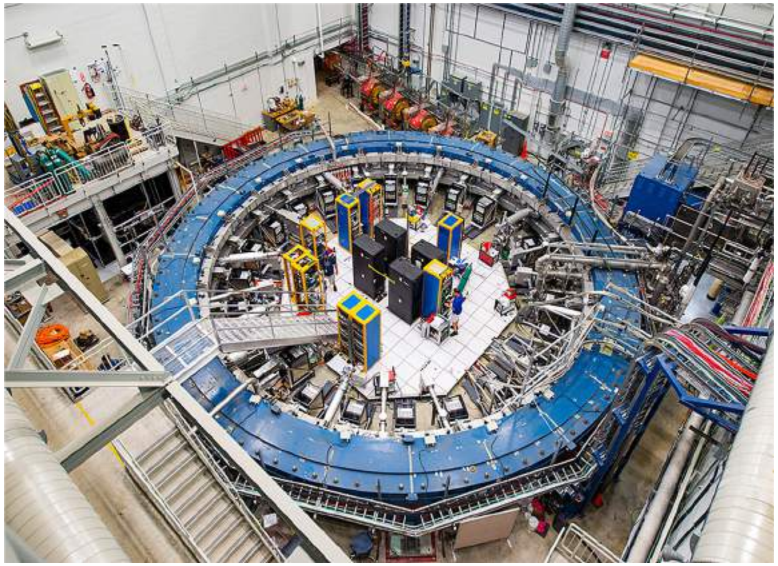
First Results From The Fermilab Muon g-2 Experiment



Alex Keshavarzi

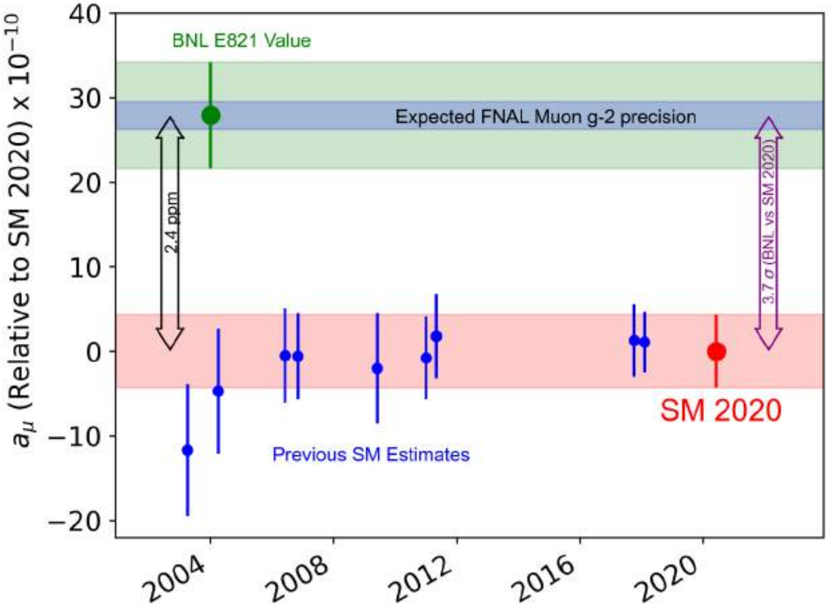
Kings College London Seminar
9th June 2021

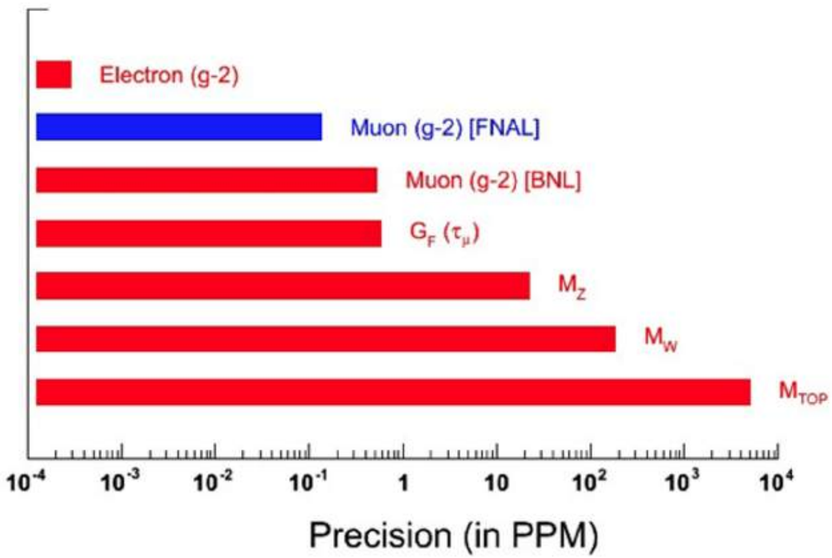
Fermilab

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^+

Magnetic moments

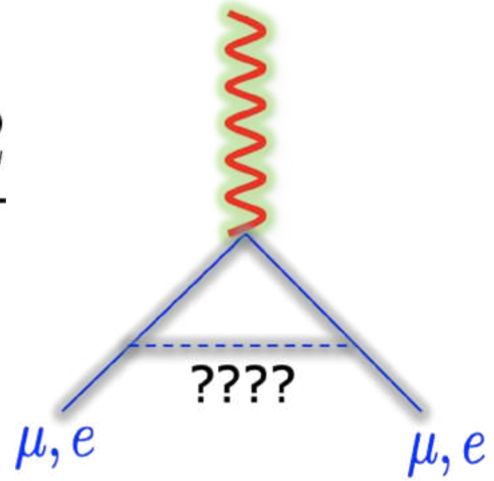
The muon has an intrinsic magnetic moment that is coupled to its spin via the gyromagnetic ratio *g*:

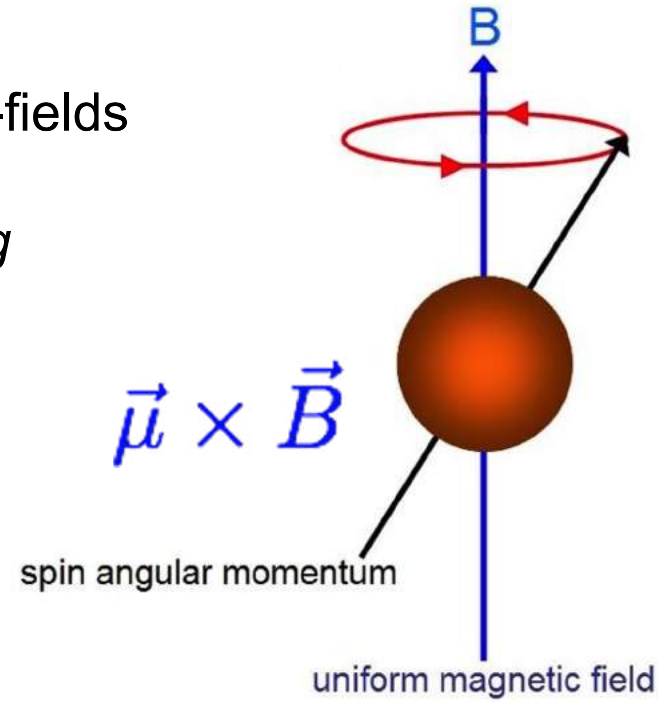
$$\vec{\mu} = g \frac{e}{2m_\mu} \vec{S}$$

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 Theory

arXiv.org > hep-ph > arXiv:2006.04822

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High Energy Physics – Phenomenology

[Submitted on 8 Jun 2020]

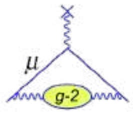
The anomalous magnetic moment of the muon in the Standard Model

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)

The Muon g-2 Theory Initiative

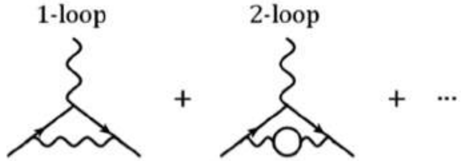
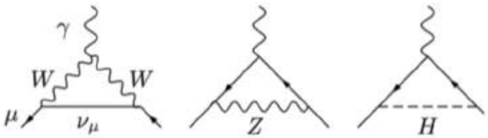
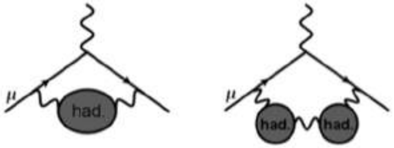
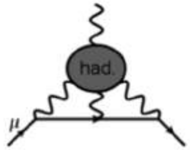
Muon g-2 in the SM

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



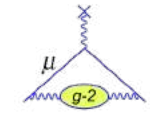
- a_μ arises due to quantum corrections / higher order interactions / loop contributions
- All SM particles contribute → Calculate and sum all sectors of the SM:

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

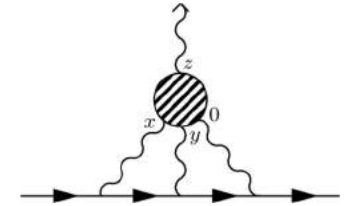
			a_μ^{SM} portion	δa_μ^{SM} portion
QED		Perturbative (Known to five-loop)	$\sim 99.99\%$	$\sim 0.001\%$
EW		Perturbative (Known to two-loop)	~ 1 ppm	$\sim 0.2\%$
HVP		Non-perturbative (Data-driven & lattice)	~ 59 ppm	**~84%**
HLbL		Non-perturbative (Data-driven & lattice)	~ 1 ppm	**~16%**

Muon g-2 in the SM: HLbL

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



- HLbL scattering - hadronic blob coupled to 3 off-shell/1 on-shell photon.
- Four point function - notoriously difficult to calculate.
- Previously only calculated from models with large systematics.

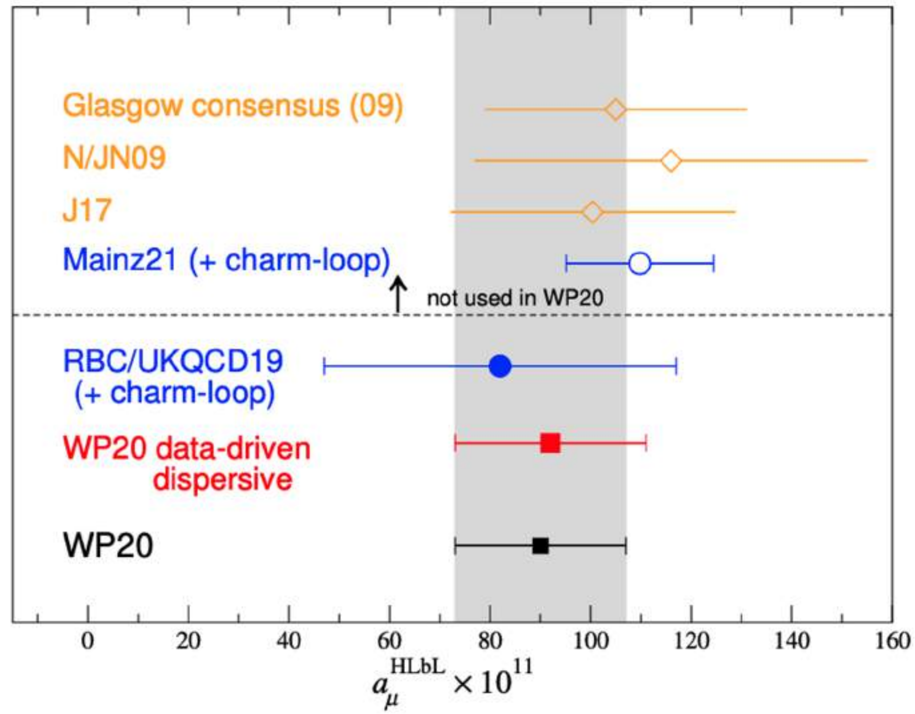


Data-driven (error ~ 0.2 ppm of a_μ^{SM})

- Model-independent dispersive evaluation, using data (e.g. π, η, η' TFFs) as input for hadronic insertions.

Lattice (error ~ 0.3 ppm of a_μ^{SM})

- Model-independent evaluation, computed on discretized Euclidean spacetime (lattice) in finite volume.



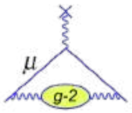
Recommended Muon g-2 TI result (before Mainz):

$$a_\mu^{\text{HLbL}} = 92(18) \times 10^{-11}$$

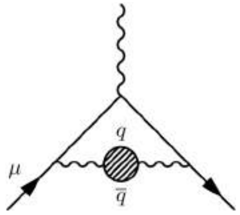
Improved, but still evolving.
Still systematics dominated
(goal < 10% uncertainty)

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})

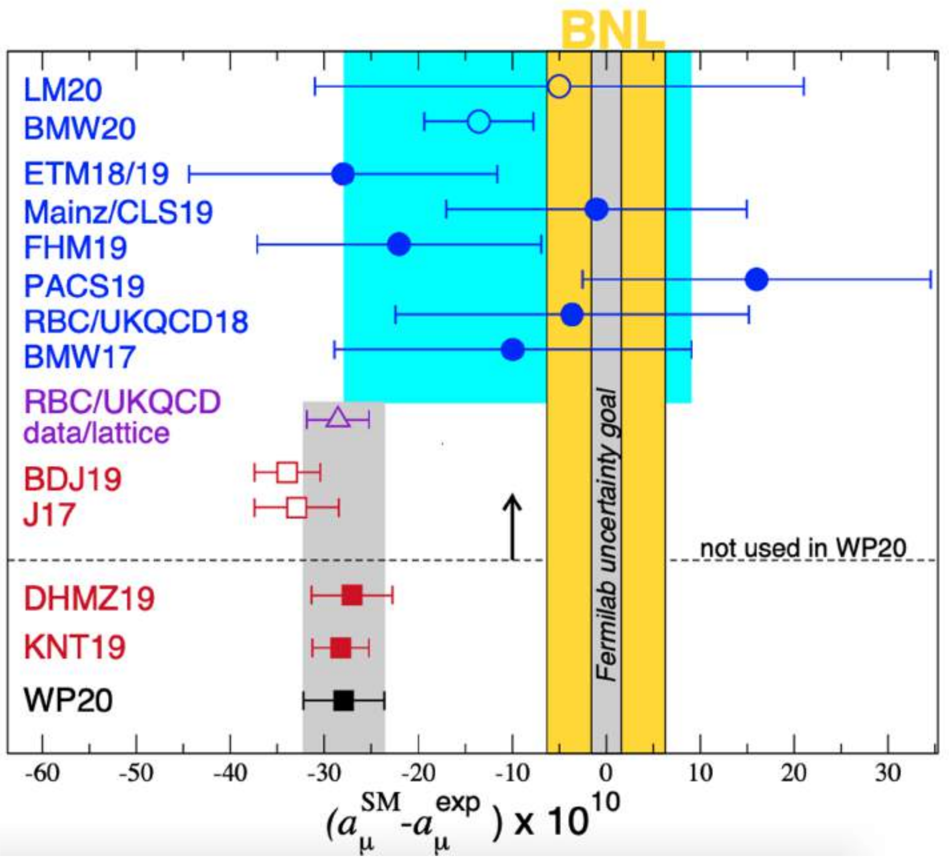
- Cross section data consistently combined and input into dispersion integral:

