上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

SJTU

The 13th International Workshop on e+e- collisions from Phi to Psi

Current Status of Muon g-2 Experiment at Fermilab

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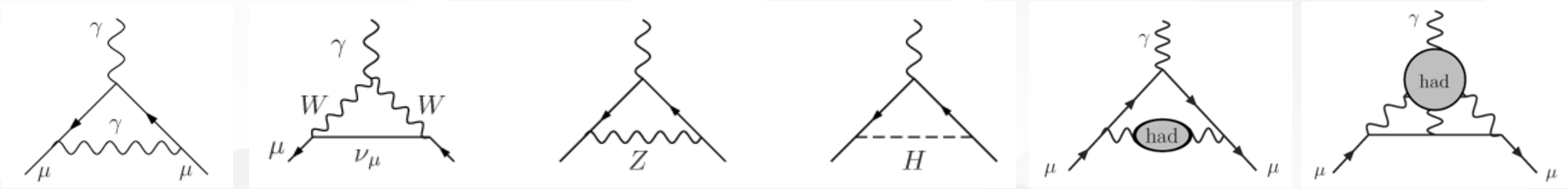
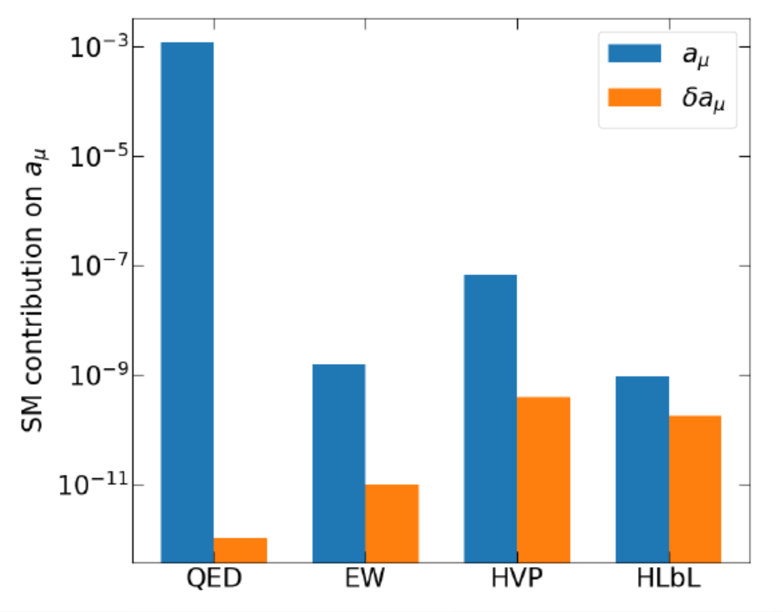
Contents

Introduction & Motivation

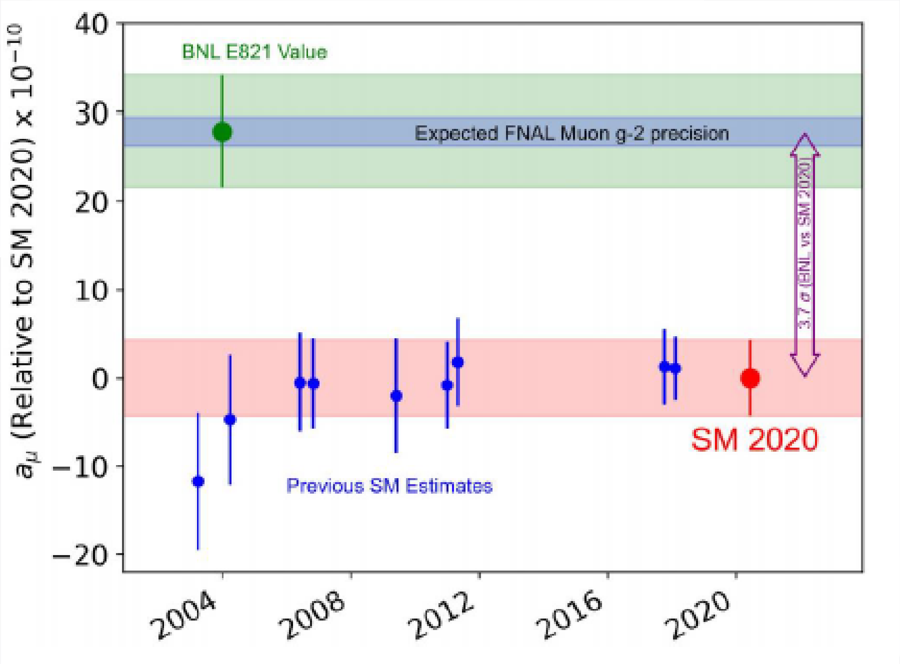
- The muon is the secondary generation lepton
- ~200 times heavier than the electron, ~40,000 times more sensitive
- $\boldsymbol{\mu} = g\frac{e}{2m}\boldsymbol{S}$, with g=2 given by Dirac for spin ½ particles
- Existence of the magnetic "anomaly"
  - ➢Known as Schwinger term: $a_l^{QED,1loop} = \frac{\alpha}{2\pi} \approx 0.00116$
- Contributions to a_μ come from QED, EW and Hadronic

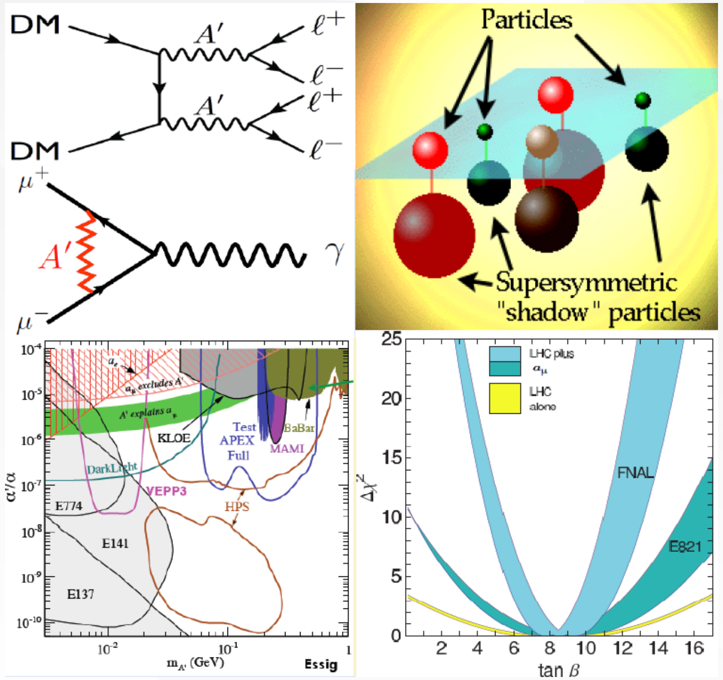
$$a_\mu = \frac{g-2}{2} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HVP} + a_\mu^{HLbL}$$





Comparison between experiment and SM





Discrepancy between SM and experiment before 2021 April: 3.7σ

BNL Result Phys Rev D**73**, 072003 (2006): $a_\mu^{\text{Exp}} = 116\,592\,089\,(63) \times 10^{-11}$ (540 ppb)

2020 Whitepaper Result arXiv:2006.04822v1: $a_\mu^{\text{SM}} = 116\,591\,810\,(43) \times 10^{-11}$ (370 ppb)

Goal: Measure a_μ to 140 ppb, a fourfold improvement over BNL result

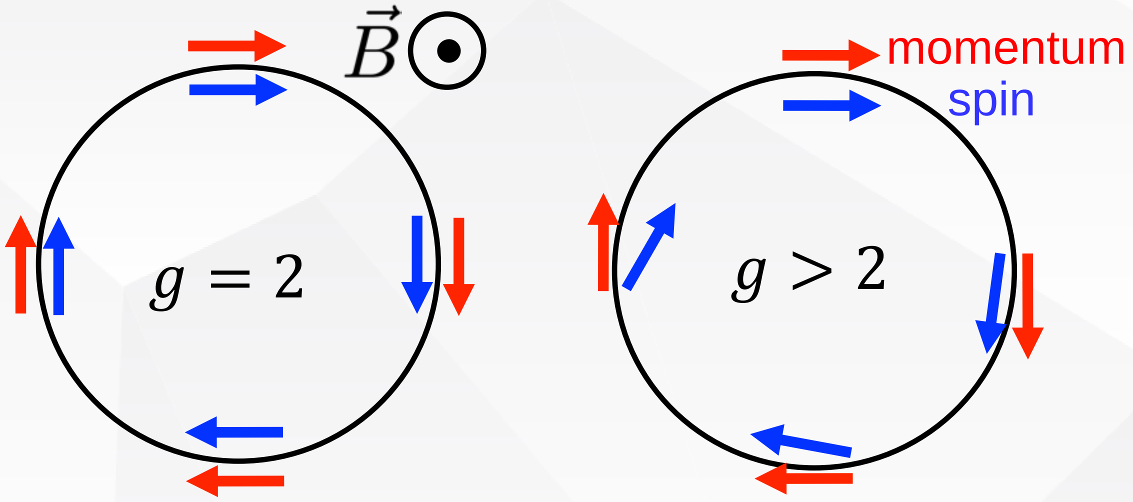
Probe Standard Model predictions for new physics effects

Overview of the Measurement Principle

$$\vec{\omega}_{\text{cyclotron}} = \frac{e}{\gamma m}\vec{B} \approx 2\pi \times 6.7\,\text{MHz}$$

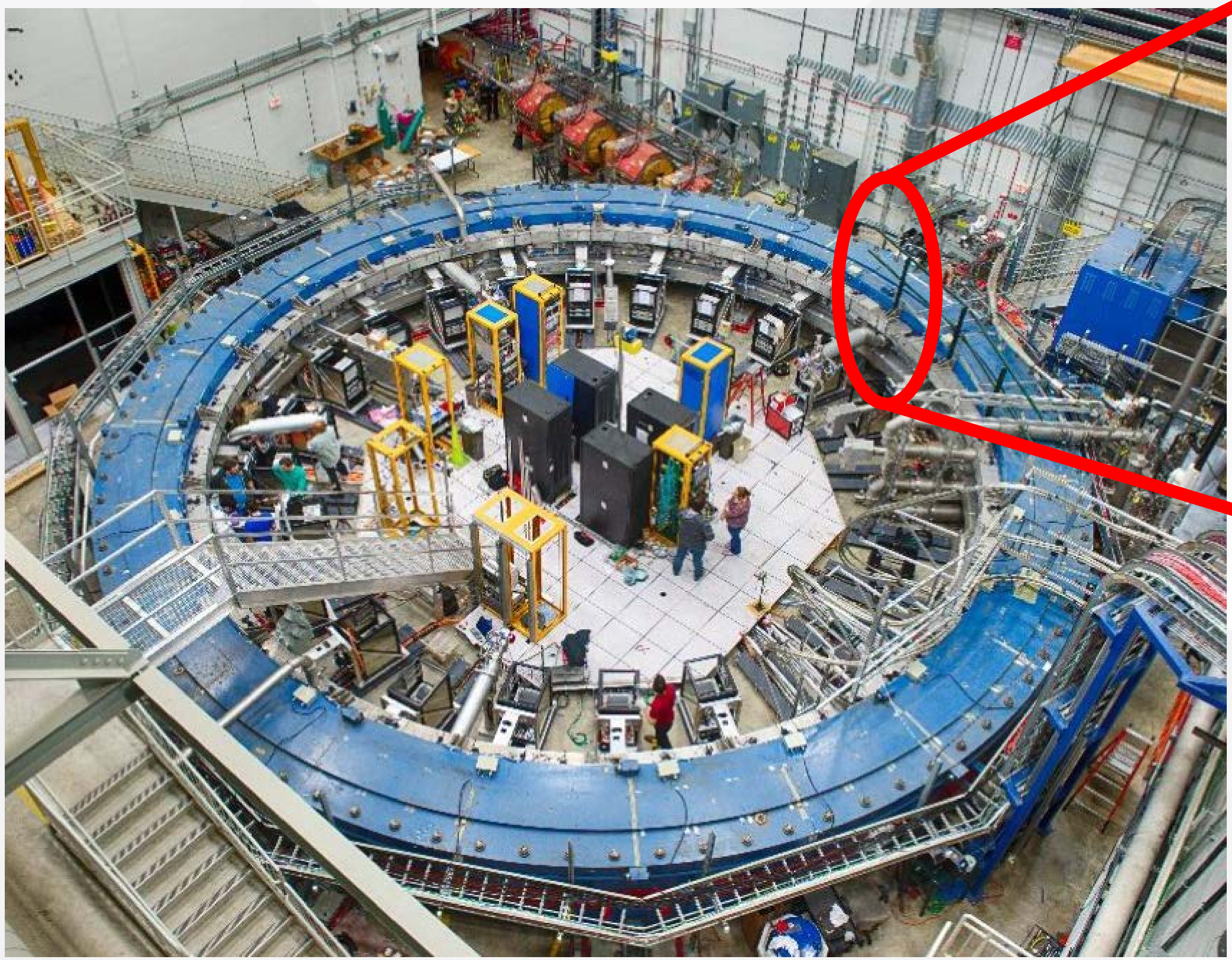
$$\vec{\omega}_{\text{spin}} = g\frac{e}{2m}\vec{B} - (1-\gamma)\frac{e}{\gamma m}\vec{B} \approx 2\pi \times 6.9\,\text{MHz}$$

$$\vec{\omega}_a = a_\mu\left[\frac{e}{m}\vec{B}\right] \approx 229\,\text{kHz}$$

