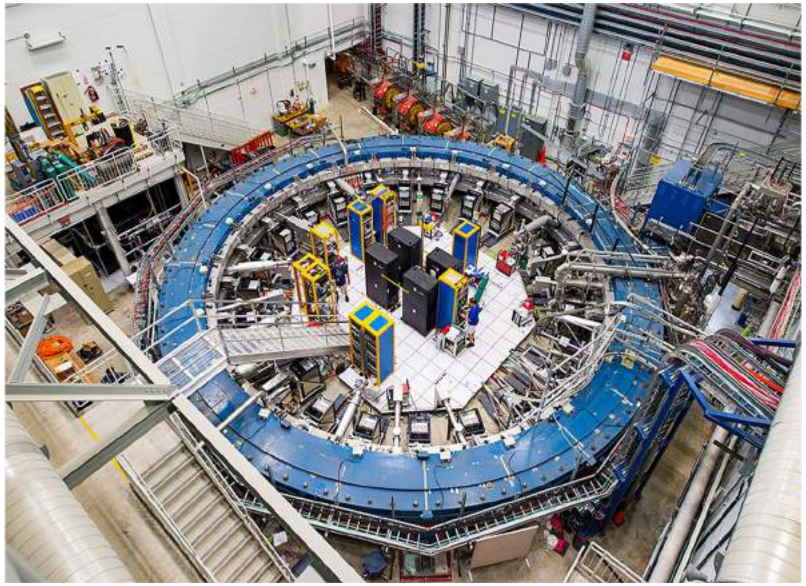
First Results From
The Fermilab Muon g-2 Experiment



Alex Keshavarzi
@AlexKeshavarzi

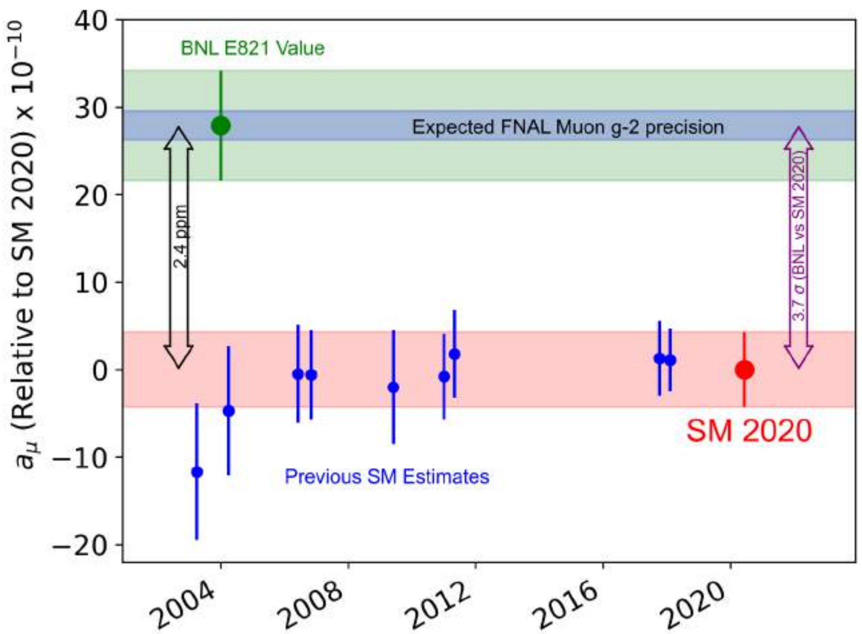
Matter To The Deepest 2021
15th September 2021

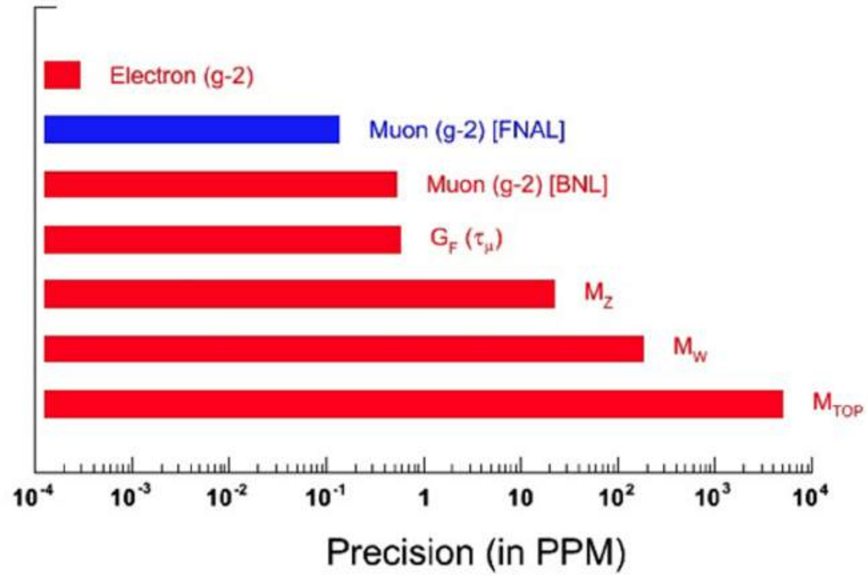
Fermilab

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^+

Magnetic moments

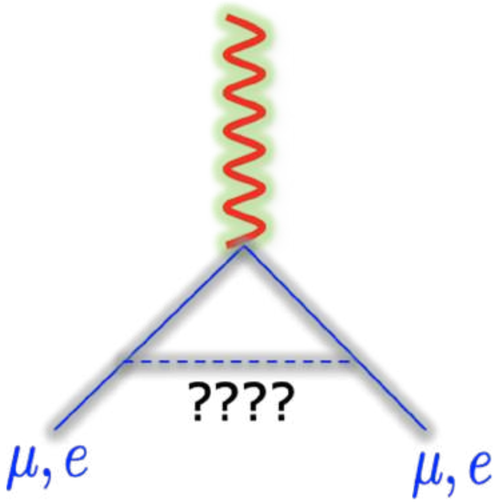
The muon has an intrinsic magnetic moment that is coupled to its spin via the gyromagnetic ratio *g*:

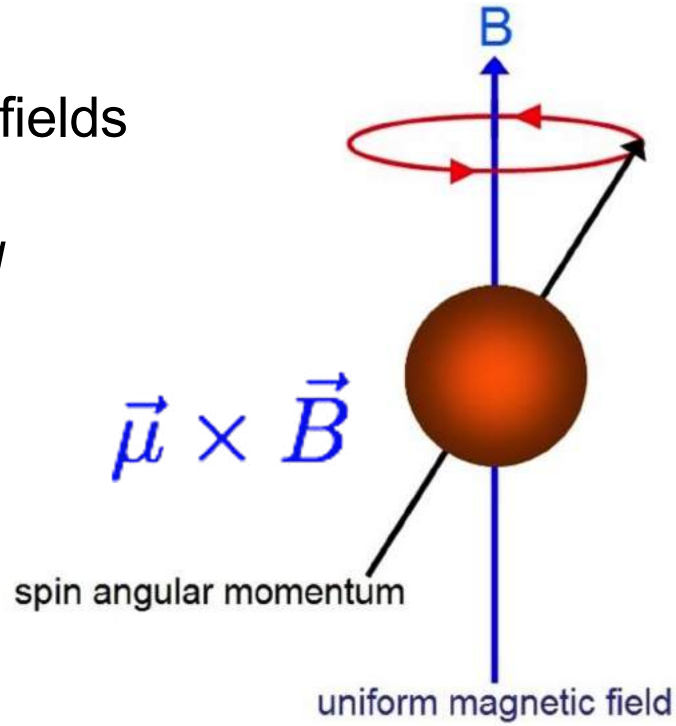
$$\vec{\mu} = g\frac{e}{2m_\mu}\vec{S}$$

Magnetic moment (spin) interacts with external B-fields

Makes spin precess at frequency determined by *g*

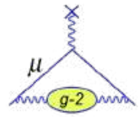
$$a_\mu = \frac{g-2}{2}$$





Muon g-2 in the SM

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



Contribution	Value $\times 10^{11}$
Experiment (E821)	116 592 089(63)
HVP LO (e^+e^-)	6931(40)
HVP NLO (e^+e^-)	−98.3(7)
HVP NNLO (e^+e^-)	12.4(1)
HVP LO (lattice, $udsc$)	7116(184)
HLbL (phenomenology)	92(19)
HLbL NLO (phenomenology)	2(1)
HLbL (lattice, uds)	79(35)
HLbL (phenomenology + lattice)	90(17)
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (phenomenology + lattice + NLO)	92(18)
Total SM Value	116 591 810(43)
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	279(76)


arXiv.org > hep-ph > arXiv:2006.04822

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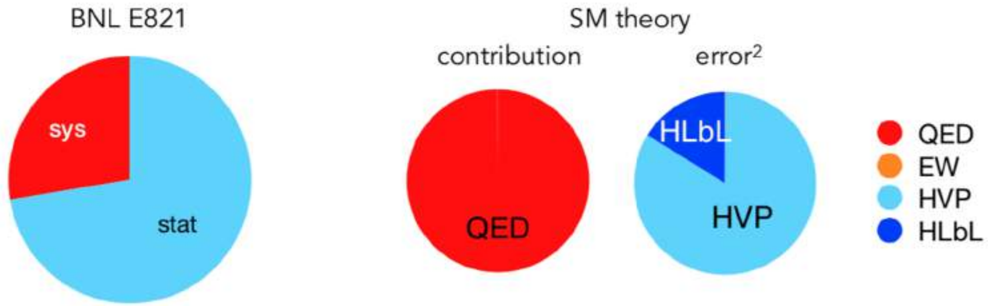
High Energy Physics – Phenomenology

[Submitted on 8 Jun 2020]

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama, N. Asmussen, M. Benayoun, J. Bijnens, T. Blum, M. Bruno, I. Caprini, C. M. Carloni Calame, M. Cè, G. Colangelo, F. Curciarello, H. Czyż, I. Danilkin, M. Davier, C. T. H. Davies, M. Della Morte, S. I. Eidelman, A. X. El-Khadra, A. Gérardin, D. Giusti, M. Golterman, Steven Gottlieb, V. Gülpers, F. Hagelstein, M. Hayakawa, G. Herdoíza, D. W. Hertzog, A. Hoecker, M. Hoferichter, B.-L. Hoid, R. J. Hudspith, F. Ignatov, T. Izubuchi, F. Jegerlehner, L. Jin, A. Keshavarzi, T. Kinoshita, B. Kubis, A. Kupich, A. Kupść, L. Laub, C. Lehner, L. Lellouch, I. Logashenko, B. Malaescu, K. Maltman, M. K. Marinković, P. Masjuan, A. S. Meyer, H. B. Meyer, T. Mibe, K. Miura, S. E. Müller, M. Nio, D. Nomura, A. Nyffeler, V. Pascalutsa, M. Passera, E. Perez del Rio, S. Peris, A. Portelli, M. Procura, C. F. Redmer, B. L. Roberts, P. Sánchez-Puertas, S. Serednyakov, B. Shwartz, S. Simula, D. Stöckinger, H. Stöckinger-Kim, P. Stoffer, T. Teubner, R. Van de Water, M. Vanderhaeghen, G. Venanzoni, G. von Hippel, H. Wittig, Z. Zhang, M. N. Achasov, A. Bashir, N. Cardoso, B. Chakraborty, E.-H. Chao, J. Charles, A. Crivellin, O. Deineka, A. Denig, C. DeTar, C. A. Dominguez, A. E. Dorokhov, V. P. Druzhinin, G. Eichmann, M. Fael, C. S. Fischer, E. Gámiz, Z. Gelzer, J. R. Green, S. Guellati-Khelifa, D. Hatton, N. Hermansson-Truedsson et al. (32 additional authors not shown)



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

Muon g-2 theory initiative recommended result:

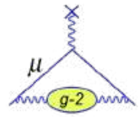
$$a_\mu^{\text{SM}} = 116\,591\,810(43) \times 10^{-11}\ (0.37\ \text{ppm})$$

Results in 3.7σ discrepancy when compared to BNL measurement.

