Latest results from the g-2 experiment at Fermilab

Joe Price
on behalf of the g-2 experiment

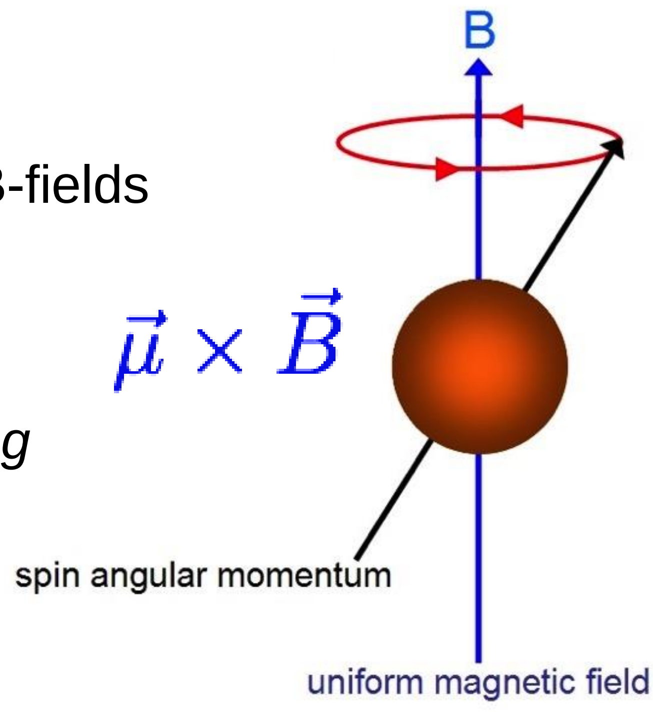
Magnetic moments

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

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

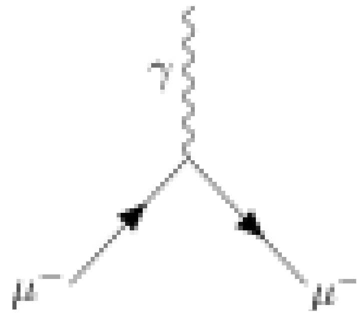
Magnetic moment (spin) interacts with external B-fields

Makes spin precess at frequency determined by *g*

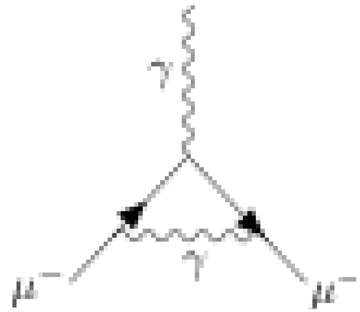


Magnetic Moments & Virtual Loops

For a pure Dirac spin-½ charged fermion, g is exactly 2

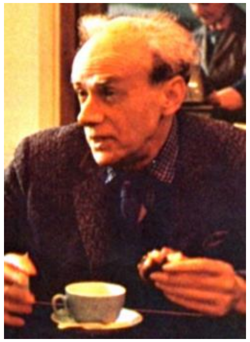


Interactions between the muon and virtual loops change the value - virtual particles could be SM or new physics:

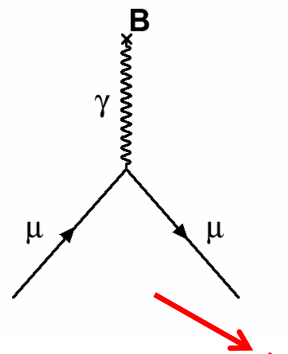


Standard Model components of g_μ

Dirac



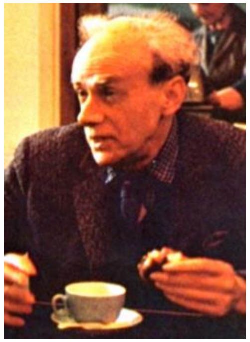
Charged,
spin ½



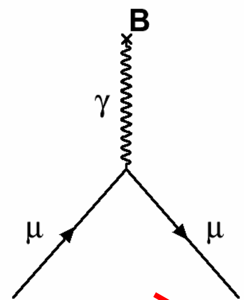
$$g_\mu^{SM} = 2$$

Standard Model components of g_μ

Dirac

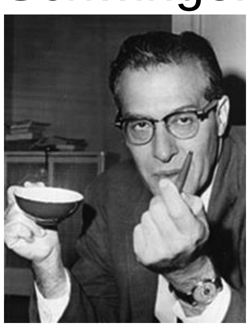


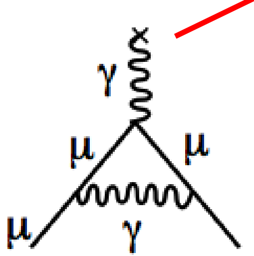
Charged,
spin ½



$$g_\mu^{SM} = 2.0023$$

Schwinger



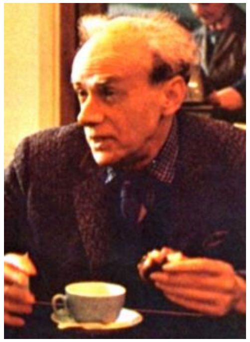


$$\frac{\alpha}{2\pi} = 0.00232$$

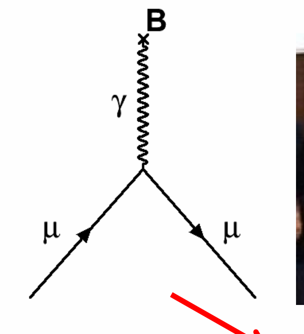
1st Order QED

Standard Model components of g_μ

Dirac

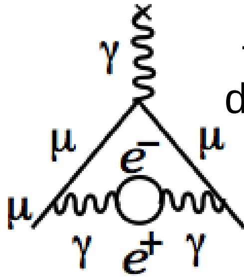


Charged,
spin ½



Kinoshita

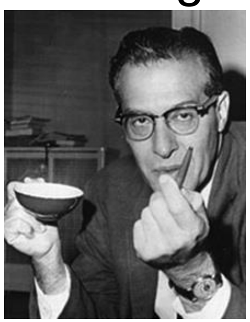
Up to 10th Order QED

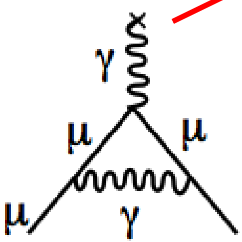


+12671 diagrams

$$g_\mu^{SM} = 2.002331$$

Schwinger



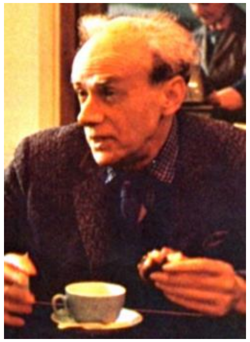


$$\frac{\alpha}{2\pi} = 0.00232$$

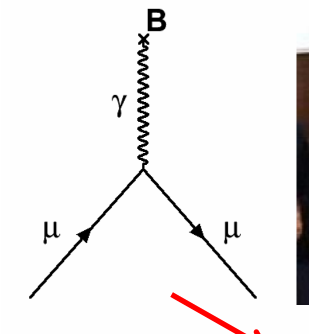
1st Order QED

Standard Model components of g_μ

Dirac

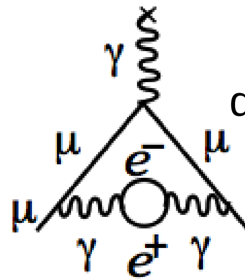


Charged, spin ½



Kinoshita

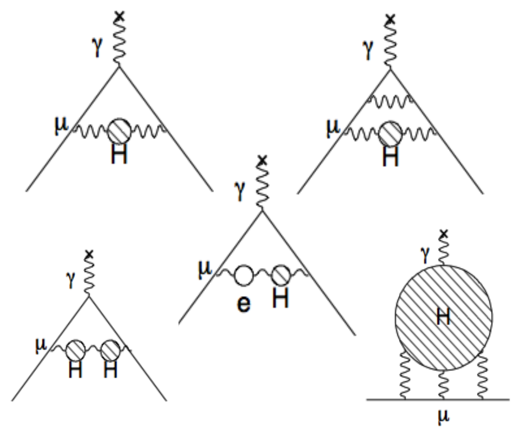
Up to 10th Order QED



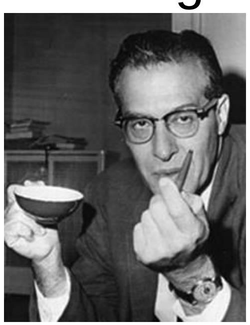
+12671 diagrams

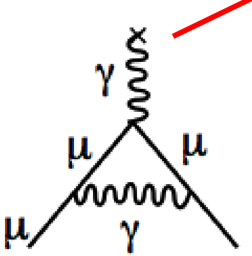
$$g_\mu^{SM} = 2.0023318 4$$

Hadronic



Schwinger



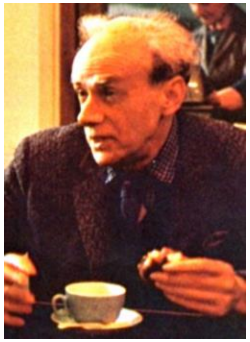


$$\frac{\alpha}{2\pi} = 0.00232$$

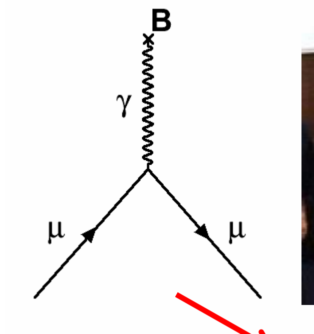
1st Order QED

Standard Model components of g_μ

Dirac

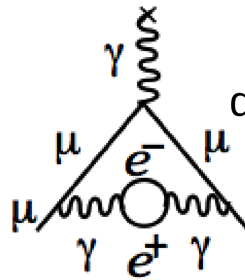


Charged, spin ½

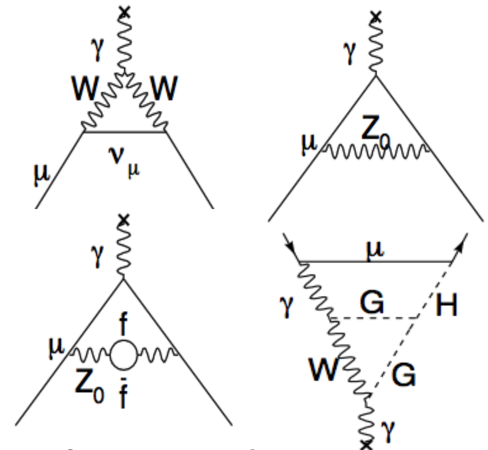


Kinoshita

Up to 10th Order QED



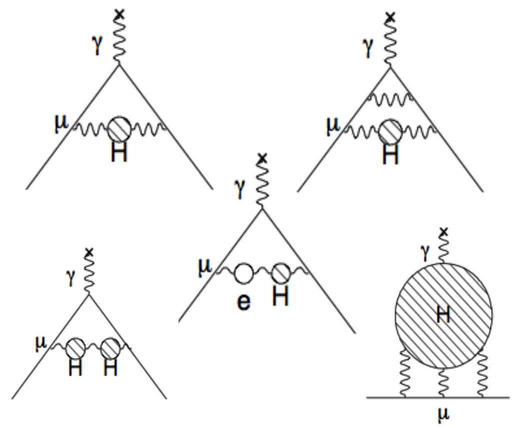
+12671 diagrams



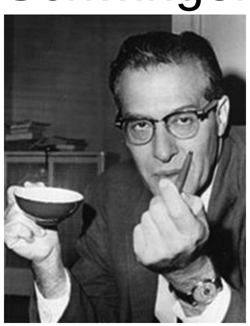
Electroweak

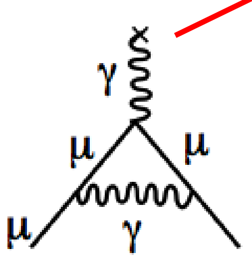
$$g_\mu^{SM} = 2.0023318407$$

Hadronic



Schwinger



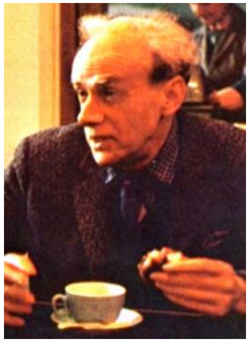


$$\frac{\alpha}{2\pi} = 0.00232$$

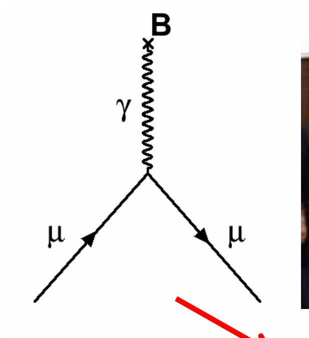
1st Order QED

Standard Model components of g_μ

Dirac

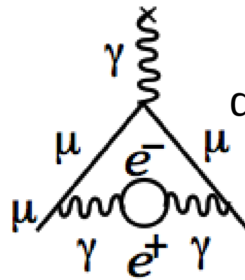


Charged, spin ½

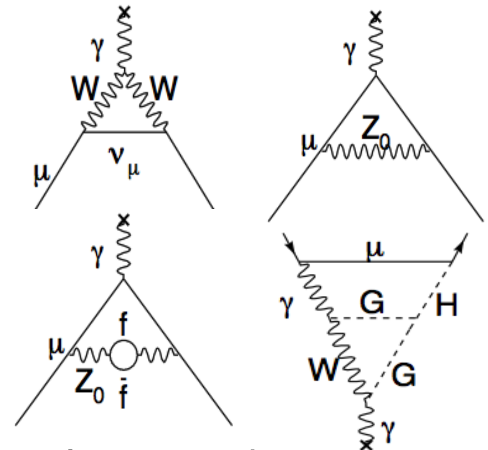


Kinoshita

Up to 10^{th} Order QED



+12671 diagrams



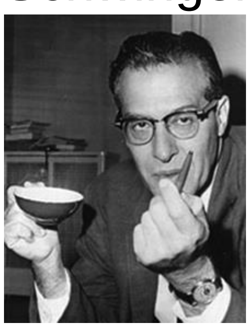
Electroweak

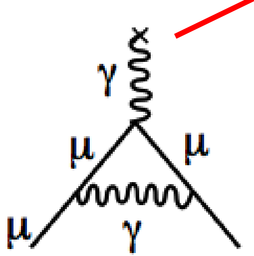
$$g_\mu^{SM} = 2.00233184 07(12)$$

Hadronic

BSM?

