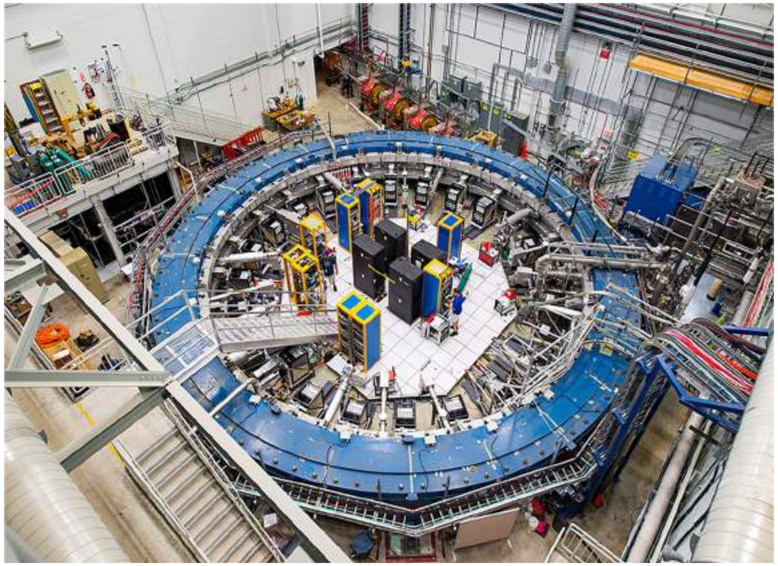
First Results From The Fermilab Muon g-2 Experiment



Alex Keshavarzi

Muon g-2 Theory Initiative Workshop

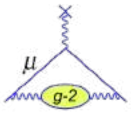
28th June 2021

Fermilab

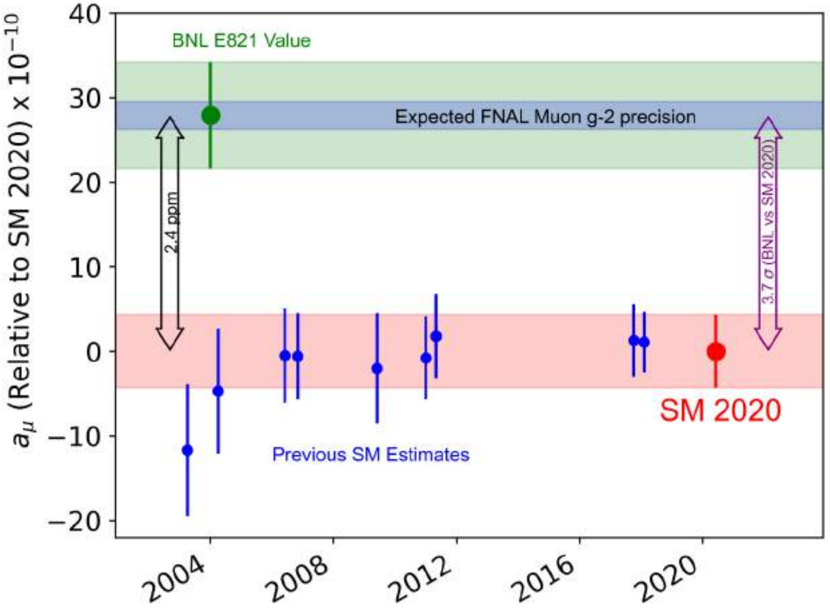
MANCHESTER 1824

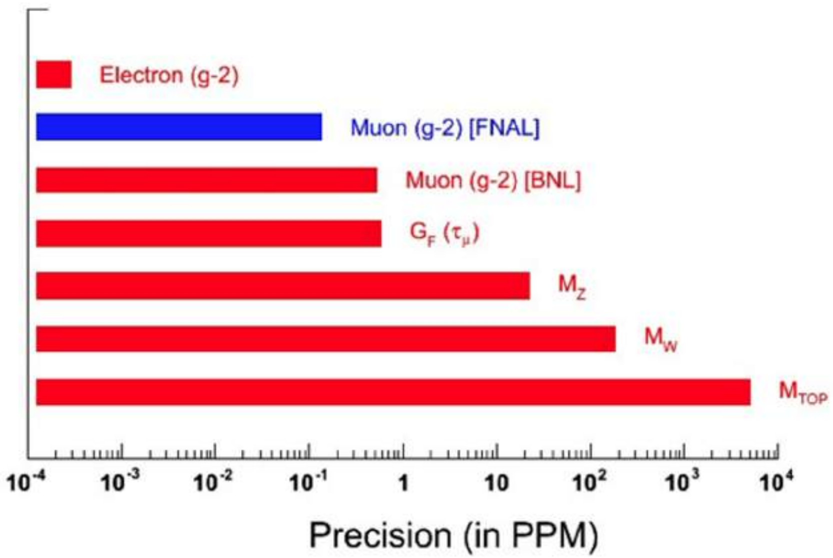
The University of Manchester

Precision



The BNL E821 measurement had a 0.54 ppm (540 ppb) uncertainty





BNL-SM discrepancy: 2.4 ppm
FNAL aim is 100 ppb stat. ⊕ 100 ppb syst.
Today's talk is on a dataset of similar size to BNL ~ 10 billion μ^+

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

4 years to build (2 years magnet ‘shimming’ …)

May 2013

2013

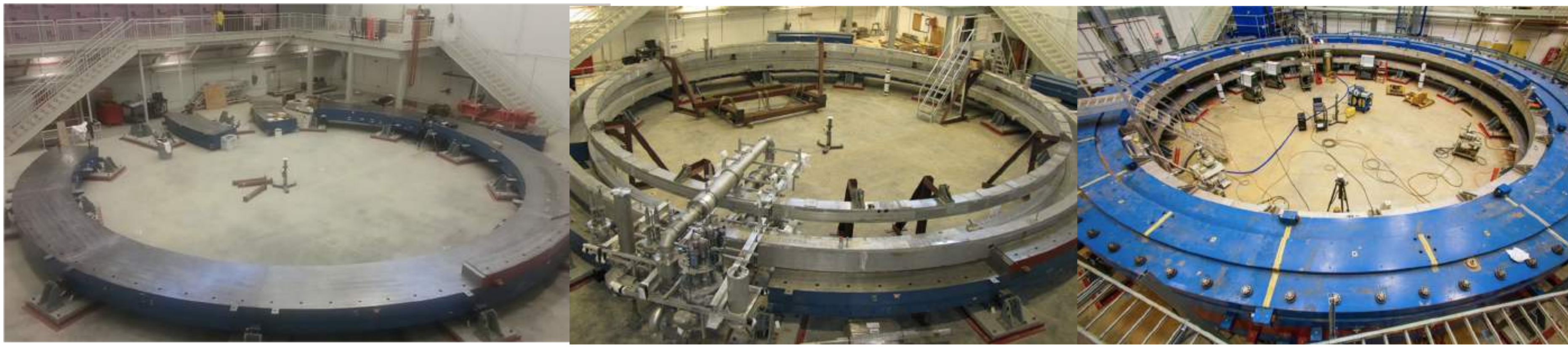
2015

2016-2017

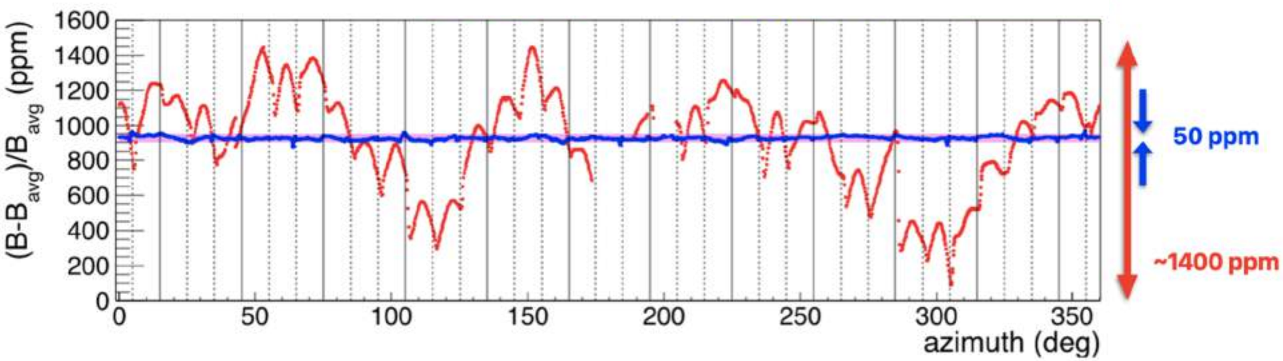
May 31 2017 (g-2)

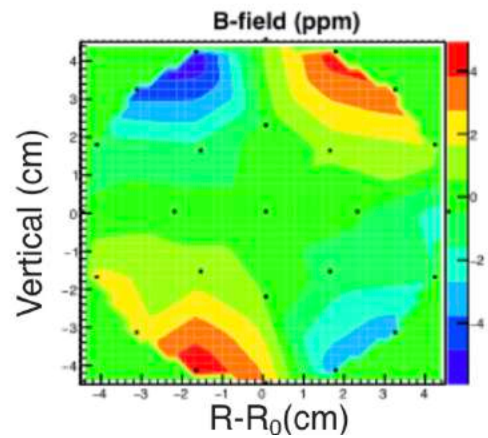
Run-1 data taking started Feb. 2018

The g-2 ring



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





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.

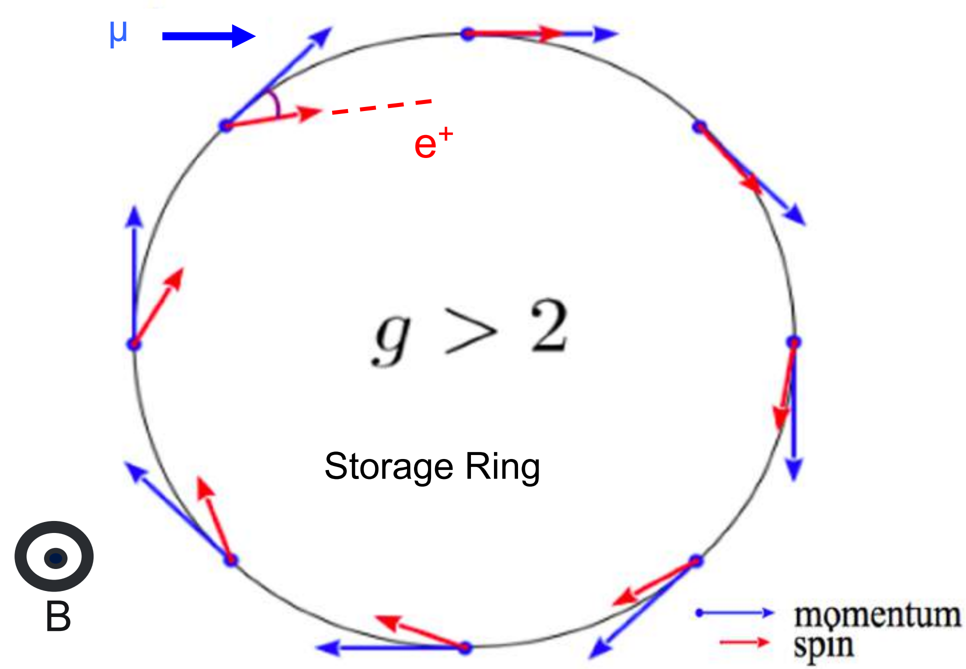
$$\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

Larmor precession

Thomas precession

Cyclotron freq.

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



Measurement details

The experiment actually measures two frequencies

3ppb 0.0003ppb

$$a_\mu = \boxed{\frac{\omega_a}{\tilde{\omega}_p}} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

22ppb

What we measure

Unblinding conversion factor

Measured $g-2$ frequency

Corrections from the beam dynamics systematic effects

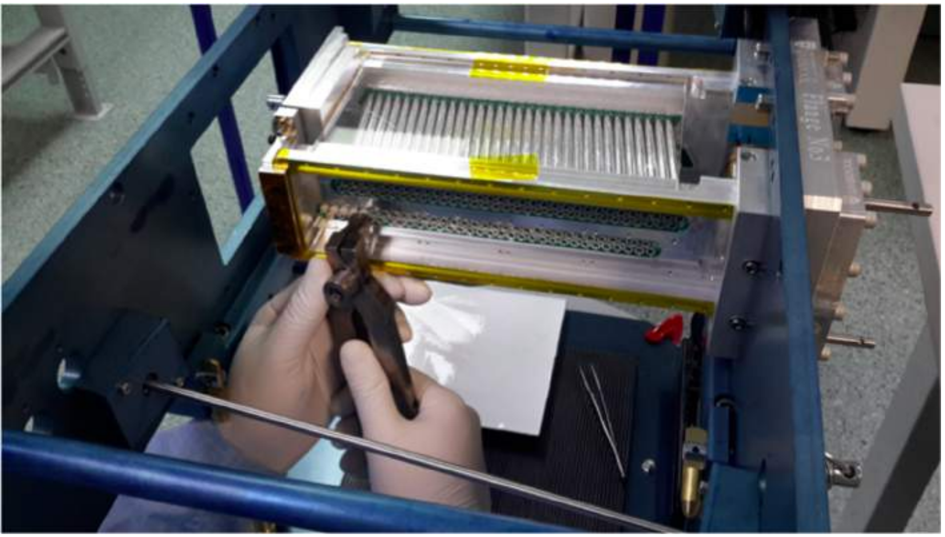
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

