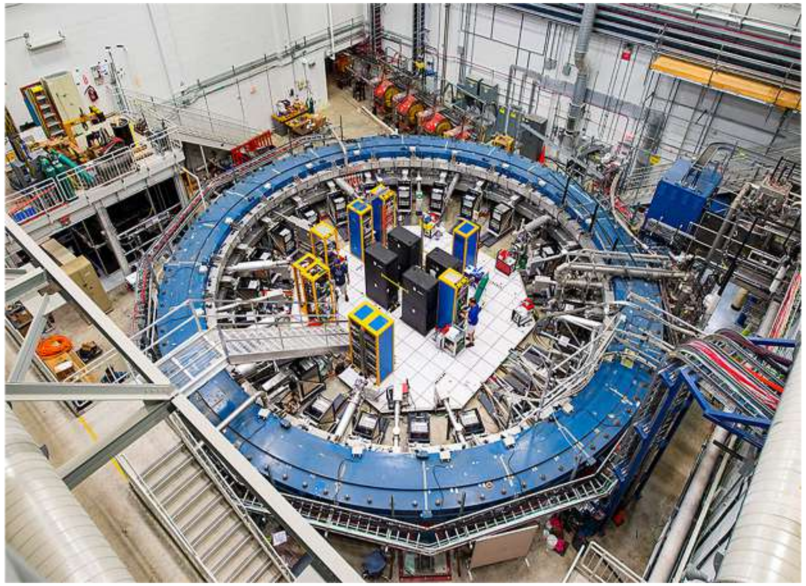
First Results From
The Fermilab Muon g-2 Experiment



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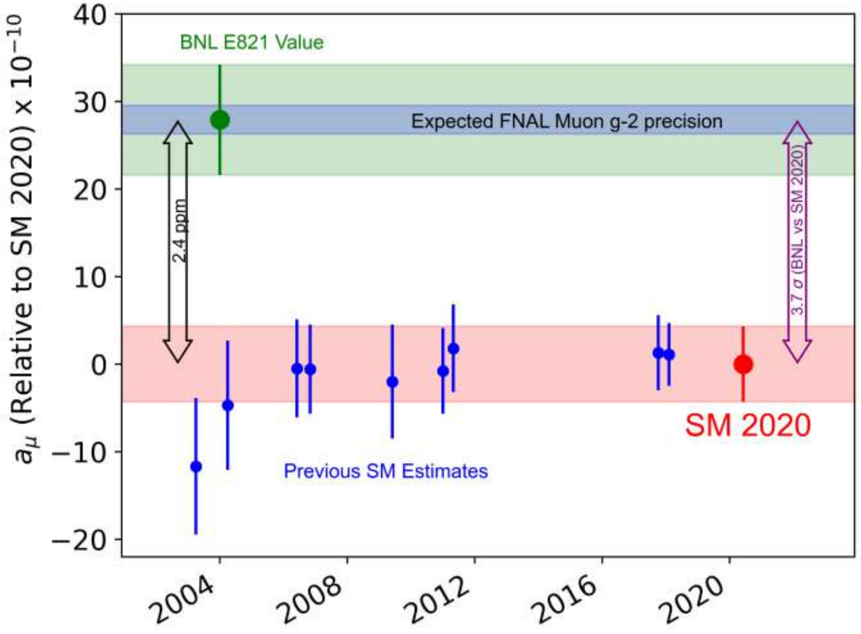
EPS-HEP 2021
28th July 2021

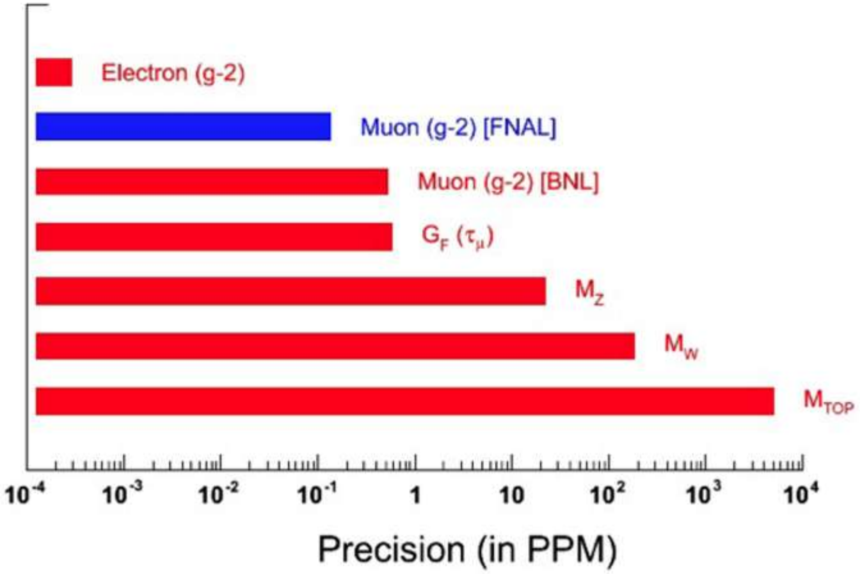
Fermilab

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. $\oplus$ 100 ppb syst.
Today's talk is on a dataset of similar size to BNL ~ 10 billion μ^+

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.

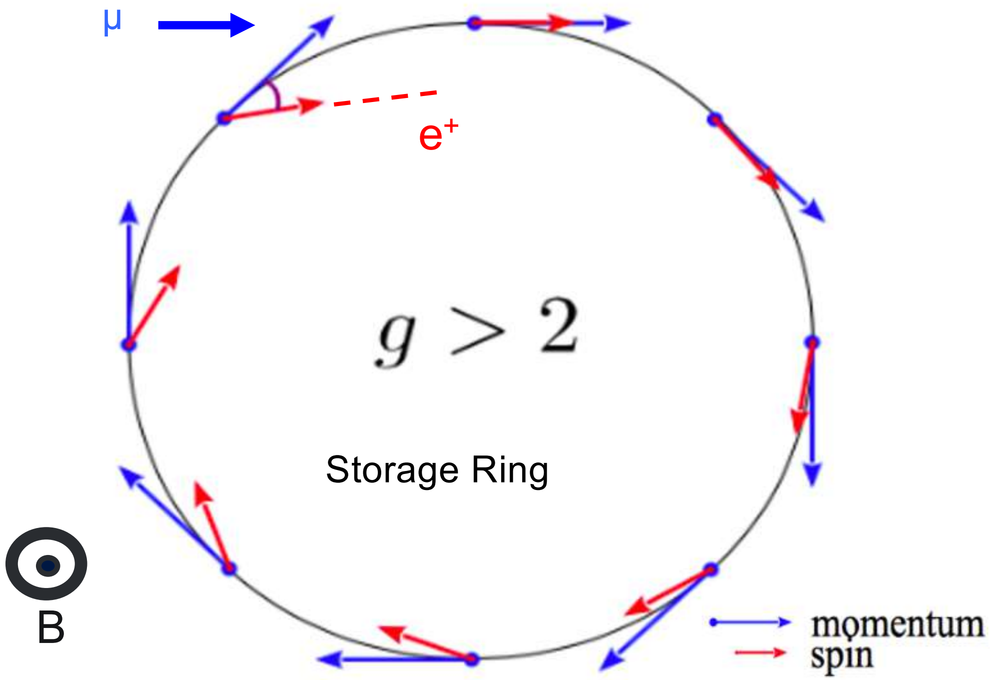
$$\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

Larmor precession

Thomas precession

Cyclotron freq.