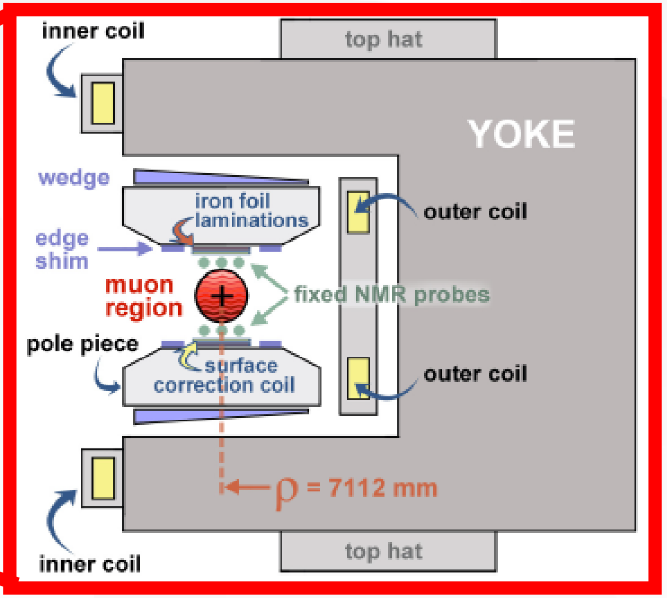


- Want $a_\mu \Rightarrow$ need to measure ω_a and $\vec{B}$
- Muon anomalous precession frequency ω_a
- Uniform magnetic field B in terms of proton NMR frequency: $\hbar\omega_p = 2\mu_p|B|$

Storage Ring Magnet



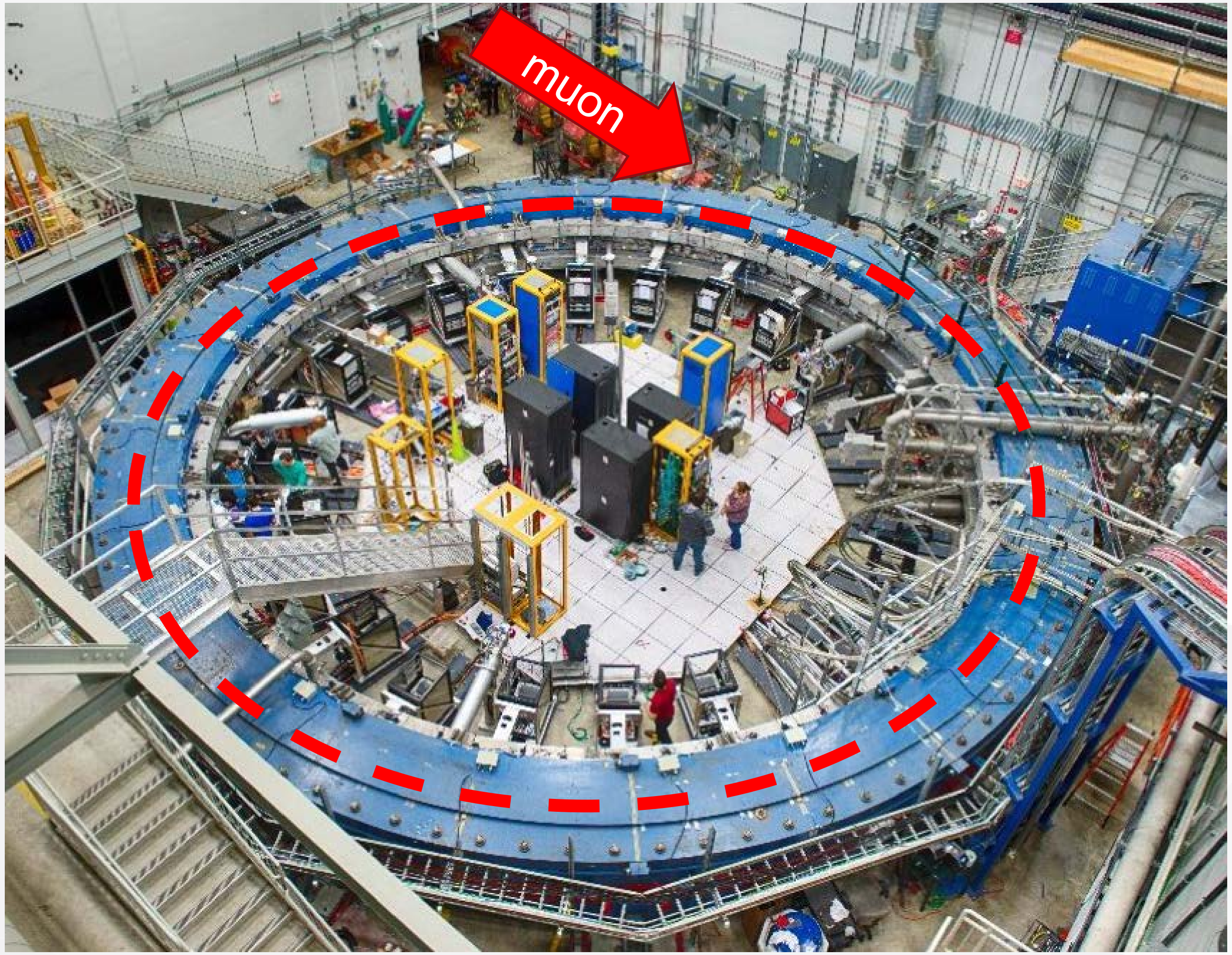
muon storage ring



cross-section
of the yoke

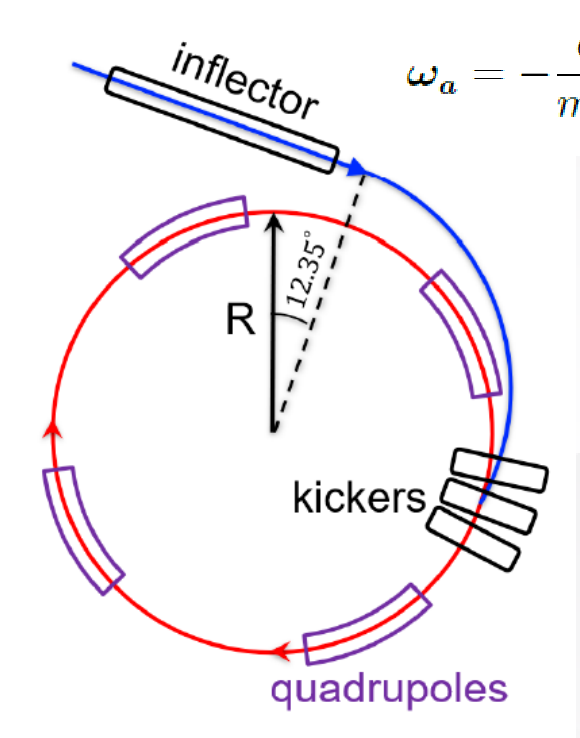
- Superconducting coils
- C-shaped yoke
- 1.45T field strength

Muon Storage



muon storage ring

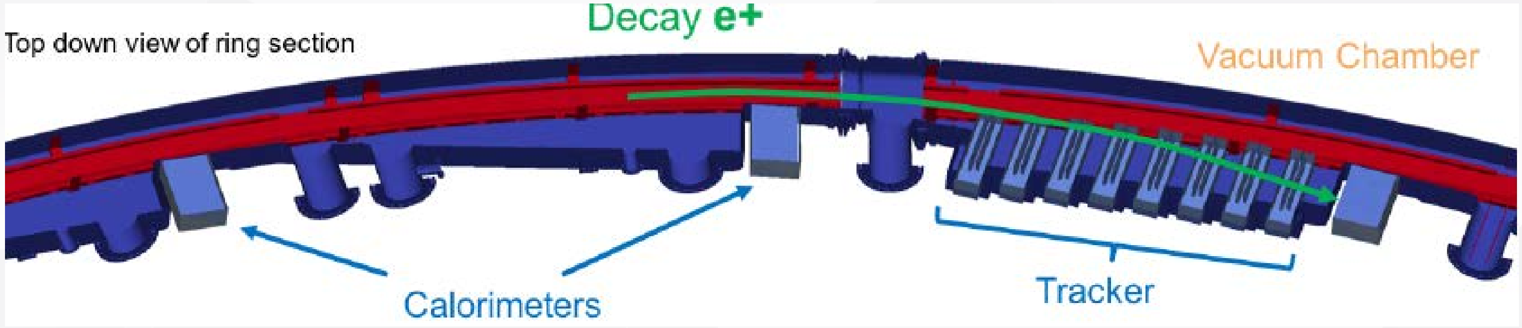
- Injection: inflector magnet
- Kick: fast-kickers
- Vertical focus: electrostatic quadrupoles (ESQ)



$$\boldsymbol{\omega}_a = -\frac{e}{m_\mu}\left[a_\mu \boldsymbol{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\boldsymbol{\beta} \times \boldsymbol{E}}{c}}\right]$$

$$\gamma = 29.3$$
$$p = 3.094GeV/c$$

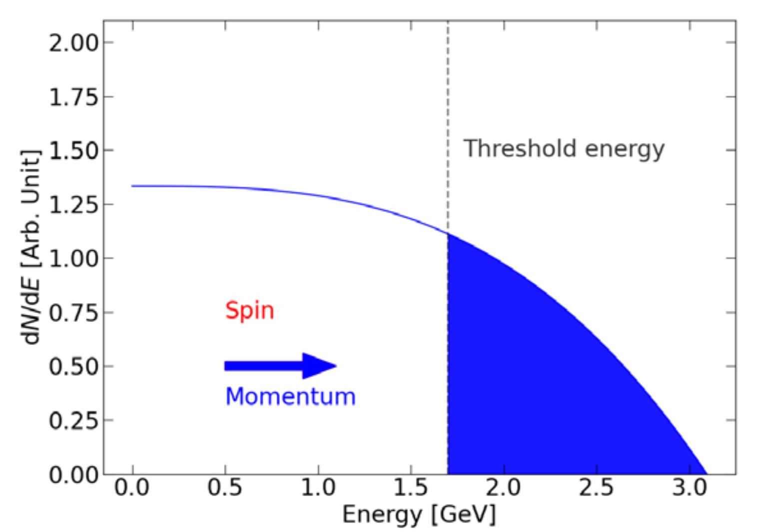
Anomalous Precession Measurement ω_a

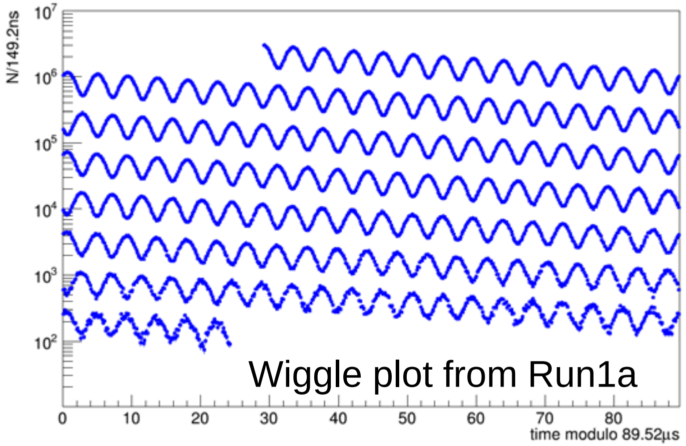


- Self-analyzing decay: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- 24 calorimeters of 9×6 PbF_2 crystals detect e^+
- Highest-energy e^+ emitted preferentially along muon spin
- Results in a “wiggle” arrival time of these e^+ in calorimeters

e^+ Signal from Muon Decay:

$$N_{\text{ideal}}(t) = N_0 \exp\left(-t/\gamma\tau_\mu\right)\left[1 + A\cos\left(\omega_a t + \phi\right)\right]$$

