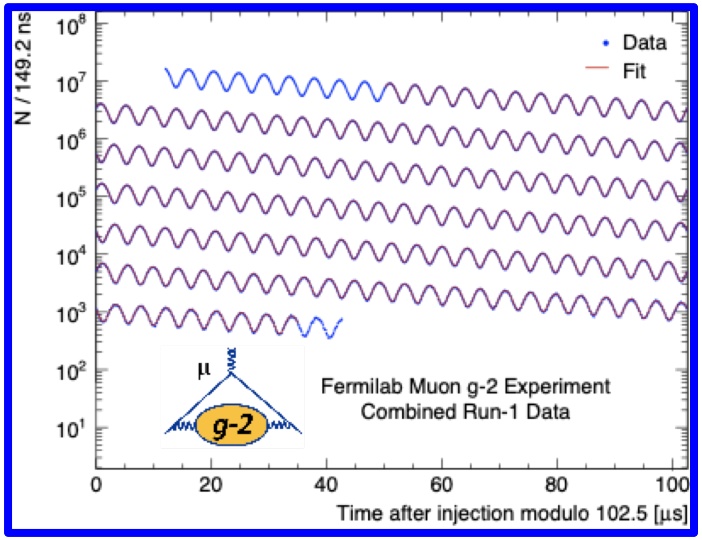





June 2018

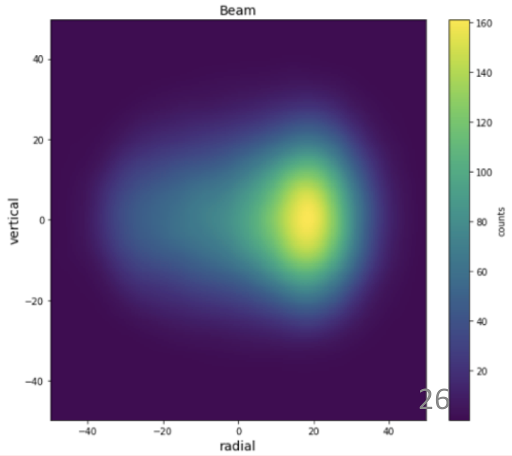
Magnetic Field Measurement



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

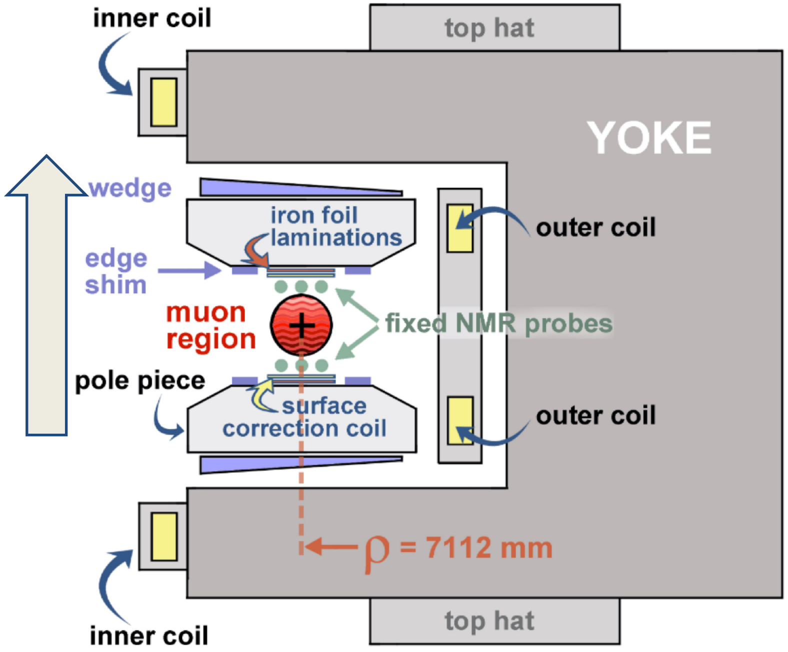
Measuring the magnetic field is the last piece

Muon beam profile



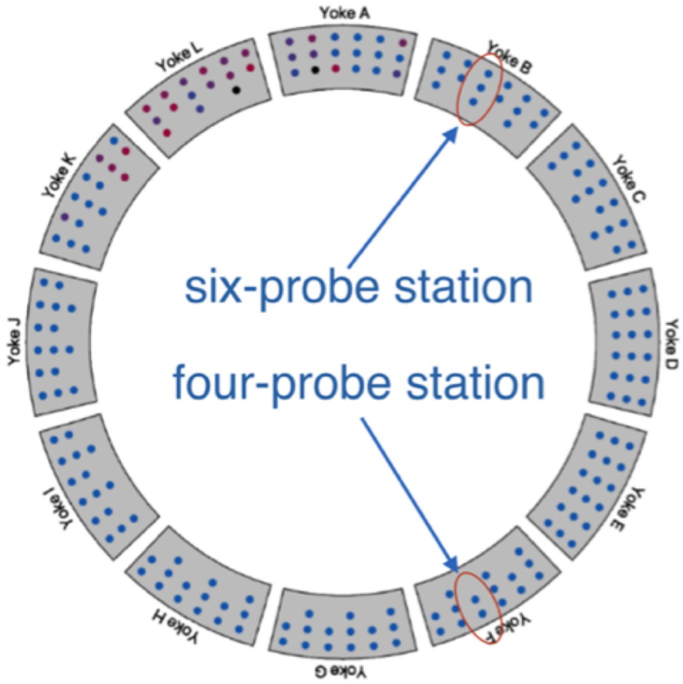
The g-2 Magnet

C-shaped magnet with vertical field (1.45T)



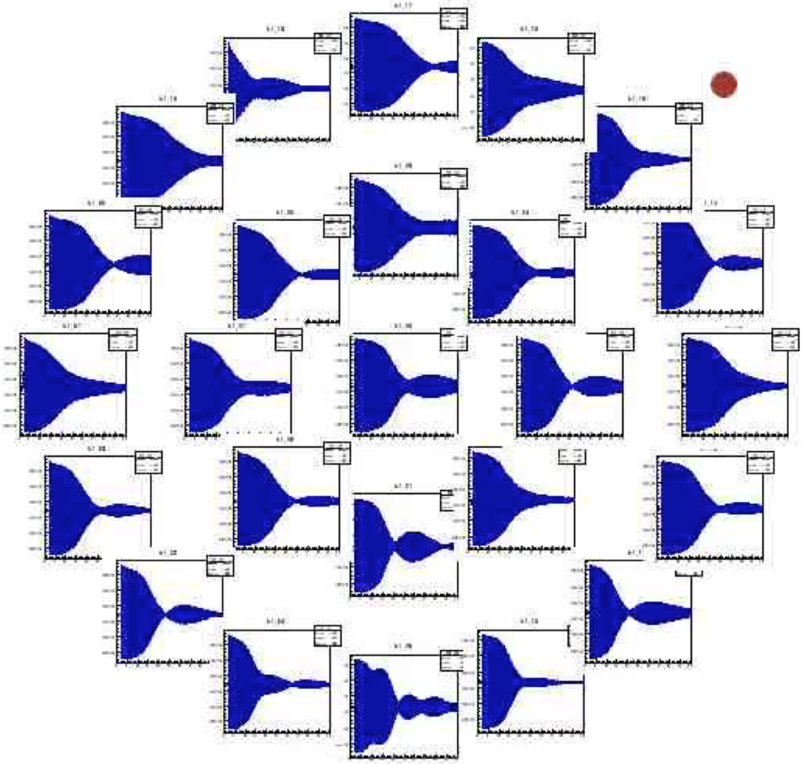
Tiny changes in the magnet geometry driven by temperature changes cause the magnet to drift over time

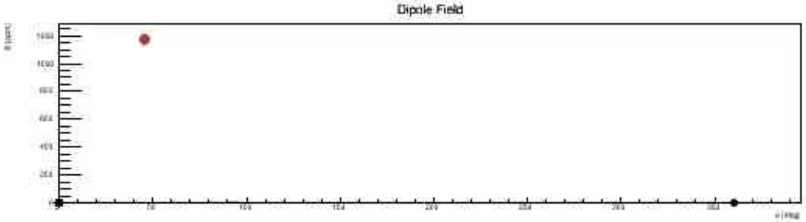
Monitor using pulsed NMR



The Trolley Measurements

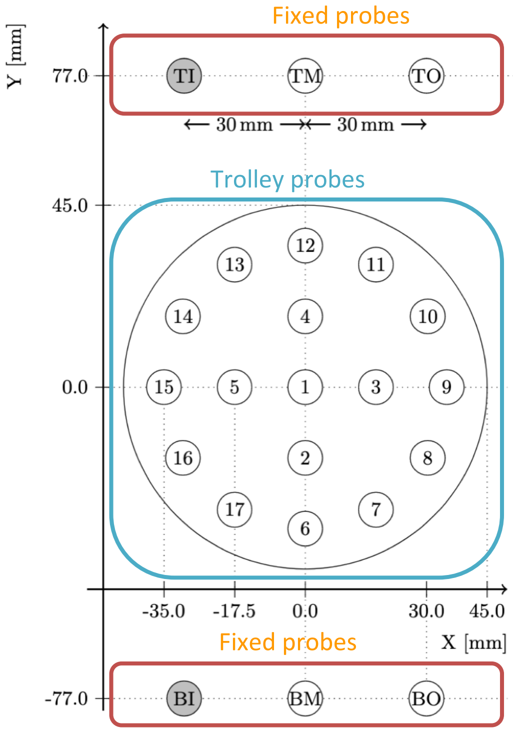
The field is measured using an in vacuum trolley with 17 NMR probes which drives around the ring every ~3 days

