Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

The Muon g – 2 Experiment at Fermilab

Kevin Labe, on behalf of the Muon g-2 Collaboration

Cornell University

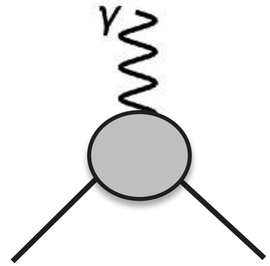
56th Rencontres de Moriond

March 15, 2022

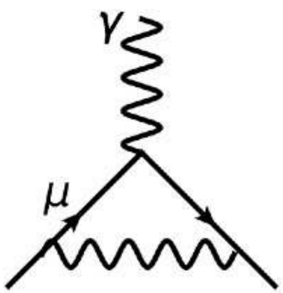
In partnership with:

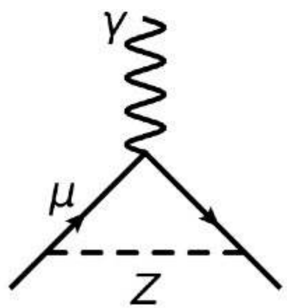
Why Muon g – 2 ?

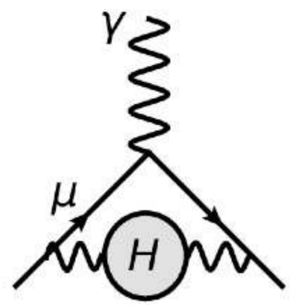
$$\mu = g\frac{q}{2m}S$$

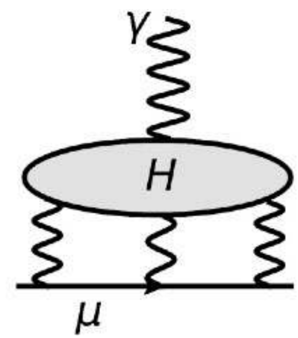


Any new particle interacting at this vertex influences magnetic moment









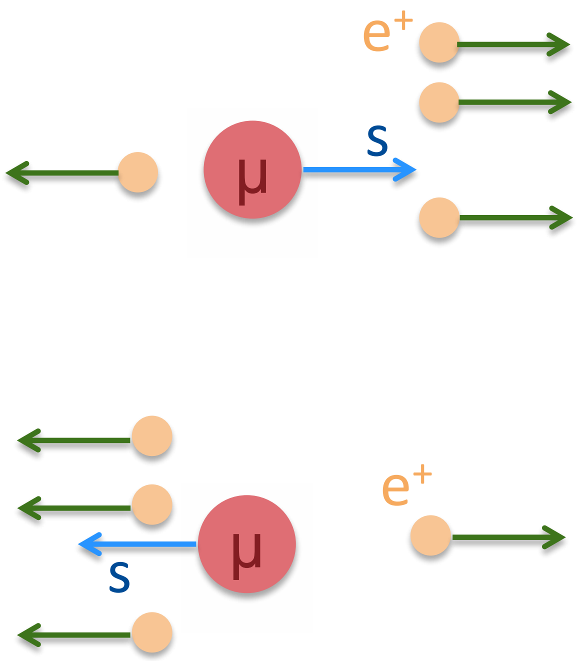
	QED 5th order	EW 2nd order	HVP Dispersive & Lattice	HLBL Dispersive & Lattice
Precision	1 ppb	10 ppb	340 ppb	150 ppb

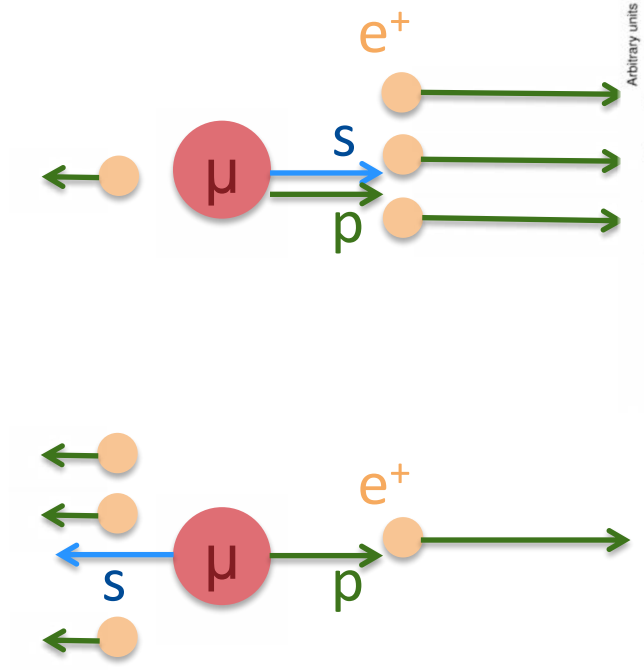
Experimental Principle

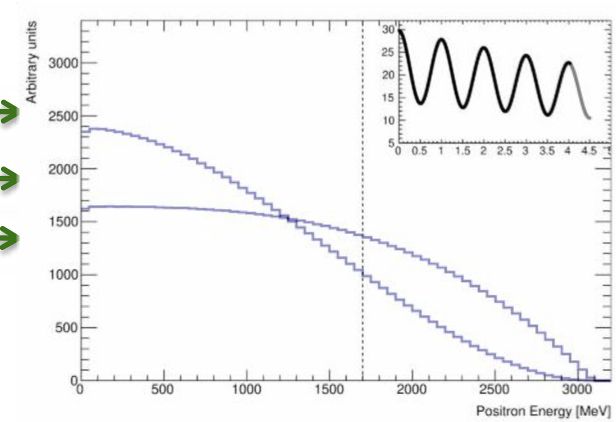
$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

