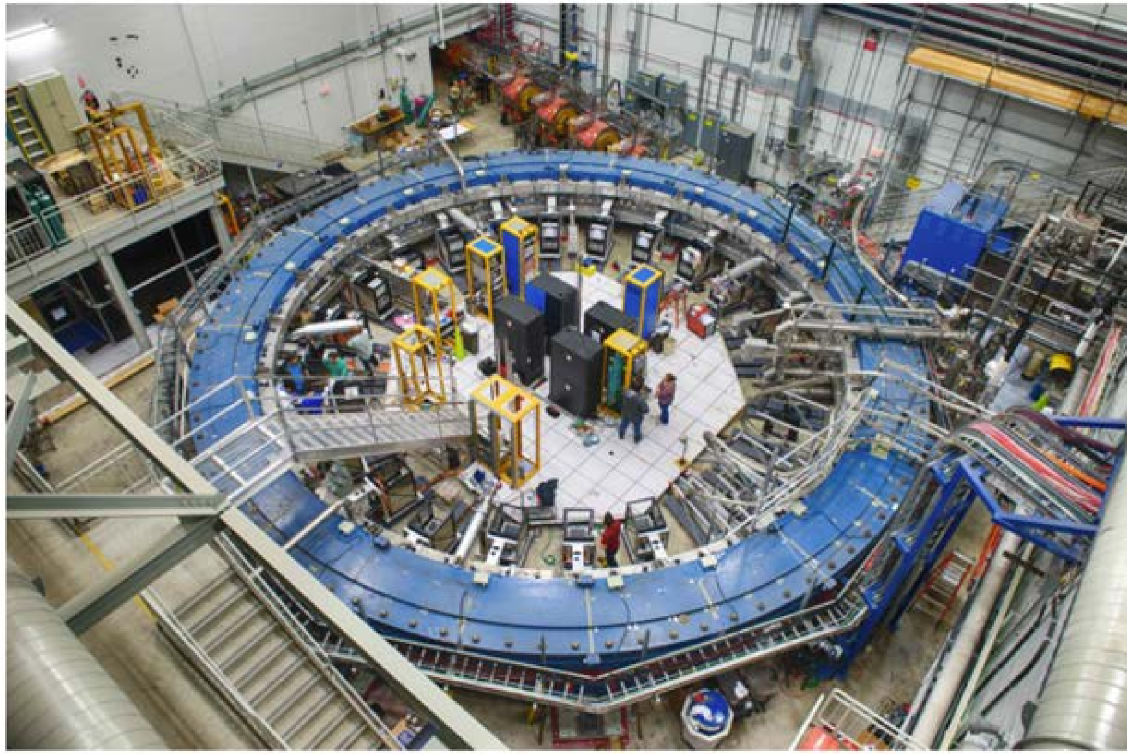
First Result From Fermilab Muon g-2 Experiment

Bingzhi Li, Shanghai Jiao Tong University

On Behalf of the Muon g-2 Collaboration

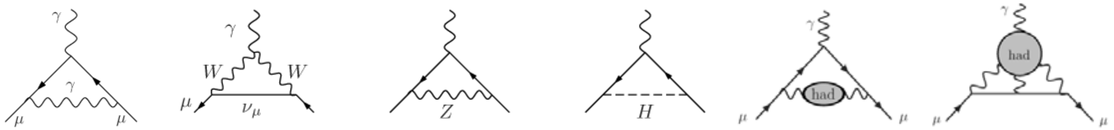
2021/08/18

The Muon g-2 Experiment at Fermilab: Motivation



- The magnetic momentum of muon is $\mu = g\frac{e}{2m}\vec{S}$, with g=2 given by Dirac equation
- Additional effects from QED, EW and Hadronic move the g factor away from 2 (0.1%)

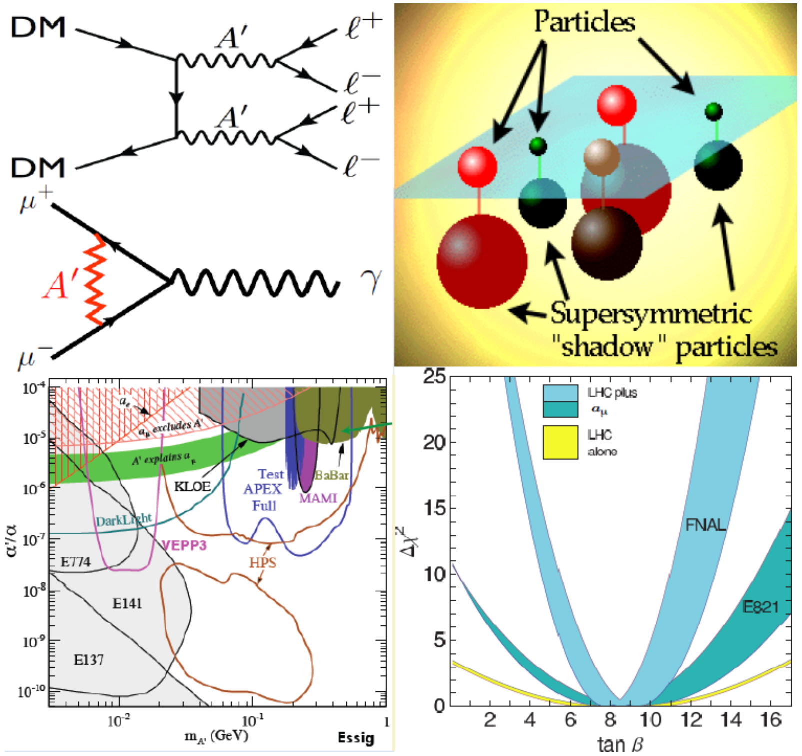
$$a_\mu = \frac{g-2}{2} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had} + (a_\mu^{NP})$$

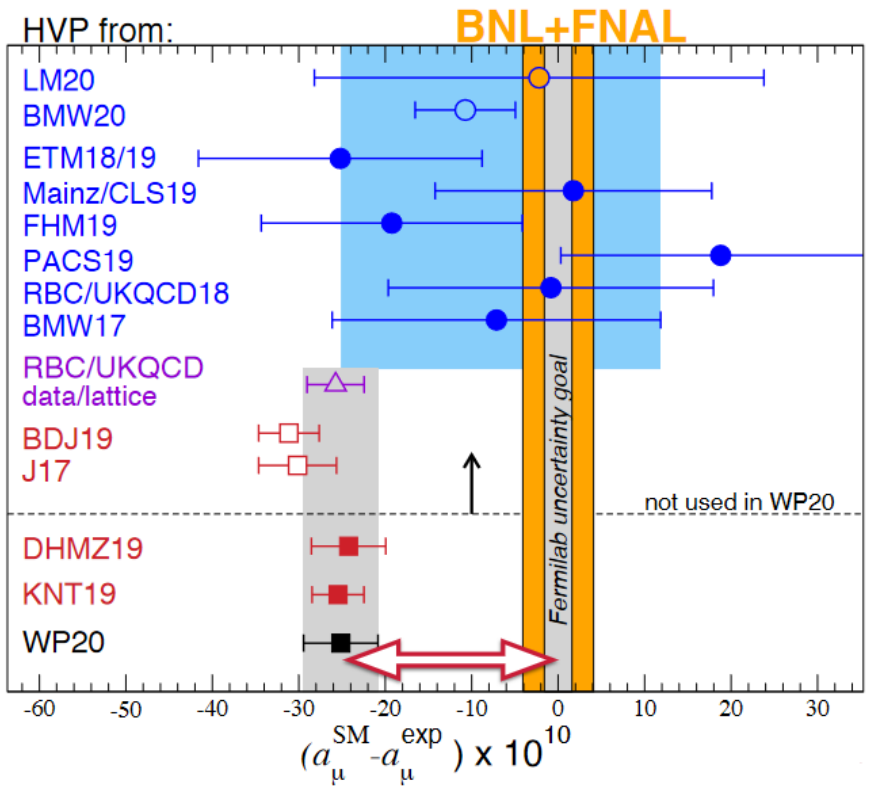


Muon g-2 of great interest because of rare combination of circumstances:

- Theorists can predict a_μ very well
- We can measure a_μ very well
- Results sensitive to new physics

The Muon g-2 Experiment at Fermilab: Motivation





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)

$$\Delta a_\mu = a_\mu^{\text{Exp}} - a_\mu^{\text{SM}} = (279 \pm 76) \times 10^{-11}$$

Goal: Measure the muon anomalous magnetic moment a_μ to 140 ppb, a fourfold improvement over the 540 ppb precision of Brookhaven. Probe Standard Model (SM) predictions for new physics effects. (pbb: parts per billion)

Muon g-2: 33 Institutions, 7 Countries, ~200 Members

Physics Week in Elba, Italy 2019

- USA
  - Boston
  - Cornell
  - Illinois
  - James Madison
  - Kentucky
  - Massachusetts
  - Michigan
  - Michigan State
  - Mississippi
  - North Central
  - Northern Illinois
  - Regis
  - Virginia
  - Washington
- USA National Labs
  - Argonne
  - Brookhaven
  - Fermilab
- China
  - Shanghai Jiao Tong University
- Germany
  - Dresden
  - Mainz
- Italy
  - Frascati
  - Molise
  - Naples
  - Pisa
  - Roma Tor Vergata
  - Trieste
  - Udine
- Korea
  - CAPP/IBS
  - KAIST
- Russia
  - Budker/Novosibirsk
  - JINR Dubna
- United Kingdom
  - Lancaster/Cockcroft
  - Liverpool
  - Manchester
  - University College London

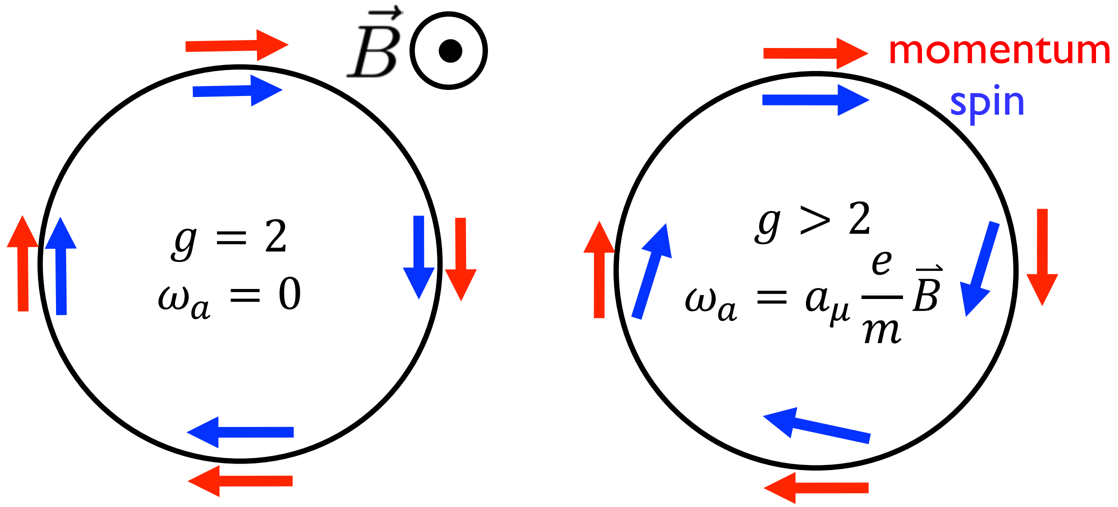
Overview of the Measurement Technique

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

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

$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = \left(\frac{g-2}{2}\right)\left[\frac{e}{m}\vec{B}\right]$$

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



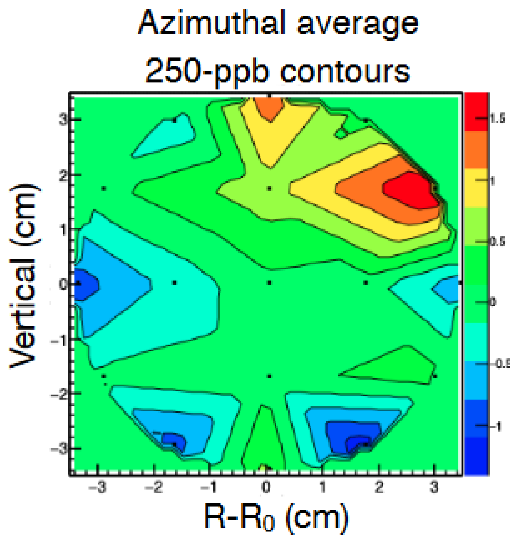
- Muon anomalous precession frequency ω_a
- Uniform magnetic field B in terms of proton NMR frequency ω_p

- Want $a_\mu \Rightarrow$ need to measure ω_a and B
- Measure B using proton NMR: $\hbar\omega_p = 2\mu_p|B|$

$$a_\mu = \boxed{\frac{\omega_a}{\tilde{\omega}'_p(T,T_r)}}\ \boxed{\frac{\mu'_p(T_r)}{\mu_e(H)}\frac{\mu_e(H)}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}}$$

we measure

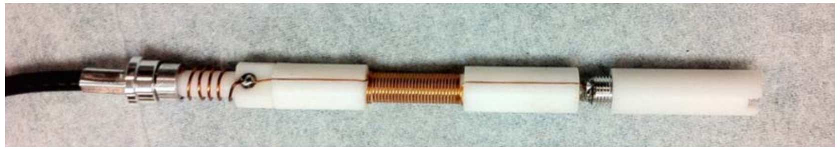
other ratios known to 22 ppb precision or better in total 25ppb

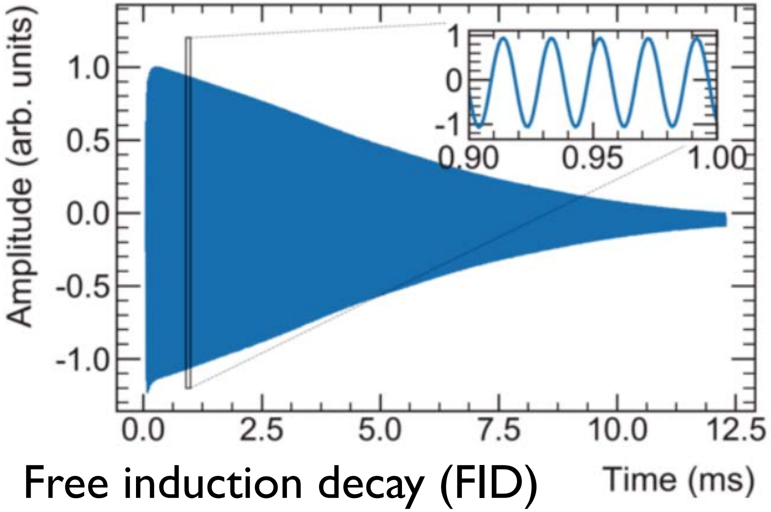


Uniform Field:
Shim to $\pm$1ppm

Measurement of ω_p

Method: Pulsed Nuclear Magnetic Resonance



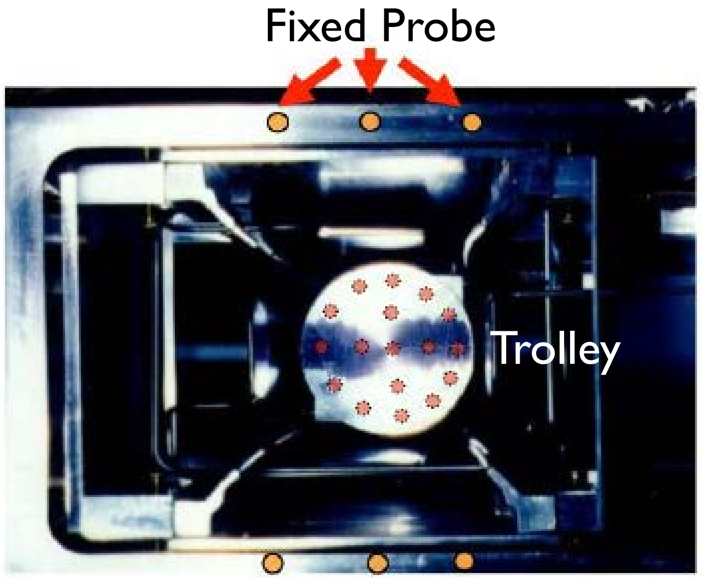


Free induction decay (FID)