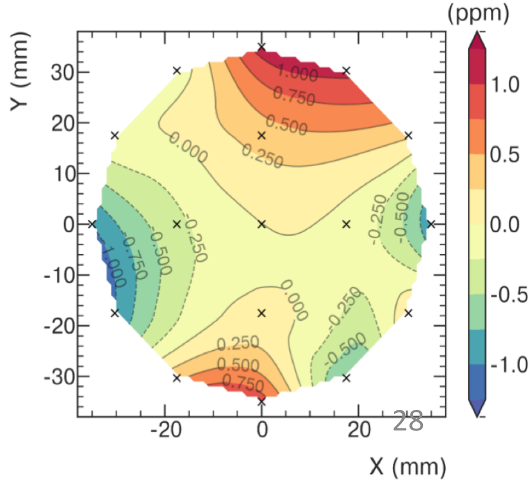




Creates a field map at ~8000 azimuthal locations

Between trolley runs fixed probes outside the storage region monitor the drift



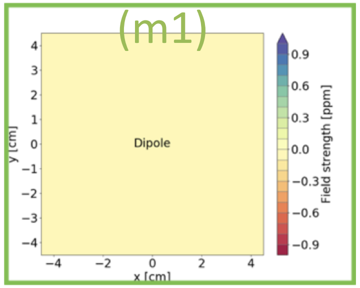


Extracting the Field Distribution

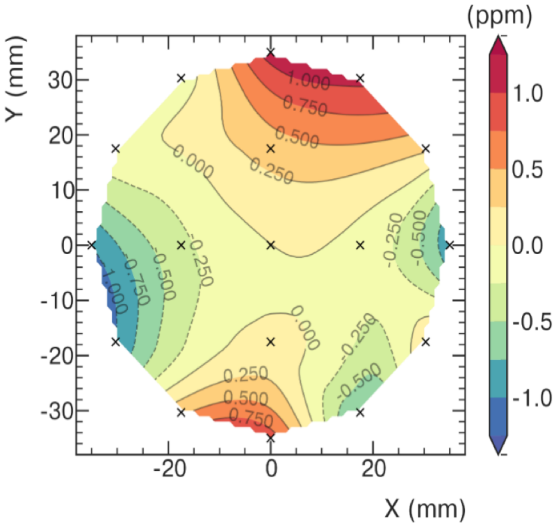
- Extract terms from a multipole (m) expansion of B in r and θ:

$$B \approx B_y = \boxed{A_0} + \sum_{n=1} \left(\frac{r}{r_0}\right)^n \left(\boxed{A_n \cos(n\theta)} + \boxed{B_n \sin(n\theta)}\right)$$

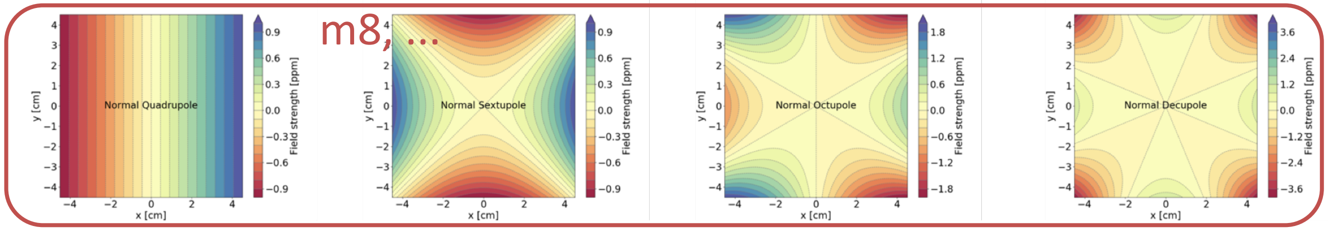
Dipole (m1)

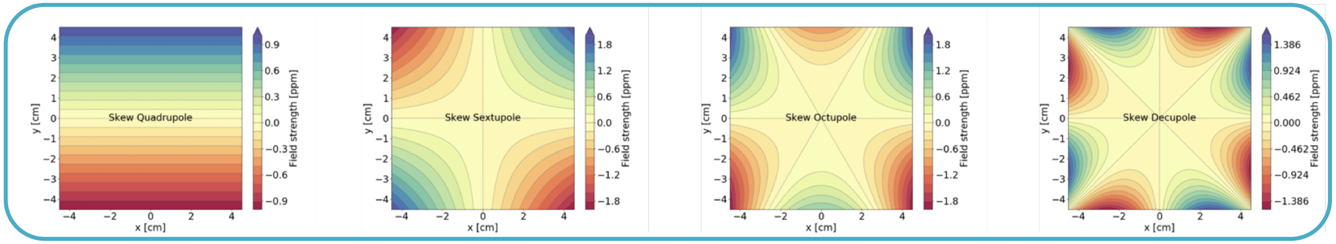


Field gradients in an azimuthal "slice"



"Normal" terms: m2, m4, m6, m8, ...

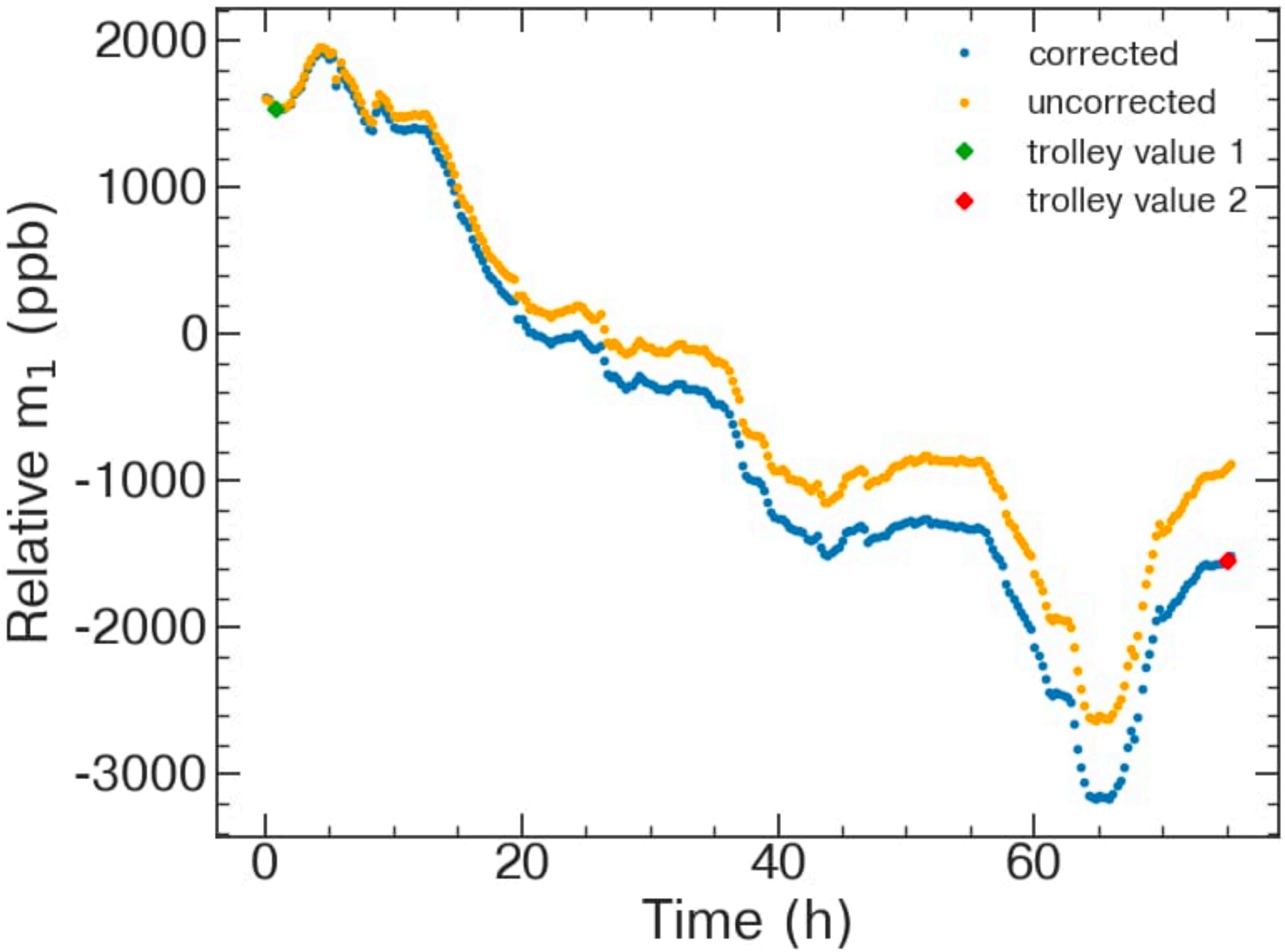




"Skew" terms: m3, m5, m7, m9, ...

Field Interpolation

The fixed probes are used to interpolate the field between trolley runs



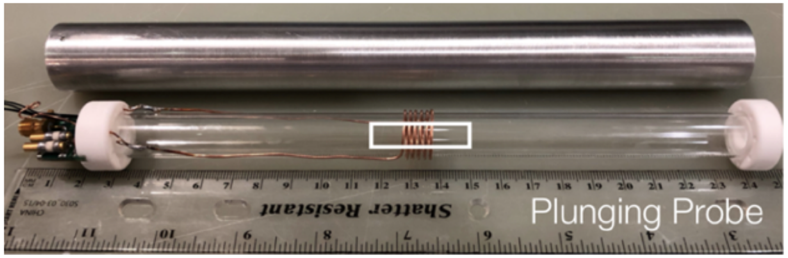
The fixed probes take data continuously

The data is calibrated by the book ending trolley runs (due to changes in the higher order terms)

Leads to a tracking error uncertainty (22 – 43 ppb)

Field Calibration

Calibration (Plunging) probe, placed inside ring and referenced to each trolley probe

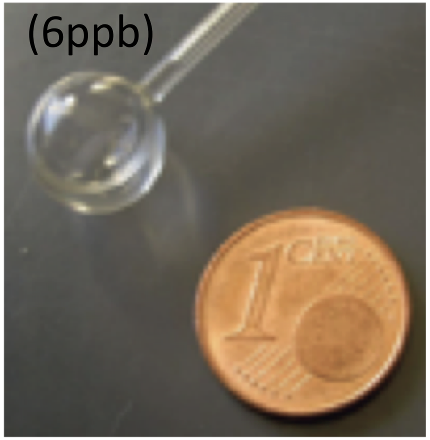


Checked against spherical water sample to get absolute number

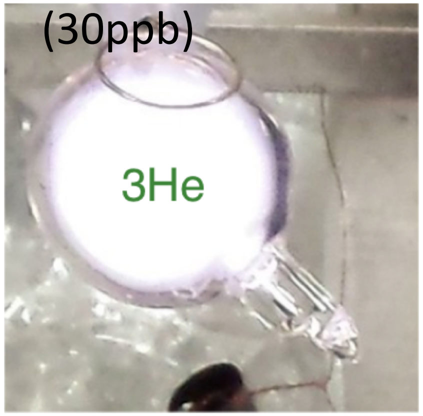
Cross checked with He3 sample, with different systematic uncertainties

Overall calibration uncertainty ~35ppb

spherical water (6ppb)