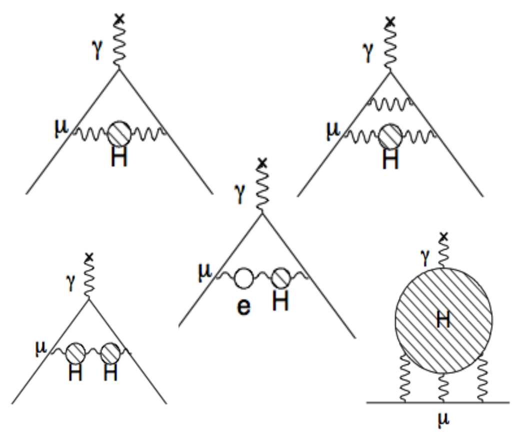
Schwinger





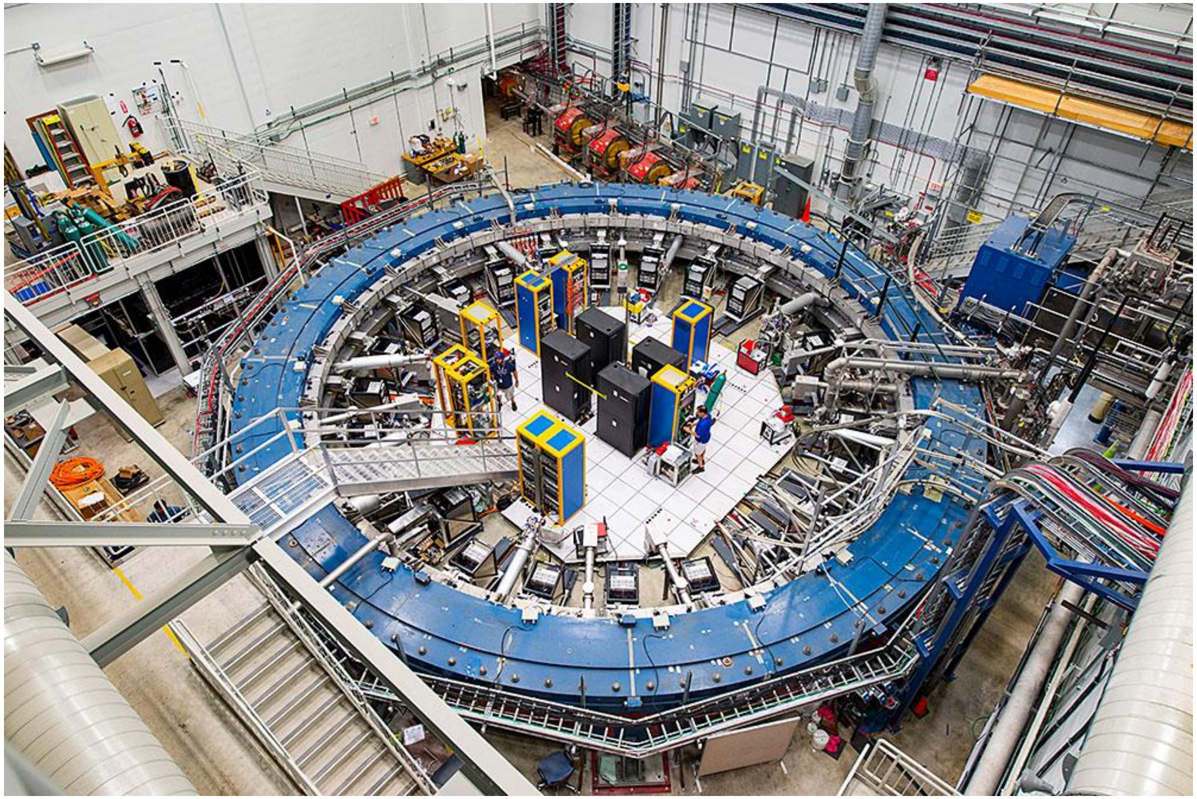
1st Order QED

$$\frac{\alpha}{2\pi} = 0.00232$$

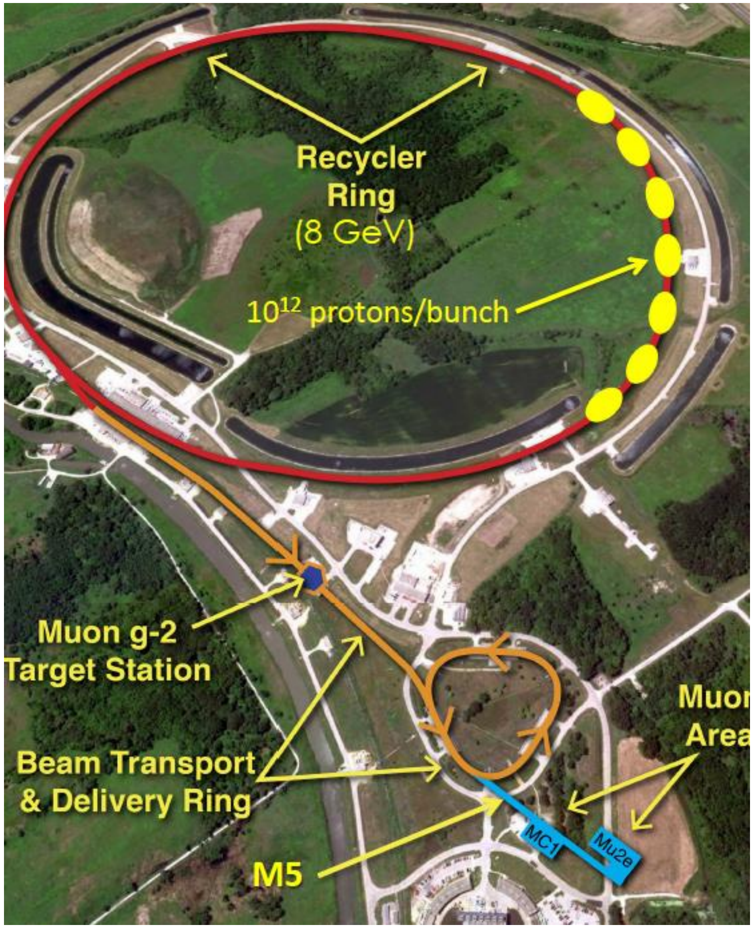


WP2025:
arXiv 2505.21476

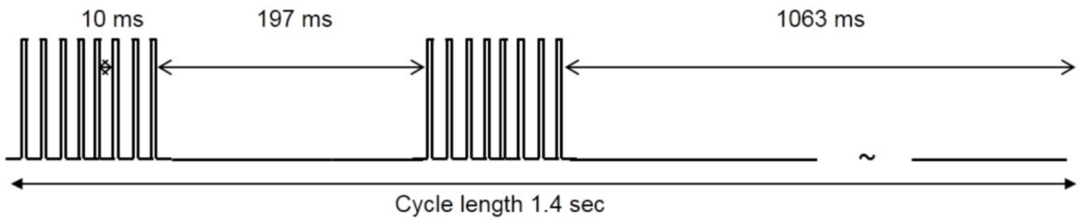
The Fermilab Muon g-2 Experiment



FNAL: Muon Campus



- Recycler ring: 8 GeV protons
  - 10^{12} protons/bunch, 10k stored muons/bunch
- 8 GeV protons → pion production target
- Pions → delivery ring → decay to μ^+,
- 3.09 GeV μ^+ → g-2 storage ring magnet
- Beam arrives in 120 ns wide bunches
- Each bunch corresponds to a “fill” → 1 ms



3.09 GeV $\mu^+ \rightarrow \gamma = 29.3 \rightarrow$ ~64μs lifetime

Measurement Principle

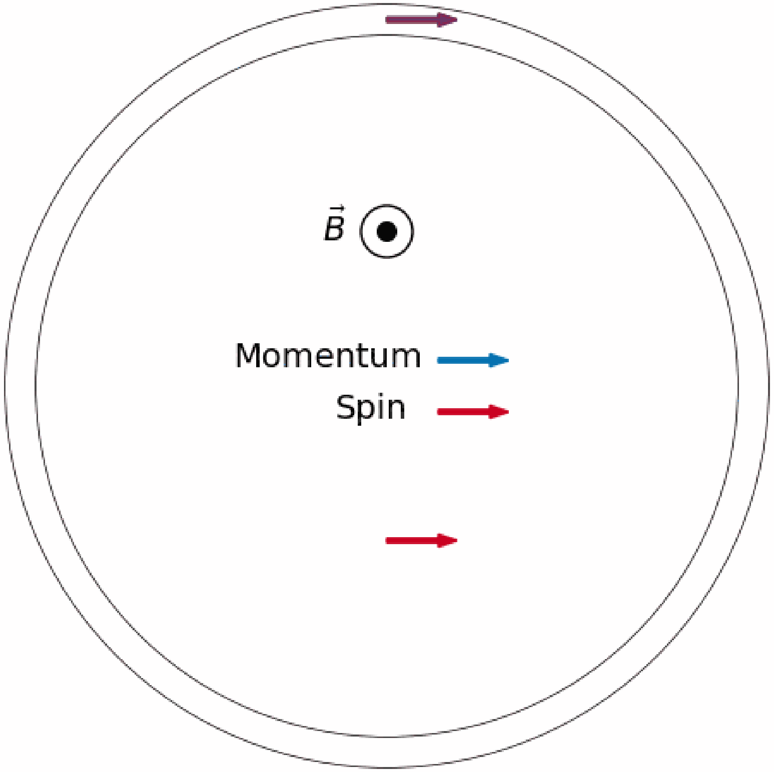
$$a_\mu = \frac{g_\mu - 2}{2}$$

- Muons orbit the ring with cyclotron frequency ω_c
- Spin precesses with frequency ω_s
- Both **spin** and **cyclotron** frequencies are proportional to **B**
- **Difference frequency** ω_a is proportional to a_μ and B

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

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

- Spin rotates ahead of momentum as the muon orbits the ring
- If g = 2 there would be no precession



Relativistic equation

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

non-relativistic limit

electron motion
non-perpendicular
to magnetic field

cyclotron motion assumed motion
perpendicular to magnetic field

pitch of electron

relativistically generated
motional magnetic field

proportional to electric field

$a_\mu^{SM} = 116591810(43)\times 10^{-11}$

disappears for γ ≈ 29.3

magic momentum

p_μ=3.094 GeV/c

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 $C_p = \frac{\Delta\omega_a}{\omega_a}$

Measurement Components

The experiment actually measures **two frequencies**

Each with a dedicated talk @ WIN2025!
ω_a: Yonghao Zeng (Tues 3.00pm)
$\tilde{\omega}'_p$: René Reiman (Tues 3.15pm)

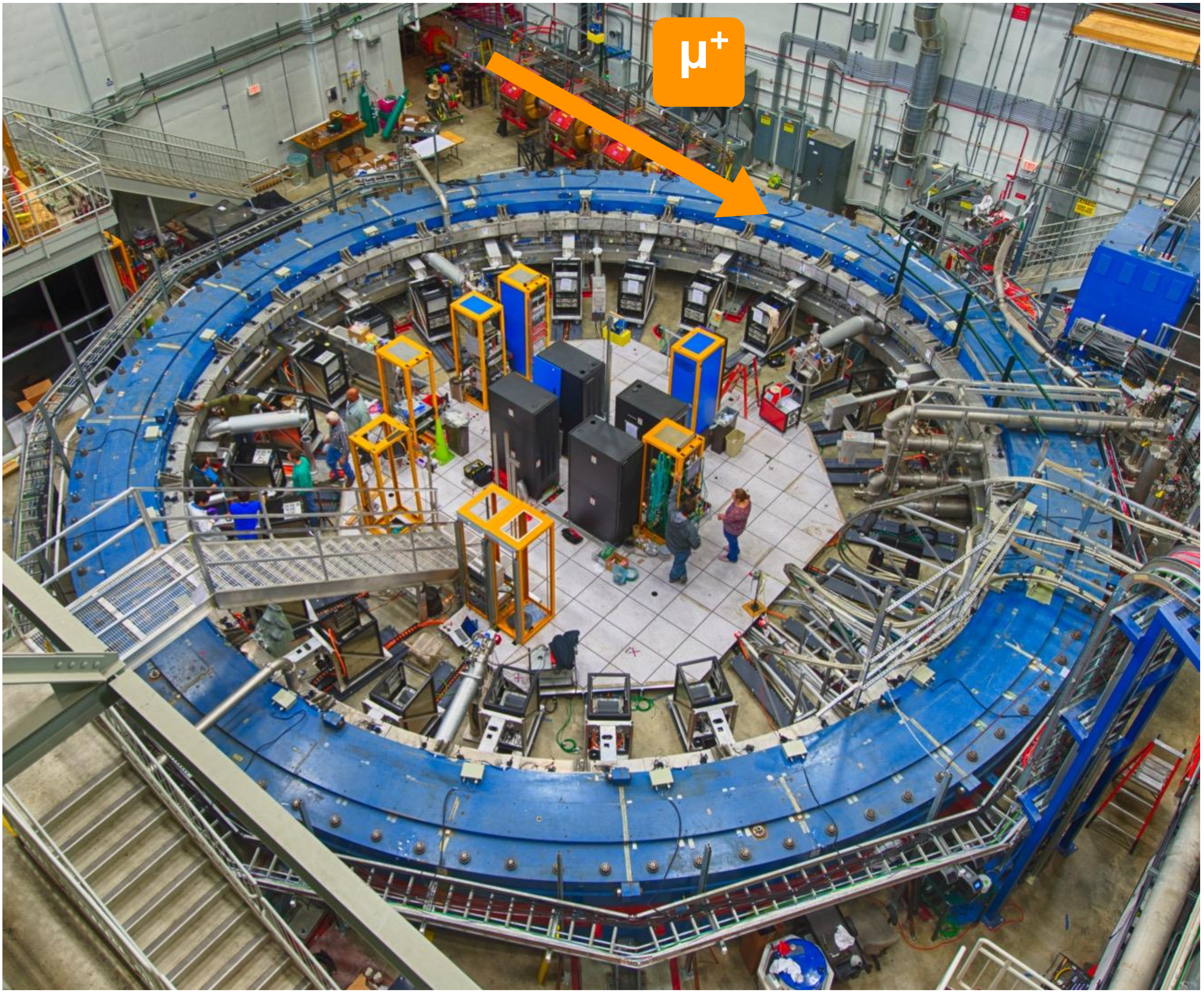
$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_B} \frac{m_\mu}{m_e}$$

Both external ratios from CODATA 2022
Rev. Mod. Phys. **97**, 025002

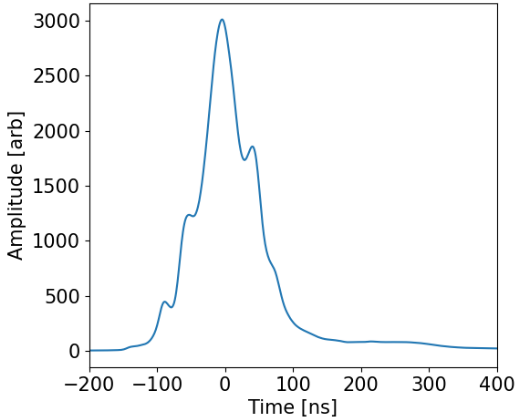
$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}} \omega_a^{\text{meas}} (1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd})}{f_{\text{calib}} \langle M(x,y,\phi) \omega'_p(x,y,\phi) \rangle (1 + B_k + B_q)}$$

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

Beam injection

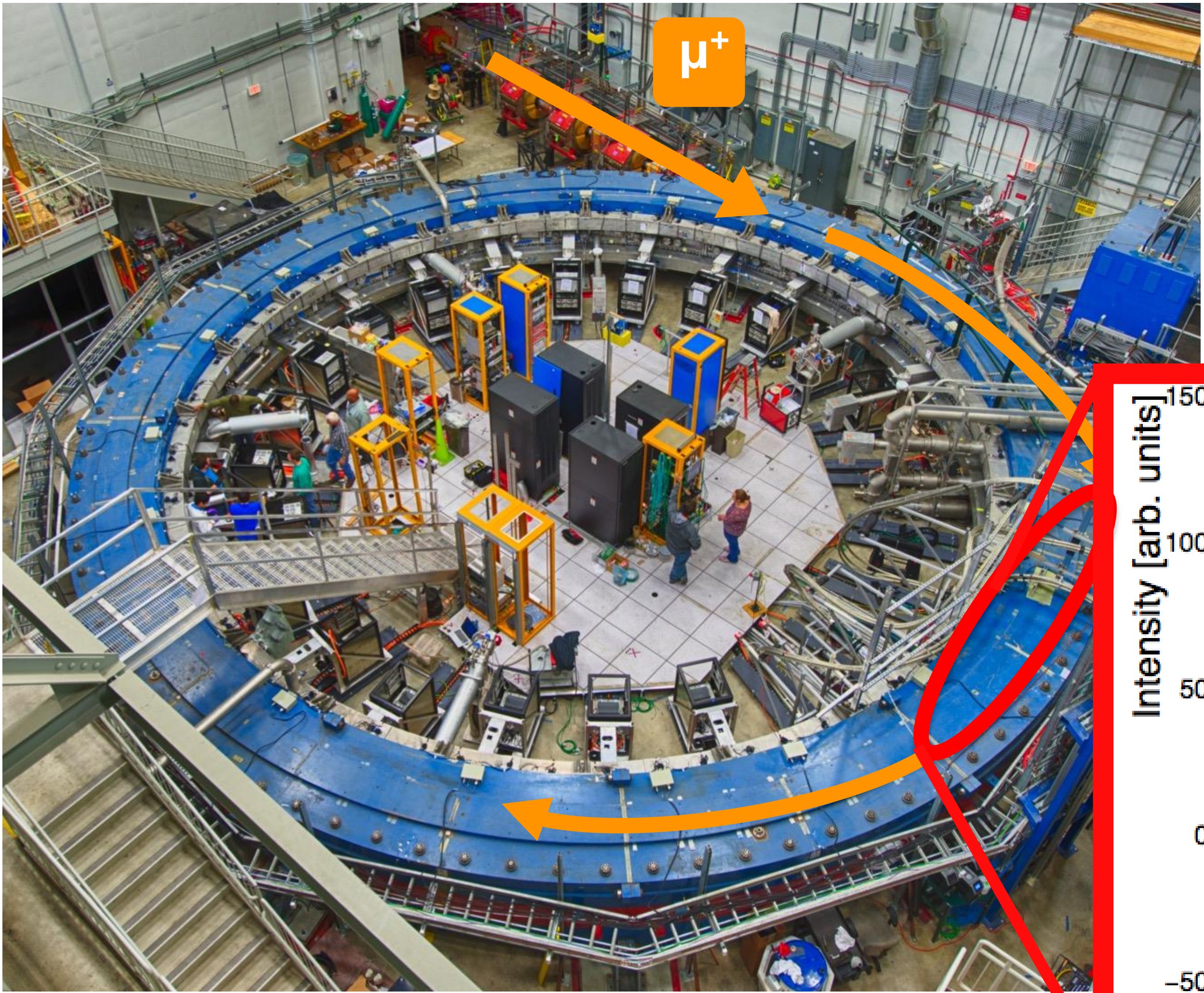


- Monitor beam profile before entrance with scintillating X and Y fibres
- Get time profile of beam using scintillating pad
- ~125ns wide

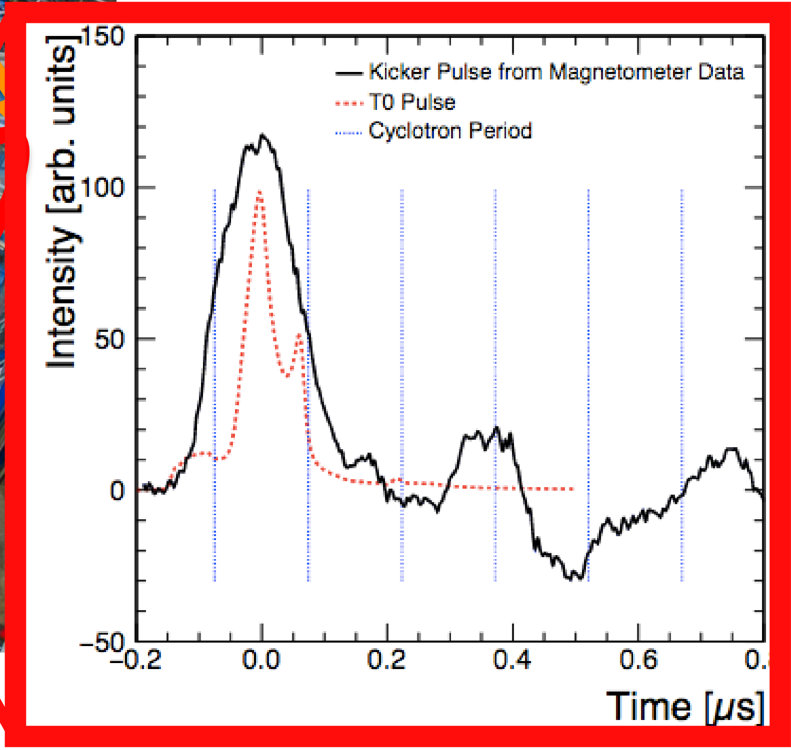


- Cancel B-field during injection using Inflector, so muons can get into the ring