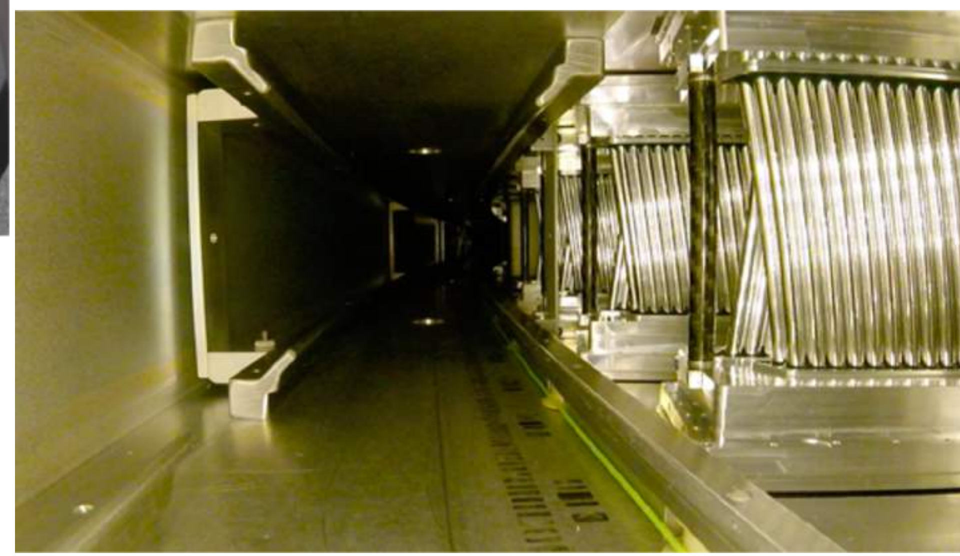
NMR probe calibration factor

Magnetic field weighted over the muon distribution and azimuthally averaged

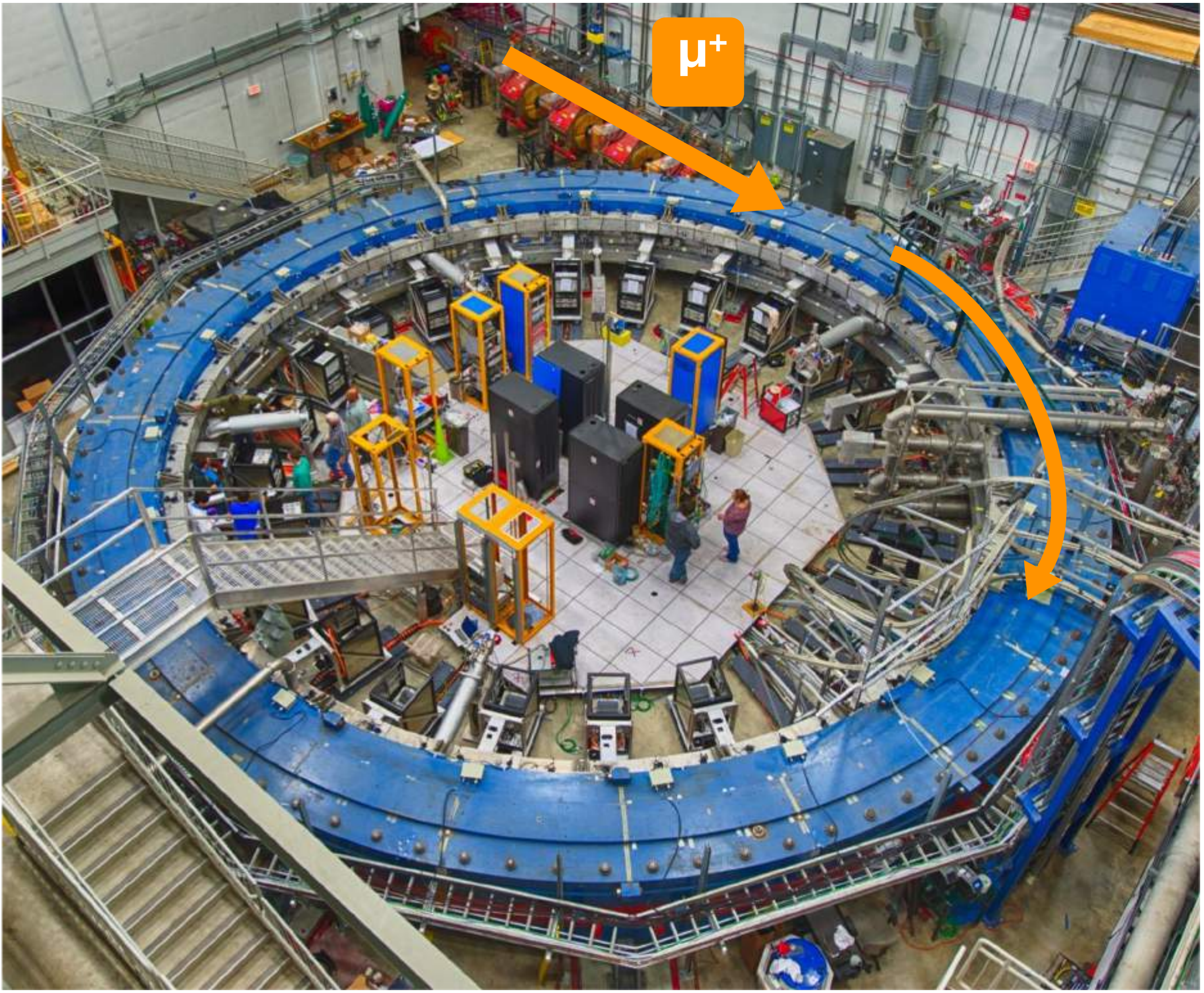
Corrections from the transient magnetic field

Storing and detecting the beam…

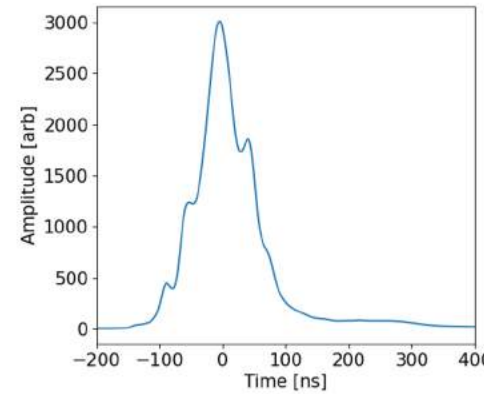




Beam injection

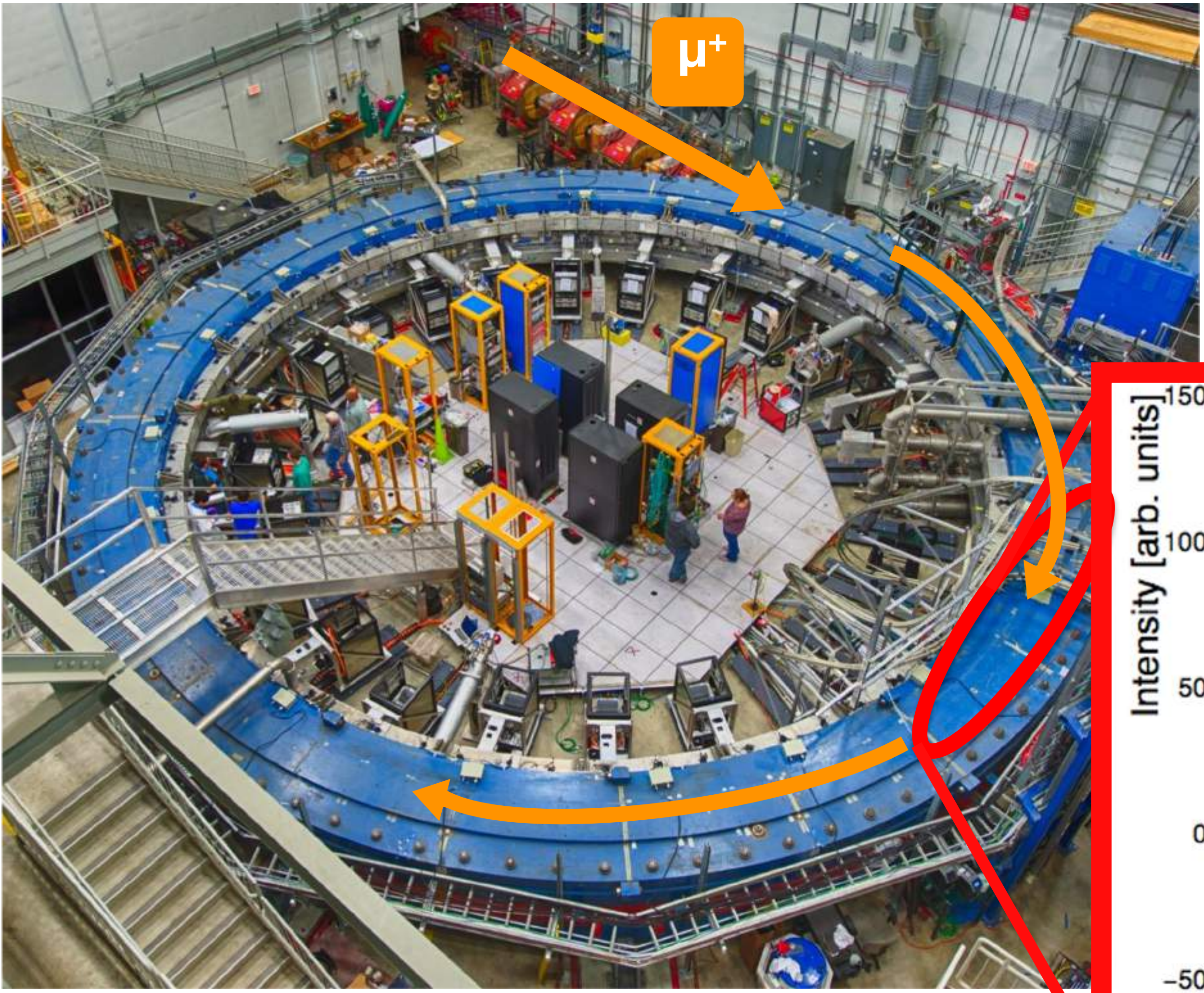


- Monitor beam profile before entrance with scintillating X and Y fibres
- Get time profile of beam using scintillating pad
- ~125ns wide

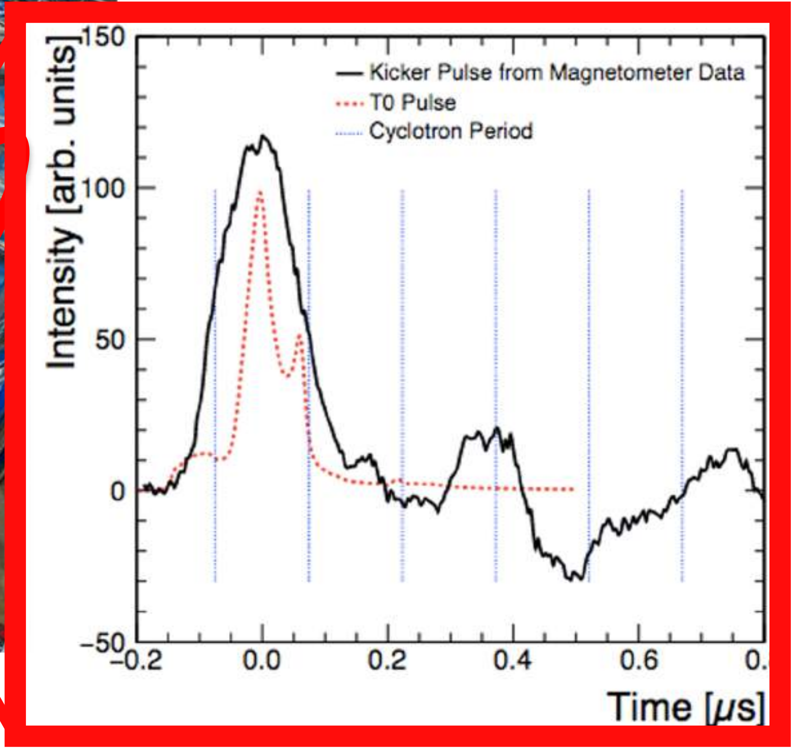


- Cancel B-field during injection using Inflector, so muons can get into the ring

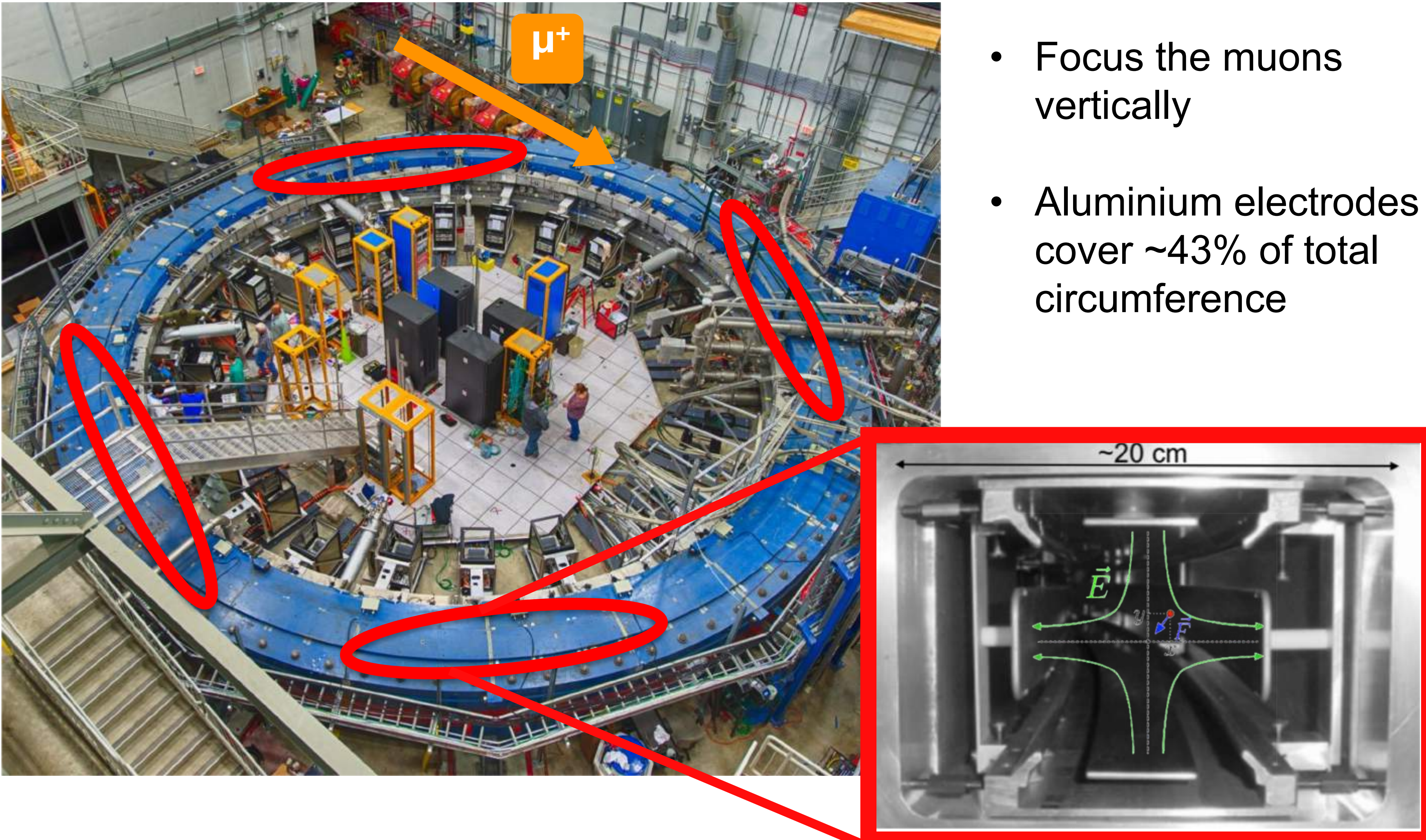
'Kick' onto correct orbit



- After Inflector muons are 77mm away from ideal radius
- Apply short magnetic pulse to 'kick' muons onto the correct orbit

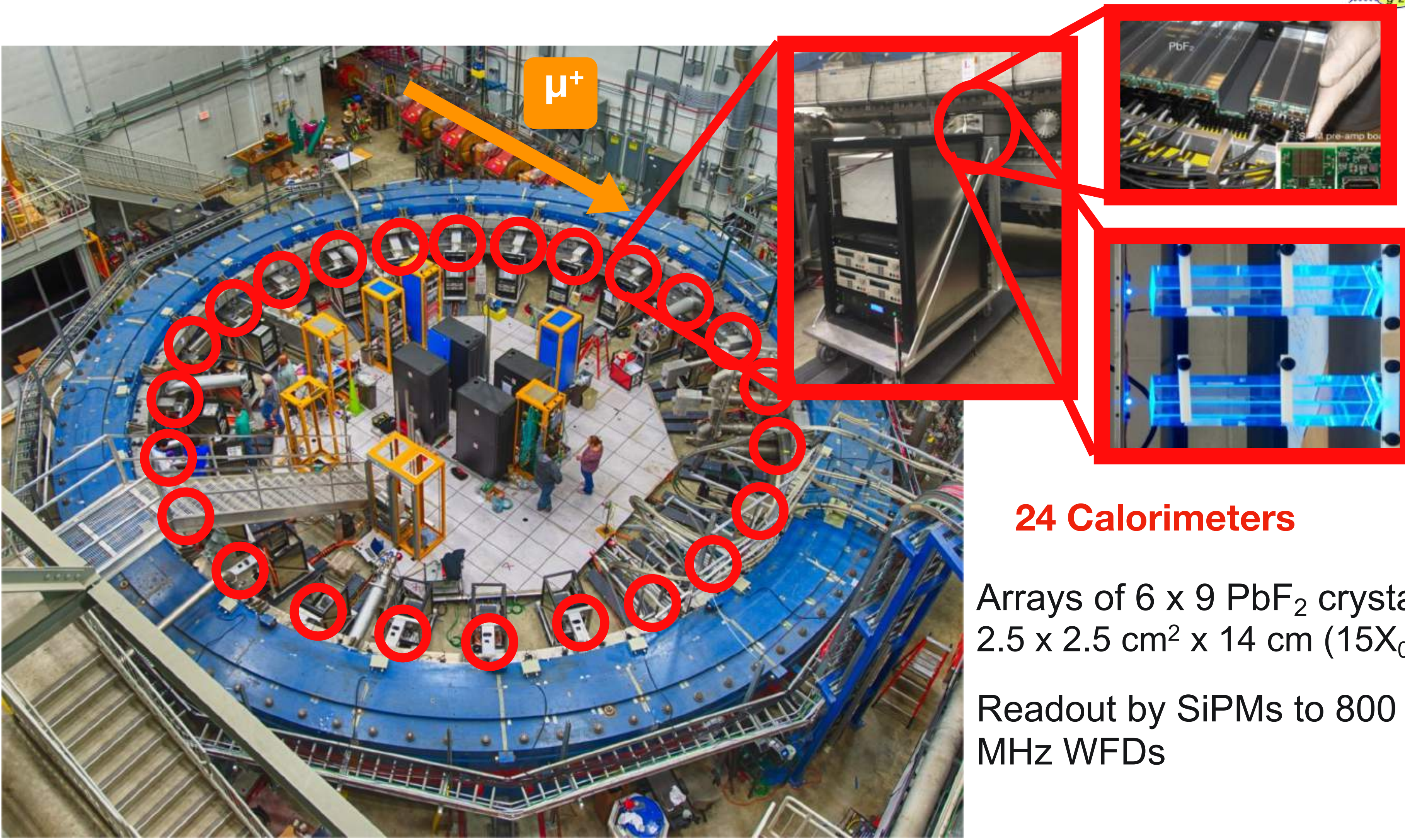


Beam focusing



- Focus the muons vertically
- Aluminium electrodes cover ~43% of total circumference