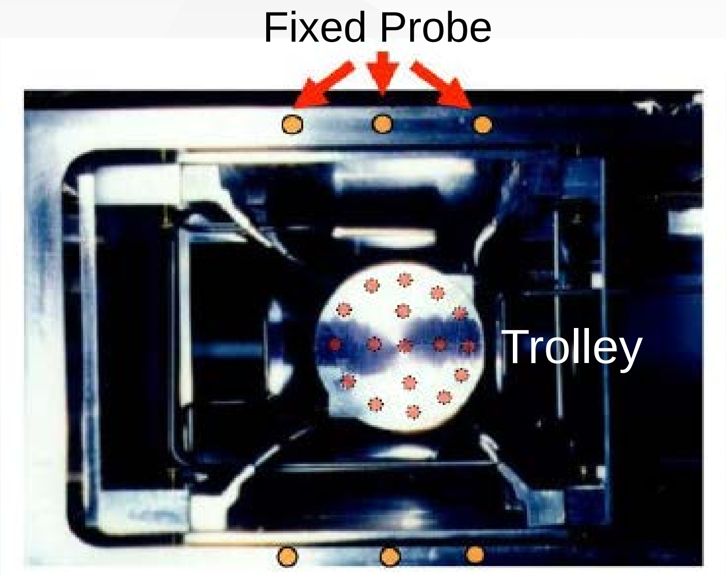


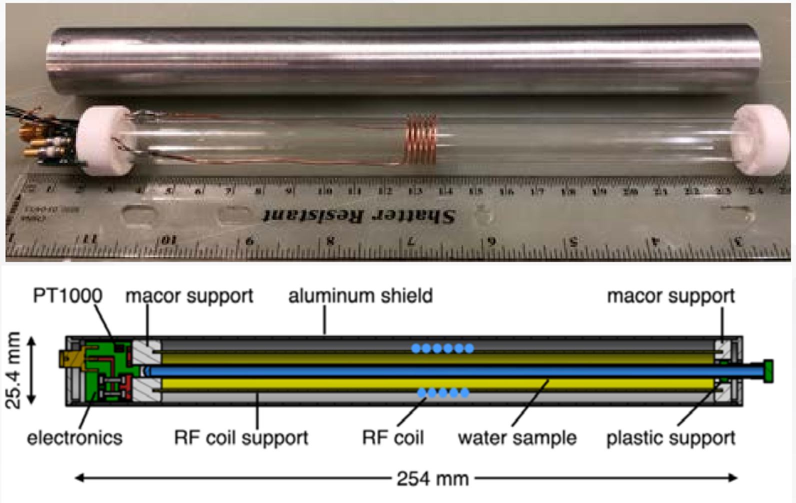


Wiggle plot from Run1a

Magnetic Field Measurement ω_p

Method: Pulsed Nuclear Magnetic Resonance





Fixed Probe:
- 378 fixed probes
- 72 azimuthal positions
- continuously track field drift

Trolley:
- 9,000 measurements for each of the 17 probes
- map the field every 2 or 3 days
- Synchronizes the fixed probes to field maps

Calibration probe (CP):
- Moveable probe
- Pure water sample
- Calibrate the trolley measurement

tracking

Mapping

Correcting

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Measurement of a_μ

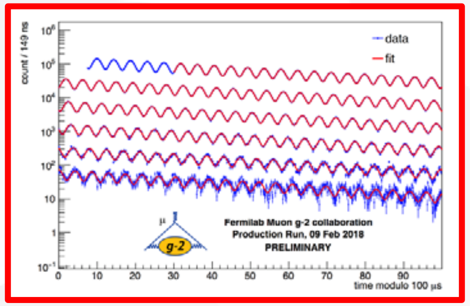
$$\vec{\omega}_a = a_\mu \left[\frac{e}{m}\vec{B}\right]$$

$$\mu_e = g_e \frac{e\hbar}{4m_e} \qquad B = \frac{\hbar\,\omega_p(T)}{2\,\mu_p(T)}$$

$$a_\mu = \boxed{\frac{\omega_a}{\tilde{\omega}'_p(T_r)}}\ \boxed{\frac{\mu'_p(T_r)}{\mu_e(H)}\frac{\mu_e(H)}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}}$$

we measure

other ratios known to 22 ppb precision or better in total 25ppb



Measured g-2 frequency

blinding factor

Corrections from the beam dynamics

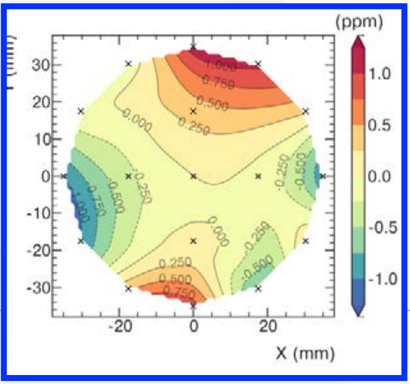
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{clock}\,\omega_a^m\ \overbrace{(1 + C_E + C_p + C_{lm} + C_{pa})}}{f_{cali}\,\langle\omega_p(x,y,\phi,T_r)\times M(x,y,\phi)\rangle\ (1 + \underbrace{B_q + B_k}_{})}$$

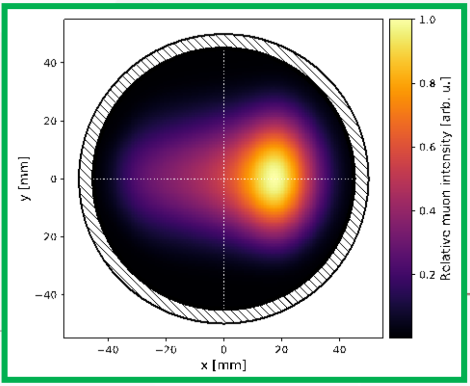
Field Calibration

Corrections from the transient magnetic field

Measured magnetic field:
- Trolley mapping
- Fixed probe tracking

Muon time and spatial distribution





blinding factor

Measured g-2 frequency

Corrections from the beam dynamics

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

Precession Frequency Analysis

- Analysis Method
- Measured g-2 Frequency
- Beam Dynamics Correction

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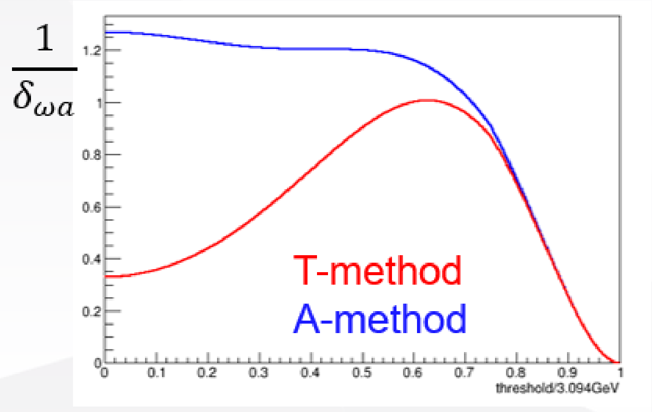
Analysis Method

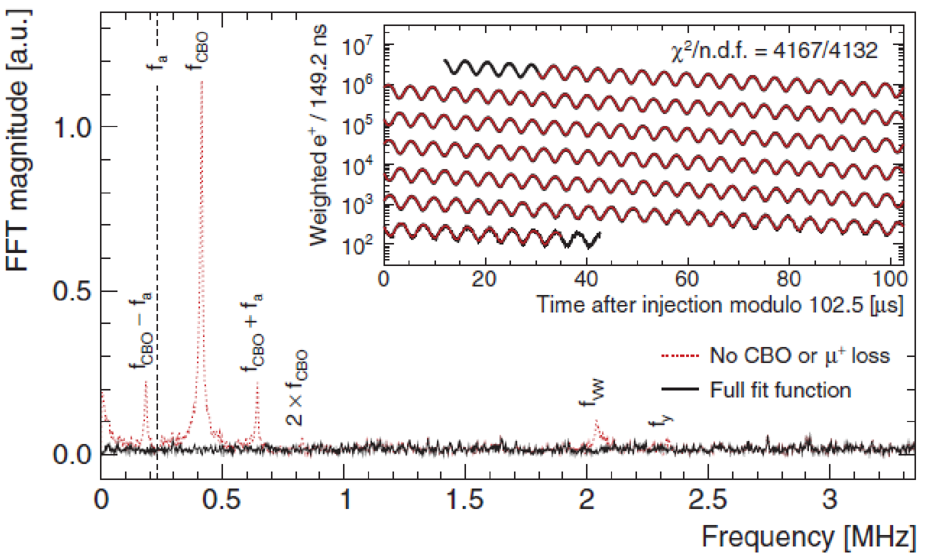
e^+ Signal from Muon Decay:

$$N_{\text{ideal}}(t) = N_0 \exp\left(-t/\gamma\tau_\mu\right)\left[1 + A\cos\left(\omega_a t + \phi\right)\right]$$

- Counting the number of e^+ above the threshold energy using different weight $w(E)$ introduces two ω_a analysis methods
  1. T-method: $w(E) = 1$
  2. A-method: $w(E) = A(E)$
- The statistical uncertainty $\propto 1/\sqrt{NA^2}$
- Fourier transform of residuals from a fit to simple 5-parameters fit function reveals additional frequencies
- Software blinded analysis:

$$\omega_a(R) = 2\pi \times 0.2291 MHz \left[1 + (R + \Delta R)\cdot 10^{-6}\right]$$





Measured g-2 Frequency

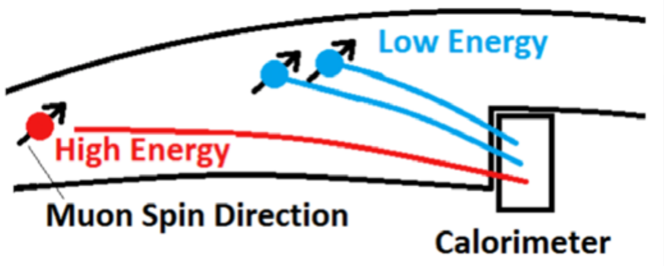
$$F(t) = N_0 \cdot N_x(t) \cdot N_y(t) \cdot \Lambda(t) \cdot e^{-t/\gamma\tau_\mu} \cdot [1 + A_0 \cdot A_x(t) \cdot \cos(\omega_a^m t + \phi_0 \cdot \phi_x(t))]$$

