The g-2 experiment at Fermilab, and MuonE at CERN

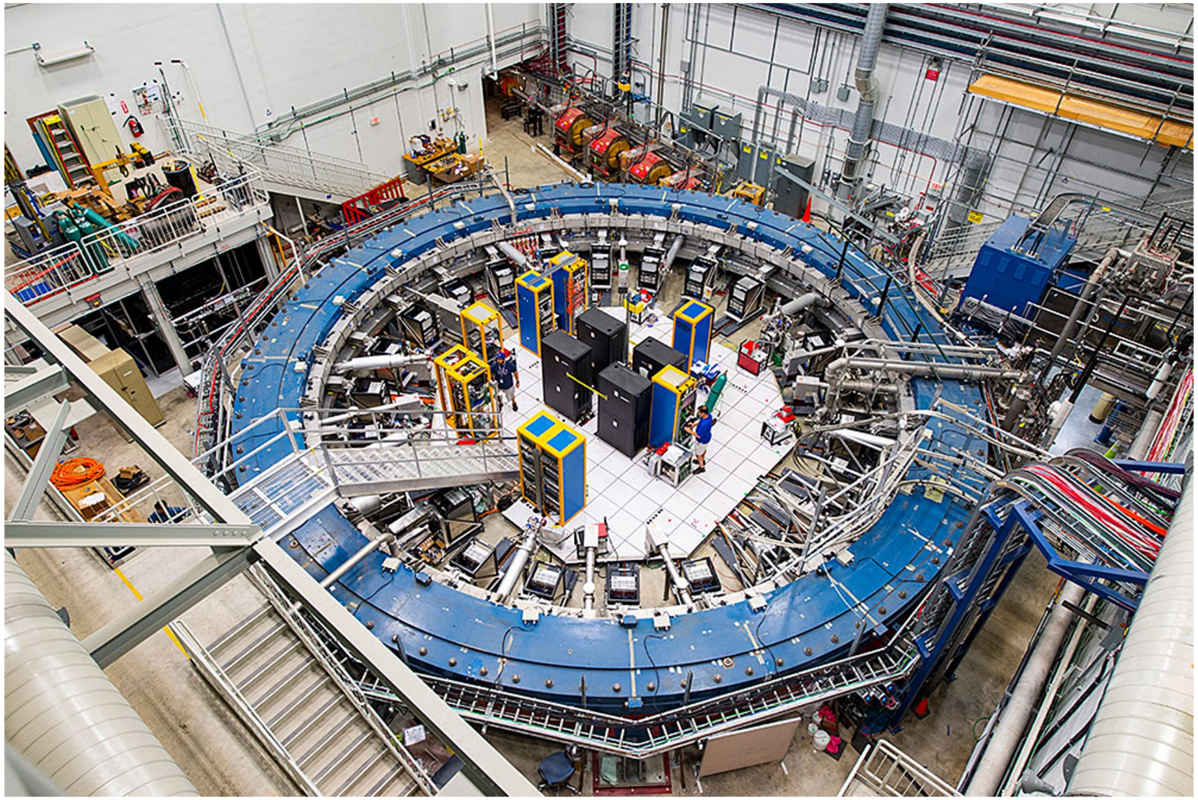
Joe Price

on behalf of the g-2 and MuonE experiment s

Fermilab

UNIVERSITY OF LIVERPOOL

The Fermilab Muon g-2 Experiment



Measurement Principle

- Inject polarised muon beam into magnetic storage ring
- Measure difference between spin precession and cyclotron frequencies
- If g = 2, $\omega_a = 0$
- g ≠ 2, $\omega_a \propto a_\mu$

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

$T_s \approx 138$ns $T_c \approx 149$ns

Spin precession freq.

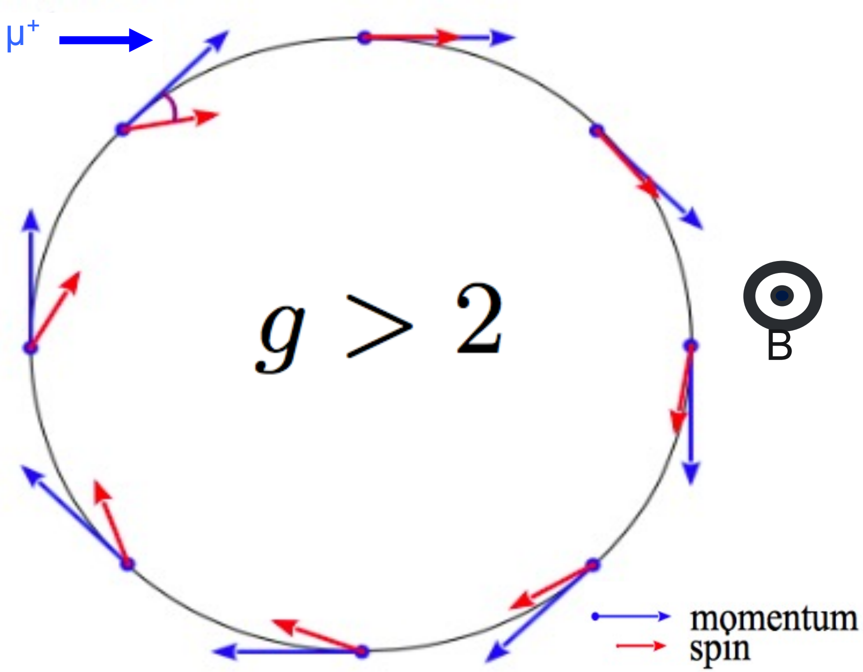
$$\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

Larmor precession

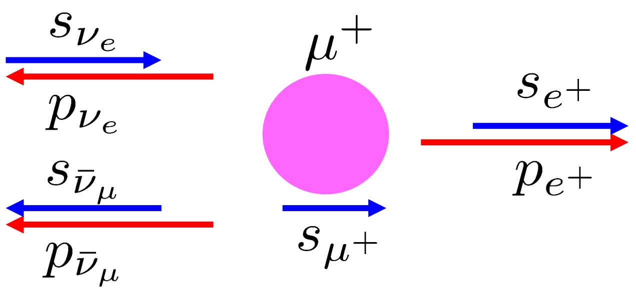
Thomas precession

Cyclotron freq.

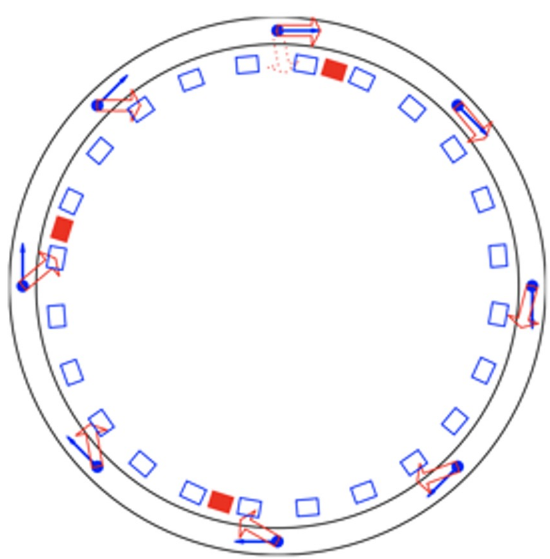
$$\omega_c = \frac{eB}{\gamma mc}$$

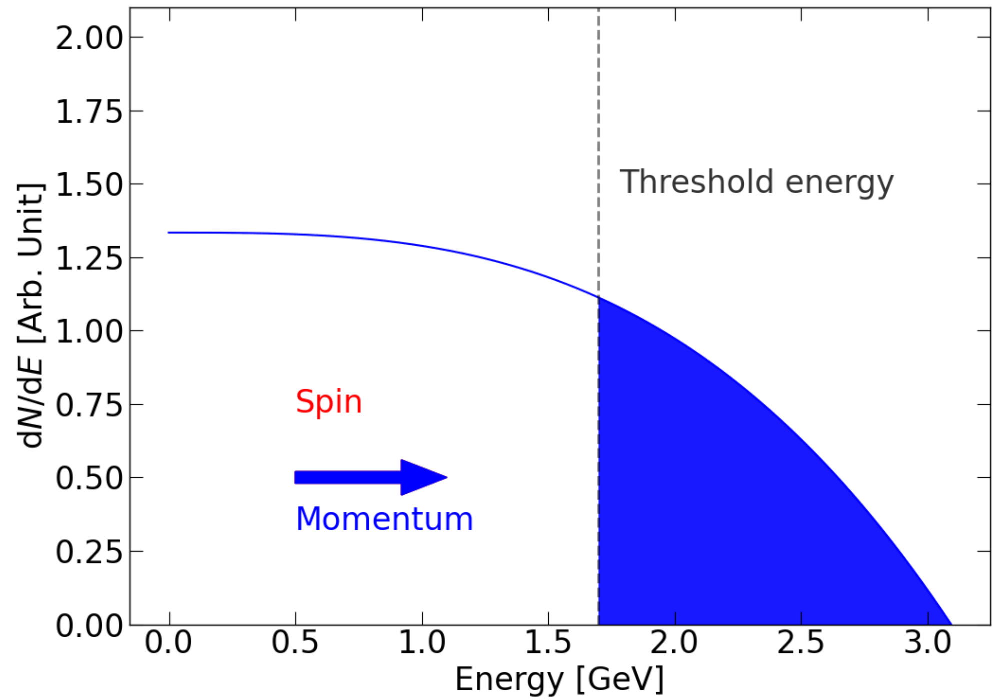


Measuring ω_a



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





Simply measure the time and energy of decay positrons and count the number above an energy threshold

Measurement Components

The experiment actually measures two frequencies

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

3ppb

0.0003ppb

22ppb

What we measure

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

Unblinding conversion factor

Measured precession frequency

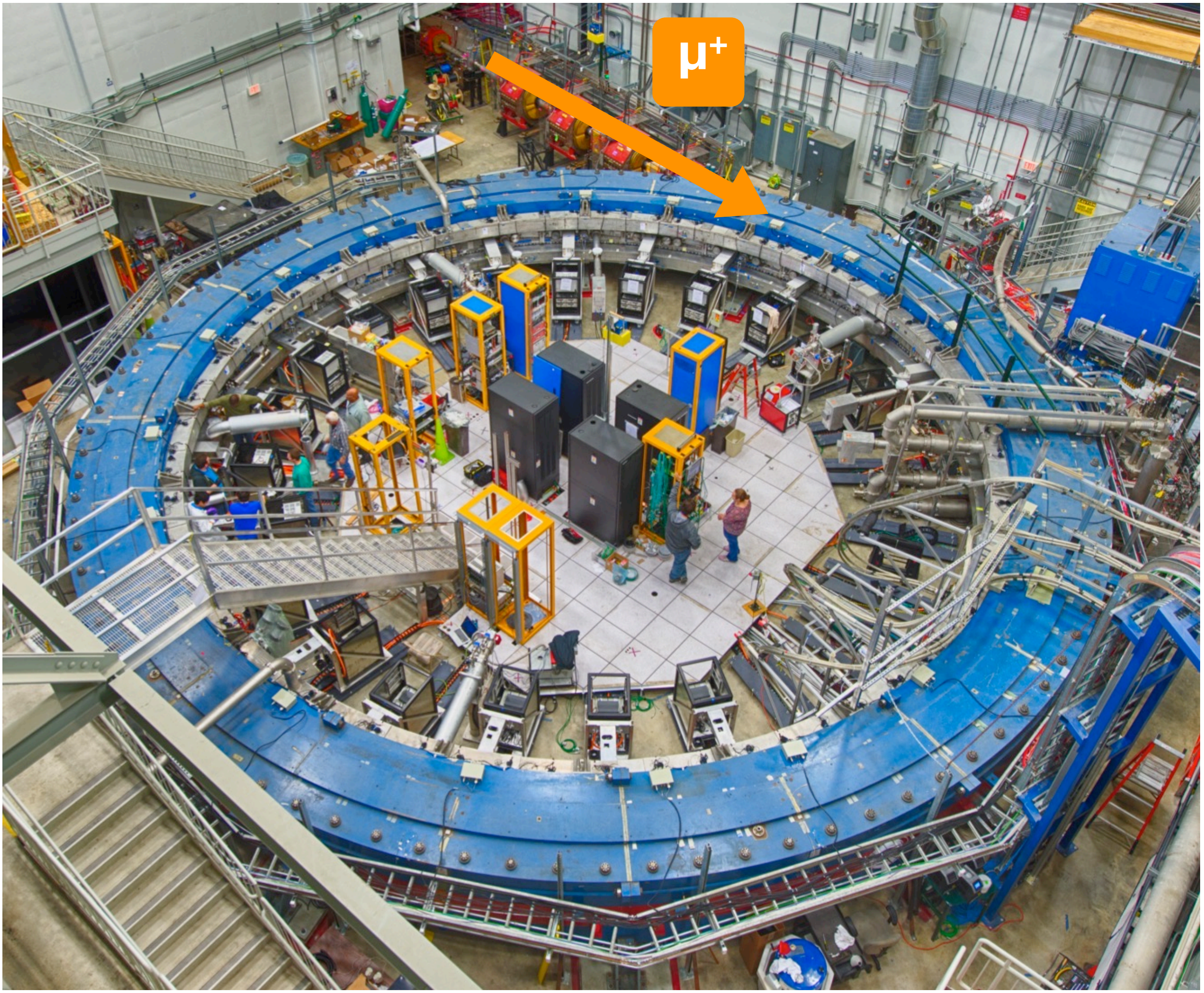
Corrections from beam dynamics systematic effects

NMR probe calibration factor

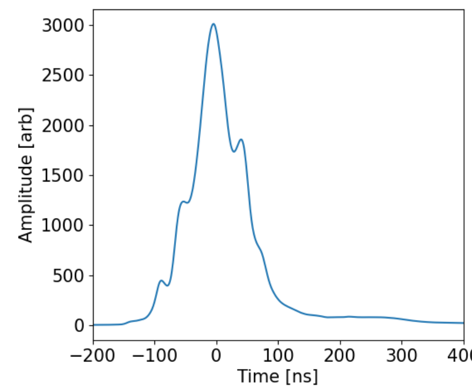
Magnetic field weighted over the muon distribution and azimuthally averaged