Parity violation
e+ prefers μ+ spin direction

Lorentz boost
Energy enhanced along p

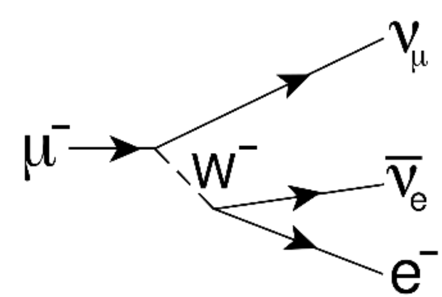


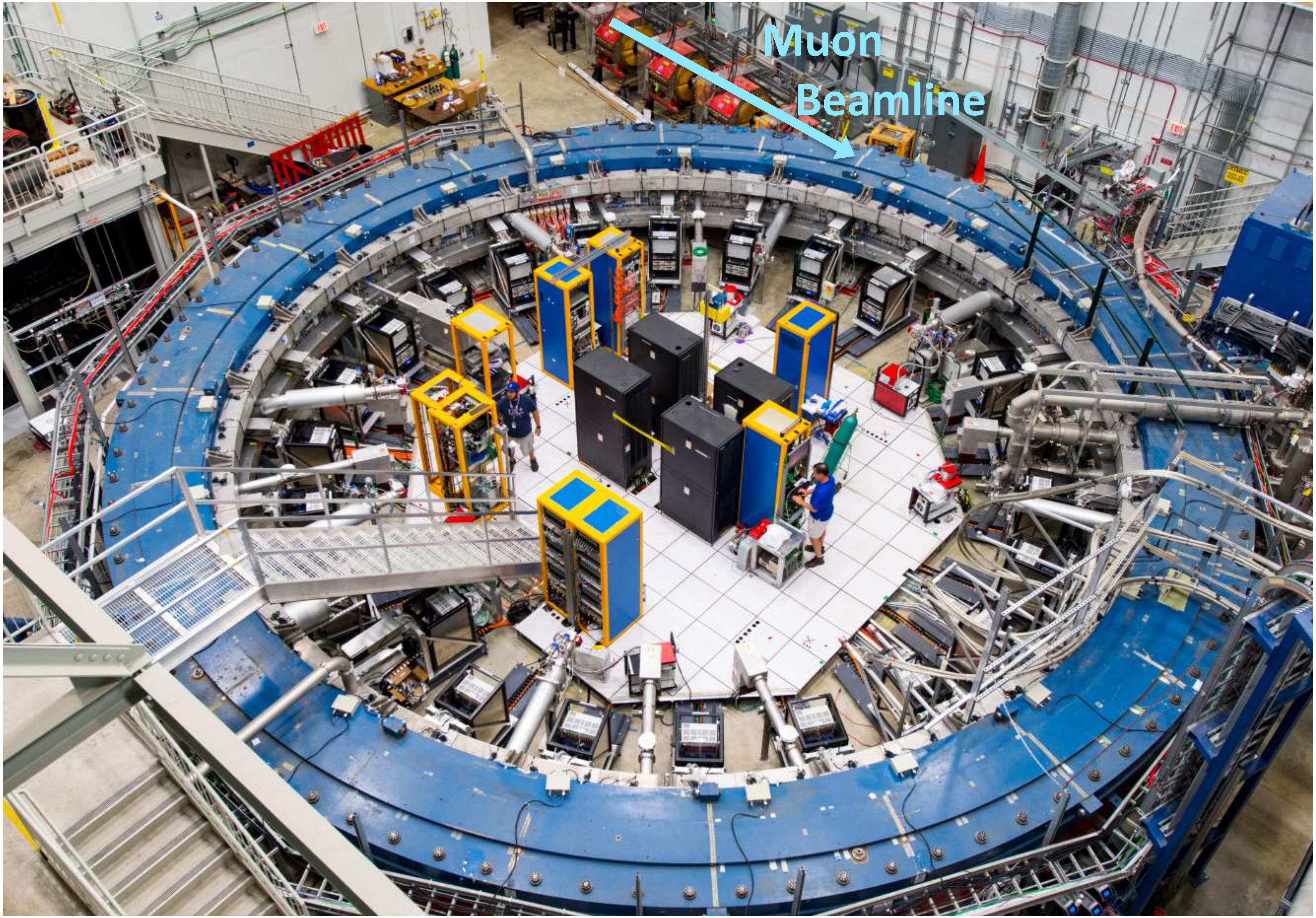


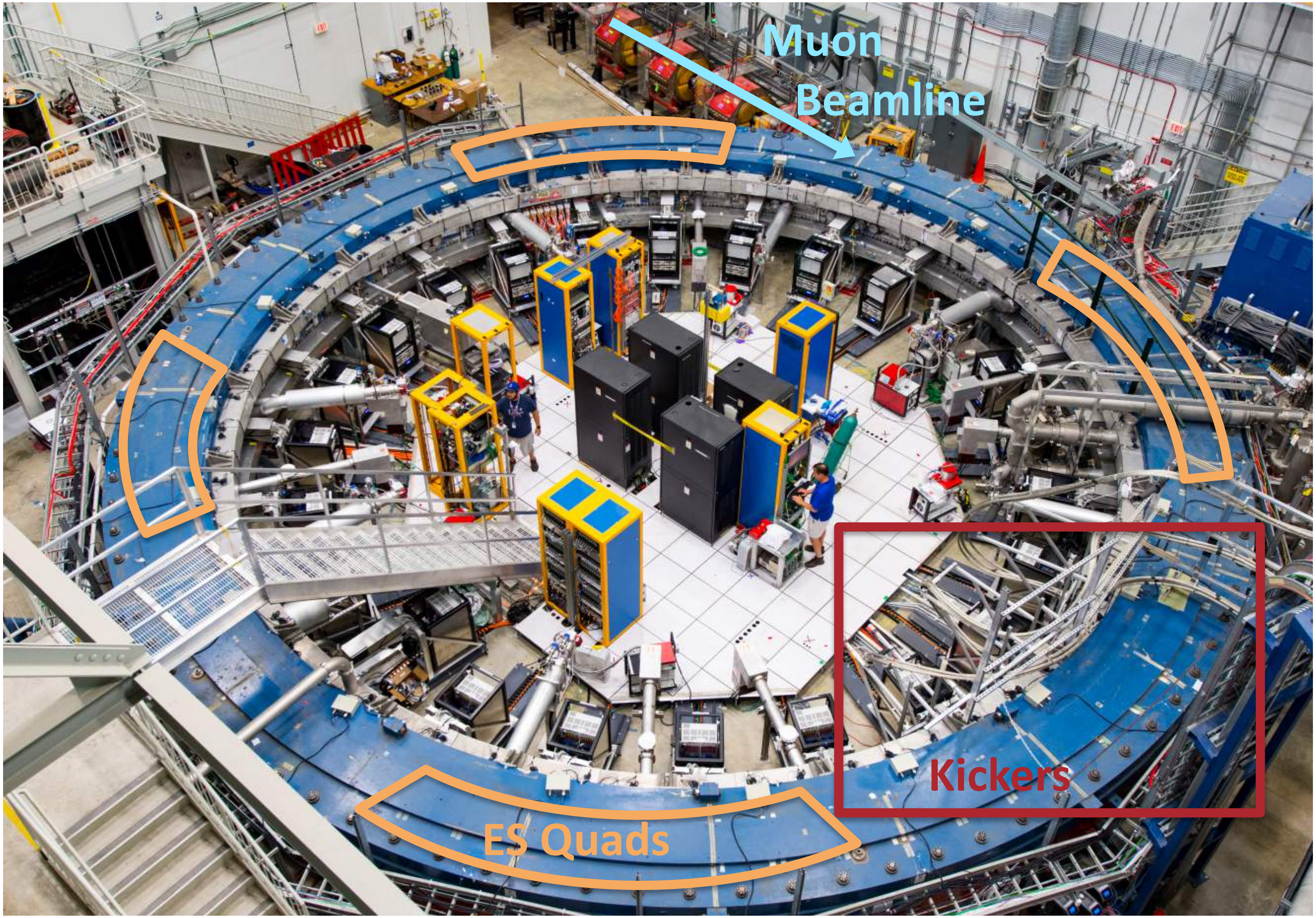


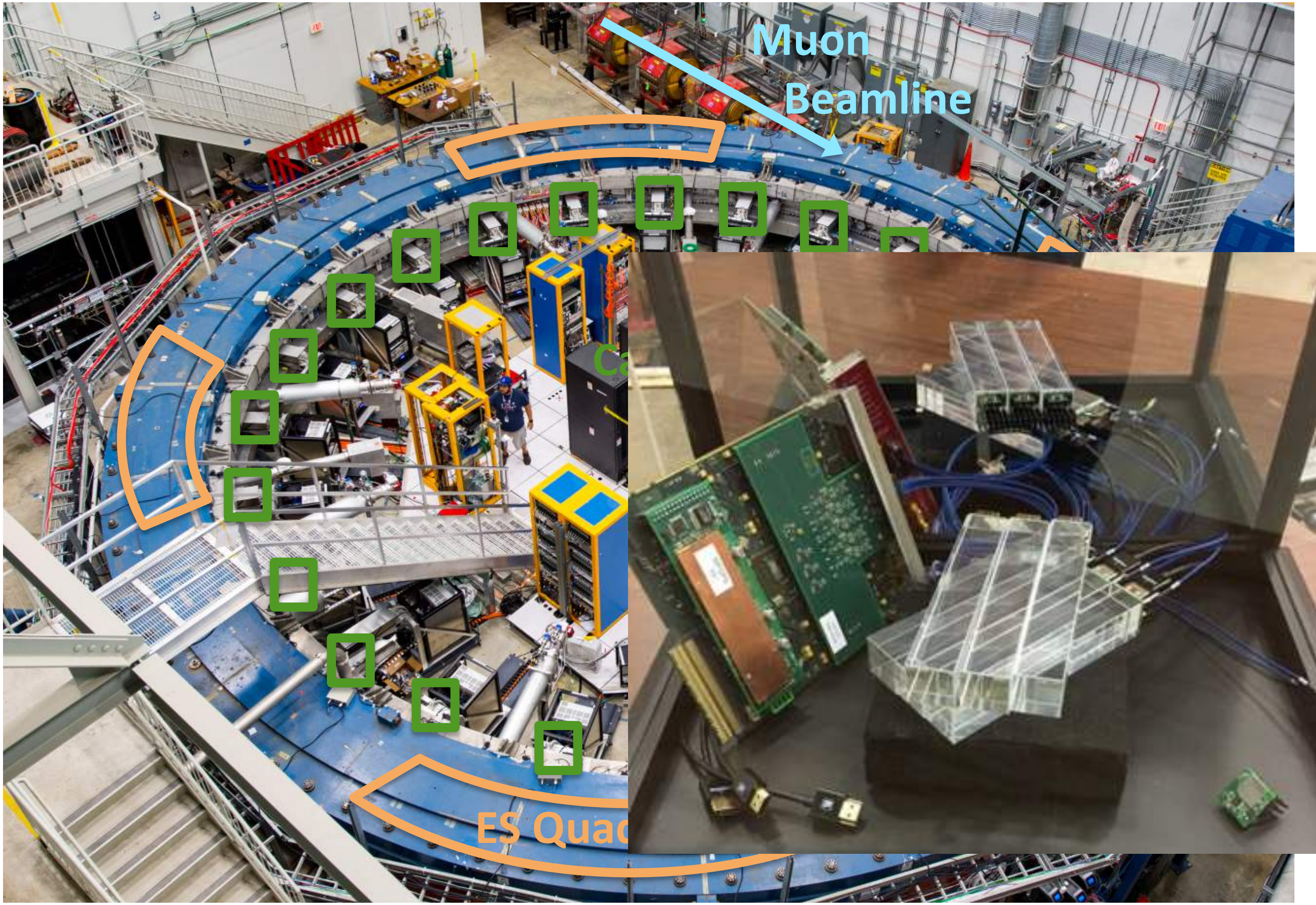
Muon Rest Frame

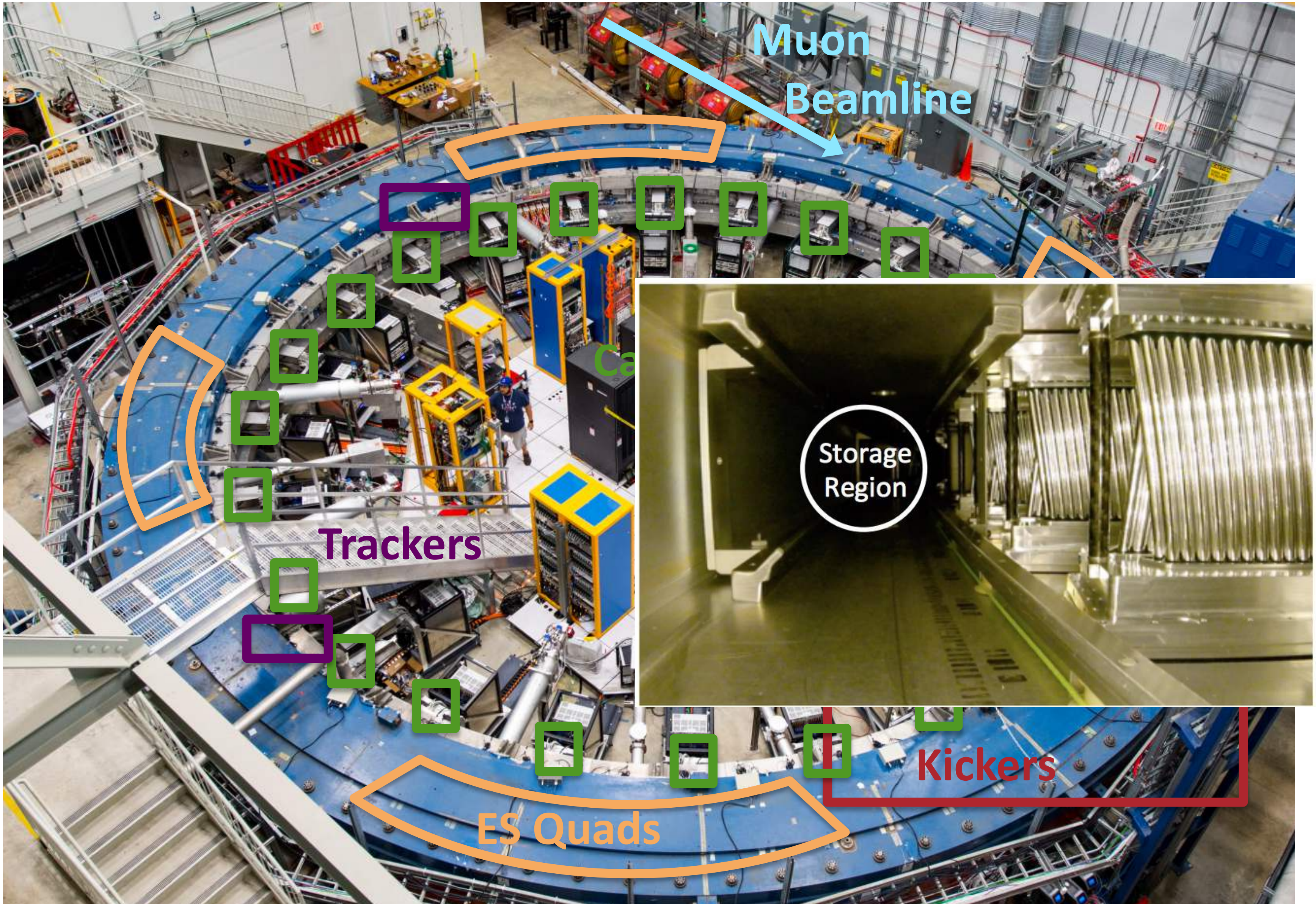
Laboratory Frame

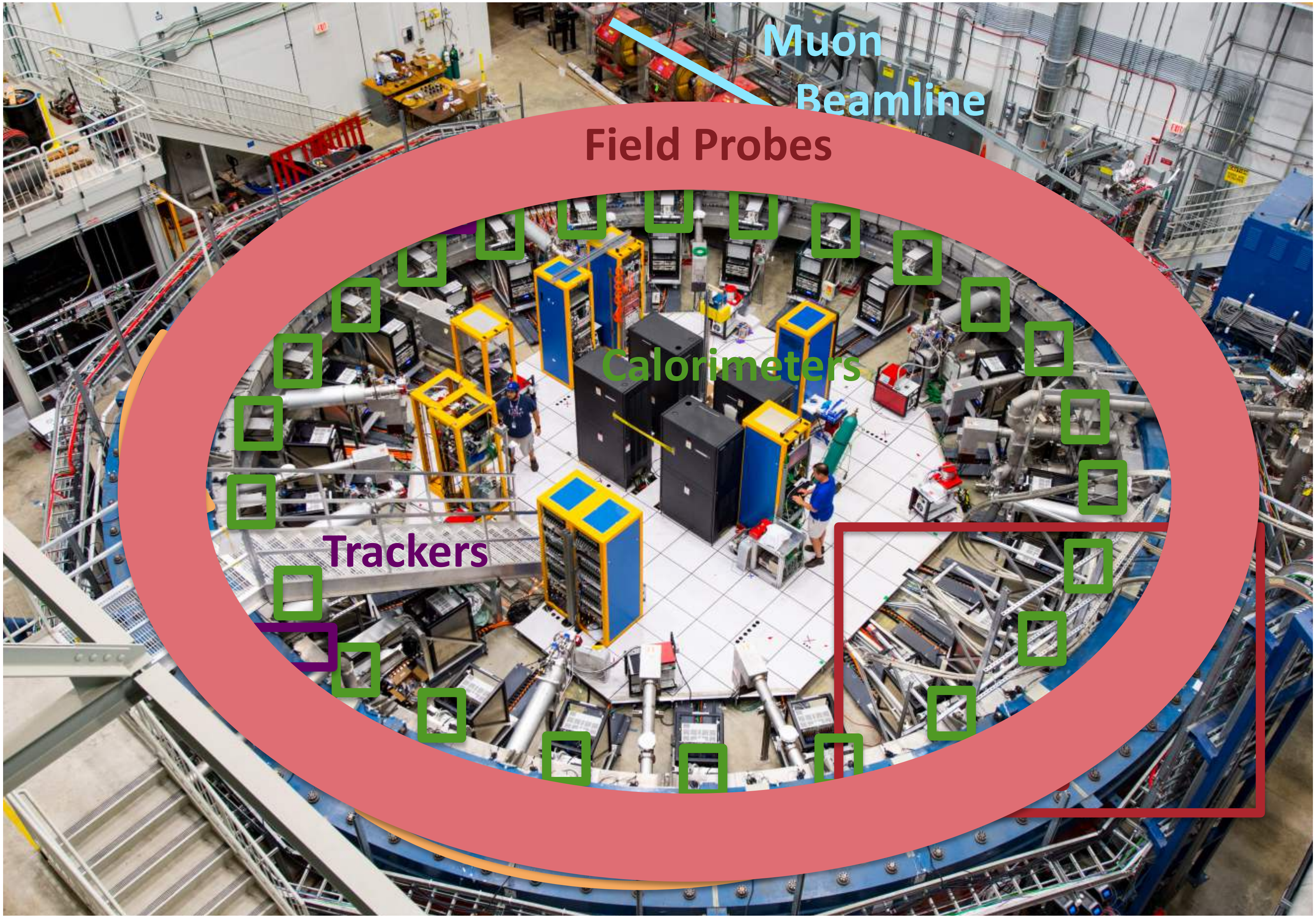



Muon
Beamline


Muon