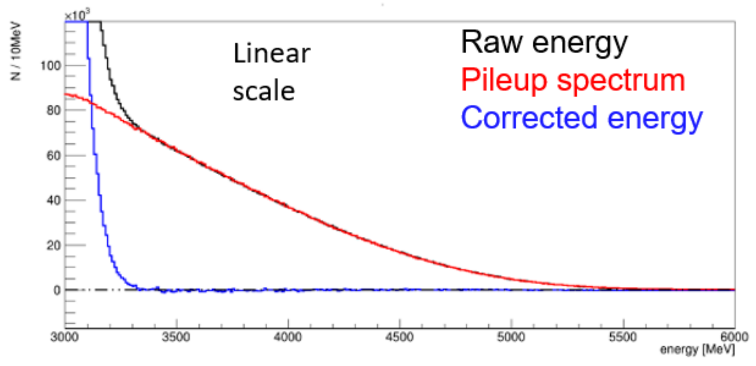
$$\boxed{\begin{aligned}
N_x(t) &= 1 + e^{-t/\tau_{\mathrm{CBO}}} A_{N,x,1} \cos(\omega_{\mathrm{CBO}} t + \phi_{N,x,1}) \\
&\quad + e^{-2t/\tau_{\mathrm{CBO}}} A_{N,x,2} \cos(2\omega_{\mathrm{CBO}} t + \phi_{N,x,2}) \\
N_y(t) &= 1 + e^{-t/\tau_y} A_{N,y,1} \cos(\omega_y t + \phi_{N,y,1}) \\
&\quad + e^{-2t/\tau_y} A_{N,y,2} \cos(\omega_{VW} t + \phi_{N,y,2}) \\
\Lambda(t) &= 1 - K_{\mathrm{loss}} \int_0^t e^{t'/\gamma\tau_\mu} L(t')\, \mathrm{d}t' \\
A_x(t) &= 1 + e^{-t/\tau_{\mathrm{CBO}}} A_{A,x,1} \cos(\omega_{\mathrm{CBO}} t + \phi_{A,x,1}) \\
\phi_x(t) &= 1 + e^{-t/\tau_{\mathrm{CBO}}} A_{\phi,x,1} \cos(\omega_{\mathrm{CBO}} t + \phi_{\phi,x,1})
\end{aligned}}$$

$$\chi^2 = \sum_{i=1}^{ndf} [\frac{N_{bin} - N_{fit}}{\sigma(N_{bin})}]^2$$

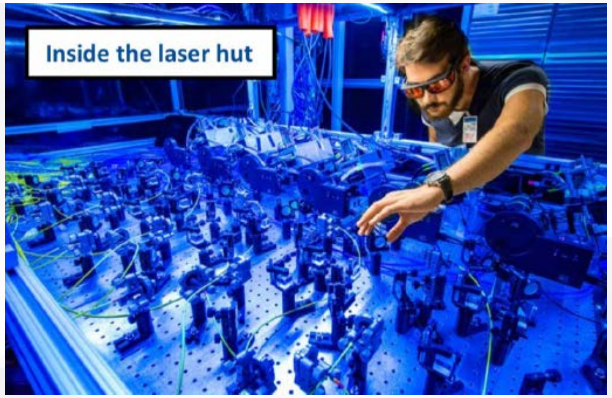
Detector effect:

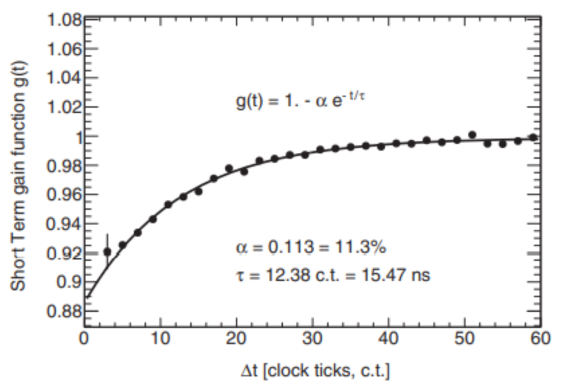
Event **pileup** which changes the phase and normalization





Gain change in calorimeter determined from laser data





Measured g-2 Frequency

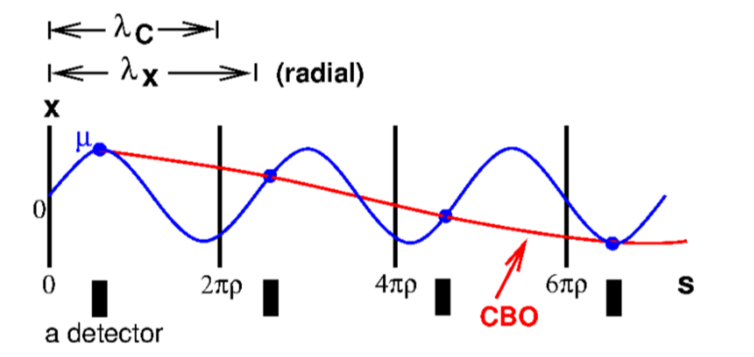
$$F(t) = N_0 \cdot N_x(t) \cdot N_y(t) \cdot \Lambda(t) \cdot e^{-t/\gamma\tau_\mu} \cdot \\ [1 + A_0 \cdot A_x(t) \cdot \cos(\omega_a^m t + \phi_0 \cdot \phi_x(t))]$$

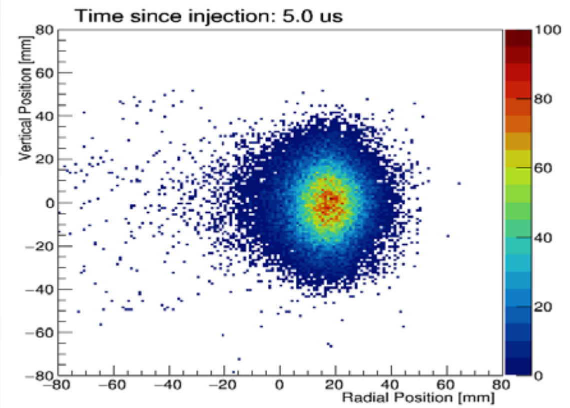
$$\begin{aligned}
N_x(t) &= 1 + e^{-t/\tau_{\mathrm{CBO}}} A_{N,x,1} \cos(\omega_{\mathrm{CBO}} t + \phi_{N,x,1}) \\
&\quad + e^{-2t/\tau_{\mathrm{CBO}}} A_{N,x,2} \cos(2\omega_{\mathrm{CBO}} t + \phi_{N,x,2}) \\
N_y(t) &= 1 + e^{-t/\tau_y} A_{N,y,1} \cos(\omega_y t + \phi_{N,y,1}) \\
&\quad + e^{-2t/\tau_y} A_{N,y,2} \cos(\omega_{VW} t + \phi_{N,y,2}) \\
\Lambda(t) &= 1 - K_{\mathrm{loss}} \int_0^t e^{t'/\gamma\tau_\mu} L(t')\, \mathrm{d}t' \\
A_x(t) &= 1 + e^{-t/\tau_{\mathrm{CBO}}} A_{A,x,1} \cos(\omega_{\mathrm{CBO}} t + \phi_{A,x,1}) \\
\phi_x(t) &= 1 + e^{-t/\tau_{\mathrm{CBO}}} A_{\phi,x,1} \cos(\omega_{\mathrm{CBO}} t + \phi_{\phi,x,1})
\end{aligned}$$

$$\chi^2 = \sum_{i=1}^{ndf} [\frac{N_{bin} - N_{fit}}{\sigma(N_{bin})}]^2$$

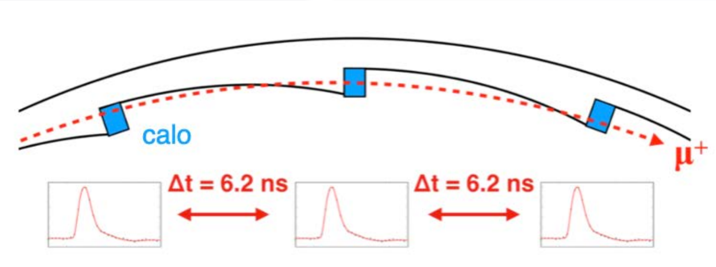
Beam Dynamic effect:

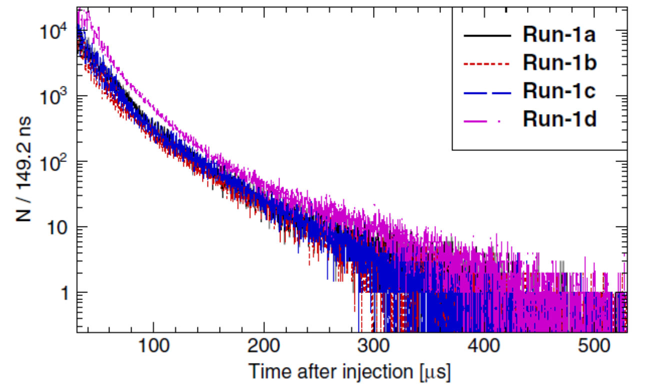
Coherent Betatron Oscillations (CBO) due to beam motion





Muon losses during storage



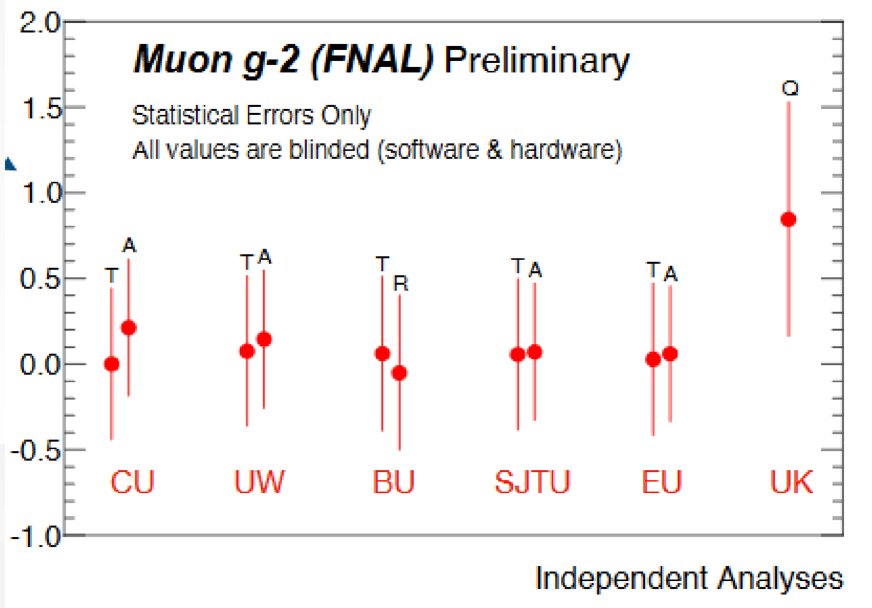


Measured g-2 Frequency

- Uncertainty for Run1:

  Statistic: 434ppb / Systematic: 56ppb

- 2 different algorithms to reconstruct positrons
- 6 different analysis groups with 4 different methods
- Final combination come from the 4 A-method due to statistically optimal