Corrections from the transient magnetic field

Beam injection

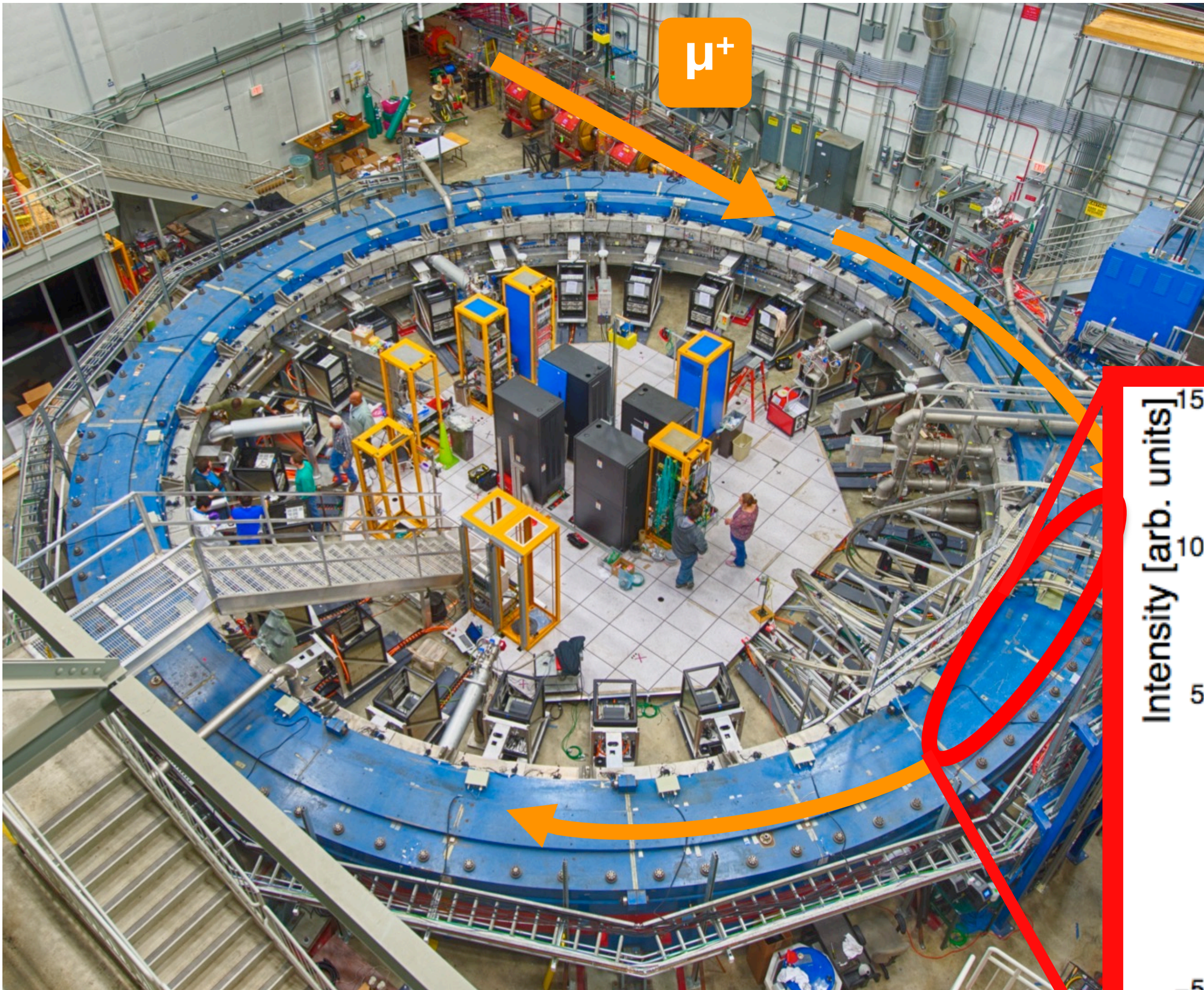


- Monitor beam profile before entrance with scintillating X and Y fibres
- Get time profile of beam using scintillating pad
- ~125ns wide

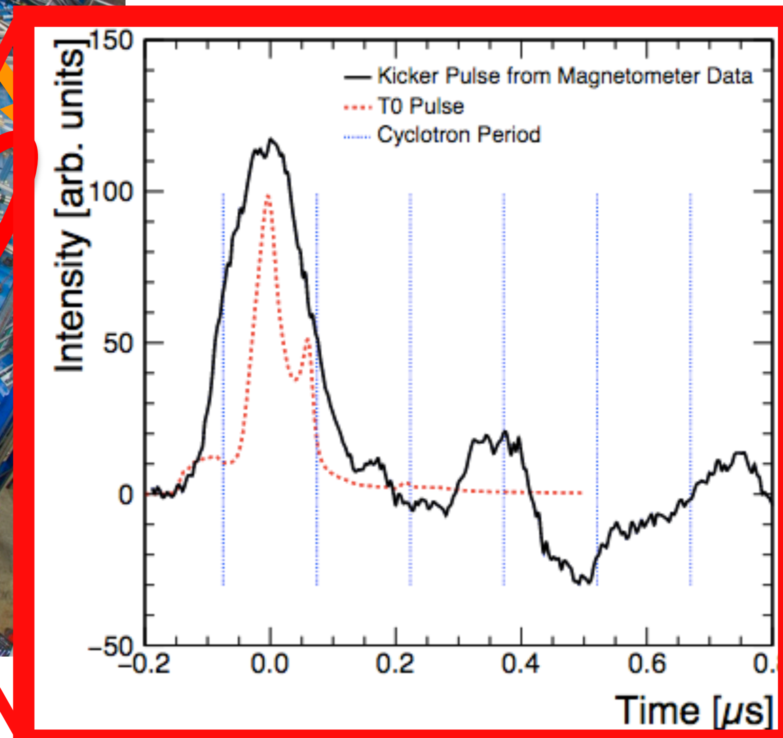


- Cancel B-field during injection using Inflector, so muons can get into the ring

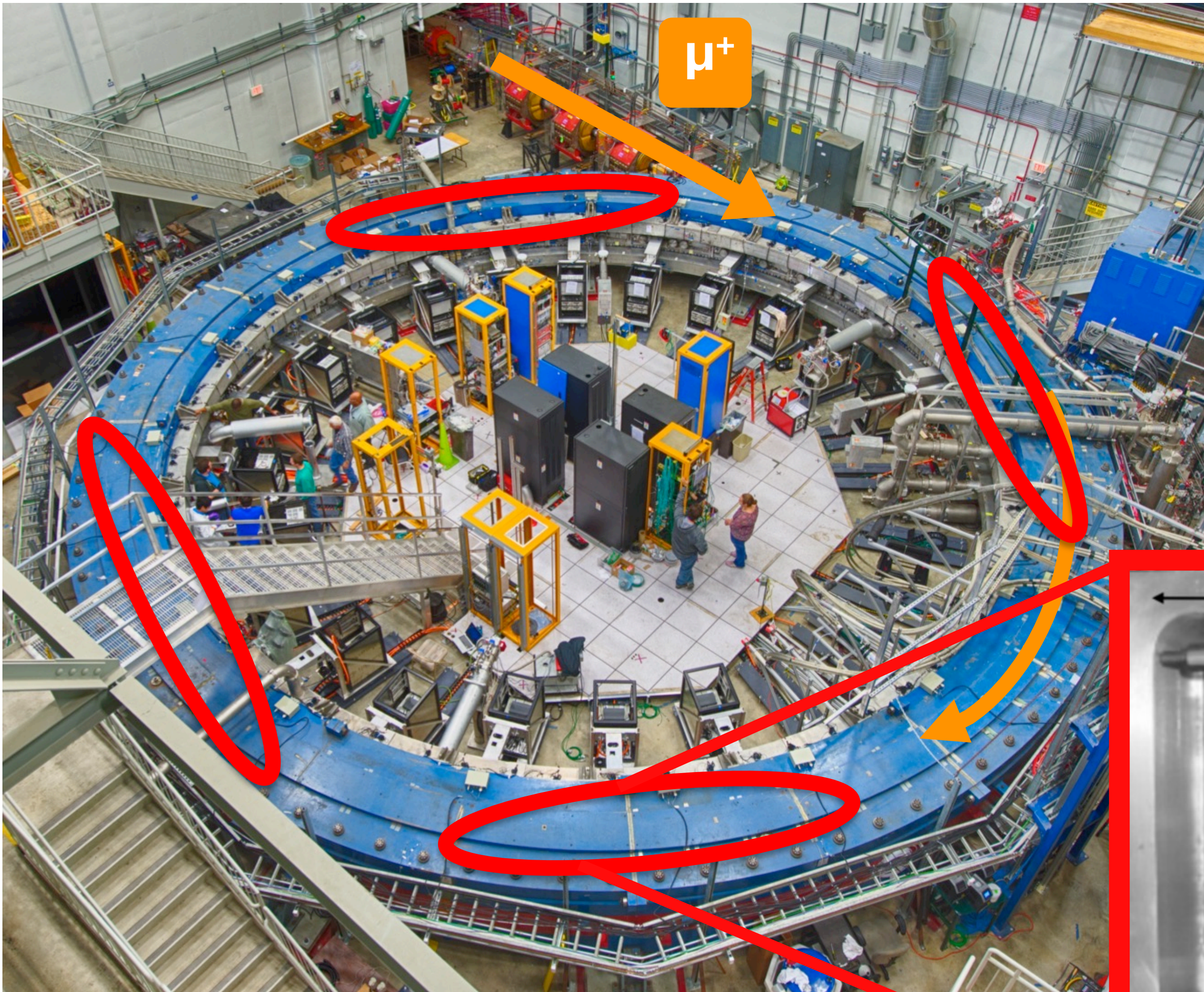
‘Kick’ onto correct orbit



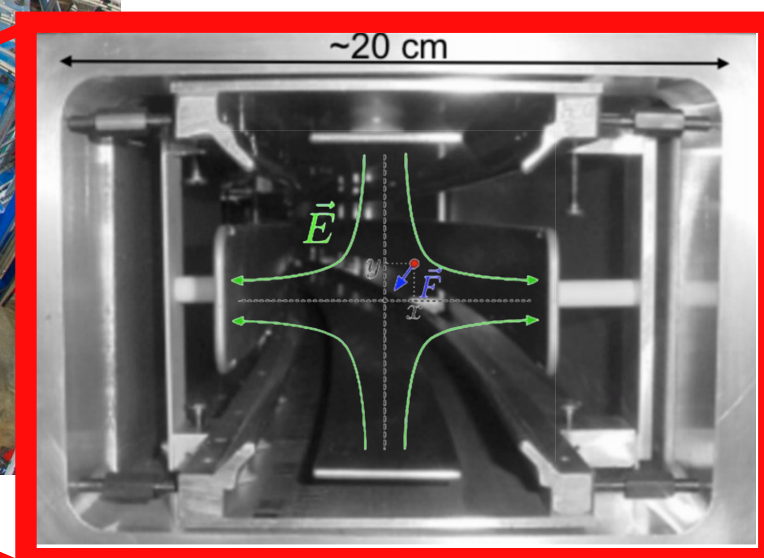
- After Inflector muons are 77mm away from ideal radius
- Apply short magnetic pulse to ‘kick’ muons onto the correct orbit



Beam focusing



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



Additional considerations

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

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

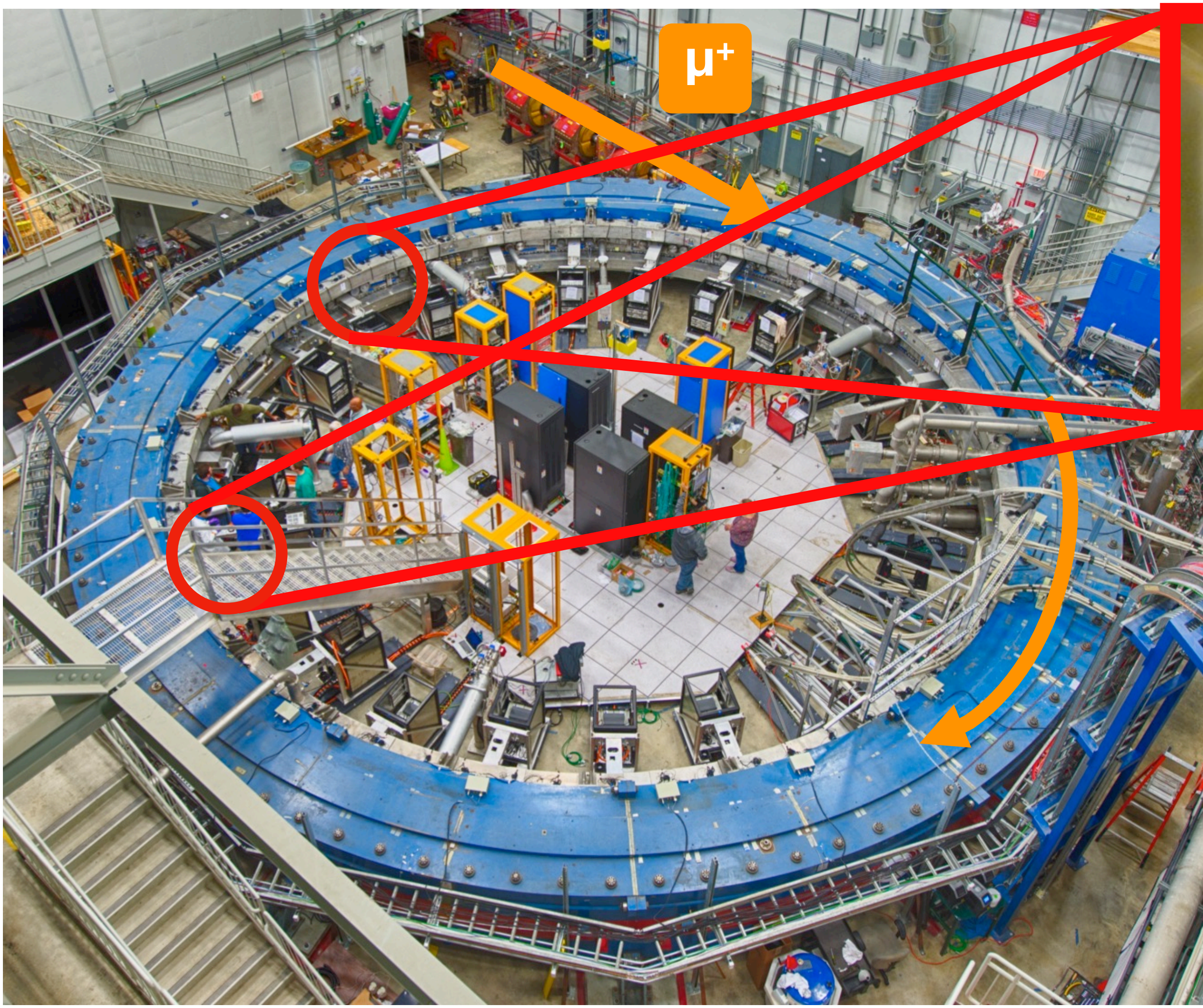
- This introduces 2 additional terms reducing the precession frequency
- We can minimise the first by choosing γ = 29.3 to give p_μ = 3.1GeV
- For a 1.45T field, this sets the radius of the ring to 7.11m
- However we now have 2 corrections to make to a_μ because:

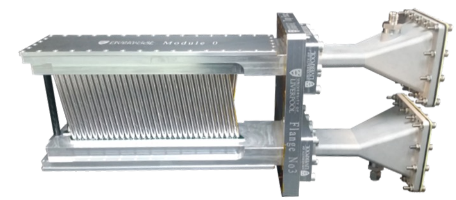
Not all muons are at the 'magic' momentum of 3.1GeV — E-field correction $C_E = \frac{\Delta\omega_a}{\omega_a}$