Monitor — Fixed Probe Station

Scan — Trolley

Correct — Calibration

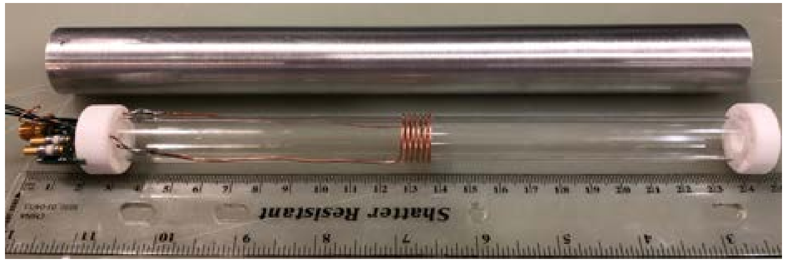


Fixed Probe Station:

- 378 fixed probes are located in 72 azimuthal positions
- Monitor the field 24/7

Trolley:

- 17 probes (petroleum jelly sample)
- Mapping the field when beam is off



Calibration:

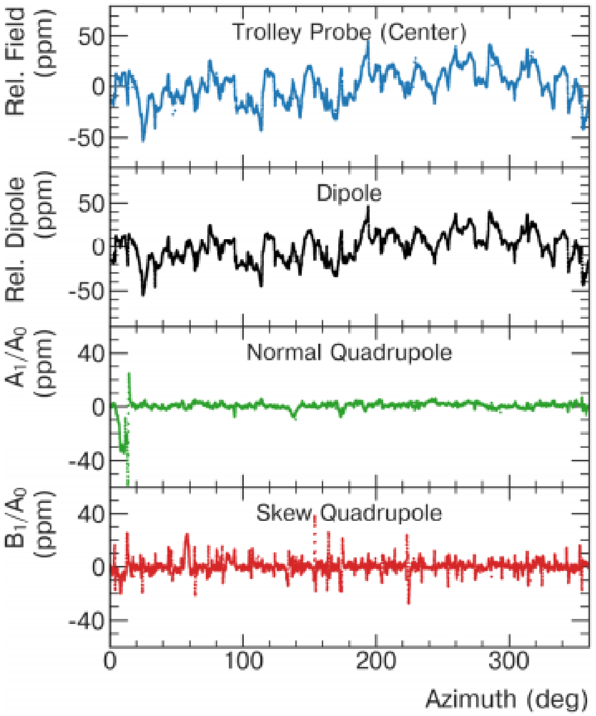
- Pure water sample NMR probe
- Calibrate the trolley probe

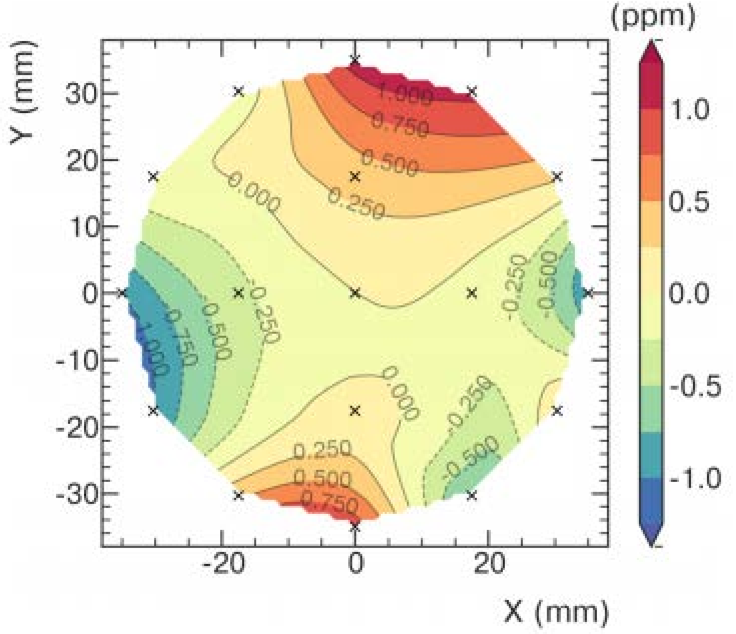
Measurement of ω_p: Trolley Map

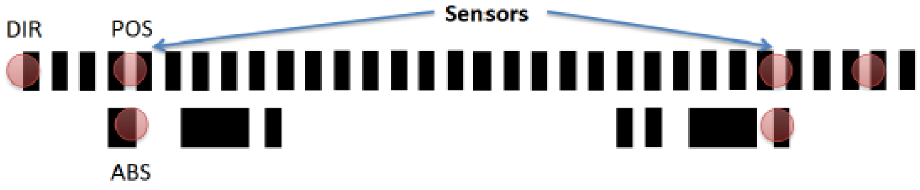
- Trolley deployed every 2~3 days to map the magnetic field
- A single trip around the ring takes ~1 hr
- ~9000 x 17 probes worth of data per run
- The positions are determined using barcode

Quantity	Dipole	
$\langle \delta_i^X \rangle$	Corr. (ppb)	Unc. (ppb)
Freq		
syst, fit	<1	10
stat	0.0	0.1
Motion	−15	18
Position		
transverse	0	12
azimuthal	0	4
Temperature	0	15–27
Multipoles	0	1
Config		
garage	−5	22
collimators	<1	<1
ground loop	−2	0
Total	−21	36–43

Ref: Phys. Rev. A **103**, 042208

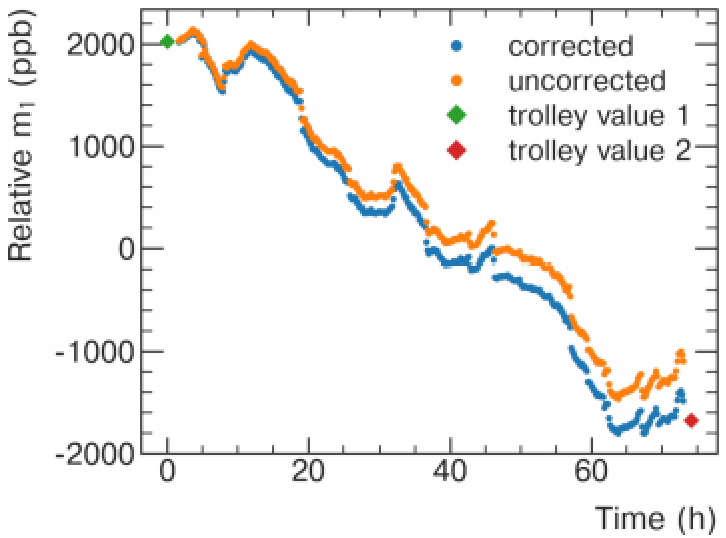






Measurement of ω_p: Fixed Probe Interpolation

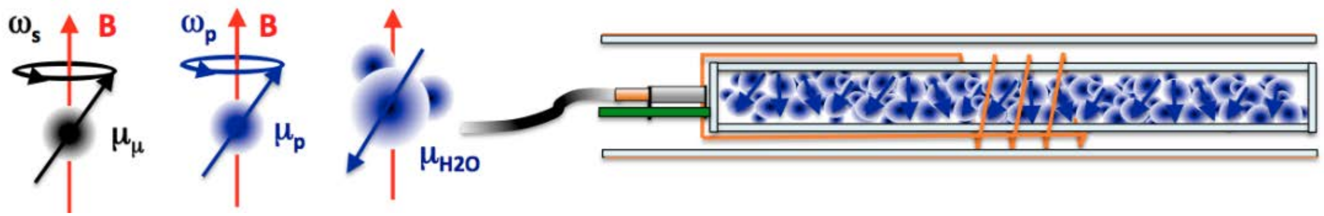
- When the beam is on, the trolley is parked in the garage
- The muon orbit field can not be measured directly
- Need to use fixed probes to track the field during data taking
- Interpolate between trolley runs using fixed probe data