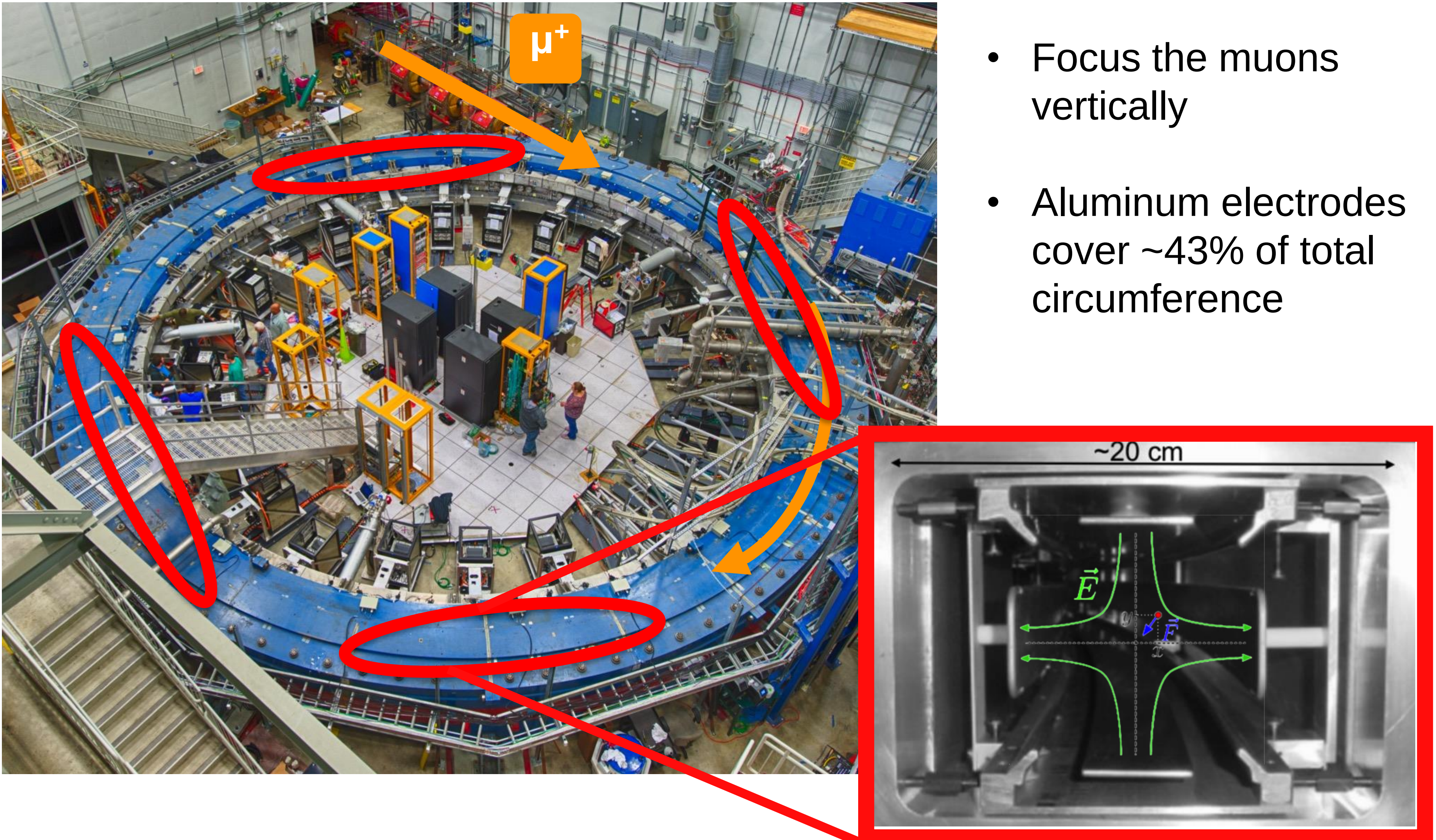
‘Kick’ onto correct orbit



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



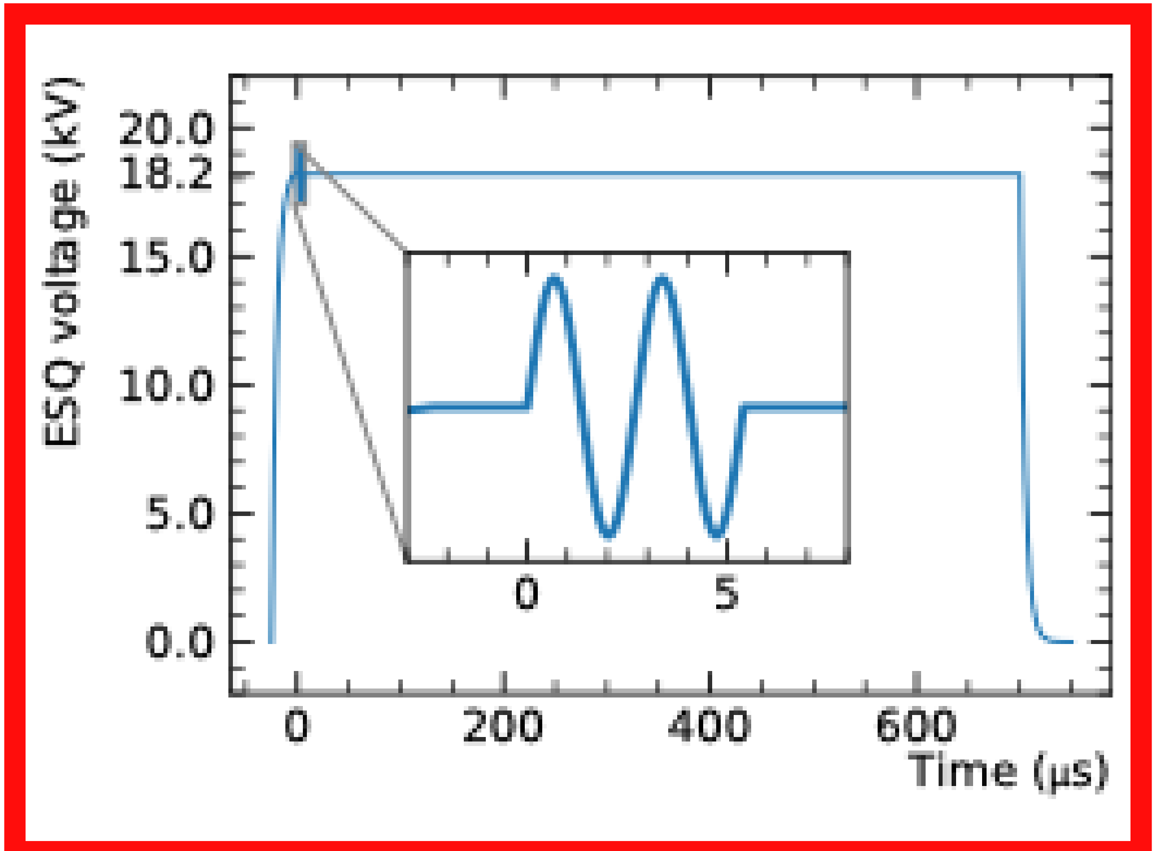
Beam focusing



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

Beam focusing

- Added **new quad RF** modulation (~1kV) for first $6\mu s$ of storage
- Reduces harmonic motion of beam
- Run 4/5/6 split into noRF, xRF, xyRF5 and xyRF6 datasets



des
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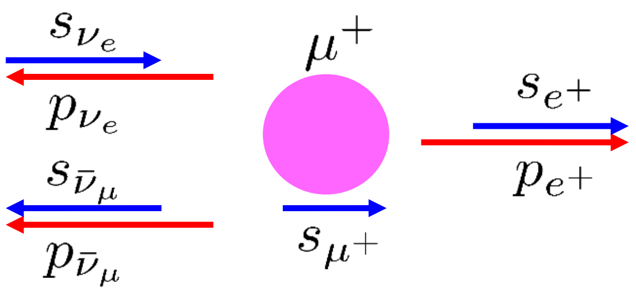
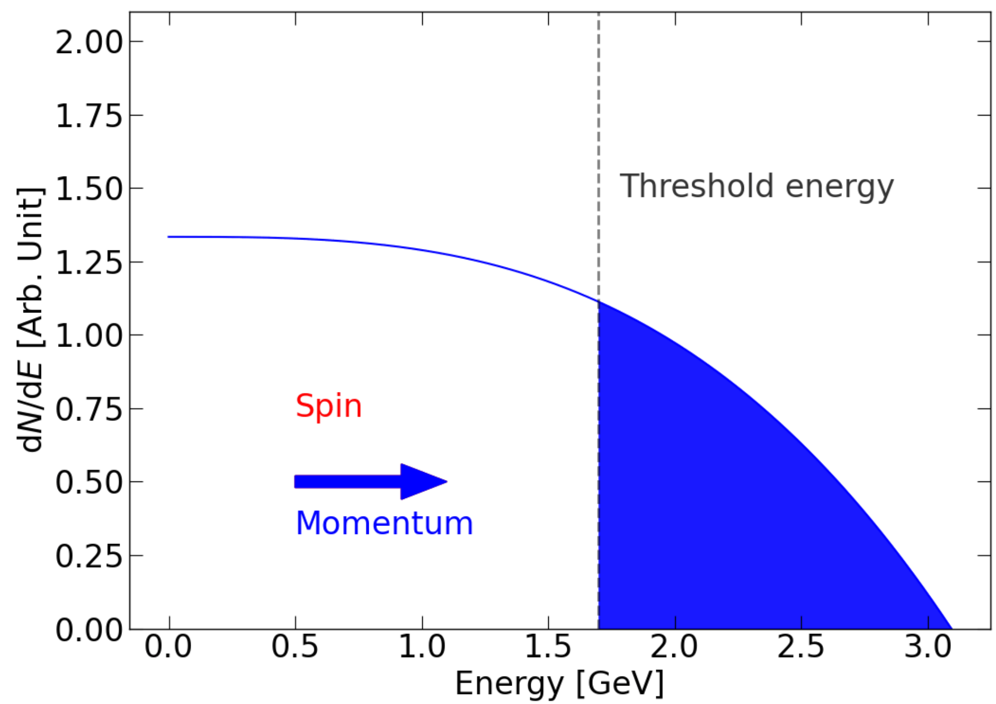
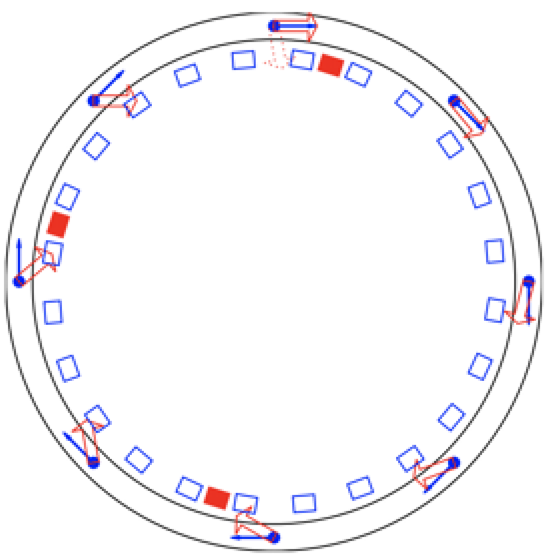
Measuring ω_a



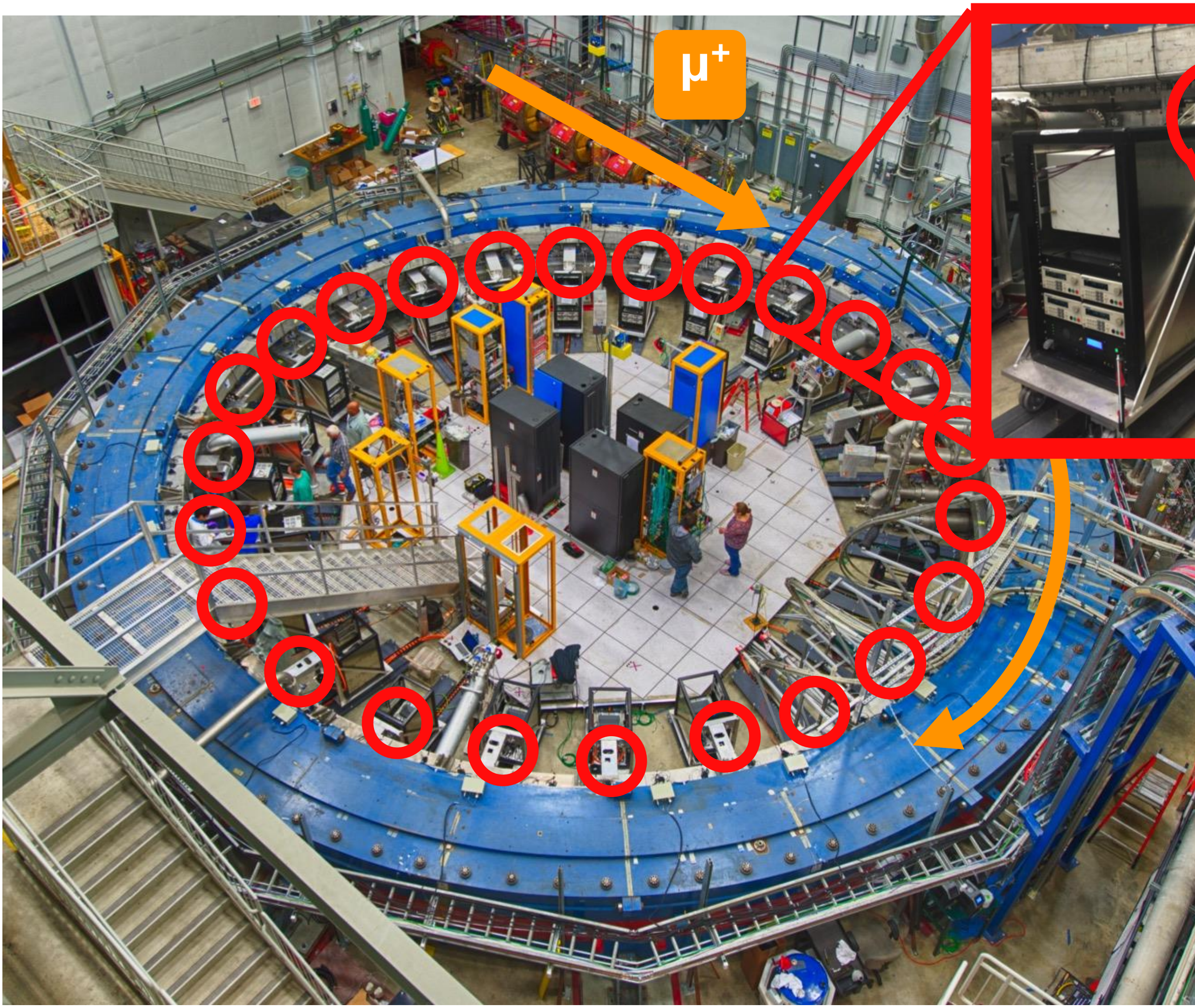
The number of high momentum positrons above a fixed energy threshold oscillates at precession frequency





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

Calorimeters



24 Calorimeters

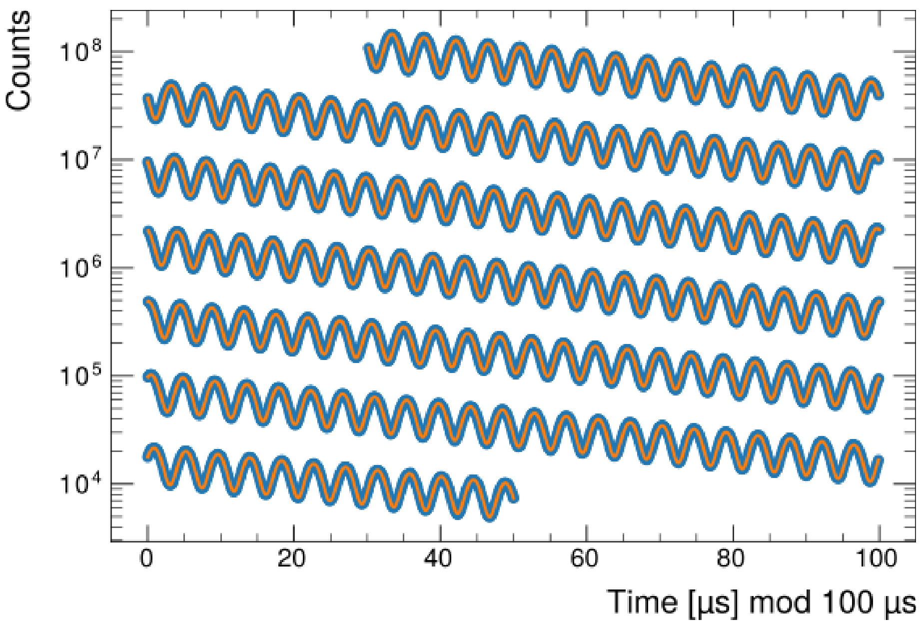
Each crystal array of 6 x 9 PbF_2 crystals - 2.5 x 2.5 cm^2 x 14 cm ($15X_0$)