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

Tracking Detectors





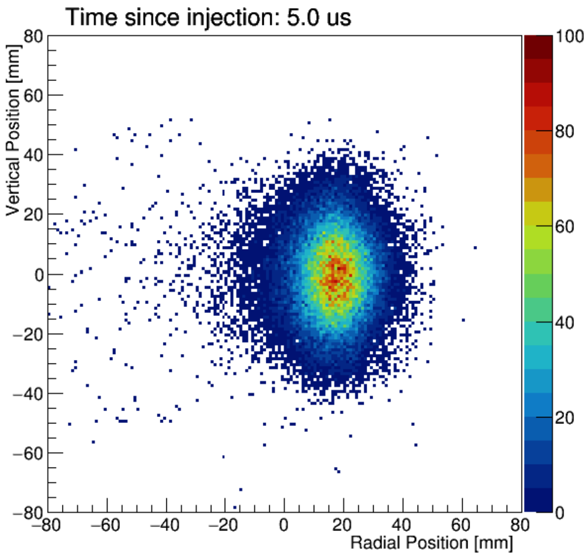
2 Tracking stations

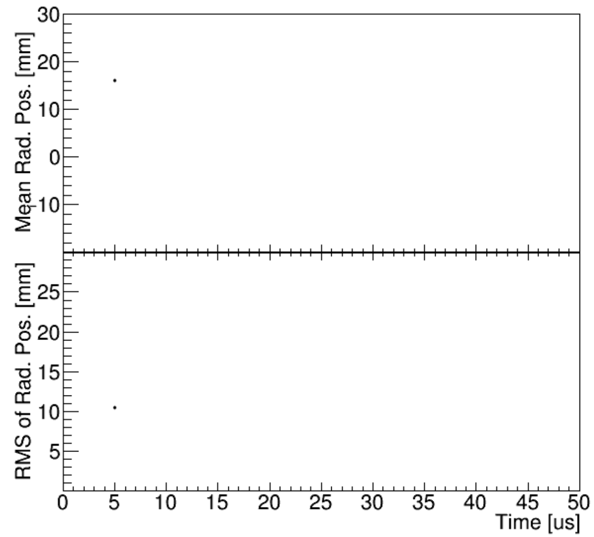
Each contain 8 modules

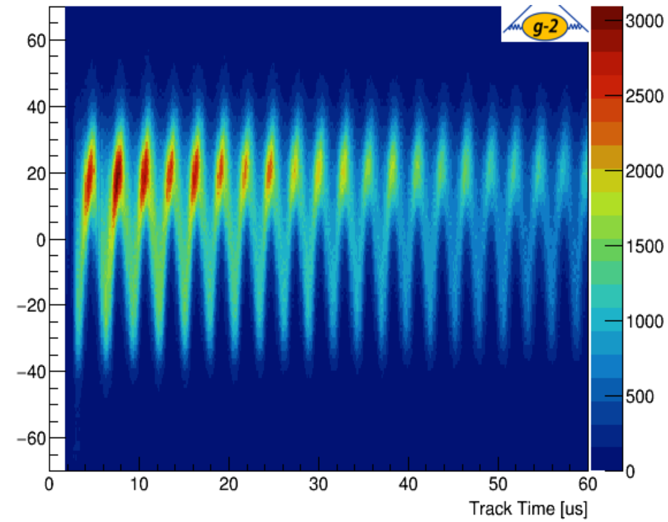
128 gas filled straws in each module

Traceback positrons to their decay point

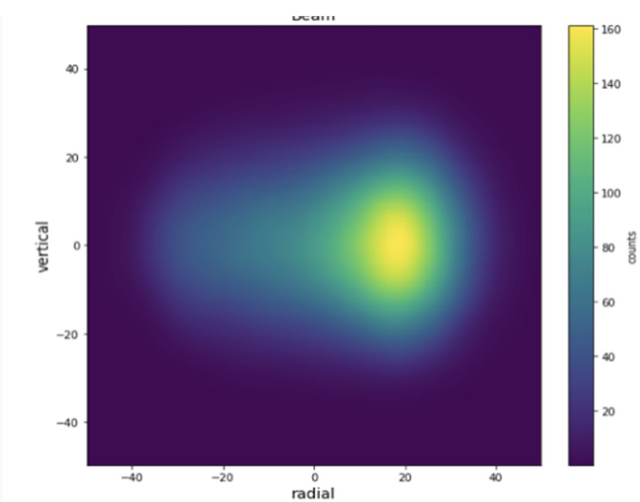
Beam Measurements





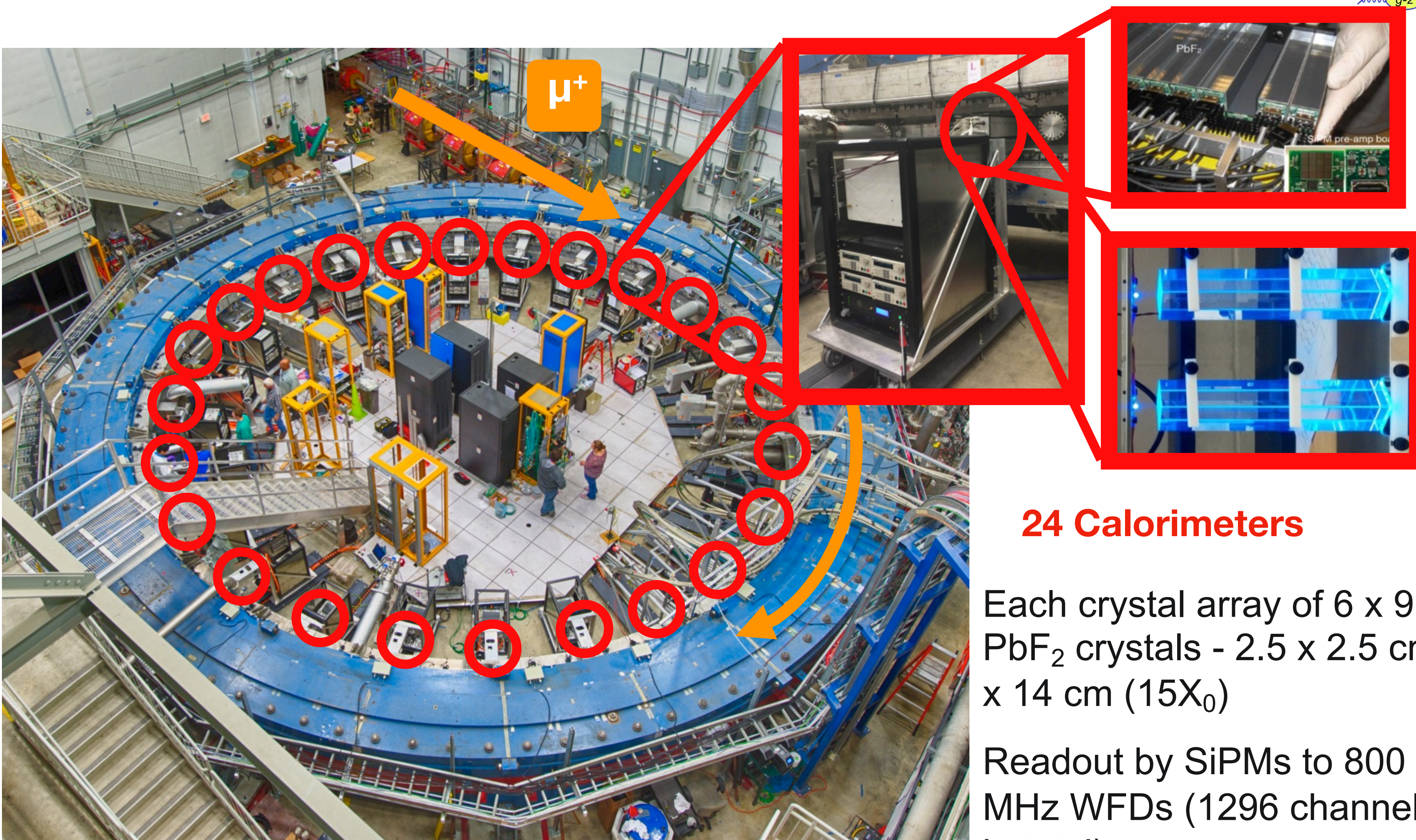


Run 1: slightly under kicked



- 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

Calorimeters

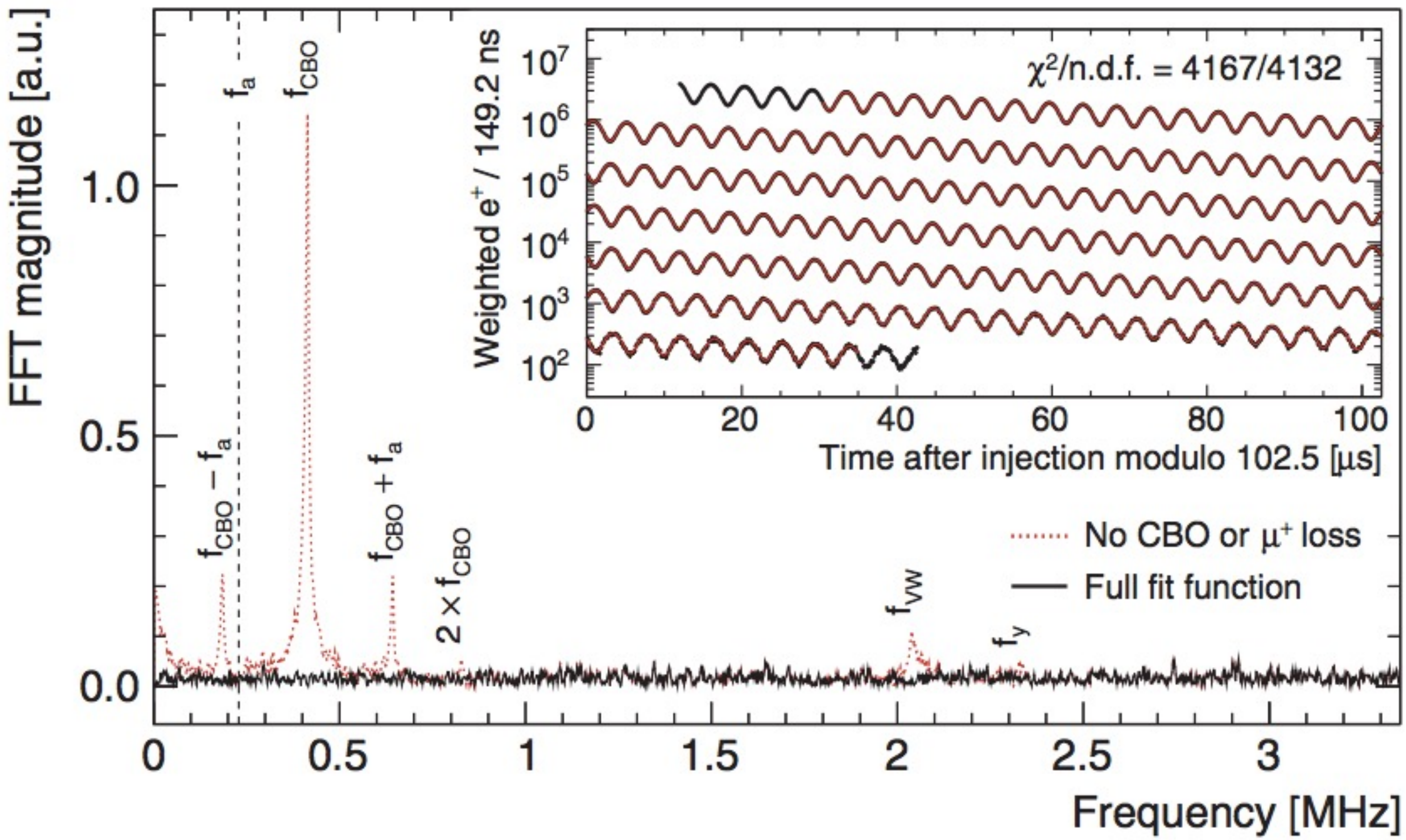


24 Calorimeters

Each crystal array of 6 x 9 PbF_2 crystals - 2.5 x 2.5 cm^2 x 14 cm ($15X_0$)

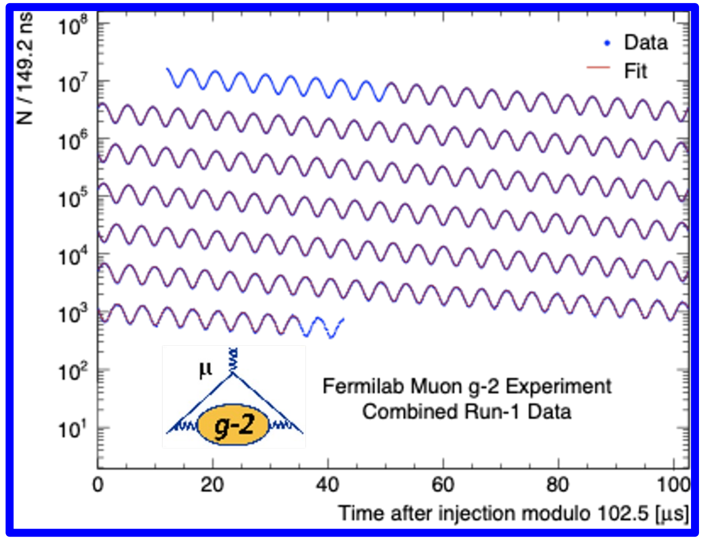
Readout by SiPMs to 800 MHz WFDs (1296 channels in total)

Fitting ω_a



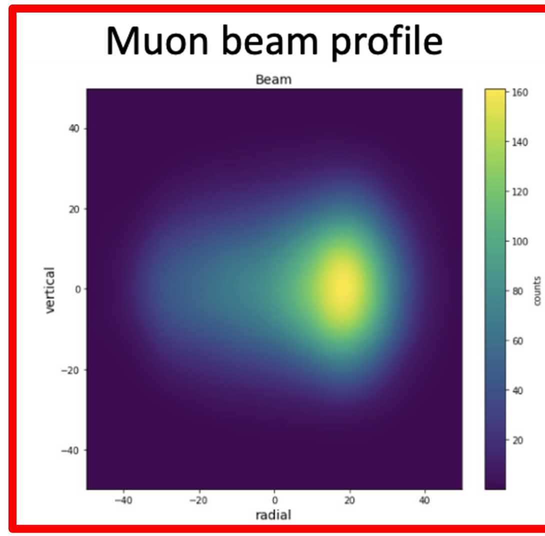
- Beam frequencies show up in the residuals of a simple 5 parameter fit, and are accounted for in the final 24 parameter fit

Field measurement



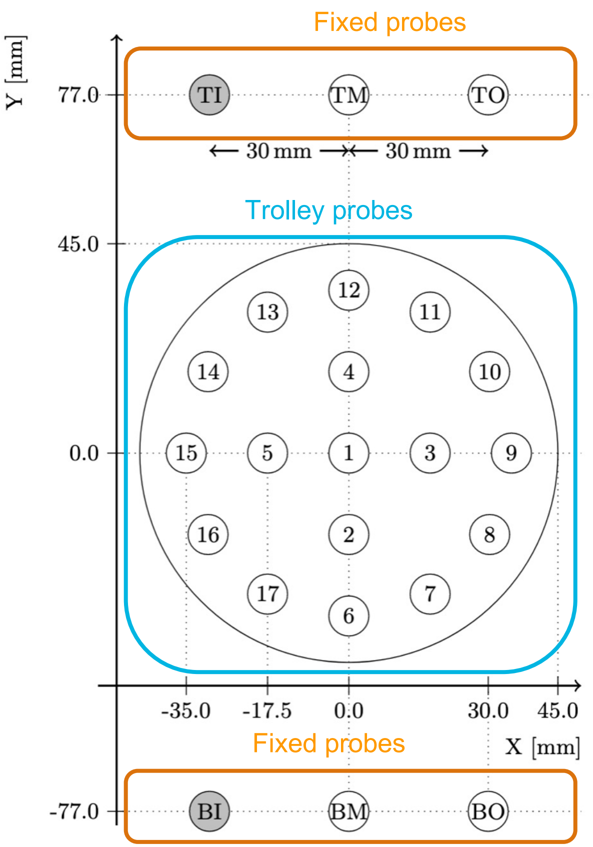
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\ (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle\omega_p(x,y,\phi) \times M(x,y,\phi)\rangle(1 + B_k + B_q)}$$