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

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

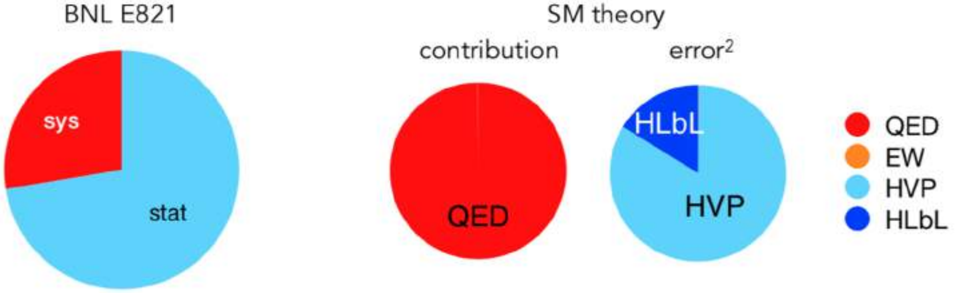
Recommended Muon g-2 TI value from data-driven result:

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



Muon g-2 in the SM and Outlook

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: $\Delta a_\mu := a_\mu^{\rm exp} - a_\mu^{\rm SM}$	279(76)



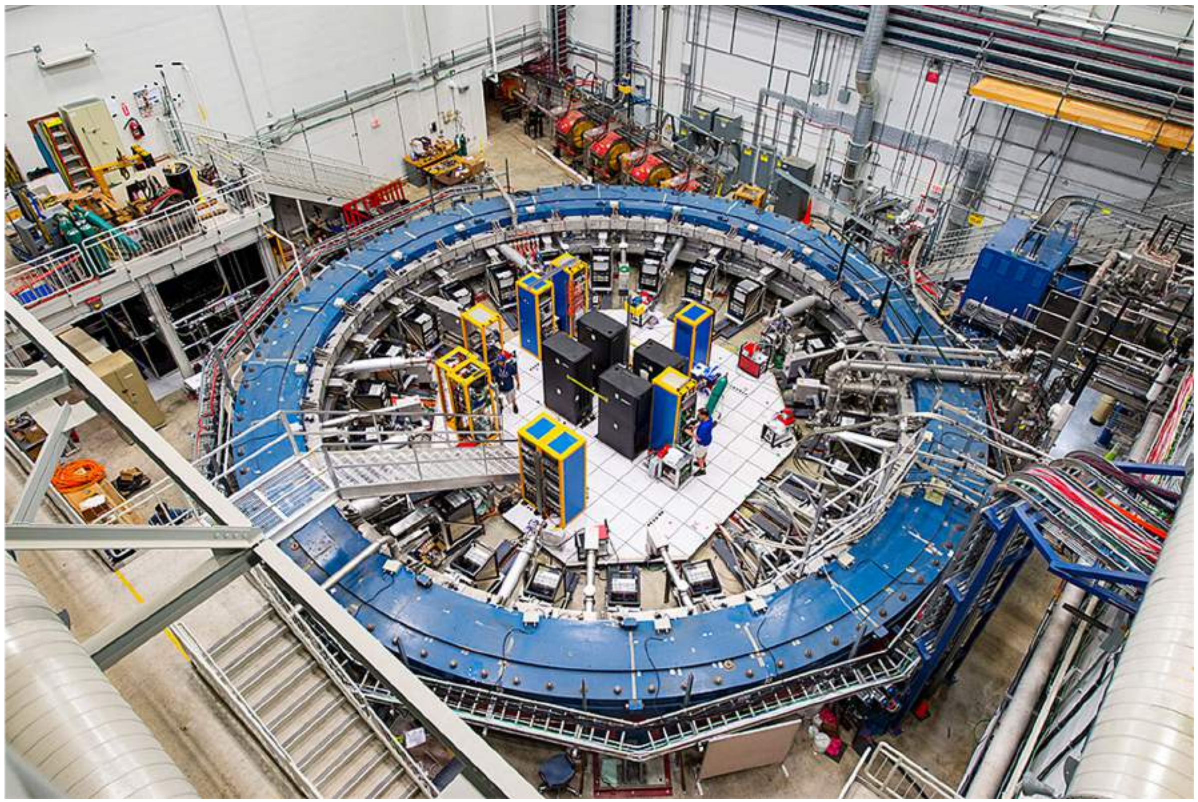
$$\Delta a_\mu = 279(76) \times 10^{-11} \rightarrow 2.39(0.65)\ \text{ppm}$$

Muon g-2 theory initiative recommended result:

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

Results in 3.7σ discrepancy when compared to BNL measurement.

The Fermilab Muon g-2 Experiment



Muons at Fermilab

Lower instantaneous rate but larger integrated rate than BNL

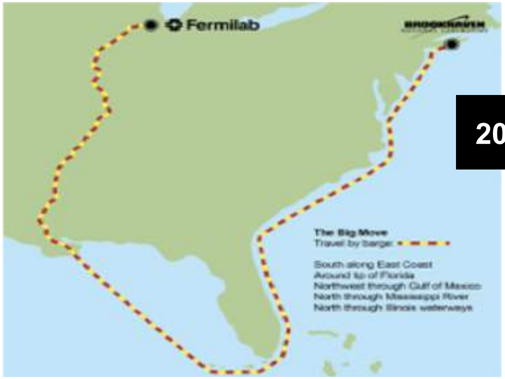
~ 10,000μ^+ (from 10^{12} p) at 3.1 GeV every 10 ms

(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

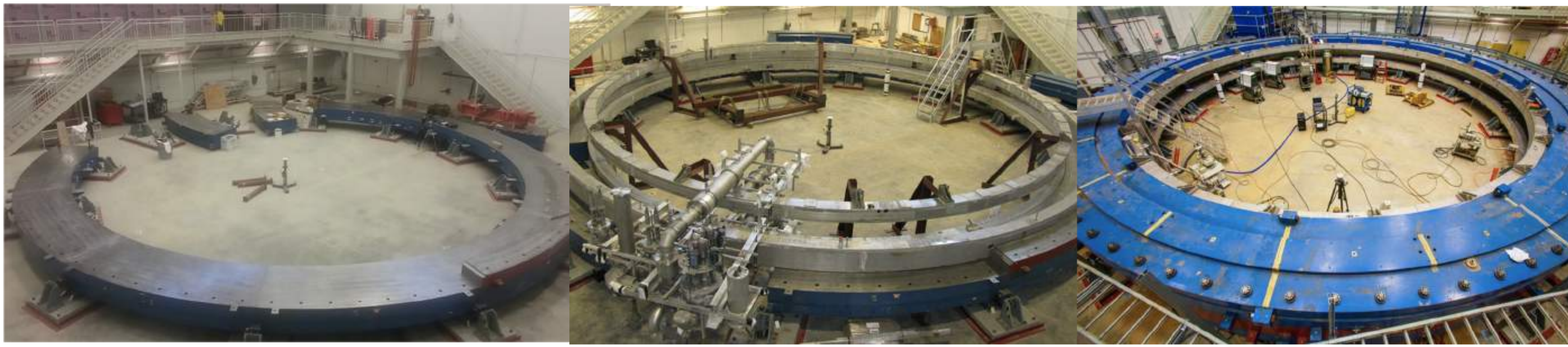
2015

2016-2017

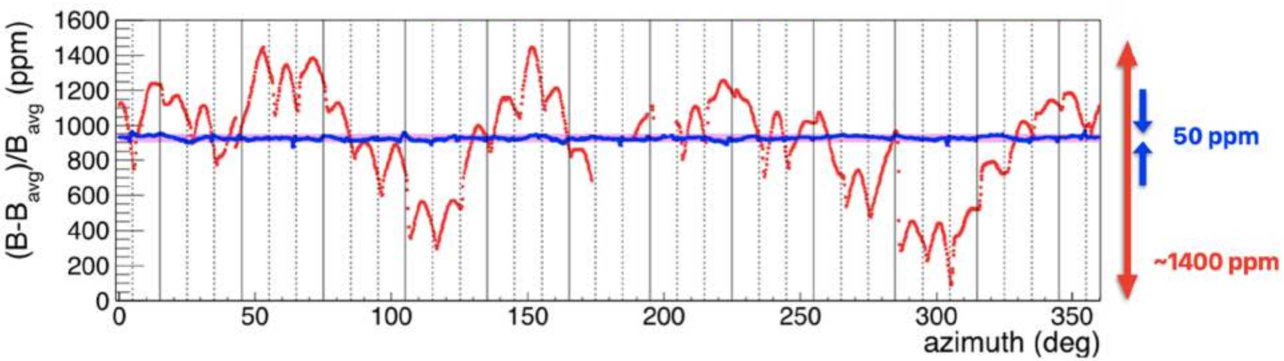
May 31 2017 (g-2)

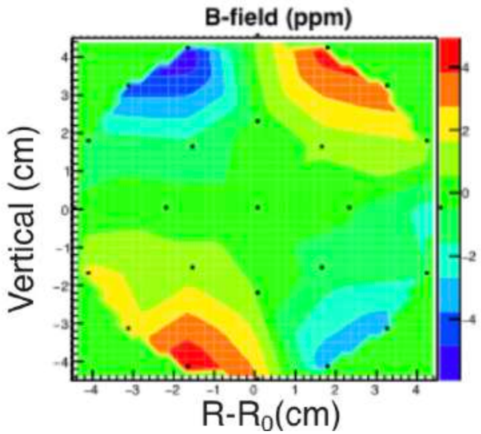
Run-1 data taking started Feb. 2018

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.

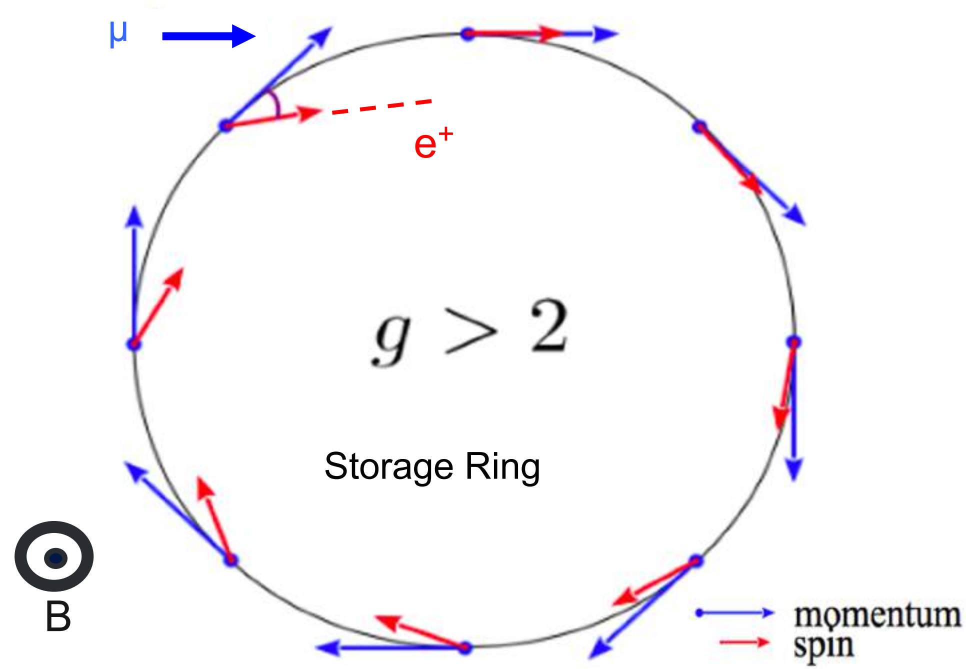
$$\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

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

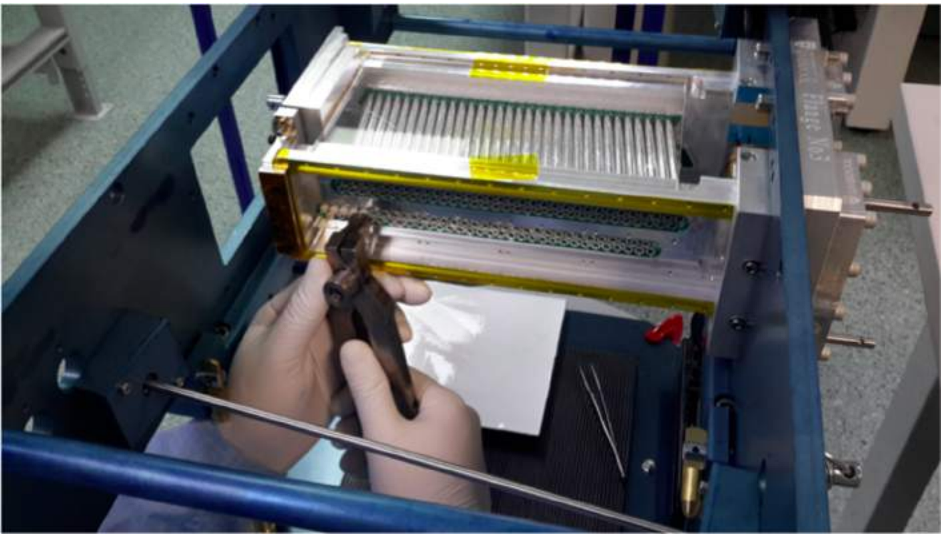
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m \left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle \left(1 + B_k + B_q\right)}$$