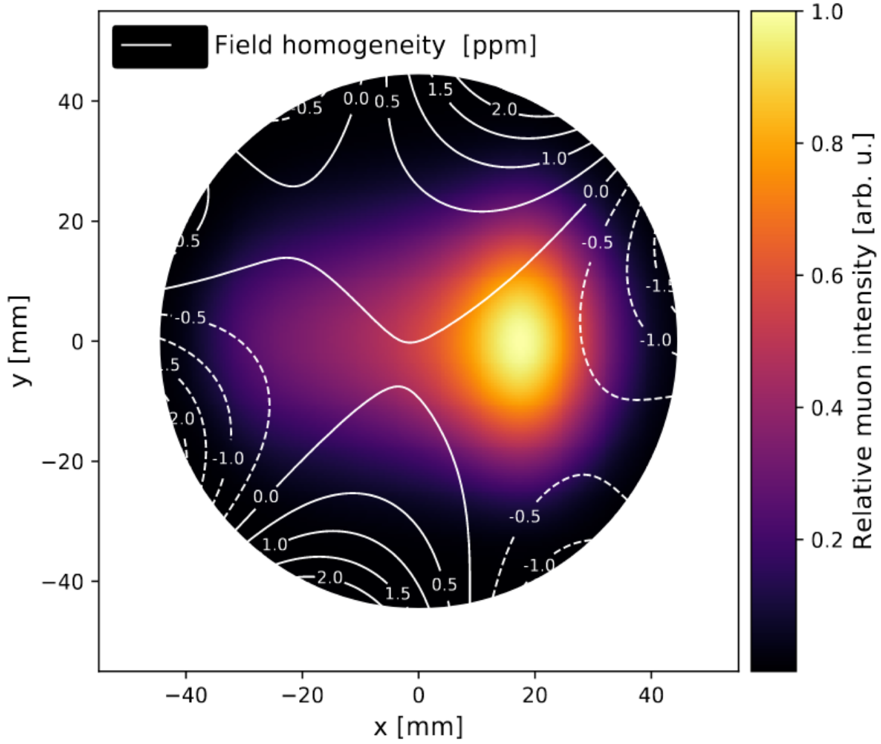
^{3}He sample (30ppb)

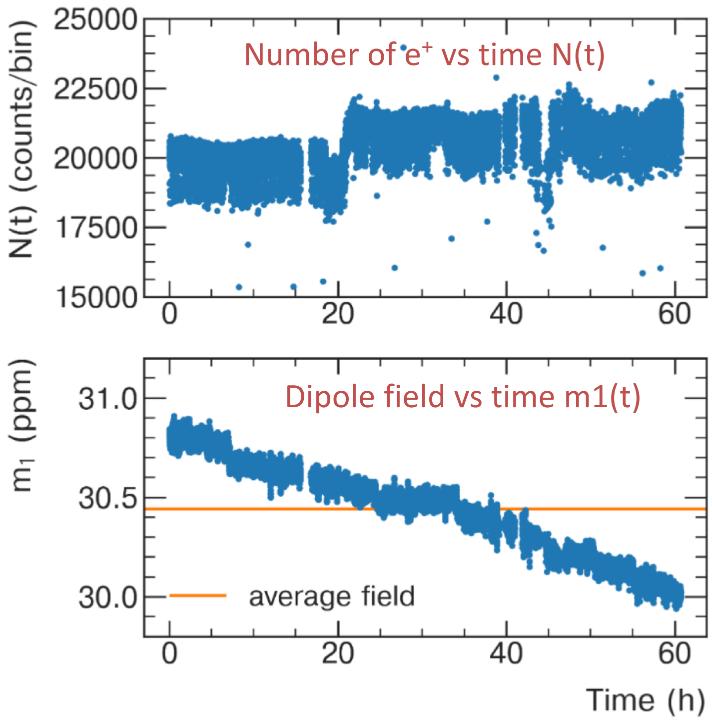


Muon-weighted Field

To obtain the field experience by the muons, the magnetic field distribution as a function of time must be weighted by:

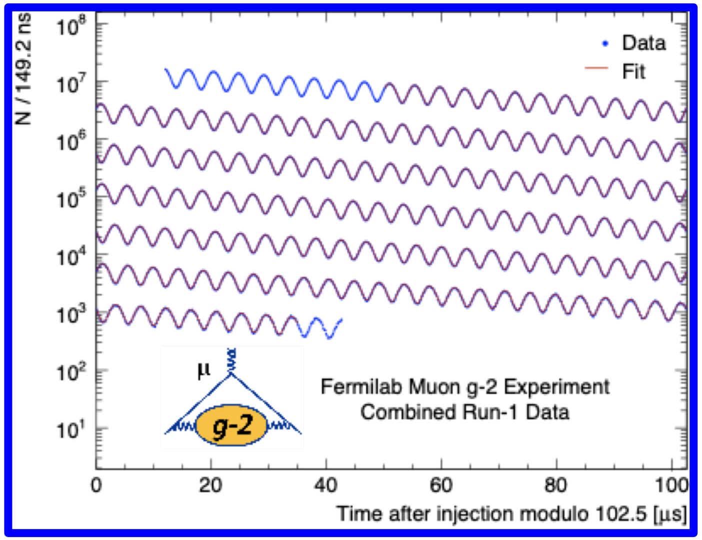
- The number of muons as a function of time, N(t)
- The beam distribution as a function of time



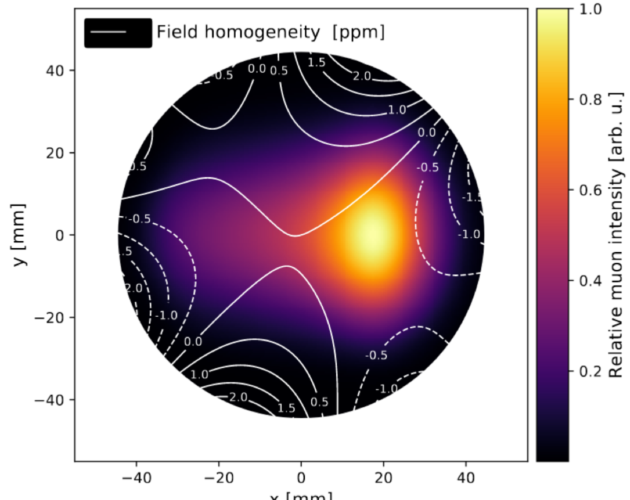


Measured field (every 1.7 s) is weighted by the number of detected e^+

Corrections



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



Corrections

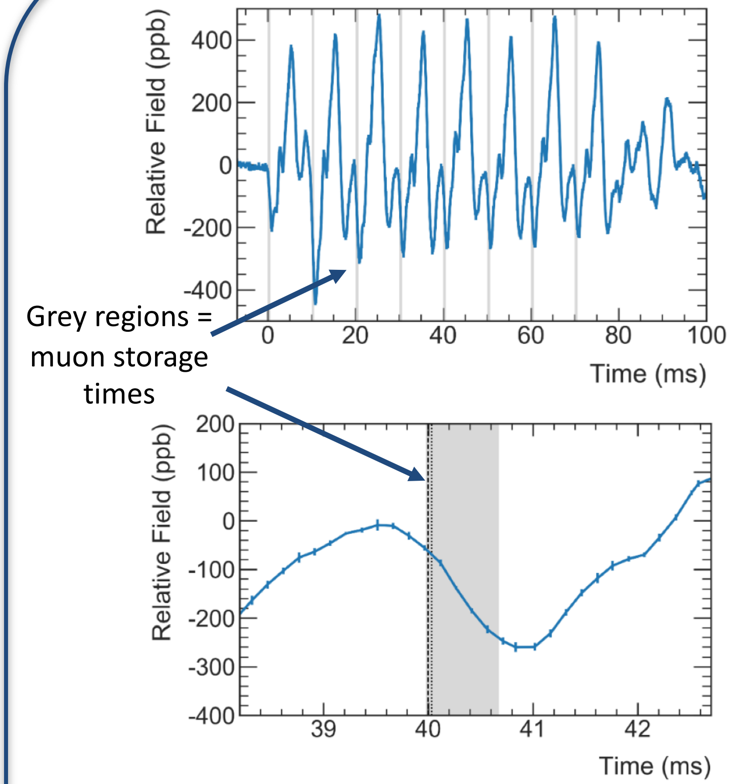
Field Transients

- Largest uncertainties come from “fast transient” fields generated by the pulsed systems (kickers and quads)

- Muons experience a field change which the fixed probes do not see (due to shielding)

- Effects were measured separately during dedicated measurement campaigns.

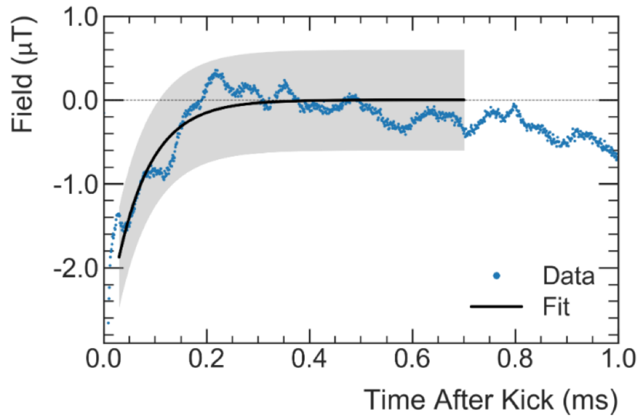
Quad



Grey regions = muon storage times

- Measured with a dedicated in-vacuum NMR probe located between quad plates during pulsing
- Quad correction: -17 (92) ppb