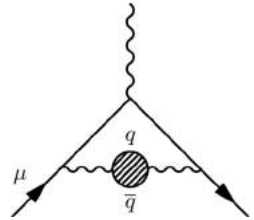
See Thomas Lenz's talk, tomorrow, 12.30pm:
"*Experimental input to the Standard Model prediction of g-2*"

Muon g-2 in the SM: HVP

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



- Hadronic Vacuum Polarisation - hadronic blob coupled to 2 photons.
- Two point function - in principal, much easier than HLbL.
- Most precisely calculated from $e^+e^- \rightarrow$ hadrons cross section data.



Lattice (error ~ 1.6 ppm of a_μ^{SM})

- Uncertainties dominated by finite volume, discretisation and isospin breaking systematics.

Data-driven (error ~ 0.3 ppm of a_μ^{SM})

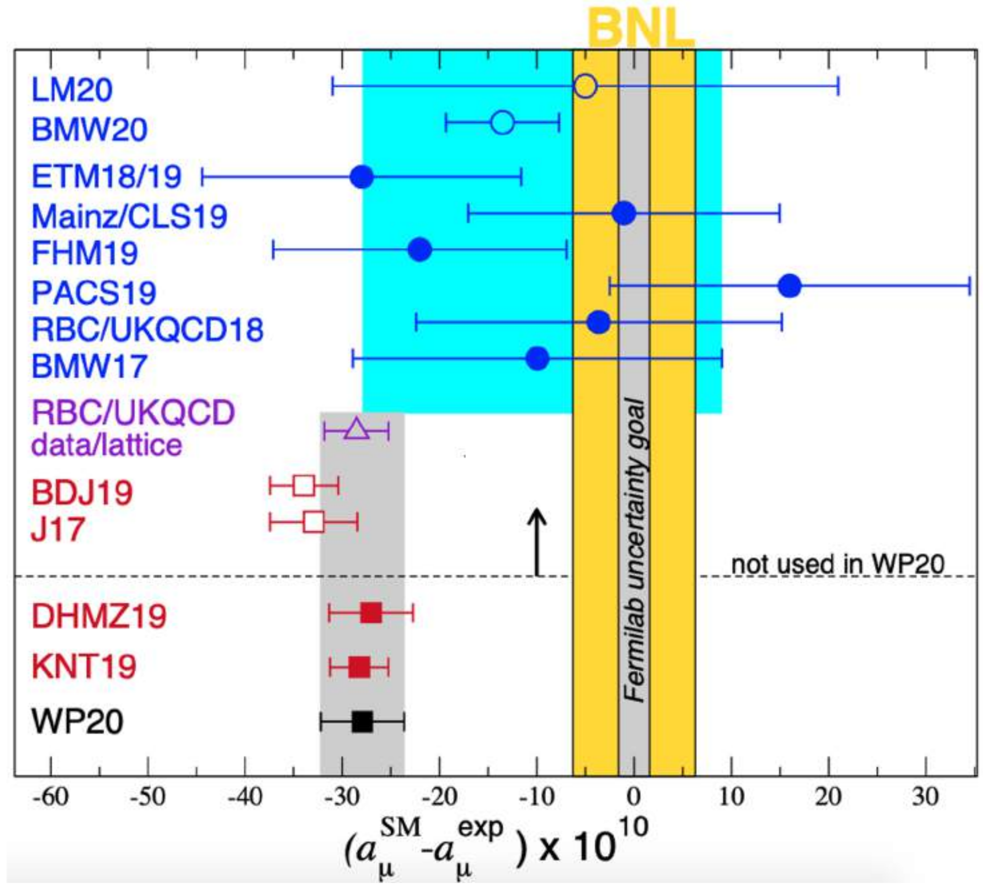
- Cross section data consistently combined and input into dispersion integral:

$$a_\mu^{\text{LO HVP}} = \frac{1}{4\pi^3}\int_{s_{th}}^{\infty} \mathrm{d}s\, K(s)\, \sigma_{\text{had}}(s)$$

- Several groups have achieved this (most precisely in the UK).

Recommended Muon g-2 TI value from data-driven result:

$$a_\mu^{\text{HVP}} = 6845(40) \times 10^{-11}$$



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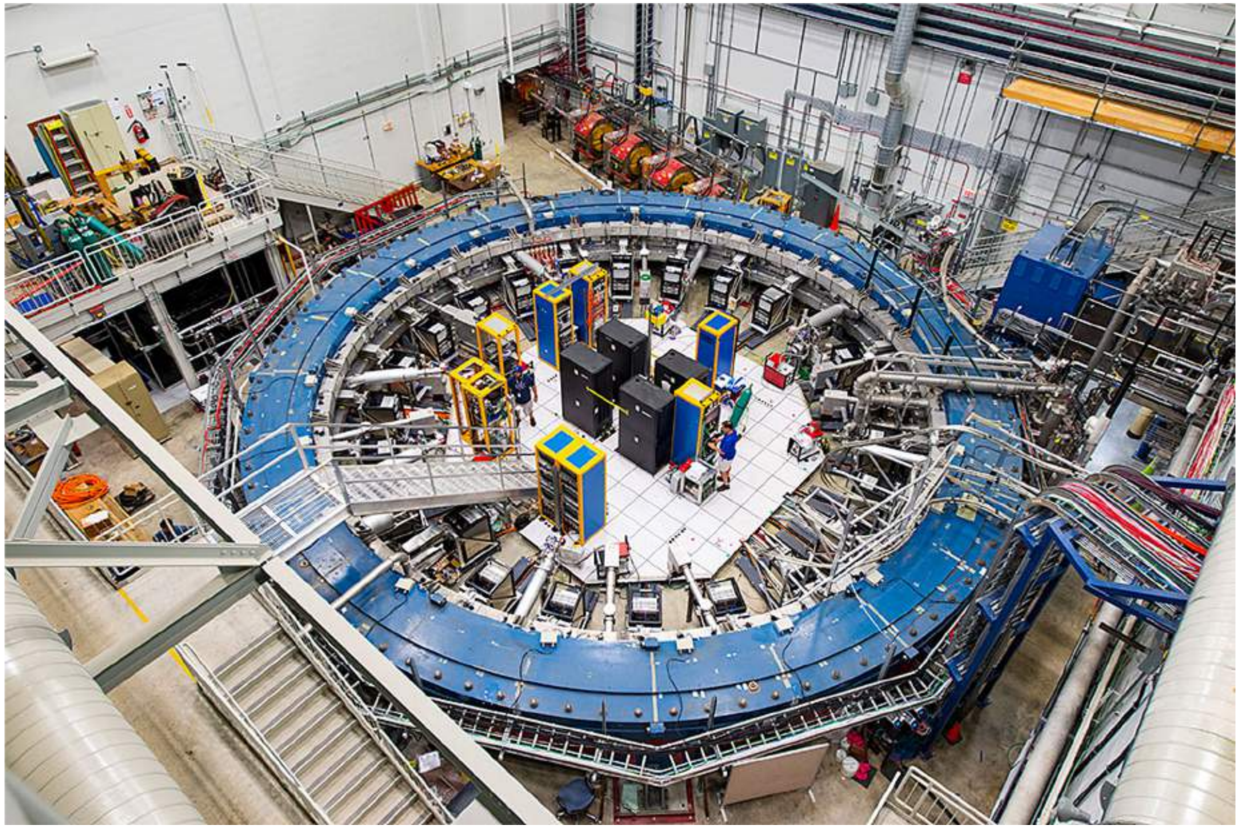
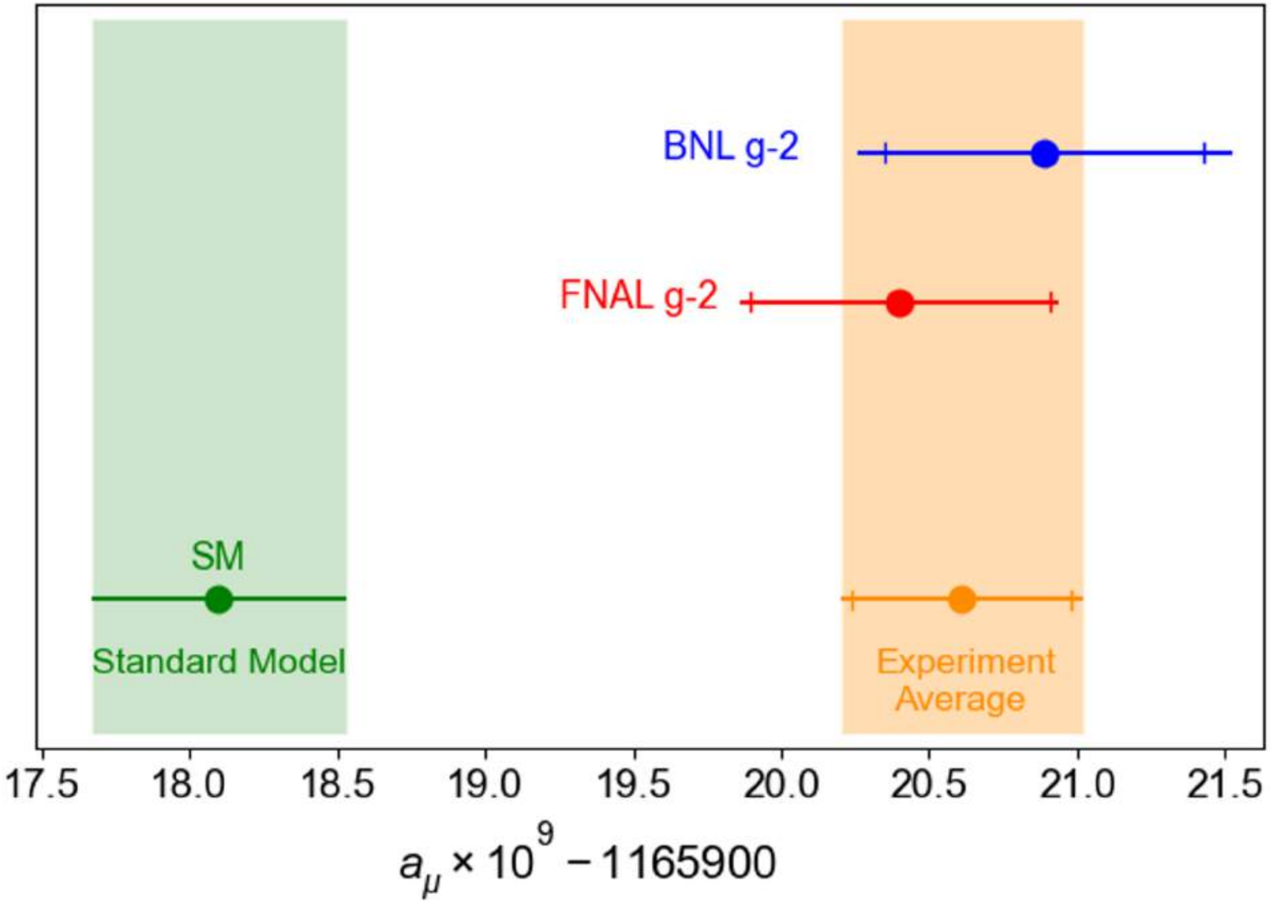
"*Experimental input to the Standard Model prediction of g-2*"