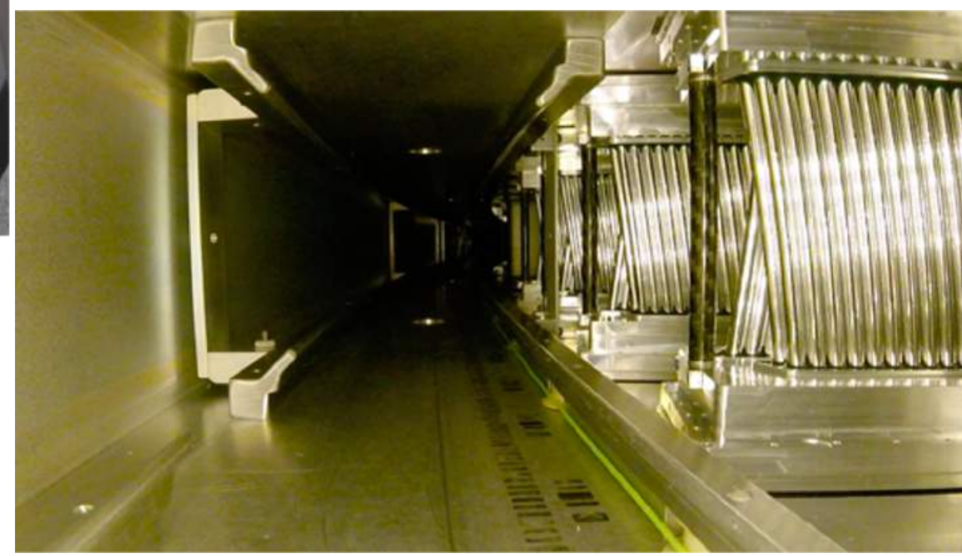
NMR probe calibration factor

Magnetic field weighted over the muon distribution and azimuthally averaged

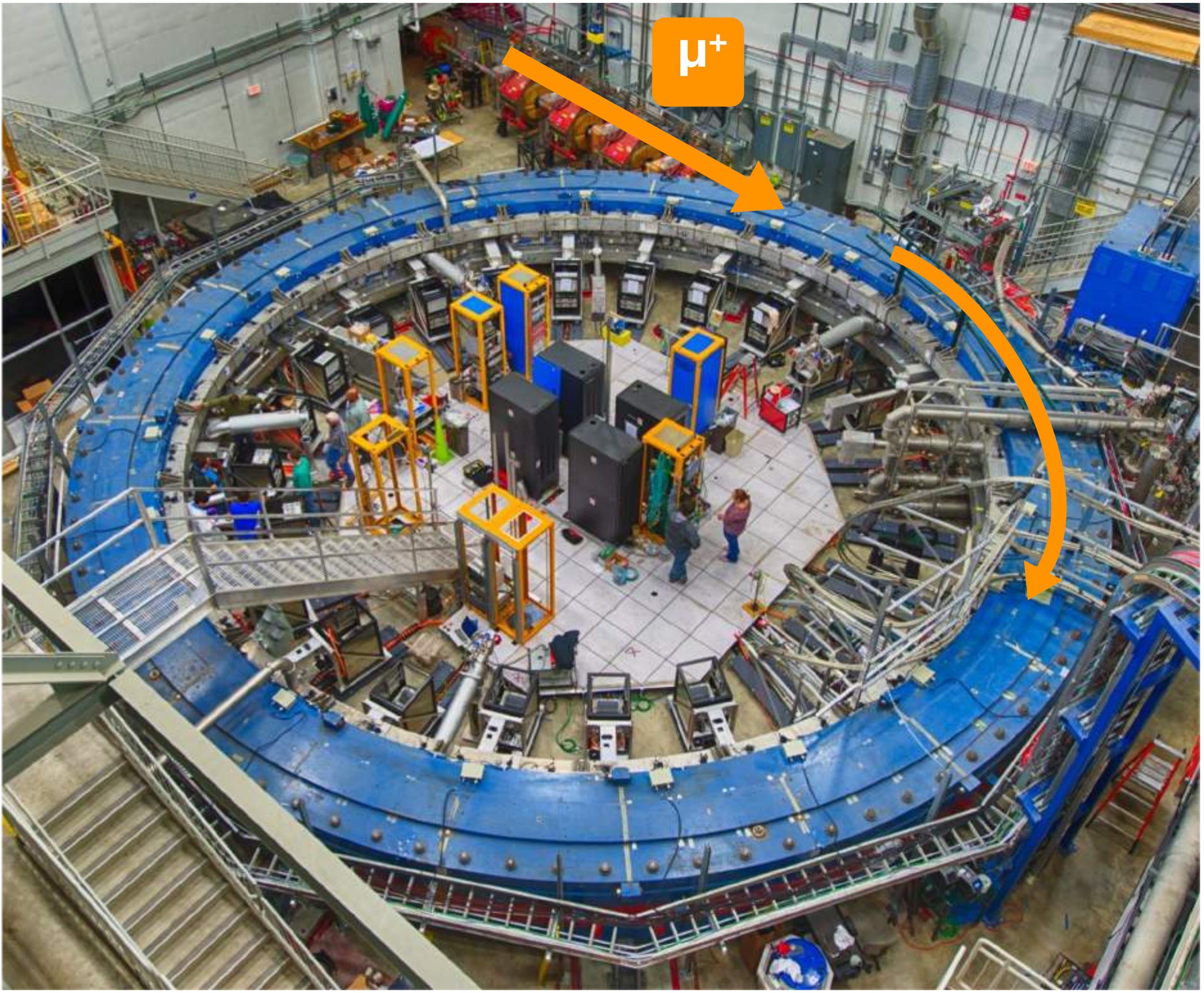
Corrections from the transient magnetic field

Storing and detecting the beam...

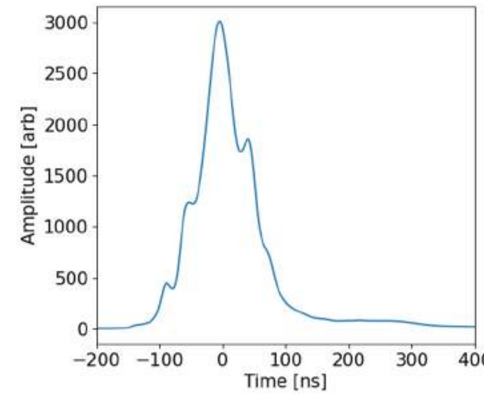




Beam injection

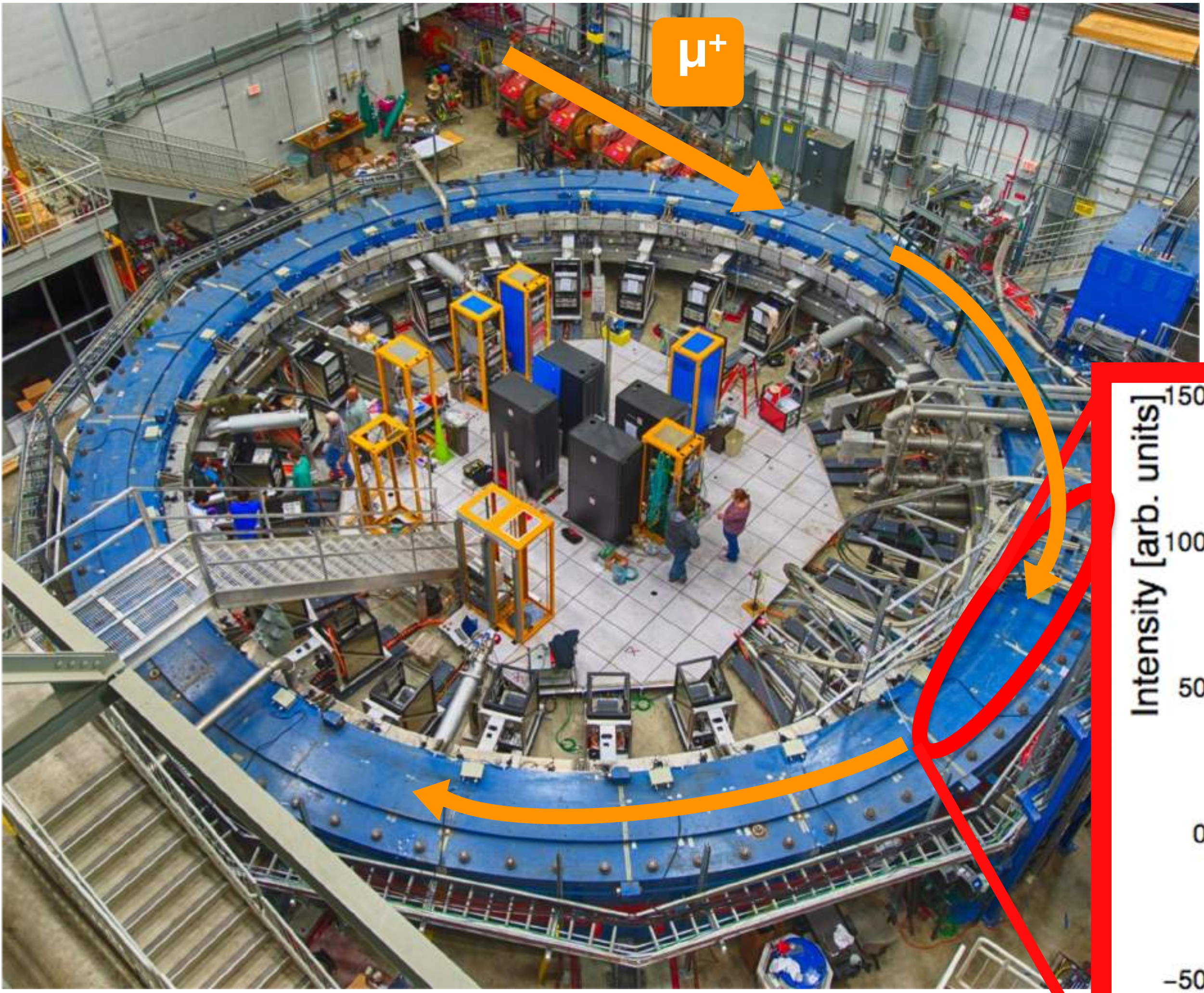


- Monitor beam profile before entrance with scintillating X and Y fibres
- Get time profile of beam using scintillating pad
- ~125ns wide

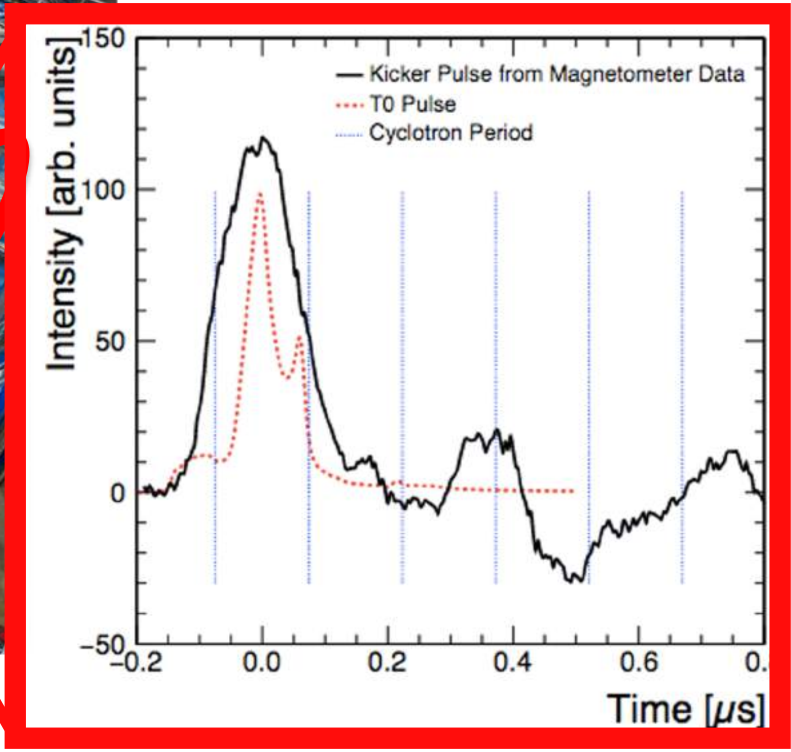


- Cancel B-field during injection using Inflector, so muons can get into the ring