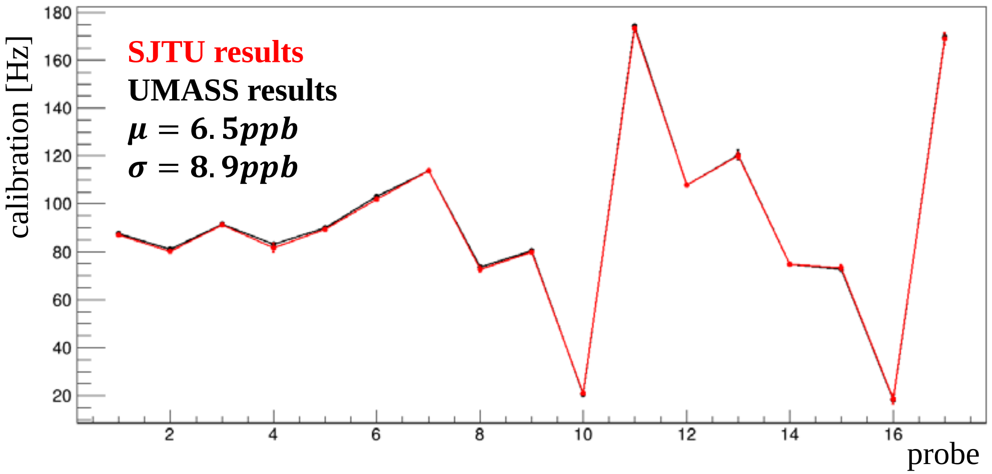


Measurement of ω_p: Calibration

- Trolley and Fixed probes use petroleum jelly sample
- Plunging probe (PP) uses pure water sample
- Fast swap trolley and plunging probe at the same location to do calibration

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

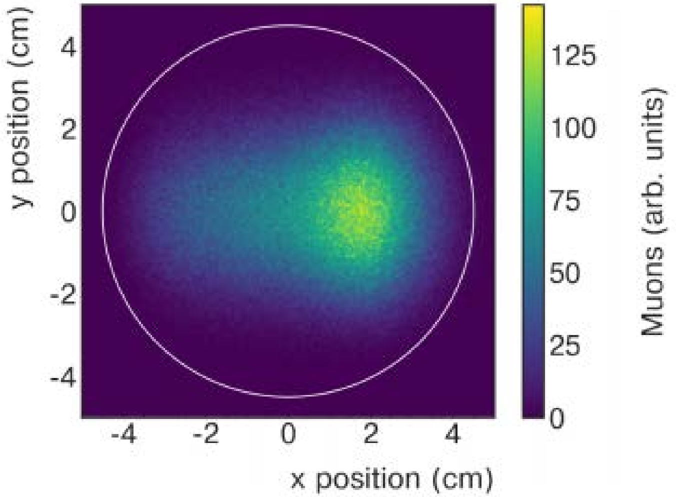




Measurement of ω_p: Muon weighted / Field Transients

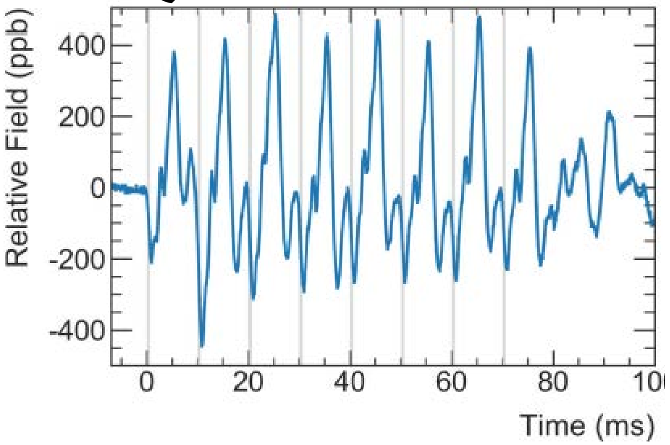
- Want the field actually experienced by muons, need to know the muon spatial distribution
- $\boldsymbol{B_q}$: The electrostatic Quad are pulsed every 10ms and the motion of these plates causes a magnetic field perturbation
- $\boldsymbol{B_k}$: The fast kicker pulse induces eddy currents in the surrounding metal and perturb the field

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

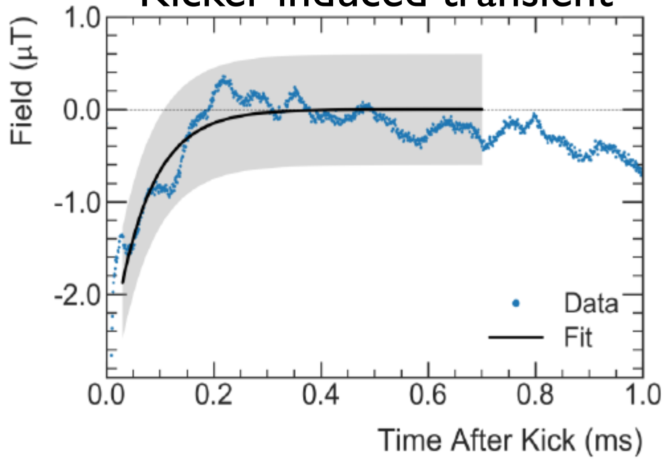


Data set	$\tilde{\omega}'_p(T_r)/2\pi$ (Hz)	Uncertainty (ppb)
Run-1a	61,791,871.2	115
Run-1b	61,791,937.8	127
Run-1c	61,791,845.4	125
Run-1d	61,792,003.4	108
	Average over all data sets	
Field Measurements		56
ESQ Transient		92
Kicker Transient		37
Total		114