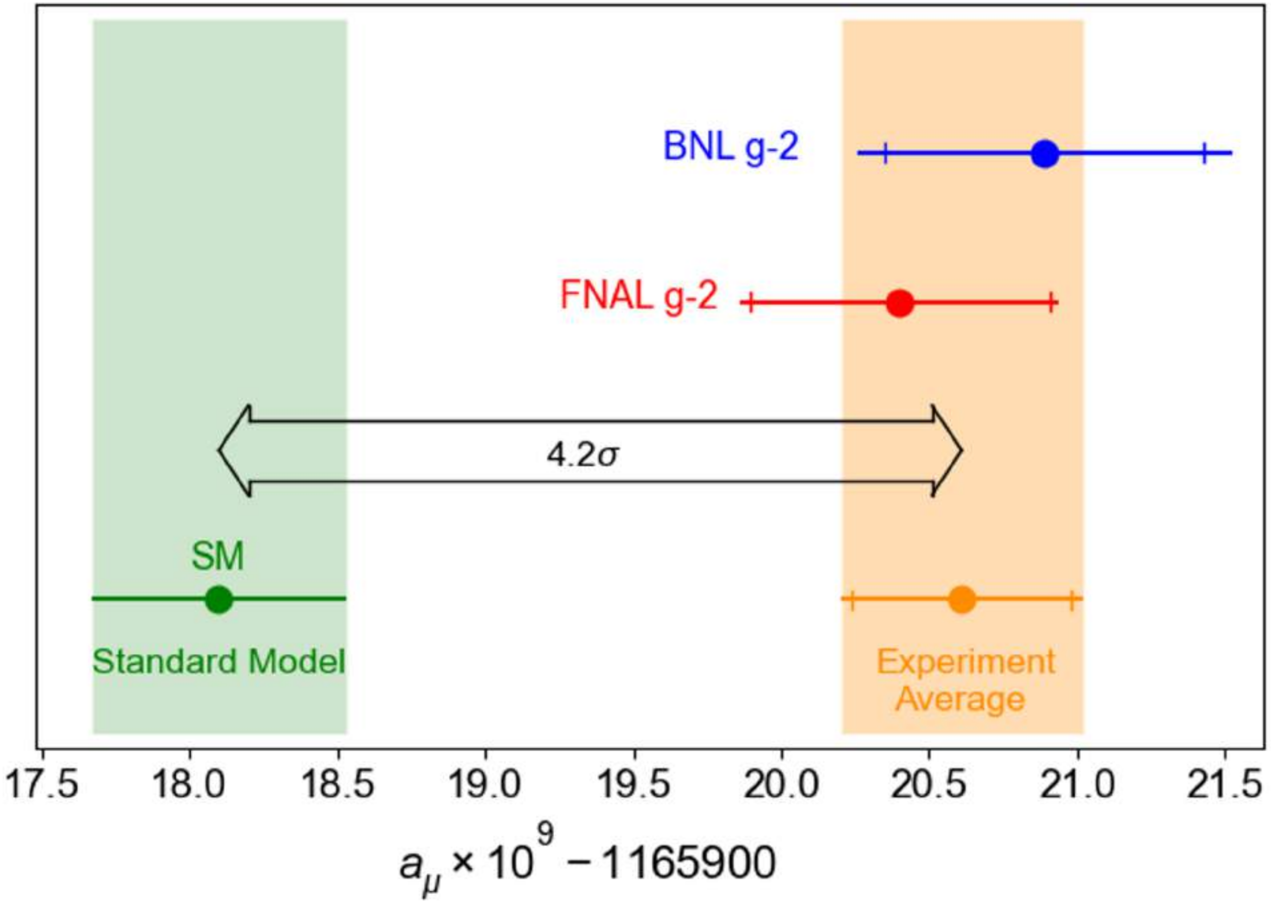
The Fermilab Muon g-2 Experiment



Unblinded result



Unblinded result



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.

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.

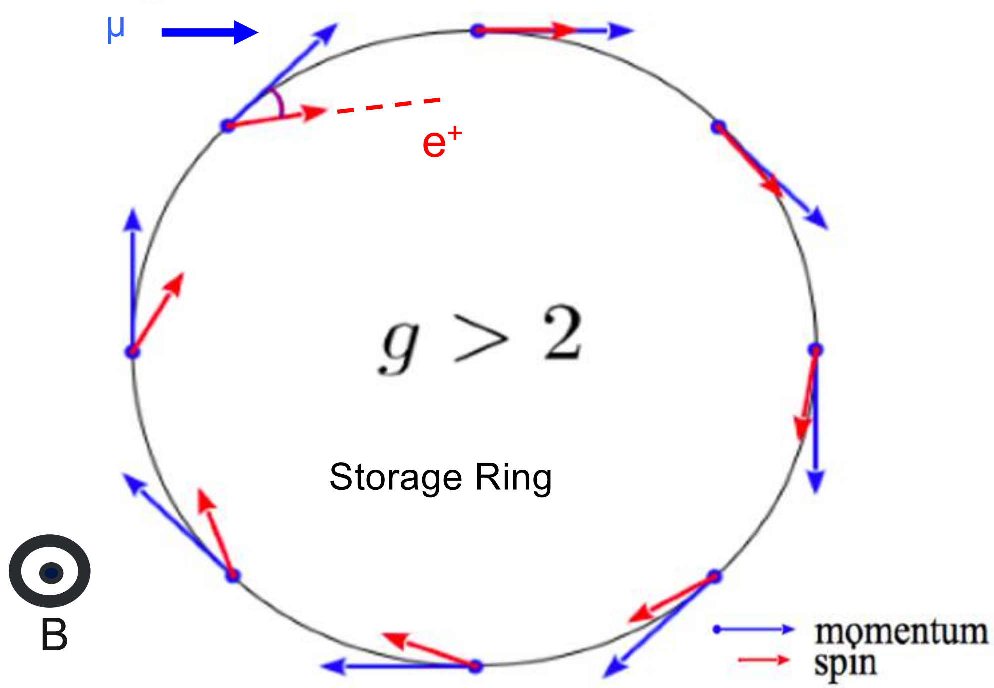
$$\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

Larmor precession

Thomas precession

Cyclotron freq.

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



Measurement details

The experiment actually measures two frequencies

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

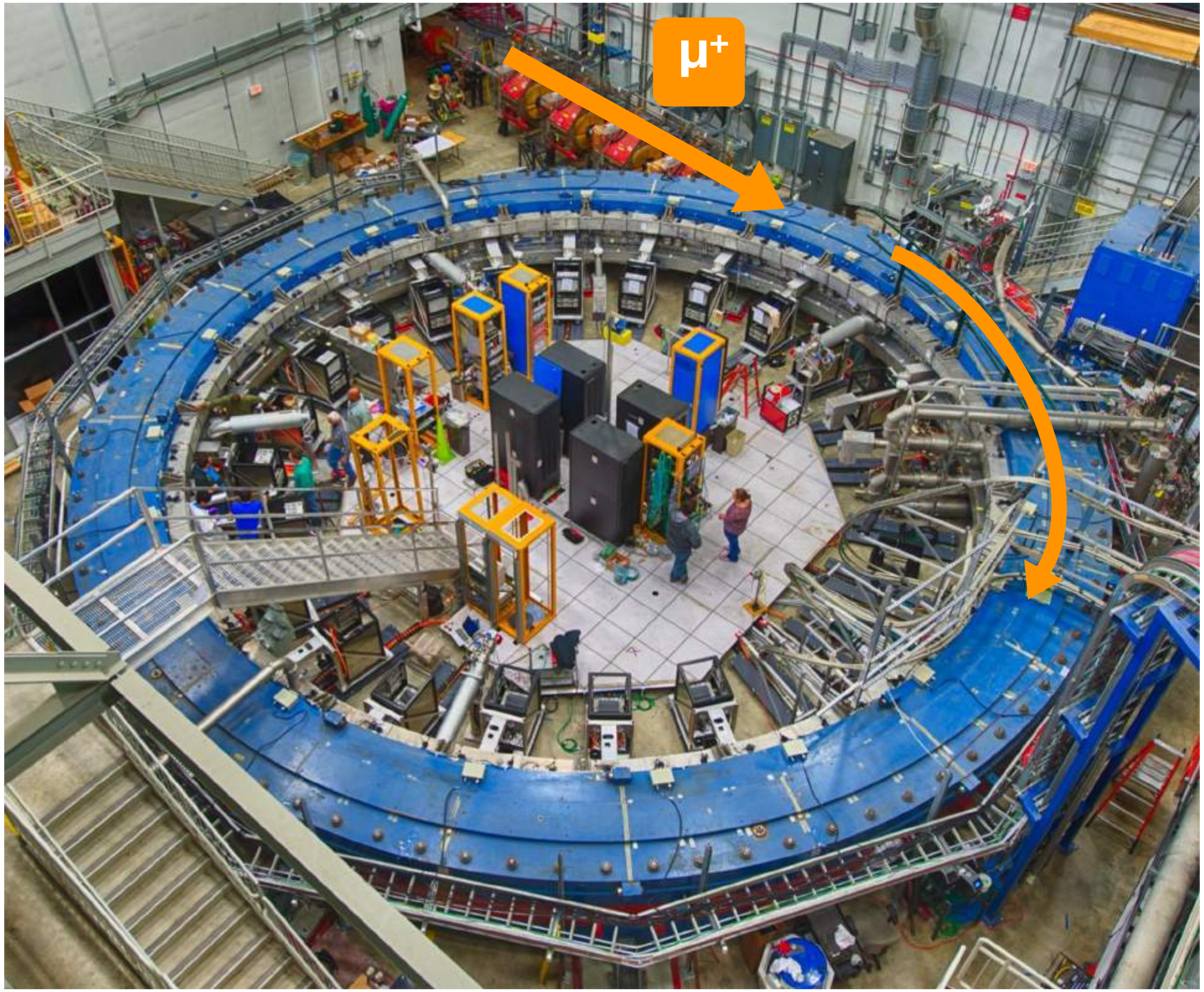
What we measure

3ppb (μ_p/μ_e), 22ppb (m_μ/m_e), 0.0003ppb ($g_e/2$)

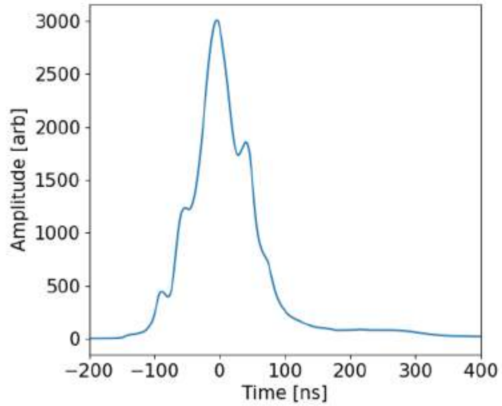
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\ (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

- Unblinding conversion factor: f_{clock}
- Measured $g-2$ frequency: ω_a^m
- Corrections from the beam dynamics systematic effects: $C_e + C_p + C_{ml} + C_{pa}$
- NMR probe calibration factor: f_{calib}
- Magnetic field weighted over the muon distribution and azimuthally averaged: $\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle$
- Corrections from the transient magnetic field: $B_k + B_q$