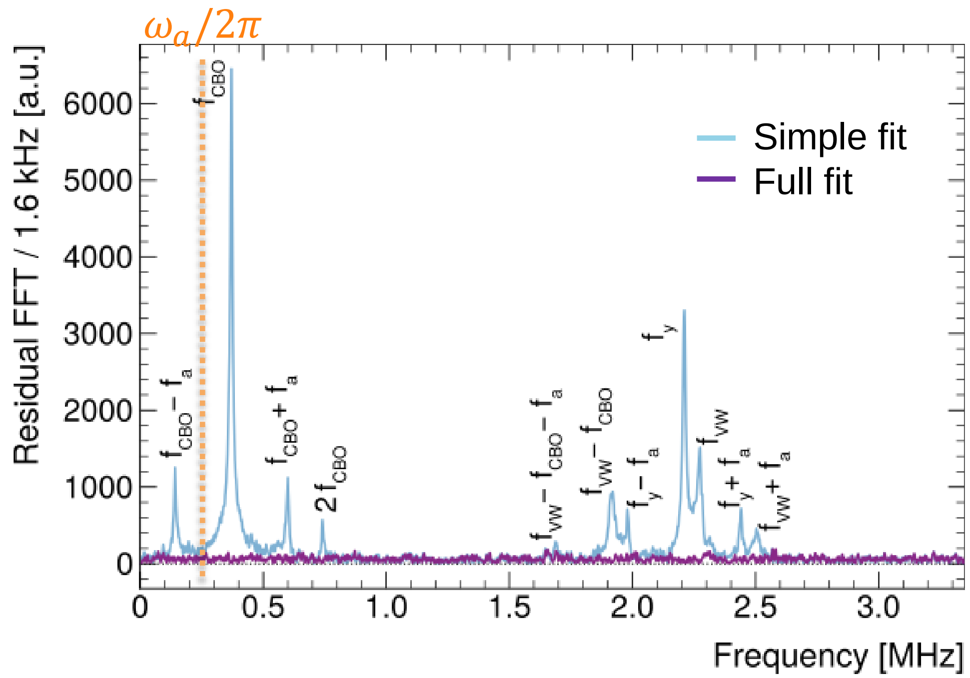
Readout by SiPMs to 800 MHz WFDs (1296 channels in total)

Fitting ω_a

Simplest fit model captures **exponential decay** & **g-2 oscillation**

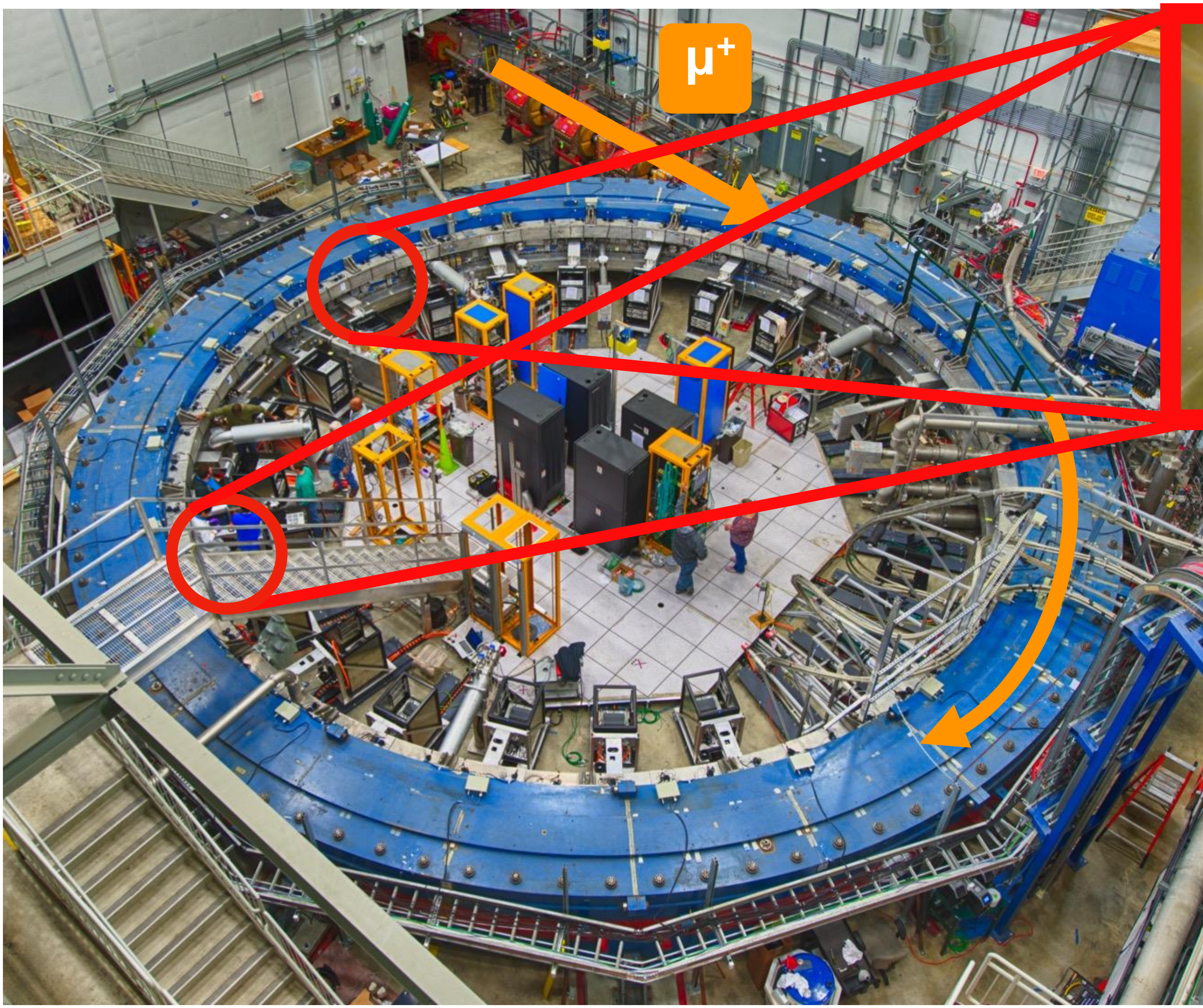
$$N(t) = N_0\, e^{-t/\tau}\,[1 + A\cos(\omega_a t - \phi_0)]$$

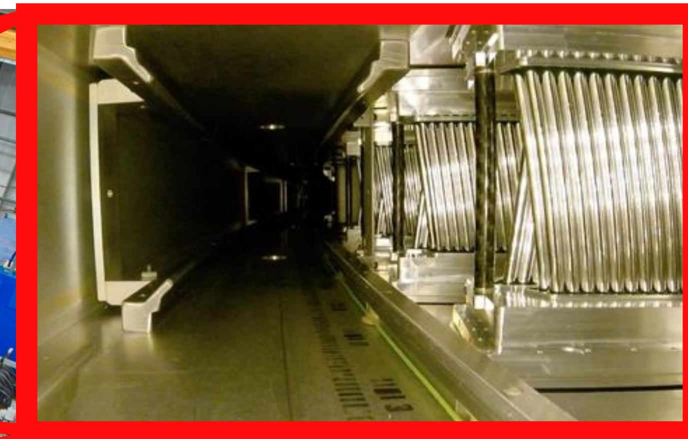


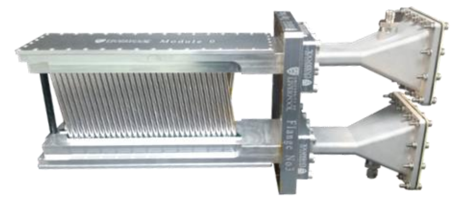


- Beam frequencies show up in the residuals of a simple 5 parameter fit
- After accounting for these frequencies in the final fit, the residuals are removed
- $\chi^2/NDF = 4007/4097$ for highest statistics dataset

Tracking Detectors







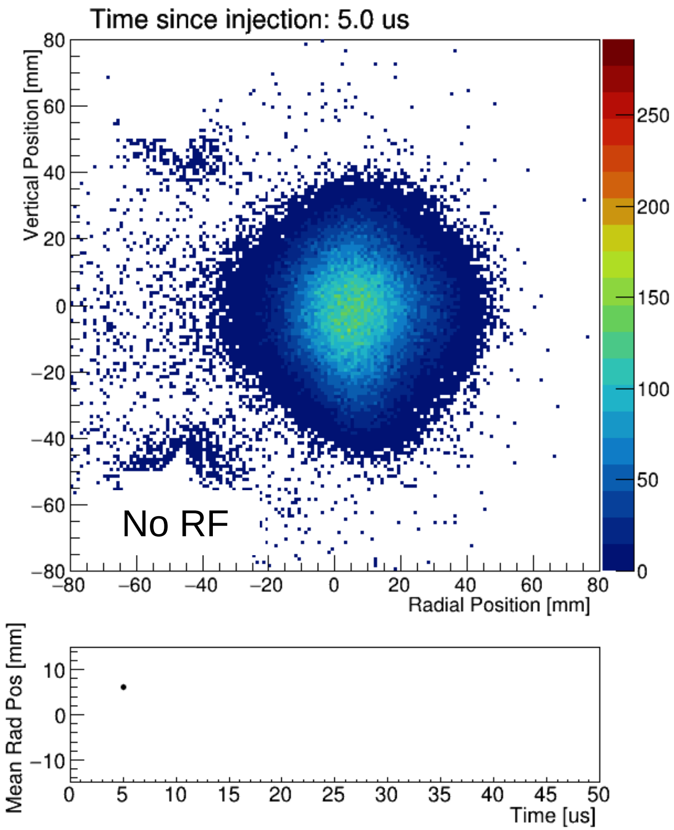
2 Tracking stations

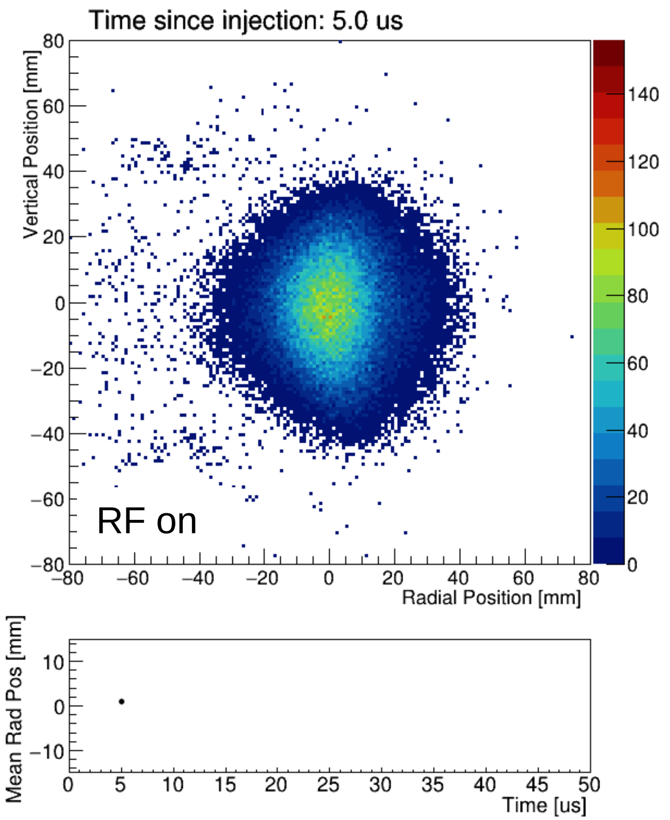
Each contain 8 modules

128 gas filled straws in each module

Traceback positrons to their decay point

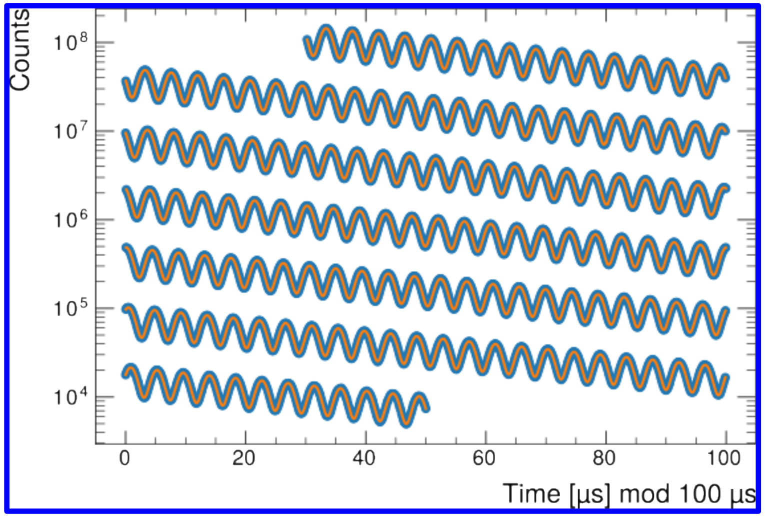
Beam Measurements





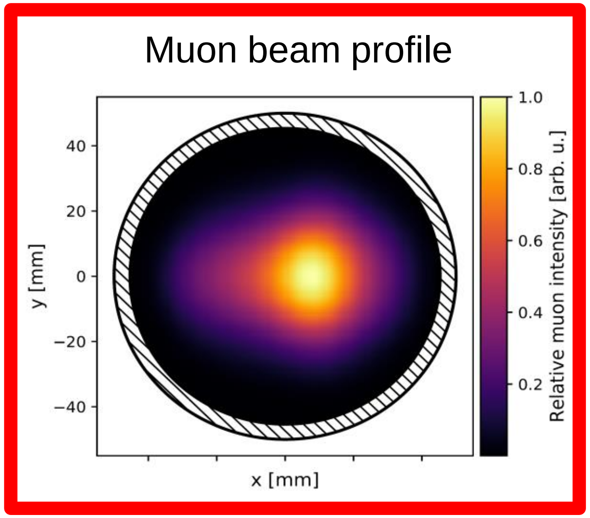
- Use the tracking detectors to measure the decay positrons to infer the decay position
- Muons oscillate radially and vertically at different frequencies, according to the quadrupole strength, and RF conditions

Field measurement



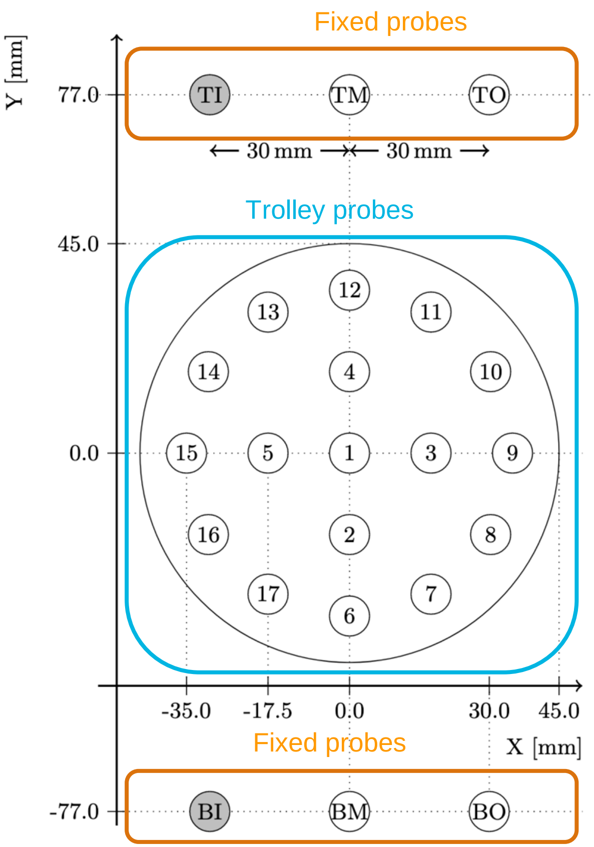
$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m (1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml})}{f_{\text{calib}}\ \langle \omega'_p(T_r) \times M \rangle (1 + B_k + B_q)}$$

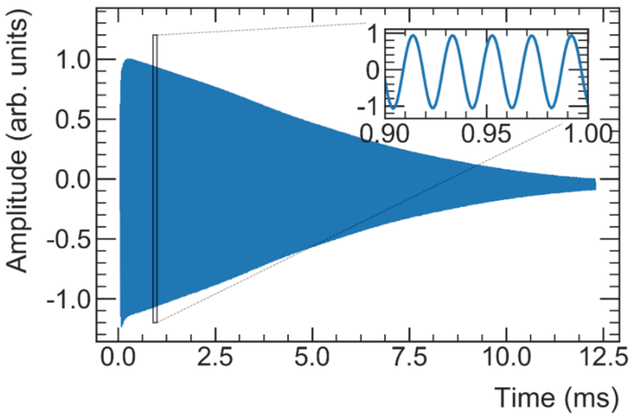
Measuring the magnetic field



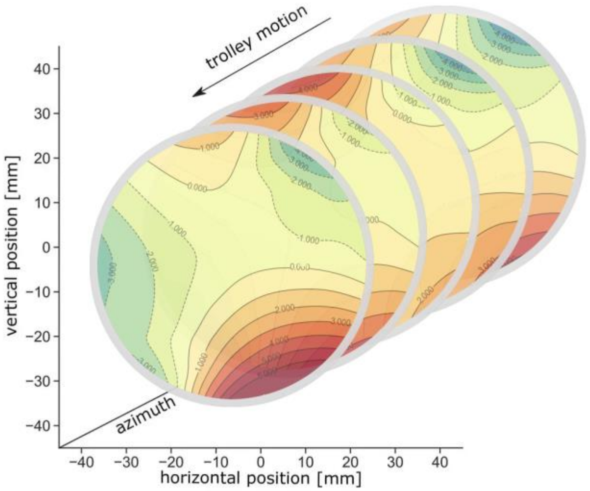
Measuring the field: the NMR Trolley

- An in-vacuum trolley with 17 NMR probes drives around the ring every ~3-7 days, mapping out the field components