Calorimeters

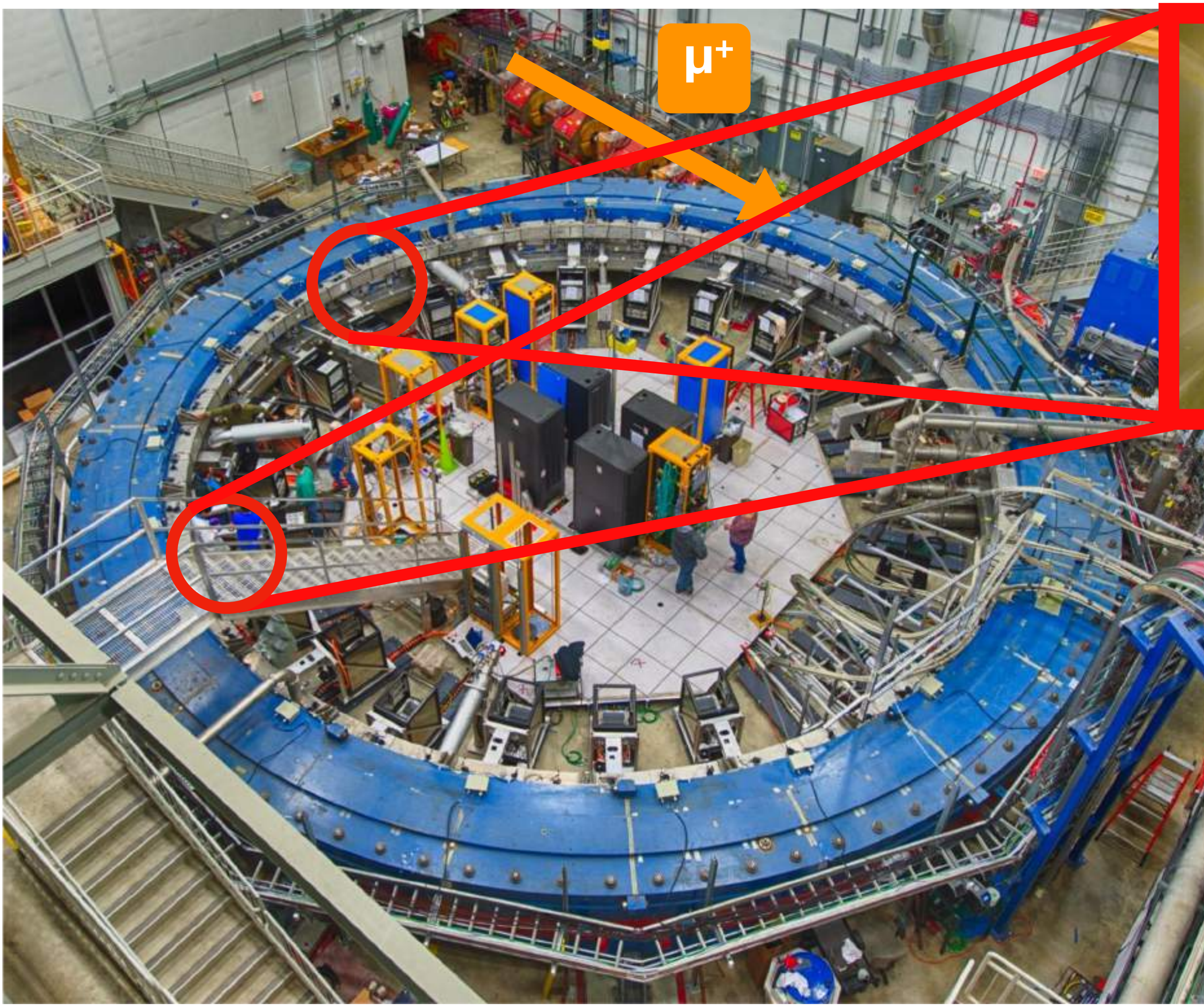


24 Calorimeters

Arrays of 6 x 9 PbF_2 crystals
2.5 x 2.5 cm^2 x 14 cm ($15X_0$)

Readout by SiPMs to 800 MHz WFDs

Tracking Detectors



2 Tracking stations

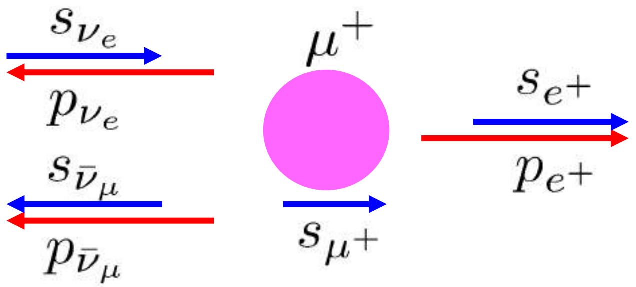
Each contain 8 modules

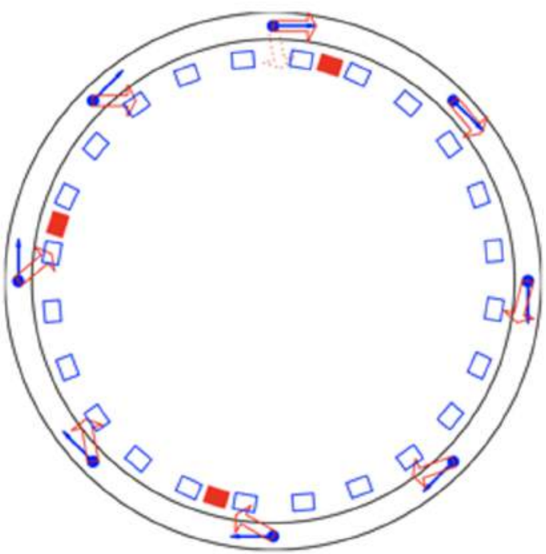
128 gas filled straws in each module

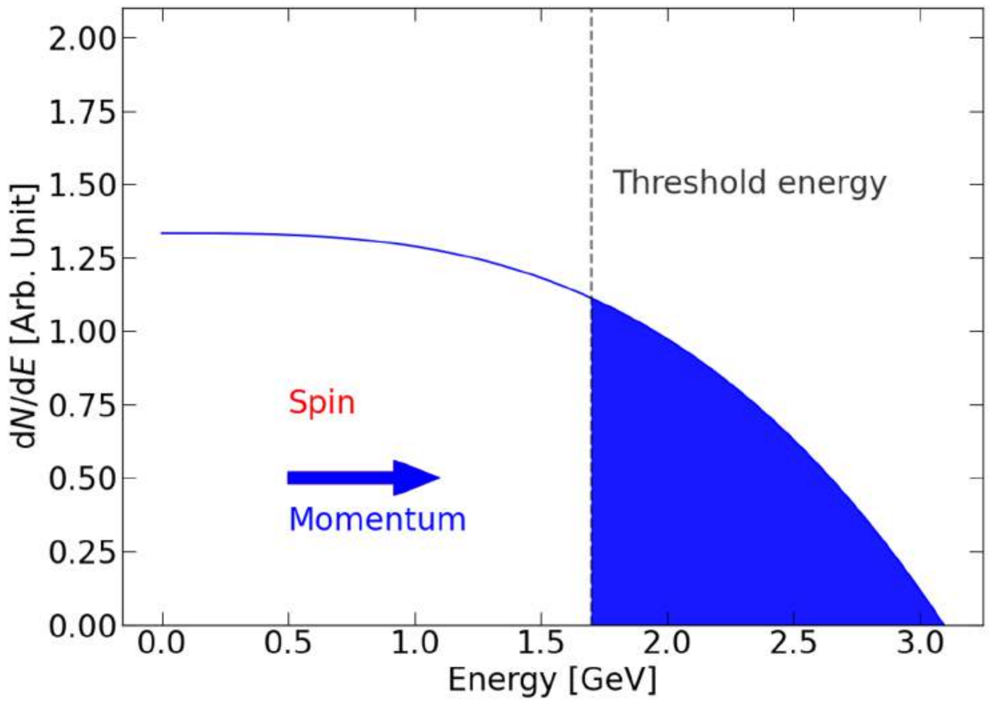
Traceback positrons to their decay point

Measuring ω_a

- e^+ preferentially emitted in direction of muon spin



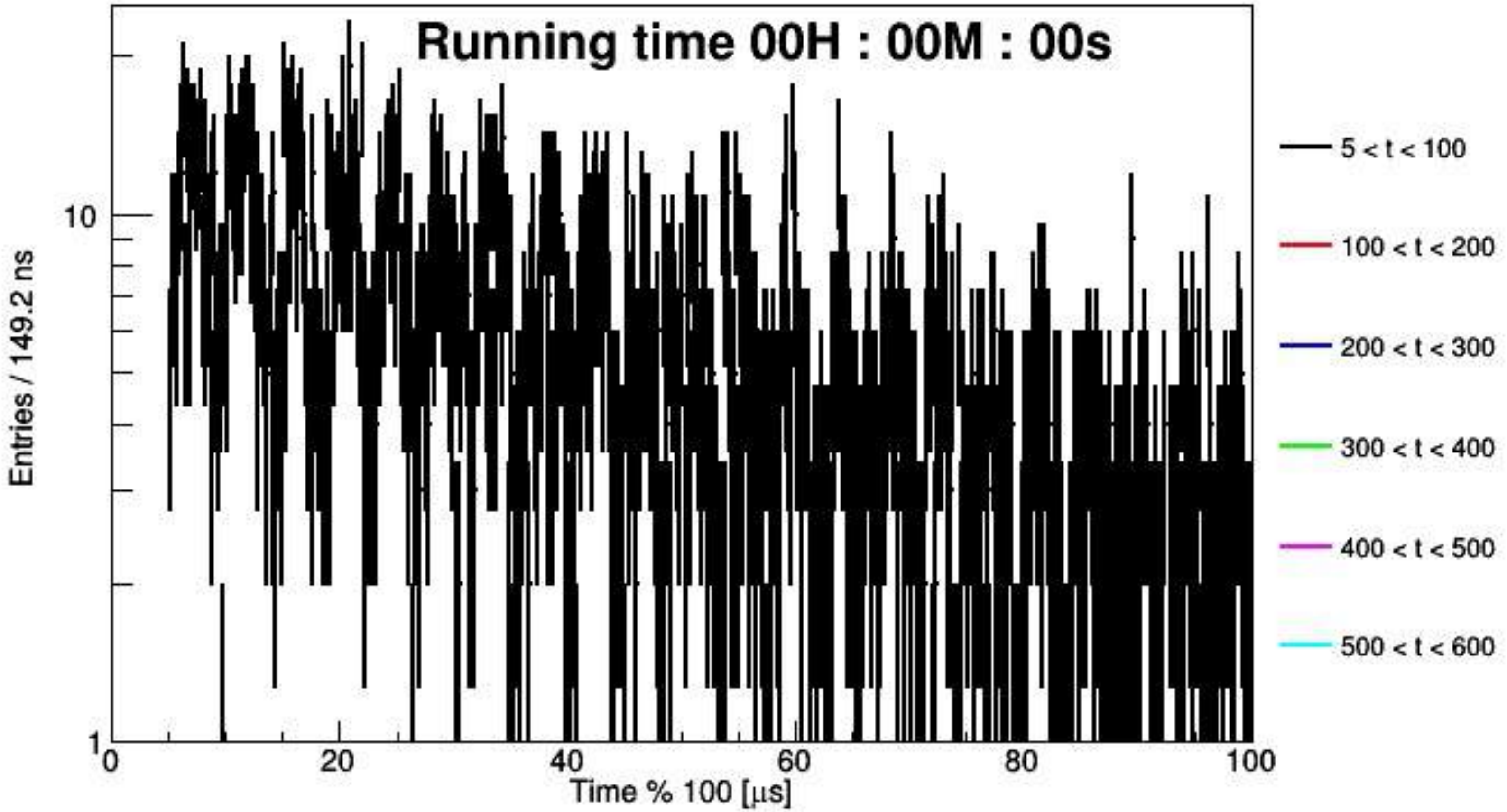




The number of high momentum positrons above a fixed energy threshold oscillates at precession frequency

Simply count the number above an energy threshold vs time

Precession in 1 hour of data



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

Beam corrections

- Injected beam has a small vertical component
- Need to use electrostatic quadrupoles to focus the beam vertically

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

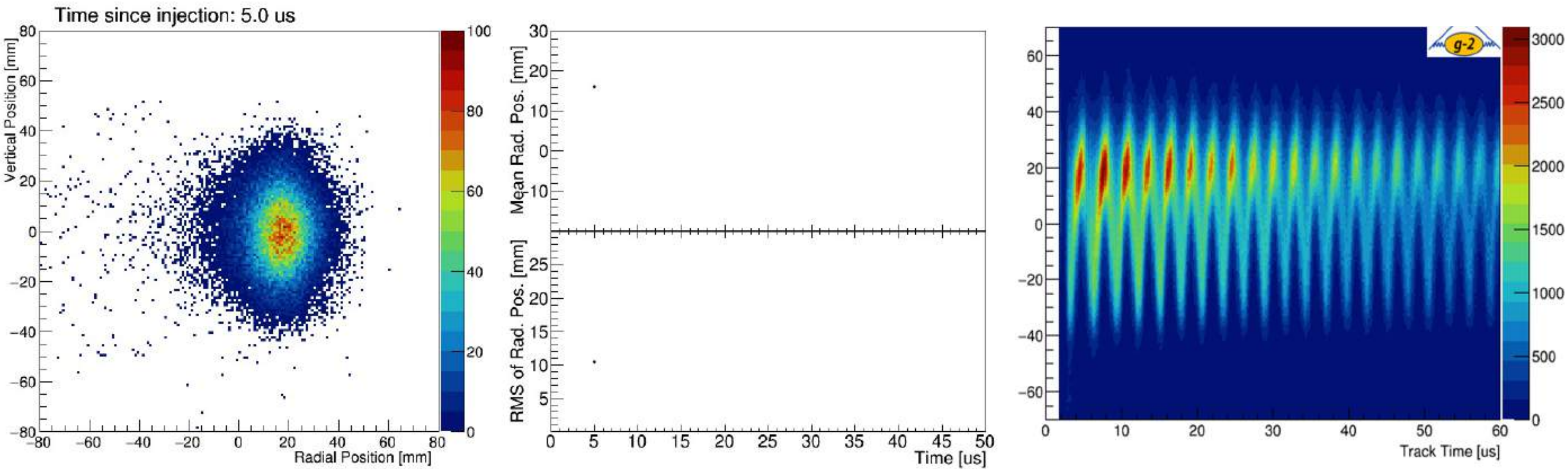
- This introduces 2 additional terms reducing the precession frequency
- We can minimise the first by choosing γ = 29.3 to give p_μ = 3.1GeV
- For a 1.45T field, this sets the radius of the ring to 7.11m
- However we now have 2 corrections to make to a_μ because:

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

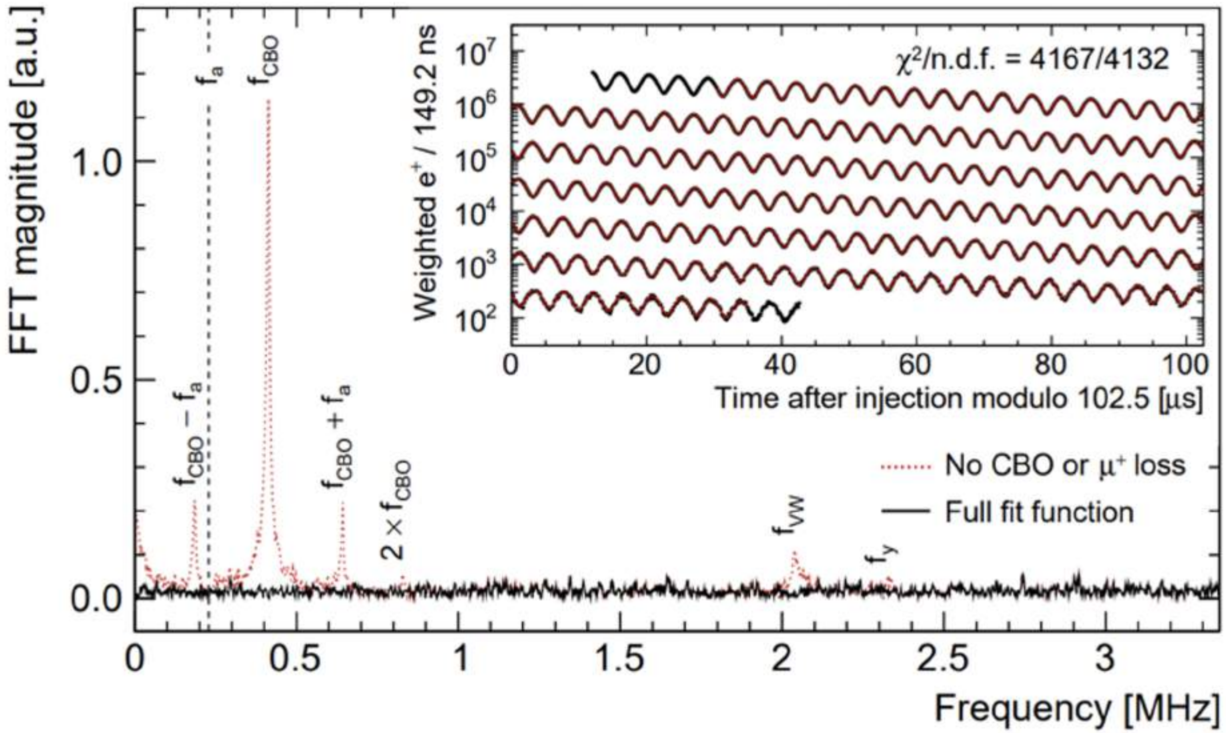
Beam Measurements



- Use the tracking detectors to measure the decay positrons to infer the decay position
- Muons oscillate radially and vertically at different frequencies, according to the quadrupole strength

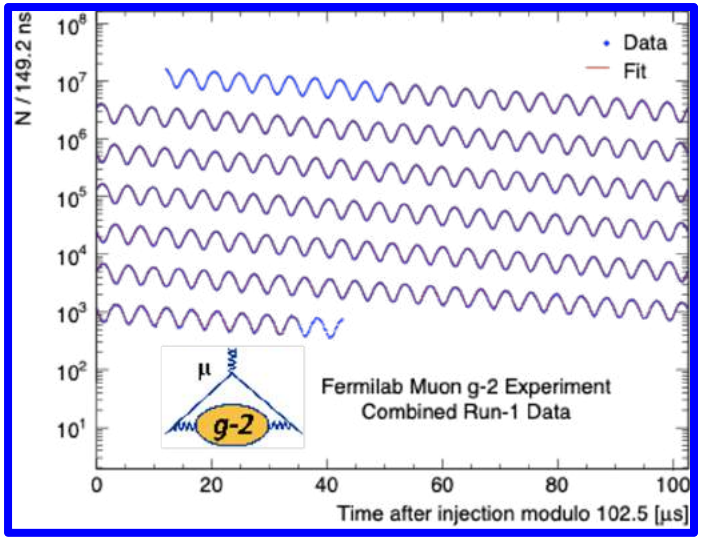
Fitting for ω_a

- A fourier transform of the residuals to the fit shows contributions from the movements of the beam, pileup and muon losses

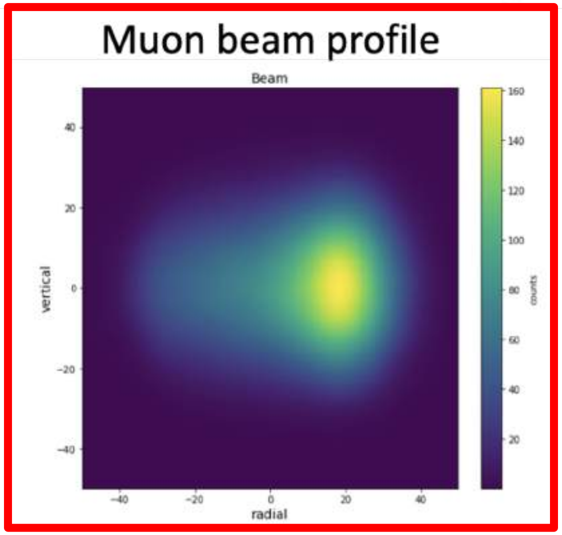


- To account for these effects additional terms are included in the final 24 parameter fit function

Field measurement

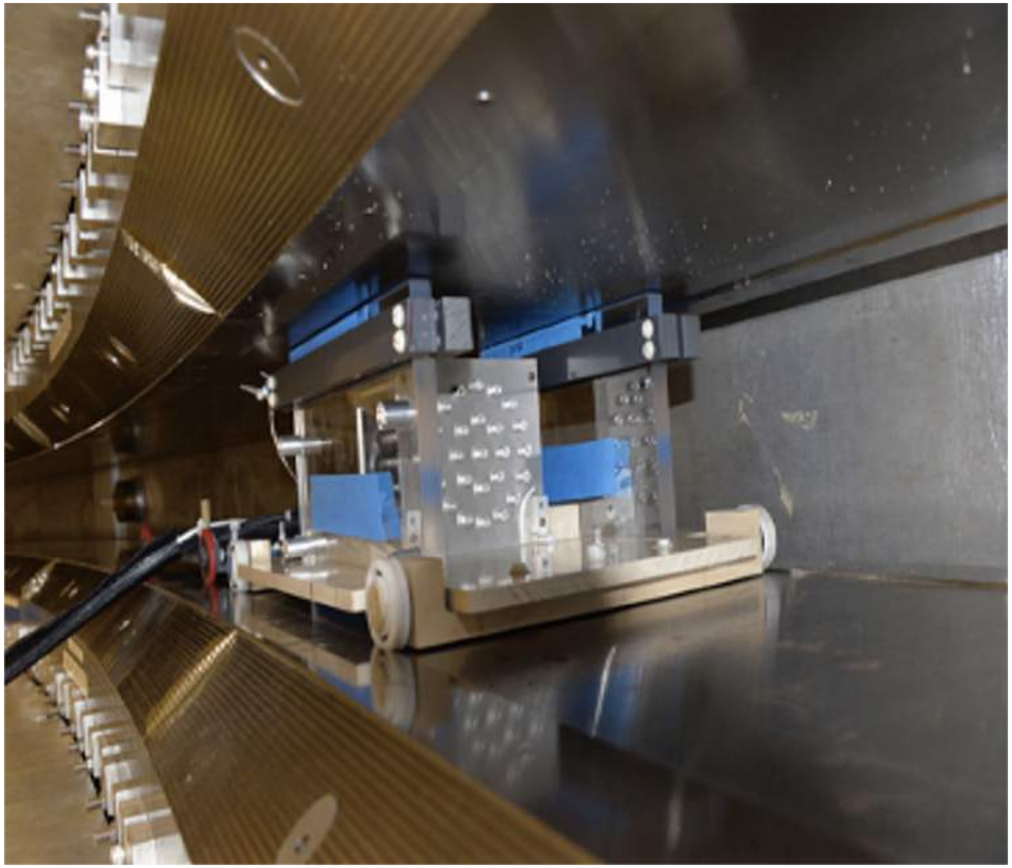


$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\rm clock}\ \omega_a^m\ (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\rm calib}\ \langle\omega_p(x,y,\phi) \times M(x,y,\phi)\rangle(1 + B_k + B_q)}$$



Measuring the magnetic field is the last piece

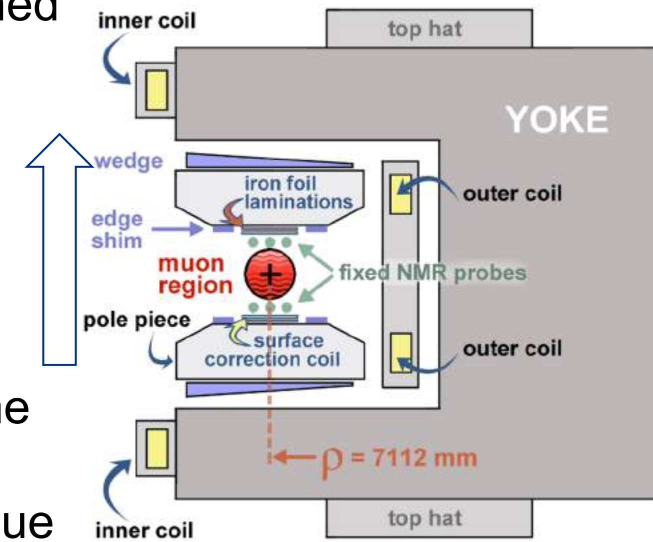
Magnetic field measurement

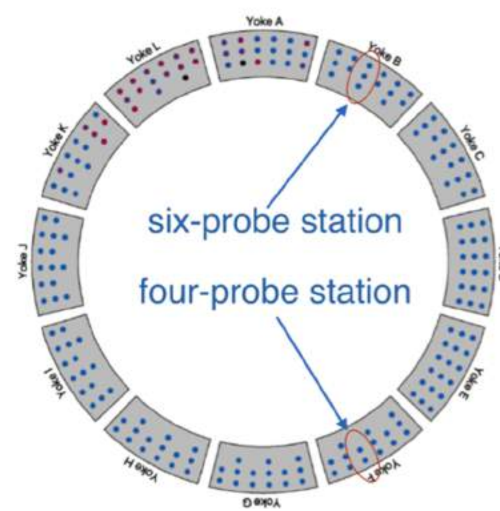


The g-2 storage ring magnet

- 7.112 m radius ‘C’-shape magnet with vertically-aligned field B = 1.45 T
- Dipole field has ppm-level uniformity (14 ppm RMS across the full azimuth)
- Tiny (ppm) changes in magnet geometry, driven by temperature changes, cause the field to drift over time
- Measured using pulsed NMR – a well-known technique that is routinely used in a wide range of applications to measure magnetic fields at the ppb level
- 378 ‘fixed’ NMR probes, built for this experiment, around the ring measure the drift continuously, and provide feedback to the magnet power supply to keep the dipole (vertical) term constant
- Shimming devices minimise gradients (transverse and azimuthal field components).

Magnet cross-section

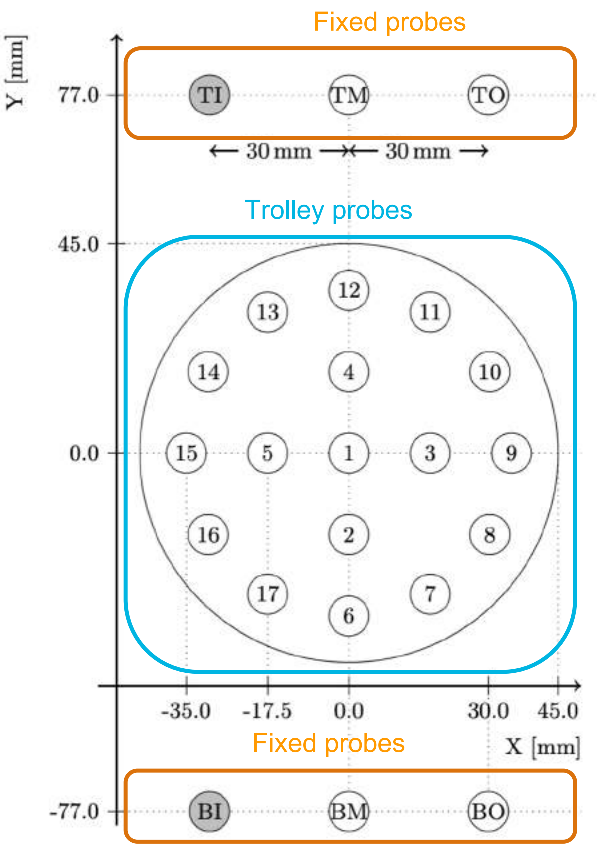


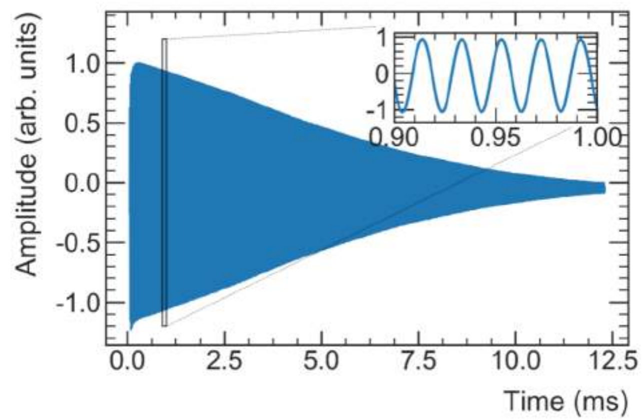


Top-down view

Measuring the field: the NMR Trolley

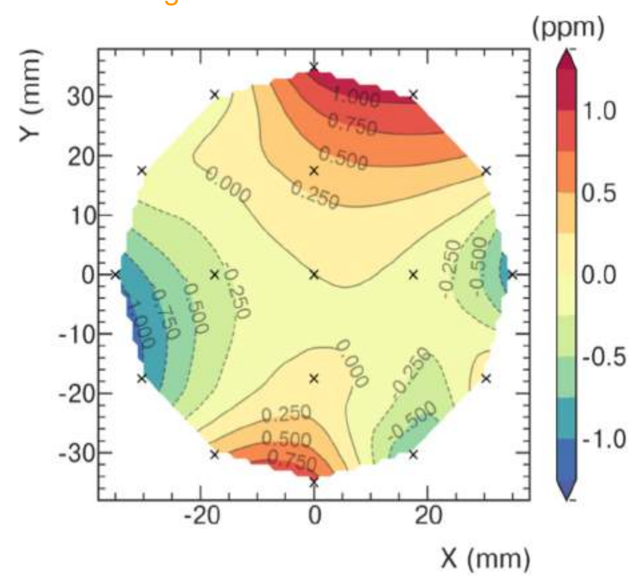
- An in-vacuum trolley with 17 NMR probes drives around the ring every ~3 days, mapping out the field components





Field measured by extracting frequency from a Free Induction Decay (FID) spectrum

Field gradients in an azimuthal "slice"



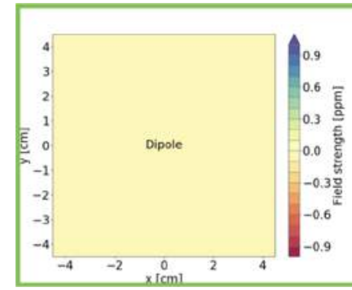
At ~8000 azimuthal locations, obtain a field contour plot from the 17 probes

Spatial dependence of B

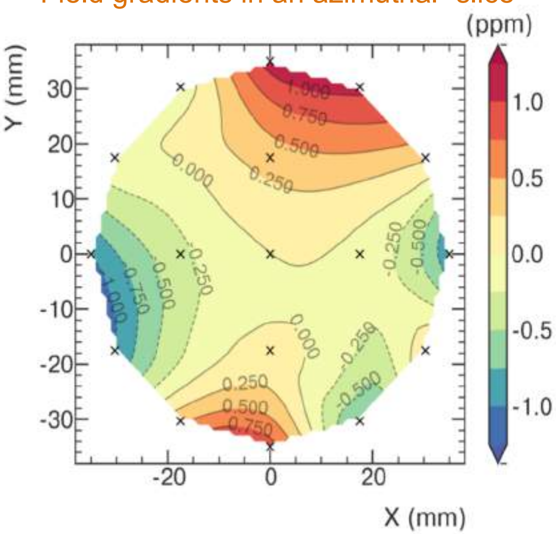
- Extract terms from a multipole (m) expansion of B in r and θ:

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

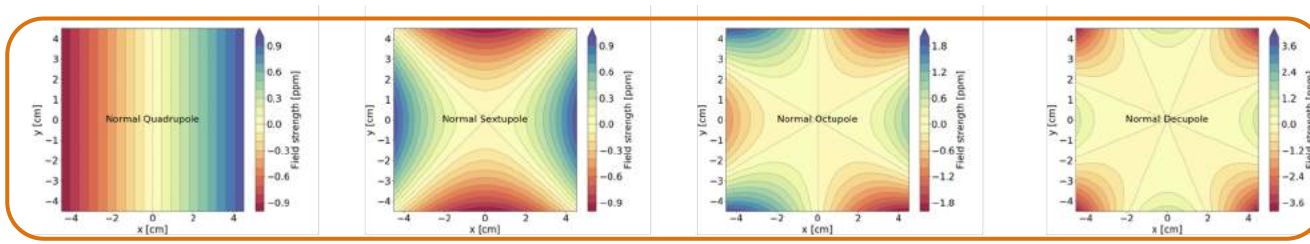
Dipole (m1)

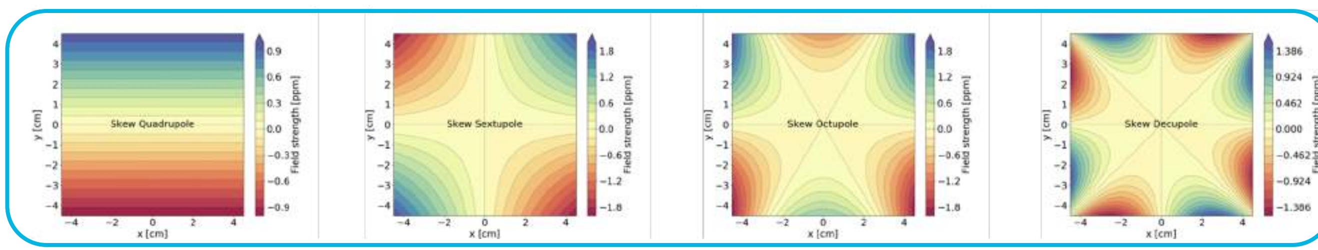


Field gradients in an azimuthal "slice"



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





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

- Trolley: Fit the 2D contour plot to extract the multipole terms (m1, m2, m3, ...)
- Fixed probes: extract terms from geometric combination of probe frequencies
- Fixed probes can track m1, m2, m3, m4 only

Interpolating between trolley runs

- Need to know the field experienced by the muons, but the trolley cannot take data when the muons are present. One trolley run takes 3 hours, every ~3 days.