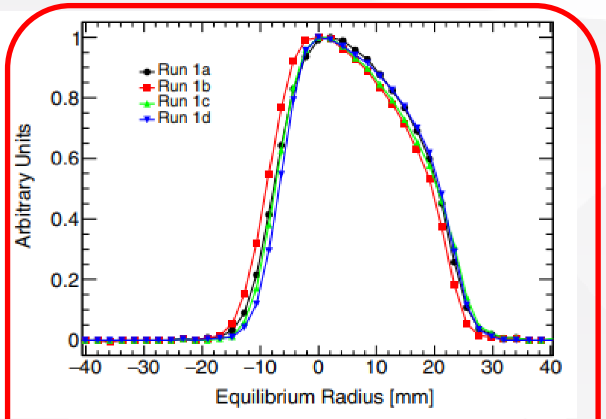


Recon.	Method	Pileup	R (ppm) for each dataset Run-1a	Run-1b	Run-1c	Run-1d	Naive R Average (ppm)
global	A	empirical	-82.98 ± 1.21	-81.70 ± 1.03	-82.30 ± 0.82	-82.34 ± 0.68	-82.30 ± 0.43
local	A	shadow	-83.23 ± 1.20	-81.77 ± 1.02	-82.35 ± 0.82	-82.48 ± 0.67	-82.41 ± 0.43
local	A	shadow	-83.17 ± 1.21	-81.84 ± 1.03	-82.50 ± 0.83	-82.45 ± 0.68	-82.44 ± 0.44
local	A	pdf	-83.39 ± 1.22	-81.72 ± 1.04	-82.32 ± 0.83	-82.42 ± 0.68	-82.39 ± 0.44
local	T	shadow	-83.55 ± 1.36	-81.80 ± 1.16	-82.67 ± 0.93	-82.45 ± 0.76	-82.54 ± 0.49
global	T	empirical	-82.96 ± 1.34	-81.96 ± 1.14	-82.77 ± 0.91	-82.47 ± 0.75	-82.52 ± 0.48
local	T	shadow	-83.64 ± 1.33	-81.83 ± 1.12	-82.64 ± 0.91	-82.63 ± 0.74	-82.62 ± 0.48
local	T	shadow	-83.49 ± 1.34	-81.75 ± 1.13	-82.64 ± 0.91	-82.42 ± 0.75	-82.50 ± 0.48
local	T	pdf	-83.37 ± 1.33	-81.76 ± 1.13	-82.65 ± 0.91	-82.47 ± 0.74	-82.51 ± 0.48
local	R	shadow	-83.72 ± 1.36	-81.96 ± 1.16	-82.67 ± 0.93	-82.52 ± 0.76	-82.62 ± 0.49
n/a	Q	n/a	-83.96 ± 2.07	-79.70 ± 1.76	-81.03 ± 1.45	-82.74 ± 1.29	-81.82 ± 0.78

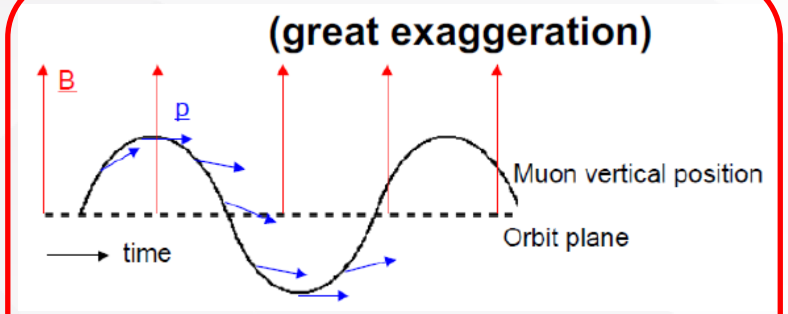
Beam Dynamic Correction

- C_e: Muons with p ≠ 3.09 GeV/c are slightly affected by the radial electric field
- C_p: A small pitch angle (vertically) modulates $\beta \times \mathbf{B}$ term and the correction is required
- C_{ml}: Muon losses (ML) induce a (tiny) phase shift
- C_{pa}: Muon phase change due to 1) beam changing from early to late and 2) the measured phase depends on the decay coordinates

	Correction (ppb)	Uncertainty (ppb)
ω_a^m statistical	$\cdots$	434
C_e	489	53
C_p	180	13
C_{ml}	−11	5
C_{pa}	−158	75
C_{total}	499	93

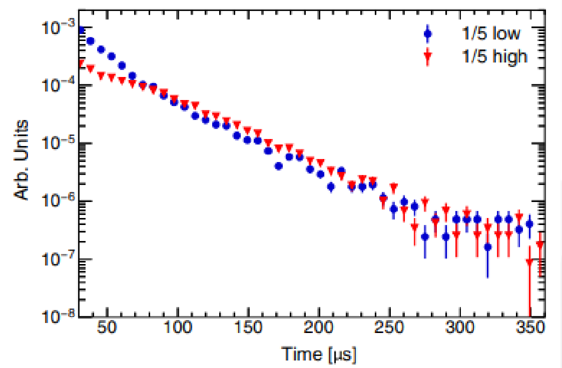


$$C_e = 2n(1-n)\beta_0^2 \frac{\langle x_e^2 \rangle}{R_0^2}$$

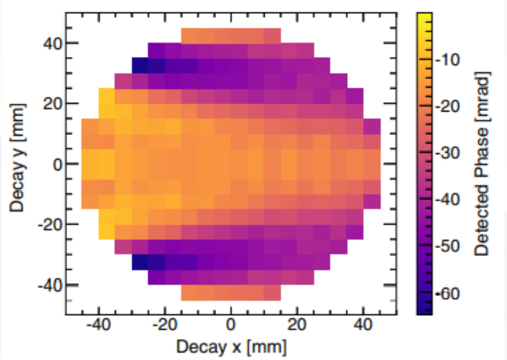


$$C_p = \frac{n}{2}\frac{\langle y^2 \rangle}{R_0^2} = \frac{n}{4}\frac{\langle A^2 \rangle}{R_0^2}$$

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



$$C_{ml}: \ \Delta\omega_a = \frac{d\phi}{dt} = \frac{d\phi}{dp}\frac{dp}{dt} \neq 0$$



$$C_{pa}: \ \Delta\omega_a = \frac{d\phi}{dt} = \frac{dY_{\mathrm{RMS}}}{dt}\frac{d\phi}{dY_{\mathrm{RMS}}} \neq 0$$

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

Field Calibration

Measured magnetic field:

- Trolley mapping
- Fixed probe tracking

Muon time and spatial distribution

Corrections from the transient magnetic field

Magnetic Field Analysis

- Field Calibration
- Measured Field
- Muon Weighting
- Transients Correction

Field Calibration

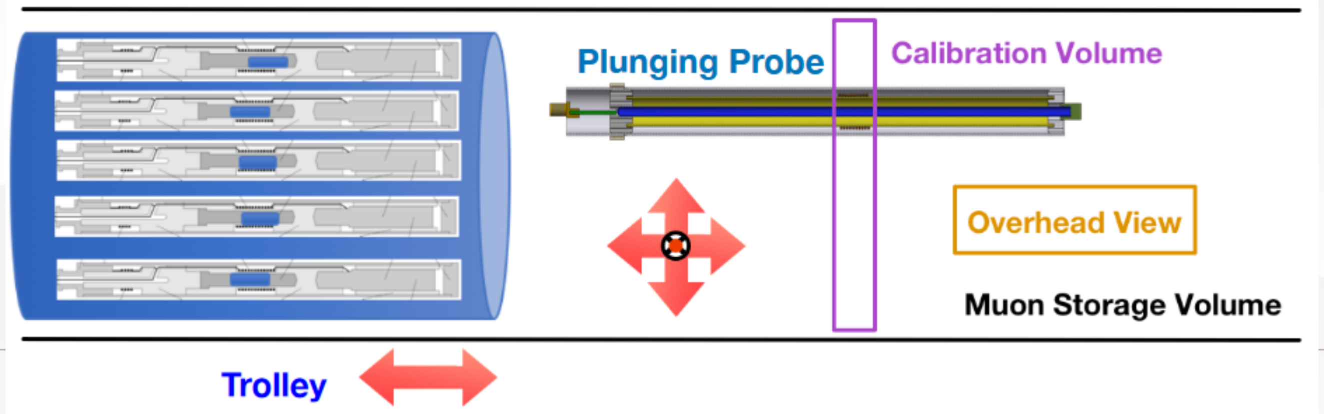
- A specially designed calibration probe provides the connection to a shielded proton in a spherical water sample: (accuracy of 15 ppb)

$$\boxed{\omega_p'(T_r) = \omega^{cp}(T)\left[1 + \delta^T\left(\mathrm{H_2O}, T_r - T\right) + \delta^b\left(\mathrm{H_2O}, T\right) + \delta^s + \delta^w + \delta^{\mathrm{RD}} + \delta^d\right]}$$

- Calibration correction that relates trolley/calibration probe measurement to equivalent shielded proton in spherical water sample frequency ω_p' is needed

$$\omega_{p,trolley} \leftrightarrow \omega_{p,cp} \leftrightarrow \omega_p'$$

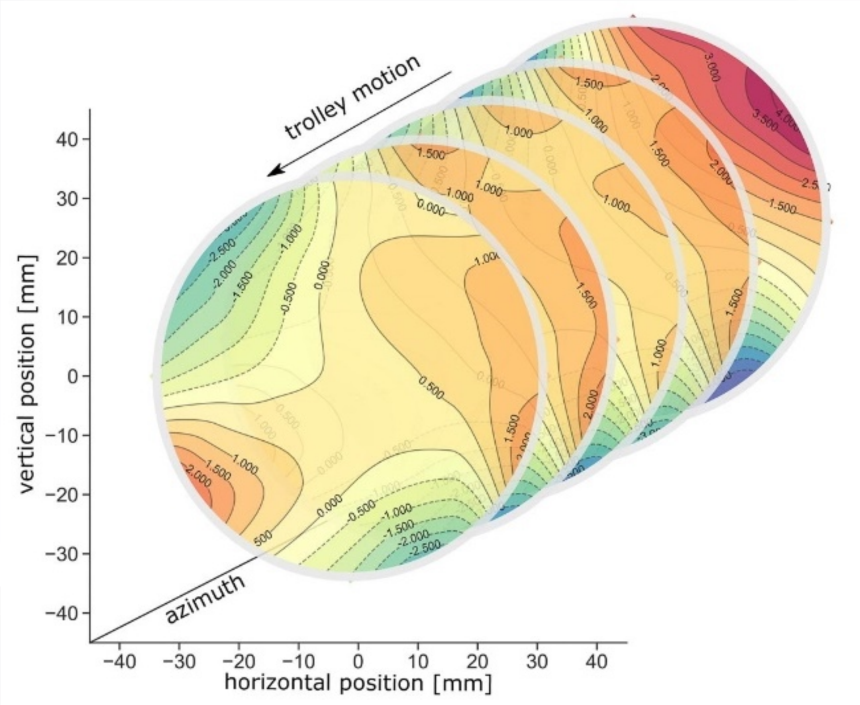
- The trolley calibration requires to measure the "same" field at the "same" position
  - ✓ Same field: uniform field (<20ppb/mm)
  - ✓ Same position: align CP and trolley probe (<0.5mm)