Beam injection

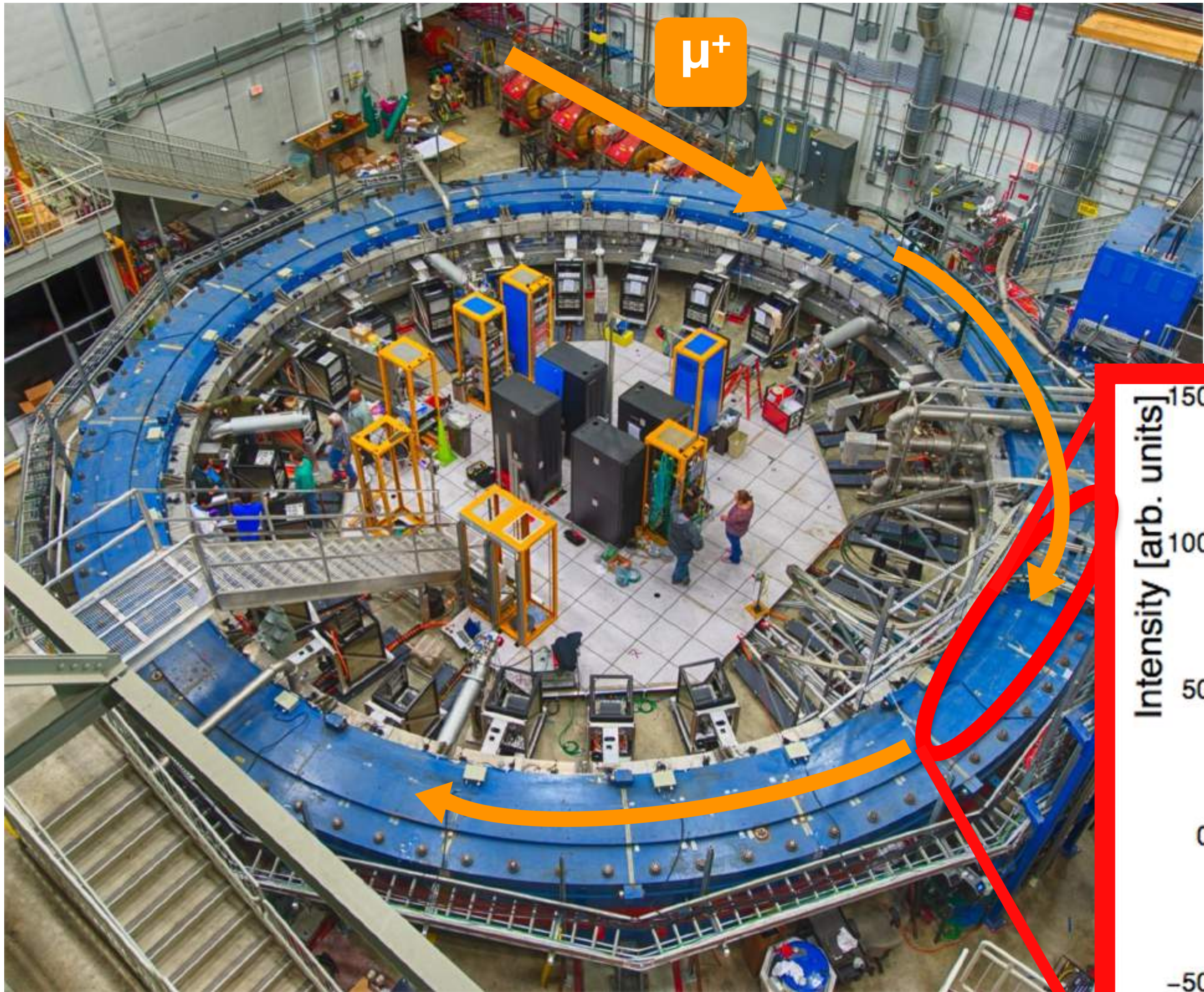


- Monitor beam profile before entrance with scintillating X and Y fibres
- Get time profile of beam using scintillating pad
- ~125ns wide

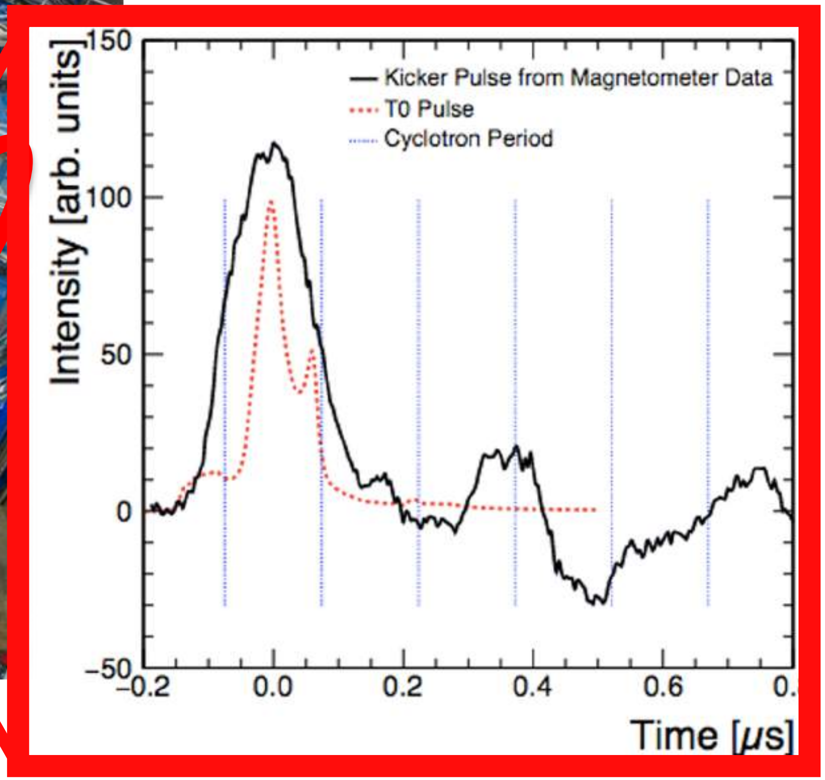


- Cancel B-field during injection using Inflector, so muons can get into the ring

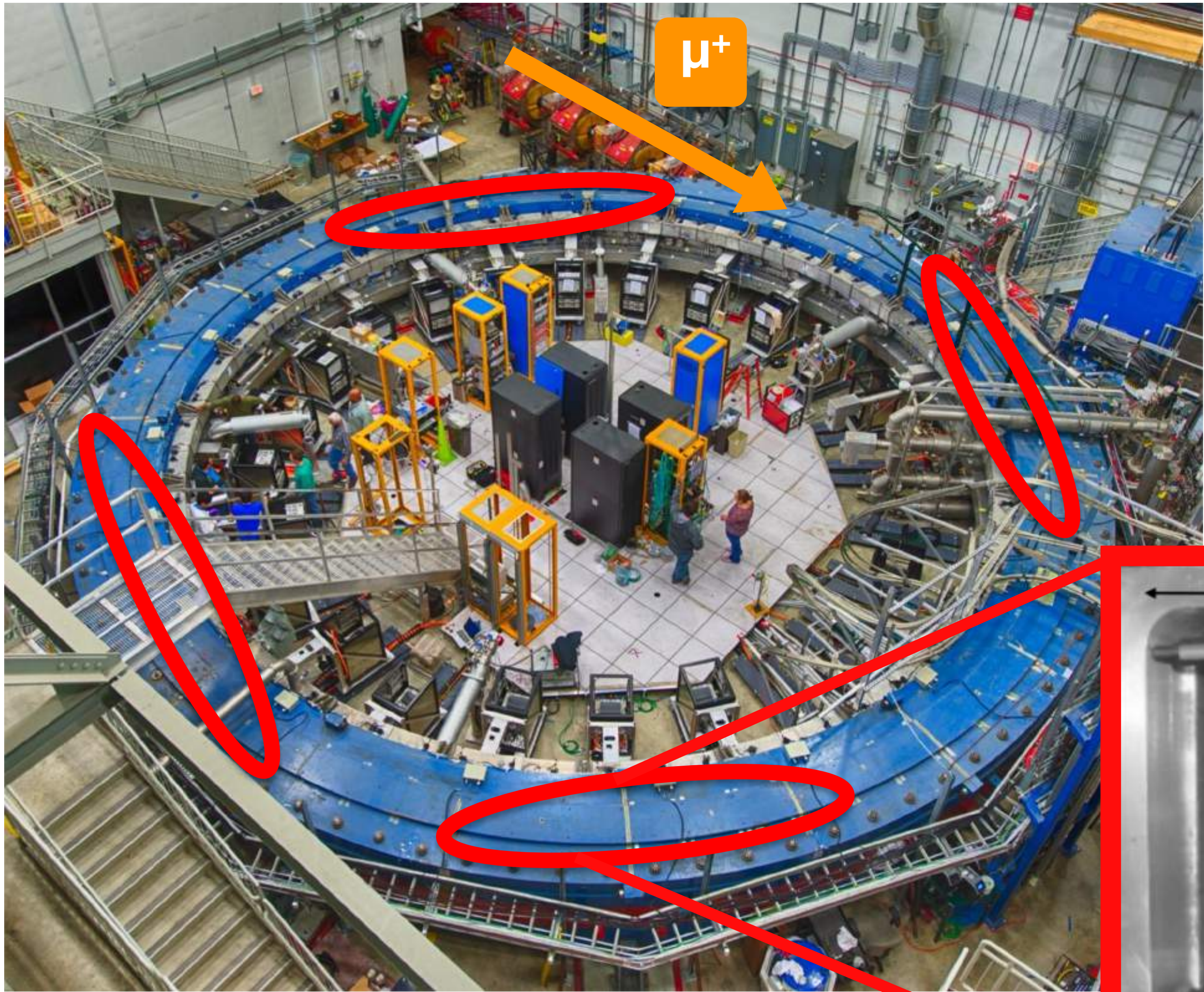
‘Kick’ onto correct orbit

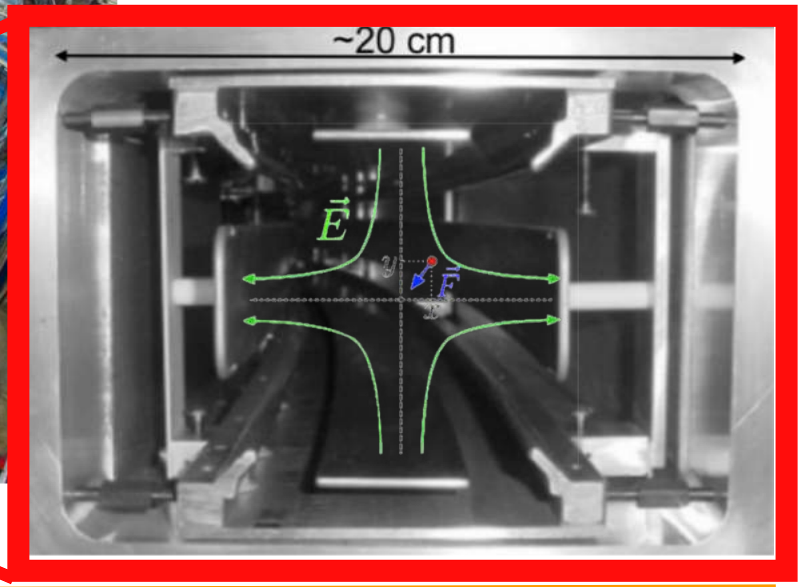


- After Inflector muons are 77mm away from ideal radius
- Apply short magnetic pulse to ‘kick’ muons onto the correct orbit