Beamline
Kickers
ES Quads

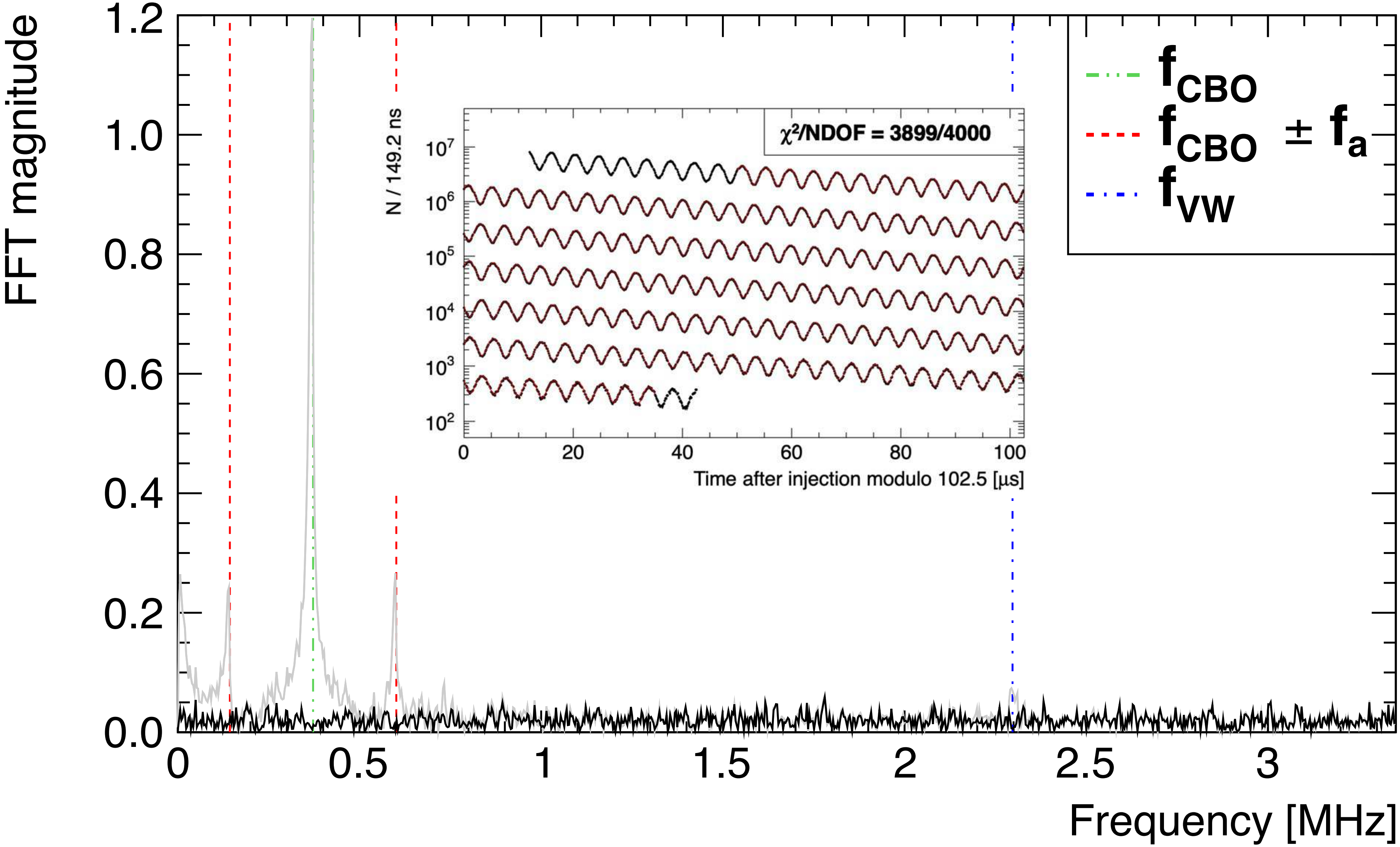

Muon
Beamline


Muon
Beamline
Trackers
Storage
Region
Kickers
ES Quads

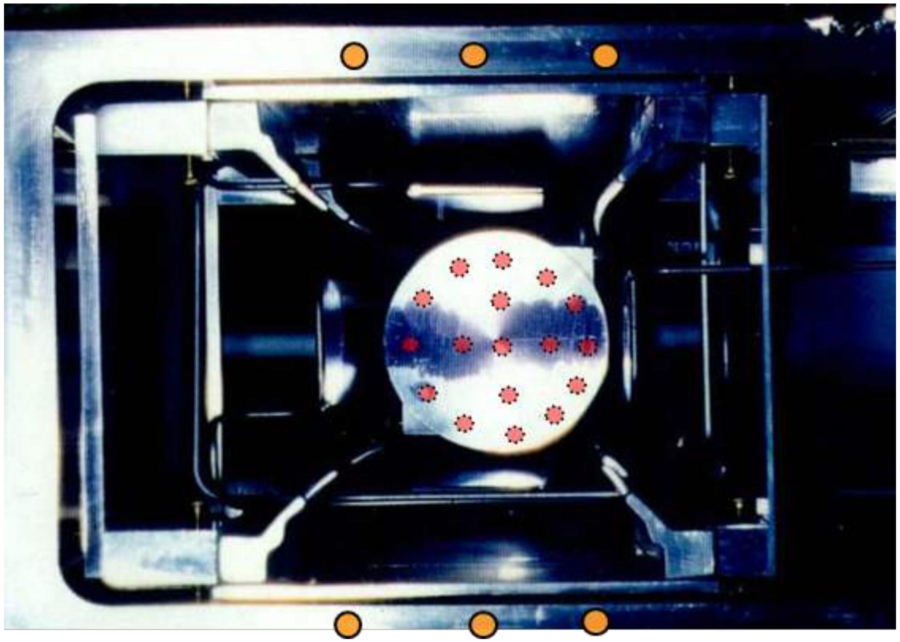

Muon
Beamline
Field Probes
Calorimeters
Trackers

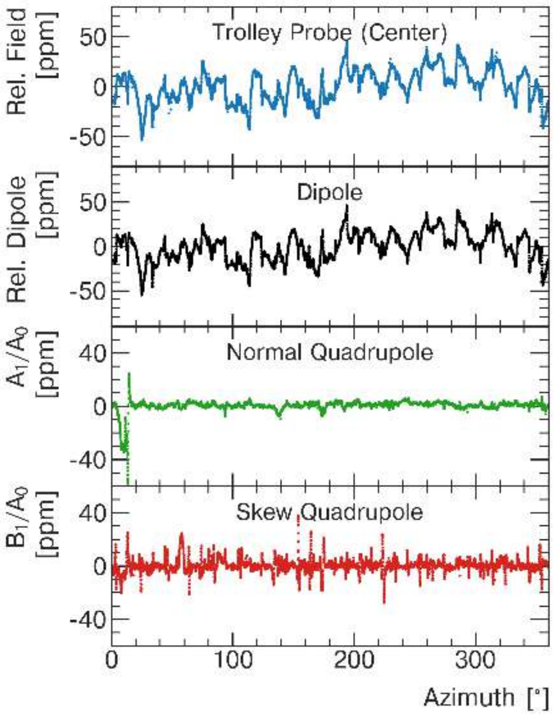
Muon precession measurement

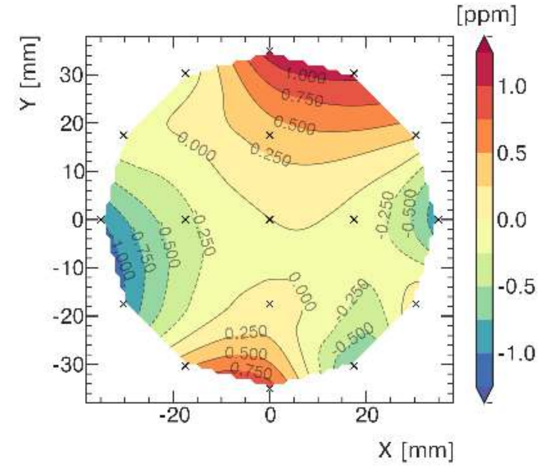
CBO – horizontal beam osc.
VW – vertical beam osc.