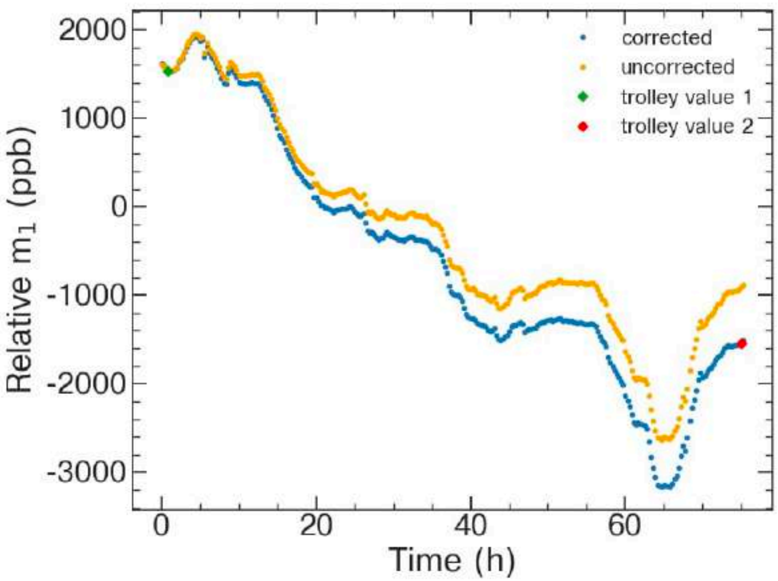
- Fixed probes take data continuously during muon fills. Use this data to interpolate between trolley runs.

- There are 72 fixed probe ‘stations’ around the ring, every ~5 degrees

- The fixed probe measurements are calibrated using the trolley measurements both times the trolley passes

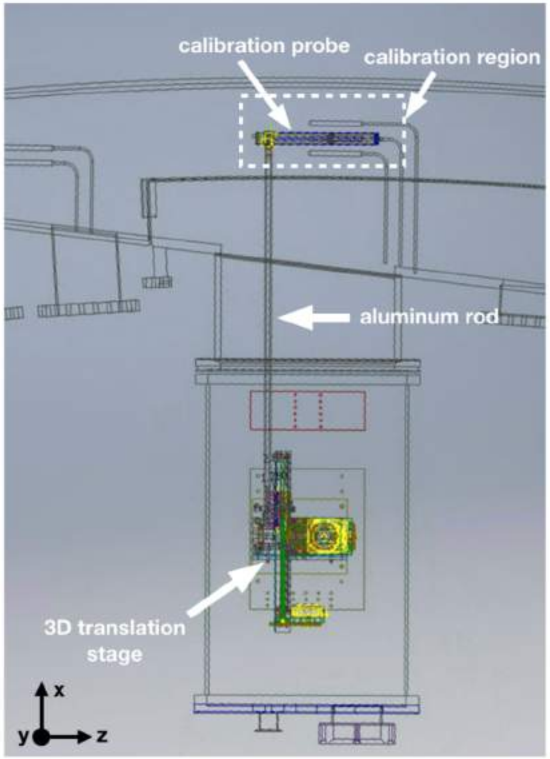
- Calibration drifts over time, due to changes in higher-order terms that cannot be tracked by the fixed probes

- Leads to the tracking error uncertainty (22 - 43 ppb in the run 1 datasets)



Absolute calibration

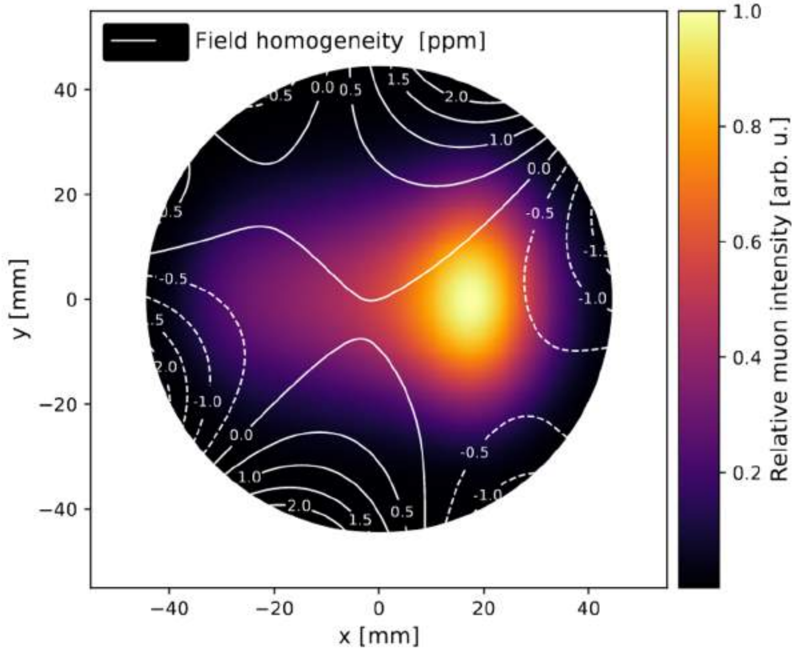
- Trolley and fixed NMR probes use petroleum jelly as the proton sample. Chosen for low volatility.
- Must calibrate with protons in a water sample (measurement standard) in order to measure a_μ
- A dedicated calibration probe with a cylindrical H_20 sample is installed inside the vacuum chamber.
- In a dedicated calibration campaign, trolley and calibration probes switch places to repeatedly measure the same field in the same place
- Calibration probe is calibrated against a different probe with a spherical water sample.
- Both calibration probes were cross-checked with a spherical 3He sample (different systematics)



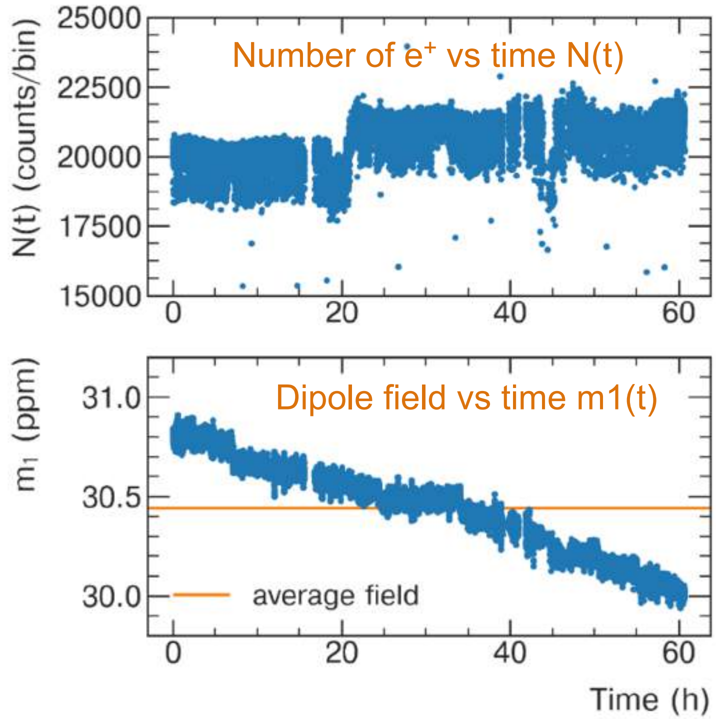
Agreement between all three calibration probes at 10 ppb level

The 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



The field is weighted by the 2D beam distribution. An average beam distribution for every 3 hours is used.



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

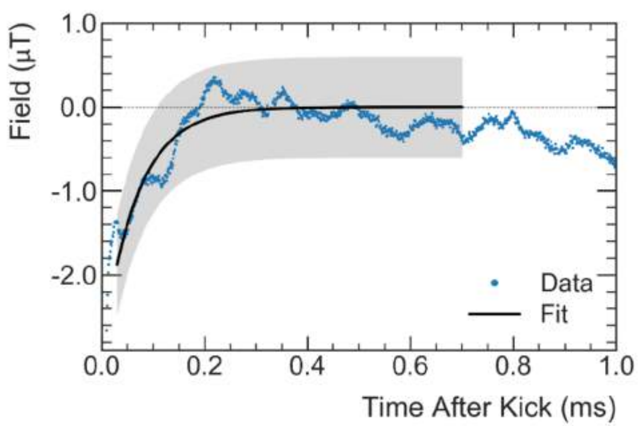
Transient fields

- 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)

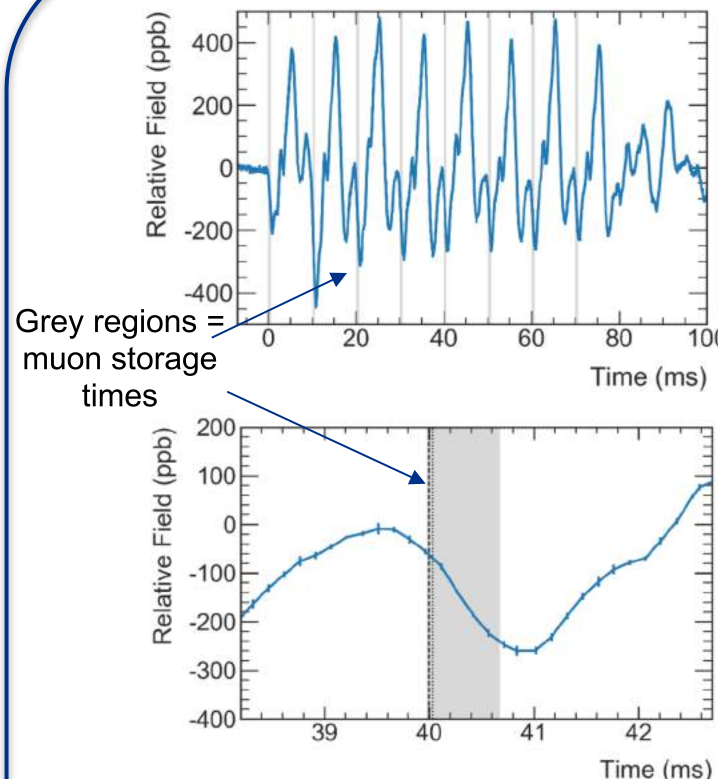
- Effects were measured separately during dedicated measurement campaigns.

Kicker



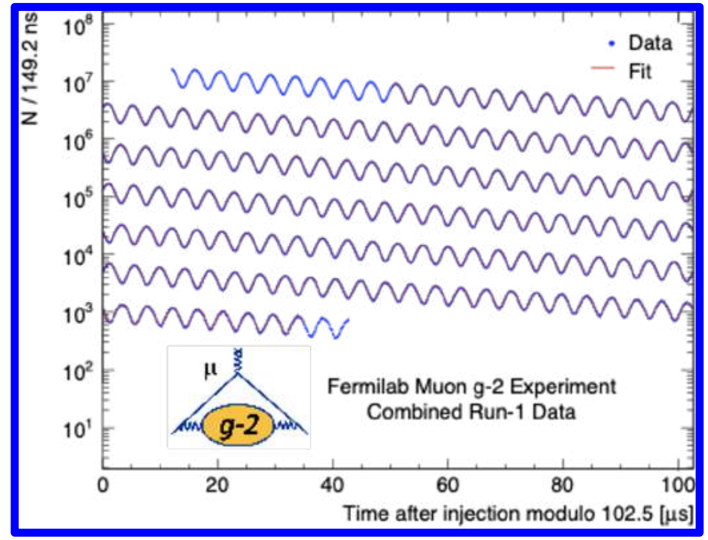
- Kicker pulse of 22 mT for 150 ns just after muon injection.
- Field change caused by residual field after kicker pulse. Muons present from 30µs to 700µs after the kick (fit region)
- Kicker correction: -27 (37) ppb

Quad

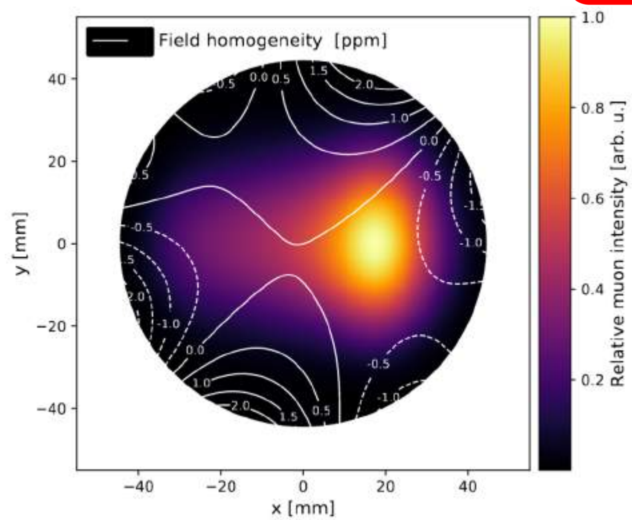


- Measured with a dedicated in-vacuum NMR probe located between quad plates during pulsing
- Quad correction: -17 (92) ppb