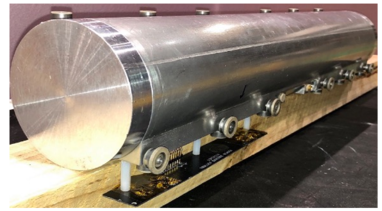
Measuring the magnetic field

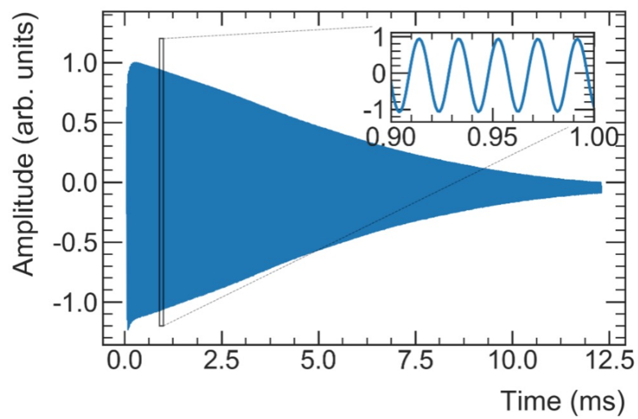


Measuring the field: the NMR Trolley

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

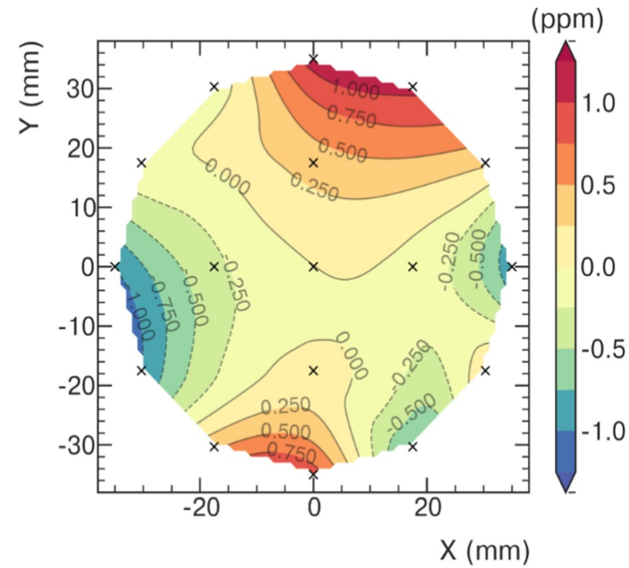






Field measured by extracting frequency from a Free Induction Decay (FID) spectrum

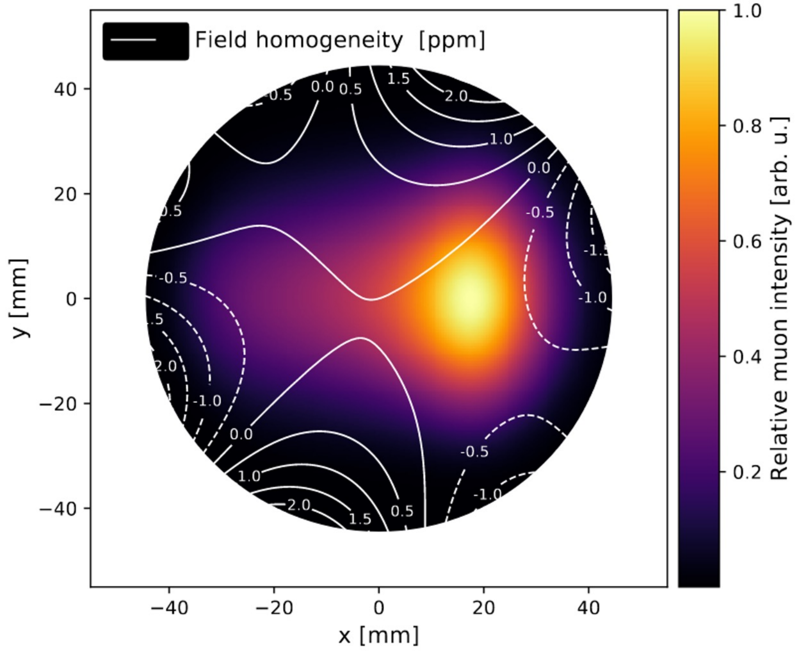
Field gradients in an azimuthal "slice"



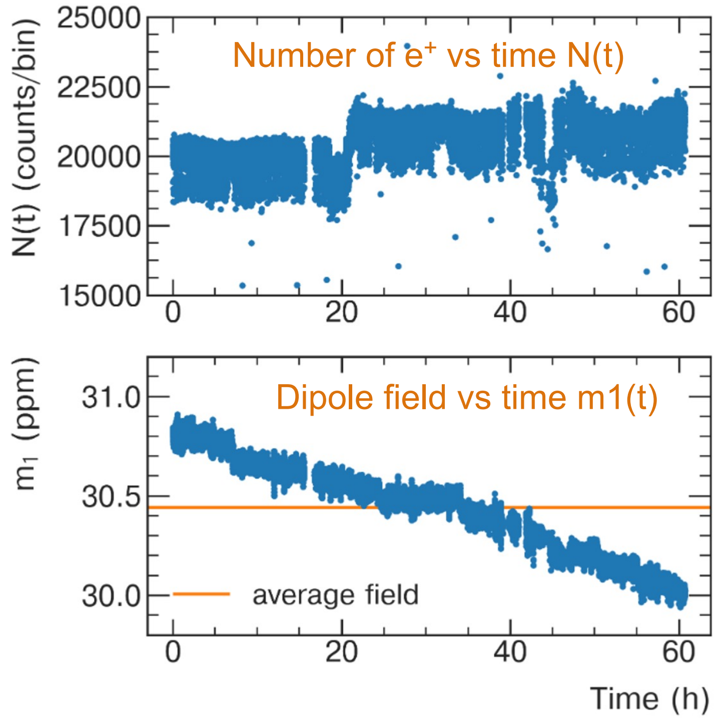
At ~8000 azimuthal locations, obtain a field contour plot from the 17 probes

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

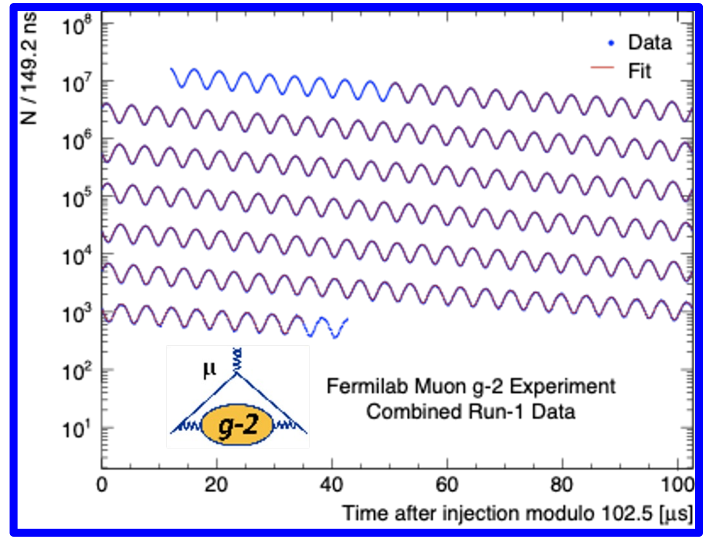


The field is weighted by the 2D beam distribution. An average beam distribution for every 3 hours is used.



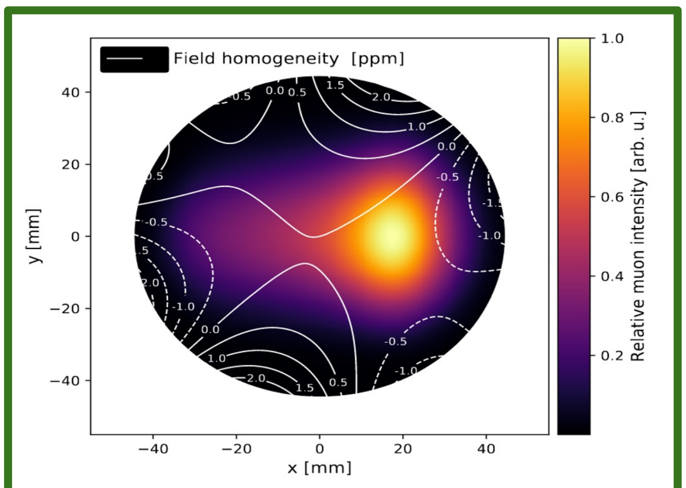
Measured field (every 1.7 s) is weighted by the number of detected e^+