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



Measurement details

The experiment actually measures two frequencies

$$a_\mu = \boxed{\frac{\omega_a}{\tilde{\omega}_p}} \overbrace{\frac{\mu_p}{\mu_e}}^{\text{3ppb}} \underbrace{\frac{m_\mu}{m_e}}_{\text{22ppb}} \overbrace{\frac{g_e}{2}}^{\text{0.0003ppb}}$$

What we measure

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

Measurement details

The experiment actually measures two frequencies

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

What we measure

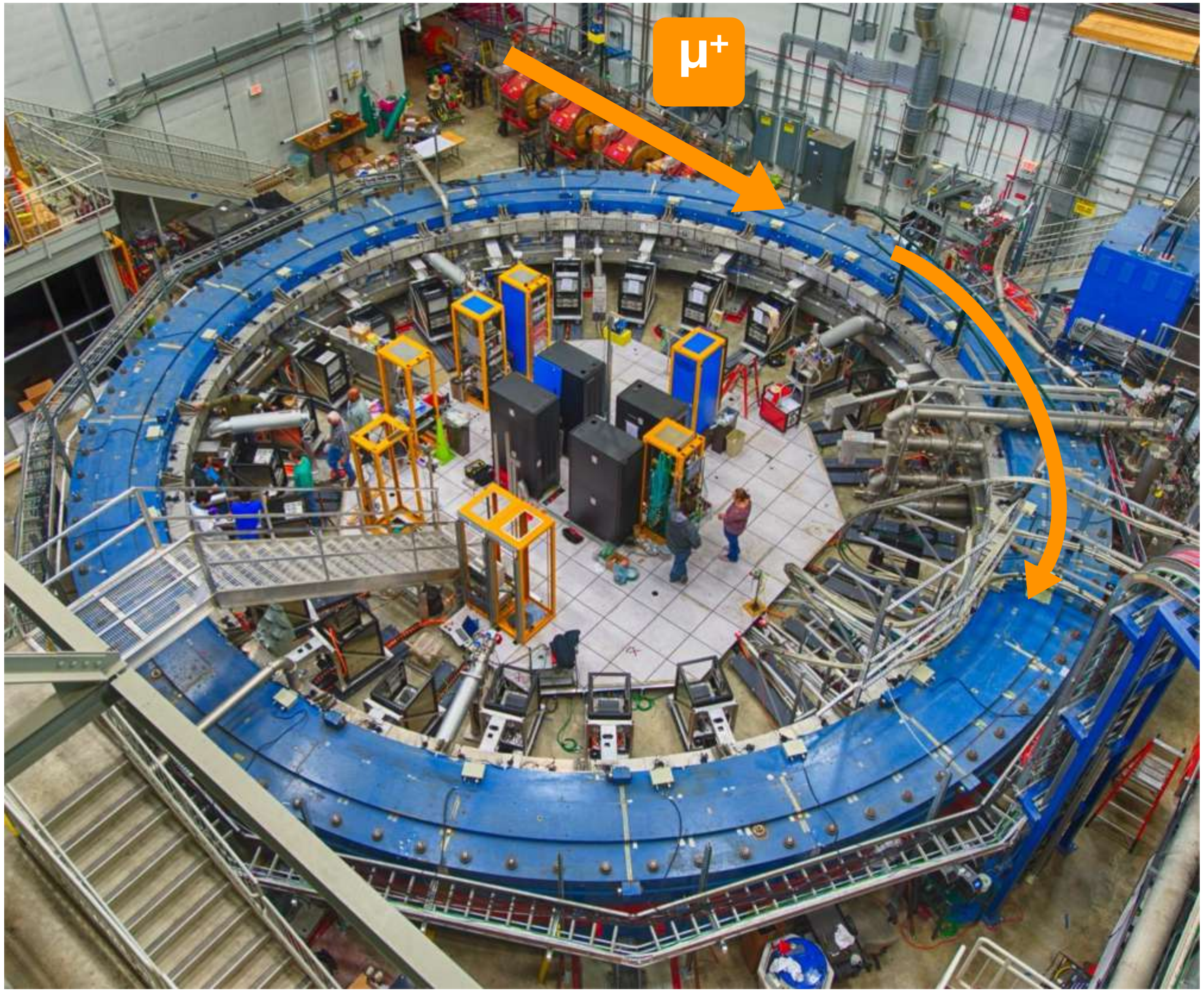
Alberto Lusiani
Thursday, July 29, 16.50pm CEST
834. Measurement of the muon precession frequency in magnetic field
for the measurement of the muon magnetic anomaly Accelerators for HEP
Poster T13: Accelerators for HEP

Elia Bottalico
Tuesday, July 27 from 5-7pm CEST
829. Beam dynamics corrections to the Run-1 measurement of the experiment Muon g-2 at Fermilab Accelerators for HEP Poster T13: Accelerators for HEP

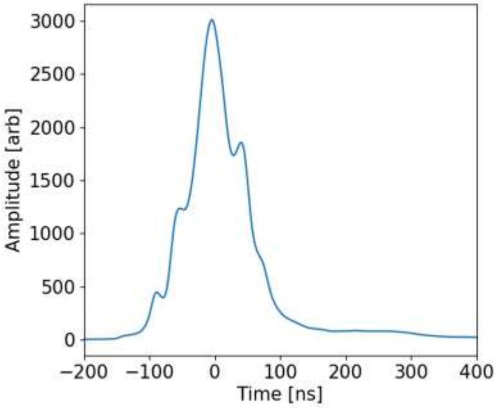
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{\overset{\text{Unblinding conversion factor}}{f_{\text{clock}}}\ \overset{\text{Measured } g-2 \text{ frequency}}{\omega_a^m}\,(1 + \overbrace{C_e + C_p + C_{ml} + C_{pa}}^{\text{Corrections from the beam dynamics systematic effects}})}{\underset{\text{NMR probe calibration factor}}{f_{\text{calib}}}\ \underbrace{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle}_{\text{Magnetic field weighted over the muon distribution and azimuthally averaged}}(1 + \underbrace{B_k + B_q}_{\text{Corrections from the transient magnetic field}})}$$

Saskia Charity
Tuesday, July 27 from 5-7pm CEST
1065. Precision measurement of the magnetic field in Run-1 of the Fermilab muon g-2 experiment Accelerators for HEP Poster T13: Accelerators for HEP

Beam injection



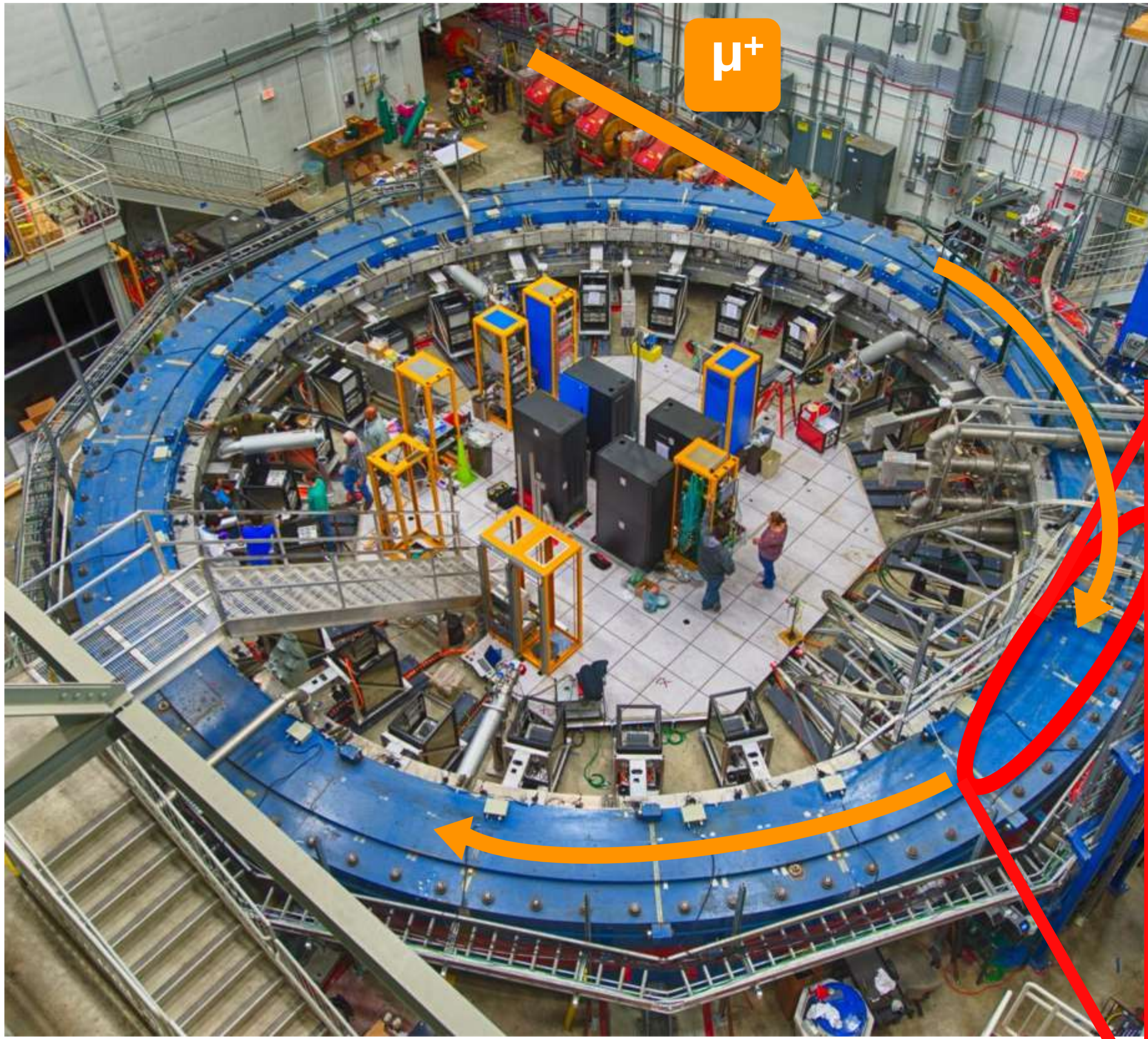
- Monitor beam profile before entrance with scintillating X and Y fibres
- Get time profile of beam using scintillating pad
- ~125ns wide