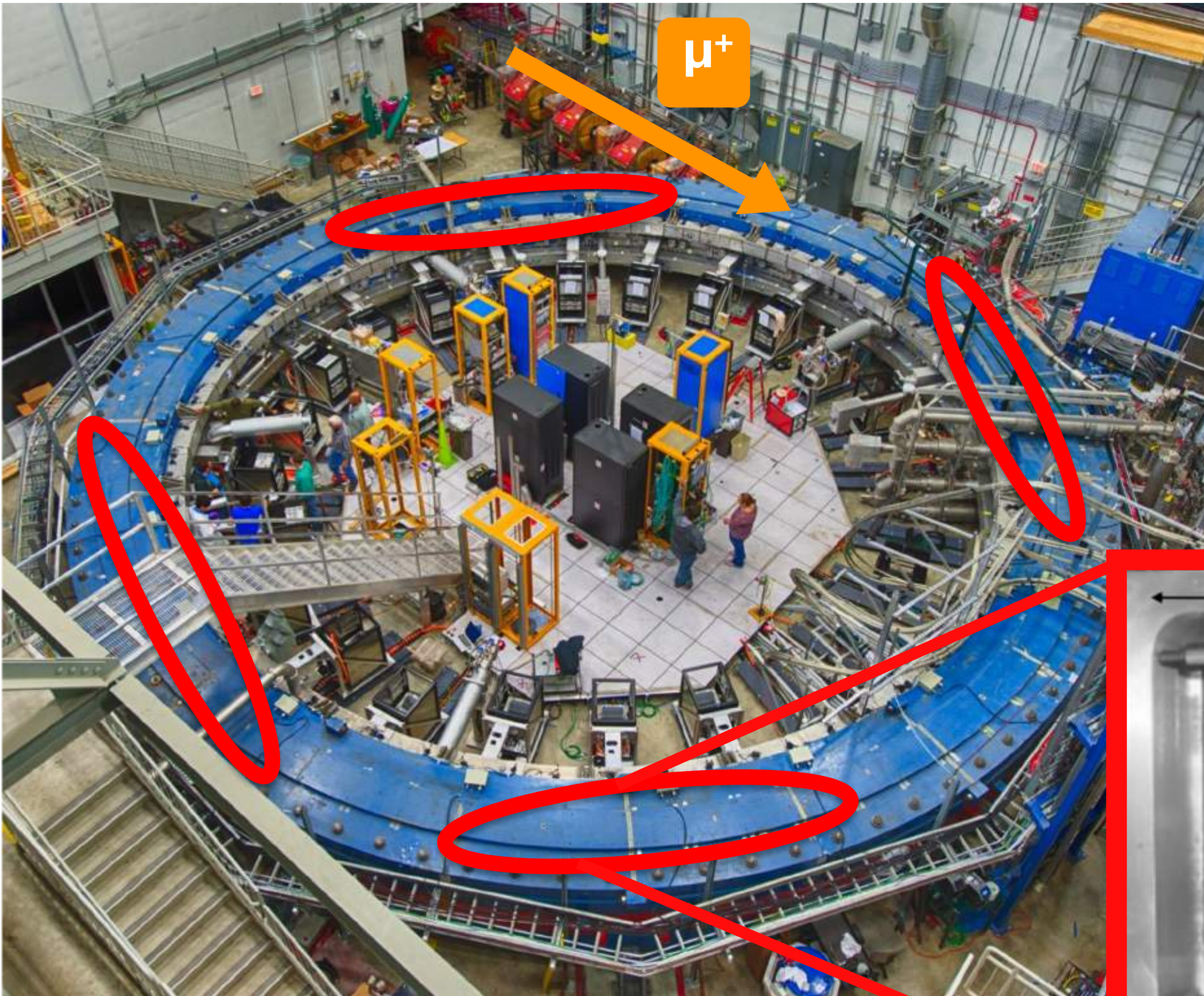
‘Kick’ onto correct orbit



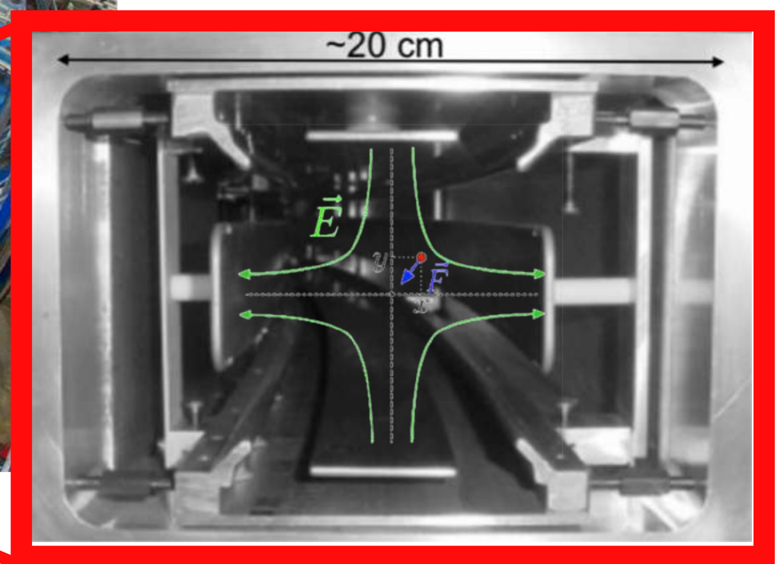
- After Inflector muons are 77mm away from ideal radius
- Apply short magnetic pulse to ‘kick’ muons onto the correct orbit



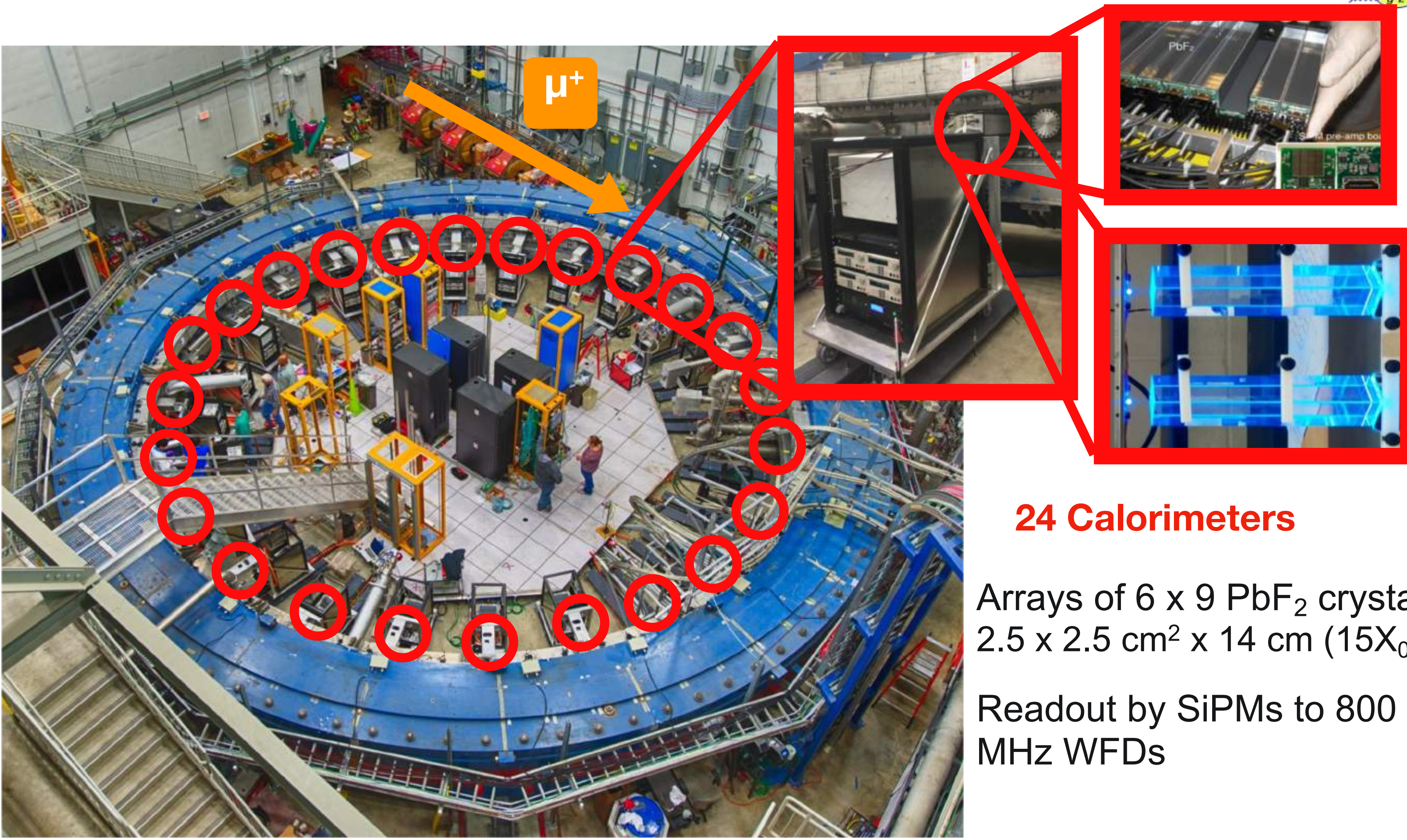
Beam focusing

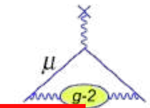


- Focus the muons vertically
- Aluminium electrodes cover ~43% of total circumference



Calorimeters



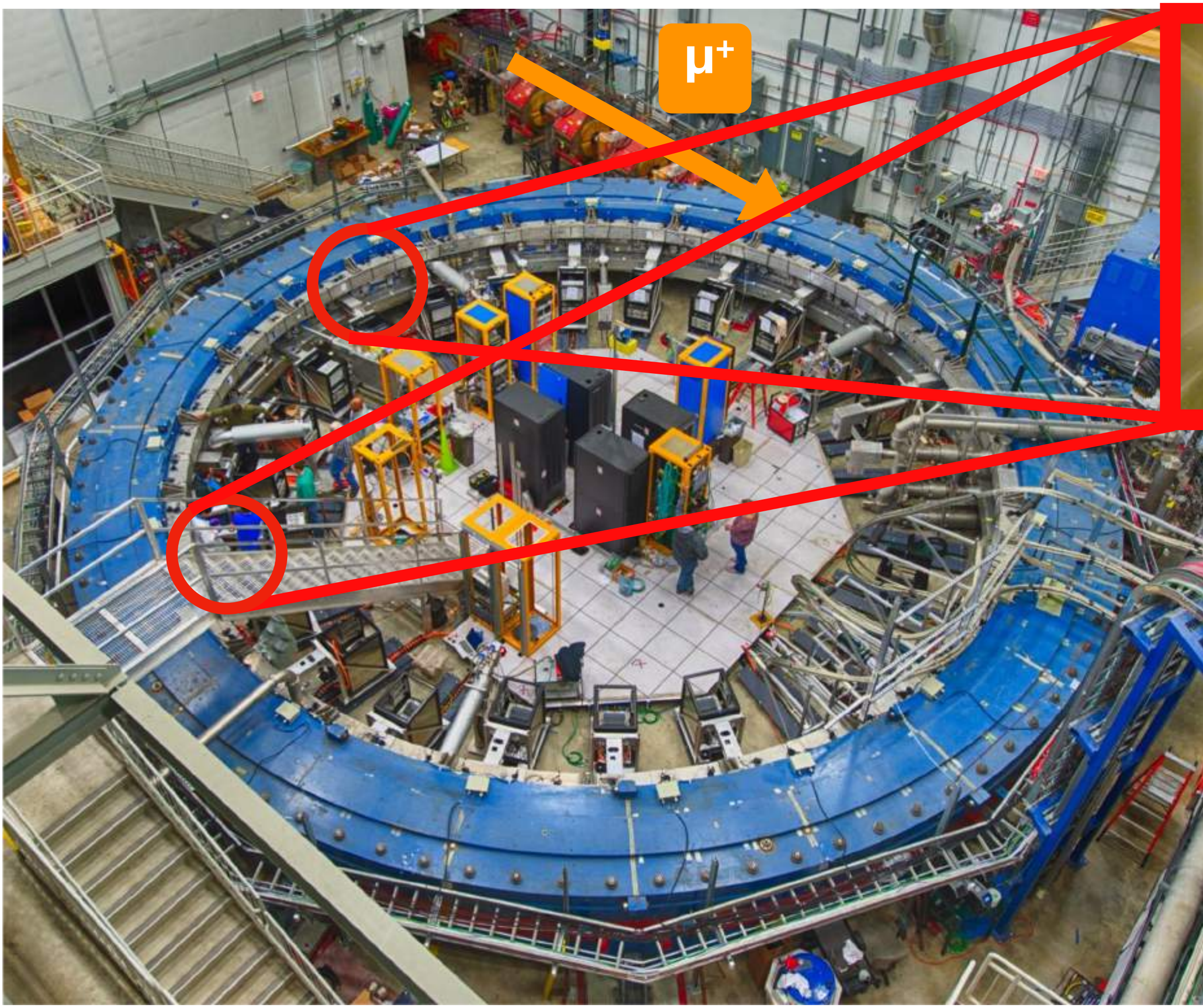


24 Calorimeters

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

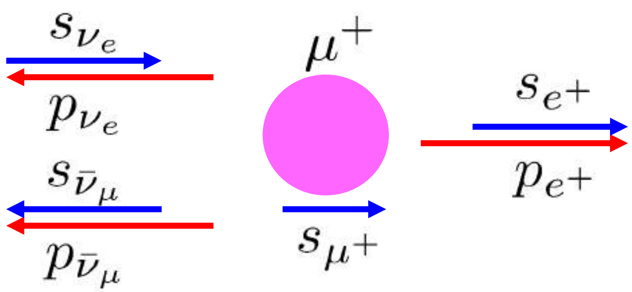
Each contain 8 modules

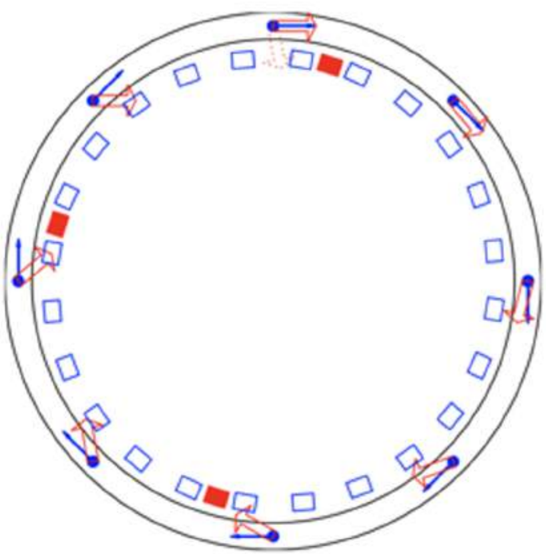
128 gas filled straws in each module

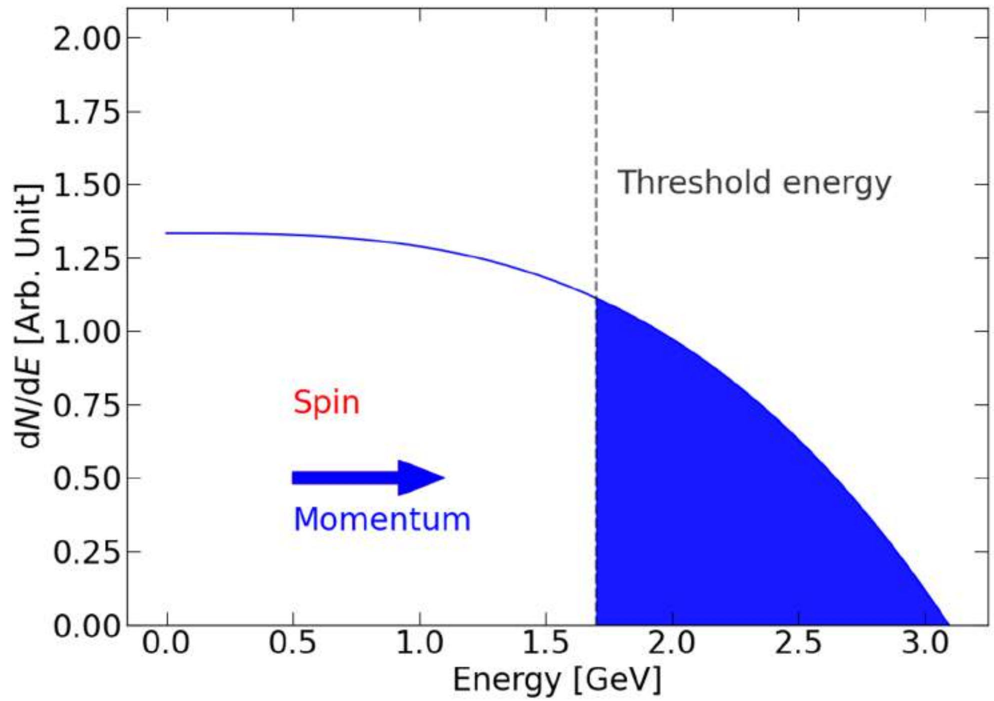
Traceback positrons to their decay point