Kicker

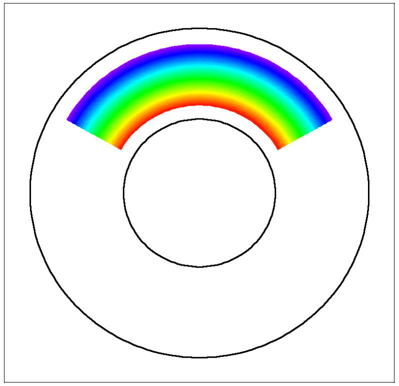


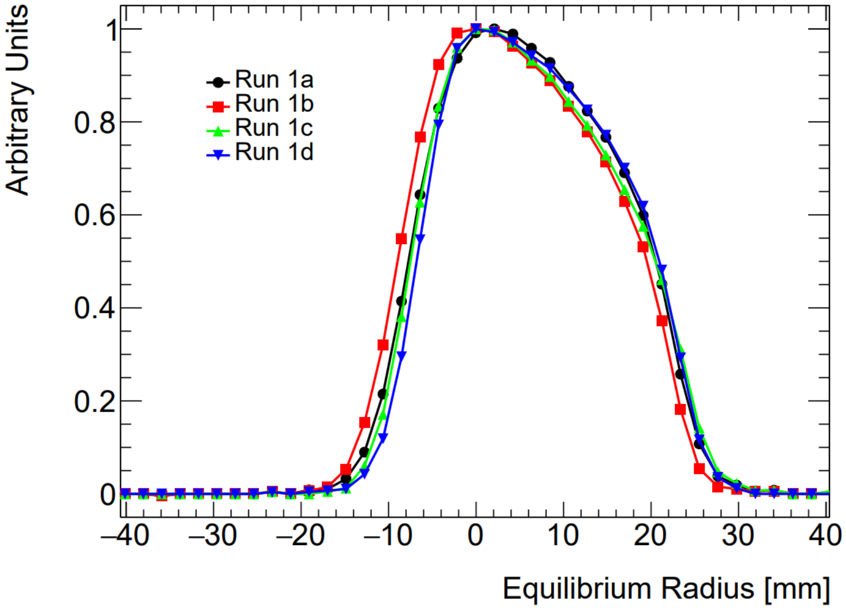
- Kicker pulse of 22 mT for 150 ns just after muon injection.
- Field change caused by residual field after kicker pulse. Muons present from 30µs to 700µs after the kick (fit region)
- Kicker correction: -27 (37) ppb

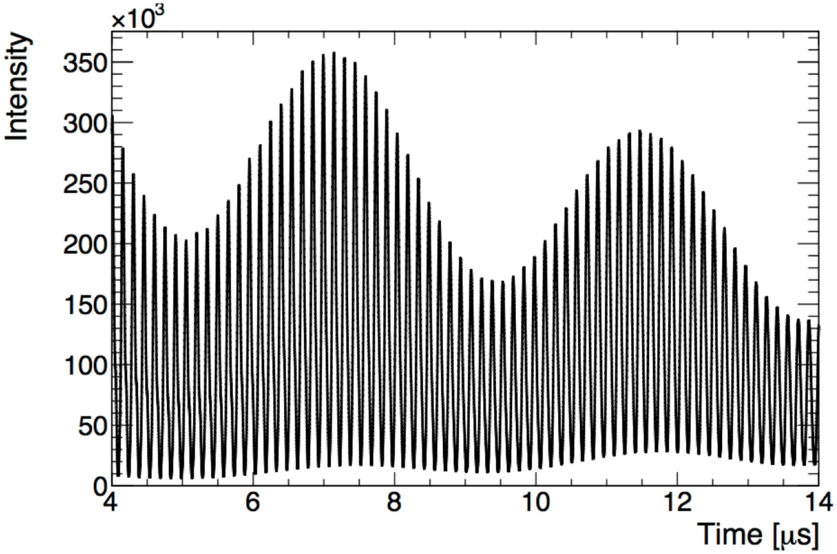
E-field Correction

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

- ~0.1% spread in momentum in the ring
- <R> of stored muons depends on *p*
- Fourier analysis to determine equilibrium positions





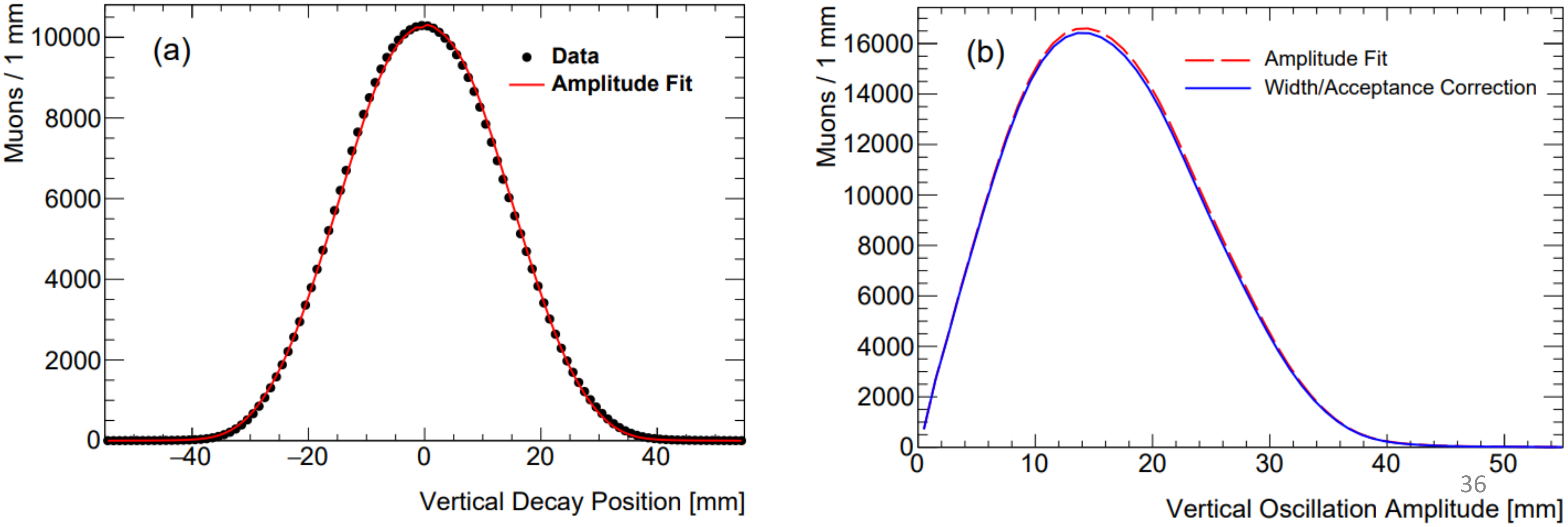


Pitch Correction

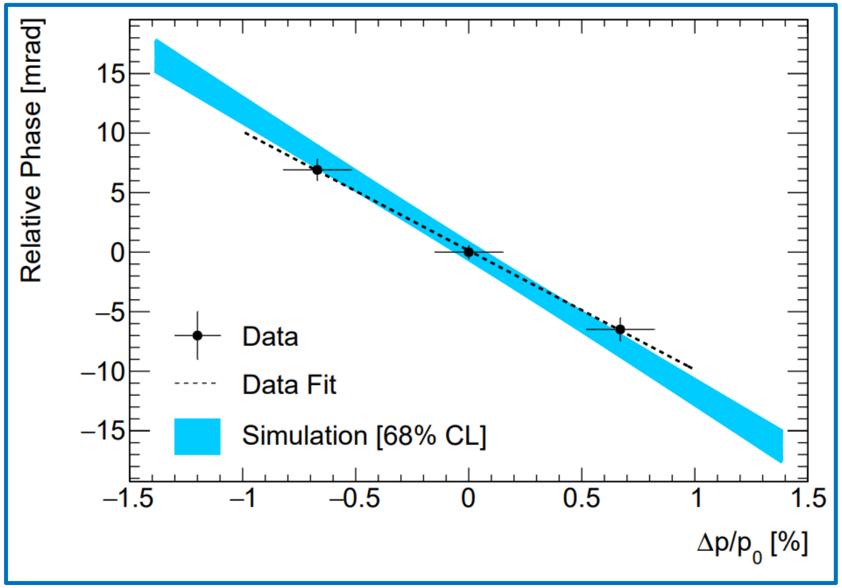
$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E} - \boxed{a_\mu \left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}.\vec{B}\right)\vec{\beta}}\,\right]$$

- Component of momentum parallel to field due to focusing
- Use tracking detectors to measure the vertical width of the beam

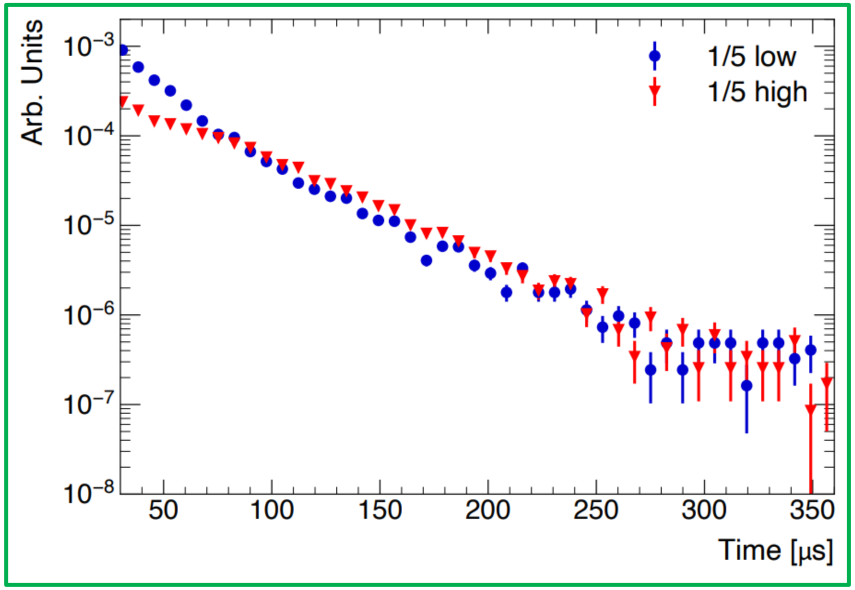
$$C_p = \frac{n}{2}\frac{\langle y^2\rangle}{R_0^2} = \frac{n}{4}\frac{\langle A^2\rangle}{R_0^2}$$