Quad-induced transient

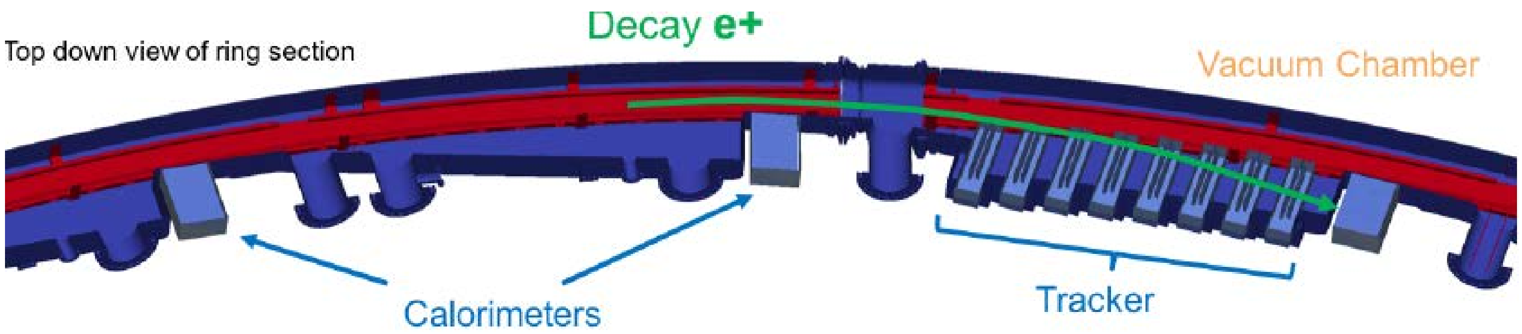


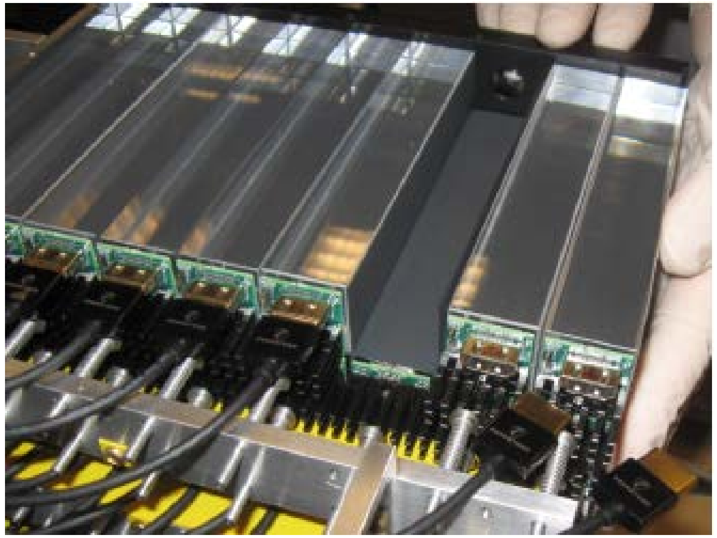
Kicker-induced transient



Ref: Phys. Rev. A **103**, 042208

Measurement of ω_a

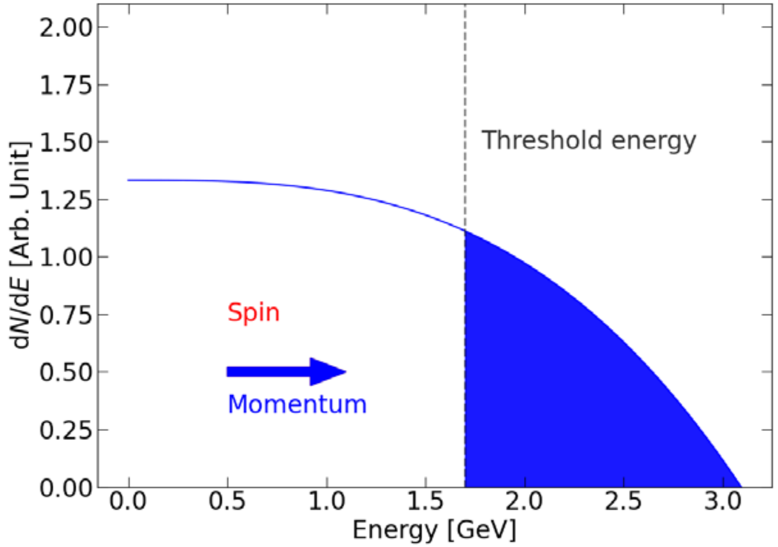


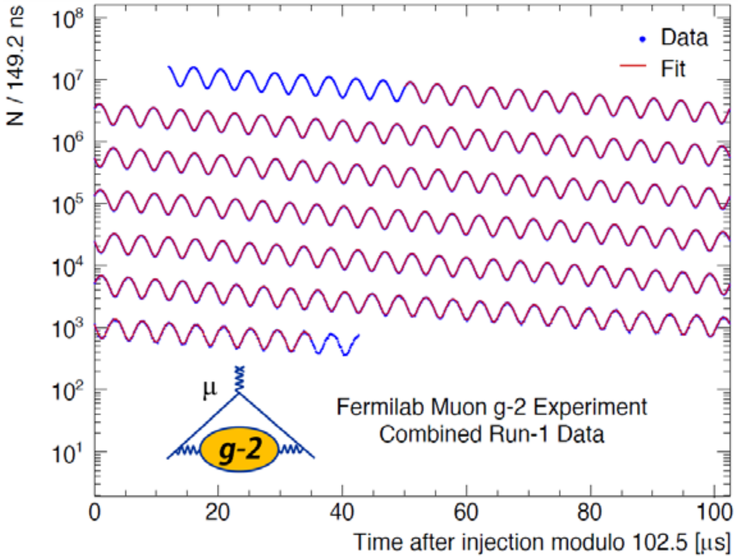


- Highest-energy e+ emitted preferentially along muon spin
- 24 calorimeters of 9×6 PbF_2 crystals detect e^+ from muon decay

e^+ Signal from Muon Decay: $N_{\text{ideal}}(t) = N_0 \exp(-t/\gamma\tau_\mu)\,[1 + A\cos(\omega_a t + \phi)]$

*PbF_2 crystals are provided by SICCAS in collaboration with SJTU





Measurement of ω_a: Fitting

$$\boxed{N = N_0 \Lambda N_{cbo} N_{2cbo} N_{vw} e^{-t/\tau}(1 - AA_{cbo}\cos(\omega_a t + \phi\phi_{cbo}))}$$

$$N_{cbo} = 1 - A_{1cbo} e^{-\frac{t}{\tau_{cbo}}} \cos(\omega_{cbo} t + \phi_{1cbo})$$

$$N^*_{2CBO} = 1 - A_{2cbo} e^{-\frac{2t}{\tau_{cbo}}} \cos(2\omega_{cbo} t + \phi_{2cbo})$$

$$N_{vw} = 1 - A_{vw} e^{-\frac{t}{\tau_{vw}}} \cos(p \cdot \omega_{vw} t + \phi_{vw})$$

$$A_{cbo} = 1 - A_{Acbo} e^{-\frac{t}{\tau_{cbo}}} \cos(\omega_{cbo} t + \phi_{Acbo})$$

$$\phi_{cbo} = 1 - A_{\phi cbo} e^{-\frac{t}{\tau_{cbo}}} \cos(\omega_{cbo} t + \phi_{\phi cbo})$$

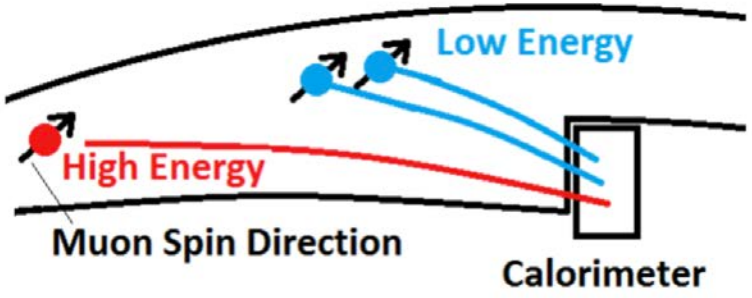
$$\omega_{cbo} = \omega_0(1 + Ae^{-\frac{t}{tau\_A}}/\omega_0 t + Be^{-\frac{t}{tau\_B}}/\omega_0 t)$$

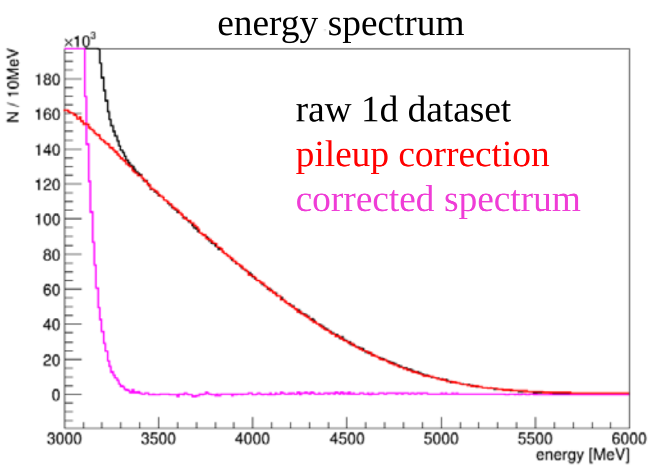
$$\omega_{vw} = \omega_c - 2\omega_y = \omega_c - 2\omega_{CBO}\sqrt{\frac{2\omega_c}{\omega_{CBO}} - 1}$$

$$\Lambda = 1 - K_{loss}\int L(t')e^{t'/64.4}dt$$

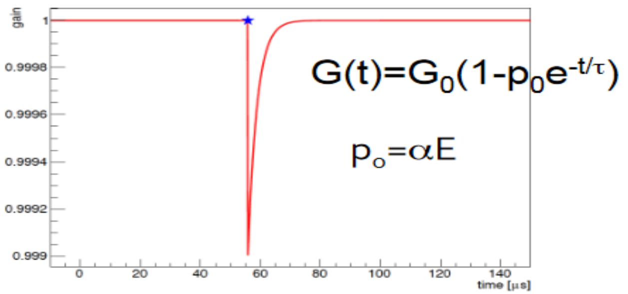
$$\chi^2 = \sum_{i=1}^{ndf}[\frac{N_{bin} - N_{fit}}{\sigma(N_{bin})}]^2$$