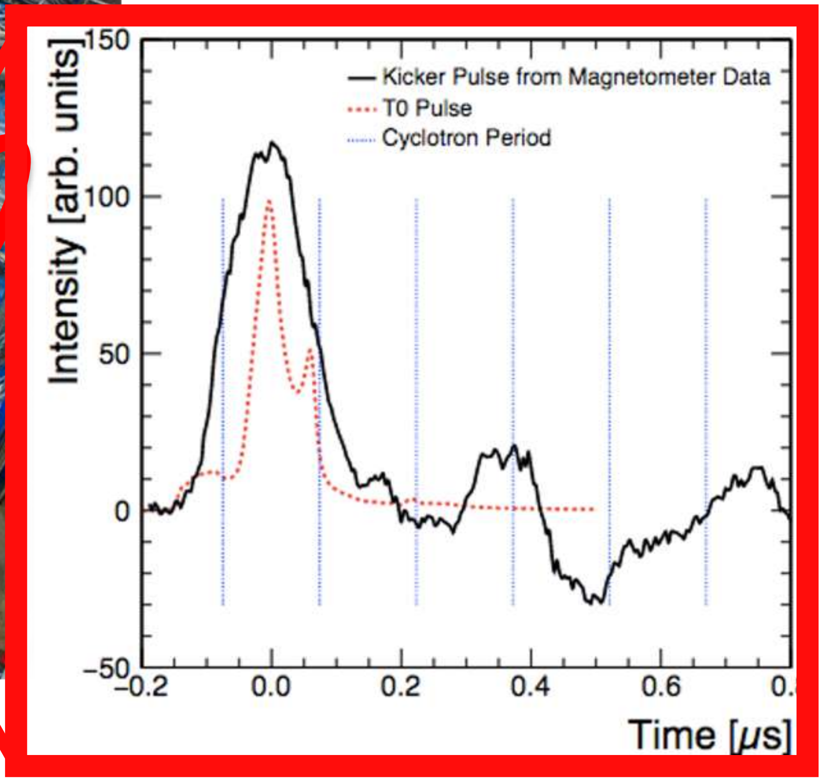


- Cancel B-field during injection using Inflector, so muons can get into the ring