Field measurement





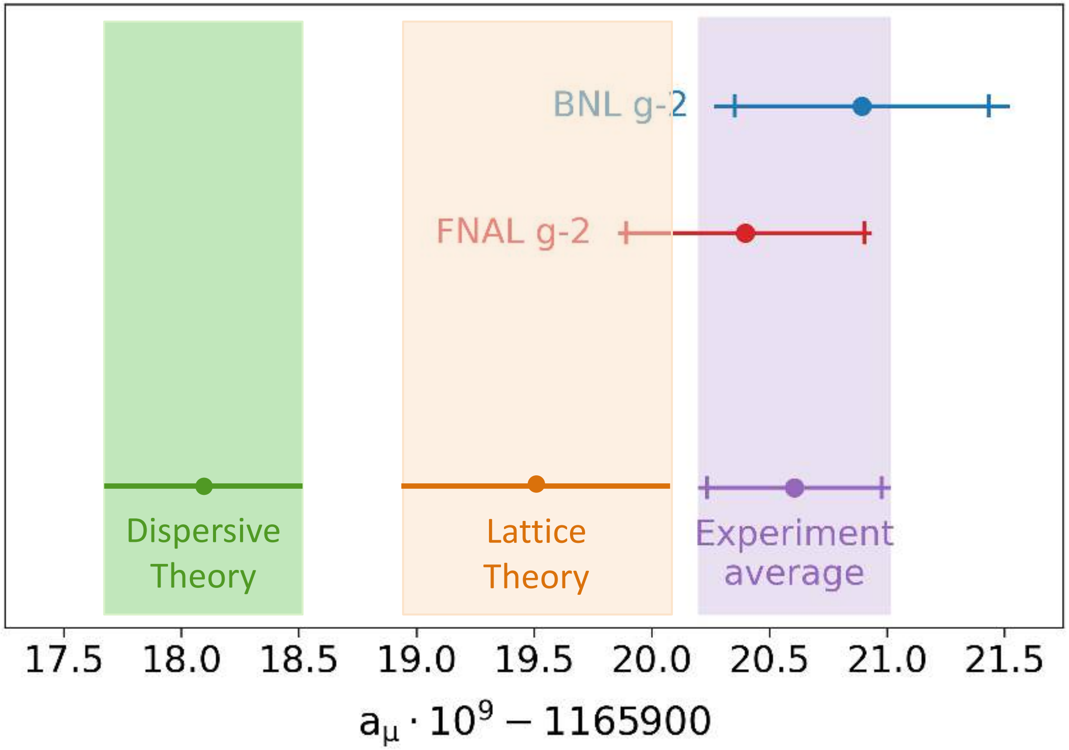


Trolley can access storage volume and is directly sensitive to field moments

Fixed probes interpolate field moments between trolley runs

Run 1 Results

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



Quantity	Uncertainty (ppb)
Precession (Stat.)	434
Precession (Syst.)	58
E field Correction	53
Phase-Acceptance	75
Magnetic Field	56
Kicker Field Transient	37
Quad Field Transient	92
External Factors	25
Total	462