Corrections

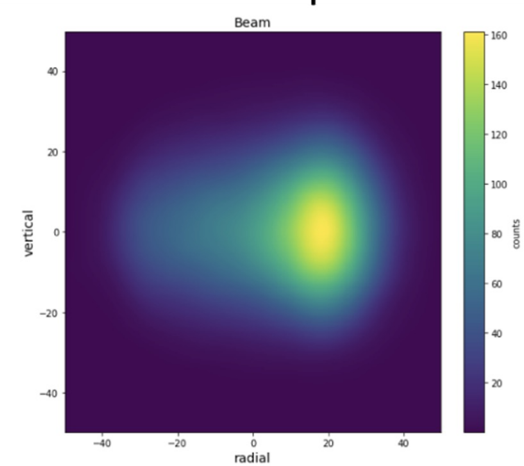


Beam Dynamics and Field Transient Corrections

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

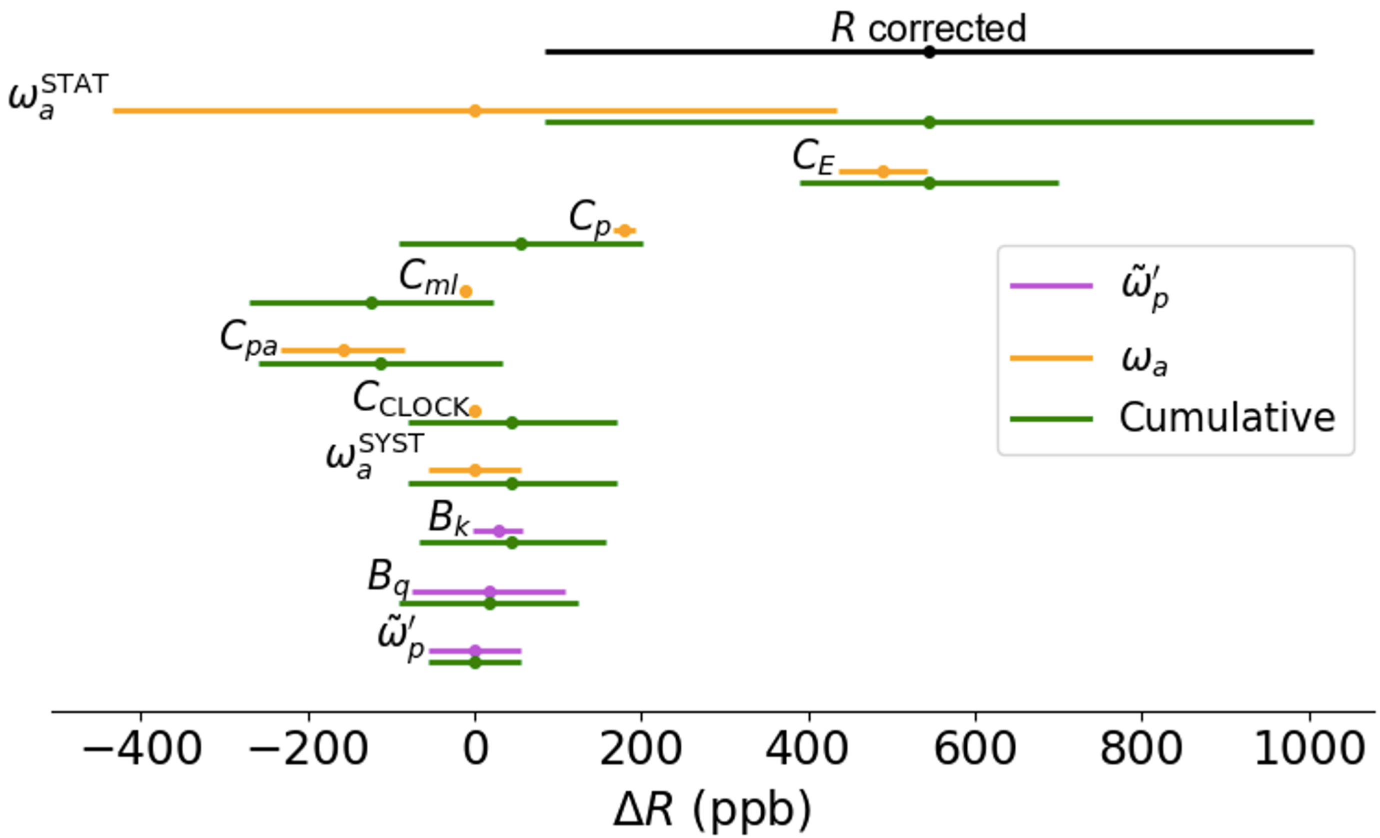


Muon beam profile

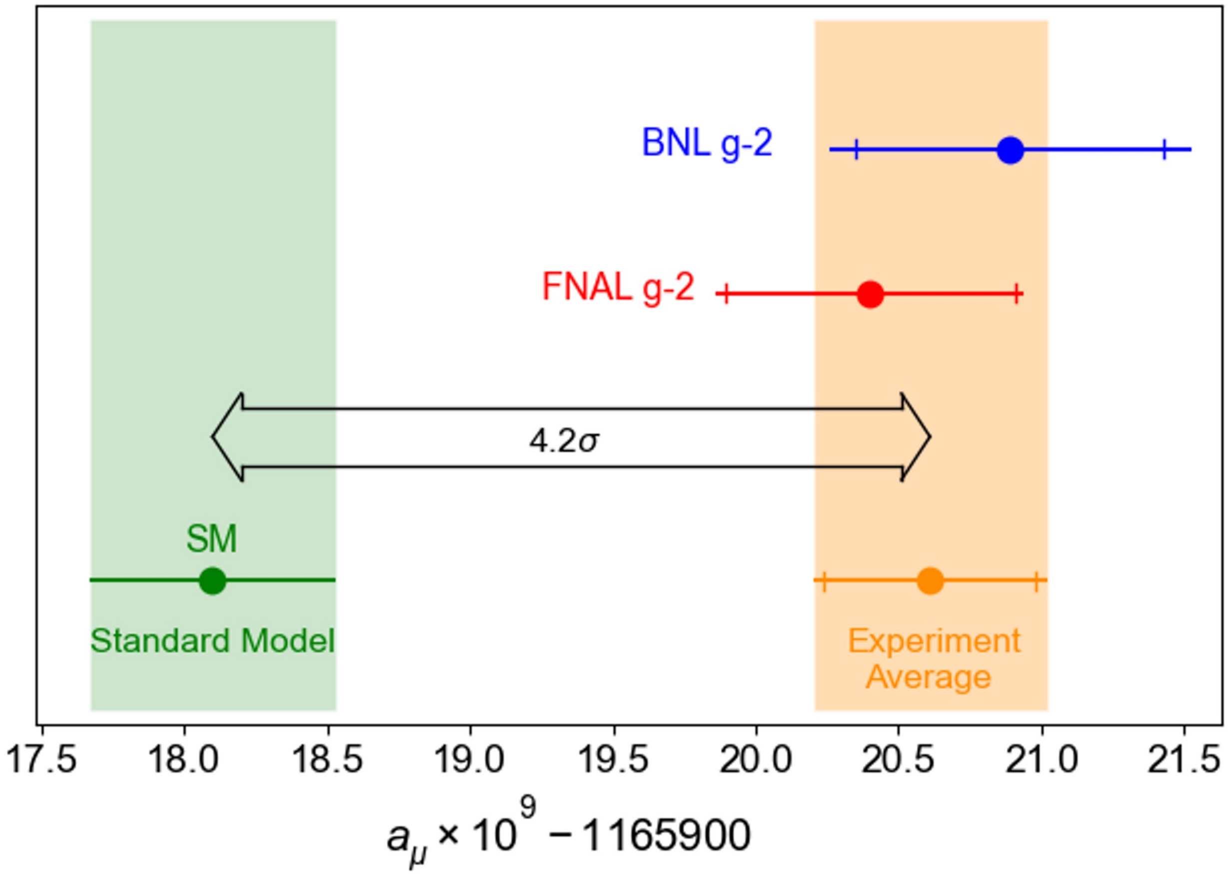


Correcting Measured R

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

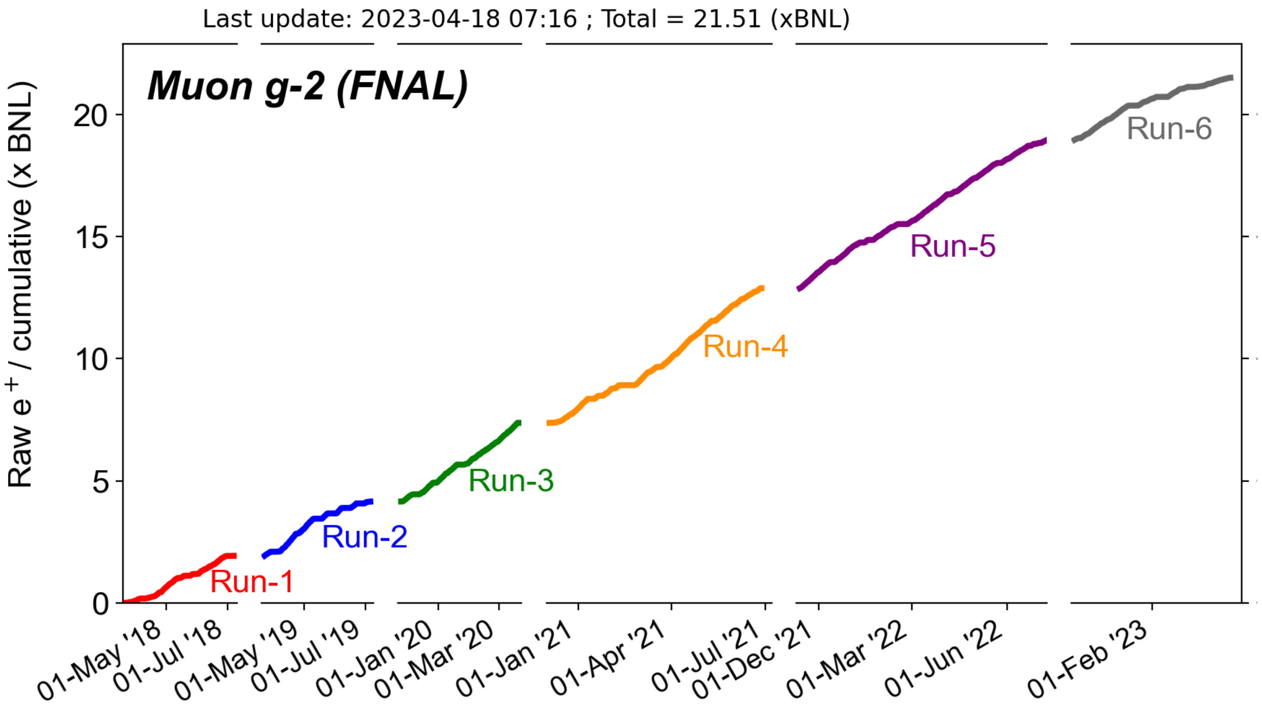


Unblinded result



Improvements for Run 2 onwards

- Quad resistors are fixed, so reduced C_{PA}, reduced muon losses, and can take longer measurements of B_q
- Full kick, muons on central orbit. Reduced C_E and δC_E
- Magnet insulation, so less field drift from temperature variations

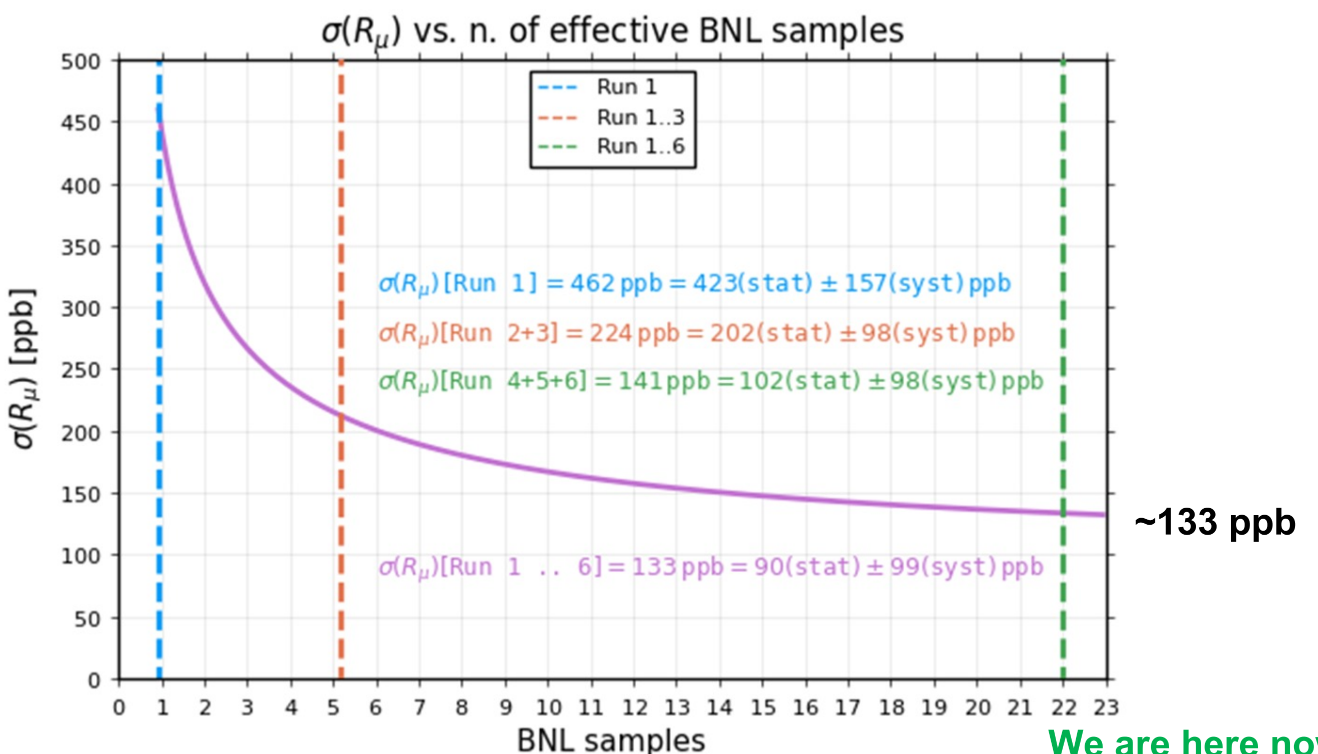


Where we are heading?

Final precision:	δa_μ = 140 ppb
Statistics	100 ppb
Precession systematics	70 ppb
Field systematics	70 ppb
Unknown	0 ppb

Trending towards

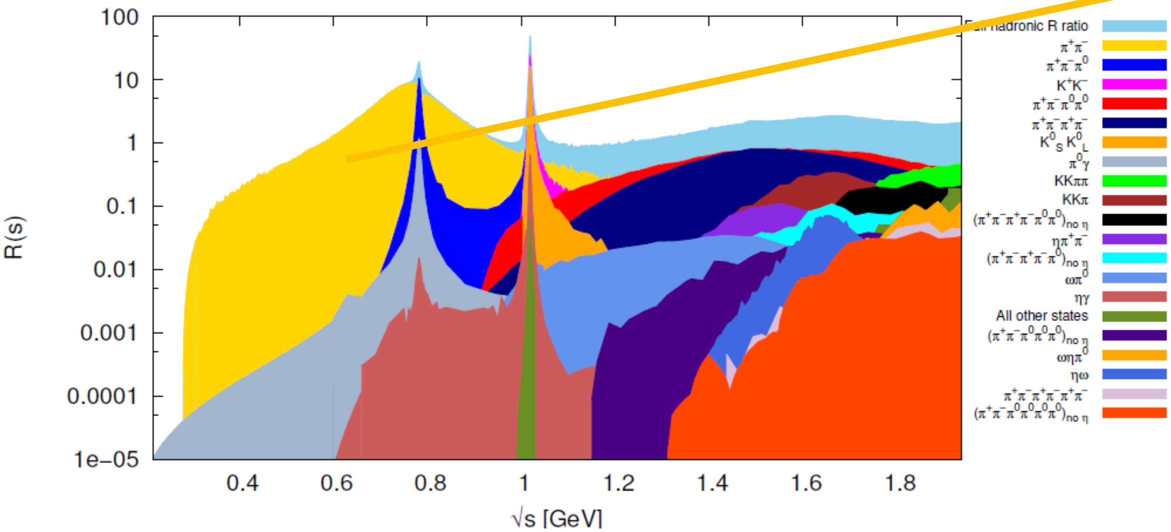
δa_μ = <140 ppb
<100 ppb
<<70 ppb
<<70 ppb
~50 ppb?

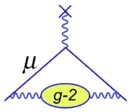


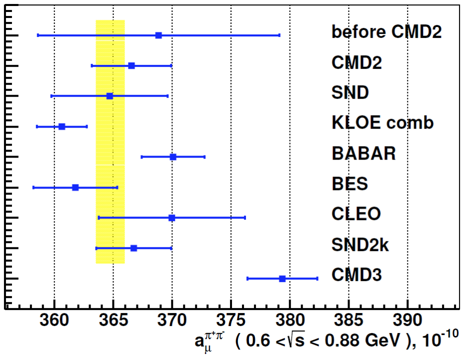
*Warning: until we look at the data, we can't be sure about final systematics, so this is just a good guess

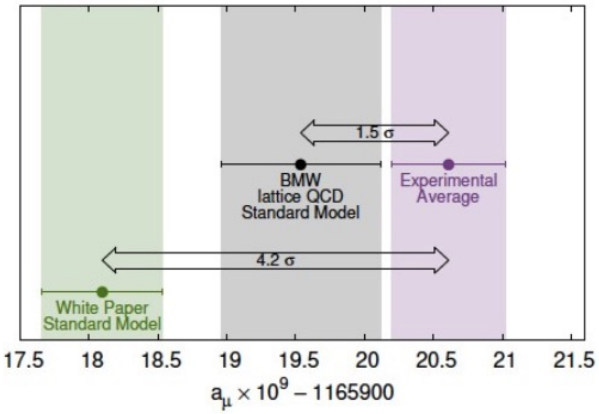
Slide courtesy of D. Hertzog

Theory calculation of a_μ^{HLO}



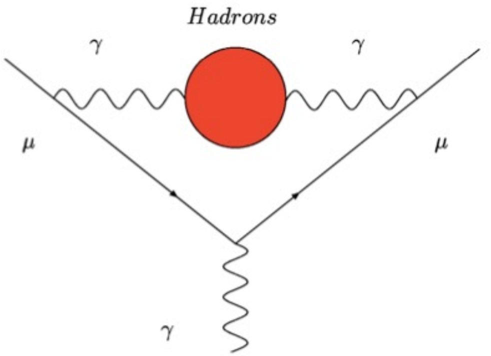






$$a_\mu^{\text{had,LO}} = \frac{\alpha^2(0)}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \text{muons})}$$



To get leading order hadronic contribution to g-2

- Data from e^+e^- scattering experiments
- Calculate on Lattice

Some tension between the 2 methods!

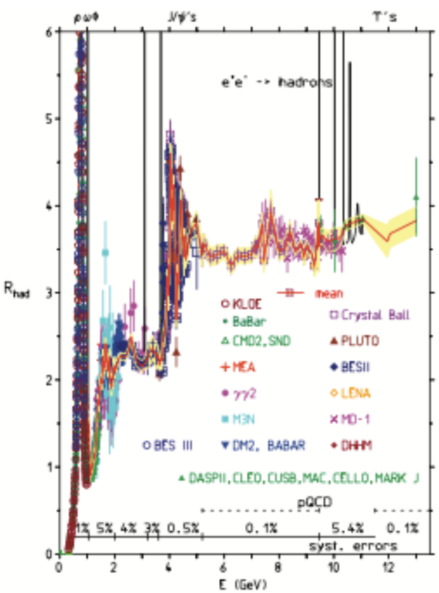
Is there another way?...