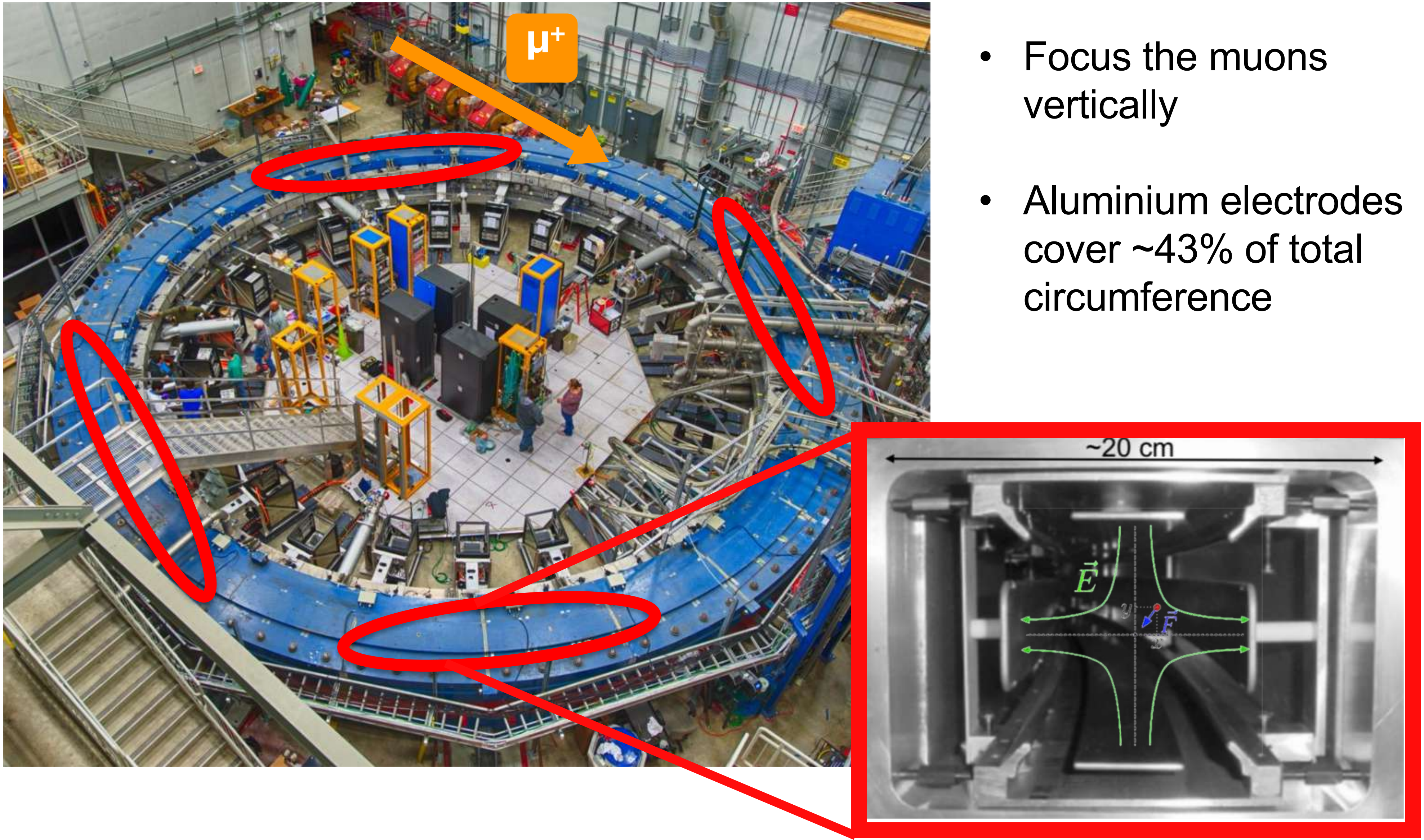
‘Kick’ onto correct orbit

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



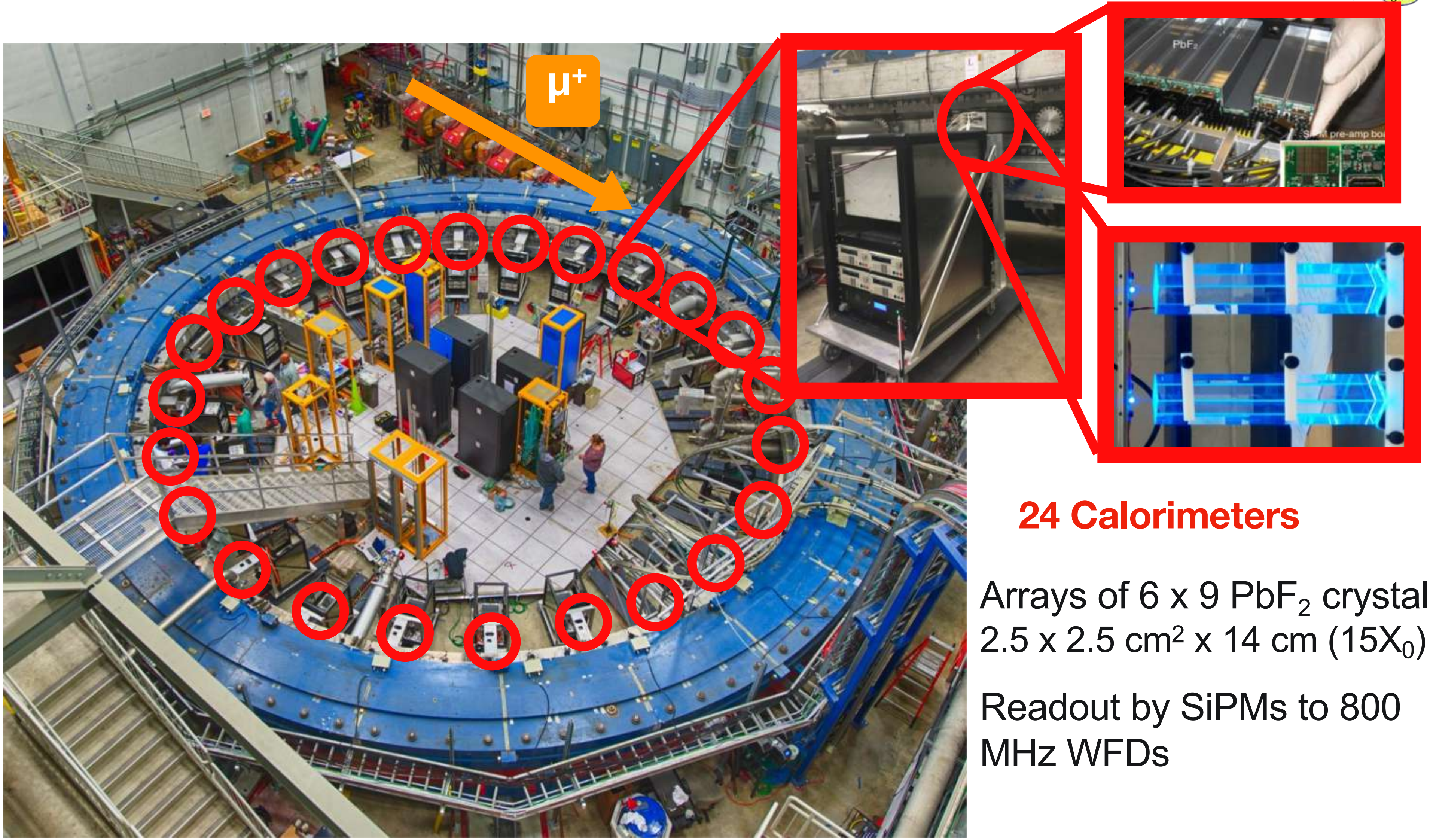


Beam focusing



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

Calorimeters

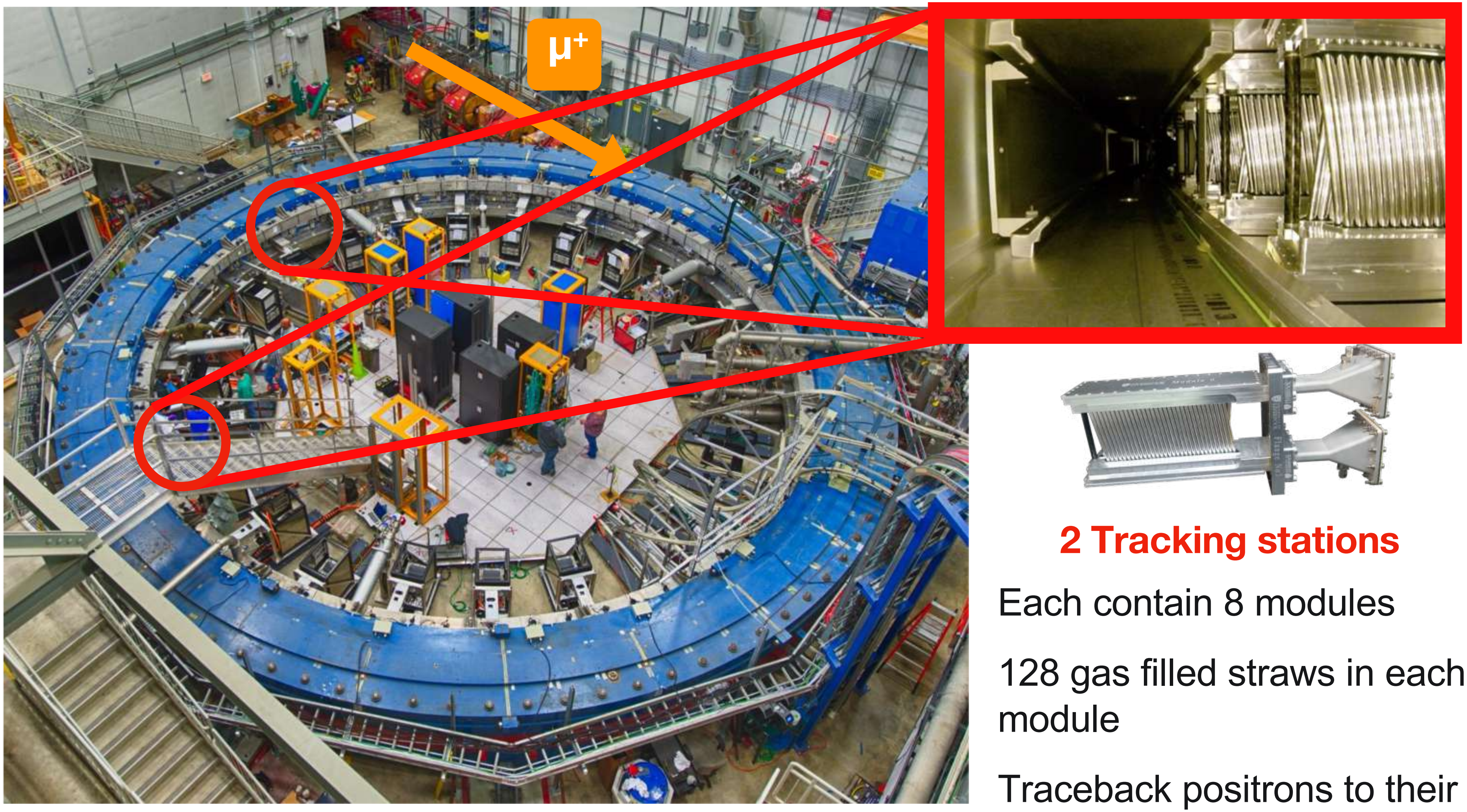


24 Calorimeters

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

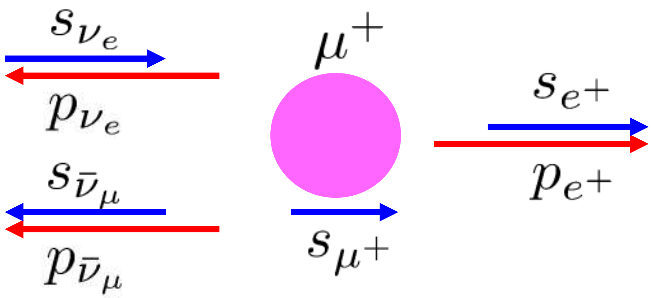
Each contain 8 modules

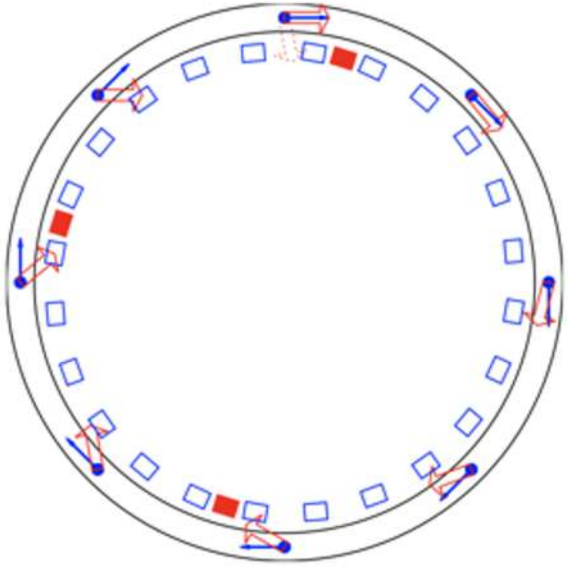