Bringing it all together



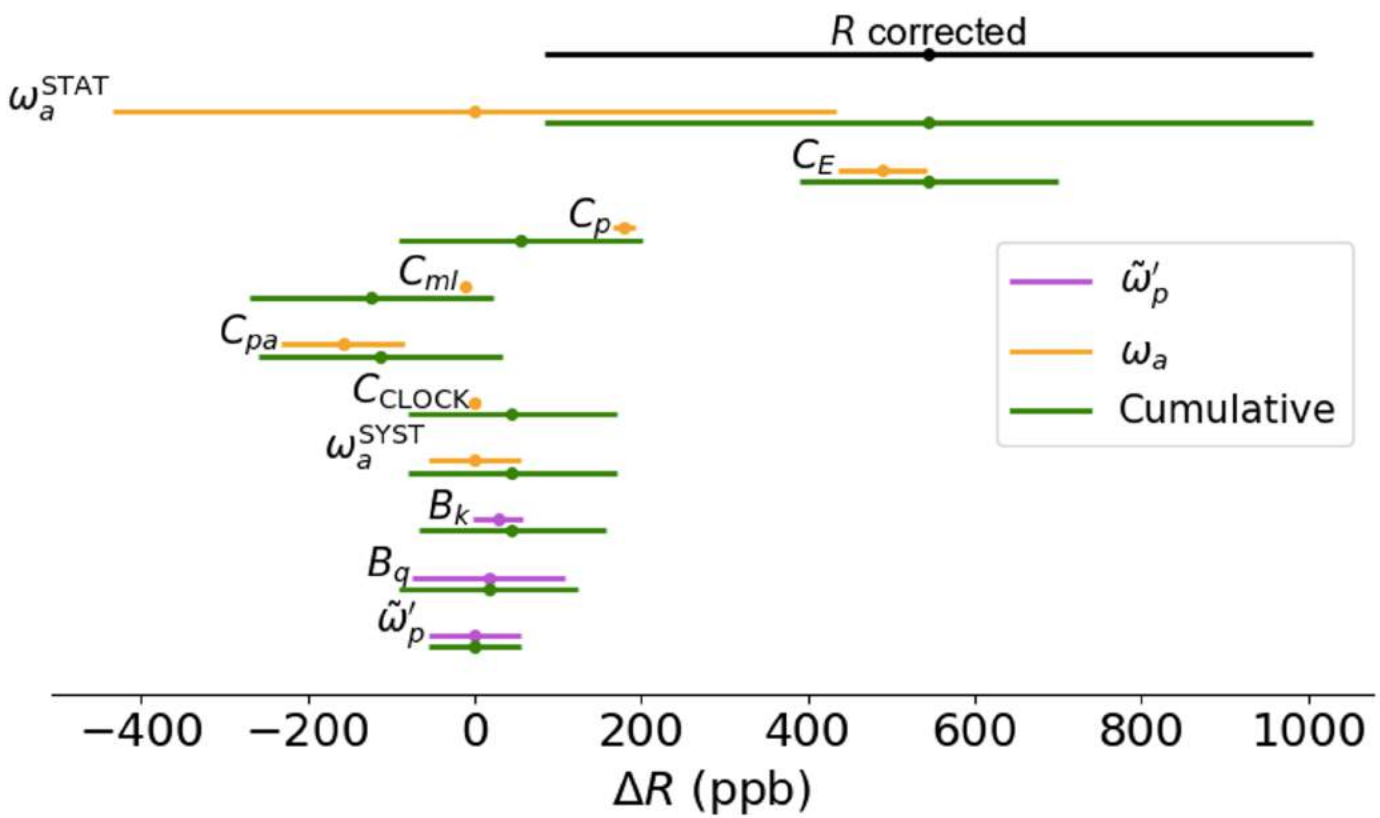
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\rm clock}\ \omega_a^m\ (1+C_e+C_p+C_{ml}+C_{pa})}{f_{\rm calib}\ \langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle(1+B_k+B_q)}$$



Corrections

Correcting Measured R

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



Systematic Uncertainties

~ 80 effects considered significant in determining the systematic uncertainty. Dedicated runs taken for some of them e.g. at different beam momentum. Documented in 98 pages of PRDs.

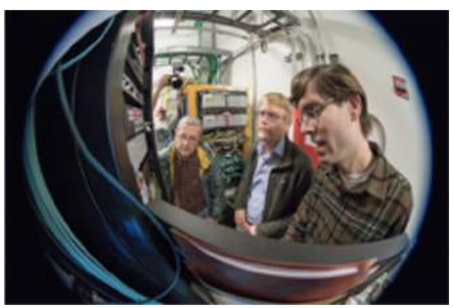
Total systematic uncertainty 157 ppb. Those above 30 ppb are below

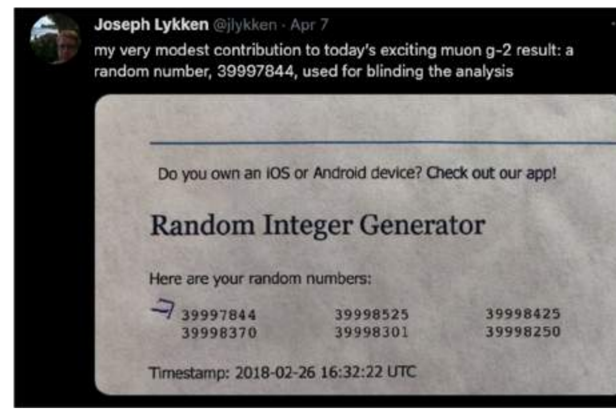
Source	Systematic Uncertainty (ppb)	Improvements undertaken
Calorimeter pileup	35	
Beam Mean Momentum & Spread	53	Increased kicker voltage: 130-161 kV
Drift of beam over measurement	75	Replaced damaged quadrupole resistors
Transient B-field (from kicker)	37	Improved magnetometer
Transient B-field (from quadrupoles)	92	More extensive measurements / damping
Total	140	

Other effects at 10-20 ppb also significantly improved by better temperature control in the experimental hall.

Clock Blinding

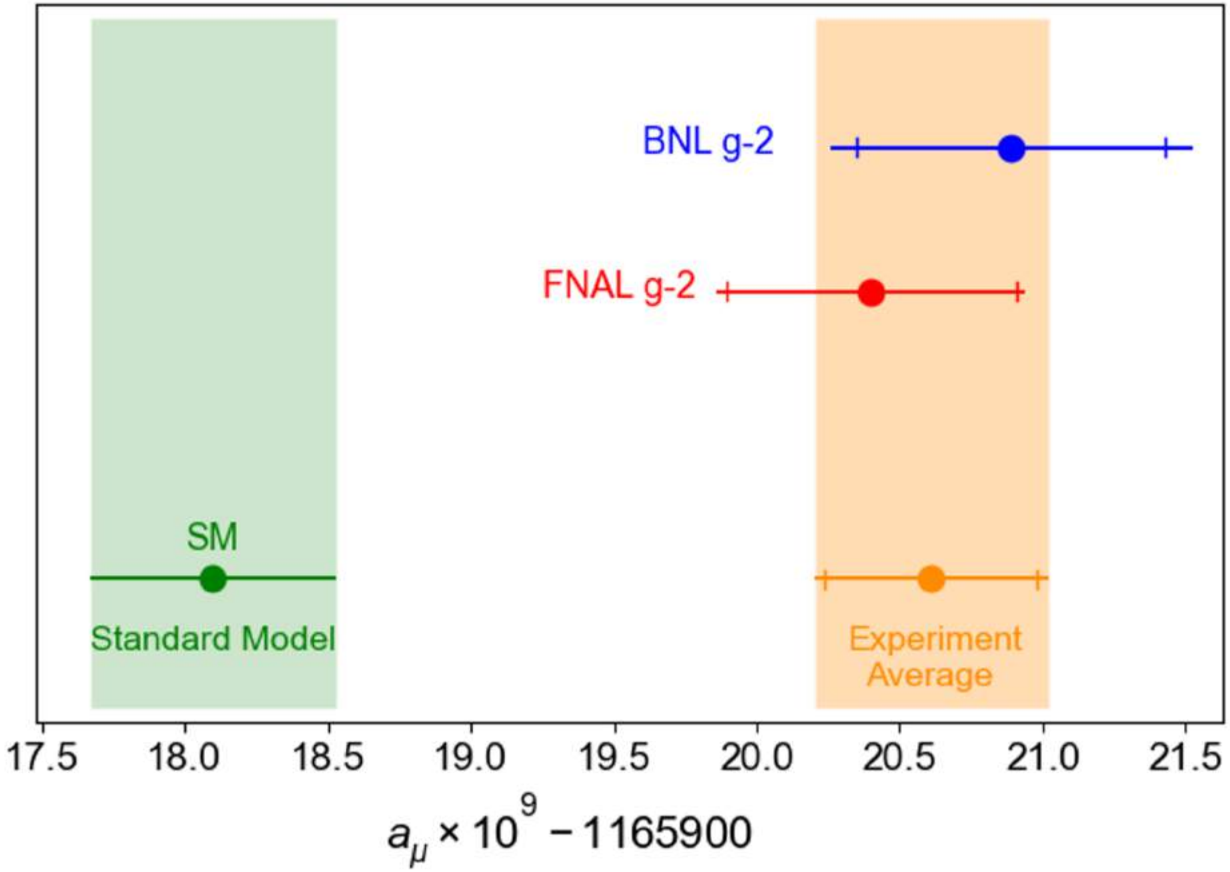
- The clock is hardware blinded to have a frequency of (40 ± ε) MHz
- Only 2 people outside of the collaboration set and know the number
- Blinding offset was ± 25 ppm (approx ×10 BNL-SM difference)



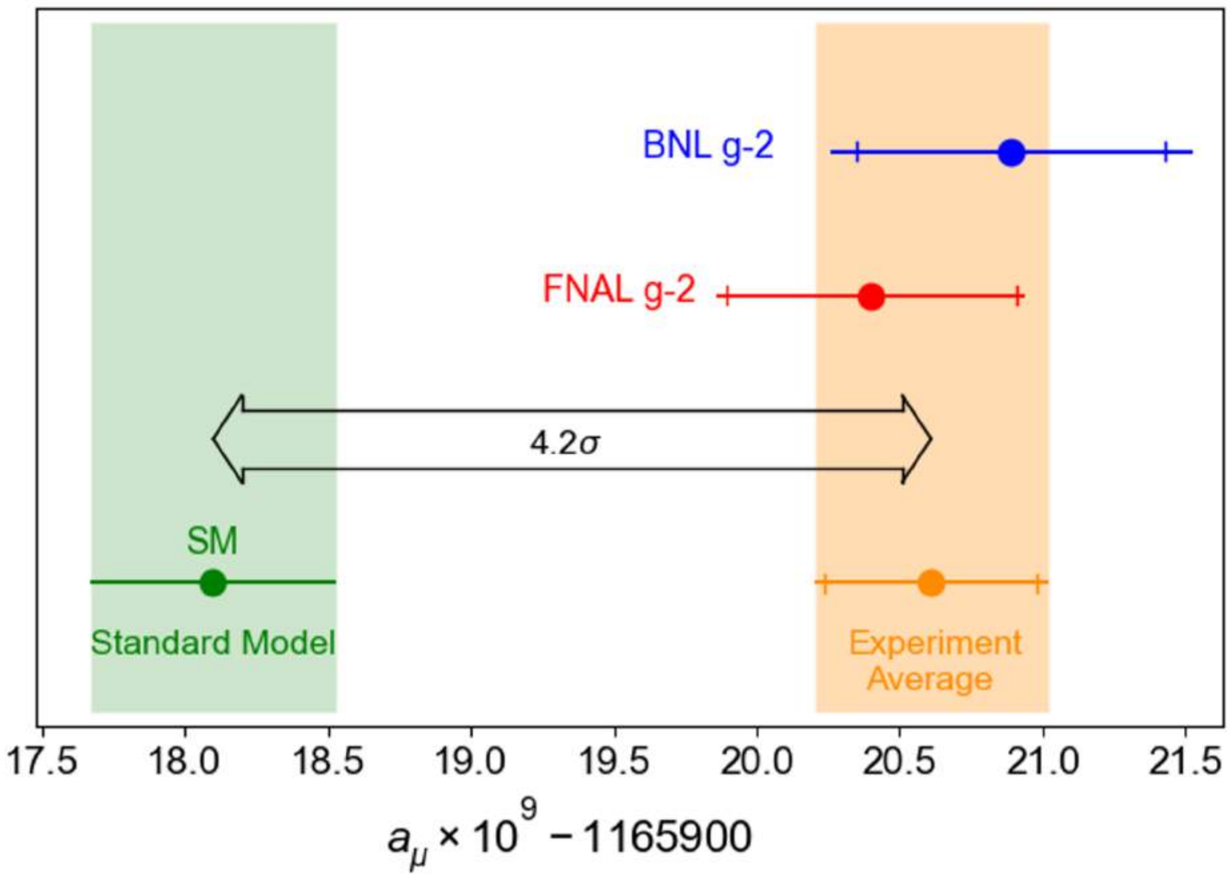


- Additionally each analysis is blinded in software

Unblinded result



Unblinded result



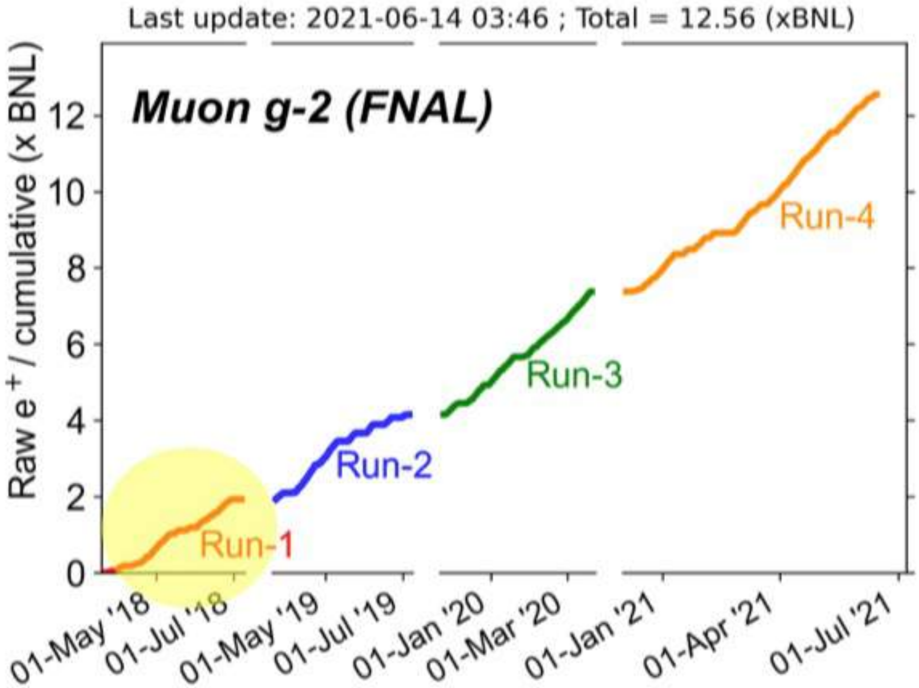
Combination with BNL

The superconducting coil, pole pieces, yoke and inflector magnet remain from BNL experiment

The underlying experimental methodology is very similar to CERN-III and BNL

- New NMR systems for magnetic field measurement
- New higher resolution calorimeter & straw trackers
- New quadrupole and kicker system
- A laser calibration system for the calorimeters (plus tracker E/p)
- Zero pion contamination and less pileup
- Full GEANT simulation and additional beam transport simulations
- More independent analyses

What next to improve/cross-check this result…



Run-4 ends in two weeks.