Run 1 Error Budget

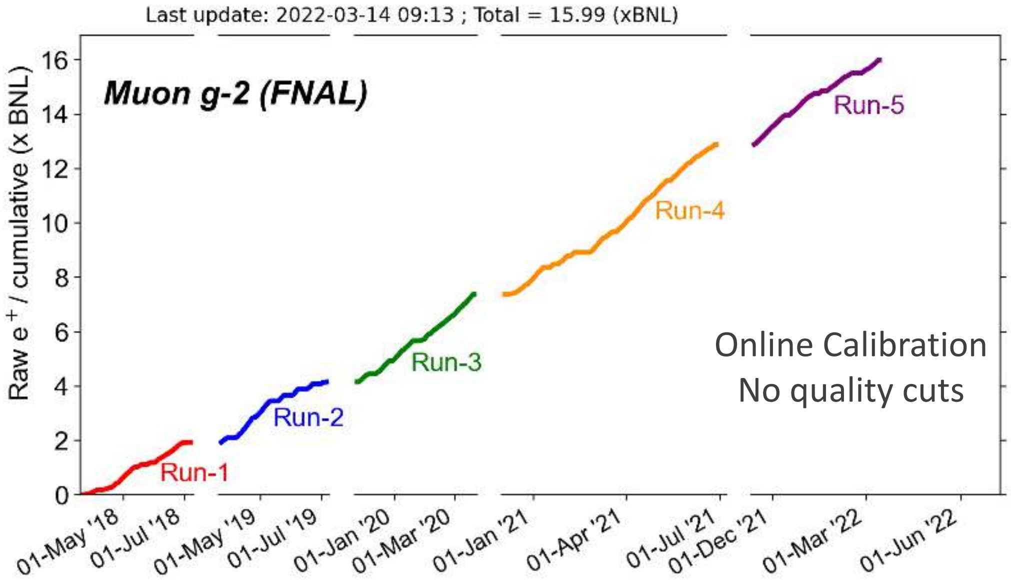
a_μ(Exp) – a_μ(WP20) = 2150 ± 510 ppb

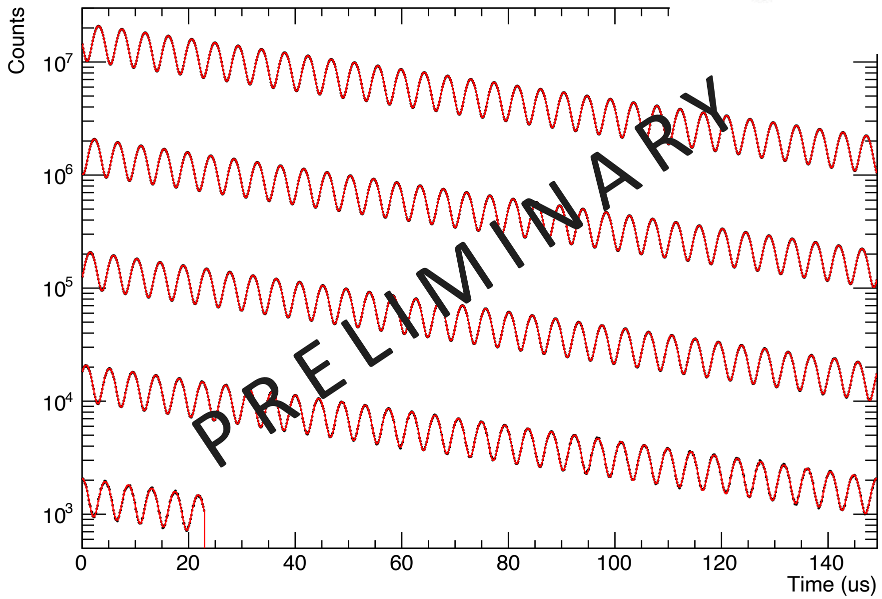
a_μ(Exp) – a_μ(BMW) = 920 ± 600 ppb

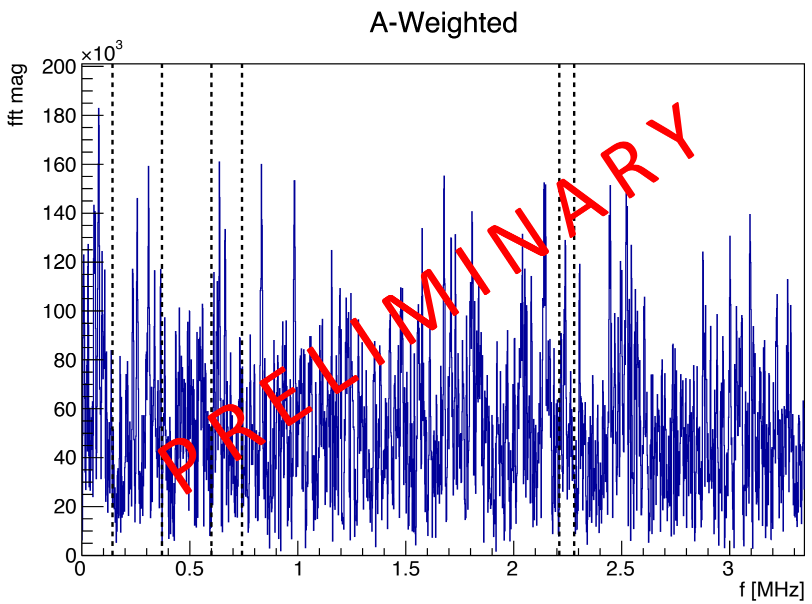
More Statistics

Run-2 and Run-3 analysis proceeding

Expected statistical uncertainty ~200 ppb



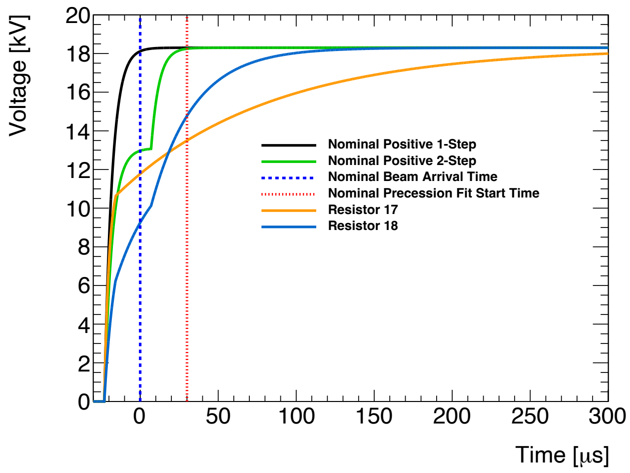


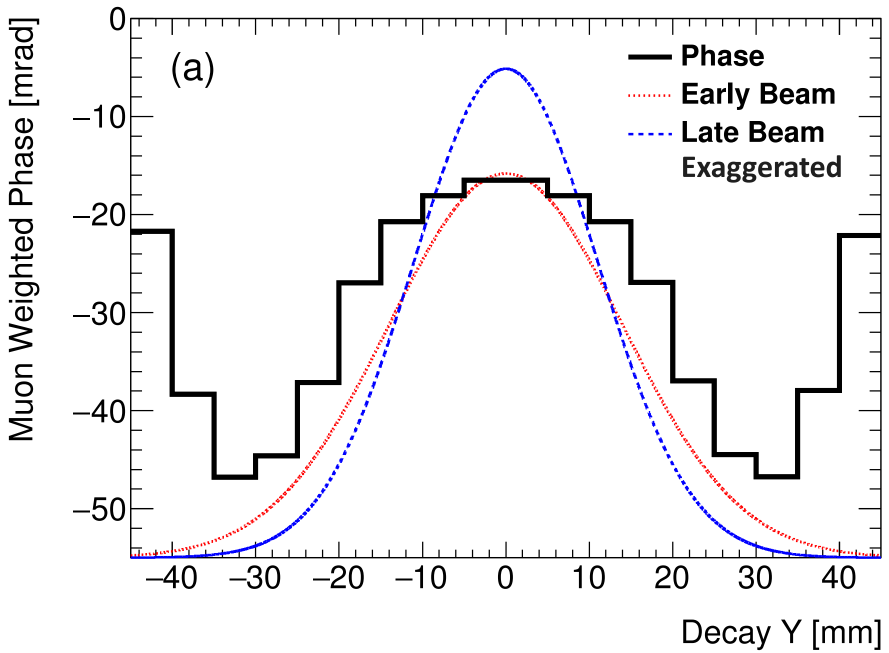


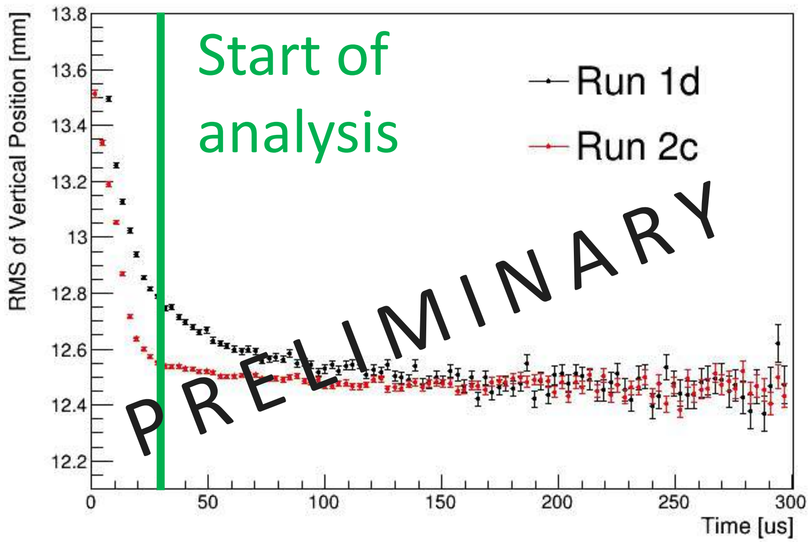
Replaced Quadrupole HV resistors

Calo acceptance effects create a phase shift as a function of decay position

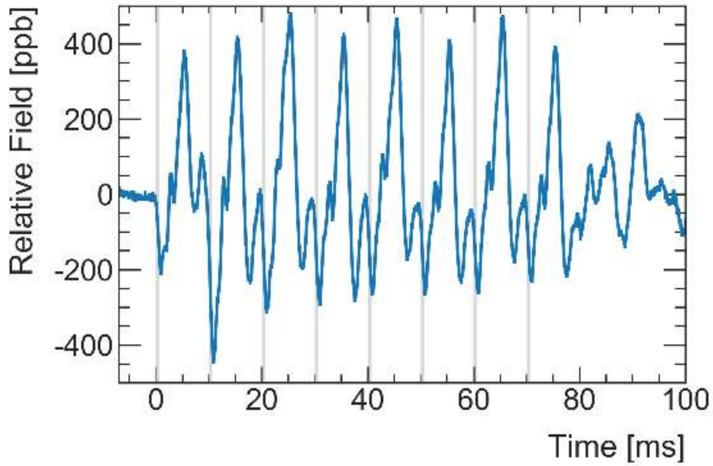
This couples to beam changes to bias the observed frequency

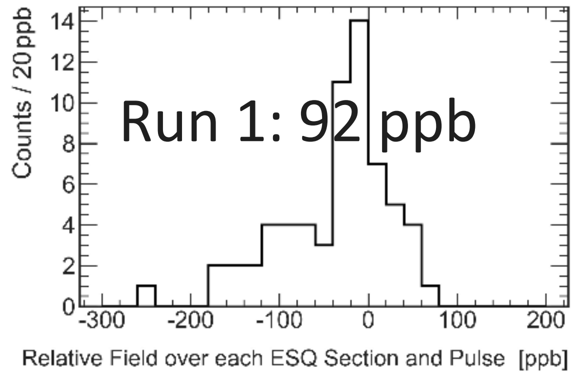






Quadrupole field transient

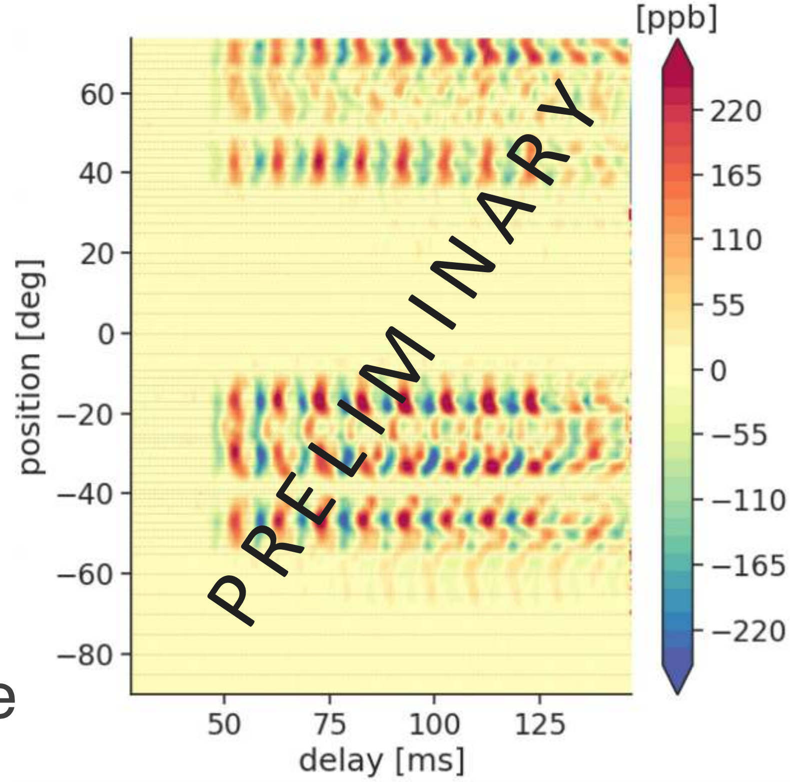




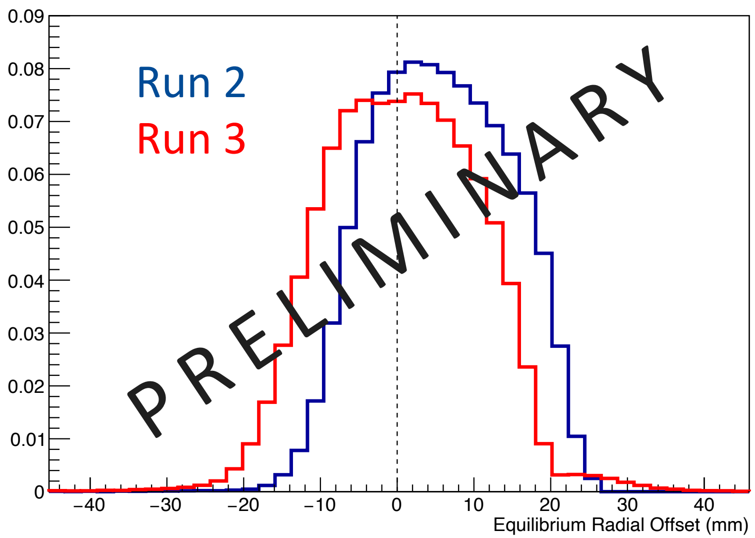
Mechanical vibration of pulsed quad plates drive field perturbations

Measured with dedicated probes

Now measured in both time and space

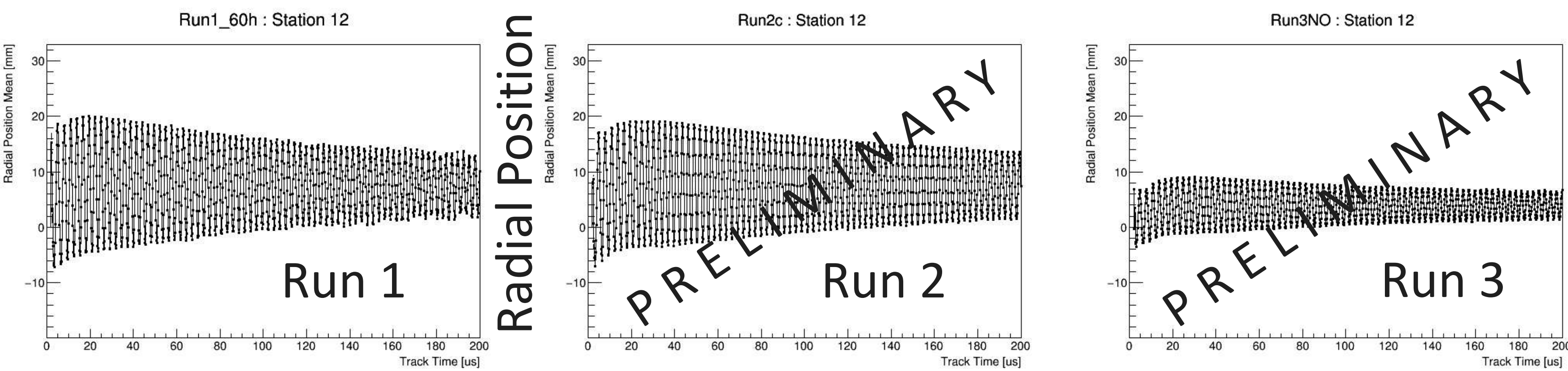


Stronger Kick



Better Beam Centering

Reduced CBO oscillation



Muon g – 2 Collaboration

Thanks to my wonderful collaborators around the world

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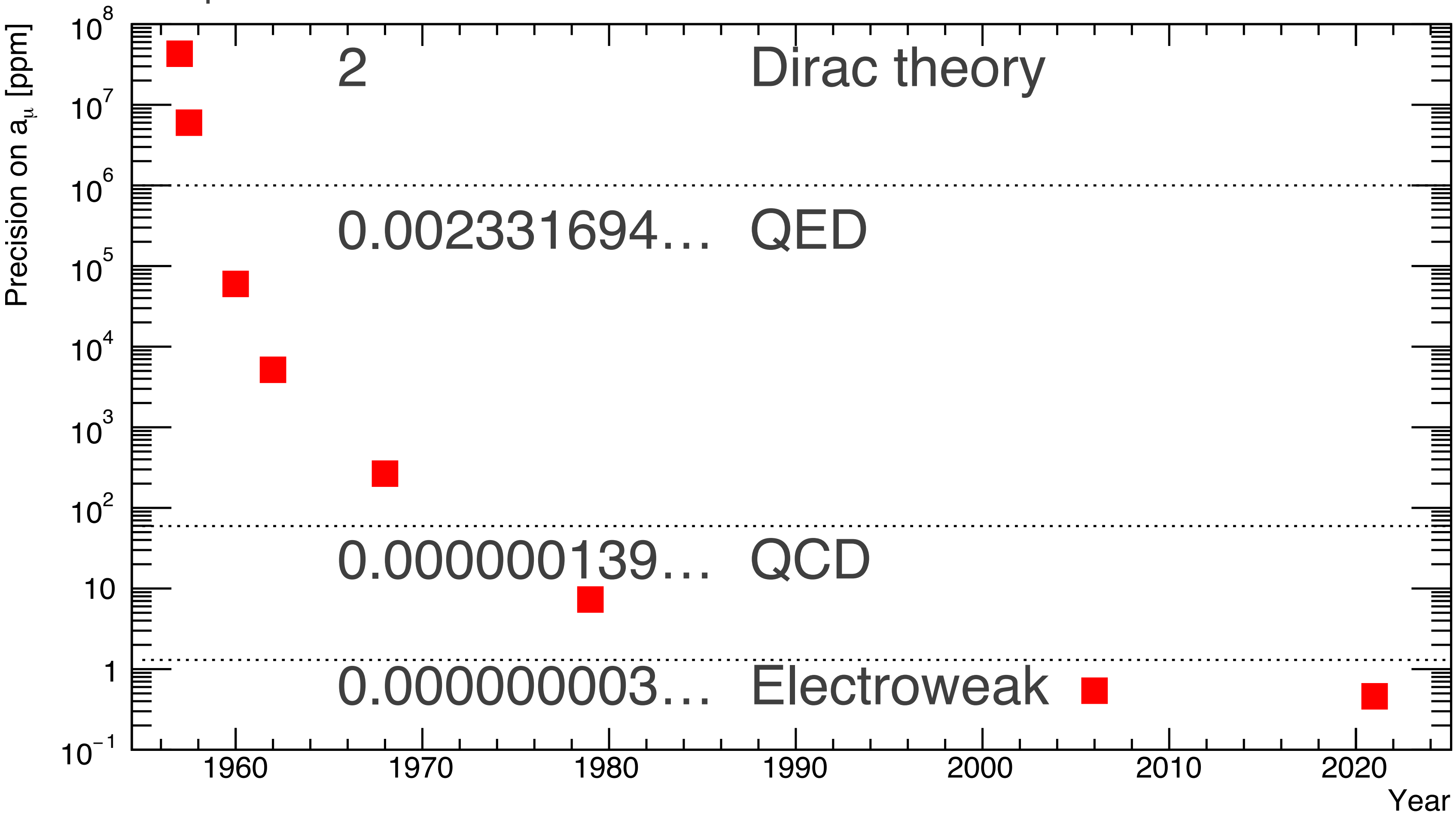
60 years of g_μ