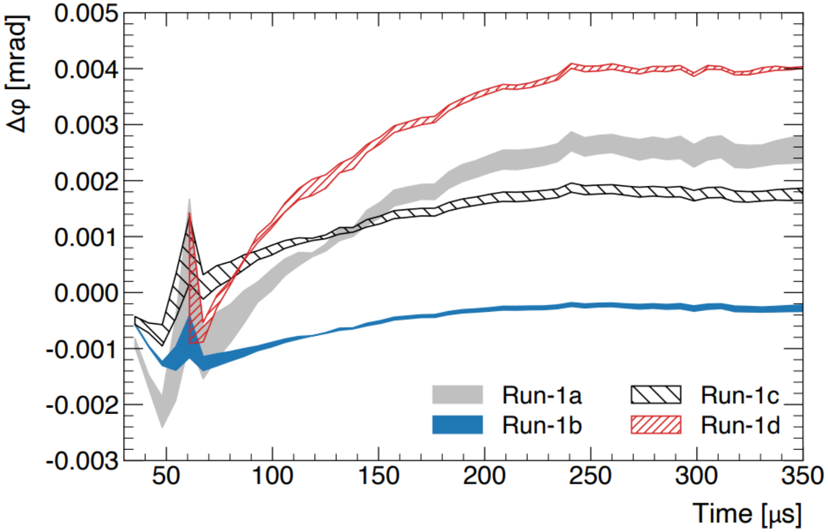
Muon Loss



Spin momentum correlation from delivery ring



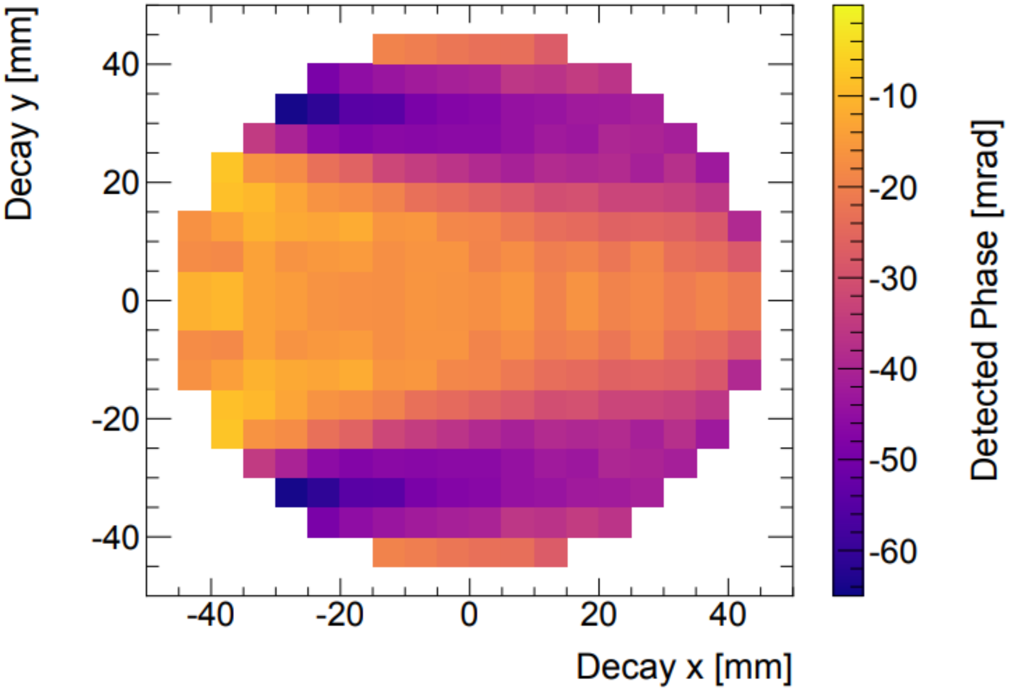
Low mom. muons are lost faster than high mom. at early times



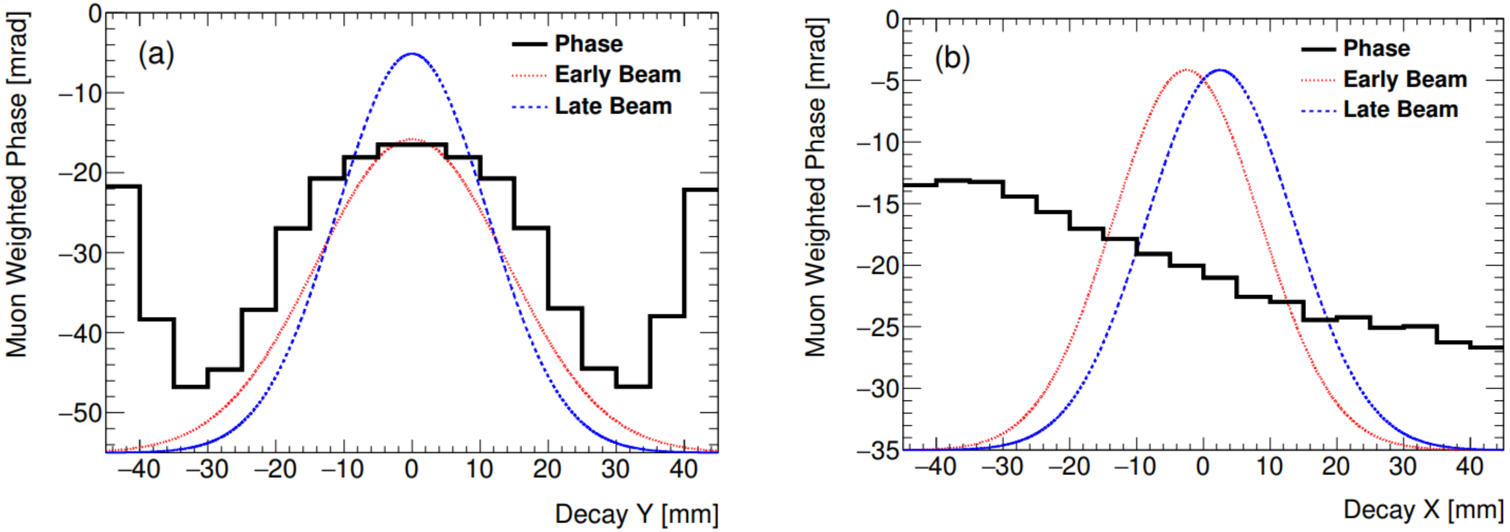
$$\frac{d\varphi_0}{dt} = \boxed{\frac{d\varphi_0}{d\langle p\rangle}}\boxed{\frac{d\langle p\rangle}{dt}}$$

- Lost muons have a slightly different phase w.r.t the ensemble, which causes a change in phase vs time
- Reduced from Run-2 onwards

Phase Correction

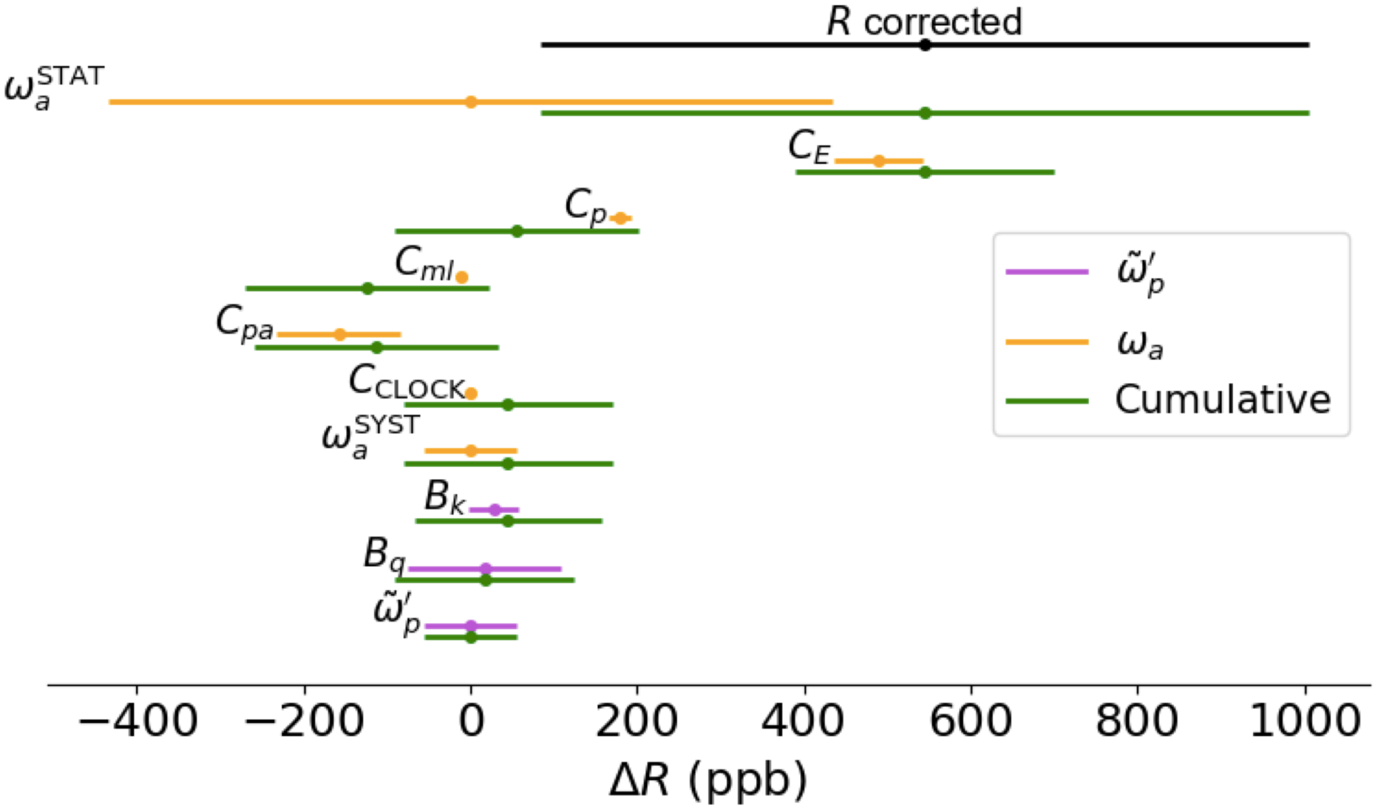


- Focusing strength of the quadrupoles changed during fill
- The non-uniform acceptance of the calorimeters causes the average phase to change during the fill
- Damaged resistors (Run-1 only) enhanced this effect