Measuring ω_a

- e^+ preferentially emitted in direction of muon spin



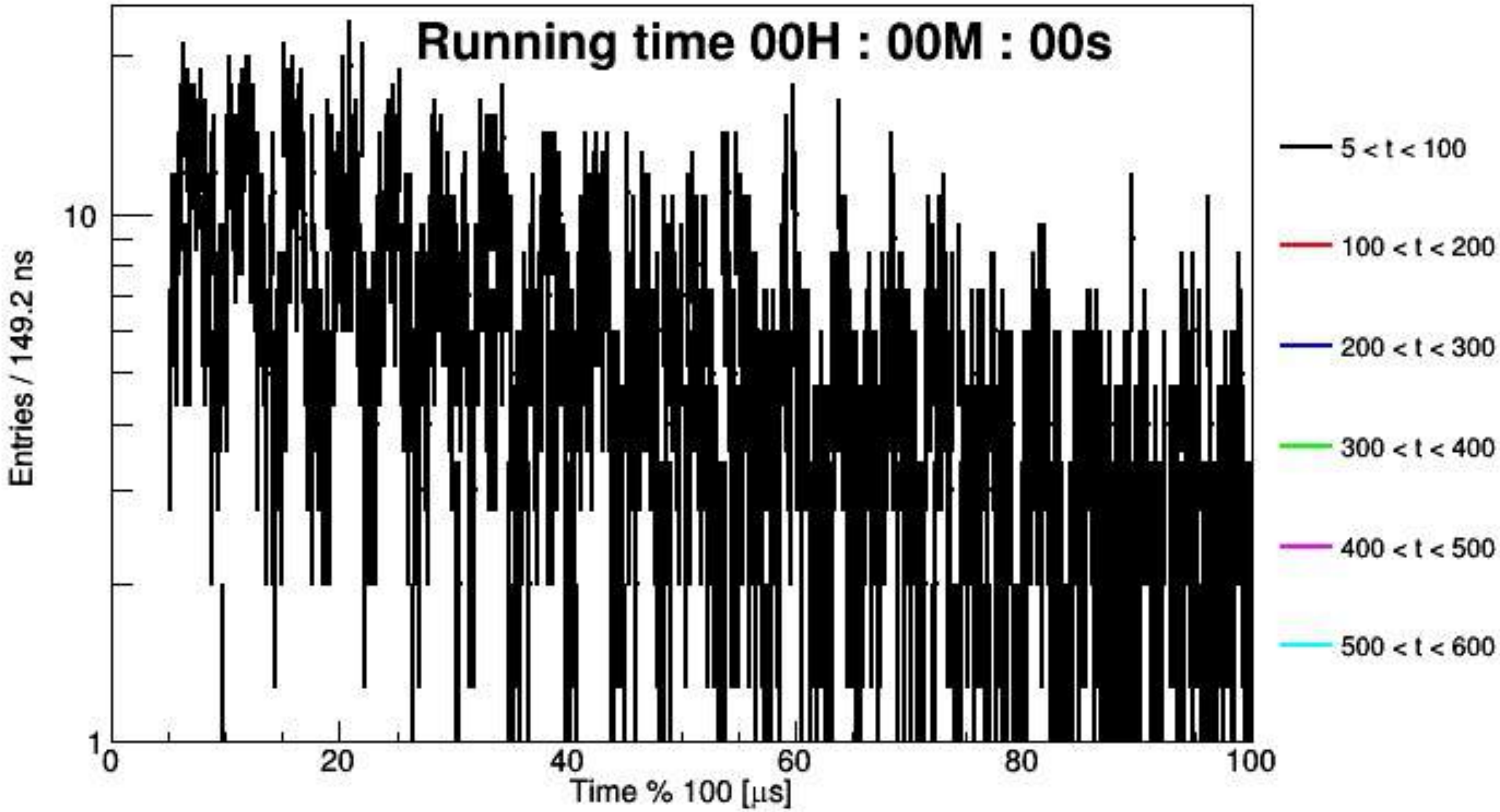




The number of high momentum positrons above a fixed energy threshold oscillates at precession frequency

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

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

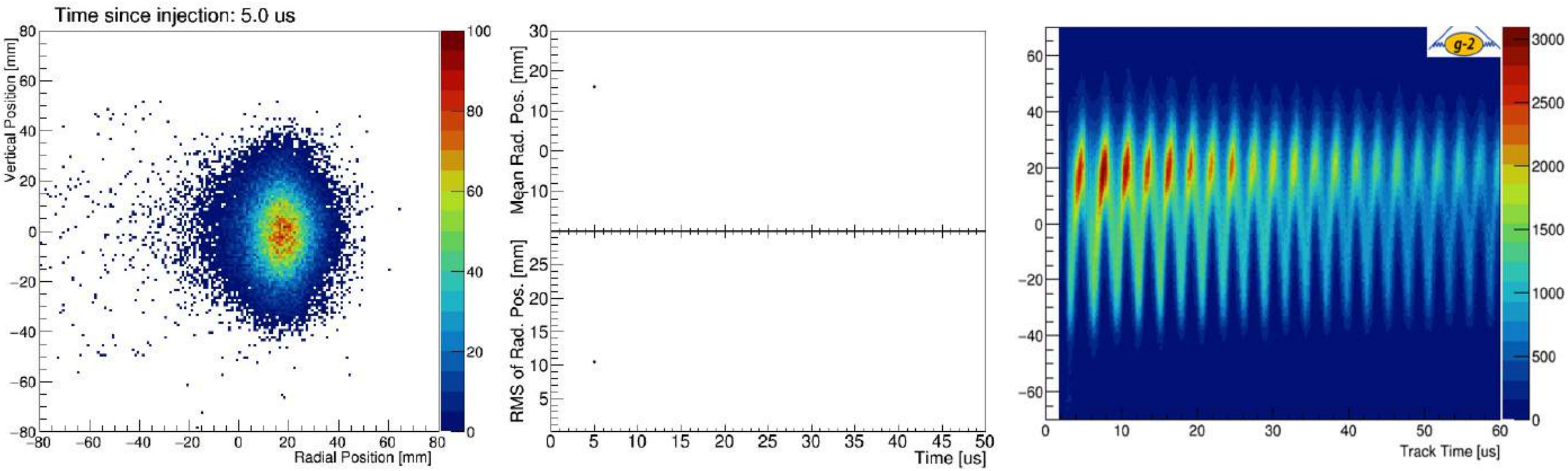
- This introduces 2 additional terms reducing the precession frequency
- We can minimise the first by choosing γ = 29.3 to give p_μ = 3.1GeV
- For a 1.45T field, this sets the radius of the ring to 7.11m
- However we now have 2 corrections to make to a_μ because:

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

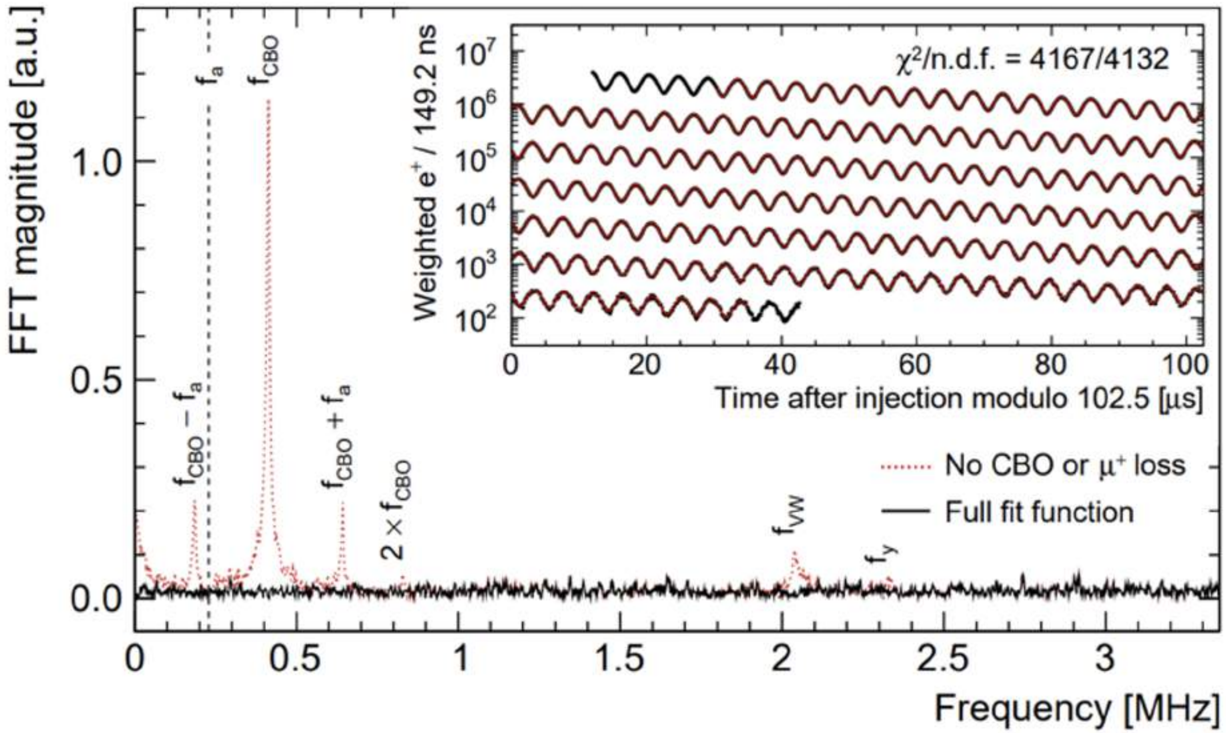
Beam Measurements



- 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

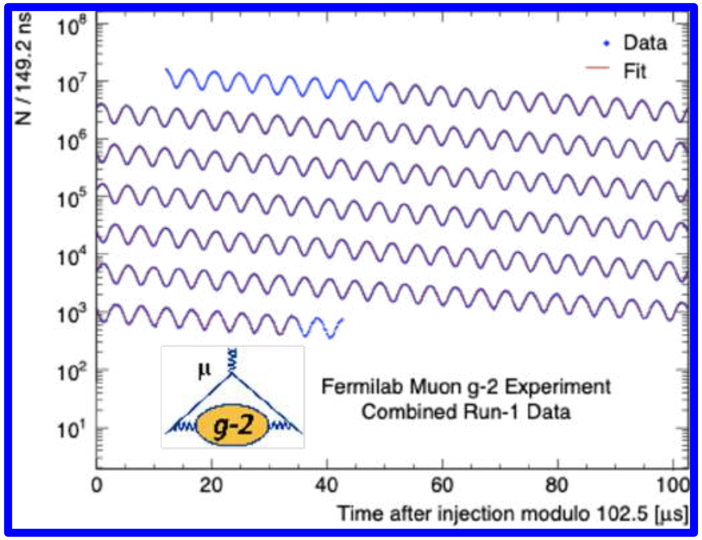
Fitting for ω_a

- 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

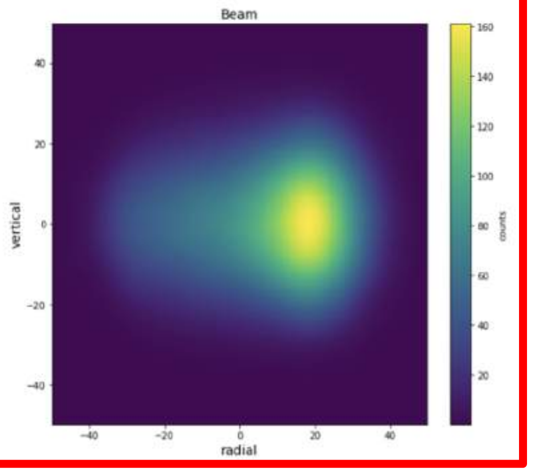
Field measurement



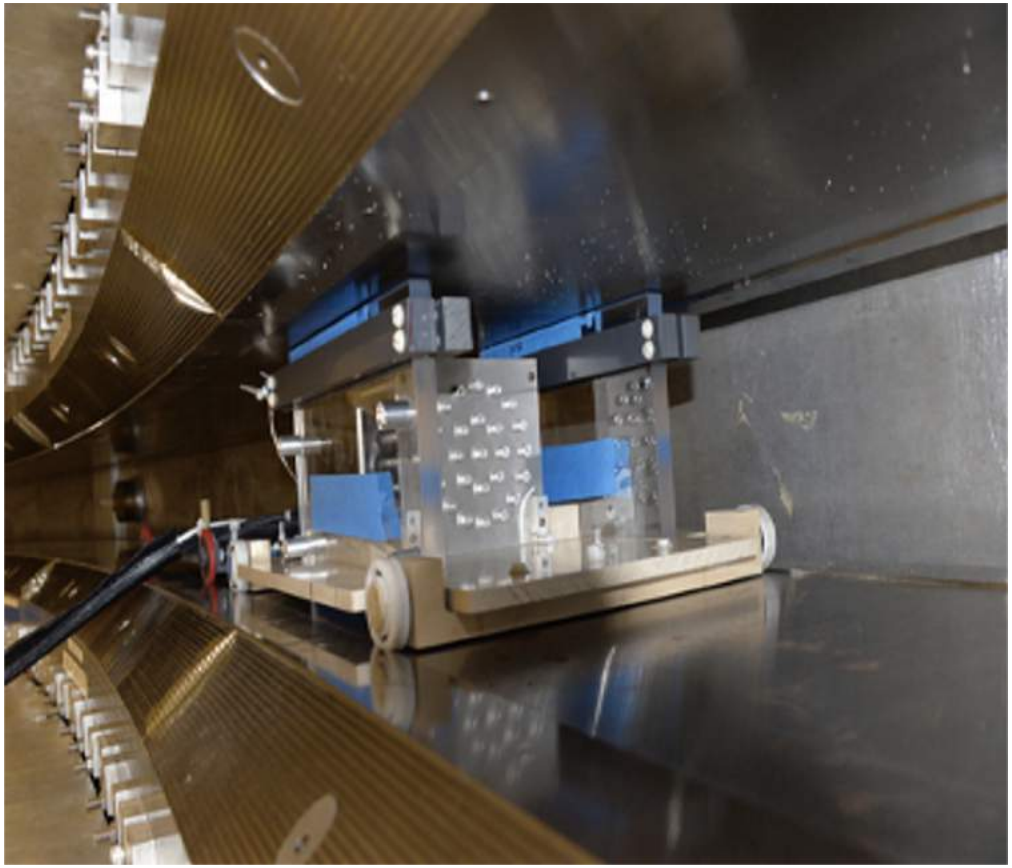
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\ (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$