$g_\mu^{SM} = 2.002331836\ldots$

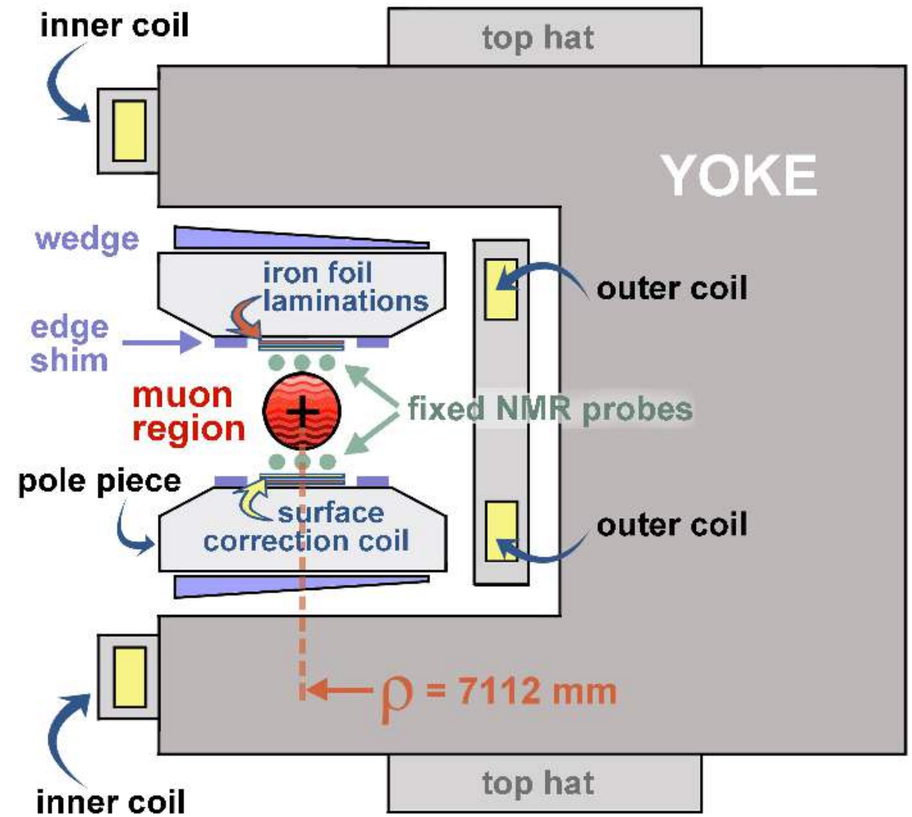


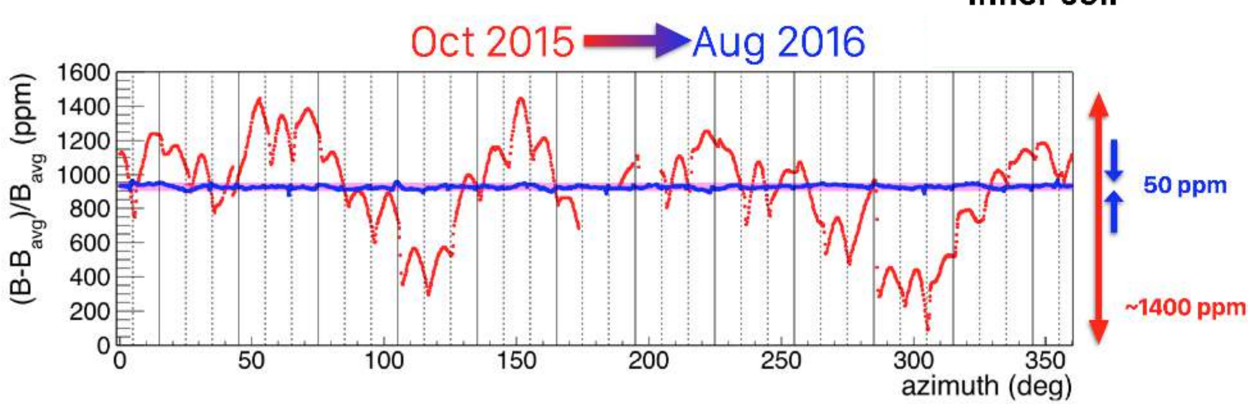
g – 2 Storage Ring

1.45T superferric magnet

Shimmed to 50 ppm uniformity

3x better than at BNL





Data Analysis

Changes to quad and kicker settings

4 Run-1 data sets

April – June 2018

~6% of statistics target

Run-1 Subset	Tune (n)	Kicker (kV)	Fills (10^4)	Positrons (10^9)
1a	0.108	137	151	0.92
1b	0.120	137	196	1.28
1c	0.120	130	333	1.98
1d	0.107	125	733	4.00

3 Kinds of Blindness

Hardware blind (± 25 ppm clock detuning)

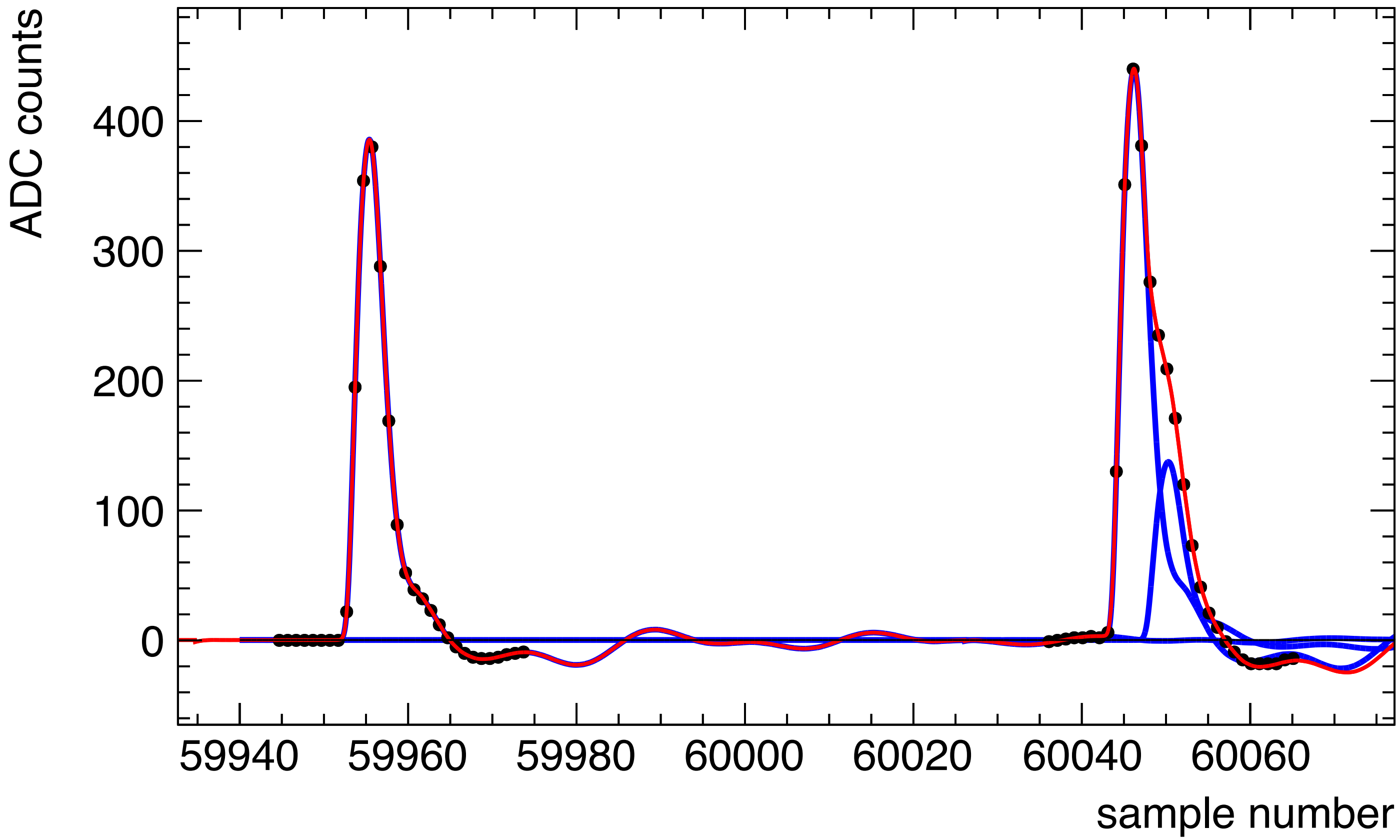
Software blind (± 25 ppm)

global or analysis-specific

Muon precession measurement

$$\frac{f_{\text{clock}}\,\omega_a^m(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\,\langle\omega_p'(x,y,\phi) \times M(x,y,\phi)\rangle(1 + B_k + B_q)}$$

Template fitting of digitized SIPM waveforms



Two clustering strategies: local, global

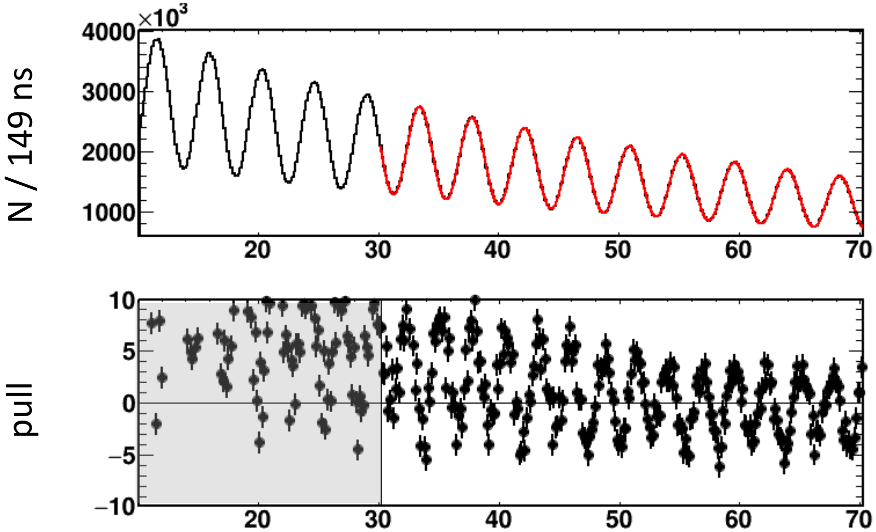
Muon precession measurement

$$\frac{f_{\mathrm{clock}}\,\omega_a^m(1+C_e+C_p+C_{ml}+C_{pa})}{f_{\mathrm{calib}}\,\langle\omega_p'(x,y,\phi)\times M(x,y,\phi)\rangle(1+B_k+B_q)}$$