128 gas filled straws in each module

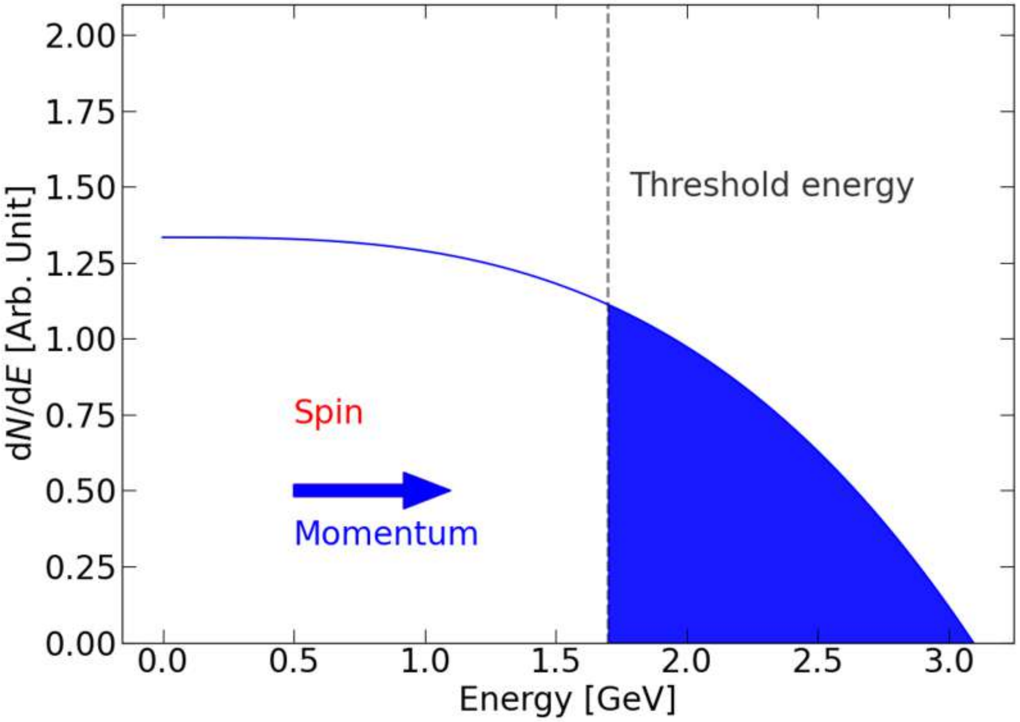
Traceback positrons to their decay point

Measuring ω_a

- e^+ preferentially emitted in direction of muon spin



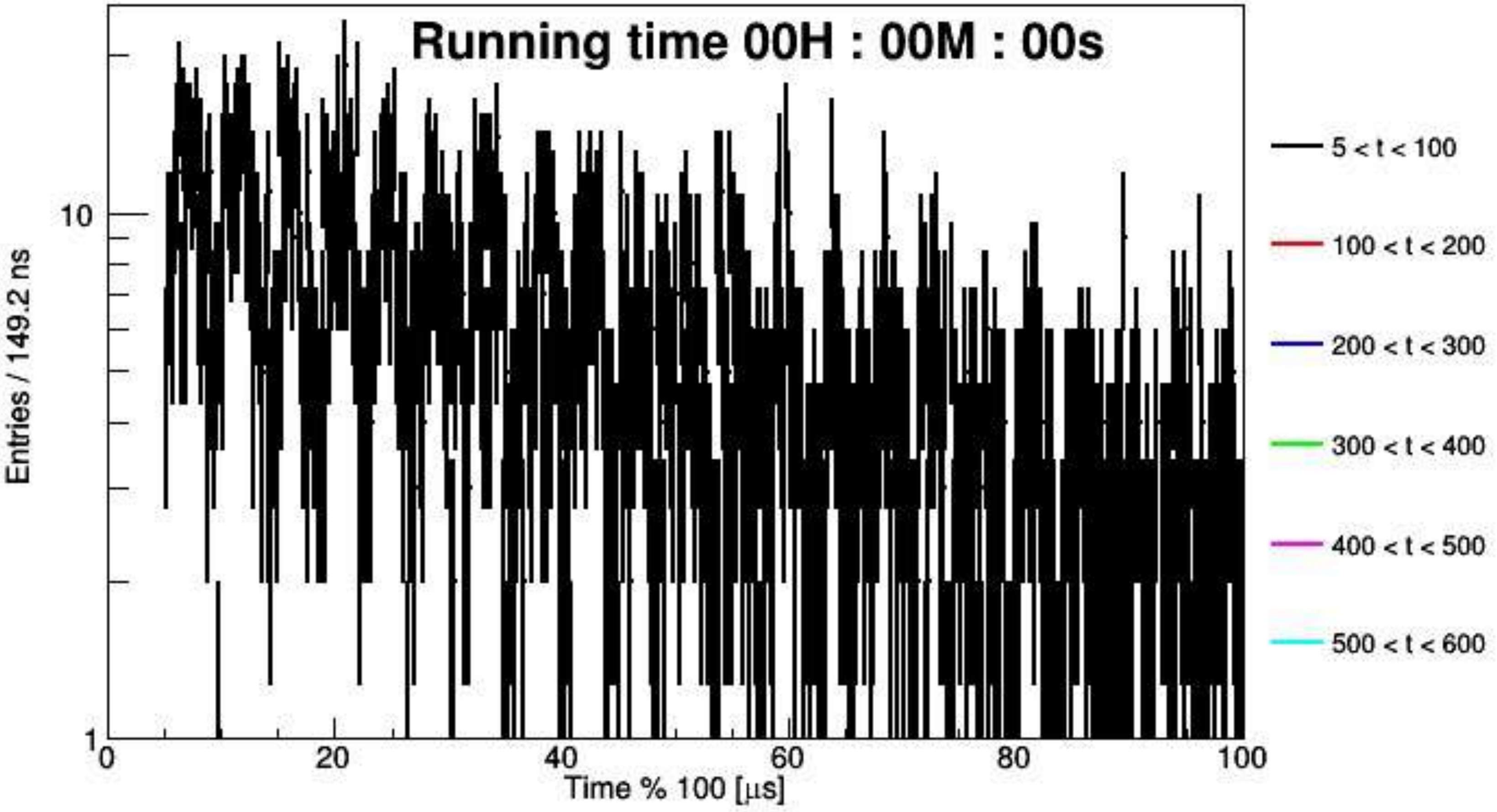




The number of high momentum positrons above a fixed energy threshold oscillates at precession frequency

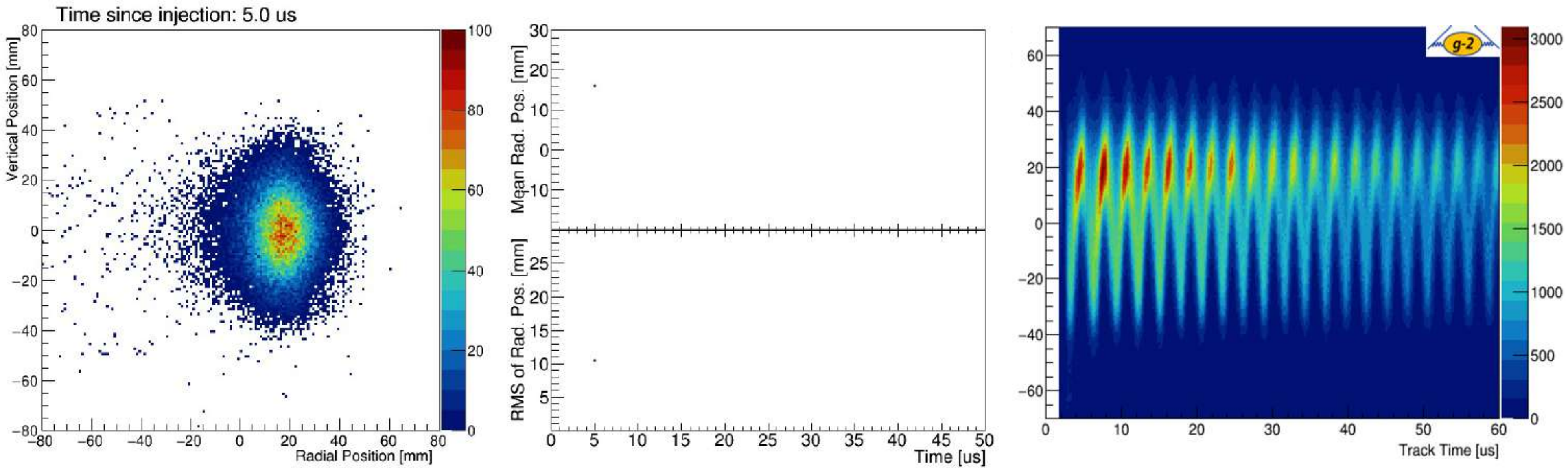
Simply count the number above an energy threshold vs time