A final Run-5 will give us a total dataset ~ x20 that of the the first publication

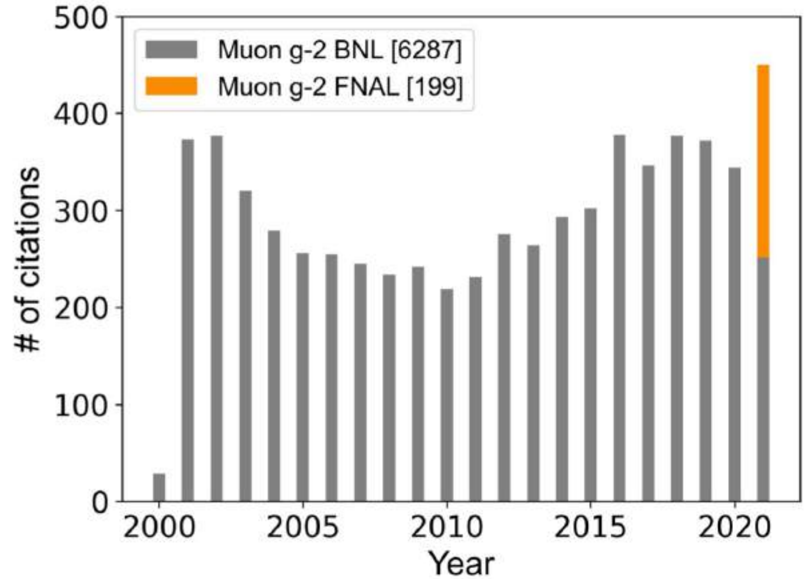
Current publication (Run-1) based on dataset ~ 1 BNL (~ 10B muon decays)

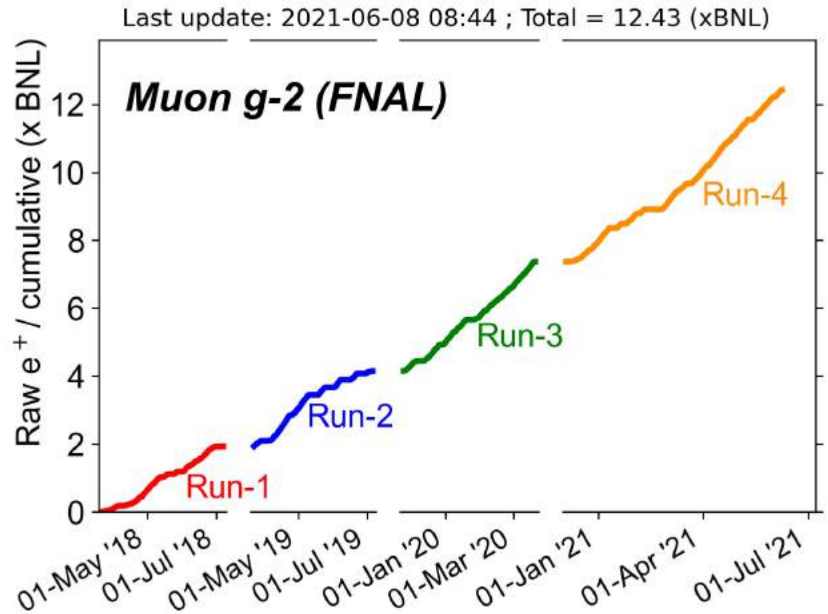
Now analysing Run-2/Run-3 : should reduce statistical uncertainty by 2 (~ 220 ppb) and expect to reach systematic uncertainty goal of 100 ppb : still statistics limited

With full dataset (upto Run-5) likely we become systematics limited

Conclusions

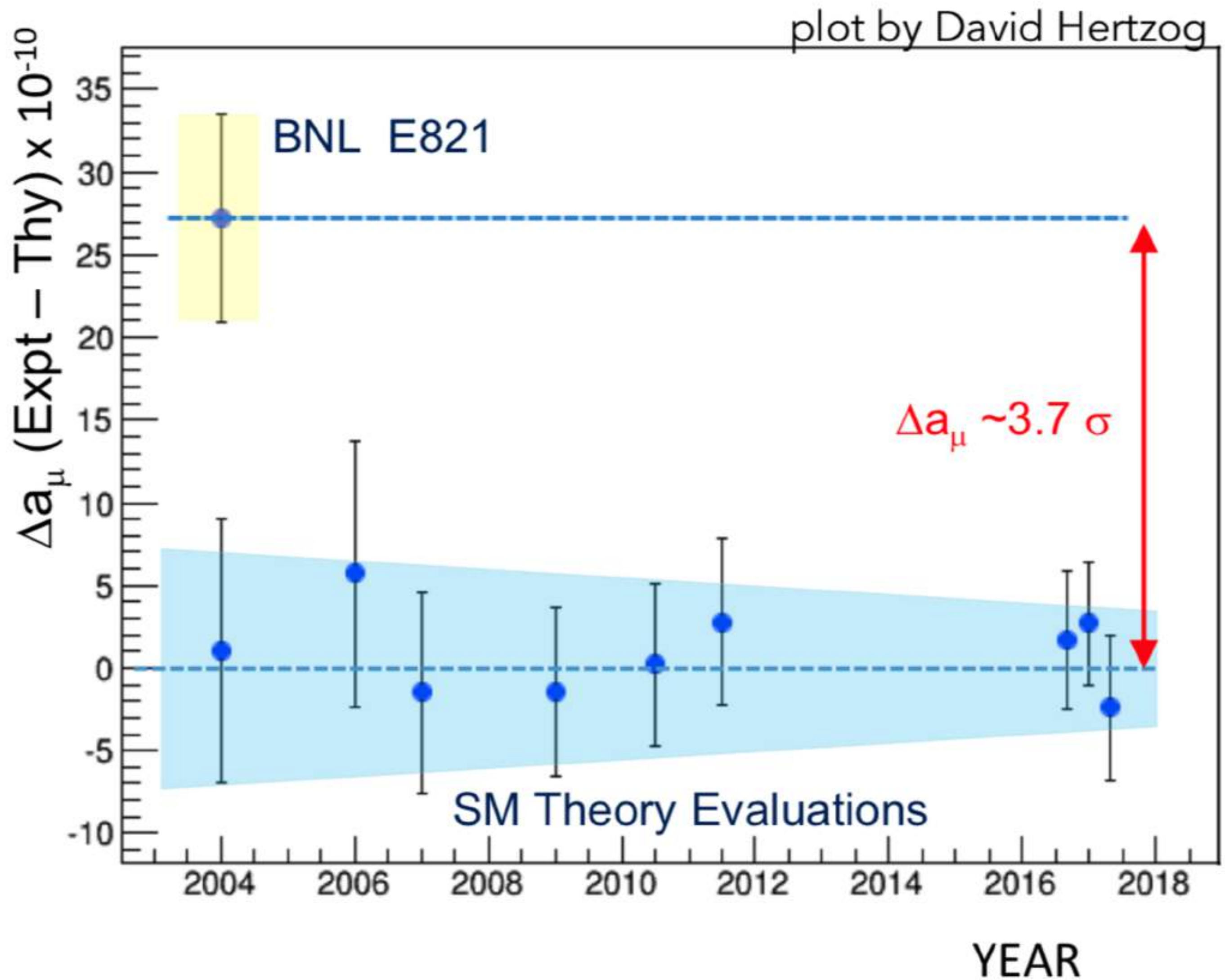
- The analysis of the Run-1 data produced a result with 460 ppb precision
- Strengthened evidence for deviation from SM in muon g-2 : 4.2σ tension with the theoretical prediction
- There is a lot more data to analyse - expect a factor 2 improvement for Run-2/3 analysis

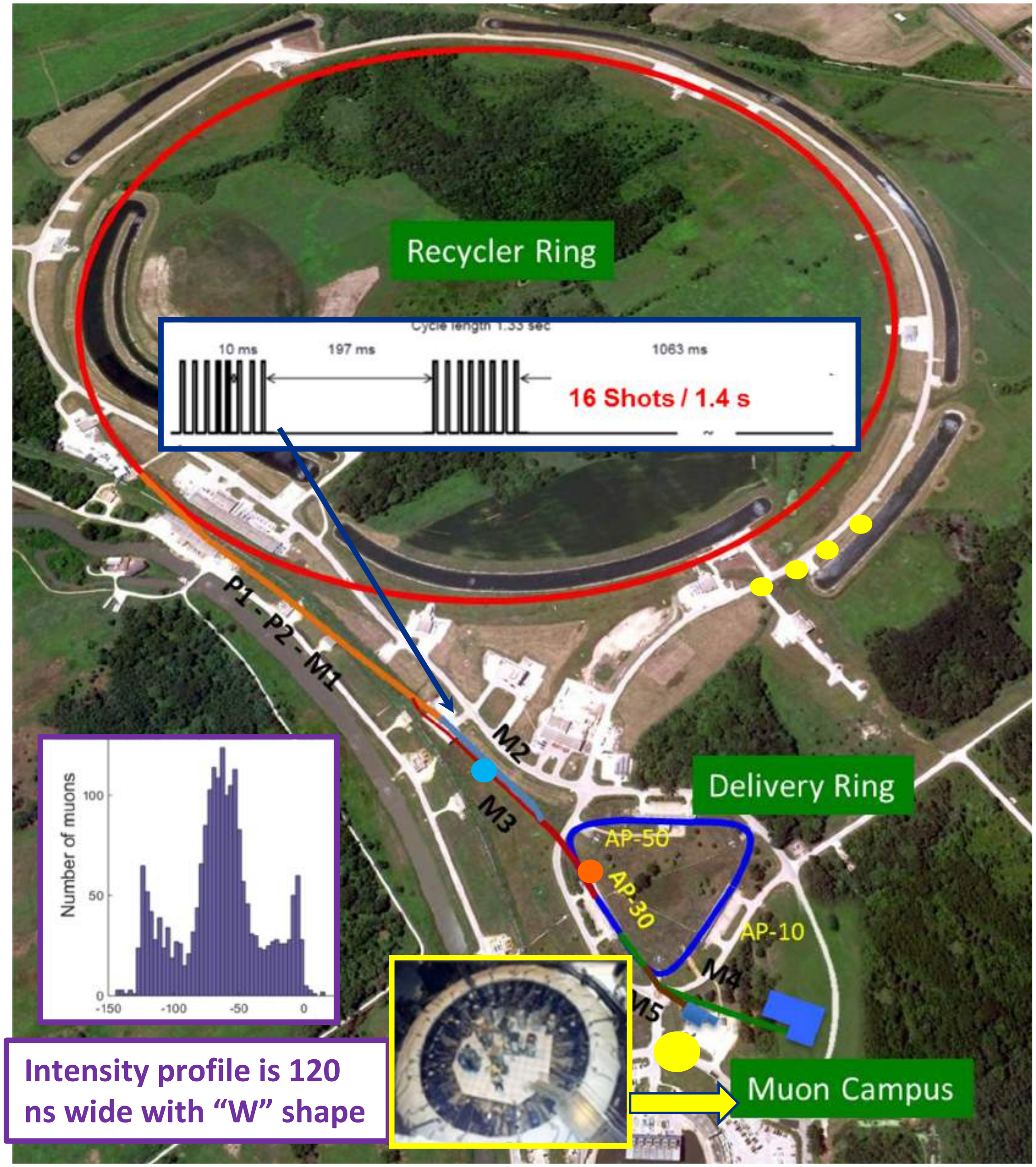




Backups

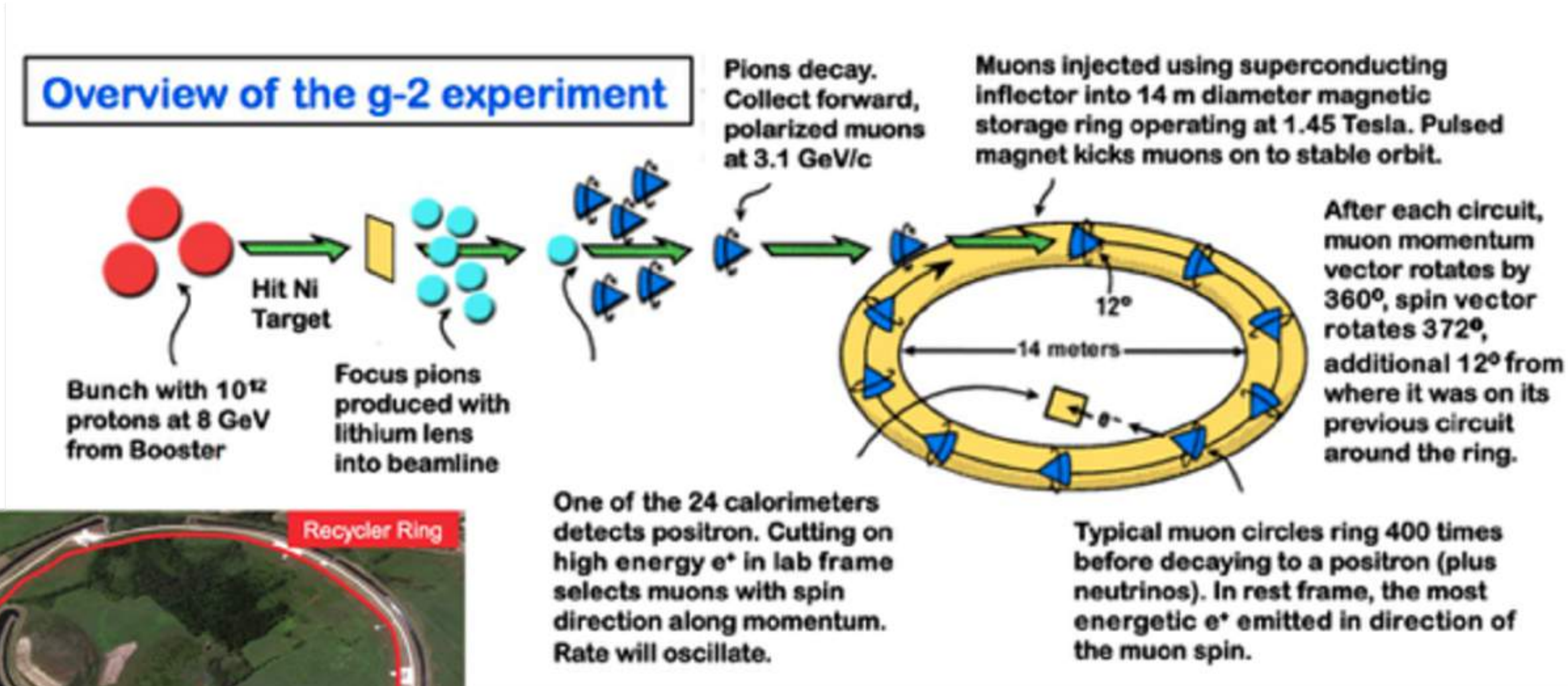
Muon g-2: History of Experiment vs Theory





Muons at Fermilab

- Deliver two 4 $\times 10^{12}$ 8 GeV proton batches to the Main Injector Recycler (graphic shows one)
- Batches are split into four bunches
- One bunch extracted every 10 msec to AP0 target hall
- 3.1 GeV pions are selected and focused by Li lens
- Transported through dense FODO lattice to Delivery Ring
- Several passes around Delivery Ring to remove protons by time-of-flight.
- Muons are focused and injected into the Muon g-2 storage ring.
- Whole cycle repeats twice every 1.4s



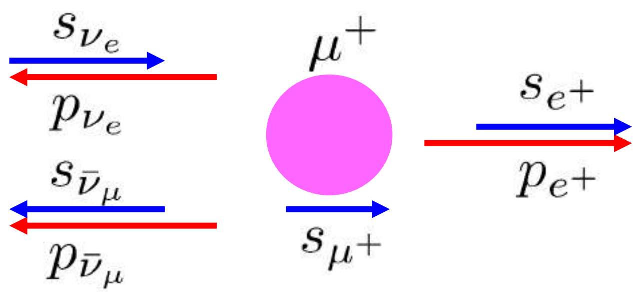
Fermilab statistics advantages

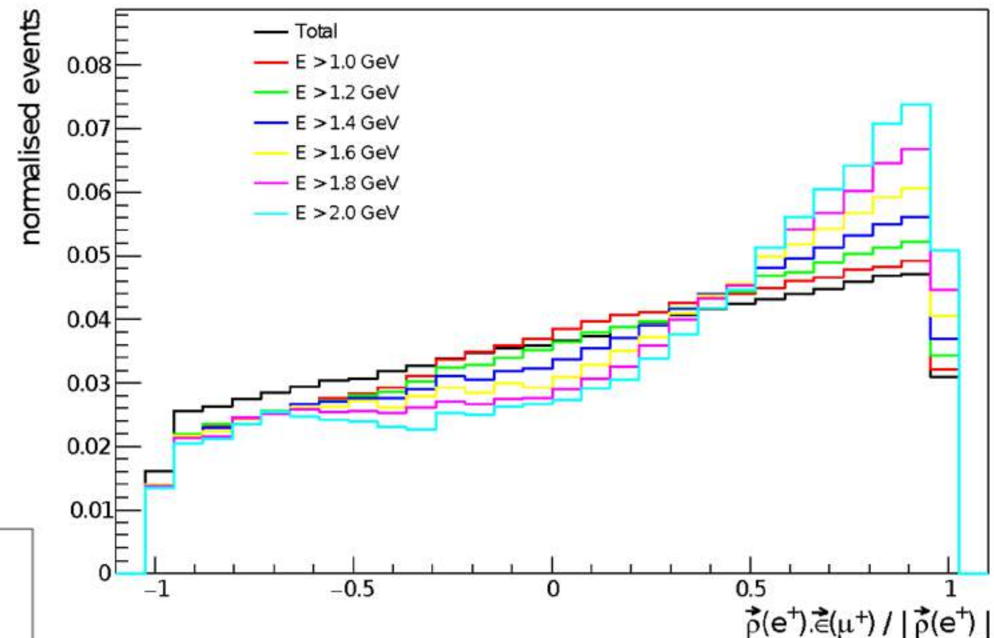
- Long decay channel for $\pi \rightarrow \mu$
- Reduced p and π in ring
- Factor 20 reduction in hadronic flash
- 4x higher fill frequency than BNL