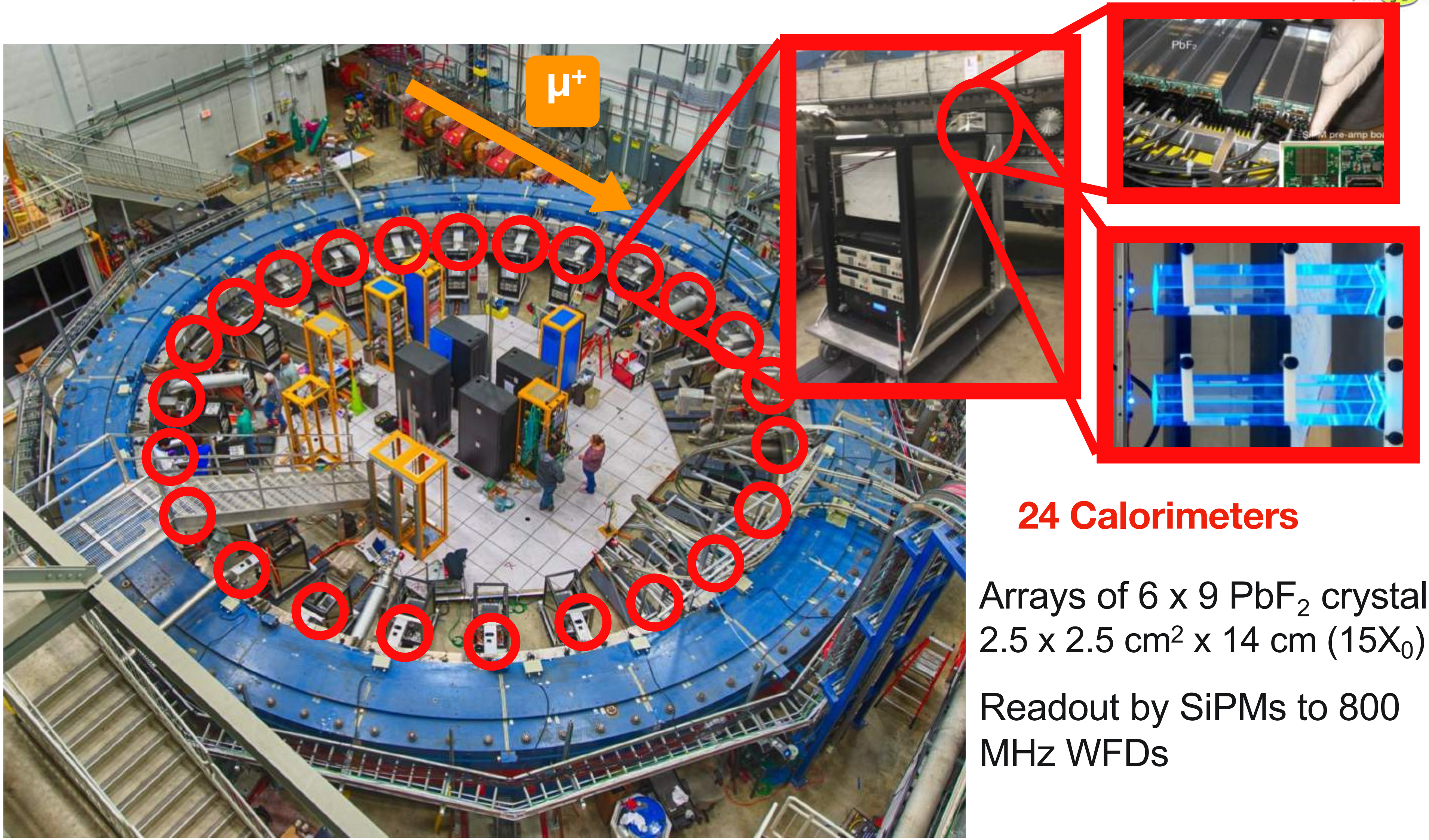
Beam focusing





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

Calorimeters

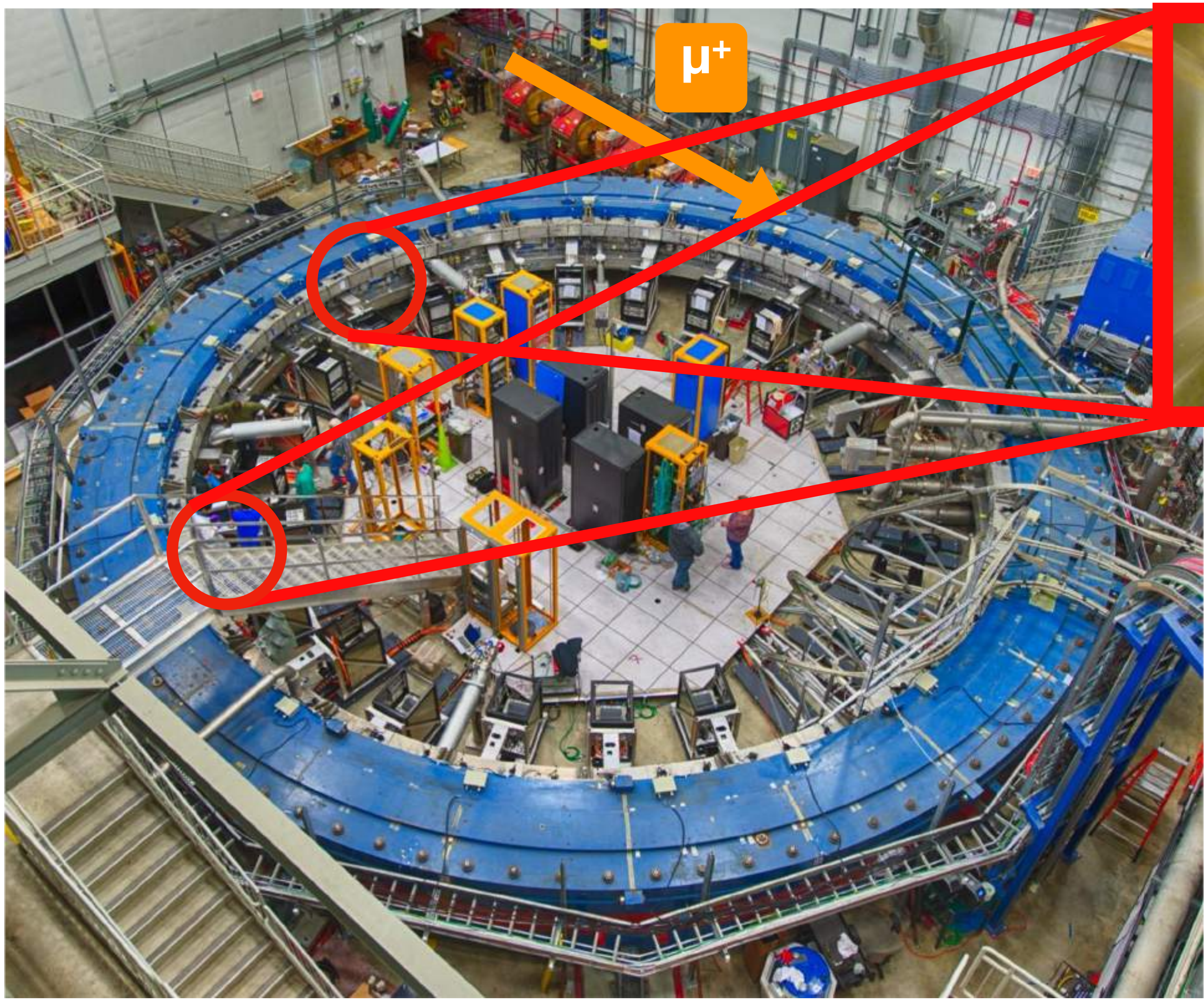


24 Calorimeters

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

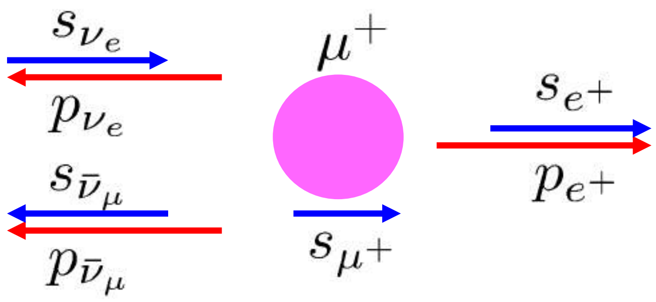
Each contain 8 modules

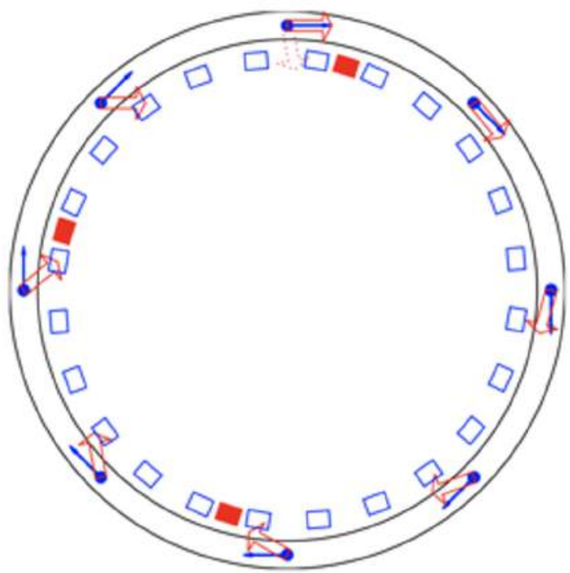
128 gas filled straws in each module

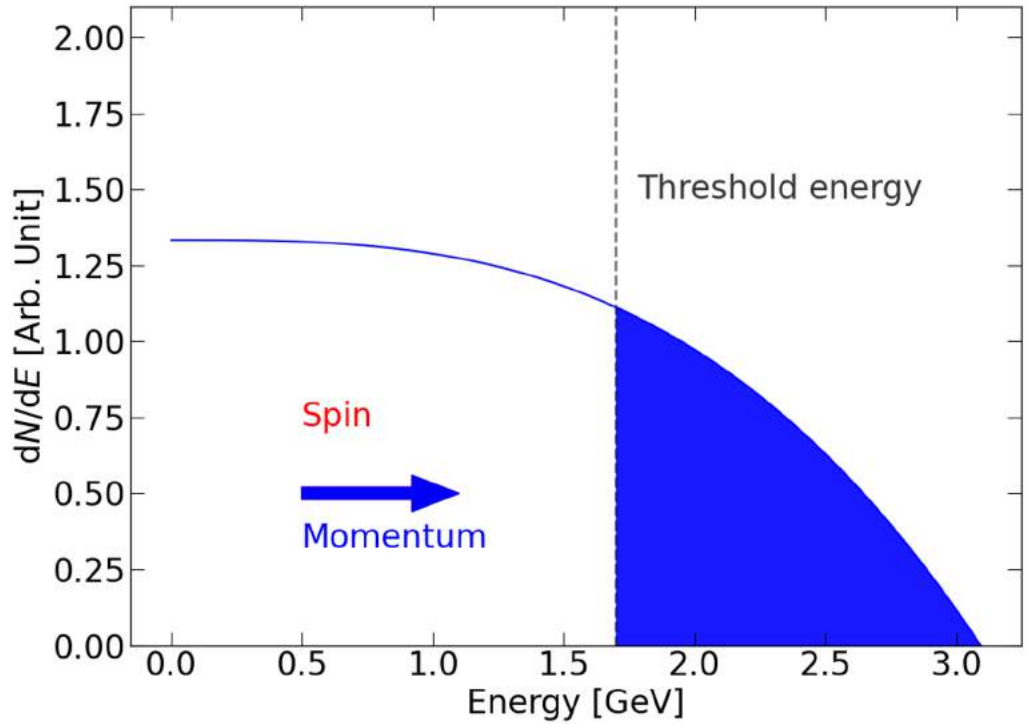
Traceback positrons to their decay point