Precession in 1 hour of data



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

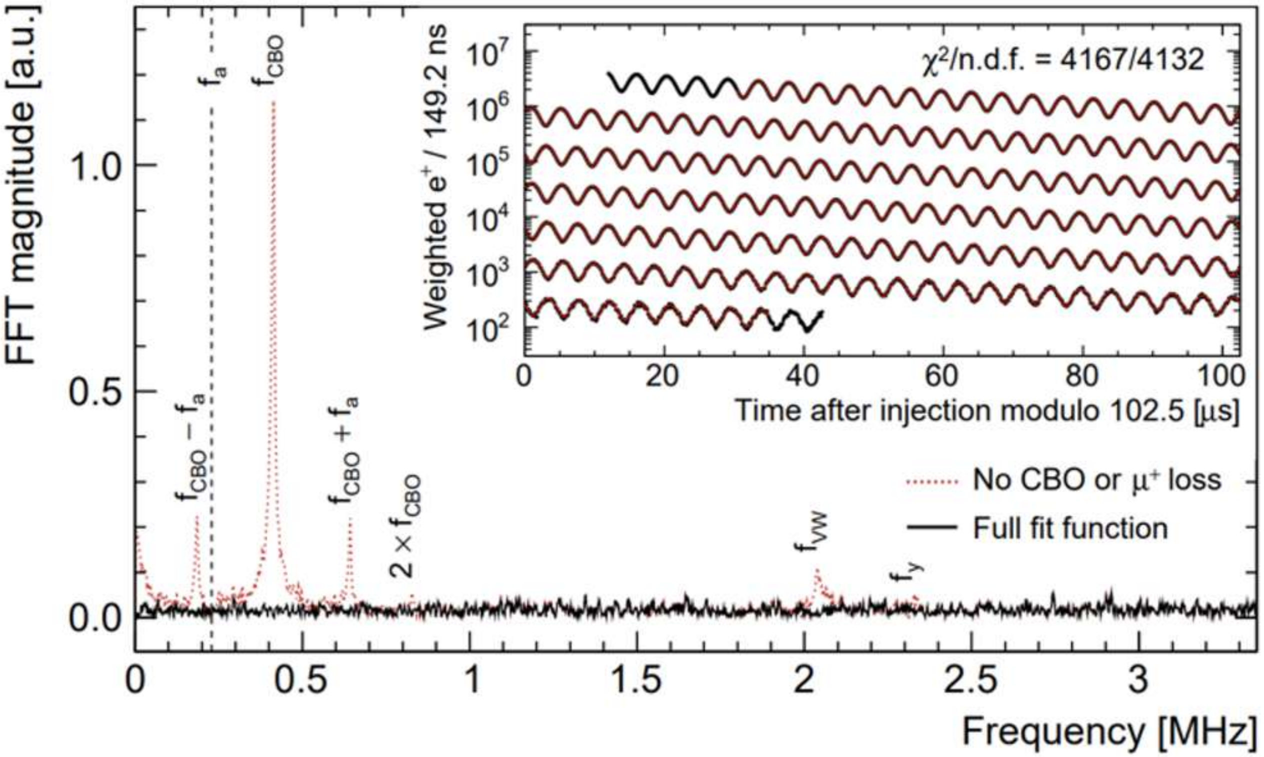
Beam Measurements



- 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

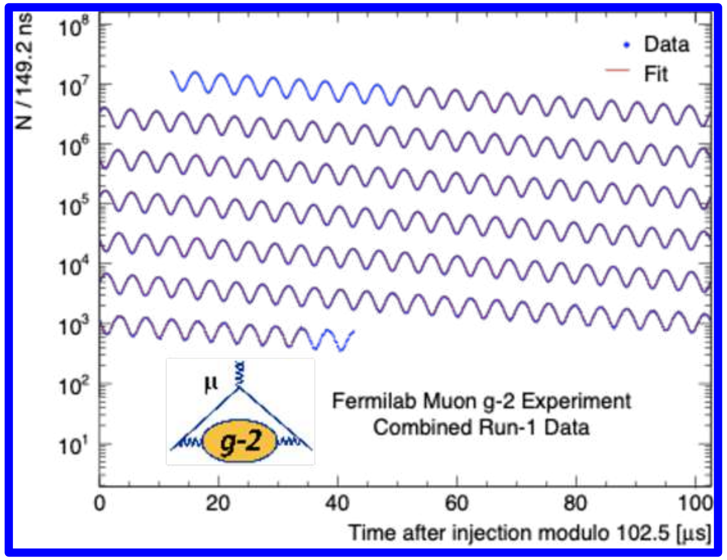
Fitting for ω_a

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



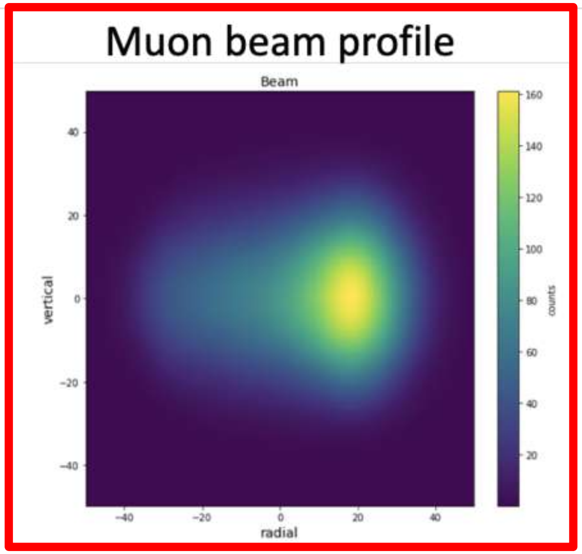
- To account for these effects additional terms are included in the final 24 parameter fit function

Field measurement



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

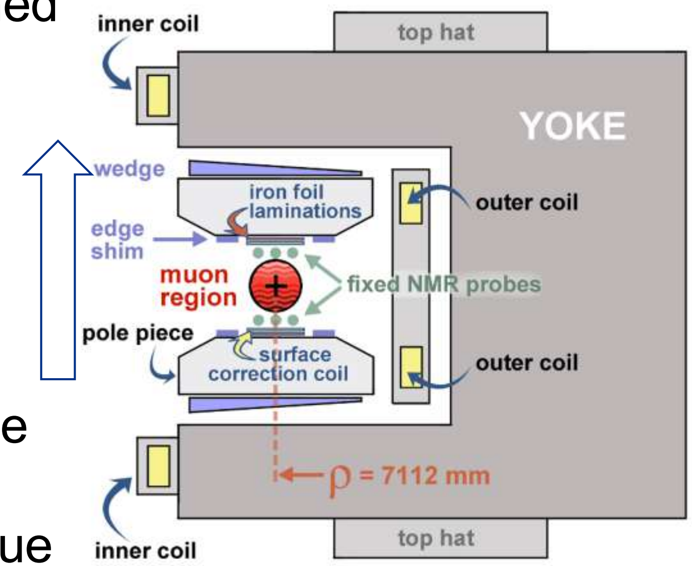
Measuring the magnetic field is the last piece