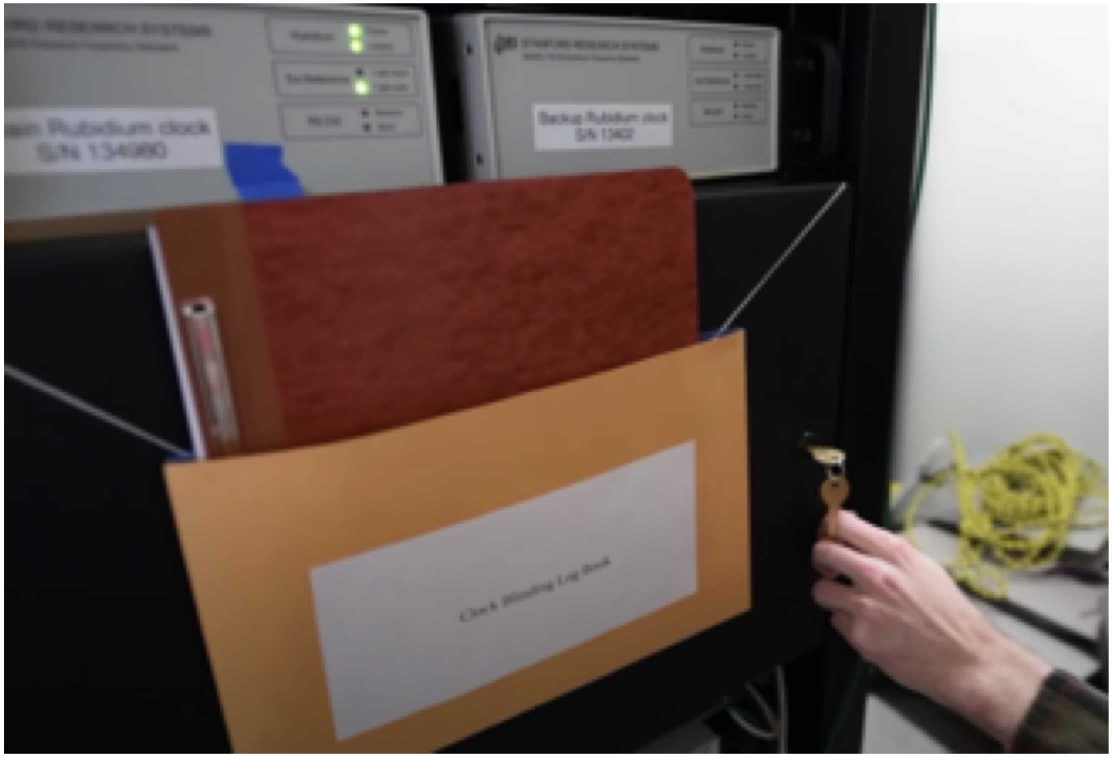
Combining the Corrections

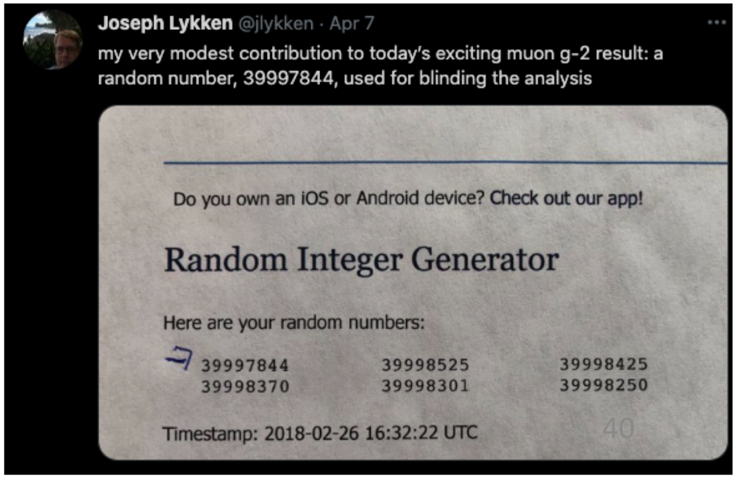
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{\boxed{f_{\text{clock}}\;\omega_a^m\,(1+C_e+C_p+C_{ml}+C_{pa})}}{f_{\text{calib}}\;\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle\boxed{(1+B_k+B_q)}}$$



Clock Blinding

- The clock is hardware blinded to have a frequency of (40 ± ε) MHz
- Only 2 people outside of the collaboration set and know the number
- Blinding offset was ± 25 ppm (approx ×10 BNL-SM difference)





Joseph Lykken @jlykken · Apr 7

my very modest contribution to today's exciting muon g-2 result: a random number, 39997844, used for blinding the analysis

Do you own an iOS or Android device? Check out our app!

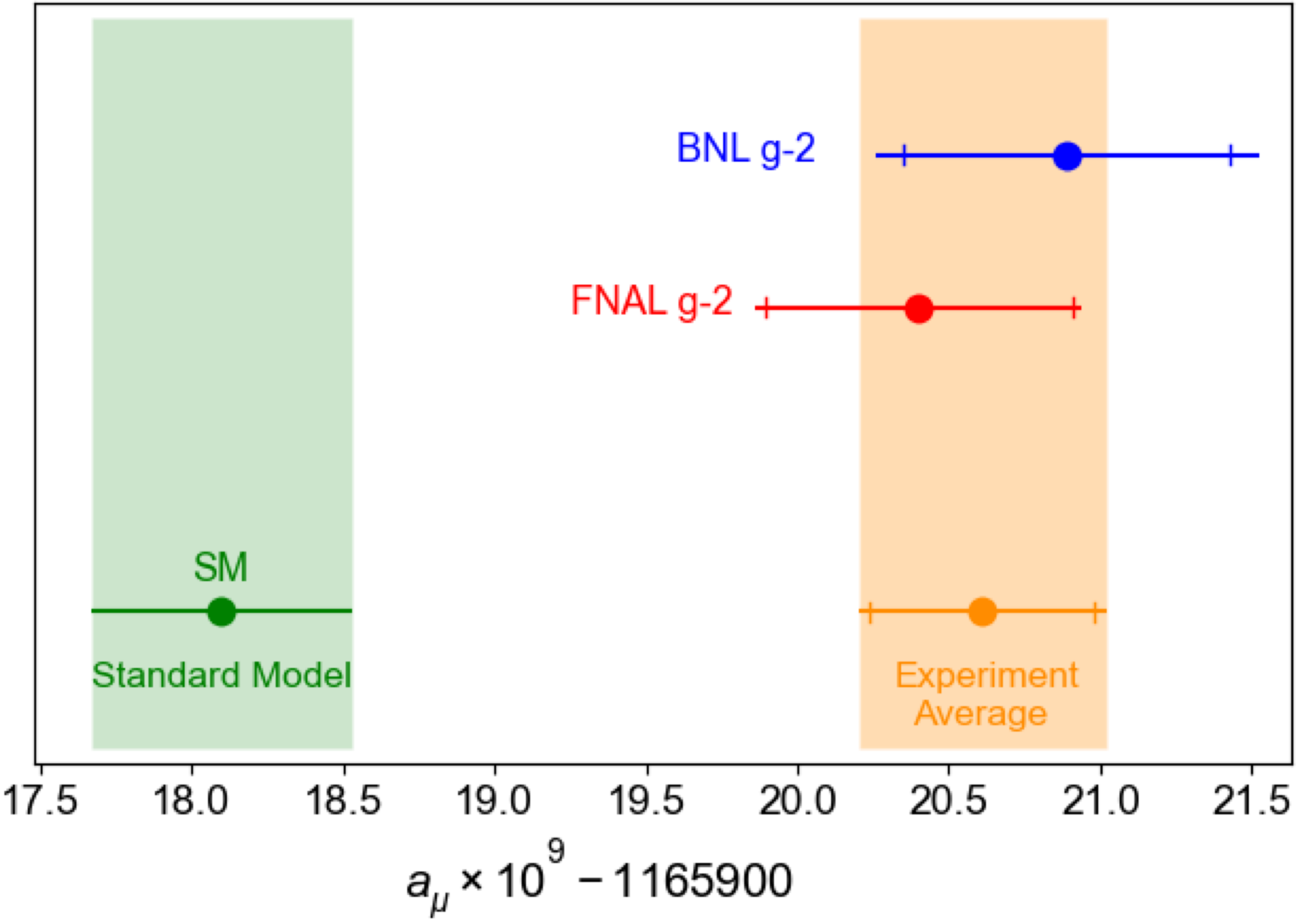
Random Integer Generator

Here are your random numbers:

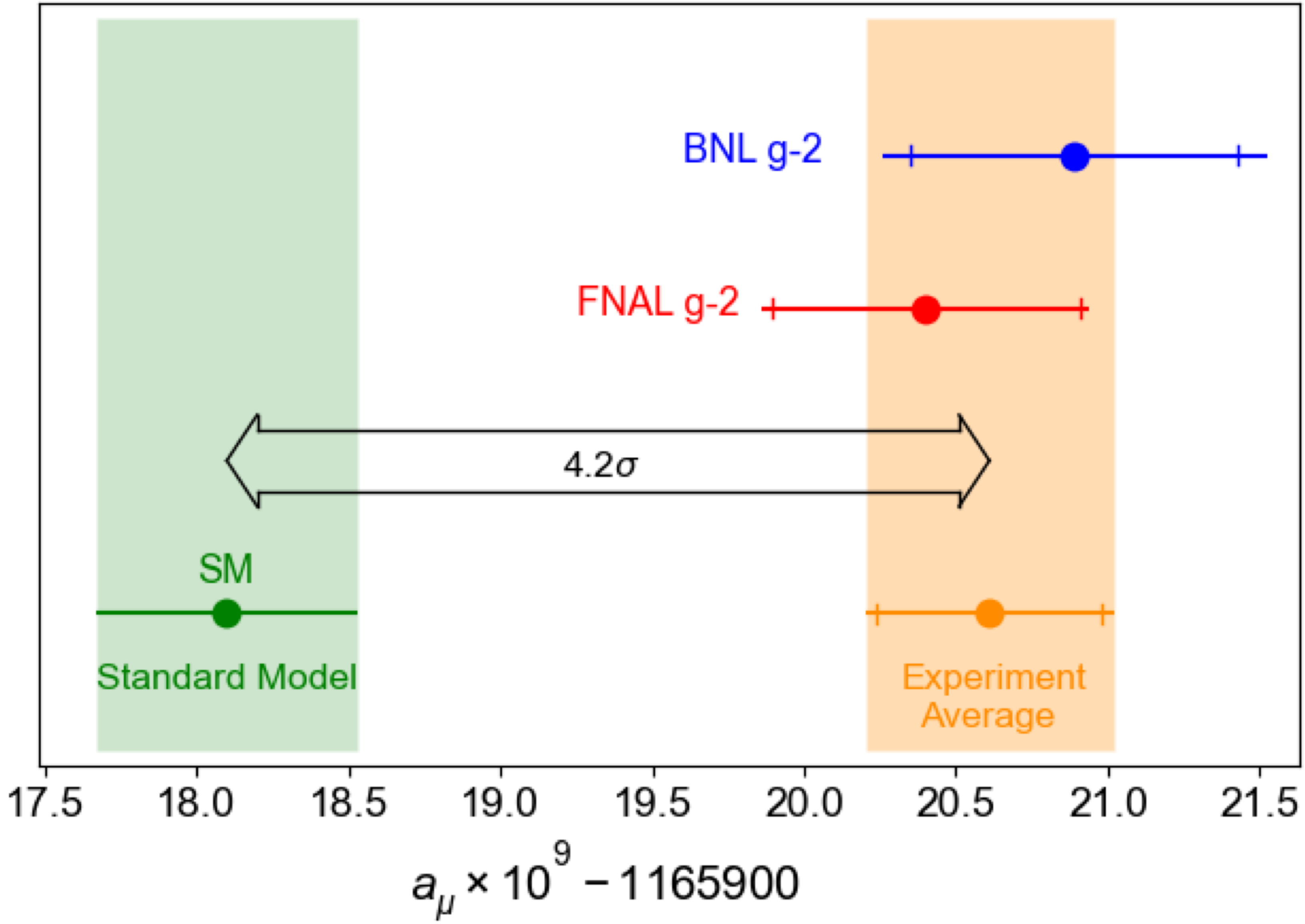
39997844	39998525	39998425
39998370	39998301	39998250