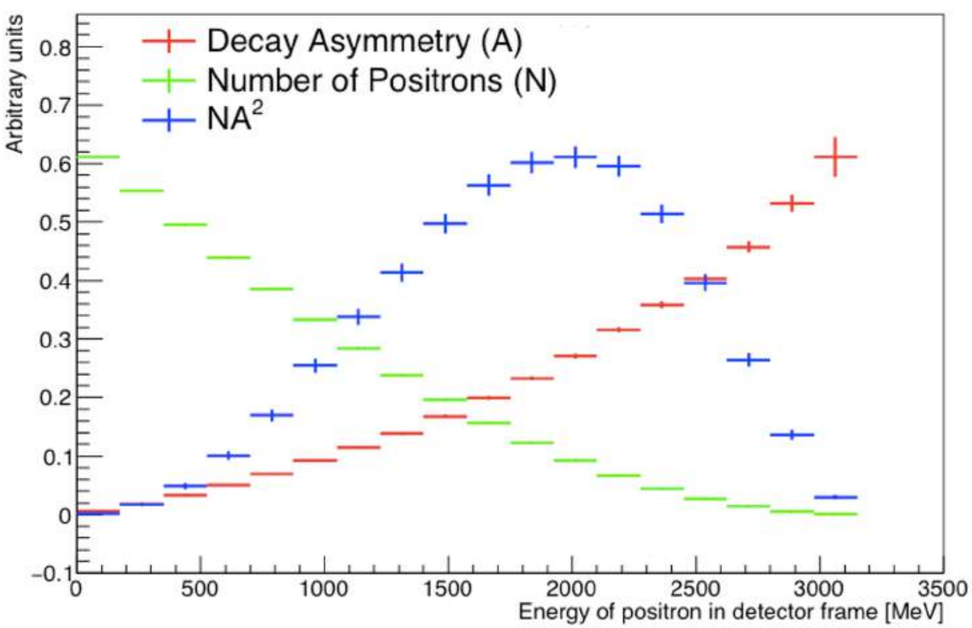
→ 21 times more positrons detected than at BNL

Muon decay

- e^+ preferentially emitted in direction of muon spin







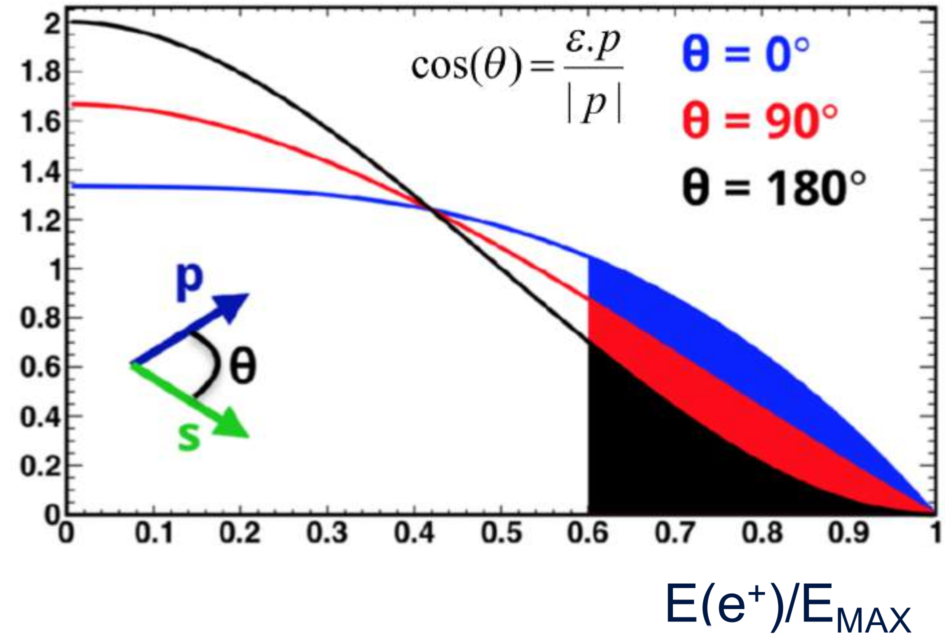
$$\frac{\Delta\omega_a}{\omega_a} \propto \frac{1}{\gamma_\mu \sqrt{NA^2}}$$

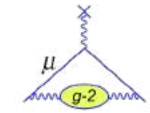
- Asymmetry is larger for higher momentum e^+
- Optimal cut at ~1.7 GeV

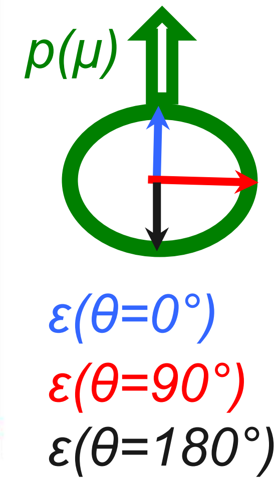
Measuring ω_a

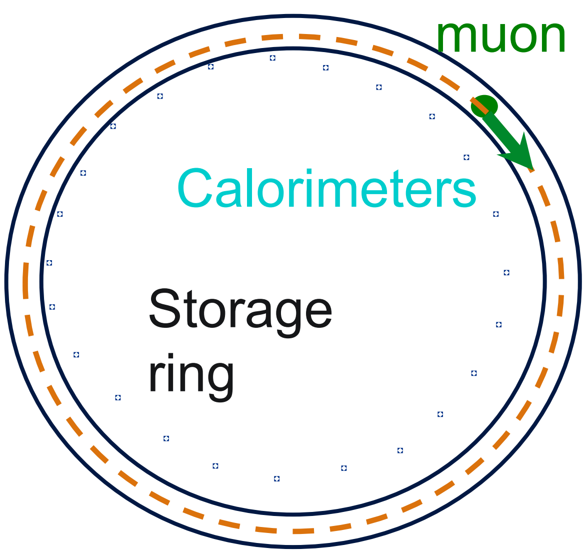
The number of high momentum positrons above a fixed energy threshold oscillates at precession frequency

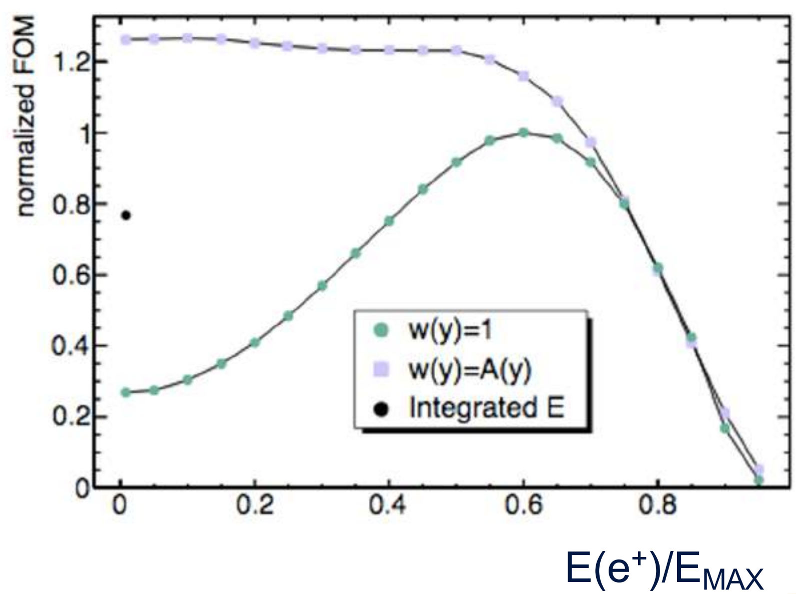
TOO MUCH IN THIS SLIDE







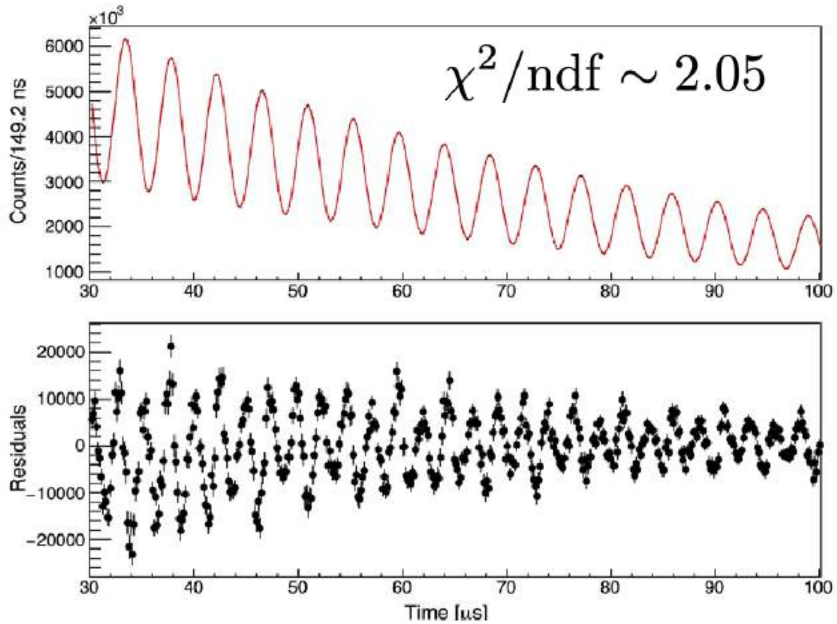


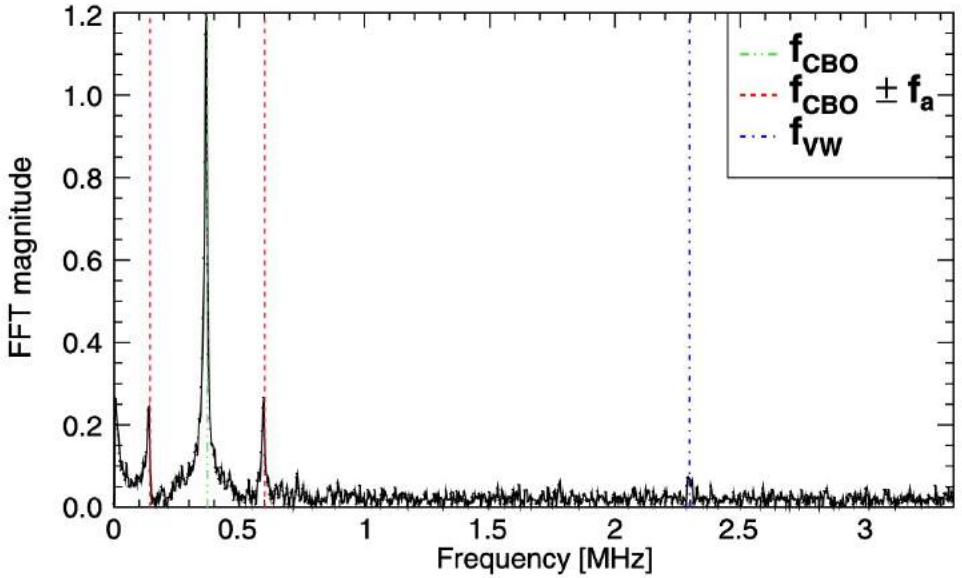


Simply measure the time and energy of decay positrons

Count the number above at each energy and weight based on asymmetry

Results of 5 parameter fit …



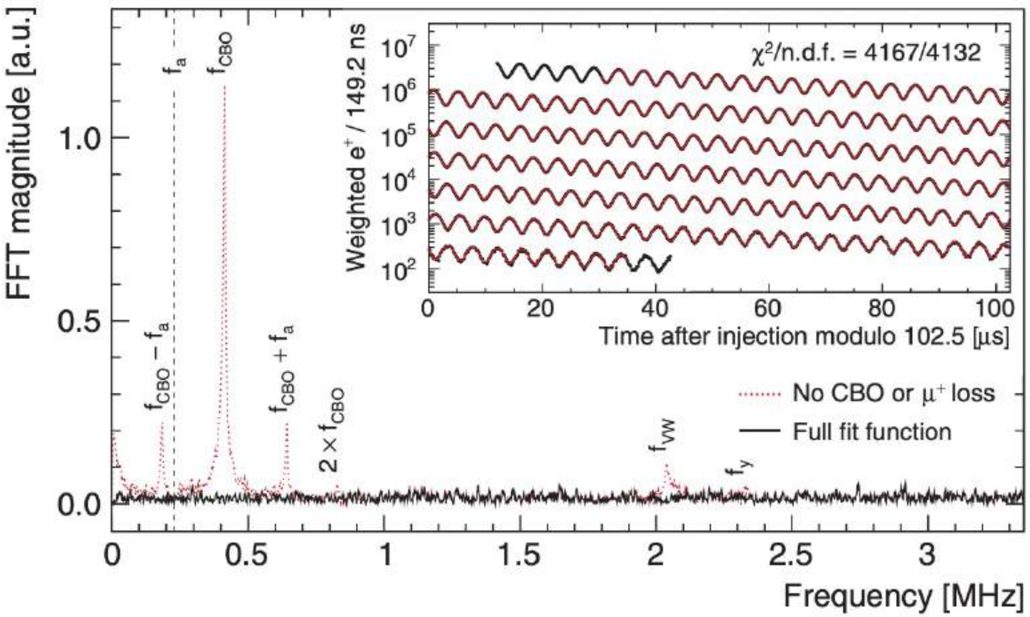


Add additional 17 terms in fit to describe:

- Muons lost from storage ring not by decaying
- Pileup (concurrent, multiple e^+ in same calorimeter crystal)
- Vertical and radial beam motion

And get $\chi^2/\text{ndf} \sim 1.008$

Resulting 22 Parameter Fit



Phys. Rev. D 103, 072002 (2021)

Statistical uncertainty from this fit : 434 ppb

Largest correction to data is : 489 ppb (total correction is 456 ppb)

Total systematic uncertainty is : 157 ppb (aim was 100 ppb)

Deviation from SM (with BNL) : 2400 ppb

Two Sets of corrections to get to (g-2)

1. Our NMR frequencies are multiplied by: $\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$ to determine the B-field

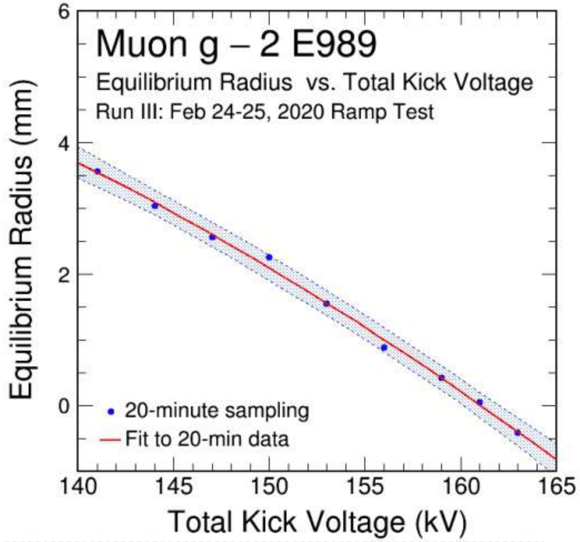
The uncertainty on this correction is very small (24 ppb) from CODATA and external to experiment

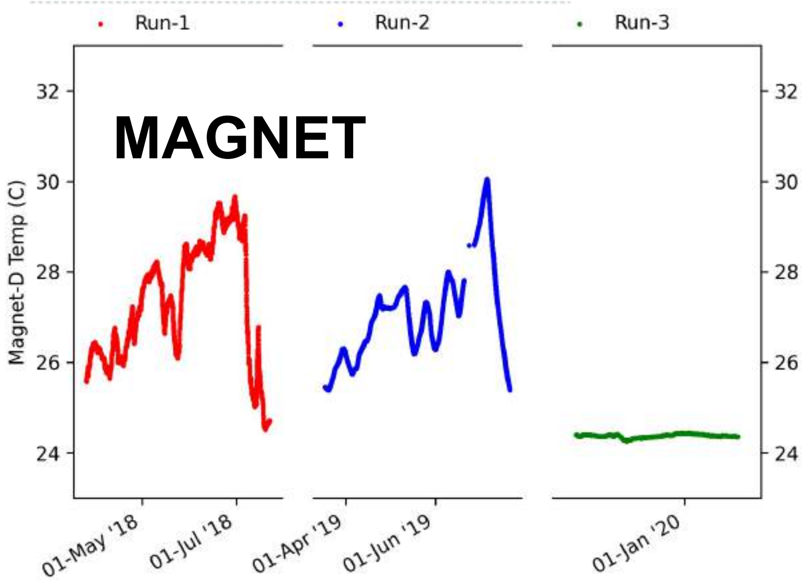
2. Corrections because the beam and apparatus are not perfect

- beam has a few MeV momentum spread
- beam has a small vertical momentum component
- mean position (and rms) of beam drifts slowly over measurement period
- there are transient magnetic fields in addition to the 1.45 T storage ring field
- muon population is depleted other than by decay & is momentum dependent

The uncertainty in these corrections largely determines the systematic uncertainty

Run-2/3 Improvements





Resistors fixed for Run-2/3