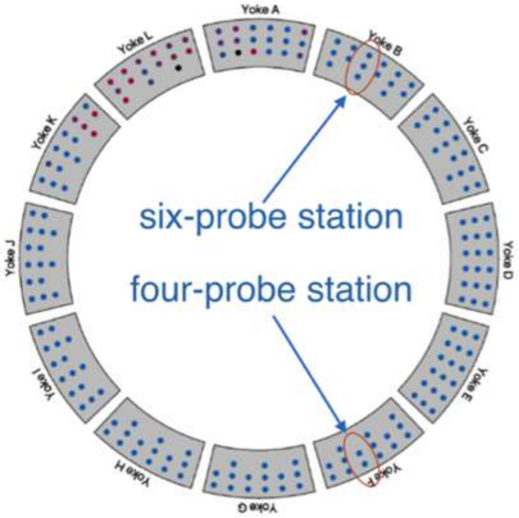

Muon beam profile

The g-2 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

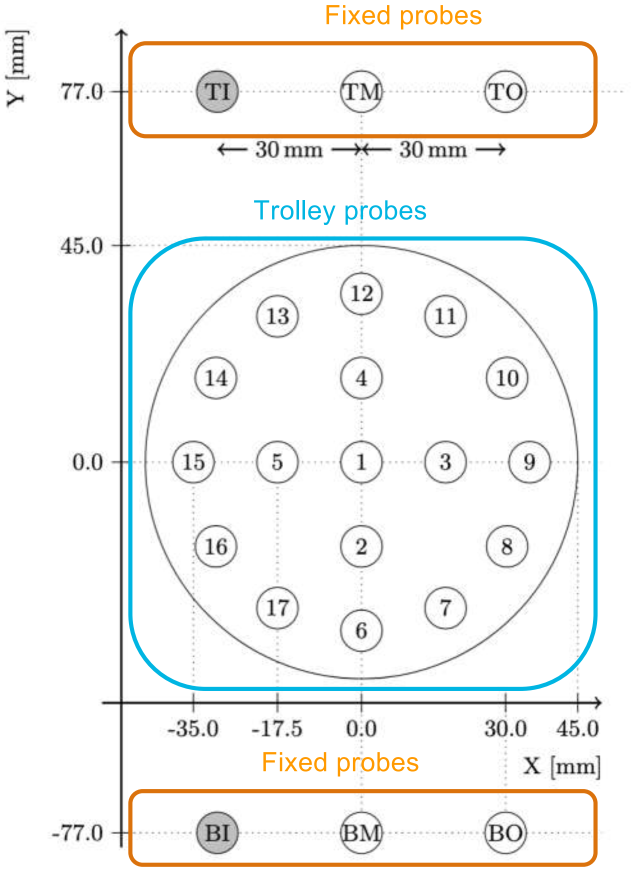


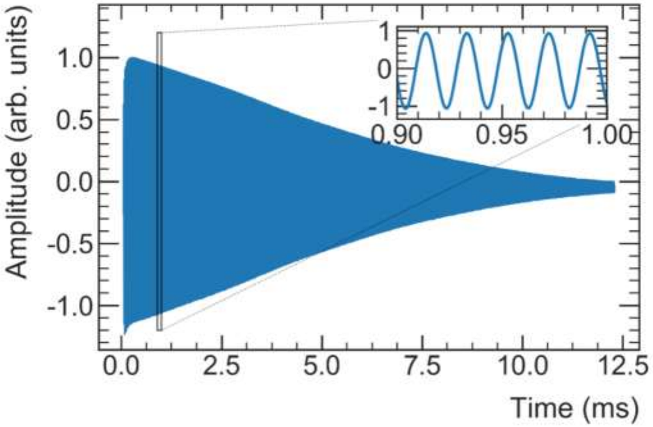


Top-down view

Measuring the field: the NMR Trolley

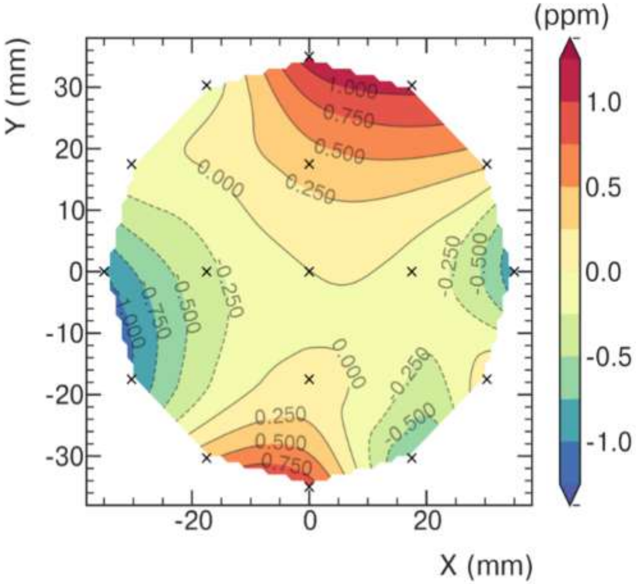
- An in-vacuum trolley with 17 NMR probes drives around the ring every ~3 days, mapping out the field components





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

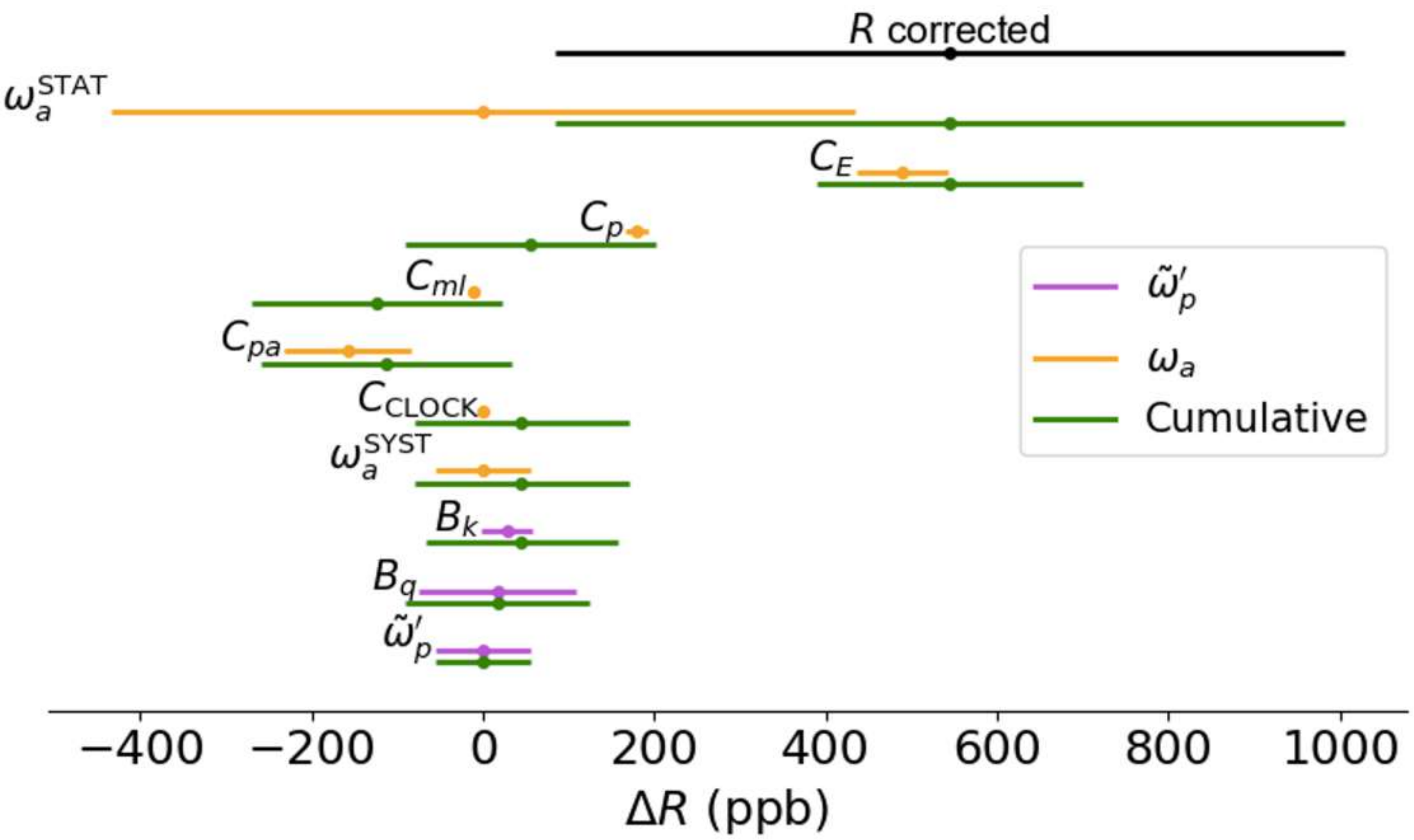
Field gradients in an azimuthal “slice”