Measuring the magnetic field is the last piece

Muon beam profile



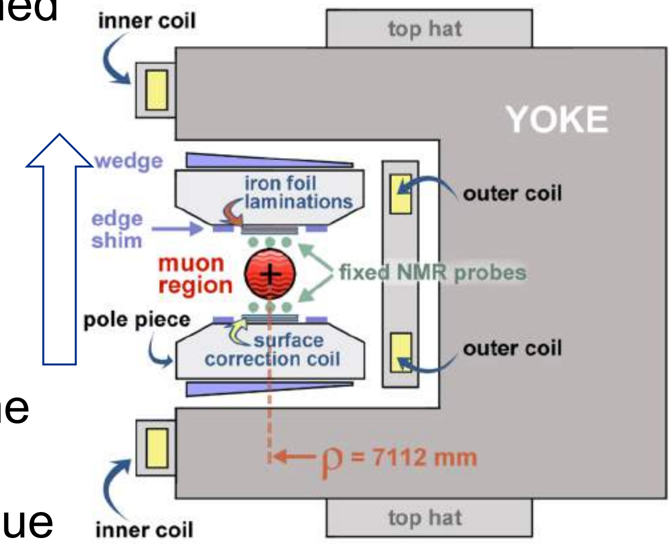
Magnetic field measurement

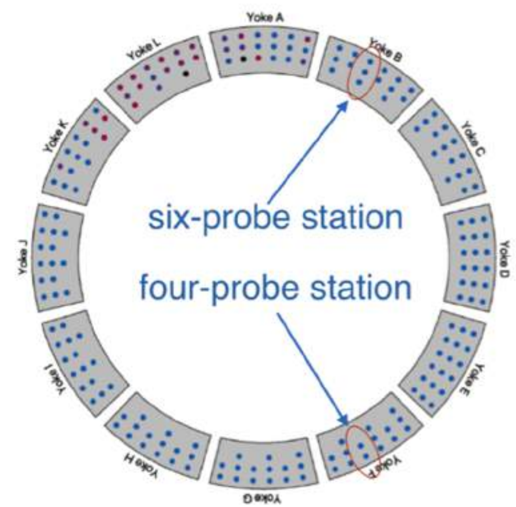


The g-2 storage ring magnet

- 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

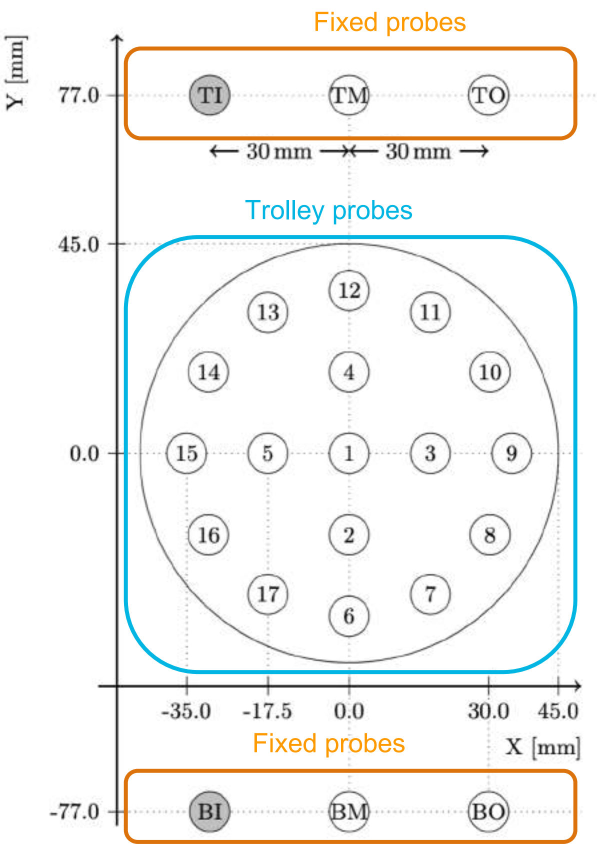


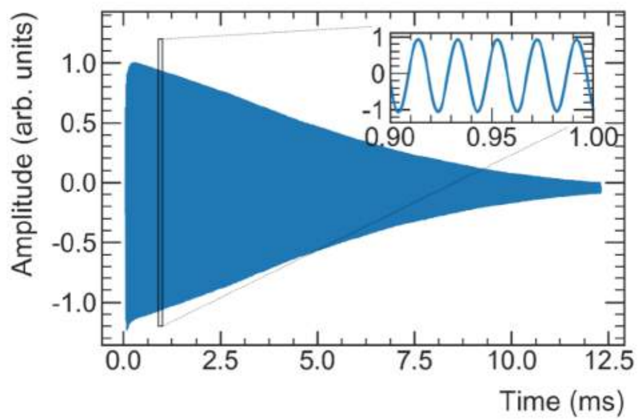


Top-down view

Measuring the field: the NMR Trolley

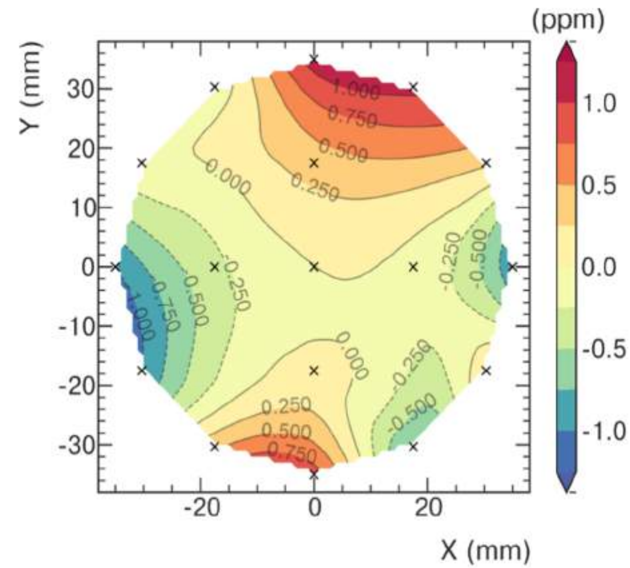
- An in-vacuum trolley with 17 NMR probes drives around the ring every ~3 days, mapping out the field components





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

Field gradients in an azimuthal "slice"



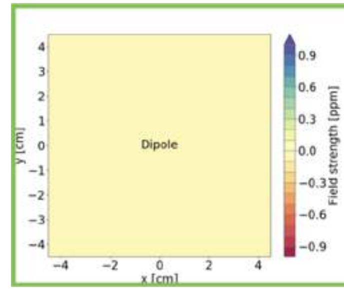
At ~8000 azimuthal locations, obtain a field contour plot from the 17 probes

Spatial dependence of B

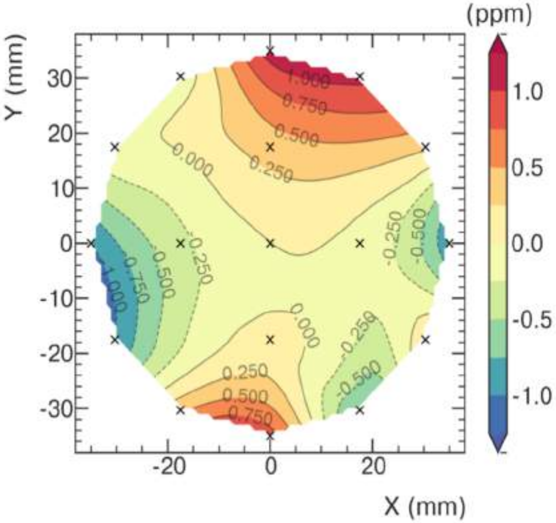
- Extract terms from a multipole (m) expansion of B in r and θ:

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

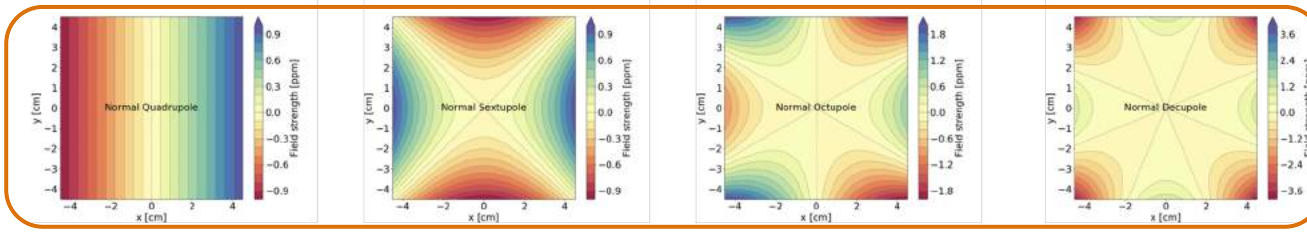
Dipole (m1)

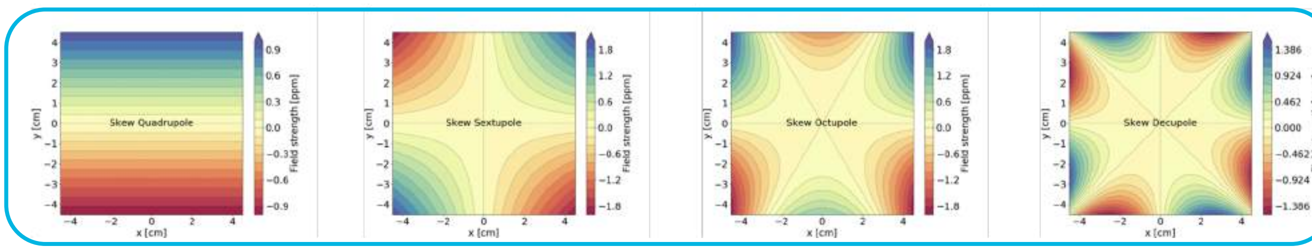


Field gradients in an azimuthal "slice"



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





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

- 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.

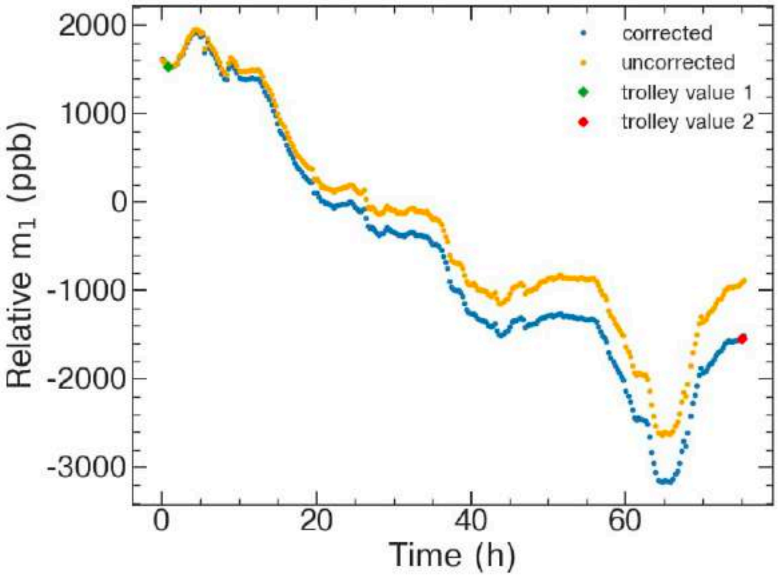
- Fixed probes take data continuously during muon fills. Use this data to interpolate between trolley runs.

- 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

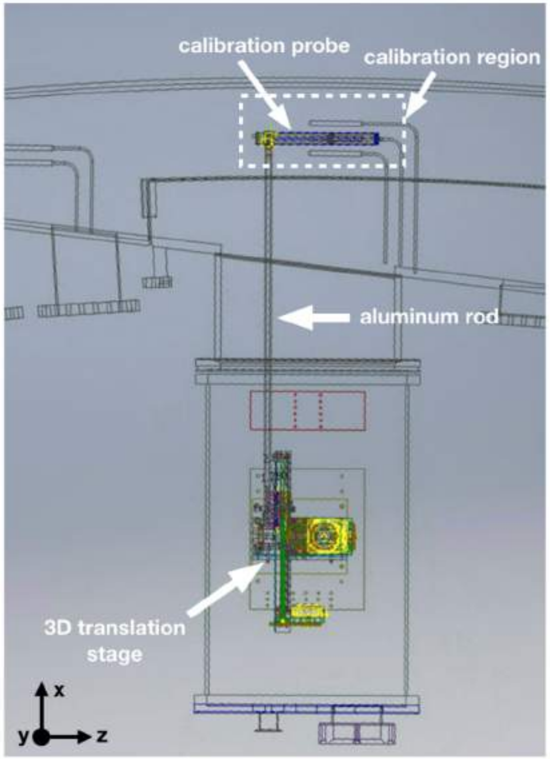
- Calibration drifts over time, due to changes in higher-order terms that cannot be tracked by the fixed probes

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



Absolute calibration

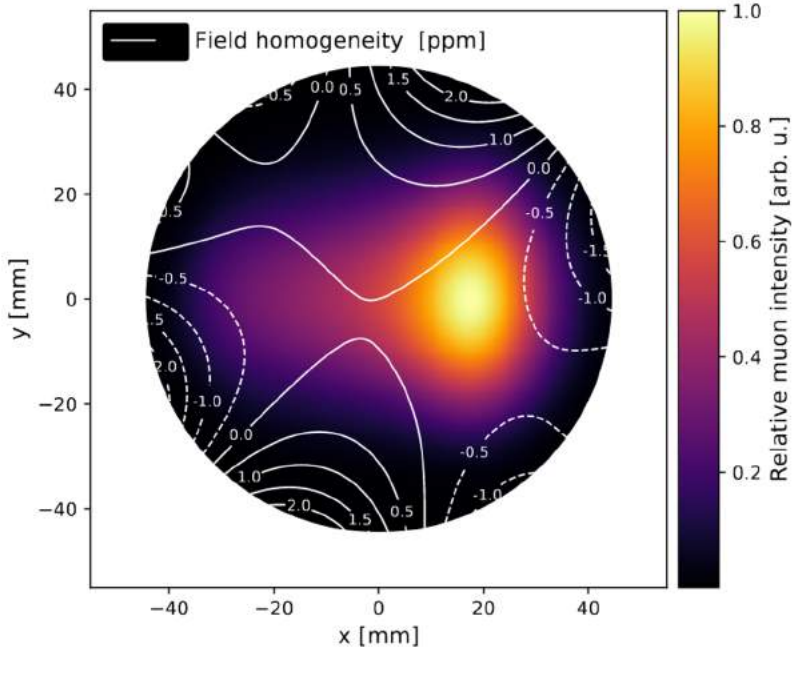
- Trolley and fixed NMR probes use petroleum jelly as the proton sample. Chosen for low volatility.
- Must calibrate with protons in a water sample (measurement standard) in order to measure a_μ
- A dedicated calibration probe with a cylindrical H_20 sample is installed inside the vacuum chamber.
- In 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)



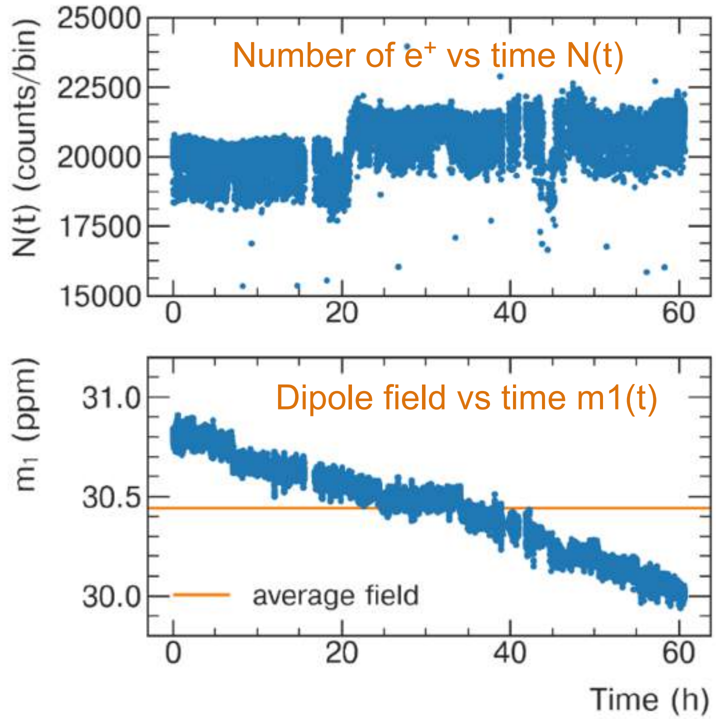
Agreement between all three calibration probes at 10 ppb level

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



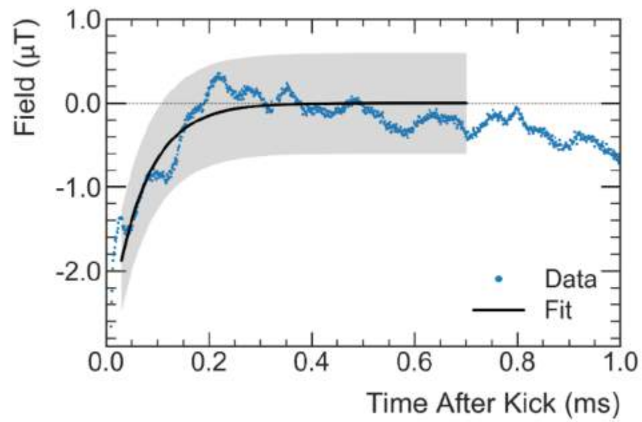
The field is weighted by the 2D beam distribution. An average beam distribution for every 3 hours is used.