Measuring ω_a

- e^+ preferentially emitted in direction of muon spin



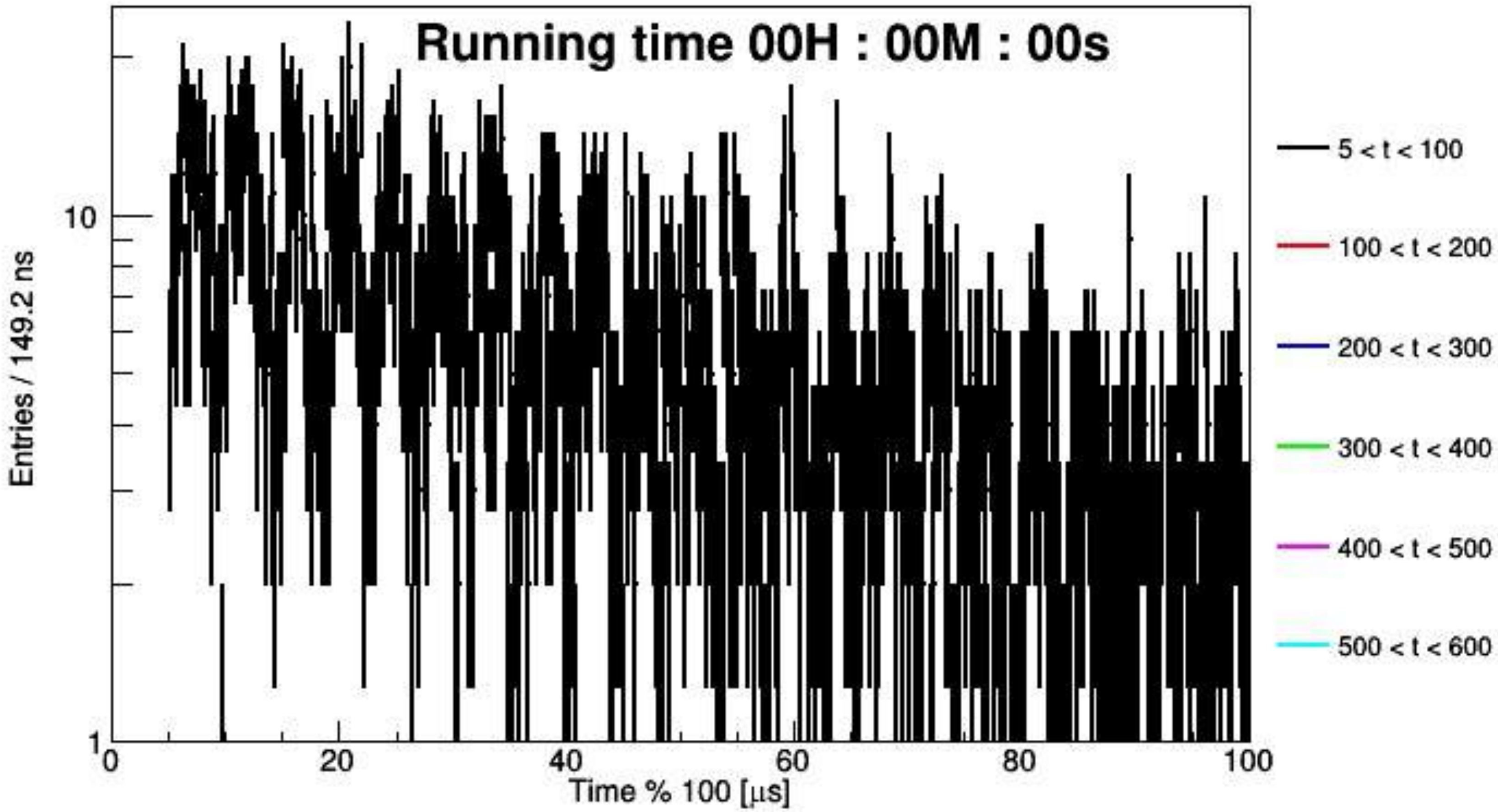




The number of high momentum positrons above a fixed energy threshold oscillates at precession frequency

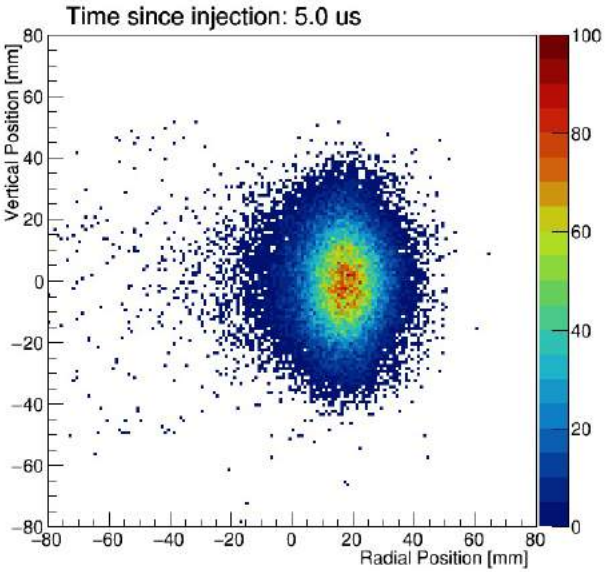
Simply count the number above an energy threshold vs time

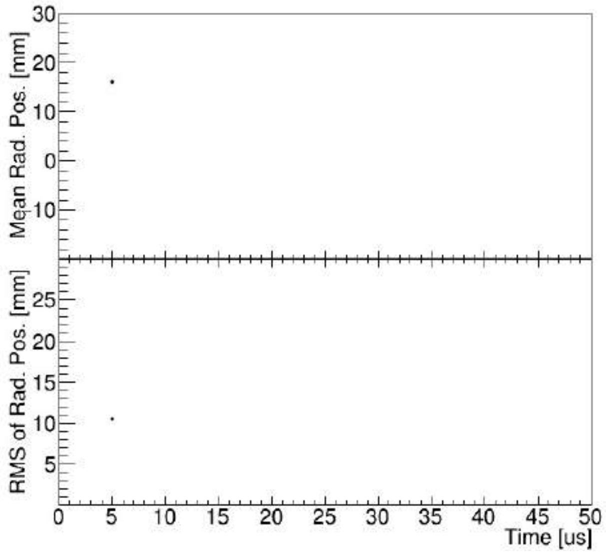
Precession in 1 hour of data

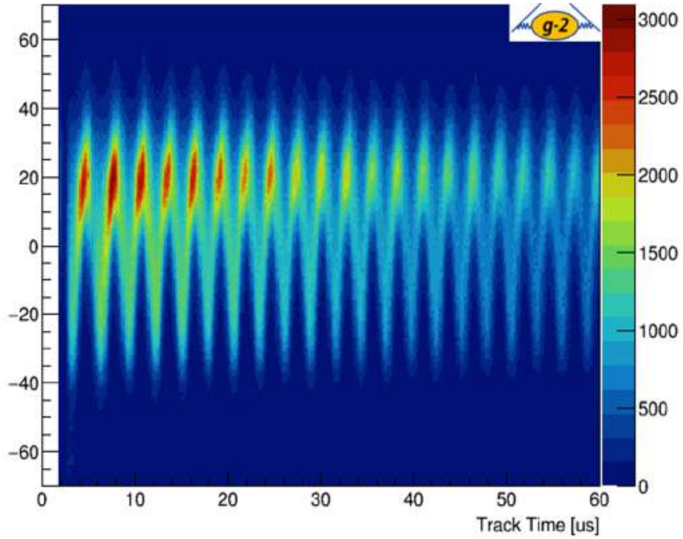


$$N_e(t) \simeq N_0 e^{-\frac{t}{\gamma\tau}}[1 - A\cos(\omega_a t + \phi_a)]$$

Beam Measurements



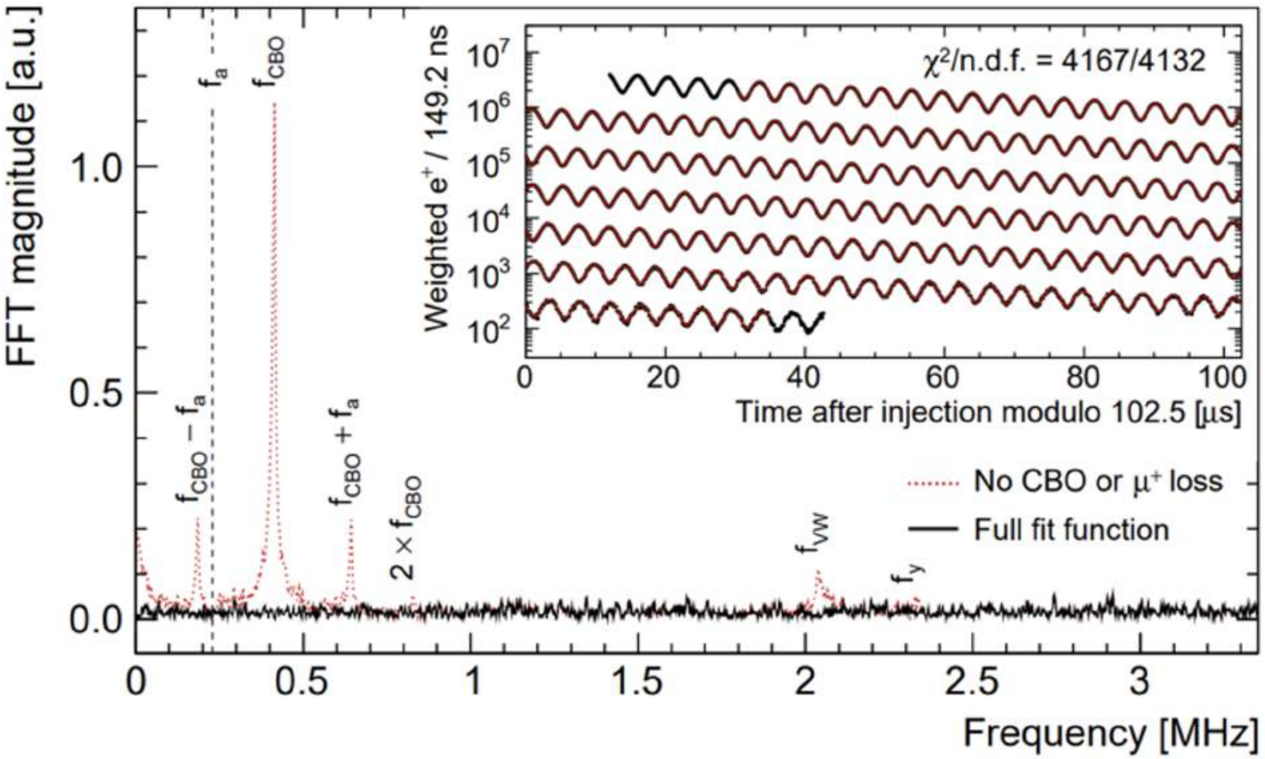




- Use the tracking detectors to measure the decay positrons to infer the decay position
- Muons oscillate radially and vertically at different frequencies, according to the quadrupole strength