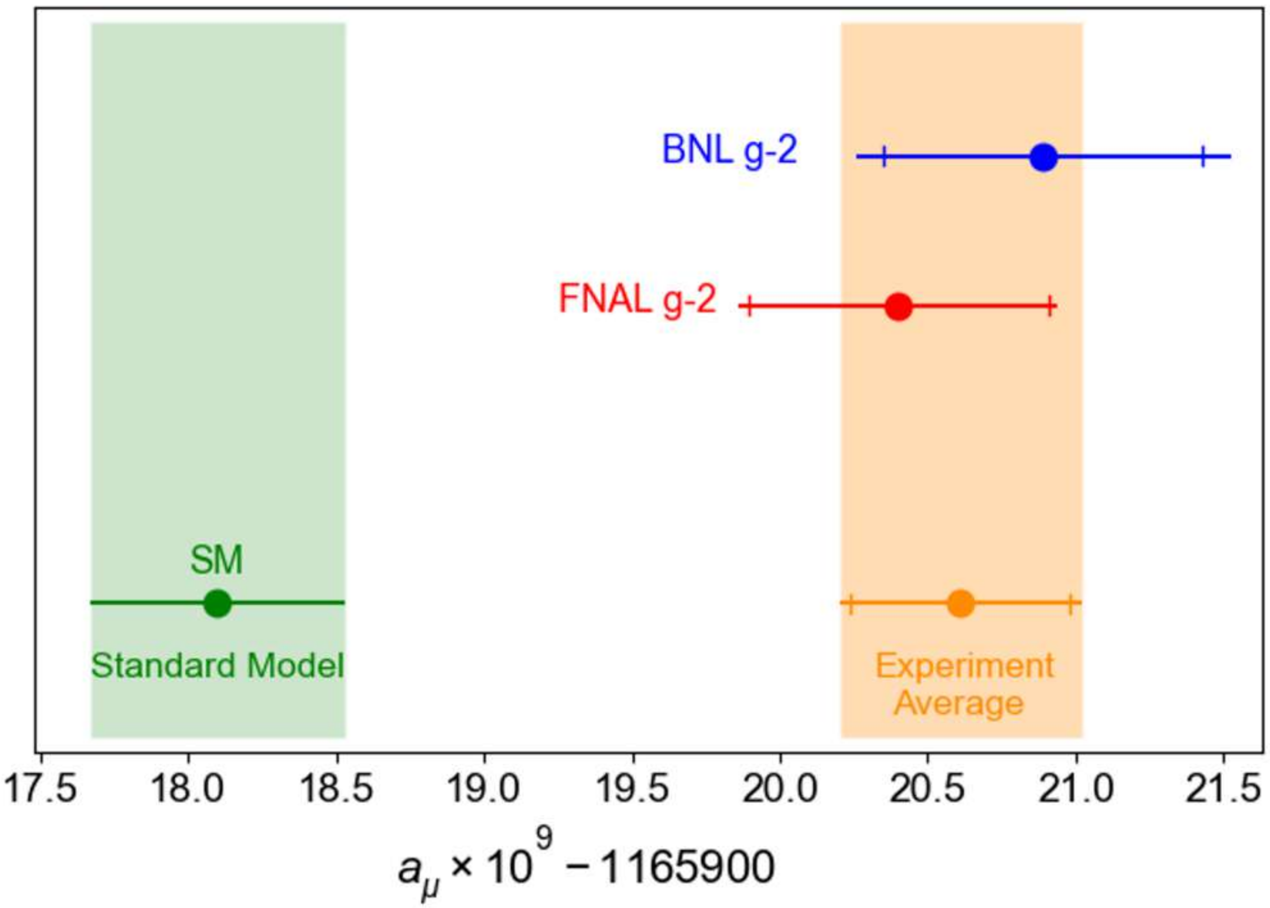
At ~8000 azimuthal locations, obtain a field contour plot from the 17 probes

Correcting Measured R

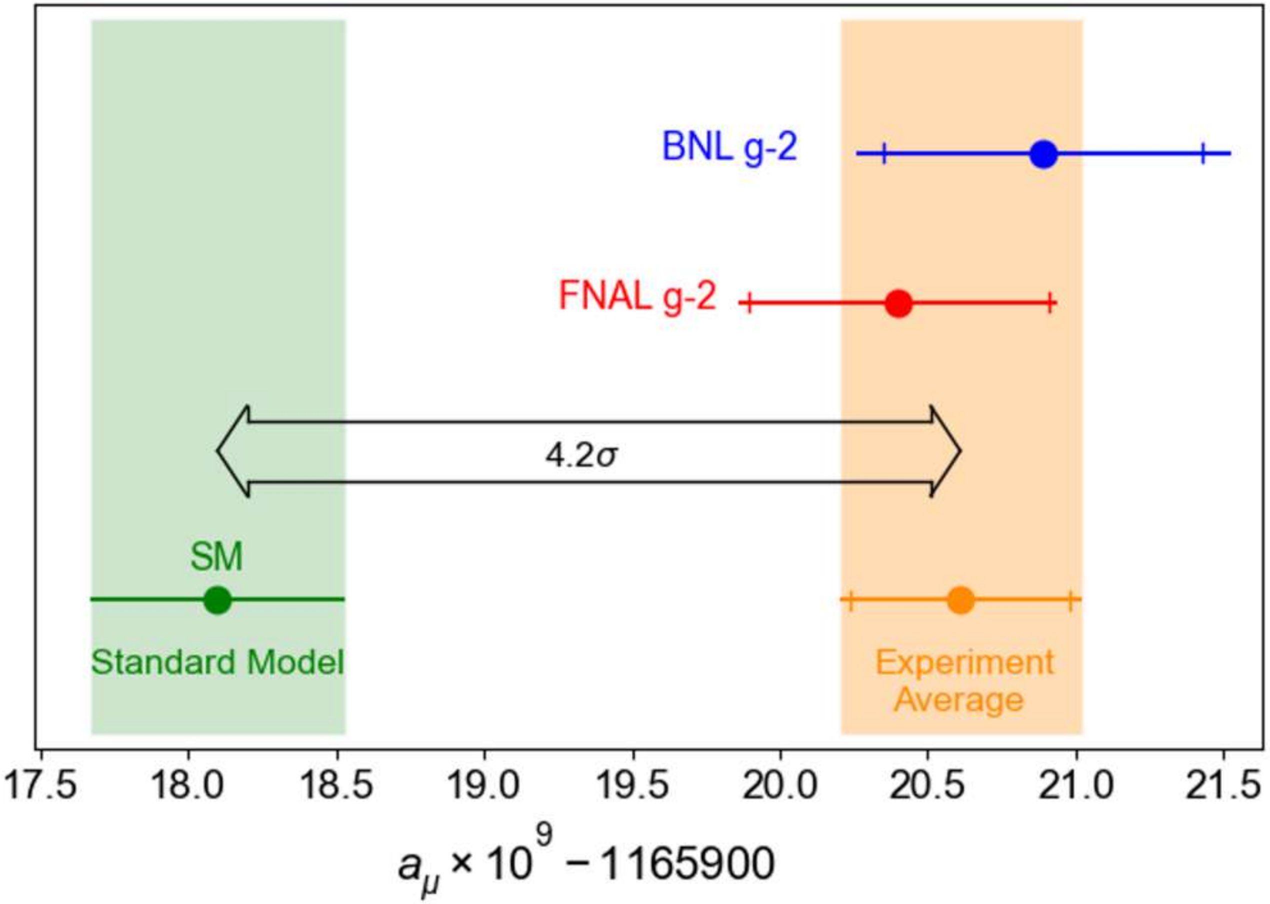
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{\boxed{f_{\text{clock}}\;\omega_a^m\,(1+C_e+C_p+C_{ml}+C_{pa})}}{f_{\text{calib}}\;\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle\boxed{(1+B_k+B_q)}}$$



Unblinded result



Unblinded result



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, still statistics limited.
- Run-5 will give us a total dataset ~ x20 of the first publication and will become systematics limited.