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

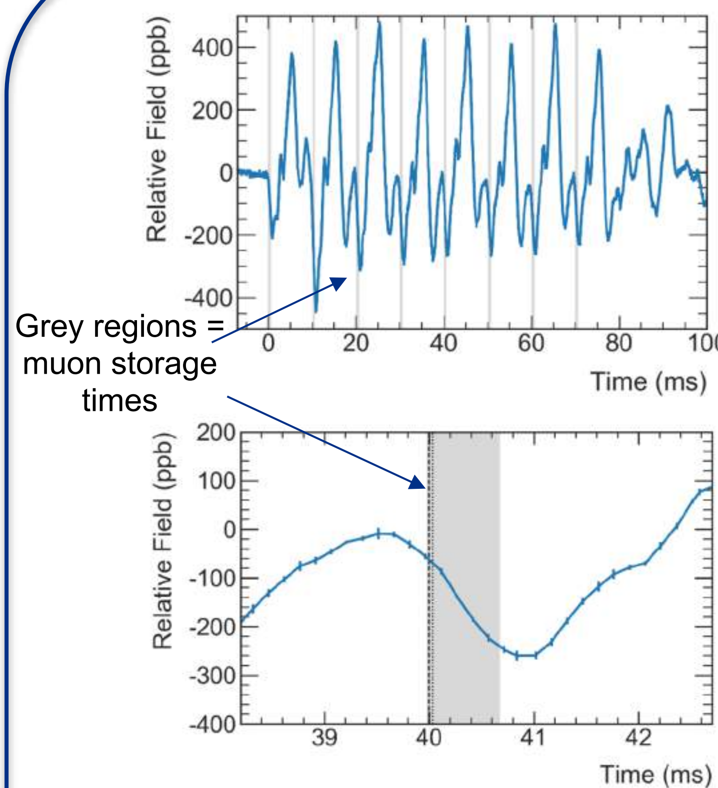
Transient fields

- 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

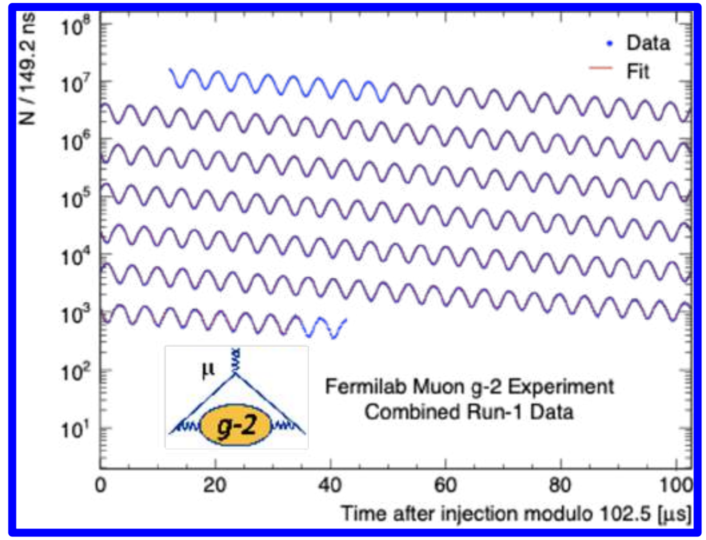
- Kicker pulse of 22 mT for 150 ns just after muon injection.
- Field change caused by residual field after kicker pulse. Muons present from 30μs to 700μs after the kick (fit region)
- Kicker correction: -27 (37) ppb

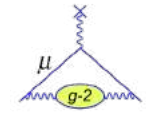


Quad

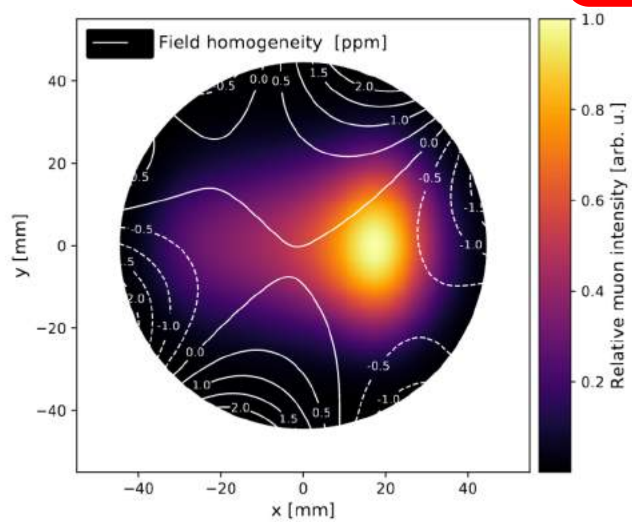
- Measured with a dedicated in-vacuum NMR probe located between quad plates during pulsing
- Quad correction: -17 (92) ppb

Bringing it all together





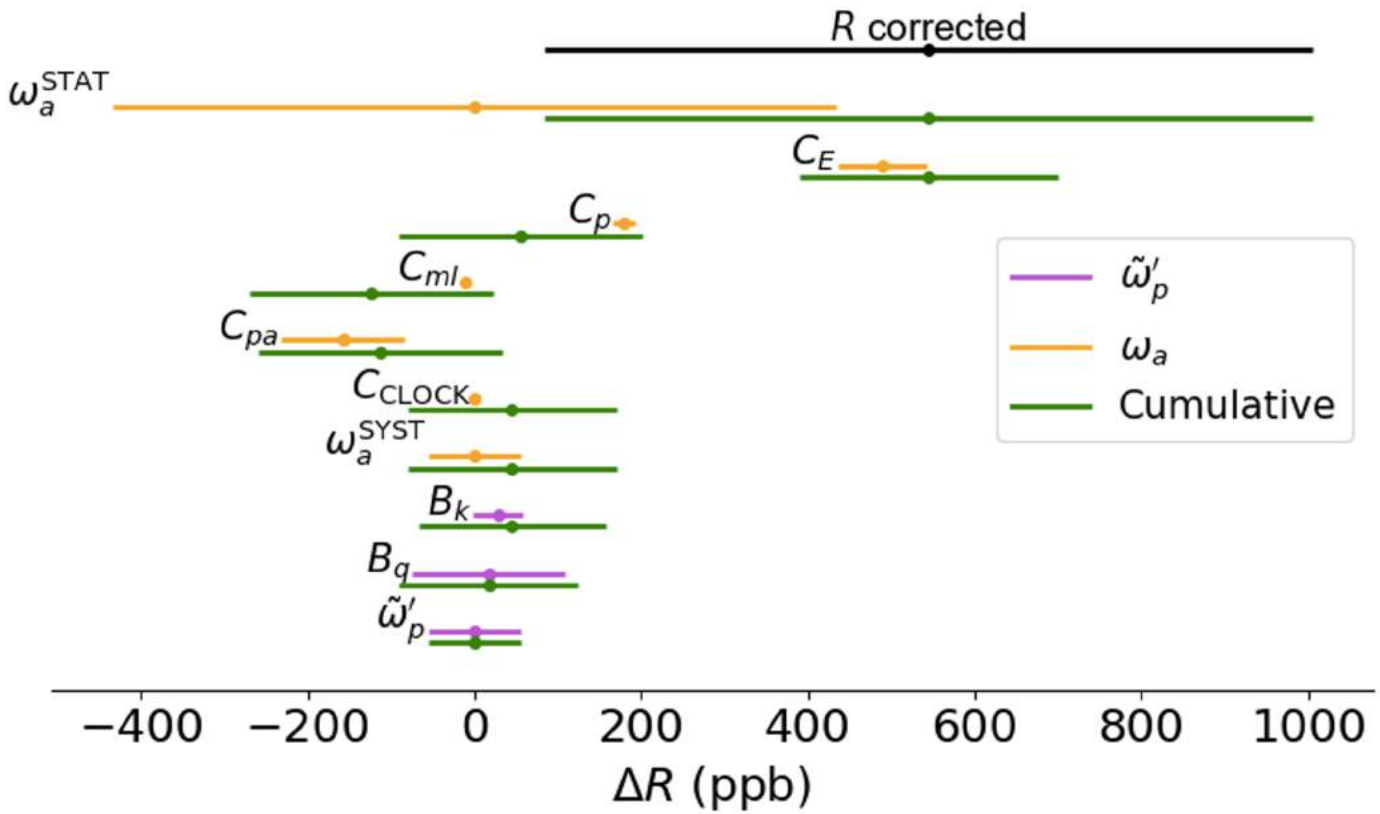
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\rm clock}\ \omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\rm calib}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$



Corrections

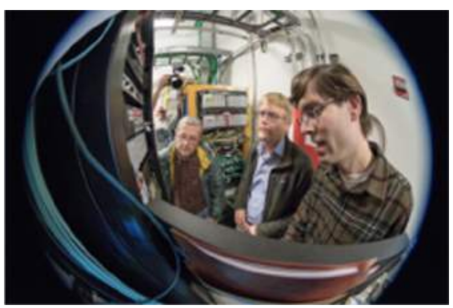
Correcting Measured R

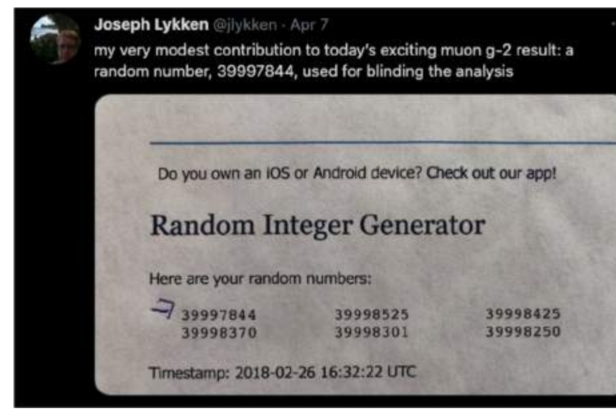
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m \left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle \left(1 + B_k + B_q\right)}$$



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

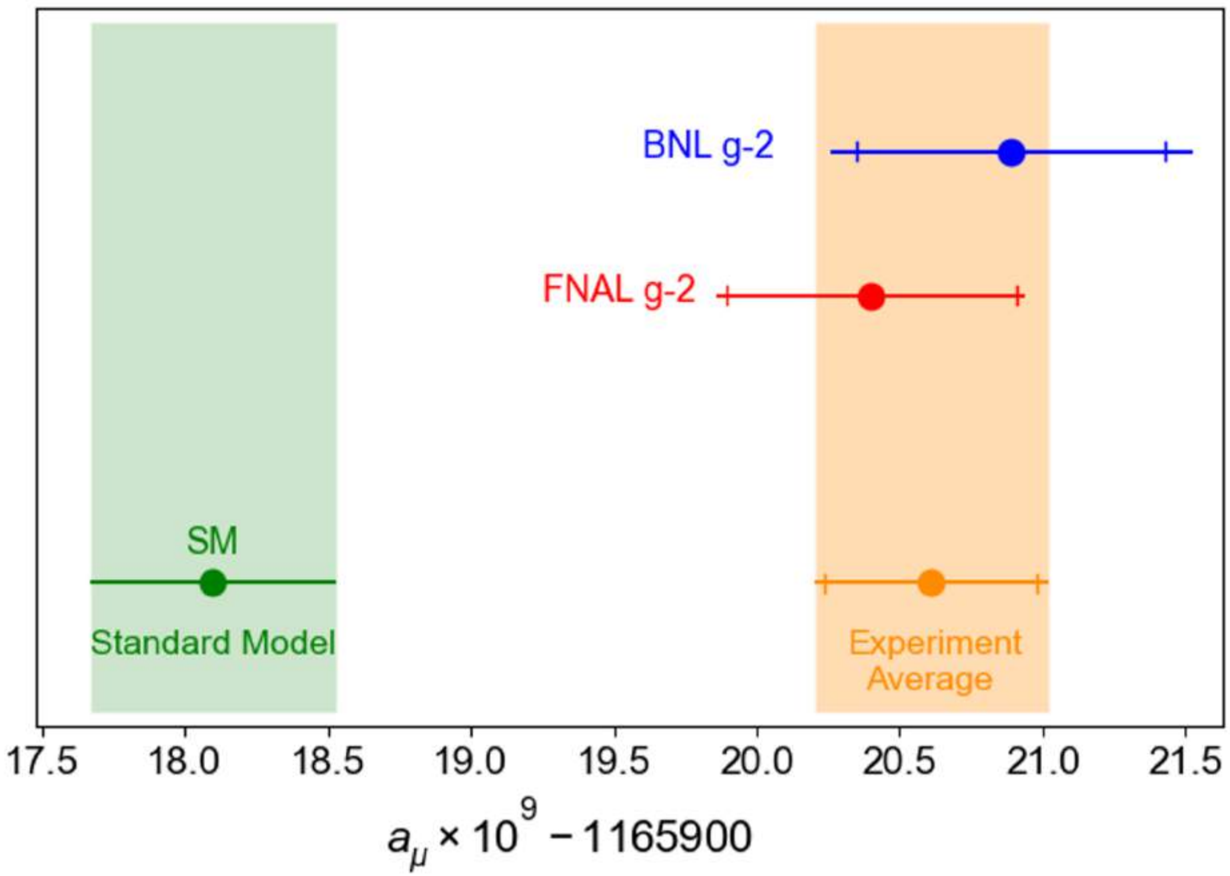
Here are your random numbers:

39997844	39998525	39998425
39998370	39998301	39998250

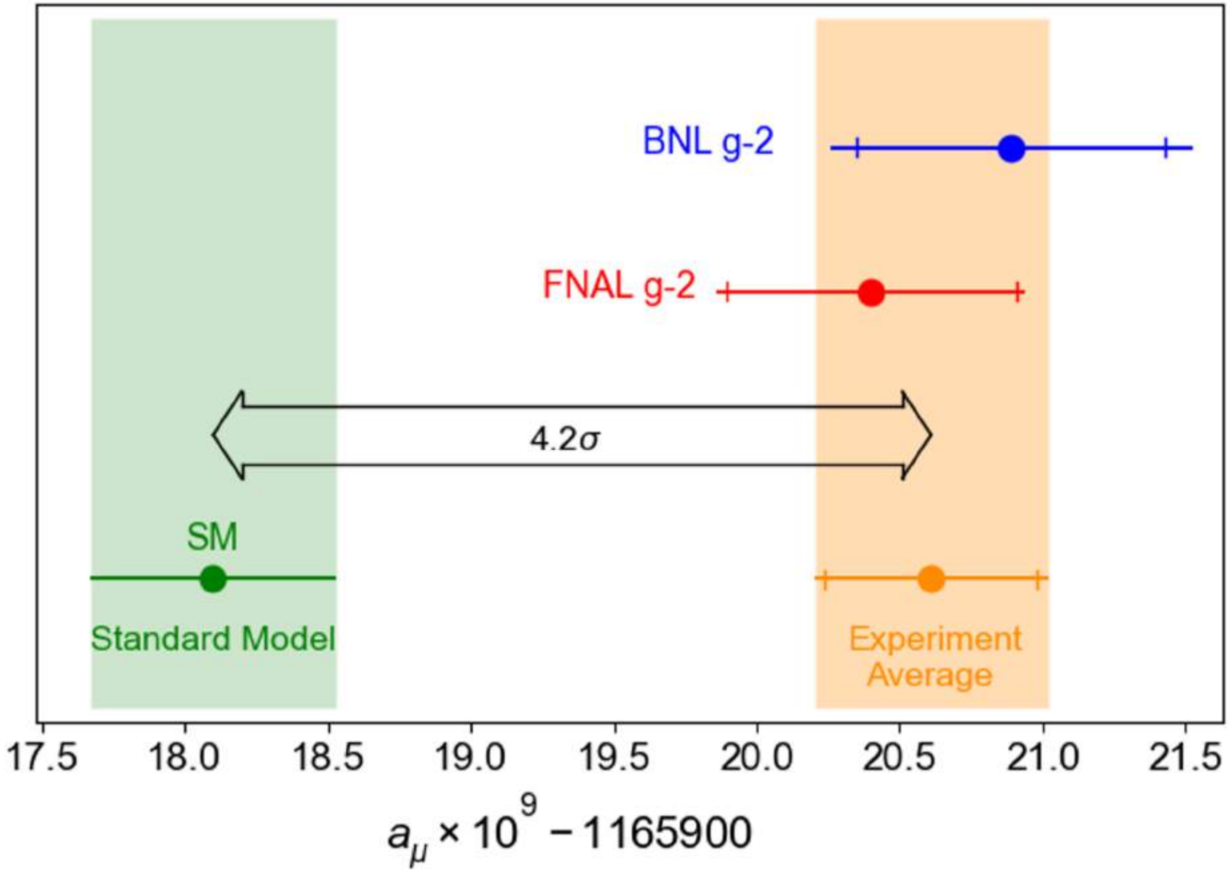
Timestamp: 2018-02-26 16:32:22 UTC

- Additionally each analysis is blinded in software

Unblinded result

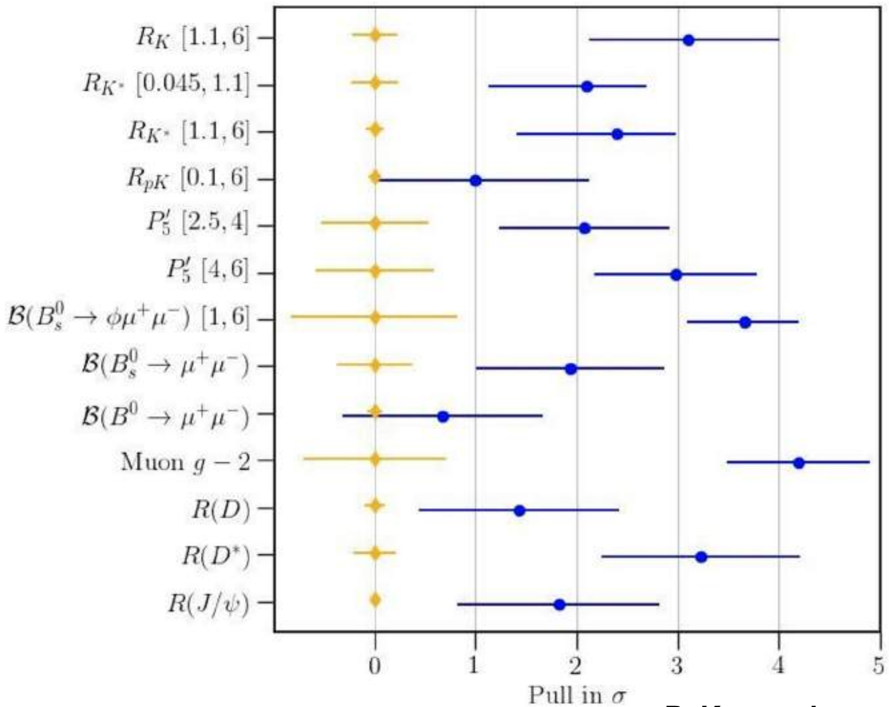


Unblinded result

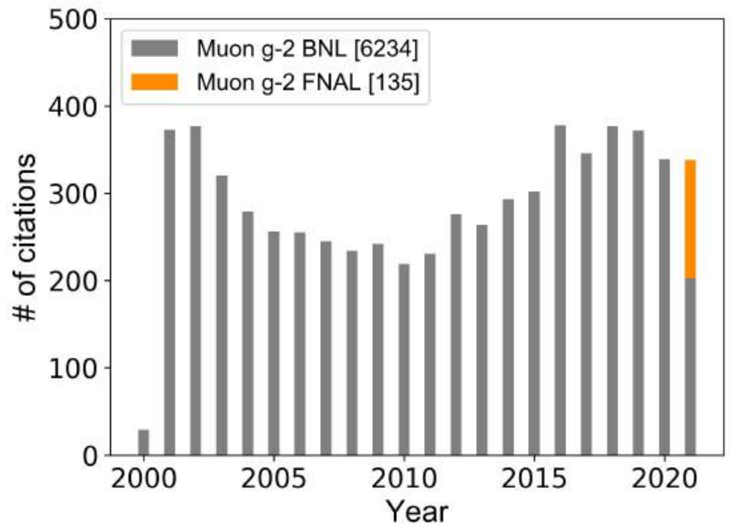


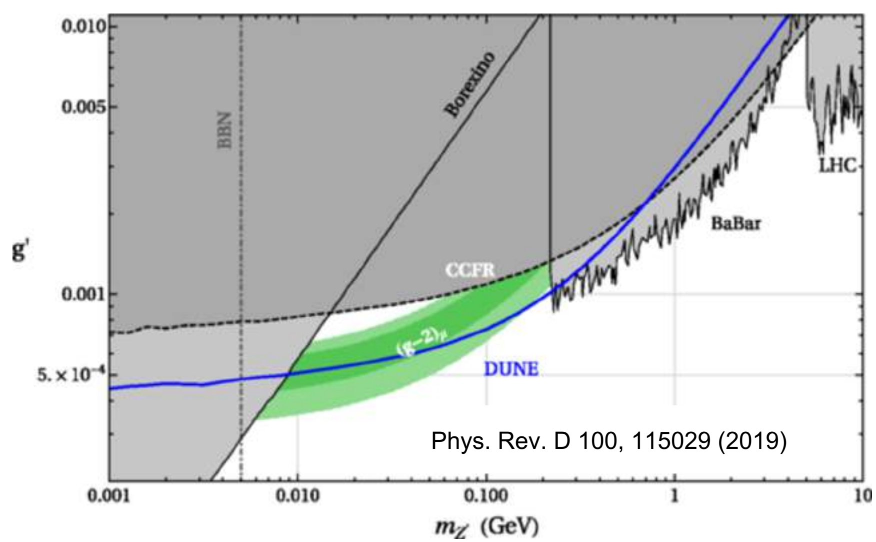
Interpretation

Needs more precision



P. Koppenberg



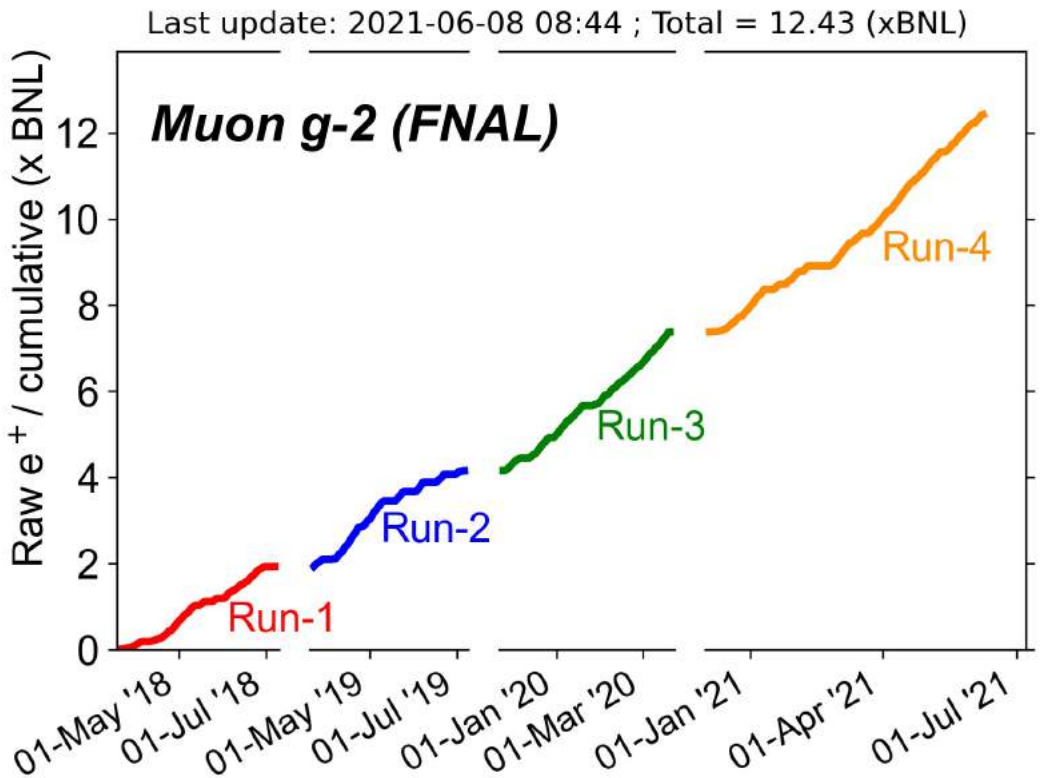


Phys. Rev. D 100, 115029 (2019)

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
- 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

Science and Technology Facilities Council

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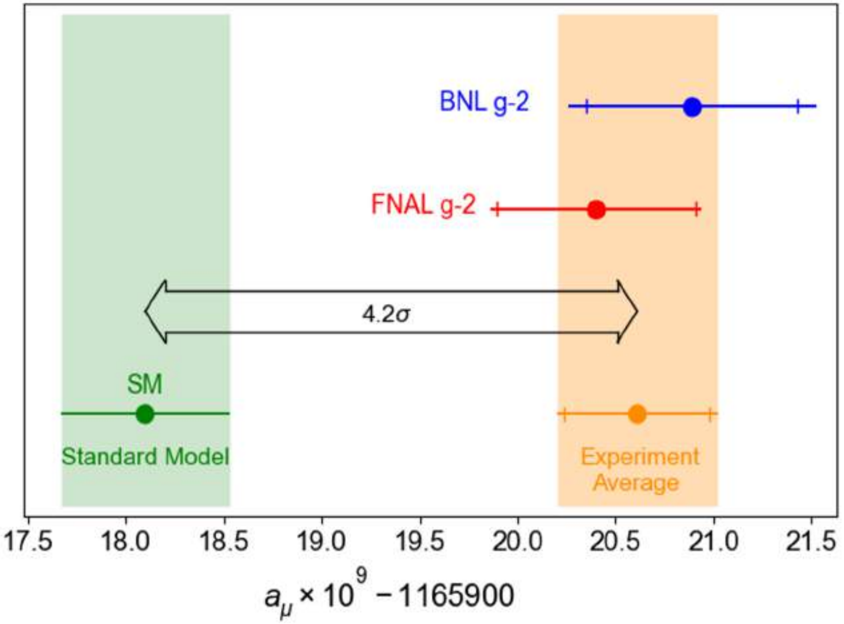
Horizon 2020



- 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: *arXiv:2104.03240 (2021)*

- Muon g-2 Theory Initiative (all contributions within): *Phys.Rept. 887 (2020) 1-166*, *https://muon-gm2-theory.illinois.edu/white-paper/*
- HVP/HLbL Plots: *Aida X. El-Khadra, First results from the Muon g-2 experiment at Fermilab (2021)*
- BMW Lattice HVP (2021): *Nature (2021)*
- Mainz HLbL: *arXiv:2104.02632 (2021)*
- BNL Final: *Phys.Rev.D 73 (2006) 072003*
- Dune/g-2 *Z'* sensitivity: *Phys. Rev. D 100 (2019) 115029*
- BSM g-2: *arXiv:2104.03691 (2021)*