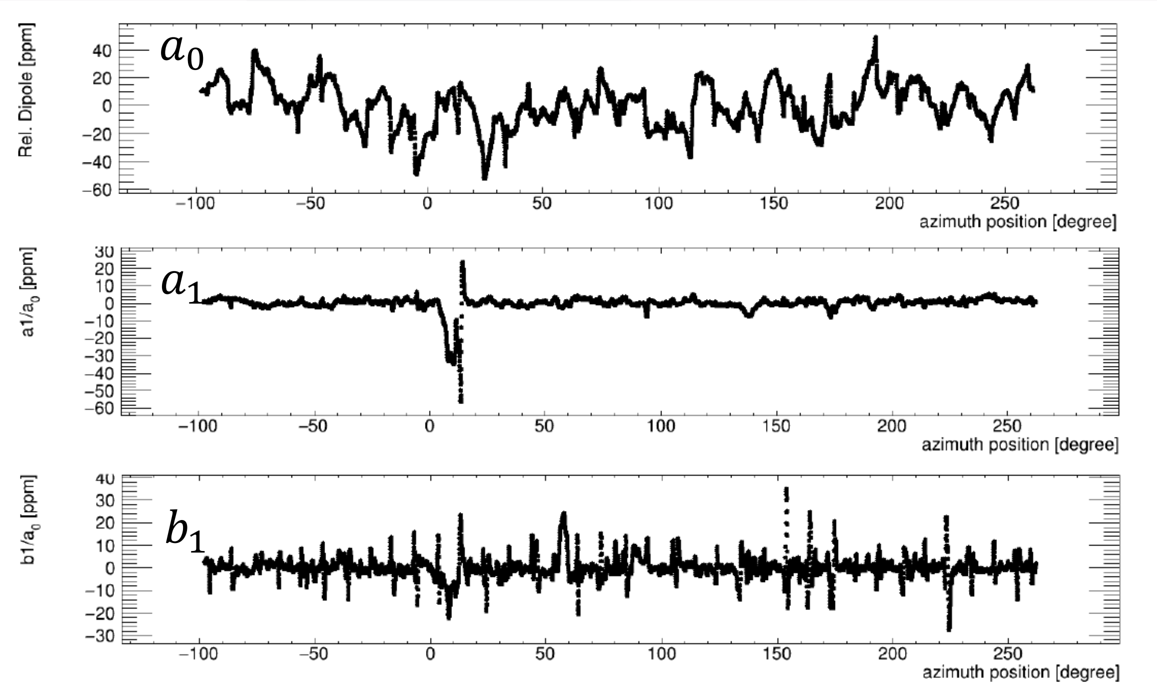


Field Mapping

- the magnetic field is measured at ~9,000 azimuthal slices ϕ
- The trolley frequency measurements at each slice can be expressed in terms of multipole moments:

$$B_y = a_0 + \sum_{n=1}^{\infty} (r/r_0)^n [a_n cos(n\theta) + b_n sin(n\theta)]$$

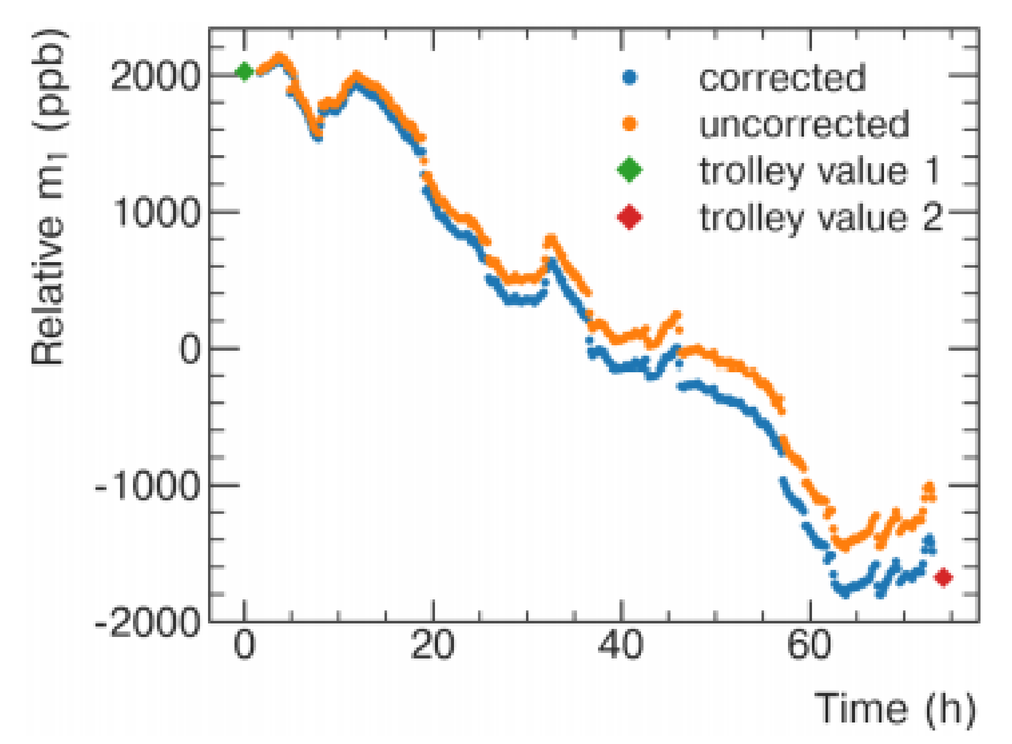




A typical trolley map

Field Tracking

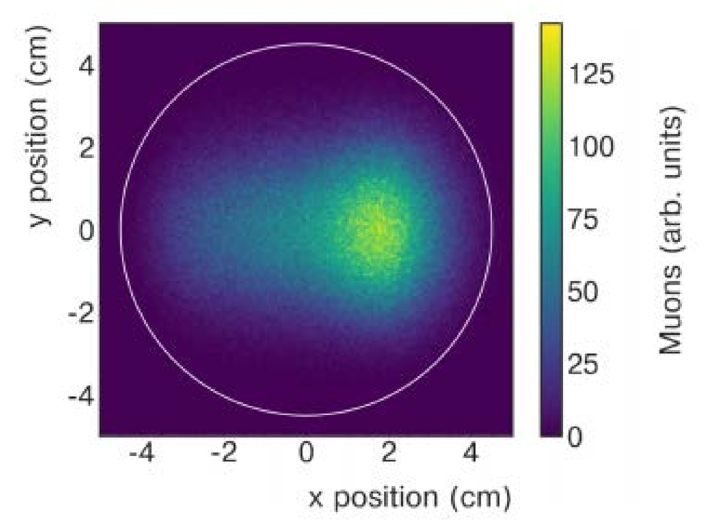
- When the beam is on, the trolley is parked in the garage
- The muon orbit field can not be measured directly
- Need to use fixed probes to track the field during data taking
- Interpolate between trolley runs using fixed probe data



Muon Weighting / Transient Correction

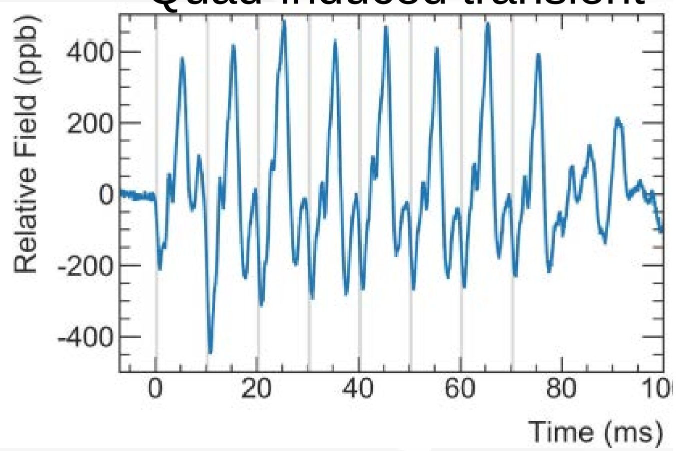
$$\tilde{\omega}'_p = \left\langle \frac{\int dx\, dy\, \omega'_p(x,y,\phi) M(x,y,\phi)}{\int dx\, dy\, M(x,y,\phi)} \right\rangle_\phi$$

- $M(x,y,\phi)$: Want the field actually experienced by muons, need to know the muon spatial & time distribution
- $\boldsymbol{B_q}$: The ESQs are pulsed every 10ms and the motion of these plates causes a magnetic field perturbation
- $\boldsymbol{B_k}$: The fast kickers pulse induces eddy currents in the surrounding metal and perturb the field

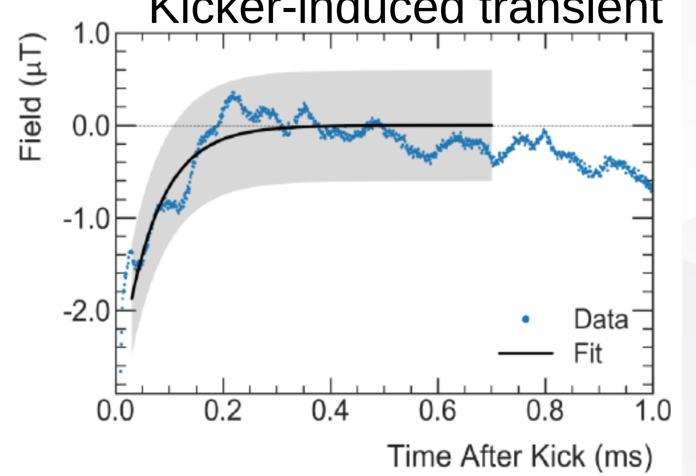


Data set	$\tilde{\omega}'_p(T_r)/2\pi$ (Hz)	Uncertainty (ppb)
Run-1a	61,791,871.2	115
Run-1b	61,791,937.8	127
Run-1c	61,791,845.4	125
Run-1d	61,792,003.4	108
	Average over all data sets	
Field Measurements		56
ESQ Transient		92
Kicker Transient		37
Total		114