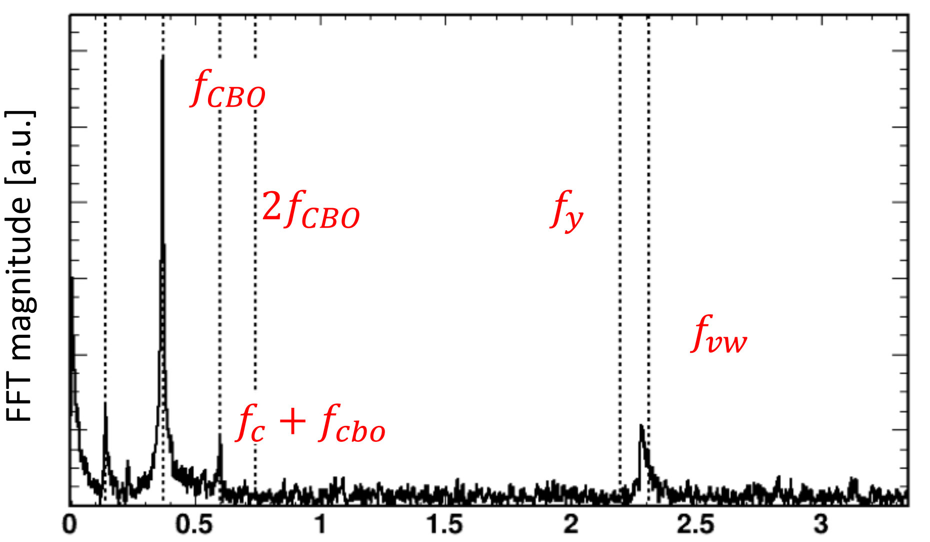
Simple model leaves out much detail

Five-Parameter T-Method Fit

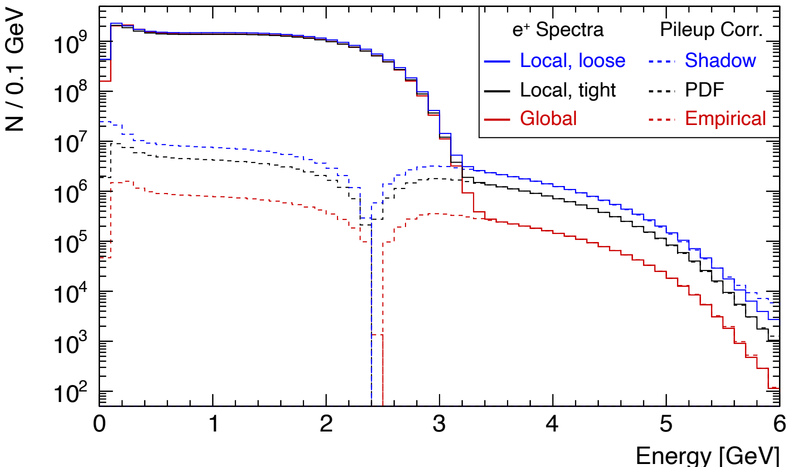
$$\frac{\chi^2}{ndf} = 9500/4150$$

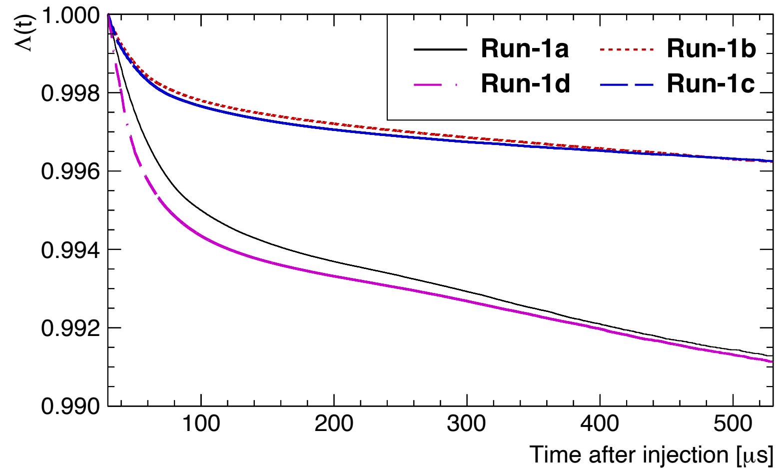


FFT of fit residuals



Muon precession measurement

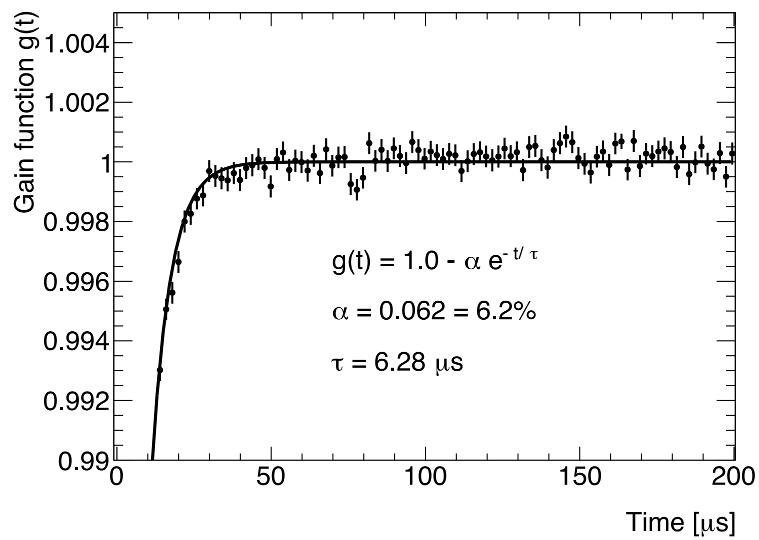




Pileup

Gain

Muon Loss



Muon precession measurement

$$\frac{f_{\text{clock}}\,\omega_a^m(1+C_e+C_p+C_{ml}+C_{pa})}{f_{\text{calib}}\,\langle\omega_p'(x,y,\phi)\times M(x,y,\phi)\rangle(1+B_k+B_q)}$$

			R [ppm] for each dataset				Naïve R
Recon.	Method	Pileup	Run-1a	Run-1b	Run-1c	Run-1d	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

11 (highly correlated) analyses found consistent results

4 most precise analyses averaged

conservative procedure that avoids unrealistic reduction in statistical uncertainty

Systematic concerns

Main concern is "early-to-late" effects

coherent from one fill to the next

Canonical example is a slow change of phase,

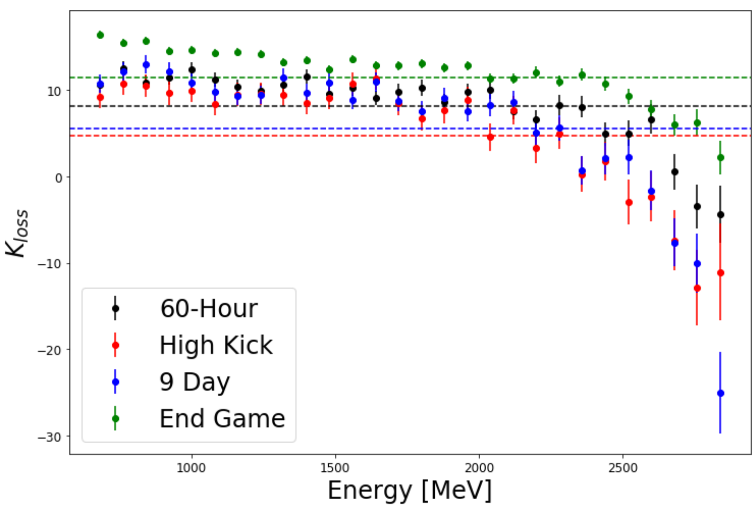
e.g. from a drifting energy calibration

$$\cos(\omega t + \varphi) = \cos\left(\left(\omega + \frac{d\varphi}{dt}\right) t + \varphi_0\right)$$

Muon precession systematics

$$\frac{f_{\mathrm{clock}}\ \omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\mathrm{calib}}\ \langle \omega_p'(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

Dataset	Run-1a	Run-1b	Run-1c	Run-1d
Gain (ppb)	12	9	9	5
Pileup (ppb)	39	42	35	31
CBO (ppb)	42	49	32	35
Randomization (ppb)	15	12	9	7
Early-to-late effect (ppb)	21	21	22	10
TOTAL (ppb)	64	70	54	49