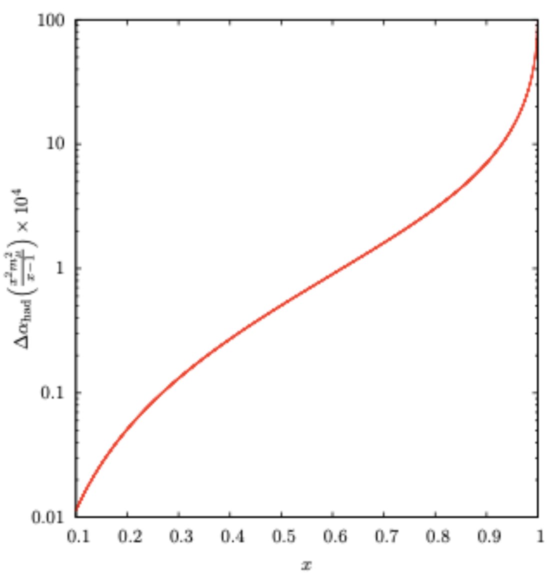
MuonE – spacelike measurement of a_μ^{HLO}

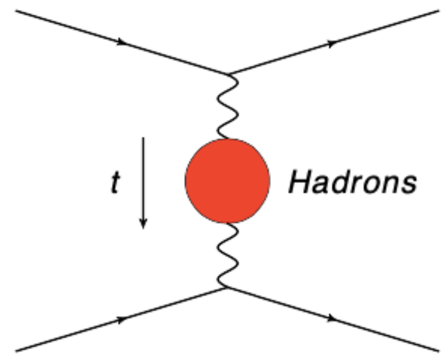
Carloni Calame, Passera, Trentadue, Venanzoni PLB 746 (2015) 325

- Still a data driven evaluation of a_μ^{HLO}
- Move from **time-like** to **space-like**

Time-like ↦ **Space-like**







Lautrup, Peterman, De Rafael, Phys. Rept. 3 (1972) 193

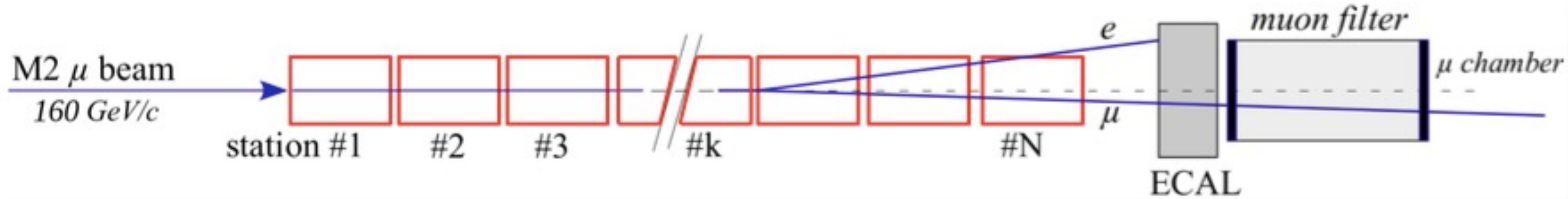
$$a_\mu^{\rm HLO} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\,\Delta\alpha_{\rm had}[t(x)]$$

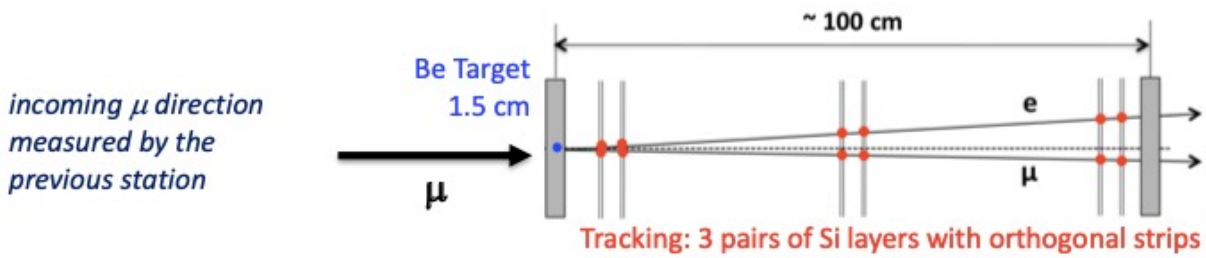
$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

- Is a pure t-channel process at tree level

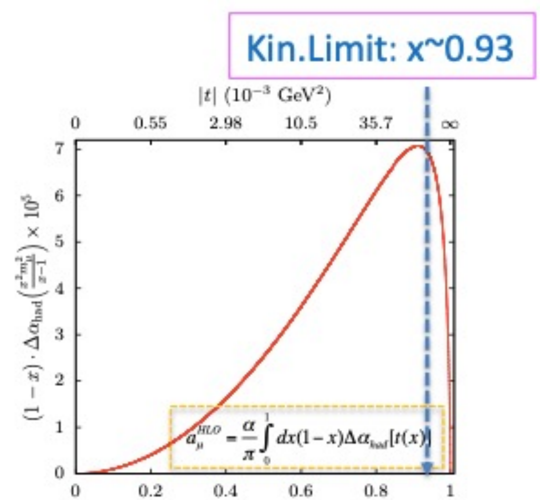
MuonE slides courtesy of R. Pilato, C.M. Carloni Calame, G. Abbiendi

MuonE measurement





- Scatter μ on e in low Z target, and measure the scattering angle
- For E(beam) = 160 GeV (CERN SPS) phase space covers ~88% of integral
- Smooth extrapolation to full integral with fit model
- Competitive precision 0.35-0.5% on a_μ^{HLO} will help solve g-2 puzzle!

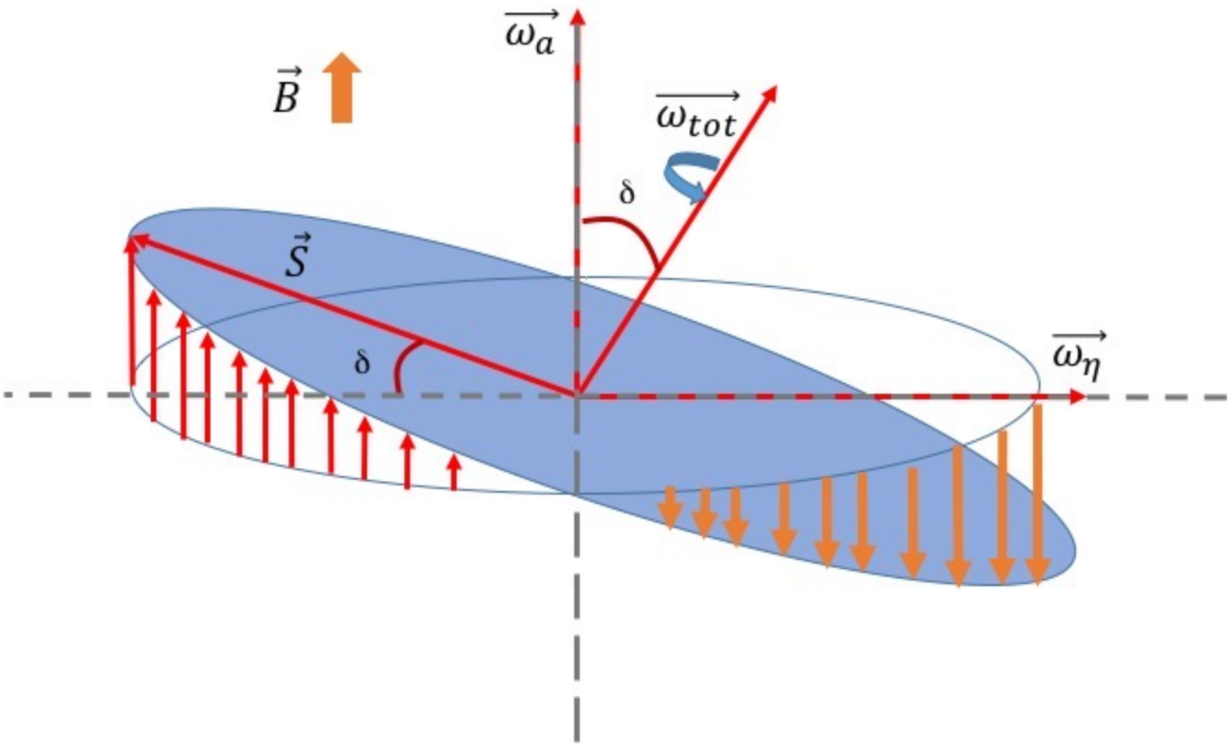


MuonE slides courtesy of R. Pilato, C.M. Carloni Calame, G. Abbiendi

Can also measure the Muon EDM

$$\vec{\omega}_{a\eta} = \vec{\omega}_a + \vec{\omega}_\eta = -\frac{Qe}{m}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] - \eta\frac{Qe}{2m}\left[\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right]$$

$$\vec{d} = \eta\left(\frac{Qe}{2mc}\right)\vec{s}$$



Causes an increase in muon precession frequency

$$\omega_{tot} = \sqrt{{\omega_a}^2 + {\omega_\eta}^2}$$

Precession plane tilts towards center of ring

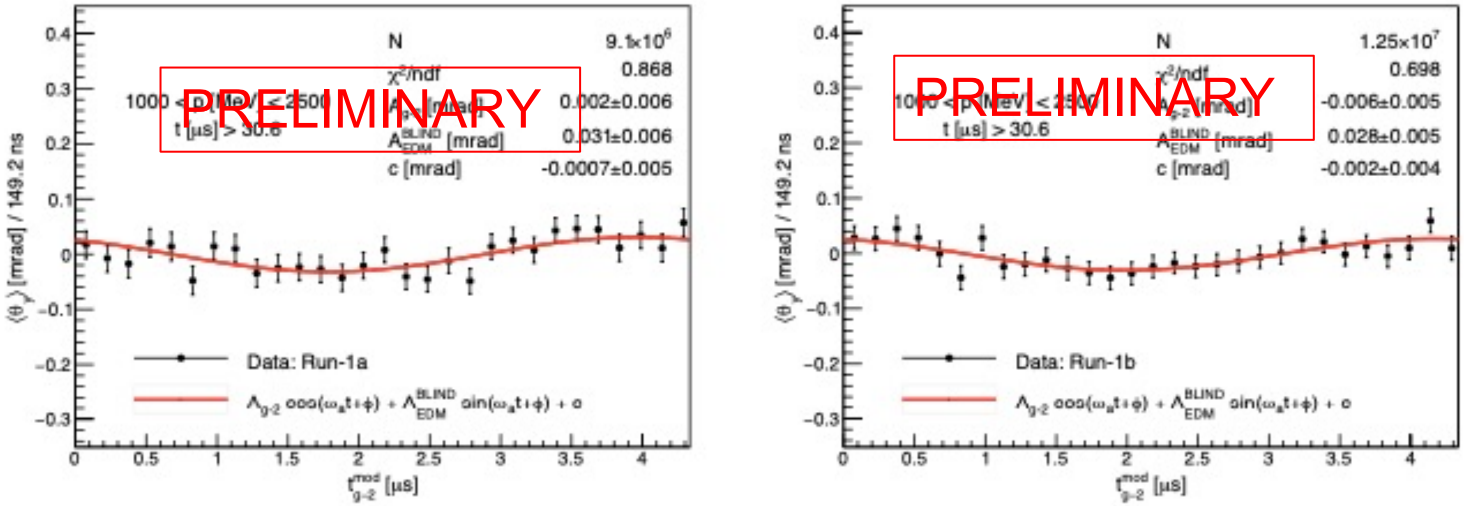
Vertical oscillation is 90° out of phase with the g-2 oscillation

EDM Projected Limits

G. W. Bennett *et al.* (Muon (g-2) Collaboration)
Phys. Rev. D 80, 052008

Current best limit is from BNL: $|d_\mu| < 1.9 \times 10^{-19} e.\mathrm{cm}$ (95% C.L.)

Blinded run 1 EDM search



- Run 1 analysis still blinded. Assuming zero signal expecting limit of:

$$|d_\mu| < 2.0 \times 10^{-19} e.\mathrm{cm}\ (95\%\ \mathrm{C.L.})$$

- Comparable with current limit, but still statistically limited
- Expect factor of **~10 improvement** for statistics accumulated so far, with tracking improvements can push towards

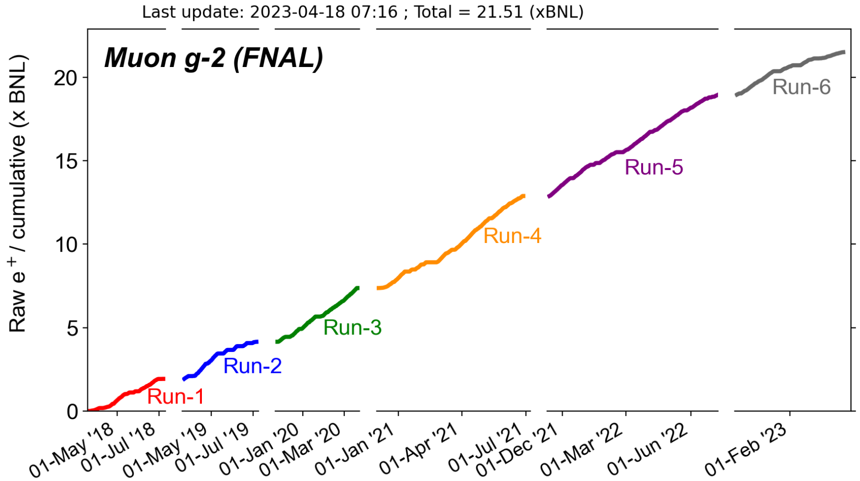
$$|d_\mu| < 1.0 \times 10^{-20} e.\mathrm{cm}\ (95\%\ \mathrm{C.L.})$$

Conclusions

- The analysis of the Run-1 data produced a result with 460 ppb precision, and 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

- On course for ~140ppb total uncertainty

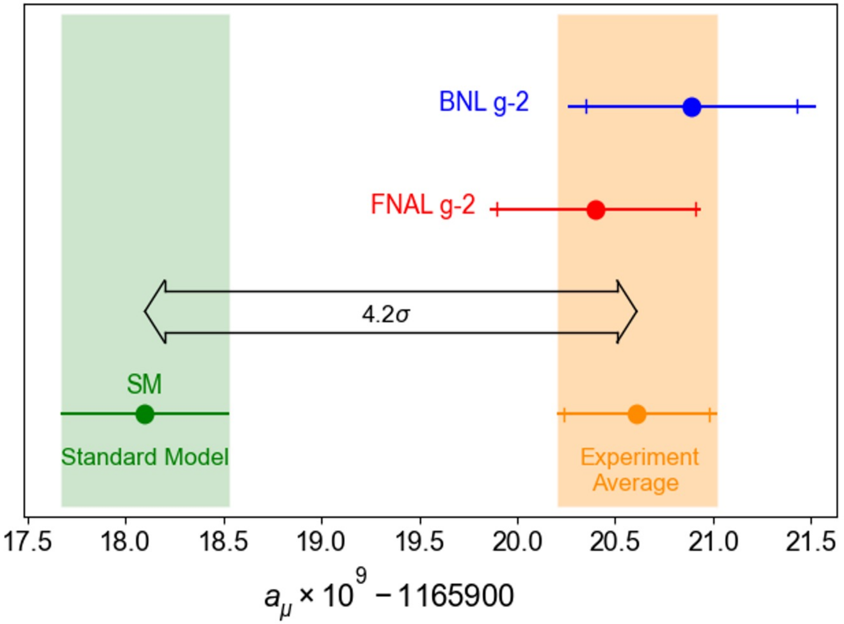


- Assuming no signal, the EDM analysis at FNAL will improve current limit by factor of 10

- **MuonE** offers third way to get a_μ^{HLO} - will help with current tension between data-driven and lattice calulations

Thank you!