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

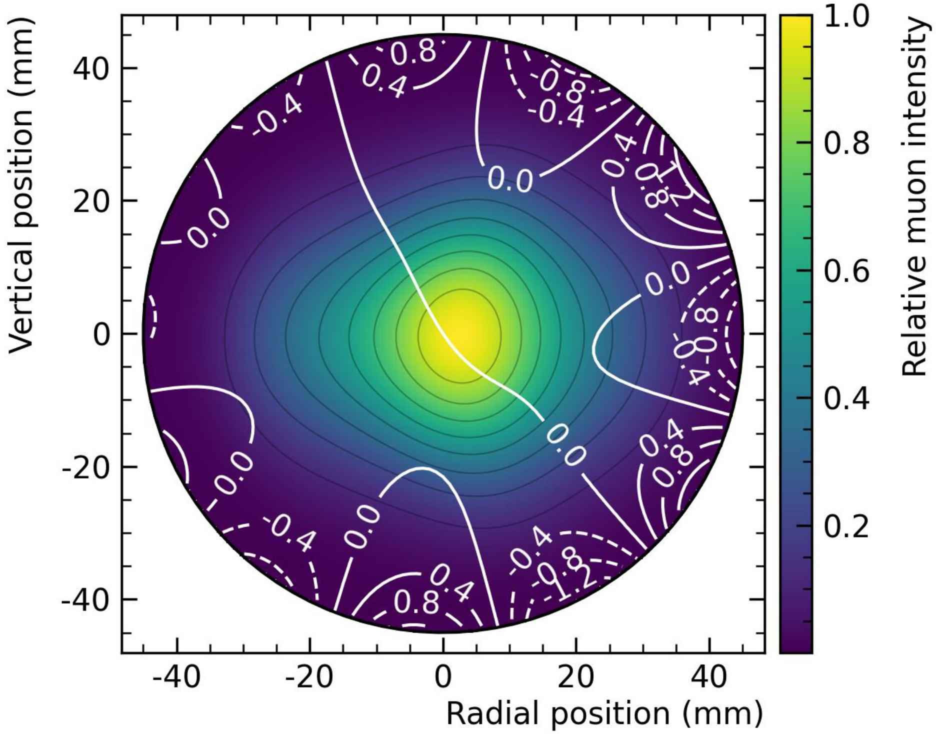


At ~8000 azimuthal locations, obtain a field contour plot from the 17 probes

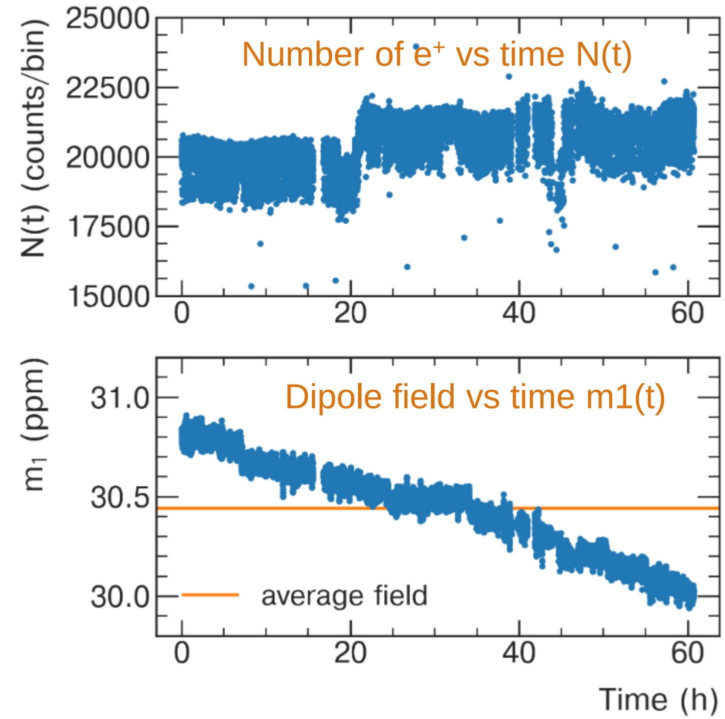
- Use fixed probe to tie together field from bookended trolley run to interpolate field during muons fills

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

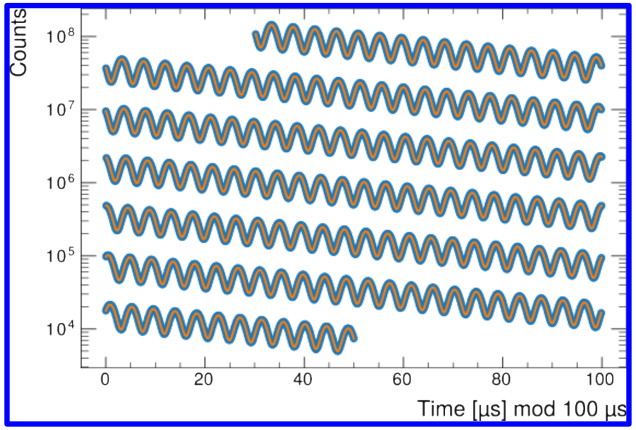


The field is weighted by the 2D beam distribution. An average beam distribution for every 3 hours is used.



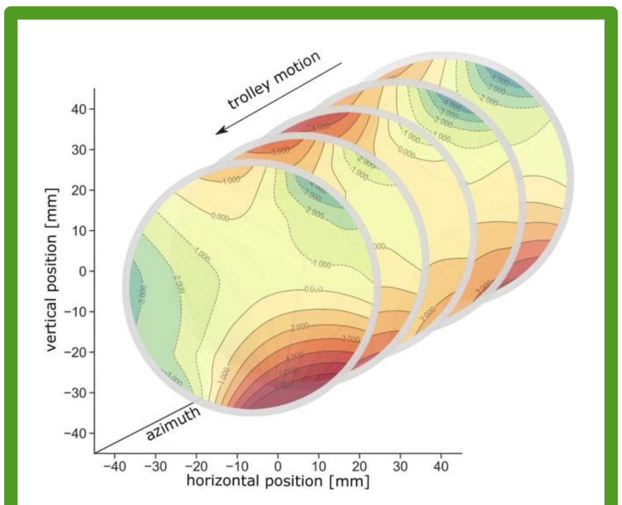
Measured field (every 1.7 s) is weighted by the number of detected e^+

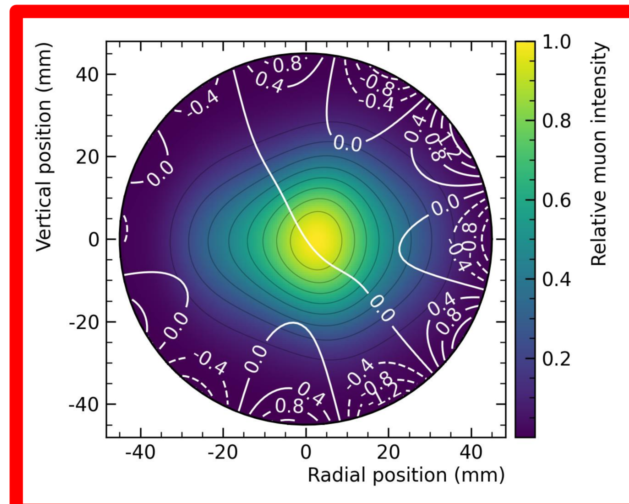
Corrections



Beam and Field Corrections

$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\,\omega_a^m(1+C_e+C_p+C_{pa}+C_{dd}+C_{ml})}{f_{\text{calib}}\,\langle\omega'_p(T_r)\times M\rangle(1+B_k+B_q)}$$



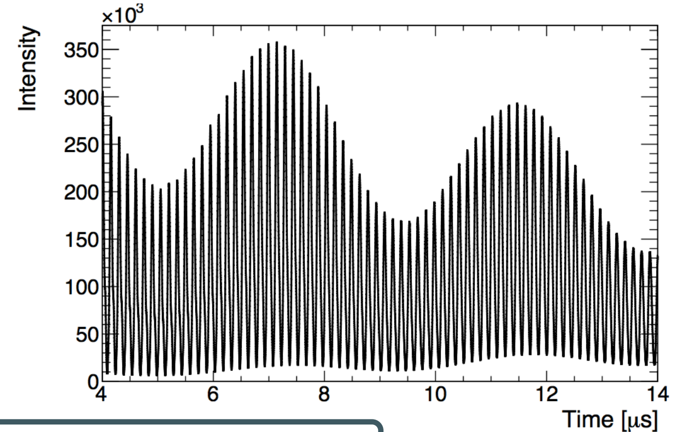


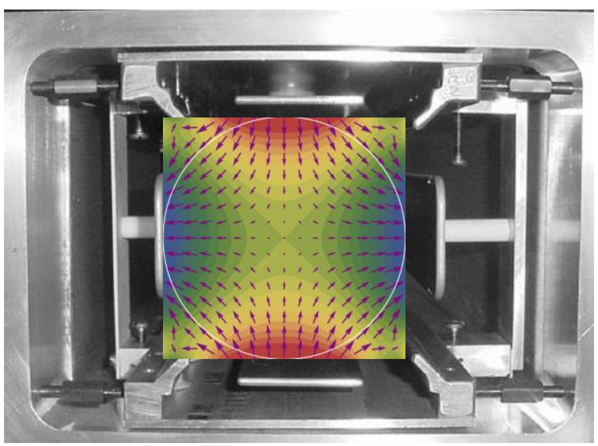
E-field Correction

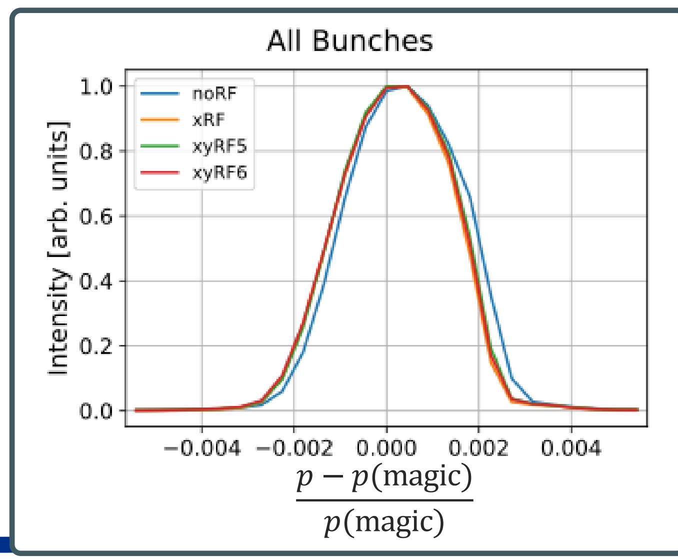
$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\, \omega_a^m (1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml})}{f_{\text{calib}}\, \langle \omega'_p(T_r) \times M \rangle (1 + B_k + B_q)}$$

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

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



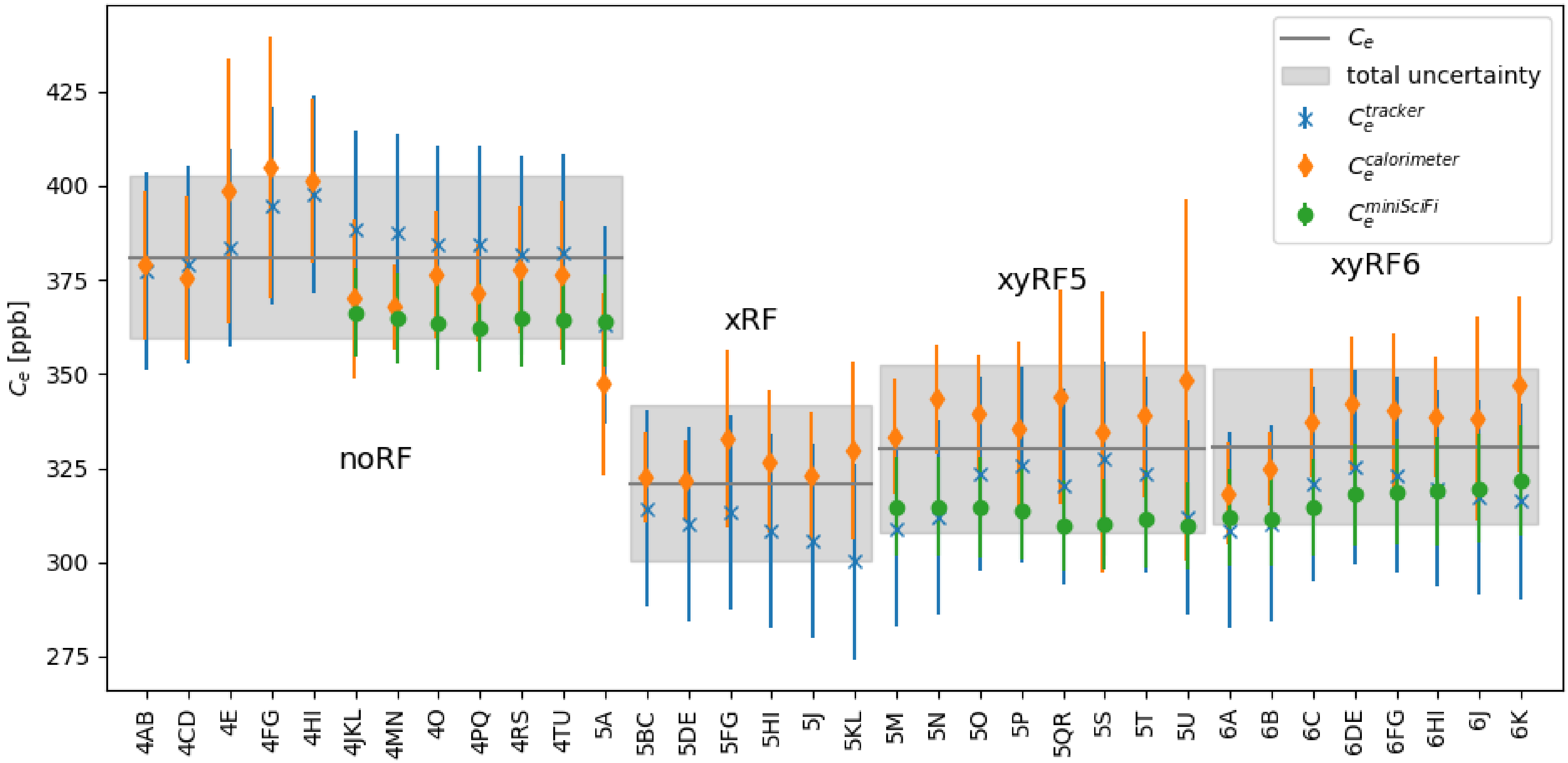




$$C_e = -2n(1-n)\beta^2 \frac{\langle x_e^2 \rangle}{R_0^2}$$

Correction is ~0.4ppm (!)

E-field Correction



- As is typical with all corrections, multiple methods were used to extract the size of the correction, and the corresponding uncertainty. Good agreement between all cross checks

Corrections - summary

347ppb 175ppb -33ppb 26ppb 0ppb

$$\omega_a = \omega_a^m\left(1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml}\right)$$

Electric-field & Up/Down motion
Spin precesses slower than
in basic equation

Phase changes over each fill:
Phase-Acceptance, Differential
Decay, Muon Losses

-37ppb -21ppb

$$\tilde{\omega}'_p = \omega'_p\left(1 + B_k + B_q\right)$$

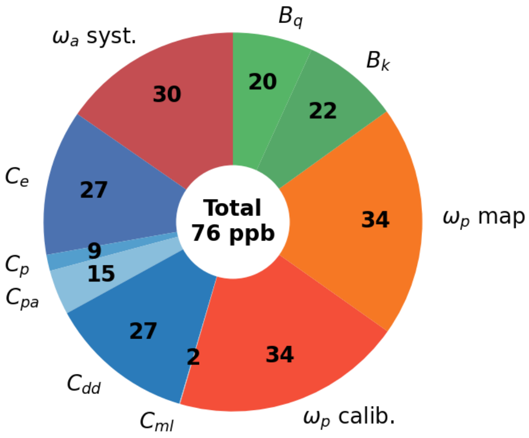
Eddy currents from the kicker
Last into fill time

Vibrations in quadrupoles
disturb the B-field

Uncertainties

Run-4/5/6

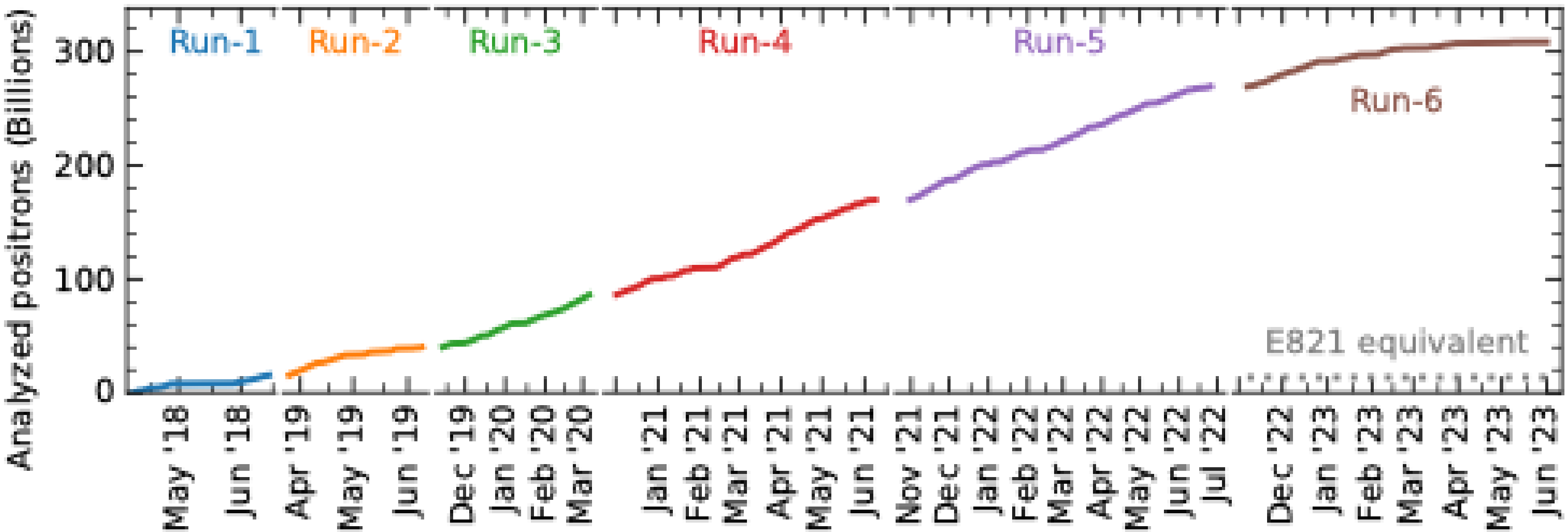
Quantity		Correction (ppb)	Uncertainty (ppb)
ω_a^m (statistical)		$\cdots$	114
ω_a^m (systematic)		$\cdots$	30
C_e	Electric Field	347	27
C_p	Pitch	175	9
C_{pa}	Phase Acceptance	-33	15
C_{dd}	Differential Decay	26	27
C_{ml}	Muon Loss	0	2
$\langle \omega_p' \times M \rangle$ (mapping, tracking)		$\cdots$	34
$\langle \omega_p' \times M \rangle$ (calibration)		$\cdots$	34
B_k	Transient Kicker	-37	22
B_q	Transient ESQ	-21	20
μ_p'/μ_B		$\cdots$	4
m_μ/m_e		$\cdots$	22
Total systematic for $\mathcal{R}_\mu'$		$\cdots$	76
Total for a_μ		572	139



TDR goal of 100ppb reached!