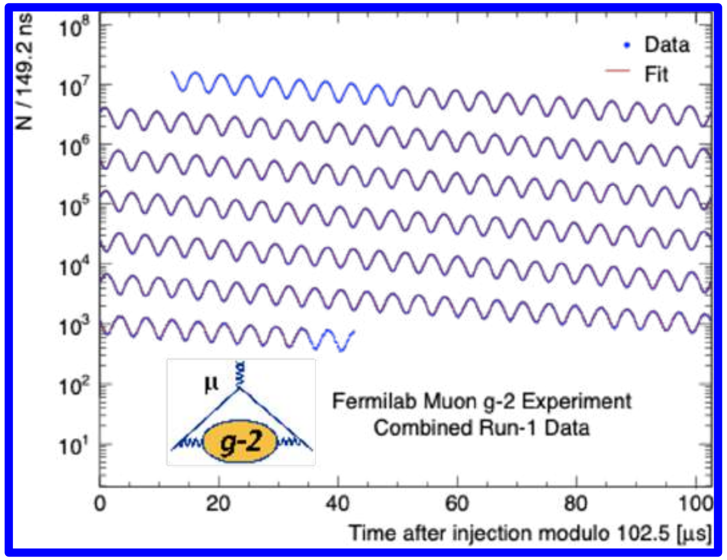
Fitting for ω_a

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

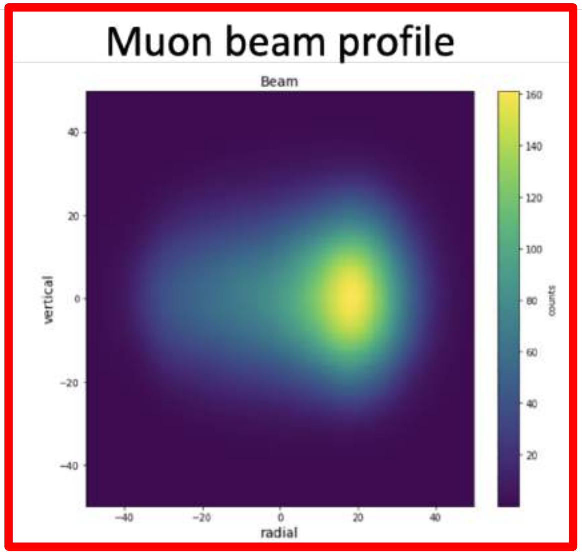


- To account for these effects additional terms are included in the final 24 parameter fit function

Field measurement



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

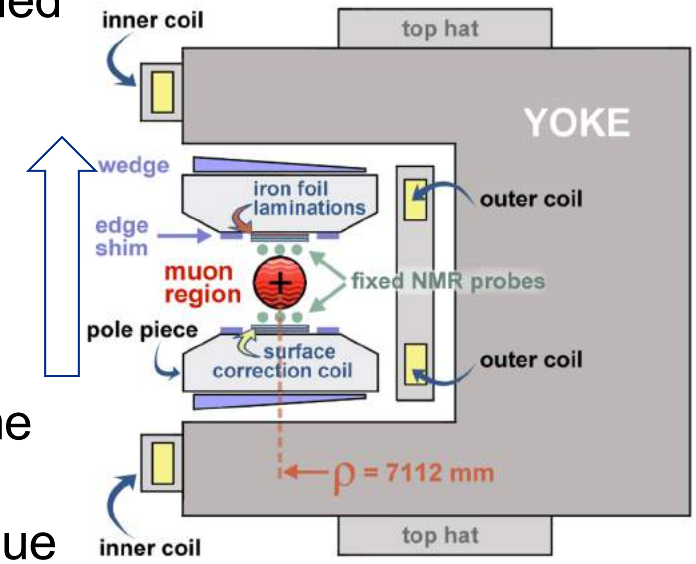


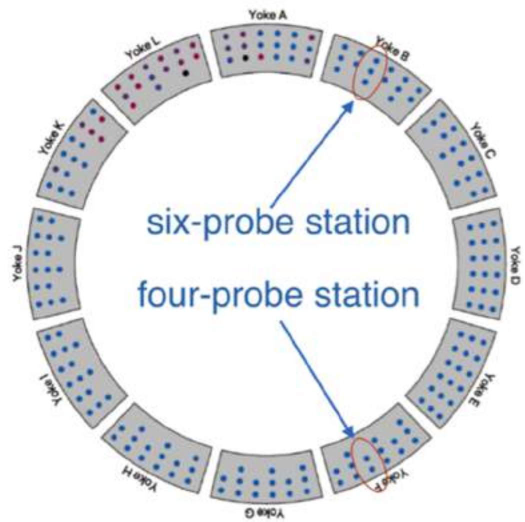
Measuring the magnetic field is the last piece

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

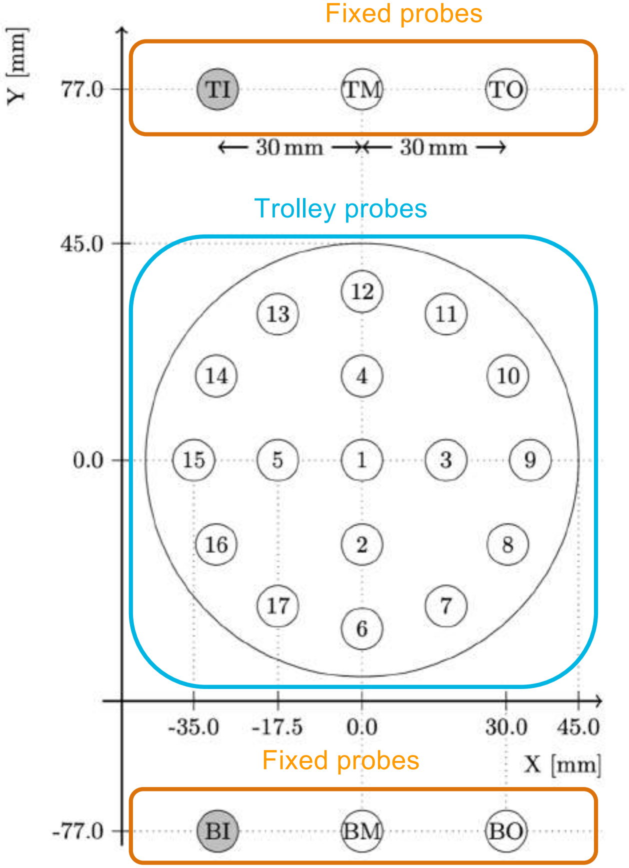


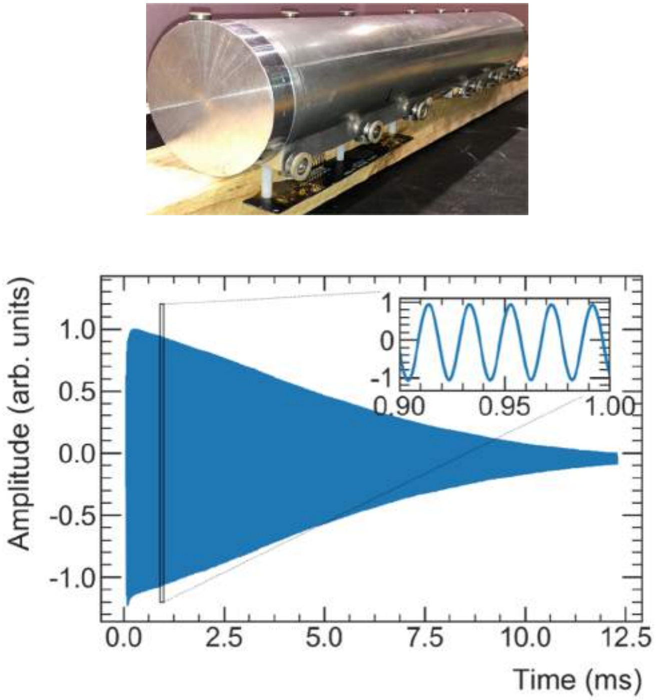


Top-down view

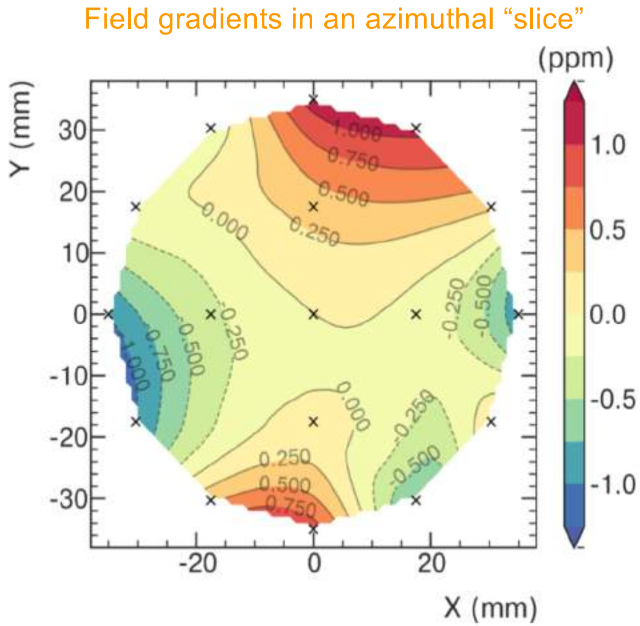
Measuring the field: the NMR Trolley

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





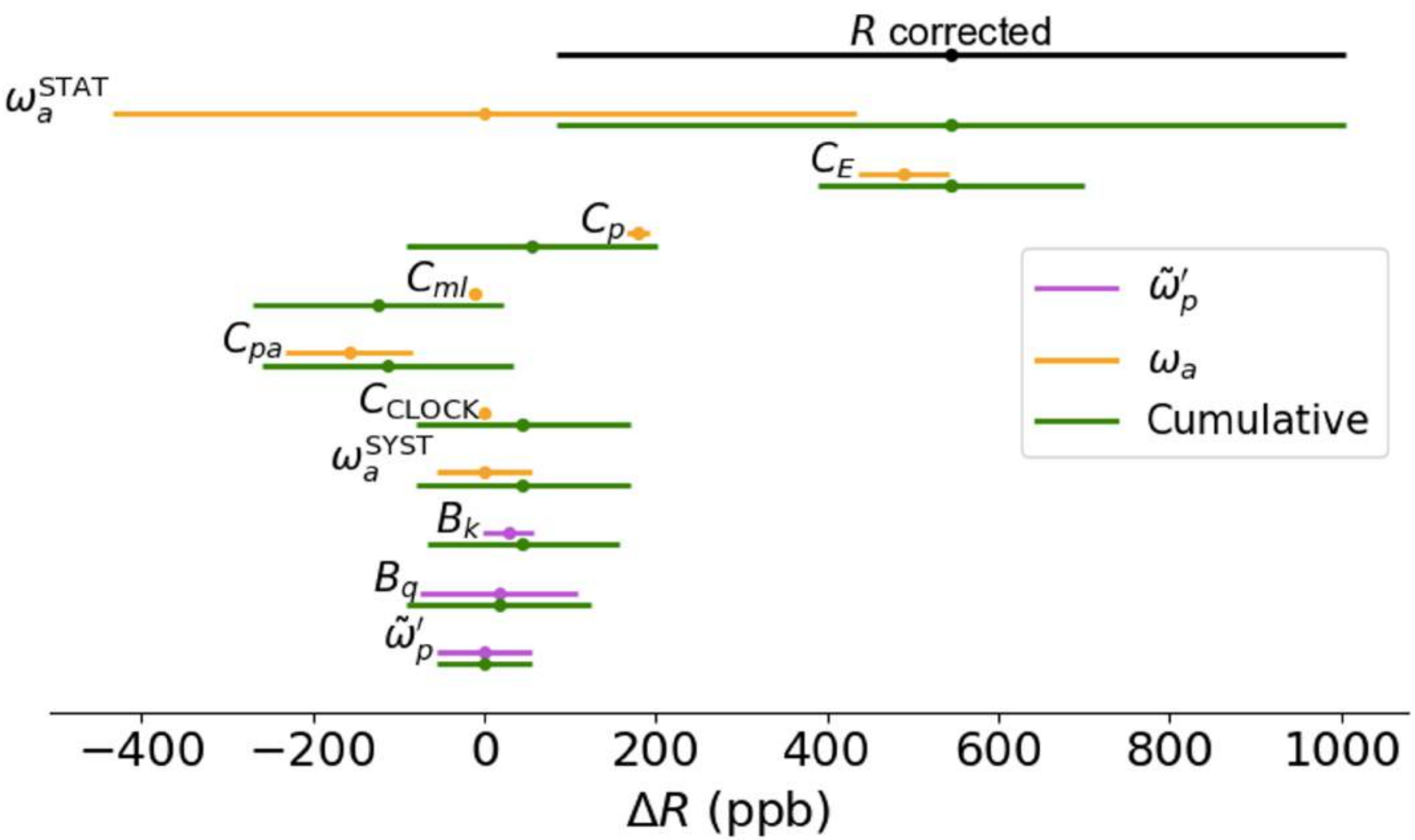
Field measured by extracting frequency from a Free Induction Decay (FID) spectrum