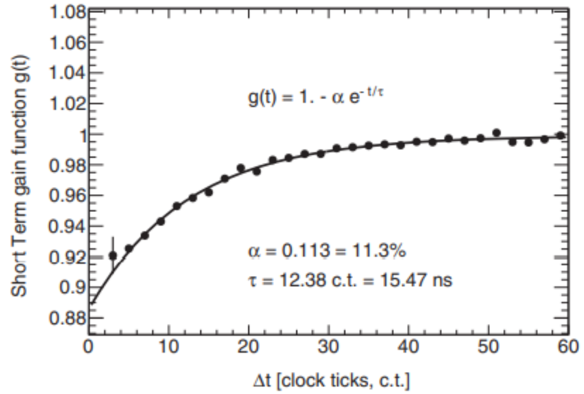
Detector effect: Pileup



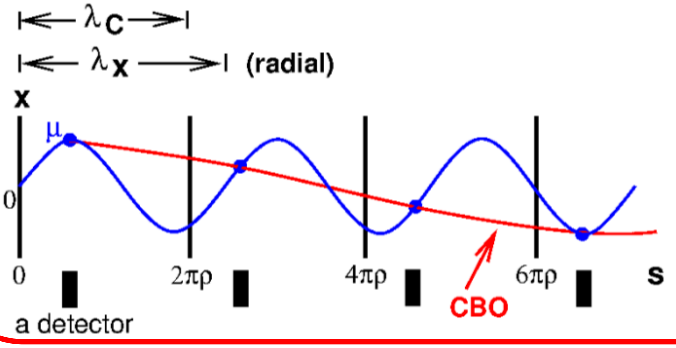


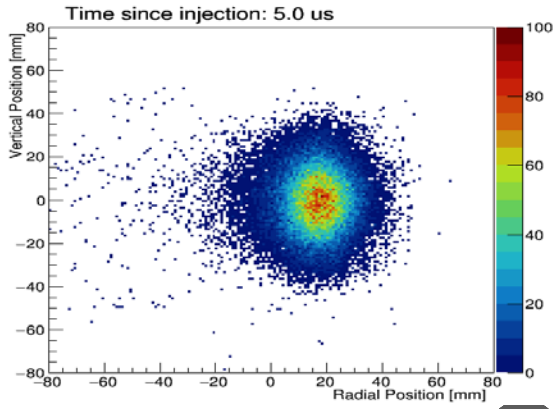
Detector effect: Gain





Beam Dynamic effect: Coherent Betatron Oscillations (CBO)

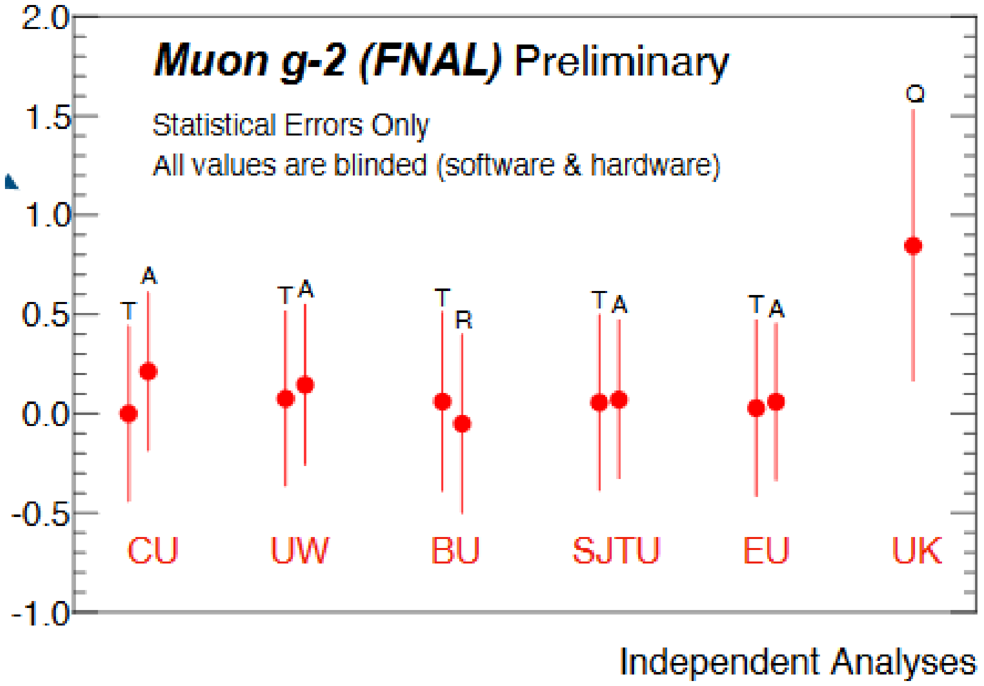




Measurement of ω_a: blinded analysis

- Software blind: analyzers' results come with random frequency offset $\omega_a \rightarrow \omega_a \pm 25$ ppm
- Hardware blind: ω_a clock detuned with true frequency $(40 - \mathrm{X})$ MHz; blinding factor in the range of 25 ppm

- 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



Run-1 dataset	1a	1b	1c	1d
$\omega_a^m/2\pi$ (s^{-1})	229 080.957	229 081.274	229 081.134	229 081.123
Δ $(\omega_a^m/2\pi)$ (s^{-1})	0.277	0.235	0.189	0.155
Statistical uncertainty (ppb)	1207	1022	823	675
Gain changes (ppb)	12	9	9	5
Pileup (ppb)	39	42	35	31
CBO (ppb)	42	49	32	35
Time randomization (ppb)	15	12	9	7
Early-to-late effect (ppb)	21	21	22	10
Total systematic uncertainty (ppb)	64	70	54	49
Total uncertainty (ppb)	1209	1025	825	676

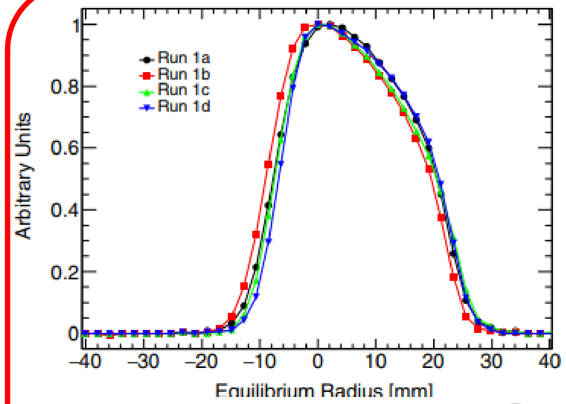
Ref: Phys. Rev. D **103**, 072002

Measurement of ω_a: Beam Dynamic Correction

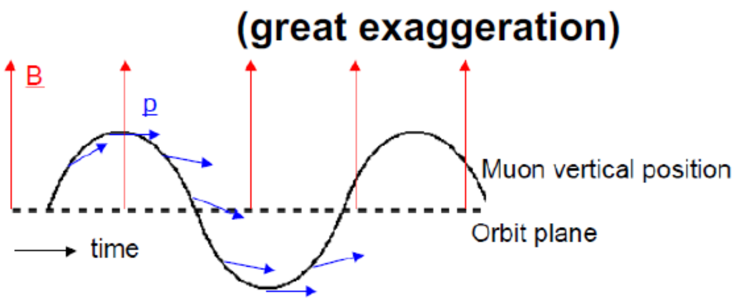
- C_e: Muons with p ≠ 3.09 GeV/c are slightly affected by the radial electric field
- C_p: A small pitch angle (vertically) modulates $\beta \times \mathbf{B}$ term and the correction is required
- C_{ml}: Muon losses (ML) induce a (tiny) phase shift
- C_{pa}: Muon phase change due to 1) beam changing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