- No dominant source
- Further improving would require to reduce in many categories

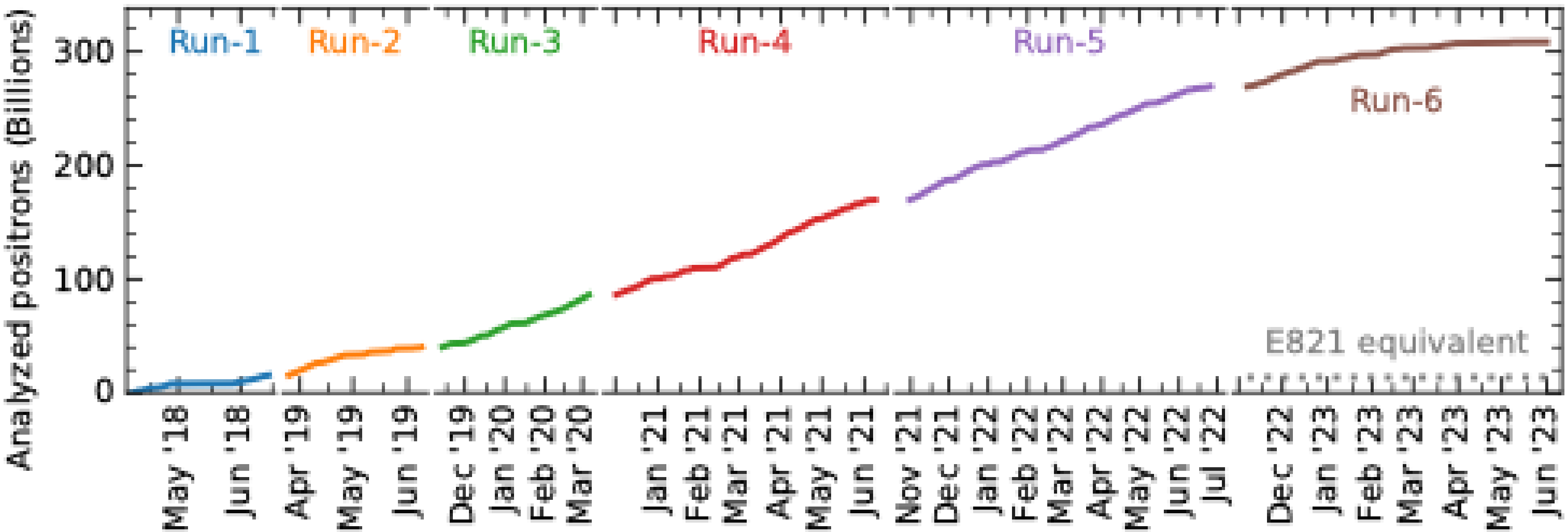
Statistical Improvement



	Analyzed Positrons (10^9)	Fraction (%)	Stat. Uncertainty (ppb)
Run-1	15.4	5	434
Run-2/3	70.9	23	201
Run-4/5/6	222.2	72	114
Run-1-6	**308.5**	…	**98**

TDR goal – 100ppb

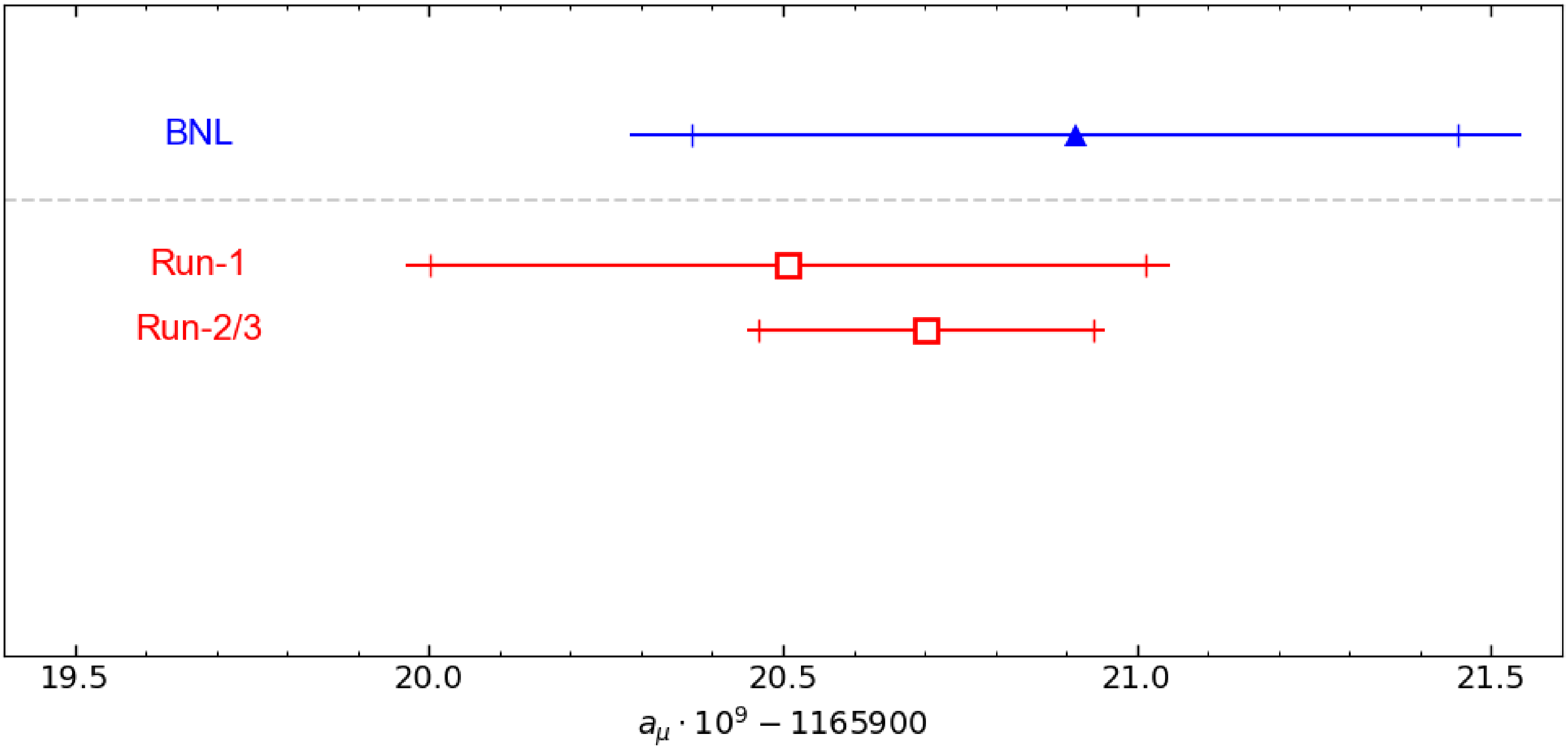
Statistical Improvement



	Stat. Uncertainty (ppb)	Syst. Uncertainty (ppb)	Total Uncertainty (ppb)
Run-1	434	159*	462
Run-2/3	201	78*	216
Run-4/5/6	114	76	137
Run-1-6	**98**	**78**	**125**

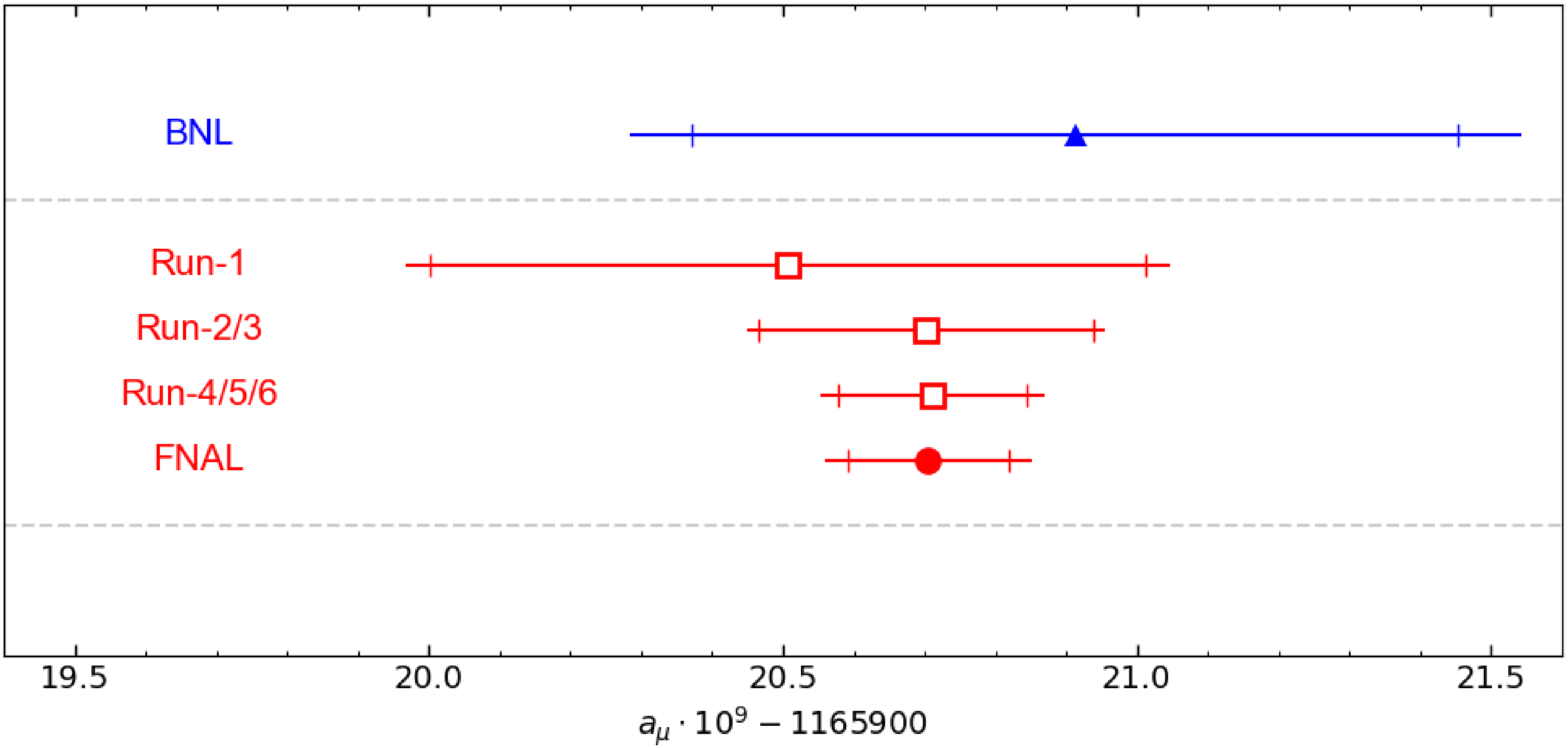
TDR goal – 140ppb

Experimental Result - 2023



- Before the result on June 3rd the experimental uncertainty was ~200ppb
- This is using the latest CODATA external measurements, and contains small corrections found in the latest analysis

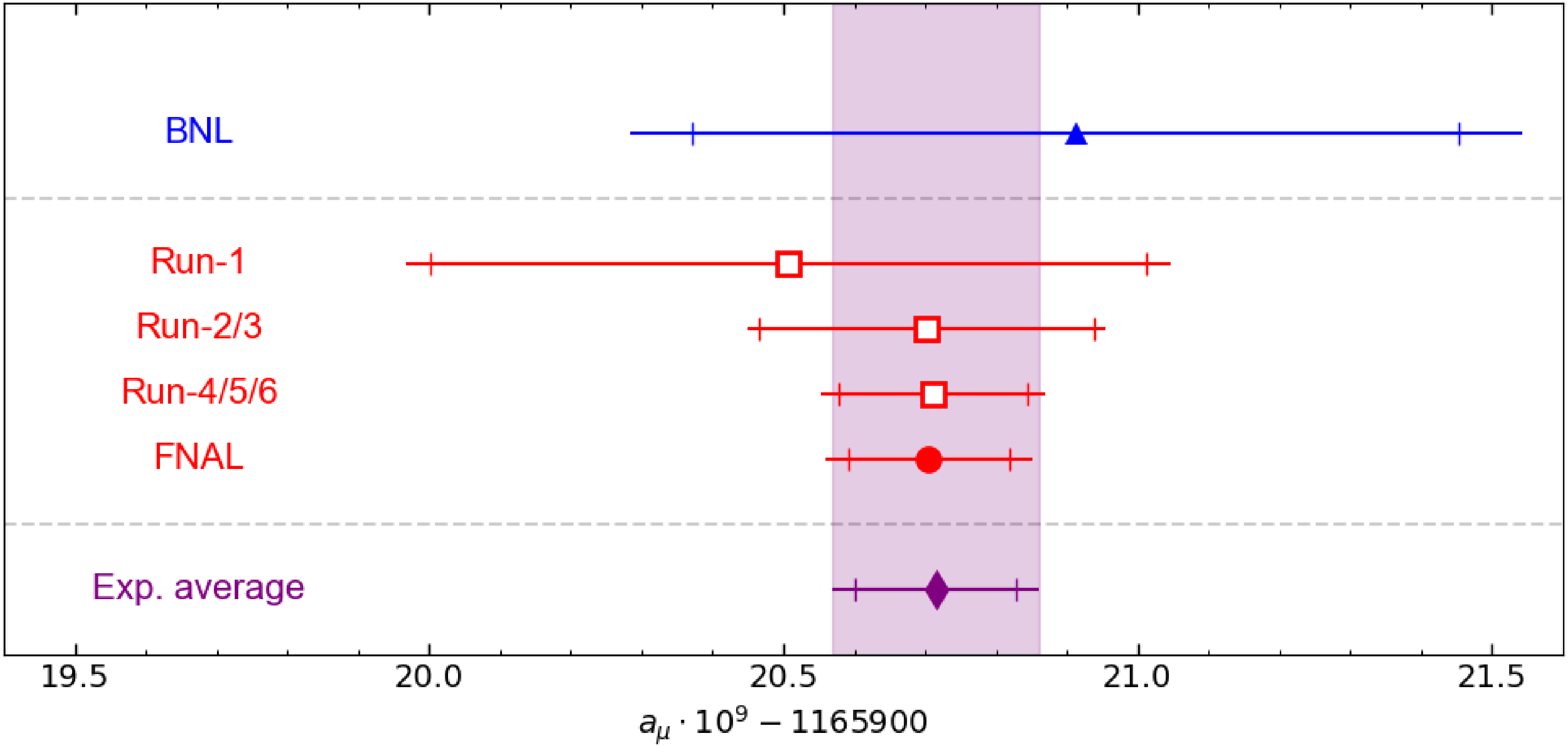
Experimental Result - 2025



- Including the latest result the **Fermilab** average is:

$$a_\mu(\text{FNAL}) = 116\,592\,0705(148) \times 10^{-12}\ (127\text{ppb})$$

Experimental Result - 2025



- Including the latest result the **Experiment** average is:

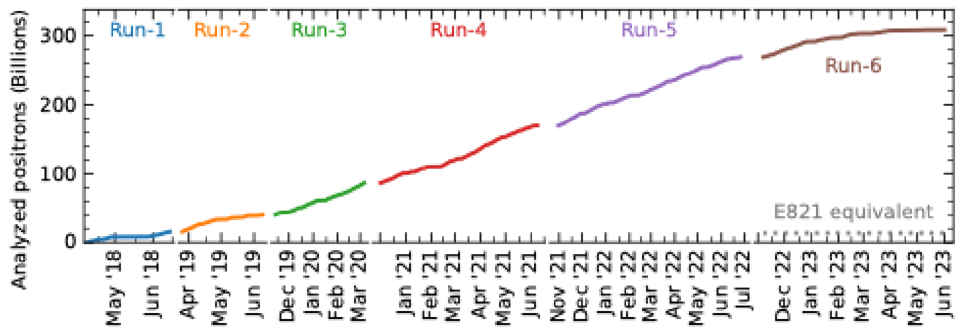
$$a_\mu(\text{EXP}) = 116\,592\,0715(145)\ \times\ 10^{-12}\ (124\text{ppb})$$

Conclusions

- High precision measurement of Muon g-2 is a stringent test of SM theory

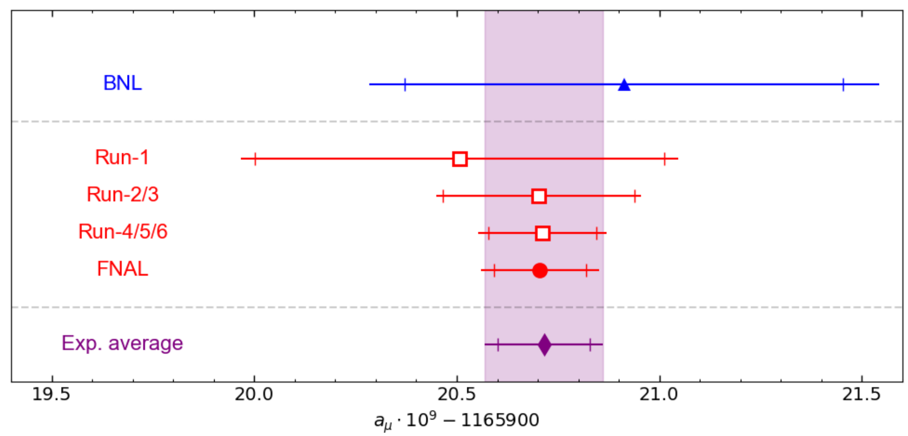
- Full FNAL dataset analysed and published:

  arXiv: [2506.03069]
  PRL pending…



- FNAL measurement surpassed TDR goals in statistics and systematics! More than 4 times more precise than BNL

- Run-4/5/6 data consistent with previous Run-1/2/3 result, and BNL



- More to come from FNAL g-2 experiment:
  EDM measurement
  CPT/Lorentz violation searches
  Dark Matter search

Thank you!