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

Backups…

Muons at FNAL

Lower instantaneous rate but larger integrated rate than BNL

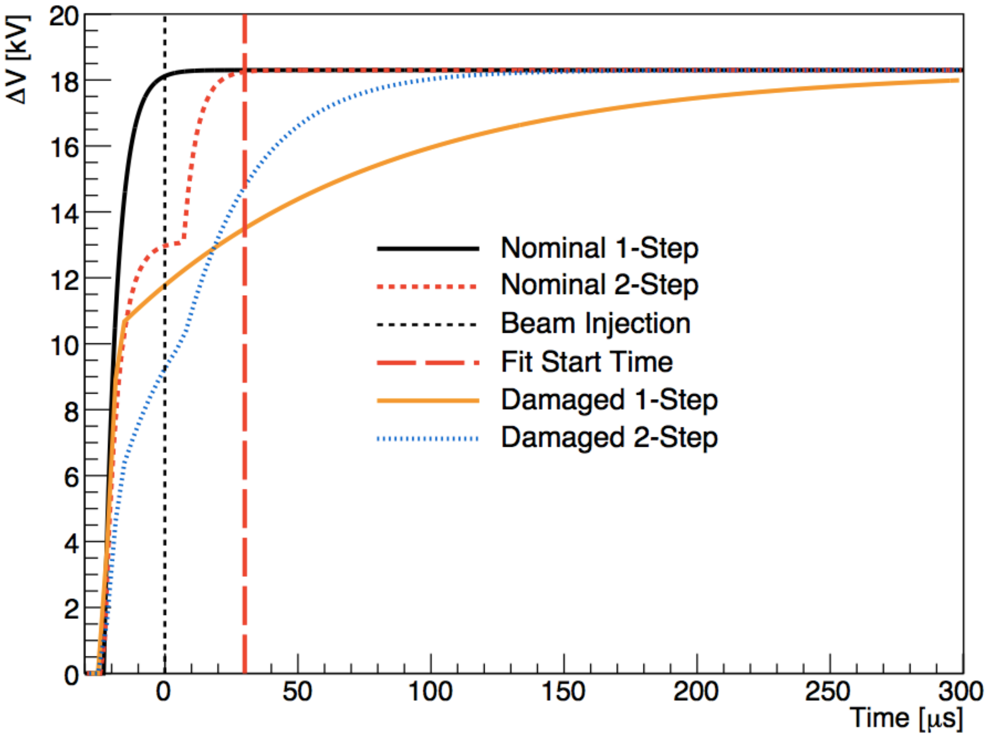
~ 10,000μ^+ (from 10^{12} p) at 3.1 GeV every 10 ms

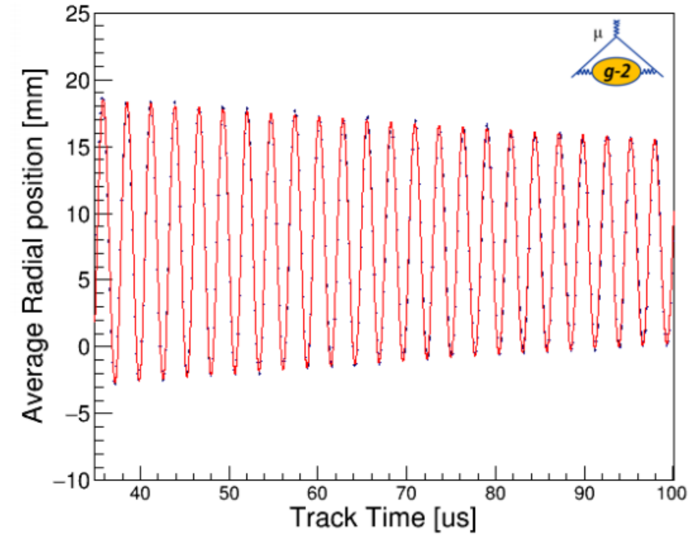
(g-2): ⅓ of proton cycles, neutrino expts: ⅔

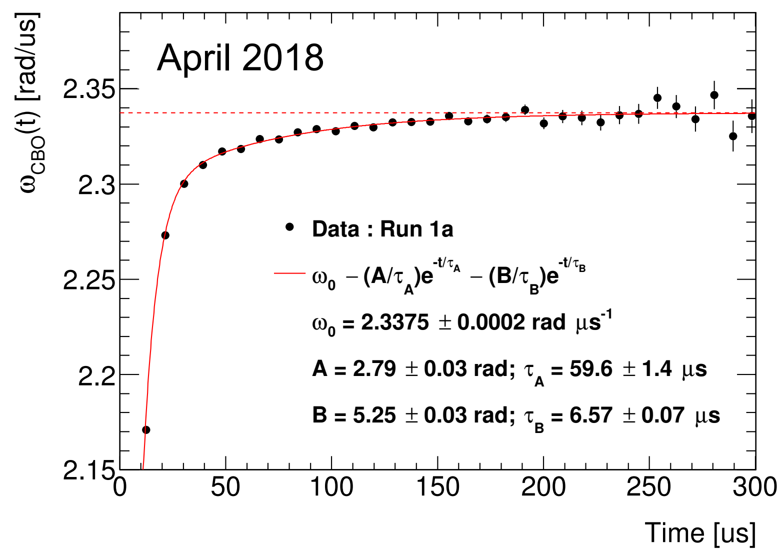
Extra 900m of instrumented beamlines

Run 1 specific problem…

- When fitting the beam oscillations using the tracker data we observed that a constant frequency didn't work
- Eventually traced this to 2/32 faulty resistors in the quads







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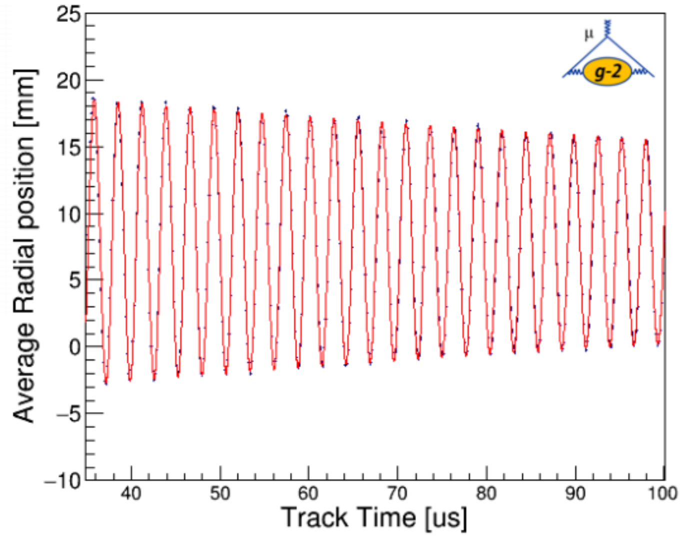
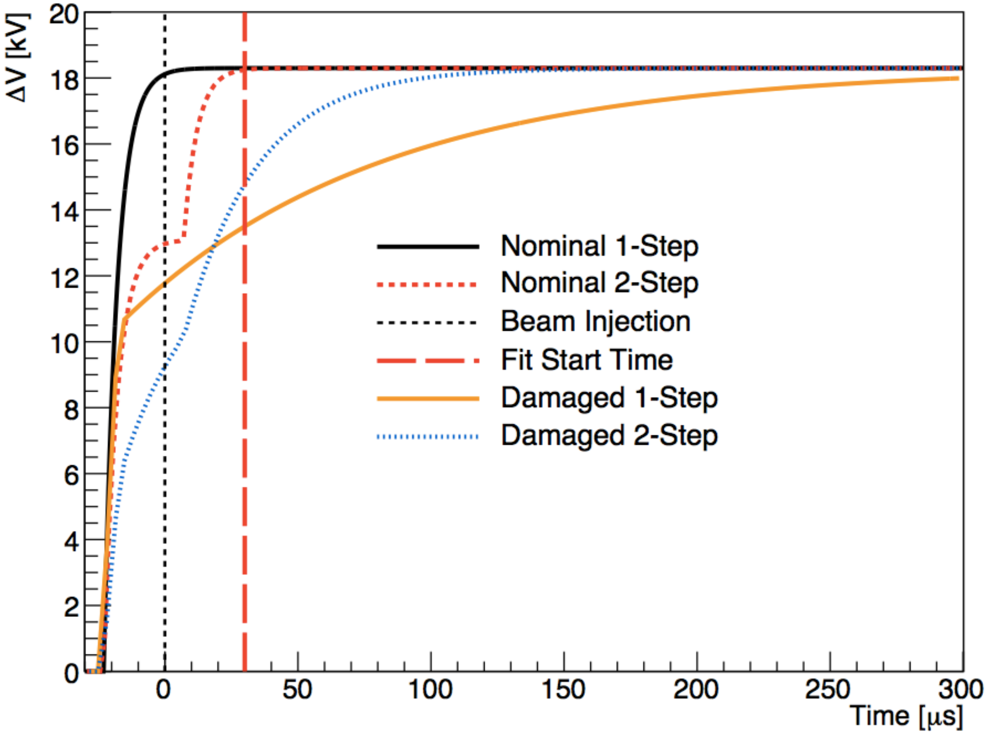
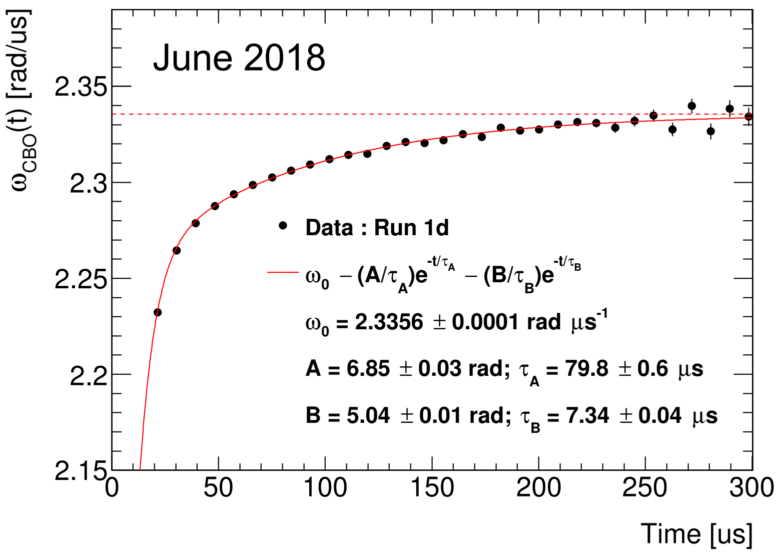
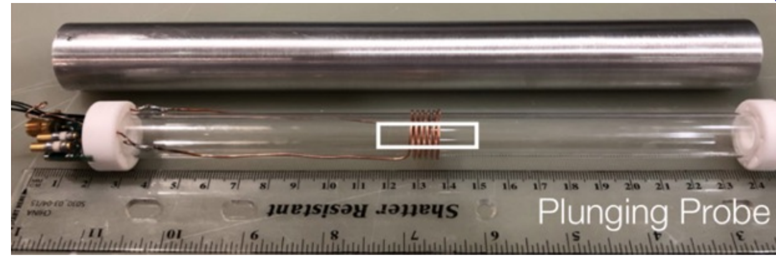






Absolute Calibration

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



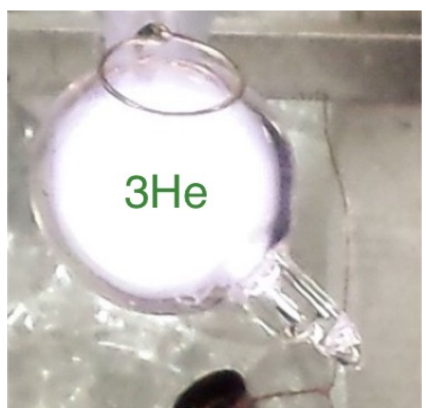
Checked against spherical water sample to get absolute number

Cross checked with He3 sample, with different systematic uncertainties

Overall calibration uncertainty ~35ppb

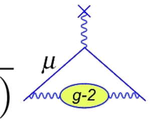
spherical water (6ppb)

^{3}He sample (30ppb)

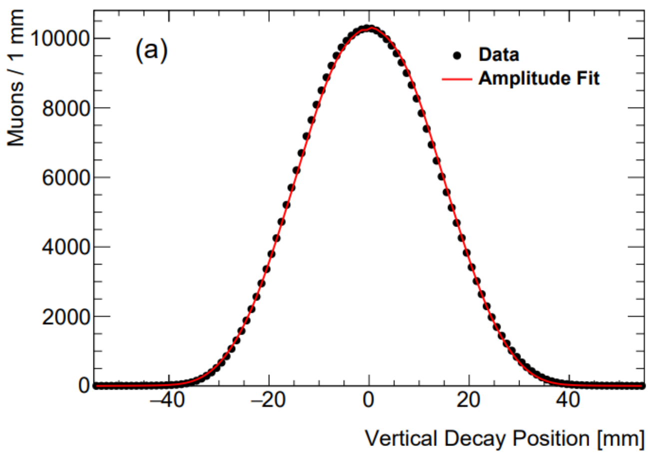


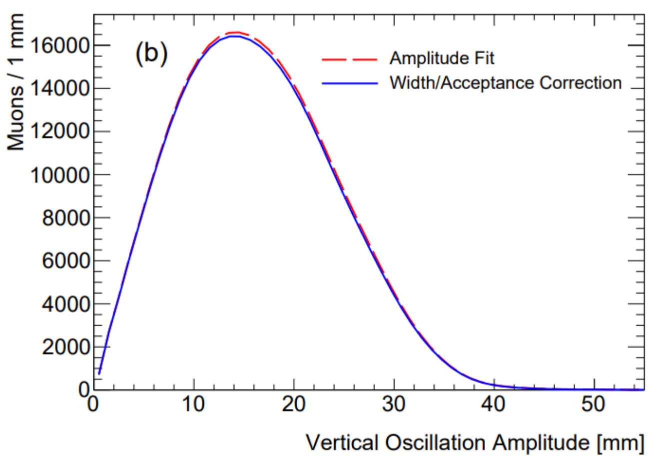
Pitch Correction

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



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





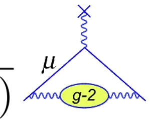
- Component of momentum parallel to field due to focusing
- Use tracking detectors to measure the vertical width of the beam

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

Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_p (ppb)	176	199	191	166
Stat. uncertainty	< 1	< 1	< 1	< 1
Tracker reco.	11	12	12	11
Tracker res. & acc	3	4	4	3
$\beta_y(\phi)$ & calo. acc.	1	1	2	1
Amplitude fit	1	< 1	1	3
Quad calibration	4	4	4	4
Syst. uncertainty	12	14	14	12

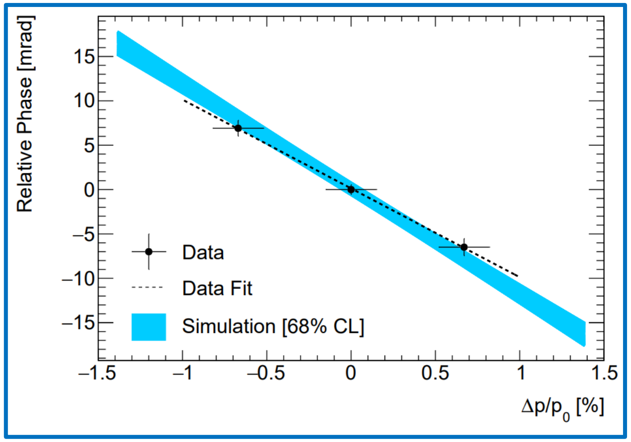
Muon Loss

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

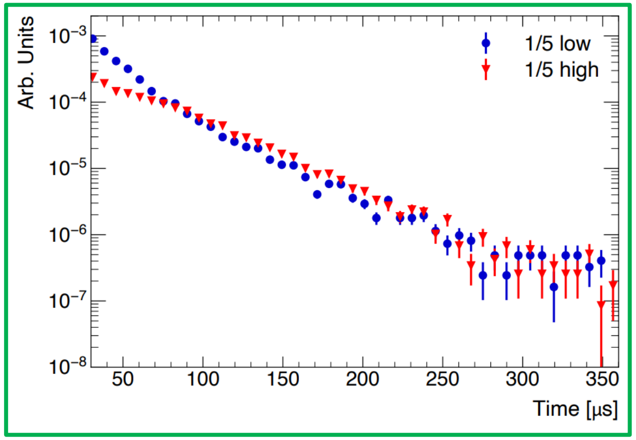


$$\frac{d\varphi_0}{dt} = \frac{d\varphi_0}{d\langle p\rangle}\frac{d\langle p\rangle}{dt}$$