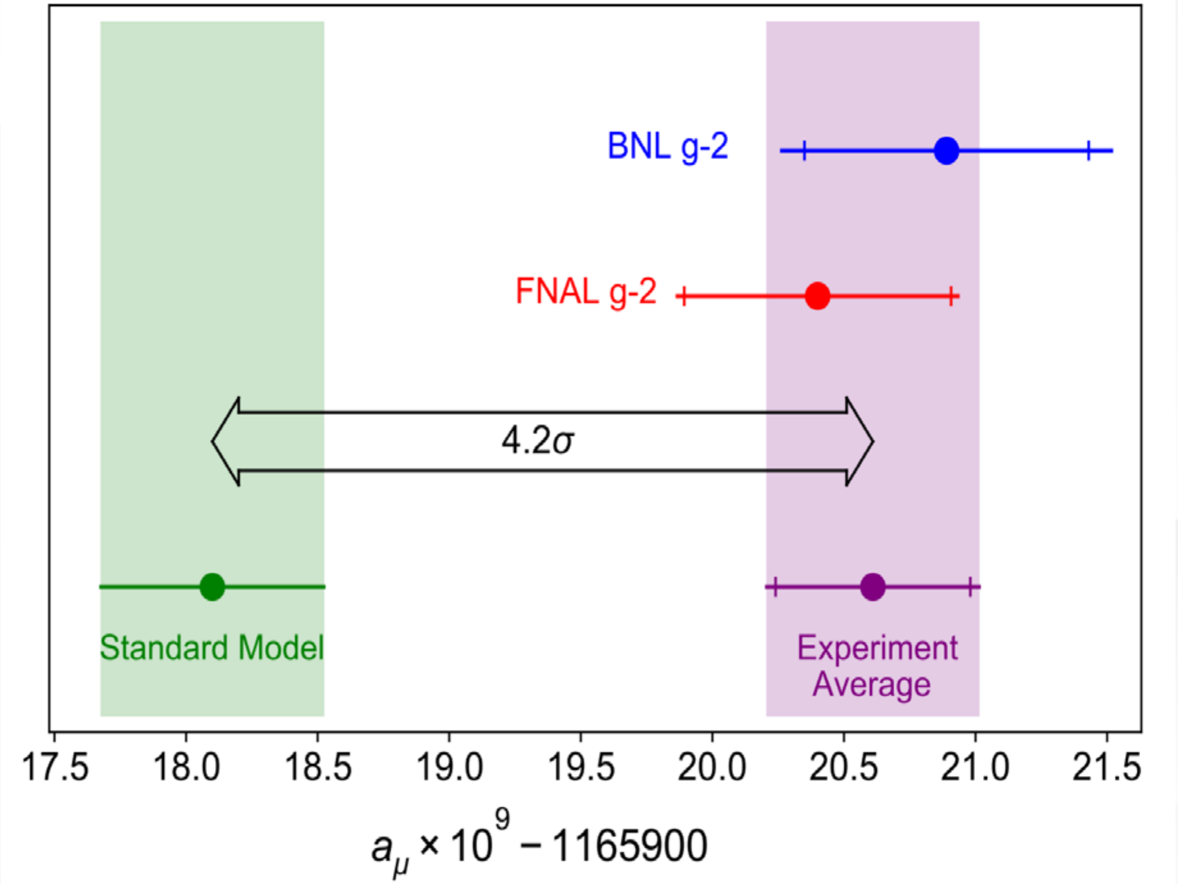
Quad-induced transient



Kicker-induced transient



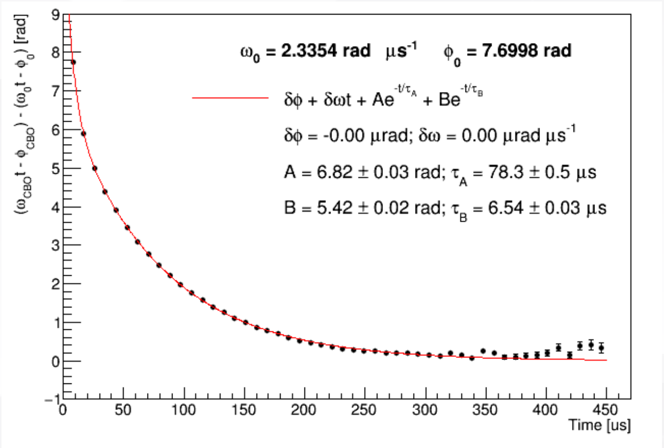
Measurement of a_μ Run1 result



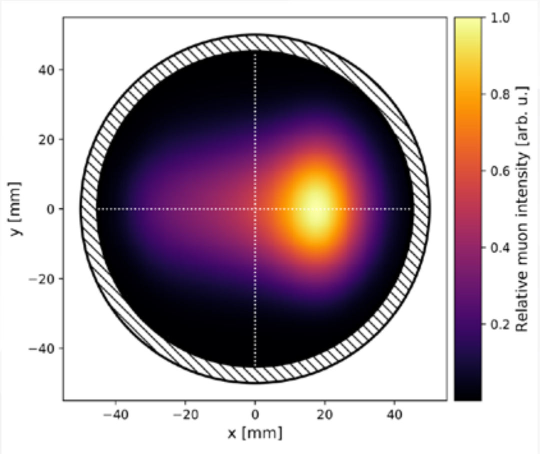
$$a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\text{ppm})$$
$$a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\text{ppm})$$

Quantity	Correction Terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	–	434
ω_a^m (systematic)	–	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{\text{calib}}\langle\omega_p(x,y,\phi) \times M(x,y,\phi)\rangle$	–	56
B_k	-27	37
B_q	-17	92
$\mu_p'(34.7^\circ)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	157
Total fundamental factors	–	25
Totals	544	462

- Measured a_μ to 0.46 ppm
- 4.2σ differ from the SM value
- Only 6% of the full data set



Changing CBO frequency



Muon distribution

Quantity	Correction Terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	–	434
ω_a^m (systematic)	–	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle$	–	56
B_k	-27	37
B_q	-17	92
$\mu_p'(34.7°)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	157
Total fundamental factors	–	25
Totals	544	462

Challenges in Run1

Bad resistors:

- 2 of 32 HV resistors on quad plates were damaged
- Observe a changing CBO frequency by tracker
- Larger phase acceptance (C_{pa}) uncertainty

Kick Strength and Shape:

- Sub-standard, non-uniform kick
- Muon equilibrium orbit displaced by ~6 mm
- Larger E-field correction (C_e) and CBO amplitude

Quad transient correction (B_q):

- Substructure not measured in Run1

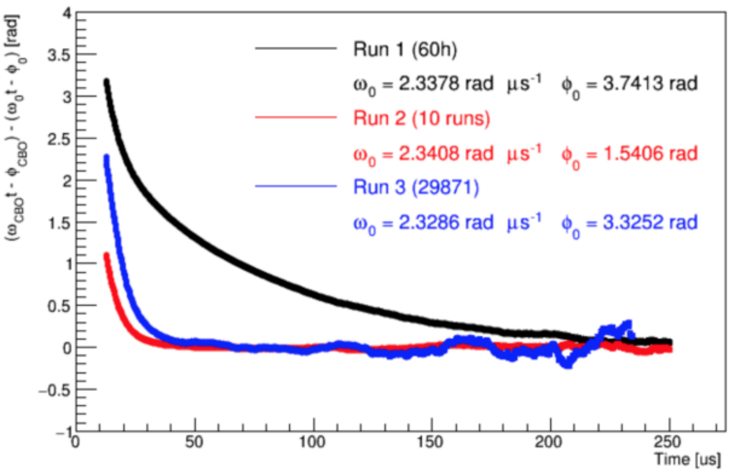
Hall temperature instability

- ppm level variations of the magnetic field

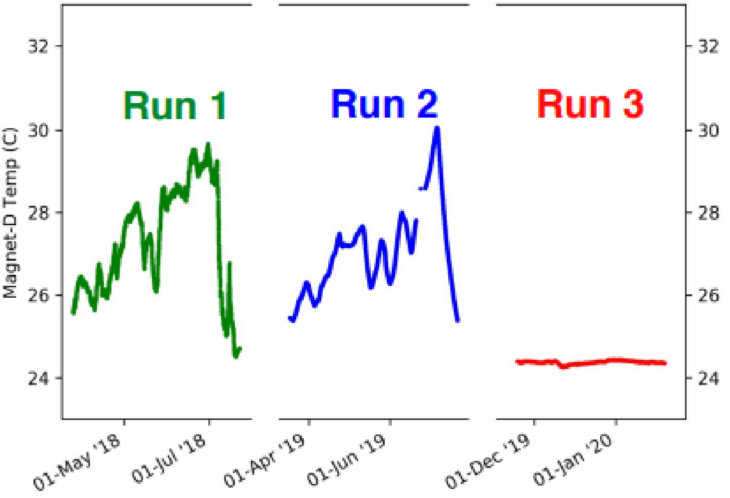
Many kicker/ESQ setting

- Need to perform individual analysis for four sub-datasets and then combine

Major Upgrades beyond Run1



CBO frequency



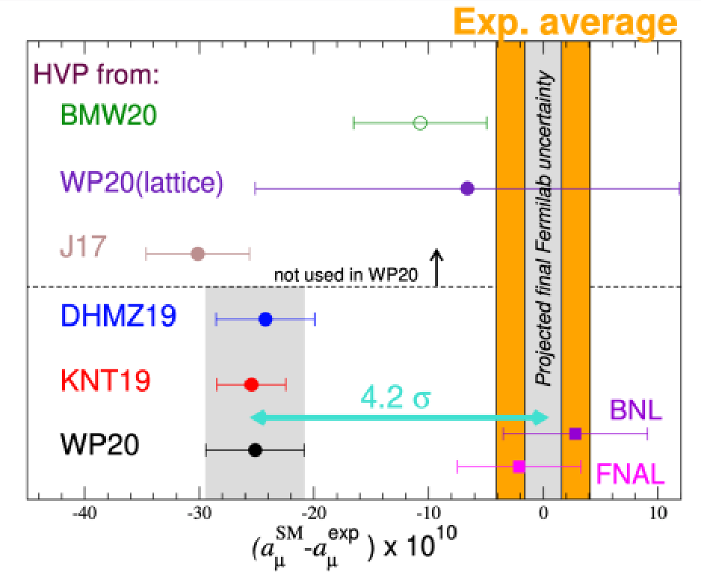
Magnet Temperature

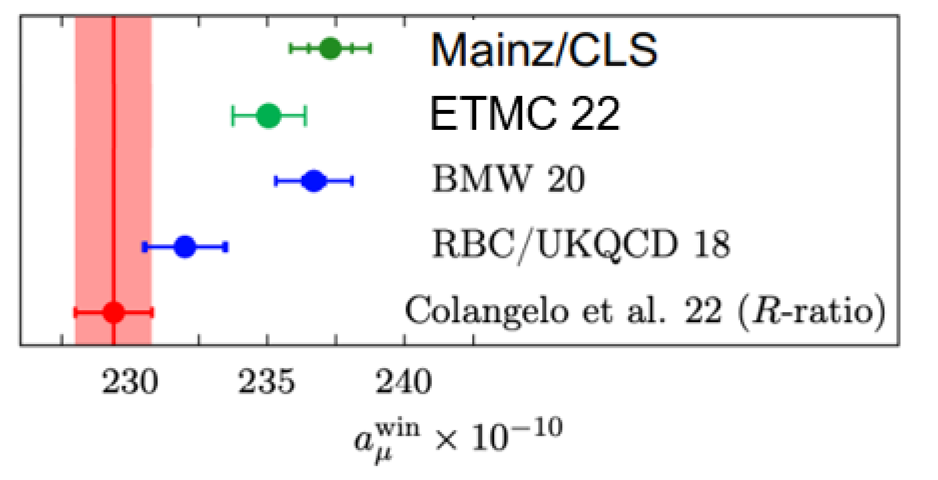
	stat unc [ppb]	sample size [xBNL]
Run 1	434	0.92
Run 2	343	1.47
Run 3	242	2.95
Run 1+2	269	2.39
Run 2+3	198	4.43
Run 1+2+3	180	5.35

- Replaced damaged resistors
- Higher kicker voltage to center beam
- More systematic measurement of transient field
- More stable temperature control
- More stable run & minimize configuration change
- Develop optimal methods in both ω_a and ω_p analysis to reduce the systematic uncertainties
- ……

Theory Update Since 2021 April

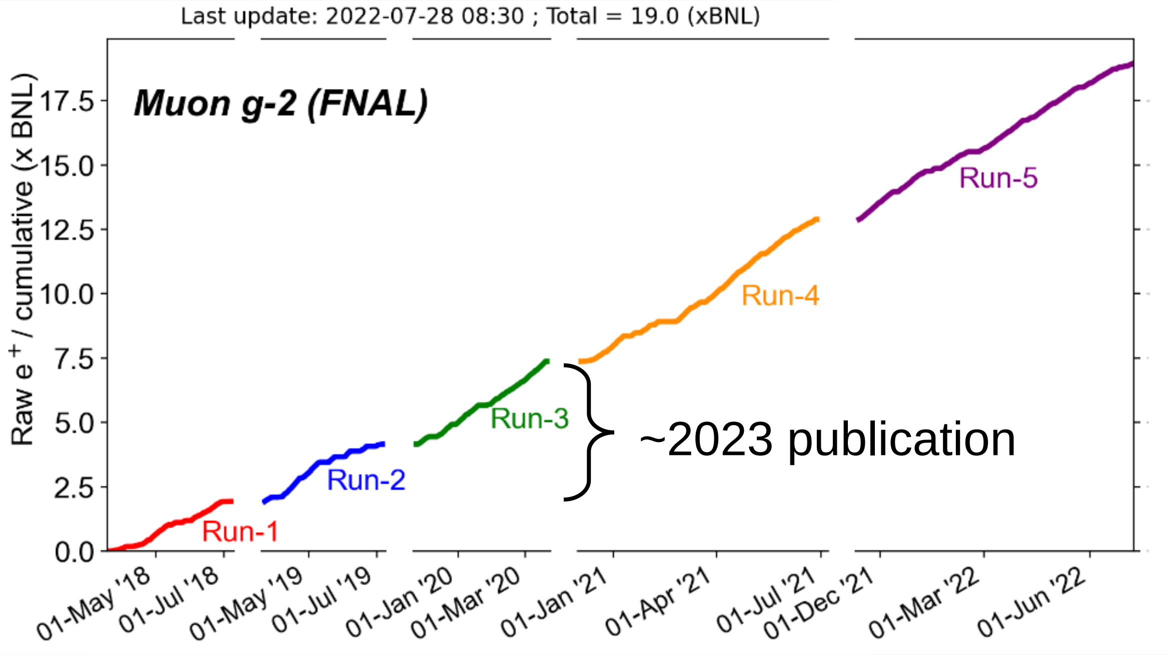
- HVP lattice calculations vary in a wide range, converging not easy
- Weight the lattice results to concentrate on an intermediate energy range where the calculations are thought to be more reliable
- Mainz/CLS and ETMC(2022) results agree with BMW20
- The lattice results conflict with the longstanding data-driven number
- New results expected soon from FNAL/MILC & RBC/UKQCD





Outlook

- The Fermilab Muon g-2 experiment measured a_μ to 0.46ppm in Run1
- The discrepancy with the Standard Model prediction is 4.2σ
- Run 1 is only 6% of the final data set
- Up to date, 5 Runs of data have been collected: 19xBNL statistics
- Stay tuned for more results to come



Thanks!