US Universities
- Boston
- Cornell
- UIUC
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central College
- Regis
- Trinity
- Virginia
- Washington
- York CUNY

US National Labs
- Argonne
- Brookhaven
- Fermilab

176 collaborators
34 Institutions
7 countries

China
- Shanghai Jiao Tong

Germany
- Dresden
- Mainz

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

Korea
- CAPP/IBS/KAIST

Russia
- Budker/Novosibirsk

United Kingdom
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London

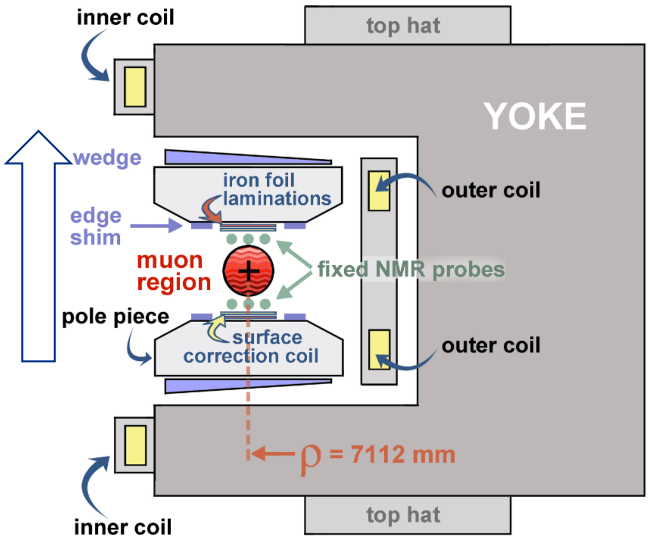
Muon g-2 Collaboration Meeting @ Liverpool July 2023

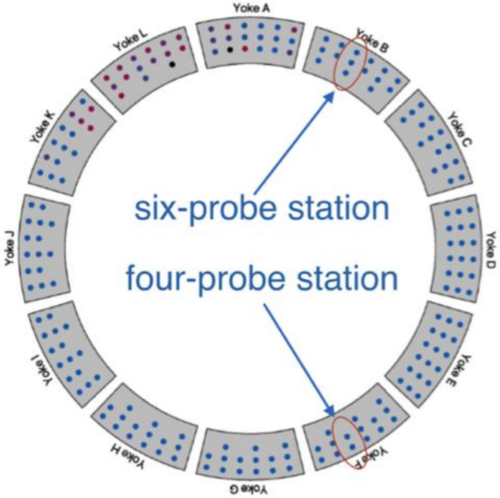
Backups…

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

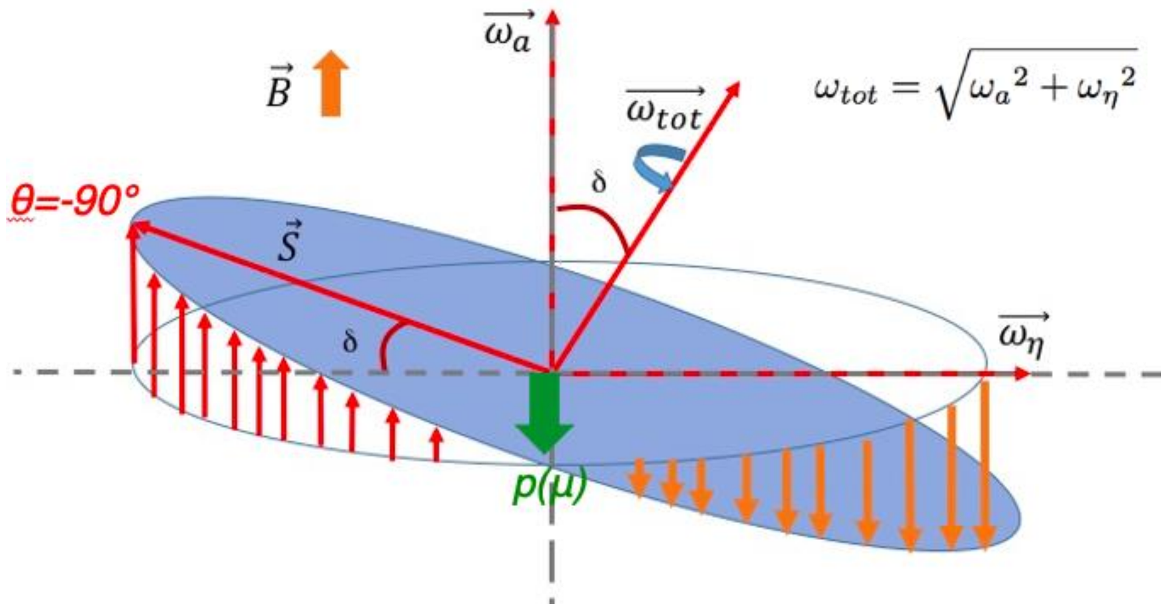




Top-down view

EDM analysis

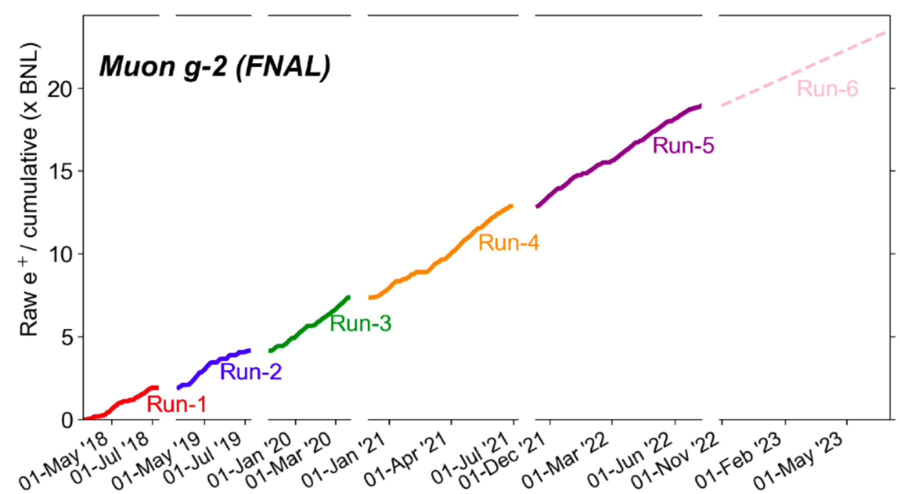
- Muon EDM causes tilt in precession plane
- Asymmetry in vertical decay angle of positrons
- Vertical angle measured by tracking detectors
- Momentum binned analysis for maximum sensitivity



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

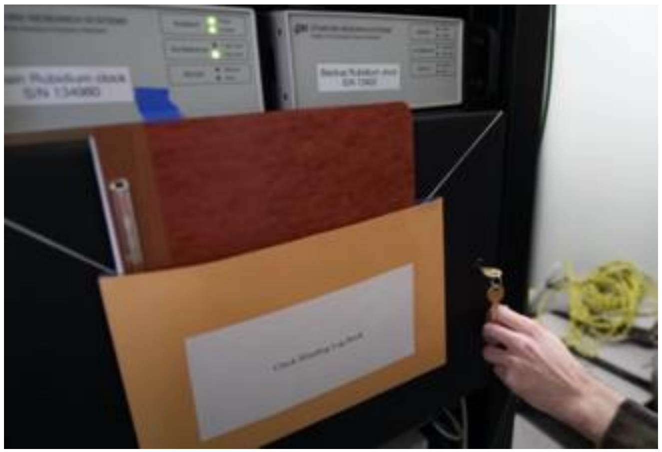
$$|d_\mu| < 2.0 \times 10^{-19} \text{e.cm (95\% C.L.)}$$

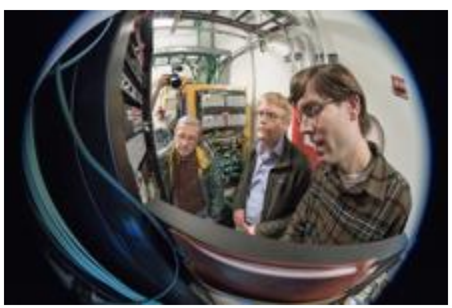
- Still statistically limited in tracker analysis
- Factor of **~10 improvement** for statistics accumulated so far, with tracking improvements

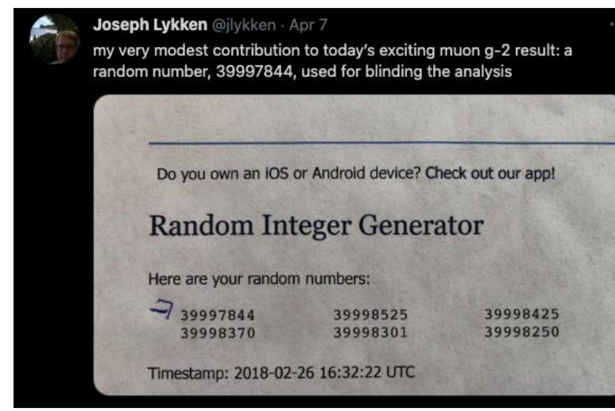


Clock Blinding

- 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 $\times$10 BNL-SM difference)







- Additionally each analysis is blinded in software

Additional measurements

Measurements

Run-4/5/6: Superior Statistics, Additional Measurements

and simulation efforts allowed for many **cross-checks and gain new insights**

To combine our results: use this Run-4/5/6 knowledge for Run-1/2/3

Identified an **Intensity-Dependent Gain Sag**

- with a magnitude below our stability design goal (10^{-4})
- however, **phase-shifted** oscillation at ω_a leads to **larger sensitivity** than orig. estimated
- **Resolved puzzle** of residual slow terms in ω_a-fits
- Run-2/3: +47 ppb $\pm$ 24 ppb (Run-1: +50 ppb $\pm$ 29 ppb)

Improved spatial-model of Kicker-Transients

- Additional, dedicated measurement after muon storage periods
- similar cross-checks for transient fields from ESQ (B_Q), confirmed used model
- Run-2/3: +19 ppb $\pm$ 23 ppb

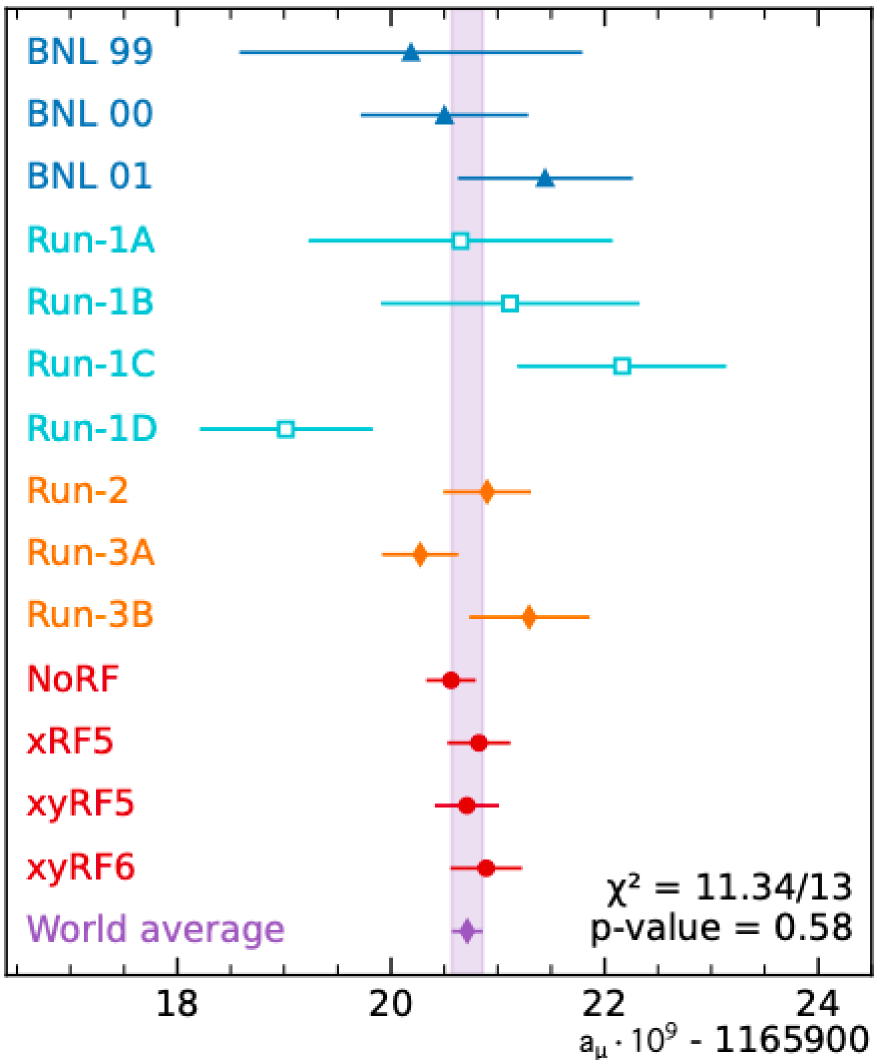
*on a_μ, correction on B_k has opposite sign

Identified and corrected a **sign error**

- in one (of three) contribution to the Differential Decay Correction ($C_{dd}^{beamline}$)
- Run-2/3: magnitude of $C_{dd}^{beamline}$: 12 ppb to 20 ppb
- Run-2/3: +32 ppb $\pm$17 ppb *uncertainty due to method not sign error

All these correction have the same sign. Run-2/3 total +89 ppb
Total Run-2/3 uncertainty: from 70 ppb to 78 ppb