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

Ref: Phys. Rev. Accel. Beams **24**, 044002

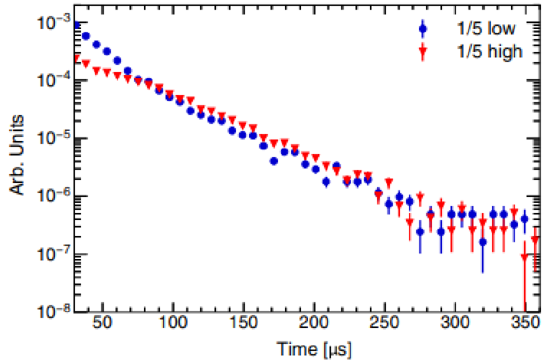


$$C_e = 2n(1-n)\beta_0^2 \frac{\langle x_e^2 \rangle}{R_0^2}$$

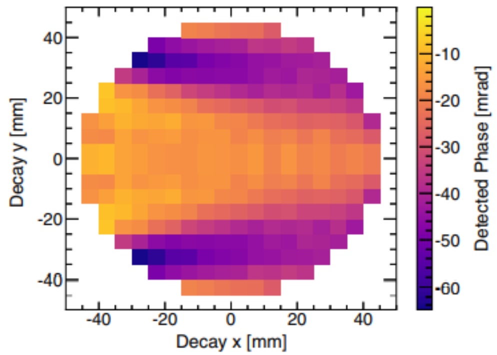


$$C_p = \frac{n}{2}\frac{\langle y^2 \rangle}{R_0^2} = \frac{n}{4}\frac{\langle A^2 \rangle}{R_0^2}$$

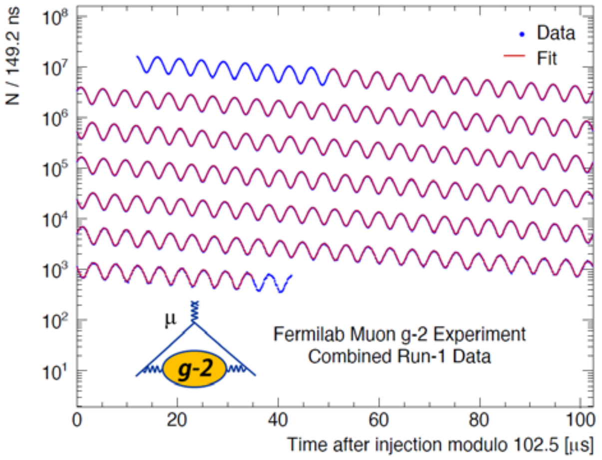
$$\vec{\omega}_a = -\frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E} - a_\mu\left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta}\right]$$



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



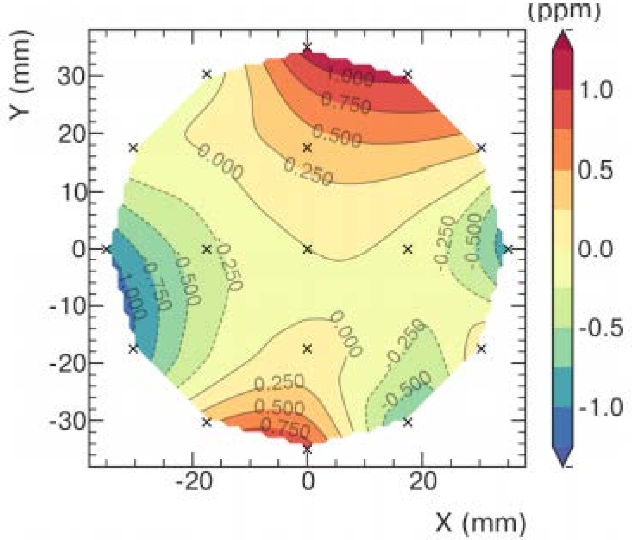
$$C_{pa}:\ \Delta\omega_a = \frac{d\phi}{dt} = \frac{dY_{\text{RMS}}}{dt}\frac{d\phi}{dY_{\text{RMS}}} \neq 0$$

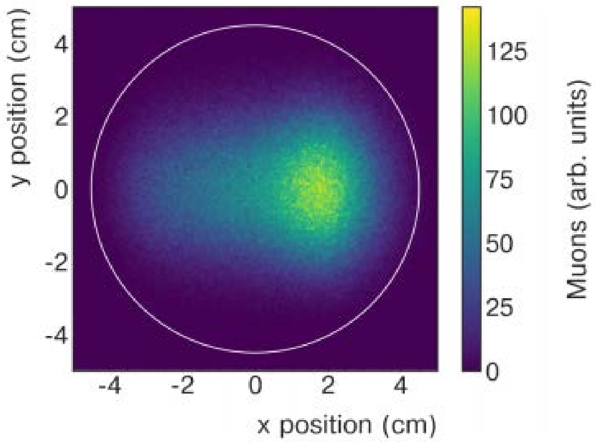


Beam Dynamics

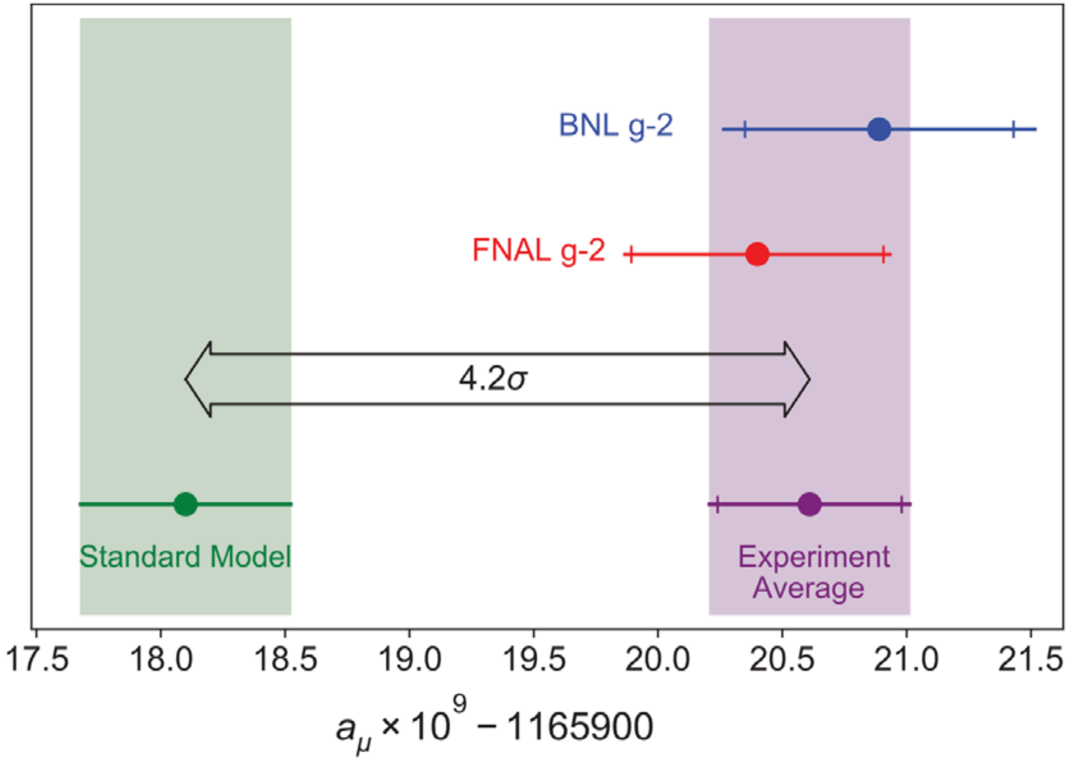
$$a_\mu \propto \frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}}\, \omega_a^{\text{meas}} \left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{f_{\text{calib}} \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle \left(1 + B_k + B_q\right)}$$