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上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Backup

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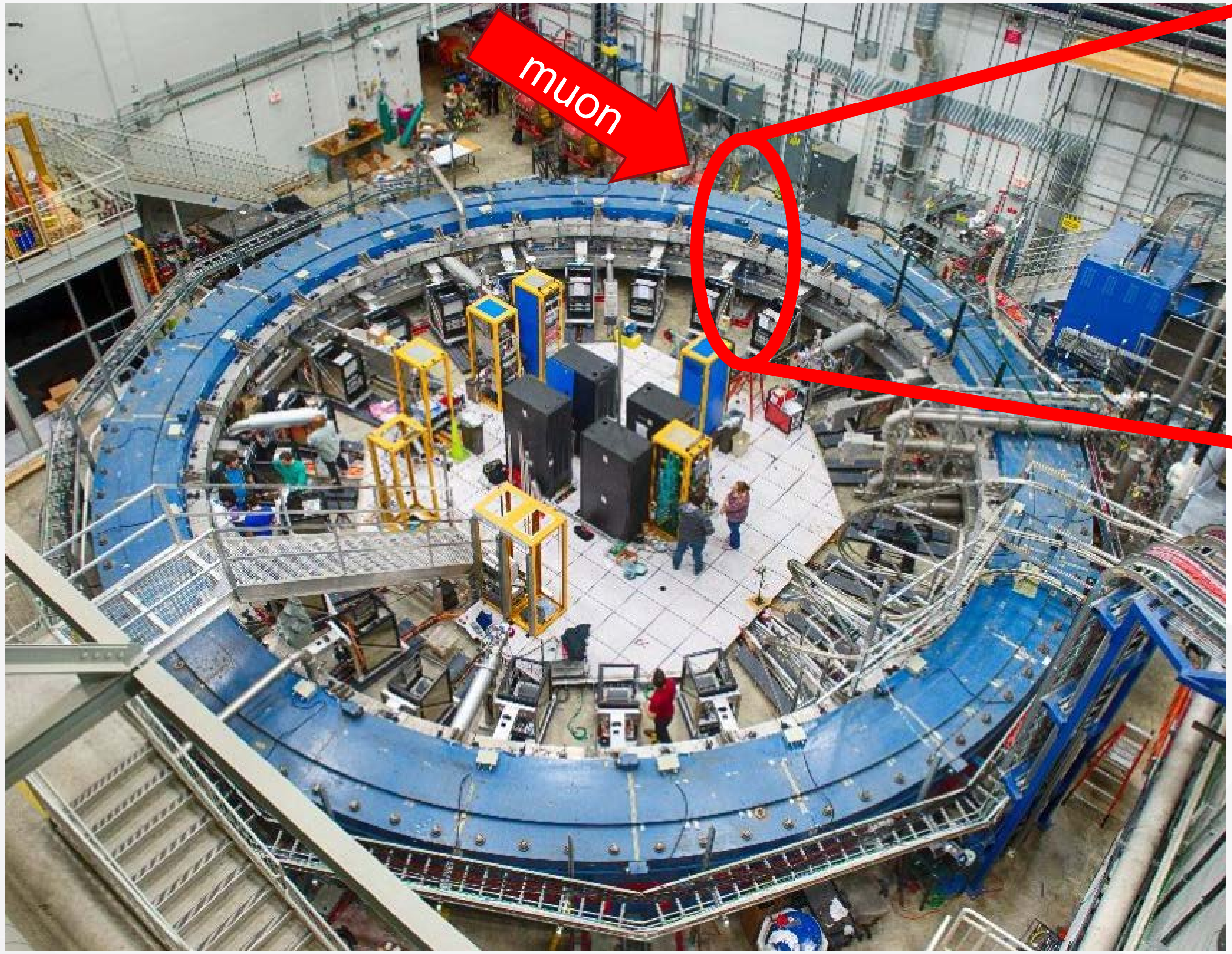
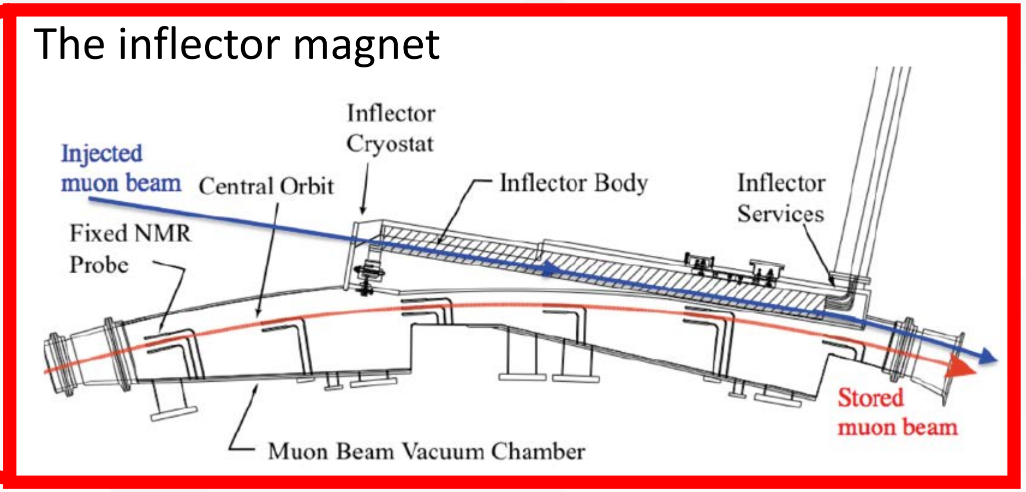
Overview of the Experiment

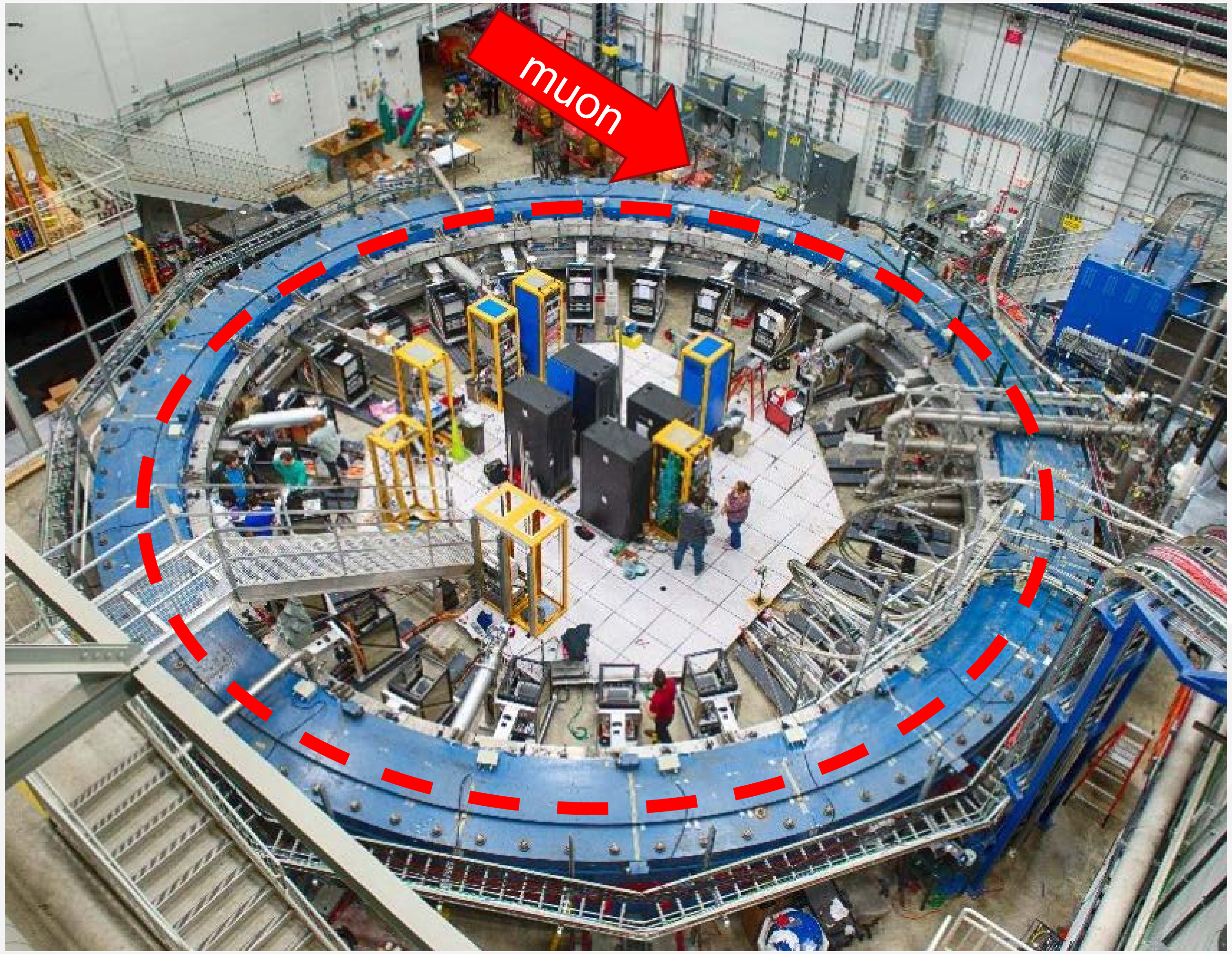


muon storage ring

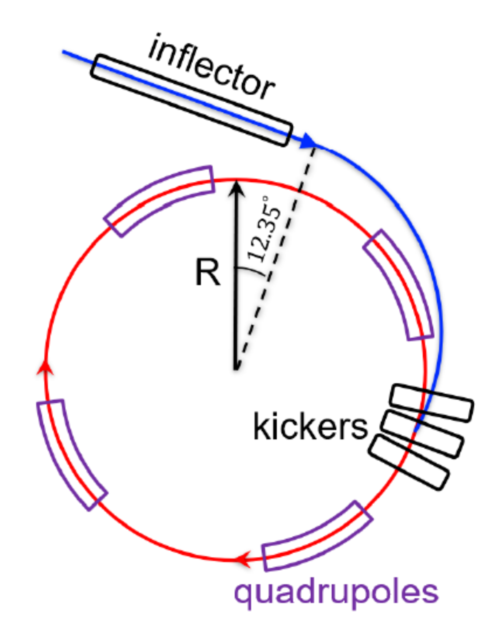


- Muon Injection
  - Need to cancel field in beam channel
  - Prevents strong deflection of the beam
  - Minimal perturbation to storage magnetic field
  - Superconducting inflector magnet are used to achieve above requirements

Overview of the Experiment



muon storage ring



- ➢ Muon Storage: Kicker
  - After inflector, muons enter storage region at 77 mm outside central closed orbit
  - The fast-kicker system steers muons onto stored orbit
- ➢ Muon Storage: Electrostatic Quadrupoles (ESQ)
  - Drives the muons towards the central part of storage region vertically
  - Aluminum ESQ cover ~43% of total ring

$$\boldsymbol{\omega}_a = -\frac{e}{m_\mu}\left[a_\mu \boldsymbol{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)}\frac{\boldsymbol{\beta} \times \boldsymbol{E}}{c}\right]$$

$$\gamma = 29.3$$
$$p = 3.094GeV$$