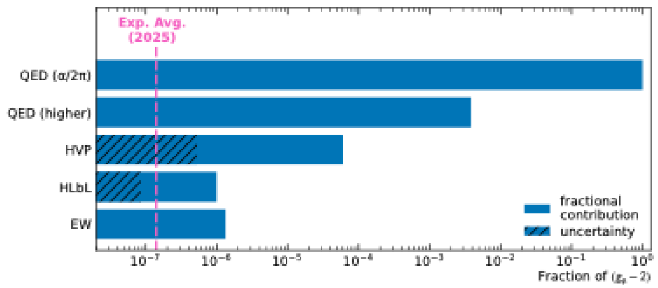
Multiple datasets



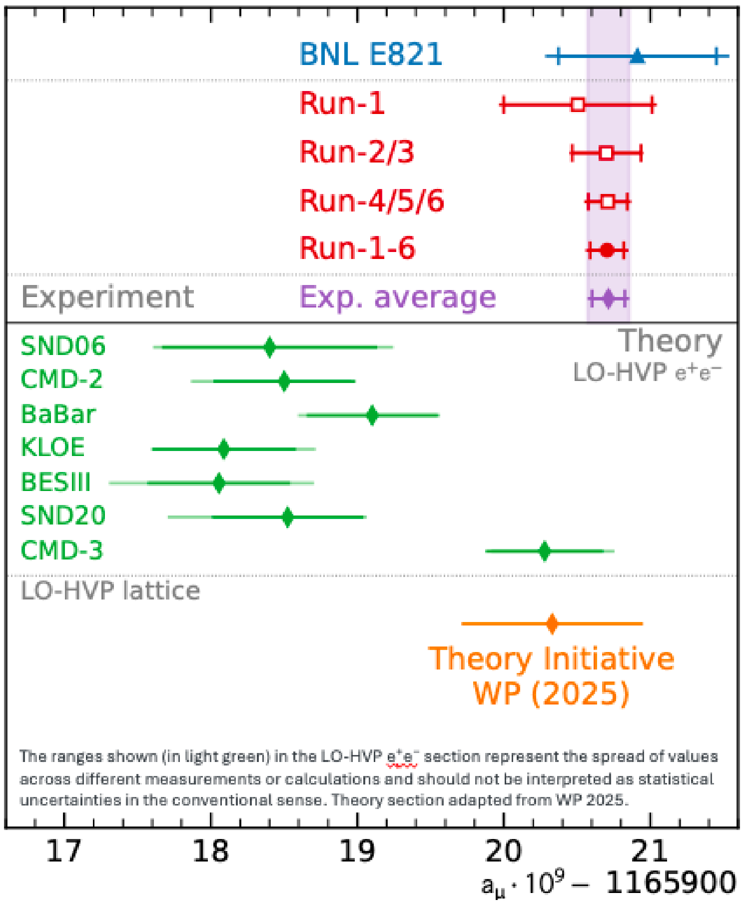
Theory comparison

$a_\mu(\text{Run}-1-6) = 0.001165920705(148)$

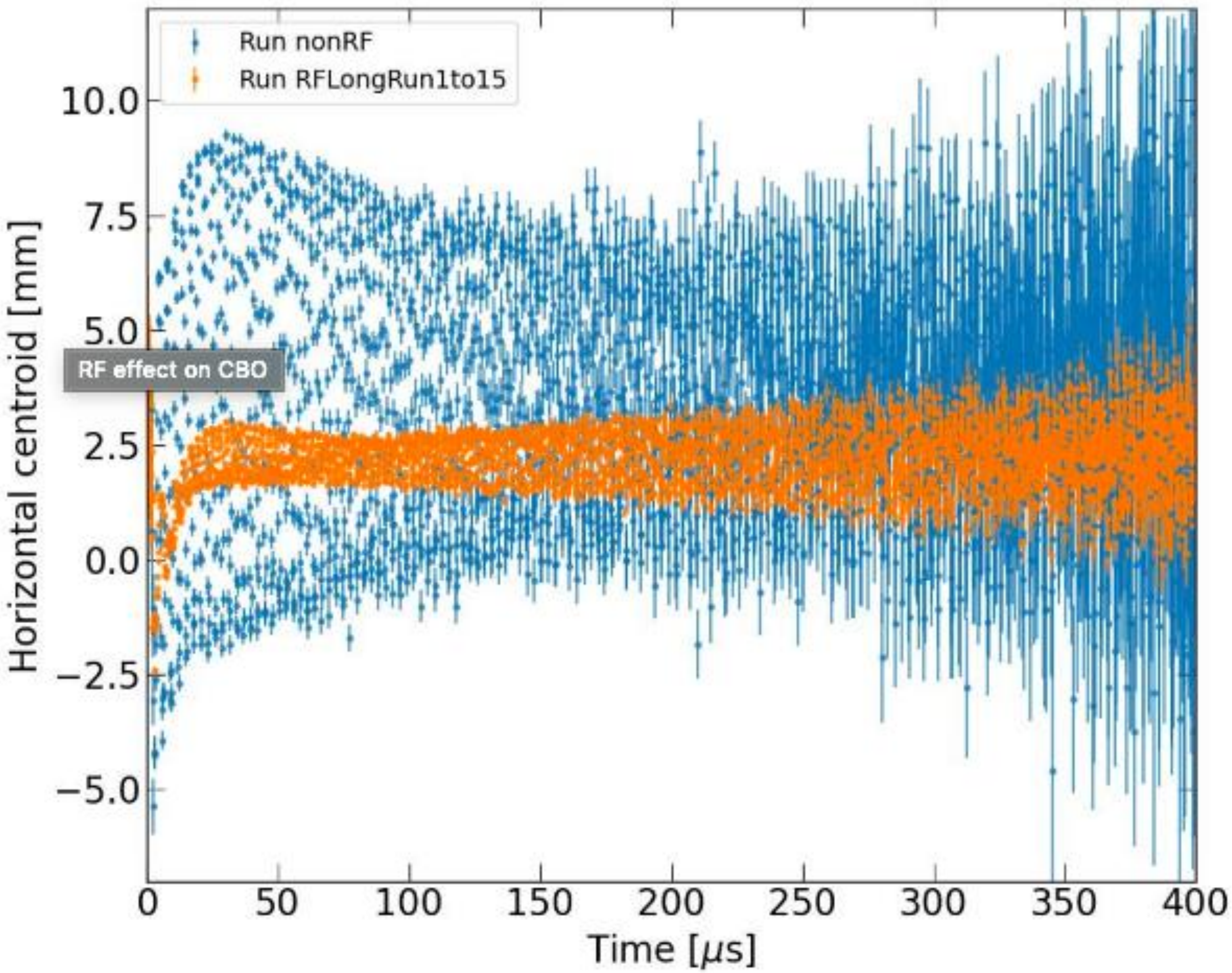
- **Most precise determination of a_μ for many years to come**
- 127 ppb measurement tests all Standard Model contributions



- benchmark for models with new particles or forces (BSM)

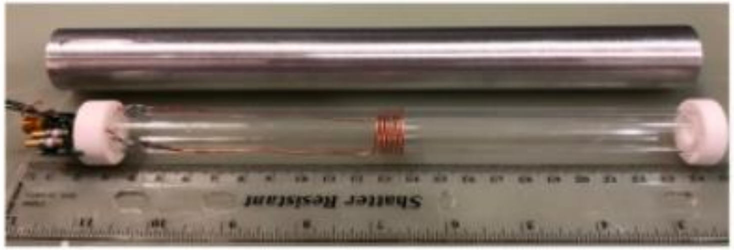


Effect of RF on the beam

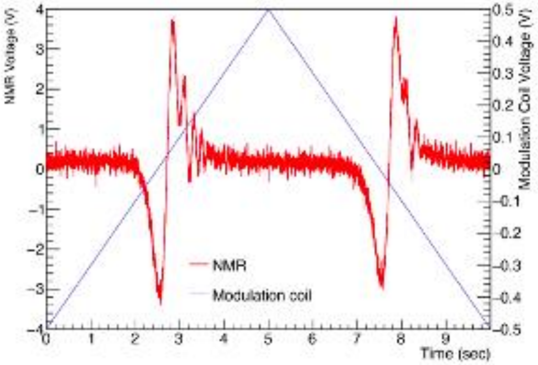


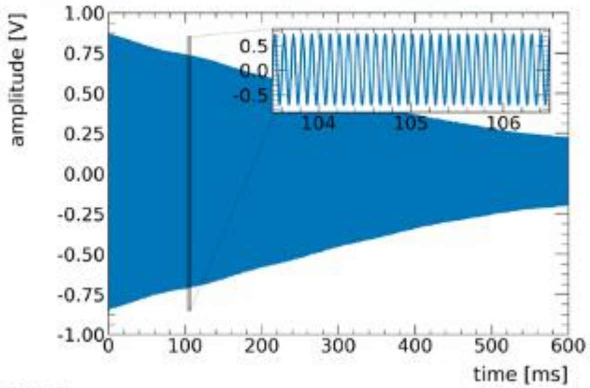
Magnetic field calibration

Water-Based Calibration Probe



J-PARC
Continuous Wave



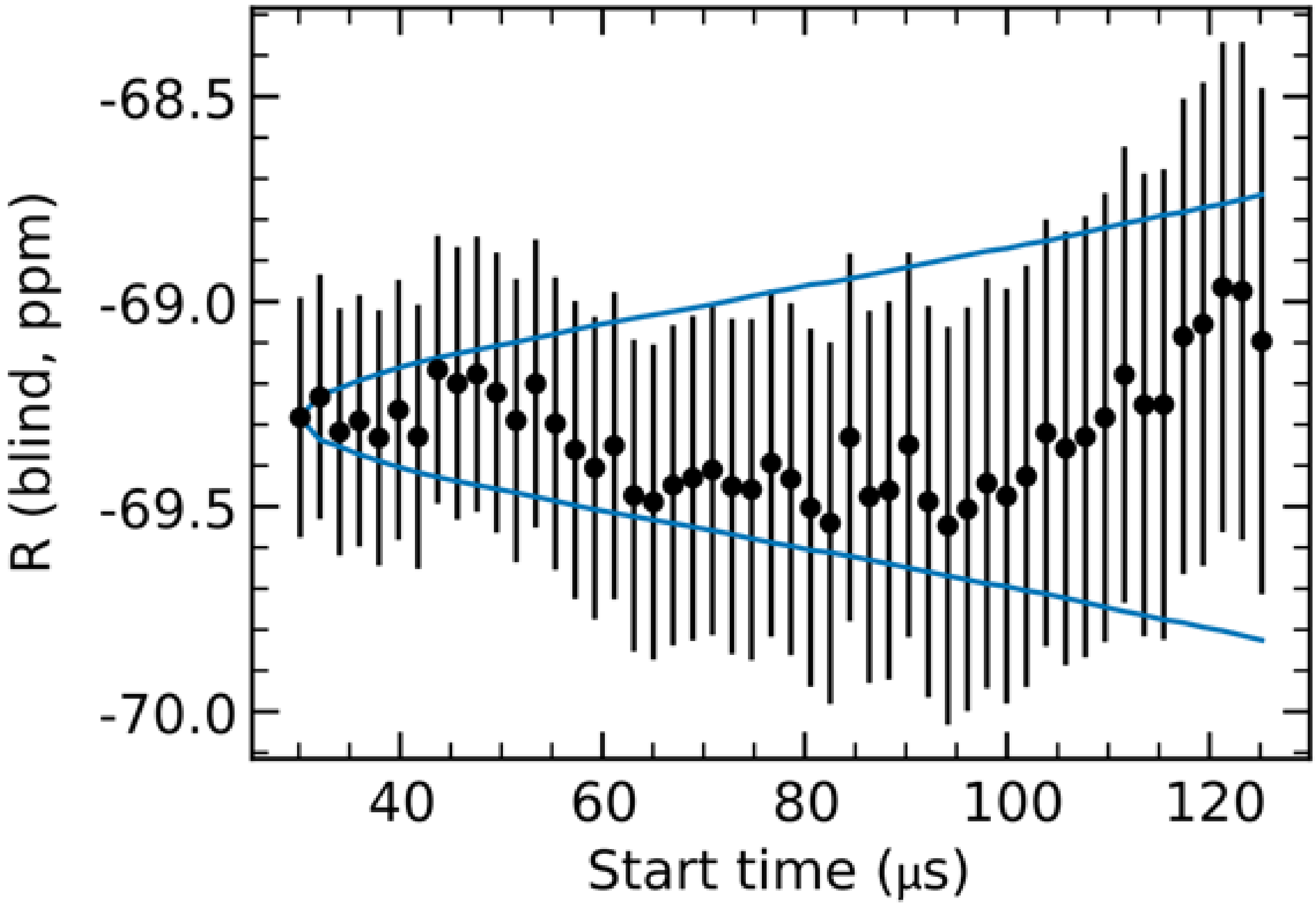


^{3}He-based
Calibration Probe

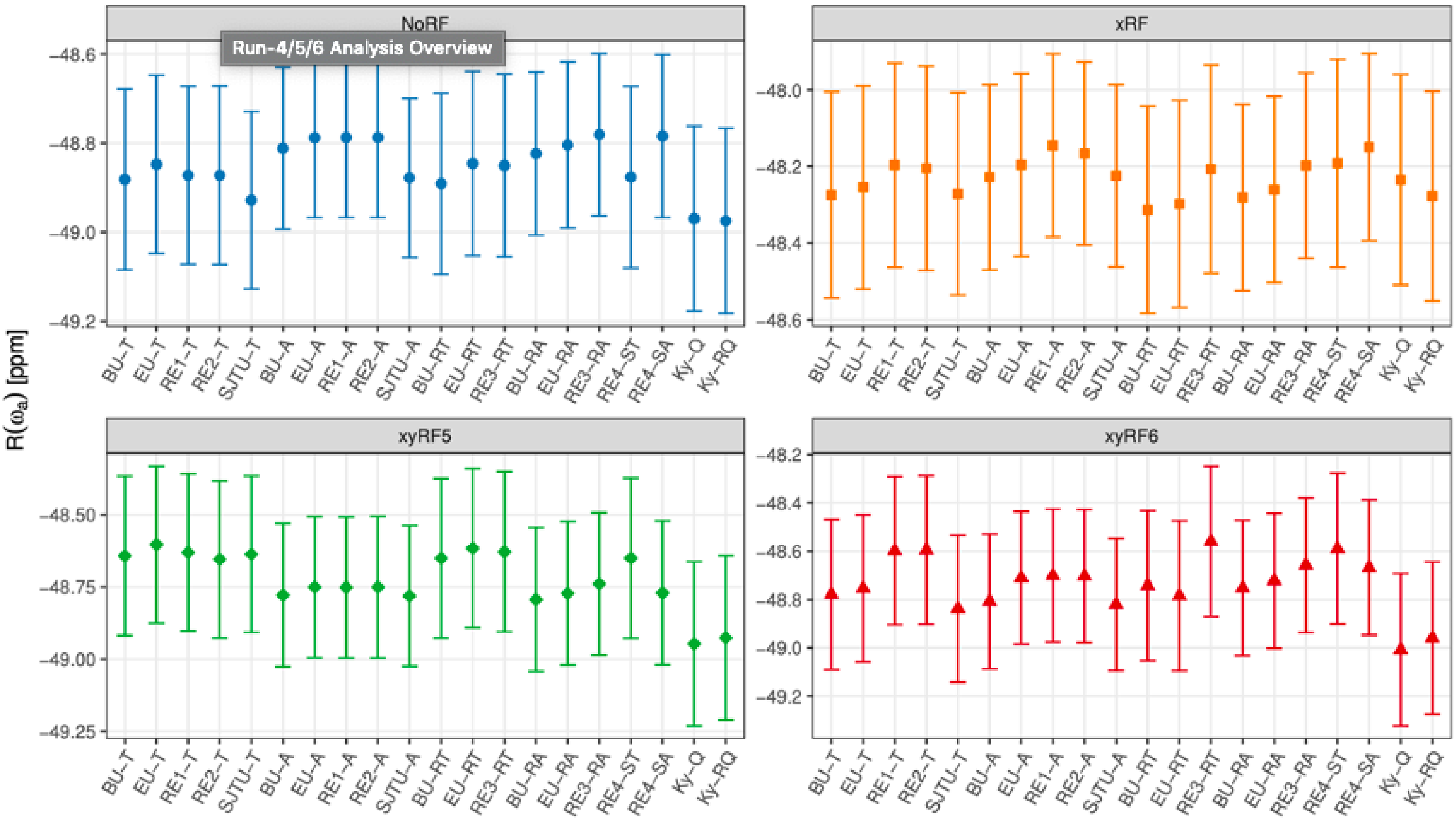
- 2019 (1.45T), 2019 (1.7T) campaigns: some inconsistencies
- 2022 (3T), 2023 (1.45T) campaigns, in good agreement

- Agreement on the 1.7 σ-level

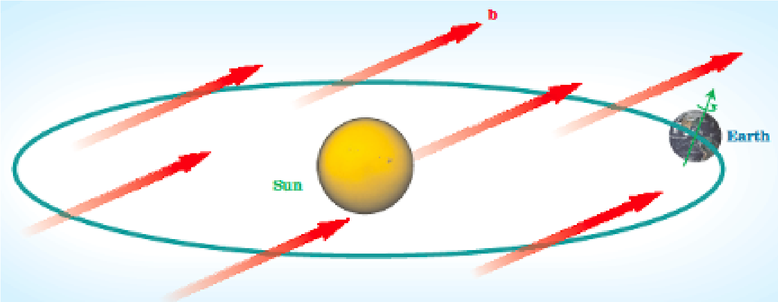
Run 4/5/6 start time scan



Run-4/5/6 Analysis Overview



CPT and Lorentz Violations



Lorentz Violation –
existence of a preferred direction

- Uniform background vector, *b*
- What could it come from?
  Spontaneous Symmetry Breaking,
  - **SM**: In EWSB, scalar field gets non-zero vacuum expectation value, filling vacuum with *Lorentz Symmetric quantities*
  - **SME**: Can have Lorentz SB, where vector field gets non-zero vev, filling vacuum with *4-dimensionally oriented quantities* → preferred direction in space → LV!
  - Possibilities: string theory, loop-quantum gravity, etc.

CPT Violation

- LV *allows* but does not *require* CPTV, because CPT Theorem no longer holds [No Title] (but CPTV does require LV)

Dark Matter - Physics Signature

Muon $g-2$ has a competitive sensitivity to the **ultralight (thus bosonic and wave-like field) muonic DM**. It is the first direct DM search with muons in a storage ring.

- Scalar field (Yukawa coupling) $\phi = \phi_0 \cos(m_\phi t)$
  - It induces oscillating m_μ.

$$\mathcal{L} \supset -g\phi\bar{\mu}\mu - g'\phi^2\bar{\mu}\mu \quad \Rightarrow \quad m_\mu \to m_\mu + g\phi + g'\phi^2$$

  - It leads ω_a to oscillate: $\omega_a \to \omega_a(1 + A_\phi \cos m_\phi t)$

- Pseudoscalar axion-like field $a = a_0 \cos(m_a t)$
  - EDM coupling induces oscillating EDM (d_μ).

$$\mathcal{L} \supset -ig_{\mathrm{EDM}}a\bar{\mu}\sigma^{\lambda\nu}\gamma_5\mu F_{\lambda\nu} \;\Rightarrow\; d_\mu \to d_\mu + g_{\mathrm{EDM}}a$$

Dark Matter - Physics Signature

  - Gradient coupling induces oscillating spin along the axis of the muon's motion.

$$\mathcal{L} \supset g_{a\mu}\partial_\lambda a\bar{\mu}\gamma^\lambda\gamma_5\mu \;\Rightarrow\; \mathcal{H} \supset g_{a\mu}\nabla a \cdot \mathbf{S}$$

  - Both lead to oscillating $\delta\boldsymbol{\omega}_a$ components perpendicular to $\boldsymbol{\omega}_a$.