Timestamp: 2018-02-26 16:32:22 UTC

Unblinded Result

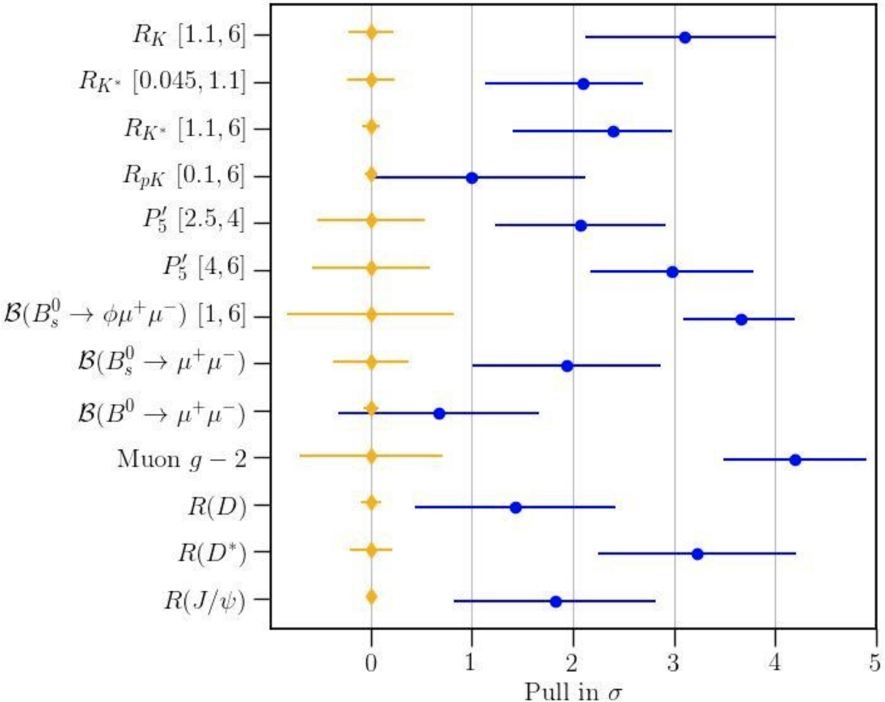


Unblinded Result

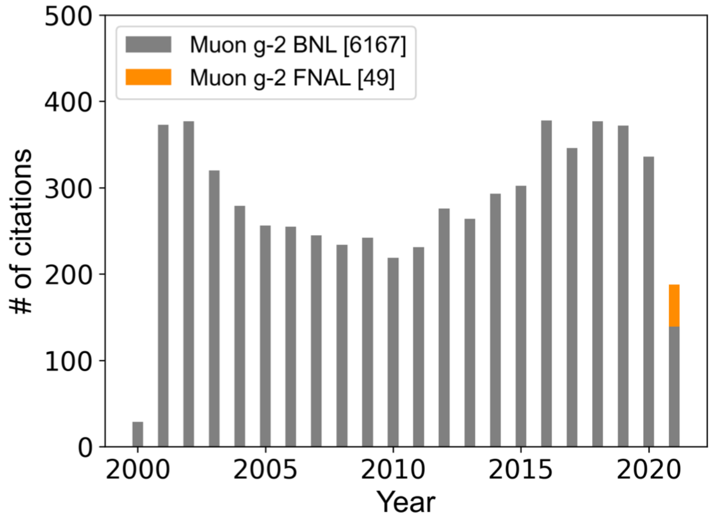


Interpretation

Needs more precision



P. Koppenberg

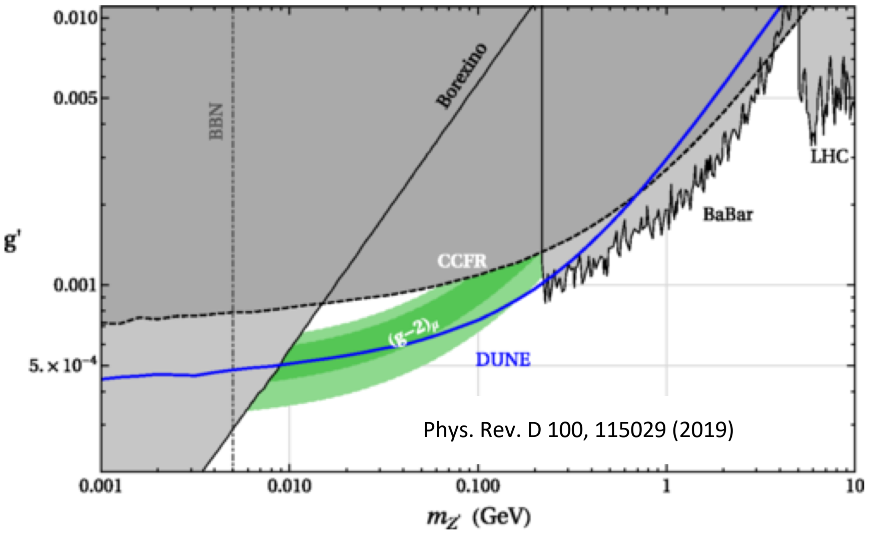


TeV Leptoquarks

Z’, ALPs

LHC evading SUSY

Tweaked Higgs extensions ...



Phys. Rev. D 100, 115029 (2019)

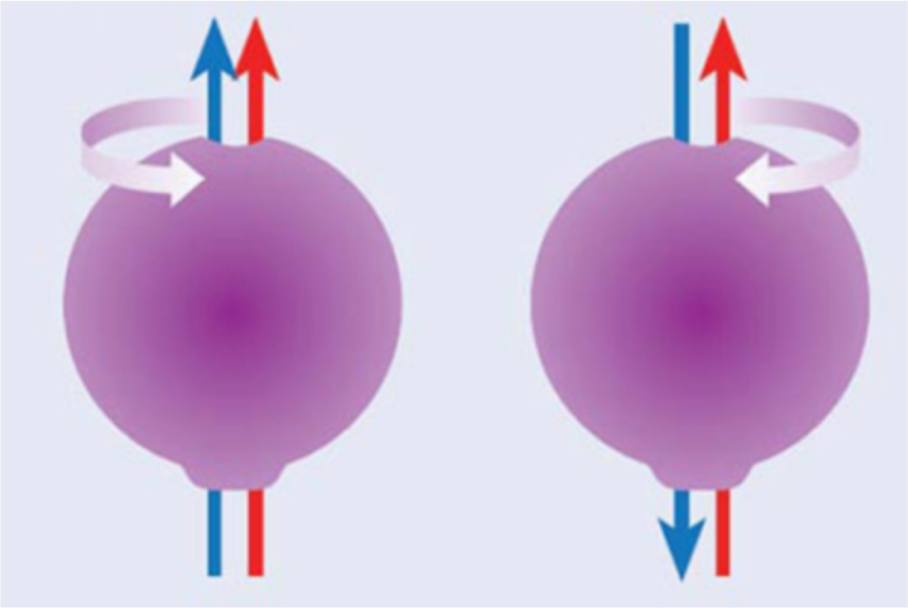
Aside : Muon EDM

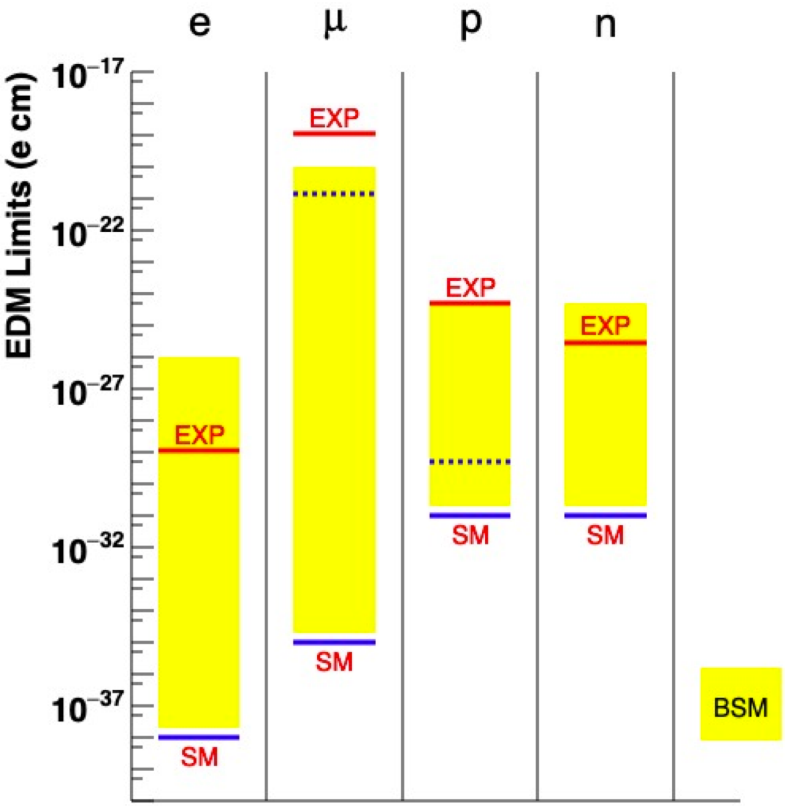
The g-2 experiment at Fermilab can also look for a potential muon EDM

Fundamental particles can also have an EDM defined by an equation similar to the MDM:

$$\vec{d} = \eta \frac{Qe}{2mc}\vec{s} \qquad \vec{\mu} = g\frac{e}{2mc}\vec{s}$$