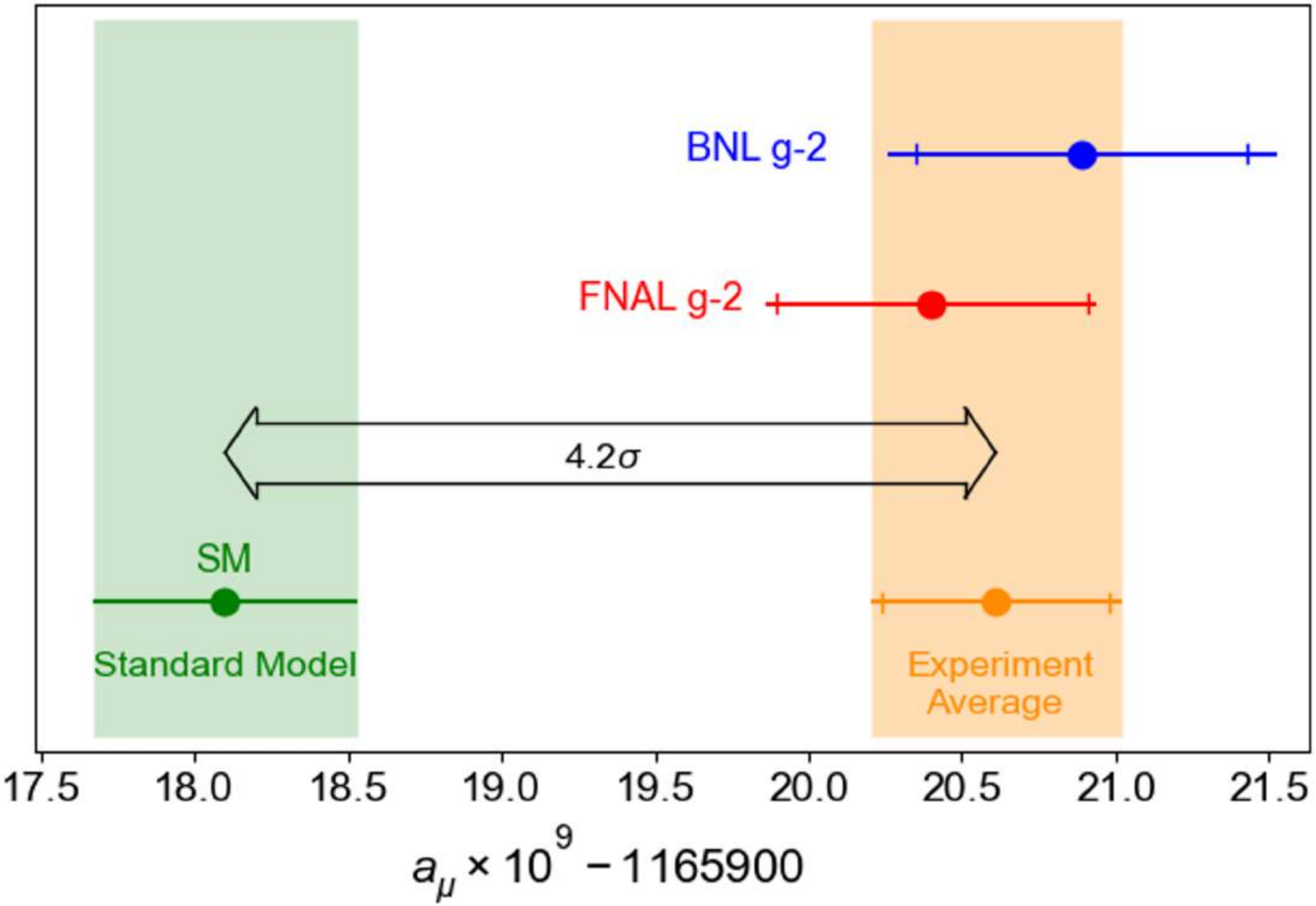
At ~8000 azimuthal locations, obtain a field contour plot from the 17 probes

Correcting Measured R

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

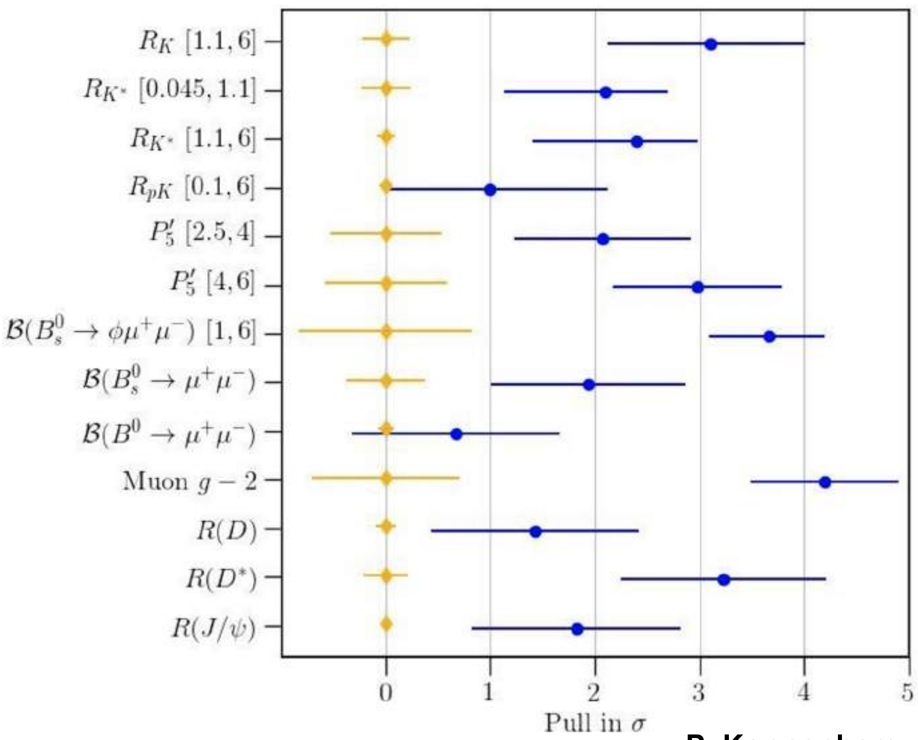


The result

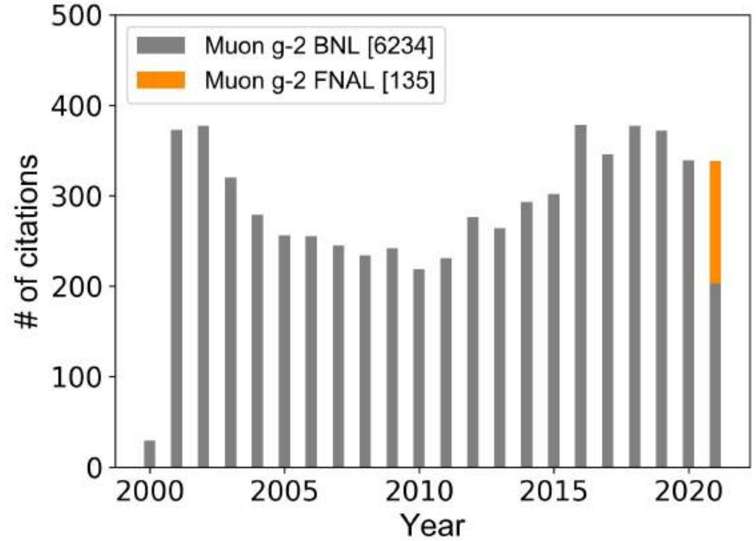

BNL g-2
FNAL g-2
4.2σ
SM
Standard Model
Experiment Average
17.5
18.0
18.5
19.0
19.5
20.0
20.5
21.0
21.5
$a_\mu \times 10^9 - 1165900$

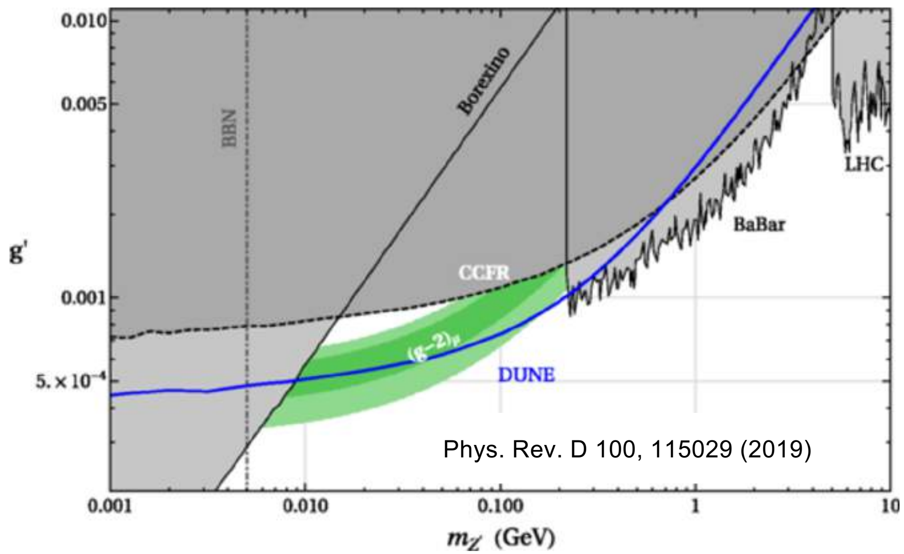
Interpretation

Needs more precision



P. Koppenberg





Phys. Rev. D 100, 115029 (2019)

TeV Leptoquarks
Z', ALPs
LHC evading SUSY
Tweaked Higgs extensions ...

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.