Field Transients





Run1 Results



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

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

$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

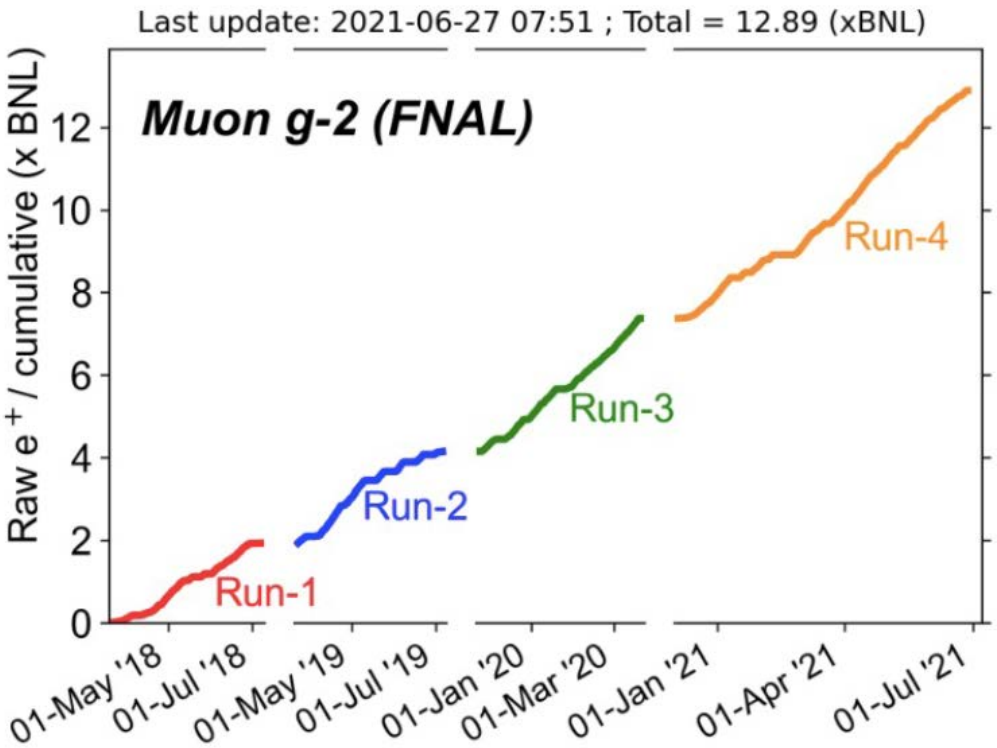
Significance: 4.2σ

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

Ref: Phys. Rev. Lett. **126**, 141801

Summary

- Our first result is consistent with the BNL measurement with improved precision
- The new averaged experiment result gives 4.2σ discrepancy with the Standard Model prediction
- Run 1 is only 6% of the final data set
- We expect an improvement in precision by a factor of 2 from Run 2 and 3 and another factor of 2 from Run4 and Run5



Backup: ω_a Fitting

$$\boxed{N = N_0 \Lambda N_{cbo} N_{2cbo} N_{vw} e^{-t/\tau}(1 - A A_{cbo} \cos(\omega_a t + \phi \phi_{cbo}))}$$

$$N_{cbo} = 1 - A_{1cbo} e^{-\frac{t}{\tau_{cbo}}} \cos(\omega_{cbo} t + \phi_{1cbo})$$

$$N^*_{2CBO} = 1 - A_{2cbo} e^{-\frac{2t}{\tau_{cbo}}} \cos(2\omega_{cbo} t + \phi_{2cbo})$$

$$N_{vw} = 1 - A_{vw} e^{-\frac{t}{\tau_{vw}}} \cos(p \cdot \omega_{vw} t + \phi_{vw})$$

$$A_{cbo} = 1 - A_{Acbo} e^{-\frac{t}{\tau_{cbo}}} \cos(\omega_{cbo} t + \phi_{Acbo})$$

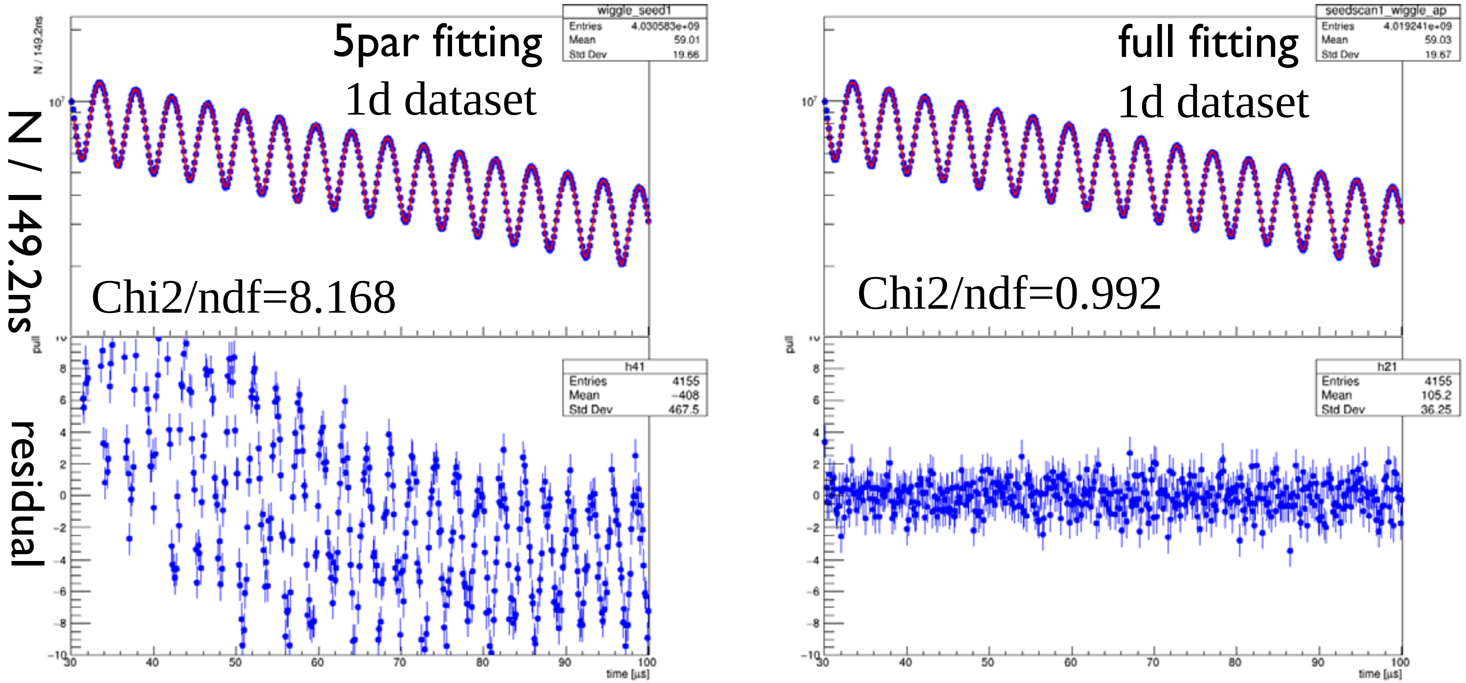
$$\phi_{cbo} = 1 - A_{\phi cbo} e^{-\frac{t}{\tau_{cbo}}} \cos(\omega_{cbo} t + \phi_{\phi cbo})$$

$$\omega_{cbo} = \omega_0 (1 + A e^{-\frac{t}{tau\_A}} / \omega_0 t + B e^{-\frac{t}{tau\_B}} / \omega_0 t)$$

$$\omega_{vw} = \omega_c - 2\omega_y = \omega_c - 2\omega_{CBO} \sqrt{\frac{2\omega_c}{\omega_{CBO}} - 1}$$

$$\Lambda = 1 - K_{loss} \int L(t') e^{t'/64.4} dt$$

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



FFT of residual: 1d dataset