Provides an additional source of CP violation





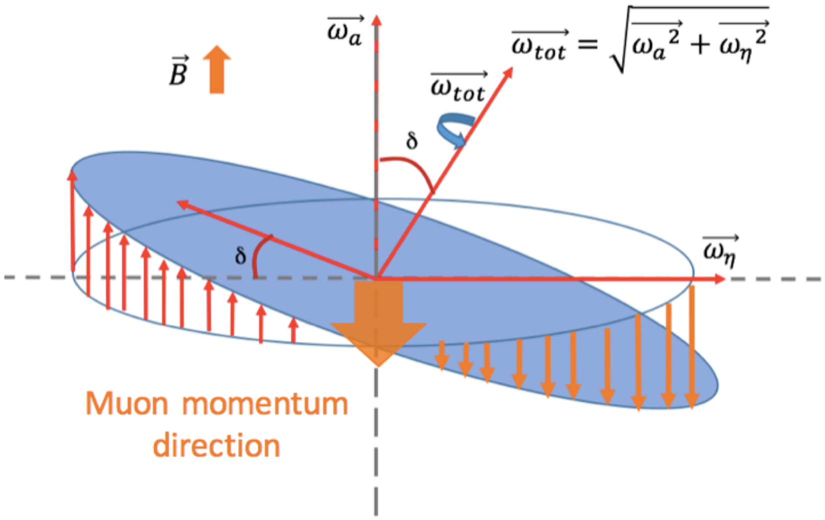
The power of EDM measurements has recently been demonstrated by the latest electron EDM measurement

Aside : Muon EDM

If an EDM is present the spin equation is modified to:

$$\vec{\omega}_{a\eta} = \vec{\omega}_a + \vec{\omega}_\eta = \overbrace{-\frac{Qe}{m}a\vec{B}}^{\text{MDM}} \overbrace{-\eta\frac{Qe}{2m}\left[\frac{\vec{E}}{c} + \boxed{\vec{\beta}\times\vec{B}}\right]}^{\textbf{EDM}}$$

Dominant term



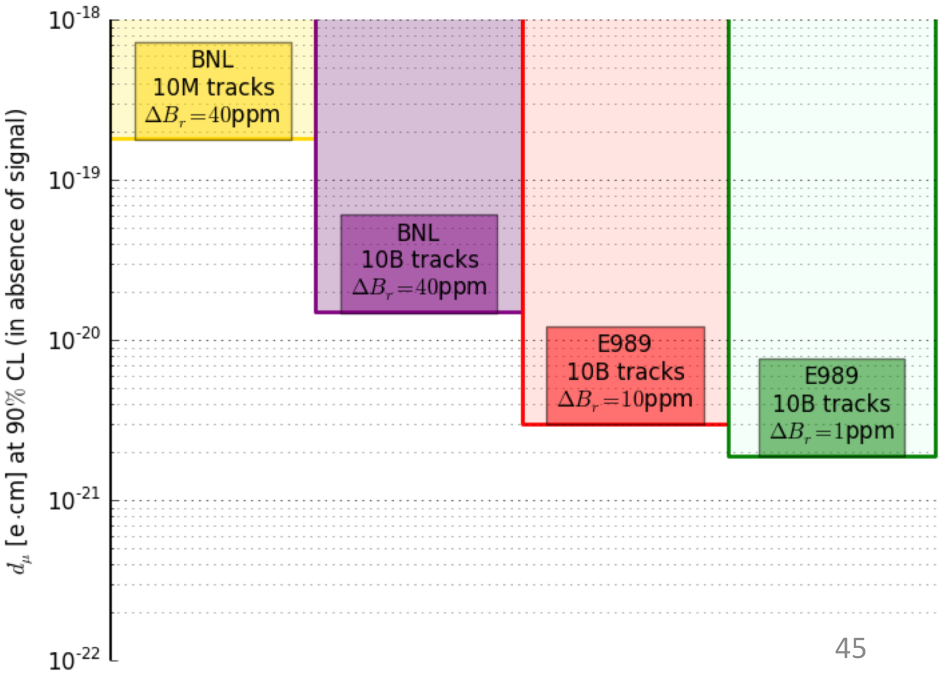
An EDM tilts the precession plane towards the centre of the ring

→ Vertical oscillation

(π/2 out of phase)

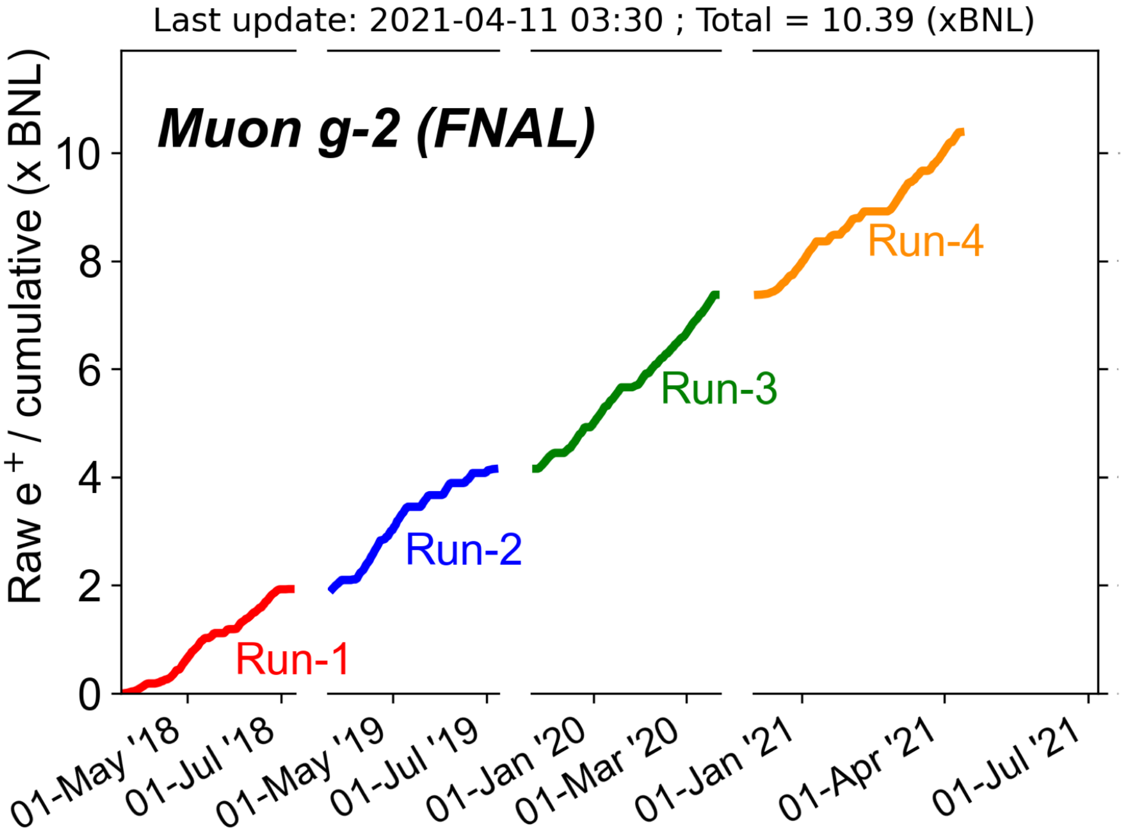
Expect tilt of ~mrad for $d_\mu \sim 10^{-19}$

An EDM also increases the precession frequency

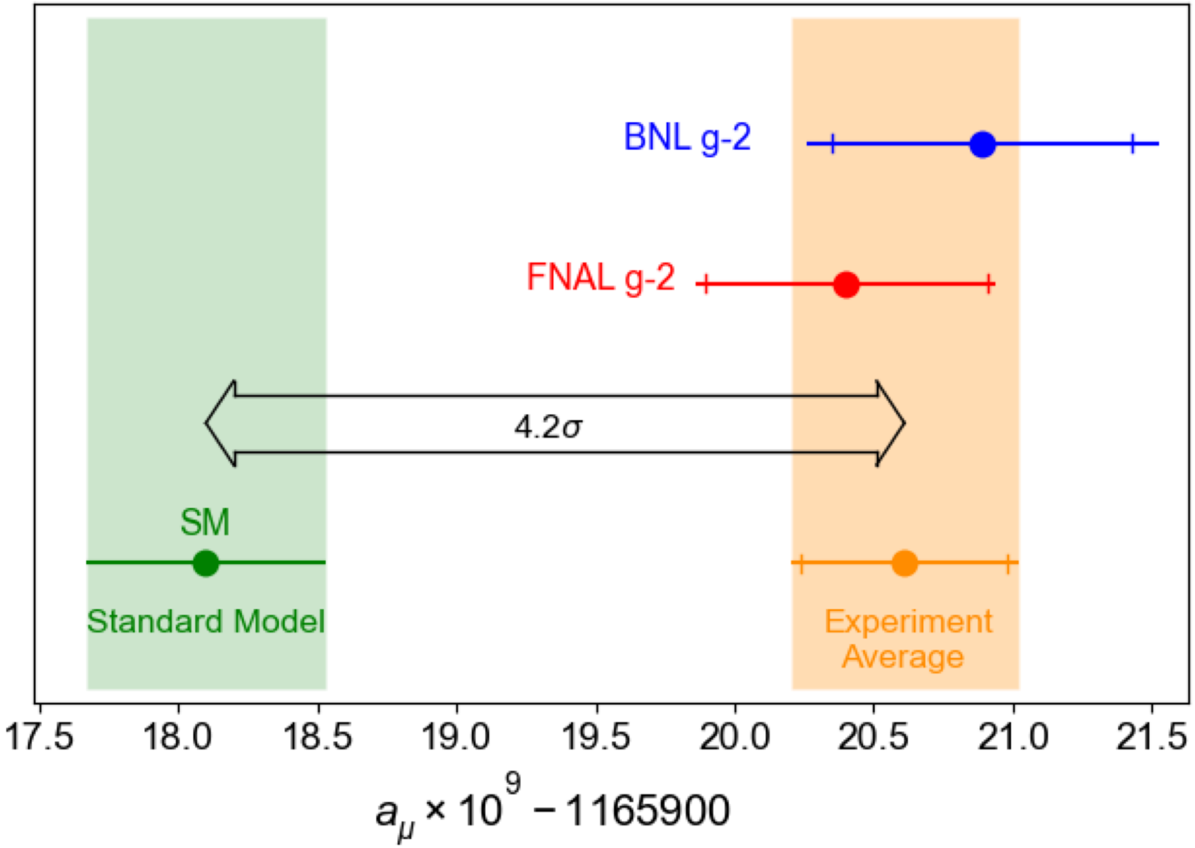


Conclusion

- The analysis of the Run-1 data produced a result with 460 ppb precision
- 4.2σ tension with the theoretical prediction
- There is a lot more data to analyse - expect a factor 2 improvement for Run-2/3 analysis



Thank you!



FNAL Main: *Phys.Rev.Lett.* 126 (2021) 141801

FNAL ω_a: *Phys.Rev.D* 103 (2021) 072002

FNAL Field: *Phys.Rev.A* 103 (2021) 042208

FNAL Beam Dynamics: *Phys.Rev.Accel.Beams 24 (2021) 044002*