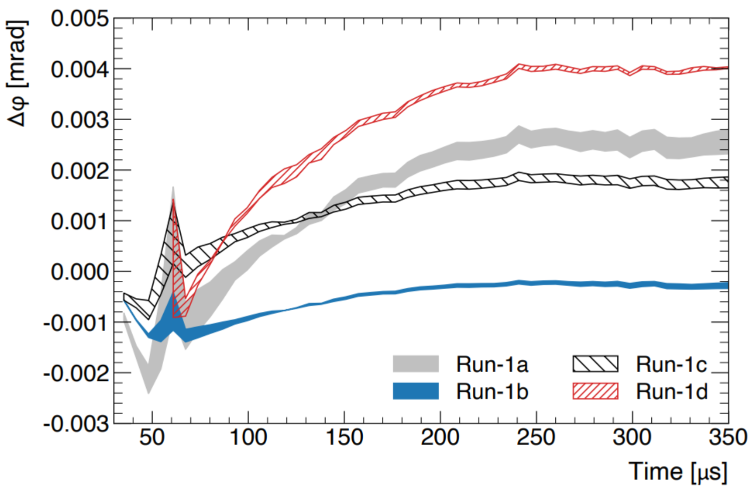
- Lost muons have a slightly different phase w.r.t the ensemble, which causes a change in phase vs time
- Reduced from Run-2 onwards



Spin momentum correlation from delivery ring



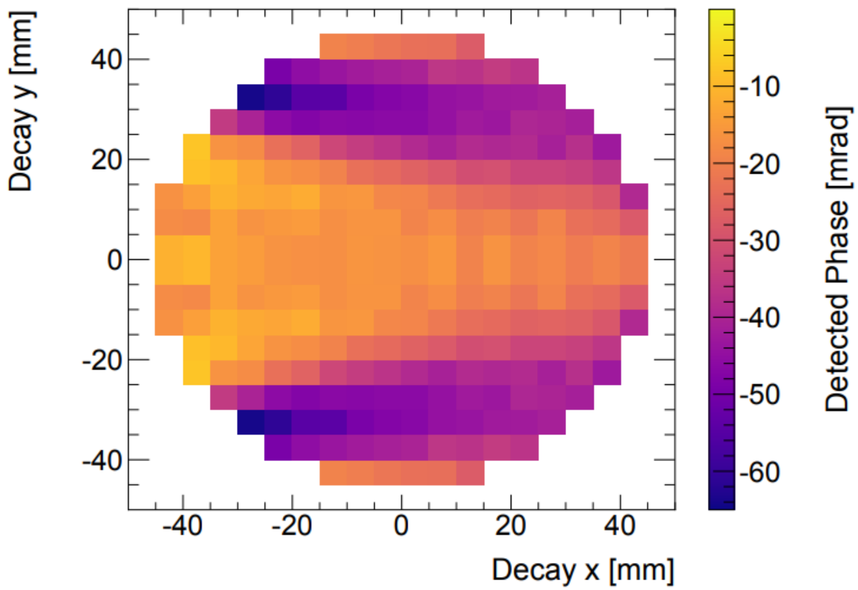
Low mom. muons are lost faster than high mom. at early times



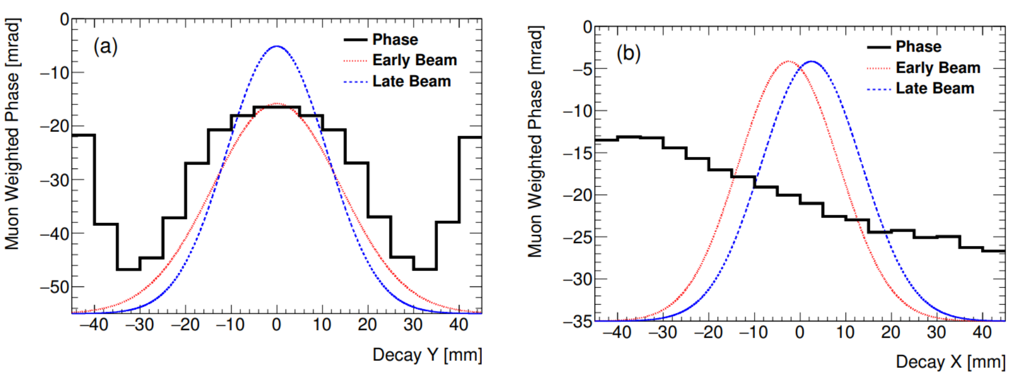
Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_{ml}	-14	-3	-7	-17
Phase-momentum	2	0	1	3
Form of $l(t)$	2	0	1	1
f_{loss} function	2	1	2	2
Linear sum ($\sigma_{C_{ml}}$)	6	2	4	6

Phase Correction

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



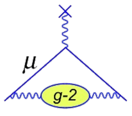
- Focusing strength of the quadrupoles changed during fill
- The non-uniform acceptance of the calorimeters causes the average phase to change during the fill
- Damaged resistors (Run-1 only) enhanced this effect



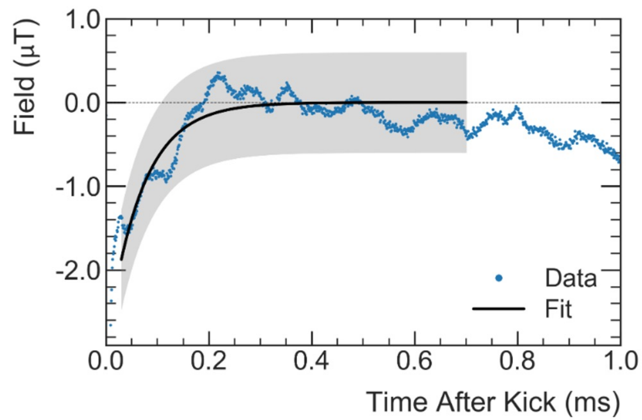
Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_{pa}	-184	-165	-117	-164
Stat. uncertainty	23	20	15	14
Tracker & CBO	73	43	41	44
Phase maps	52	49	35	46
Beam dynamics	27	30	22	45
Total uncertainty	96	74	60	80

Transient fields

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



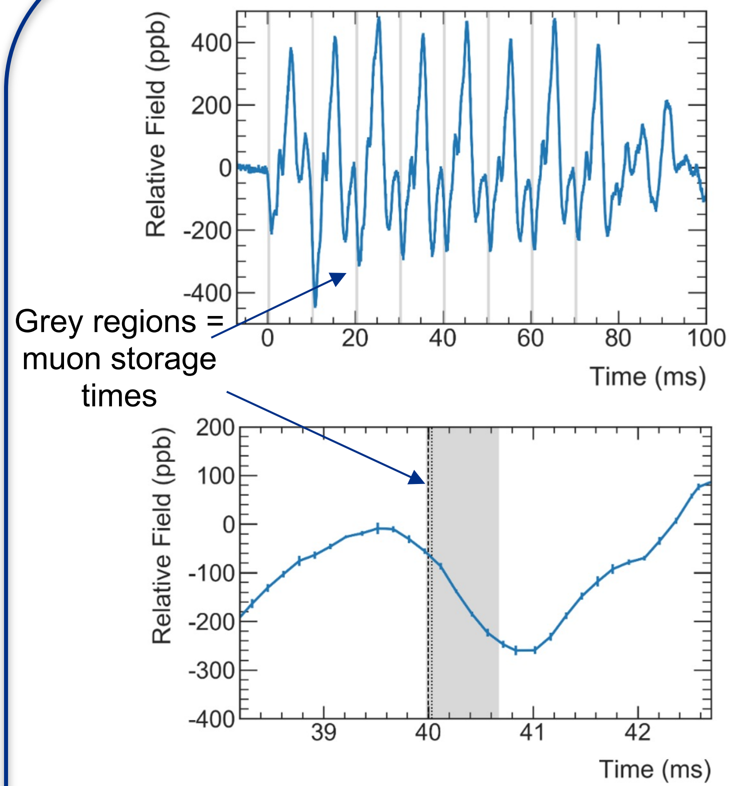
- Largest run-1 uncertainties come from “fast transient” fields generated by the pulsed systems (kickers and quads)
- Muons experience a field change which the fixed probes do not see (due to shielding)
- Effects were measured separately during dedicated measurement campaigns.



Kicker: B_k

- 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 B_q



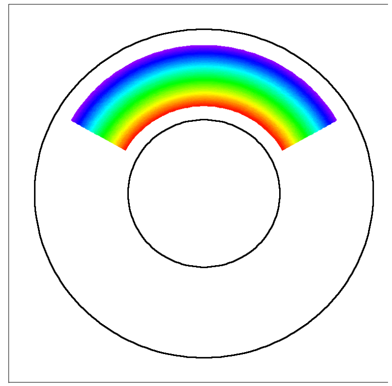
- Measured with a dedicated in-vacuum NMR probe located between quad plates during pulsing
- Quad correction: -17 (92) ppb

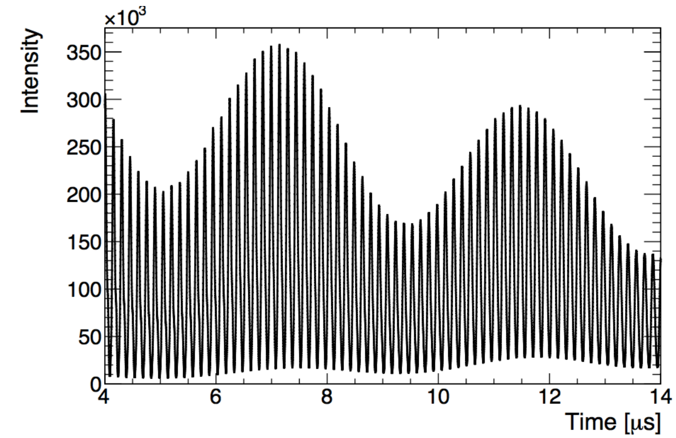
E-field Correction

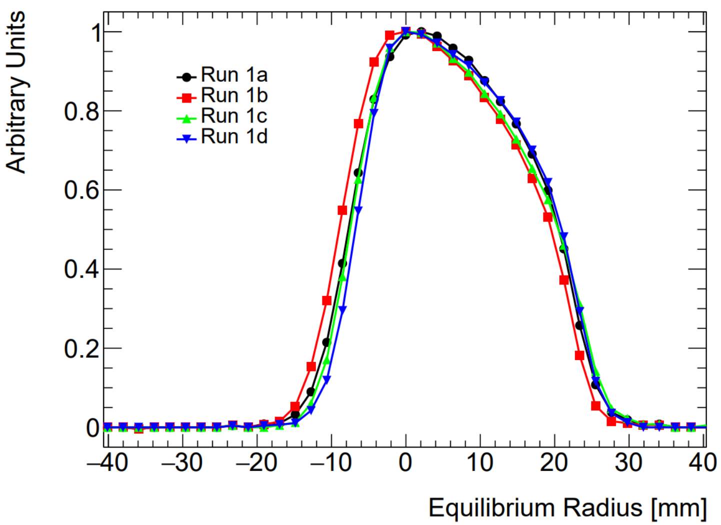
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\rm clock}\ \omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\rm calib}\ \langle \omega_p(x,y,\phi)\times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$

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

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





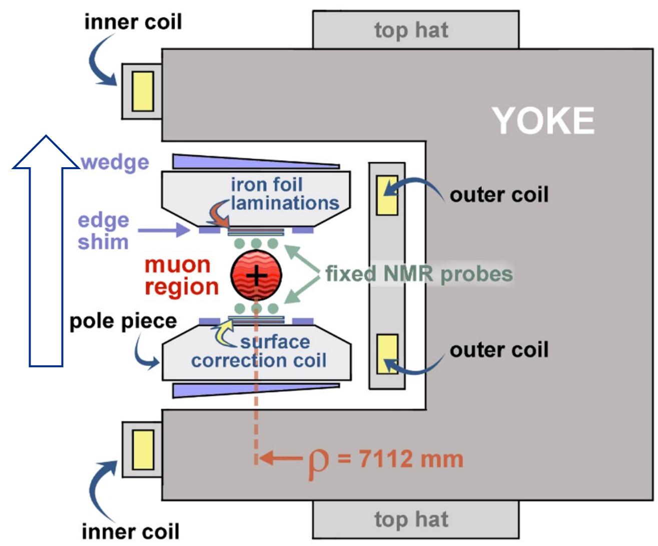


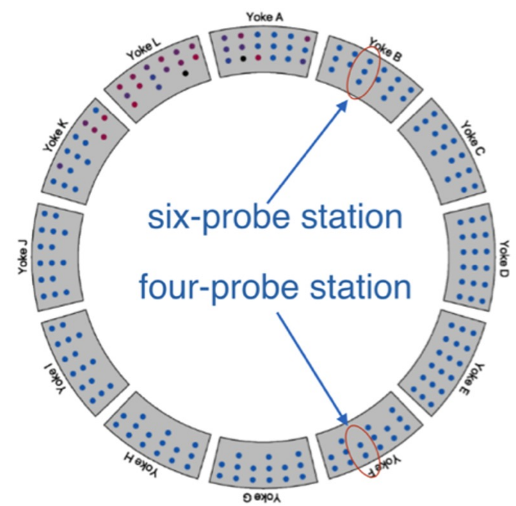
Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_e	471	464	534	475
Stat. uncertainty	< 1	1	< 1	< 1
Fourier method	8	13	14	4
Momentum-time	52	52	52	52
Quadrupole calibration	6	6	6	6
Field index	2	2	2	4
Syst. uncertainty	53	54	54	53

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
- Tiny (ppm) changes in magnet geometry, driven by temperature changes, **cause the field to drift over time**
- 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

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.**

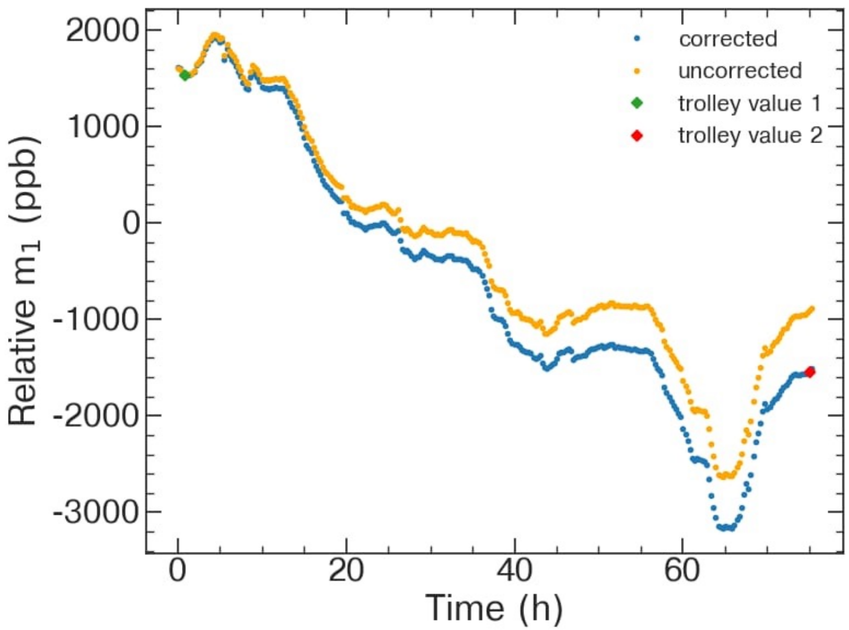
- Fixed probes take data continuously during muon fills. Use this data to interpolate between trolley runs.

- 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)



Improved kicker run 2-3