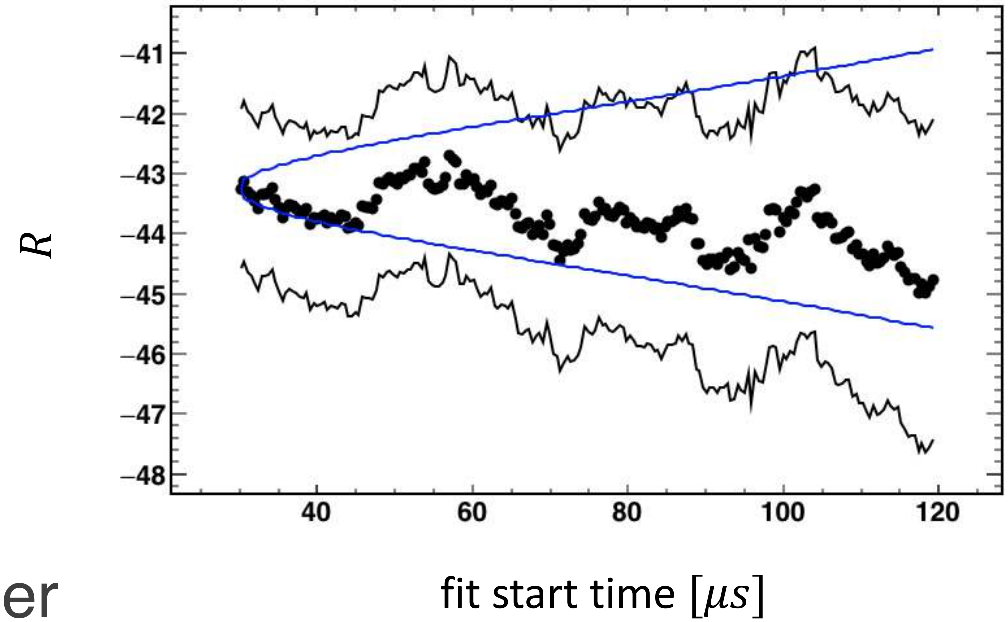


Muon precession measurement

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

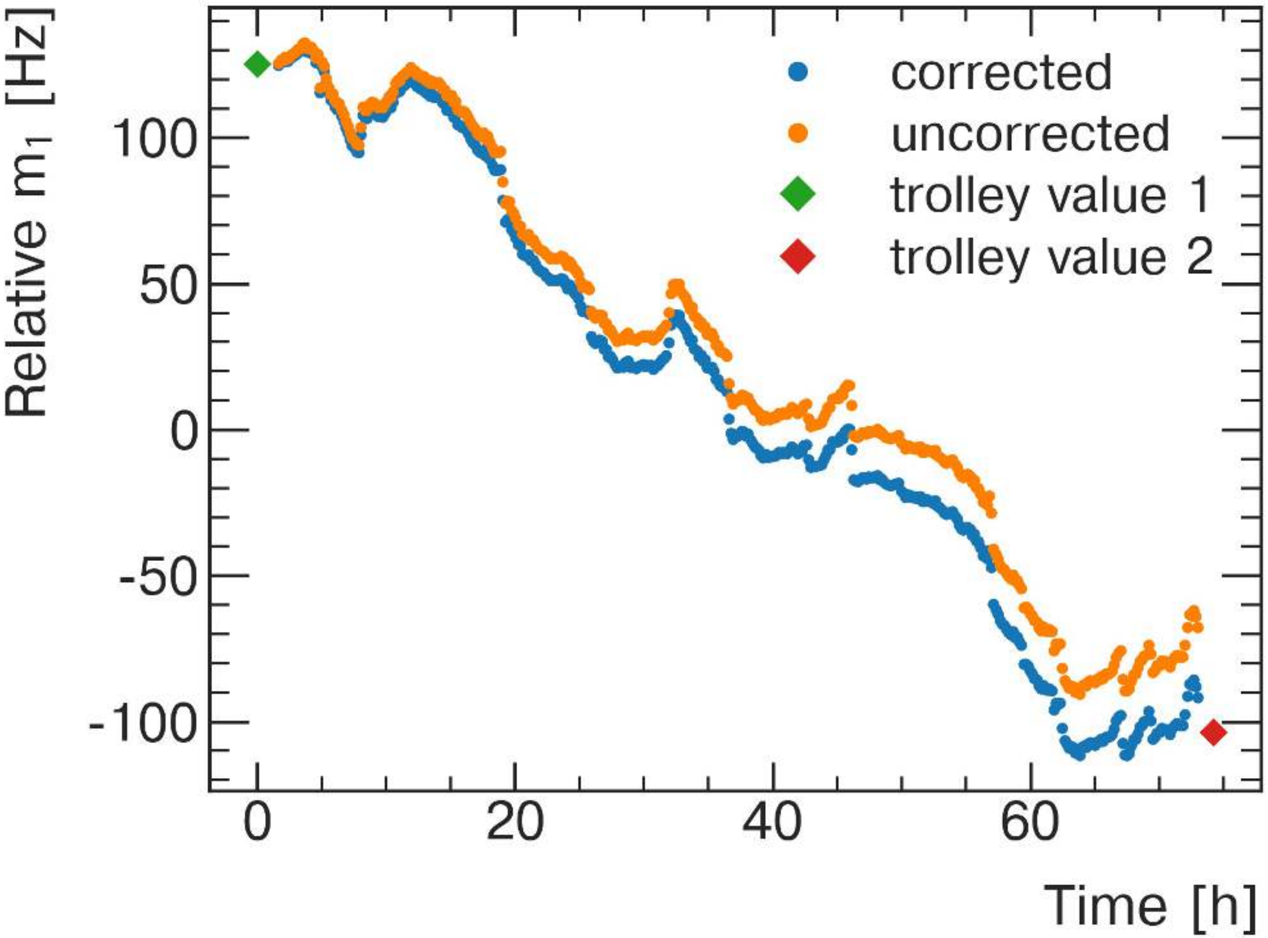
Fit frequency independent of...

- Fit start time
- Calorimeter station
- Bunch number
- Run number
- Time of day
- Energy bin
- Position within calorimeter
- …



Field measurement

$$\frac{f_{\text{clock}}\, \omega_a^m \,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\, \langle \omega_p'(x, y, \phi) \times M(x, y, \phi) \rangle (1 + B_k + B_q)}$$



Field moments between trolley runs interpolated with fixed probe data

Random walk (Brownian bridge) model

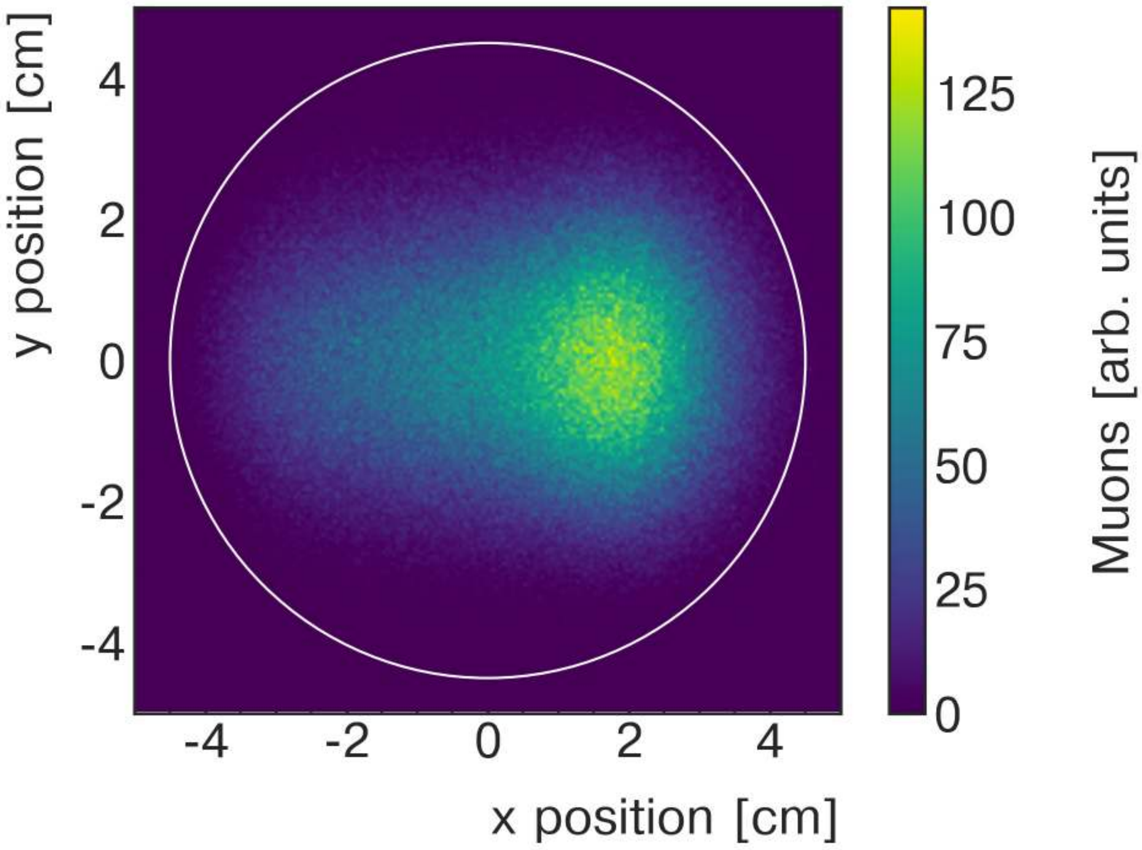
Field measurement

$$\frac{f_{\text{clock}}\ \omega_a^m\ (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p'(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$

Muon beam moments estimated with tracker

Field and beam intensity folded at 10s scale

Field and beam moments folded at hourly scale



Field systematics

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

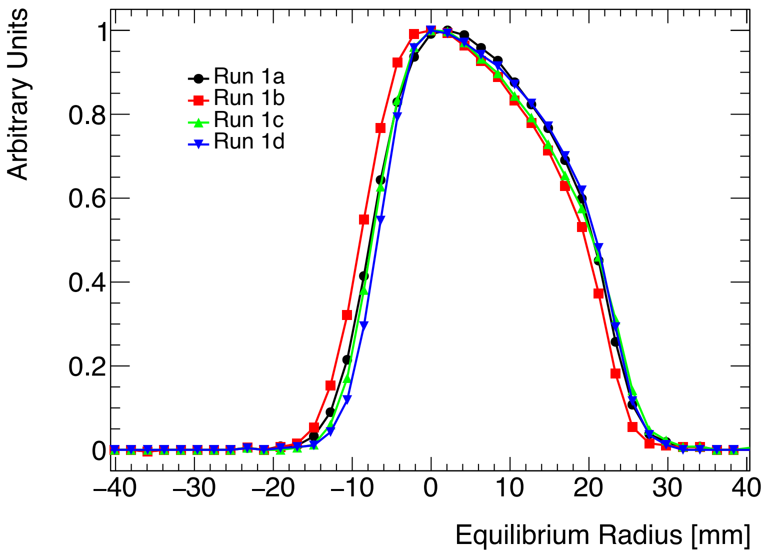
Dataset	Run-1a	Run-1b	Run-1c	Run-1d
Field Tracking	43	34	25	22
Trolley Calibration	28	28	28	28
Trolley Temperature	28	25	21	15
Trolley Baseline	25	25	25	25
Muon Weighting	11	14	16	20
Absolute Calibration	13	13	13	13
Fixed Probe Baseline	8	8	8	8
Fixed Probe Runs	1	1	1	1
TOTAL	70	60	54	52

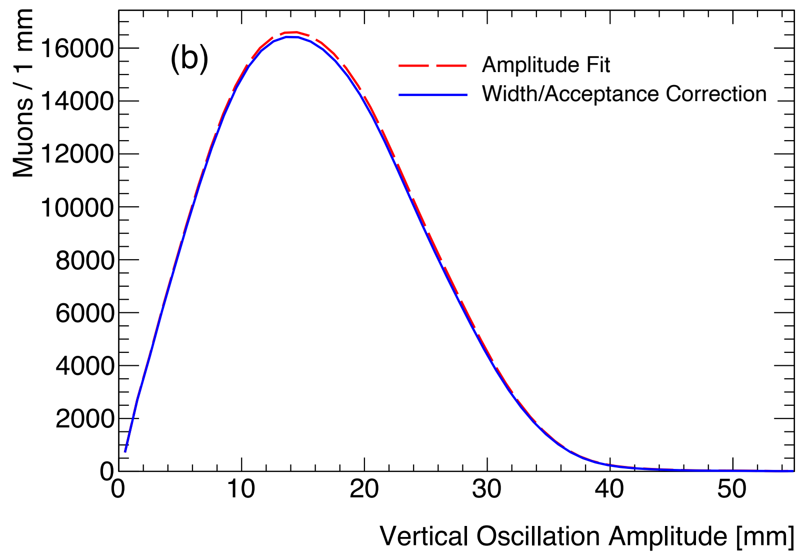
E Field and Pitch Corrections

$$\frac{f_{\text{clock}}\,\omega_a^m\,(1+C_e+C_p+C_{ml}+C_{pa})}{f_{\text{calib}}\,\langle\omega_p'(x,y,\phi)\times M(x,y,\phi)\rangle(1+B_k+B_q)}$$

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

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





Dataset	Run-1a	Run-1b	Run-1c	Run-1d
Correction [ppb]	471 ± 53	464 ± 54	534 ± 54	475 ± 53

Dataset	Run-1a	Run-1b	Run-1c	Run-1d
Correction [ppb]	176 ± 12	199 ± 14	191 ± 14	166 ±12

Muon Losses

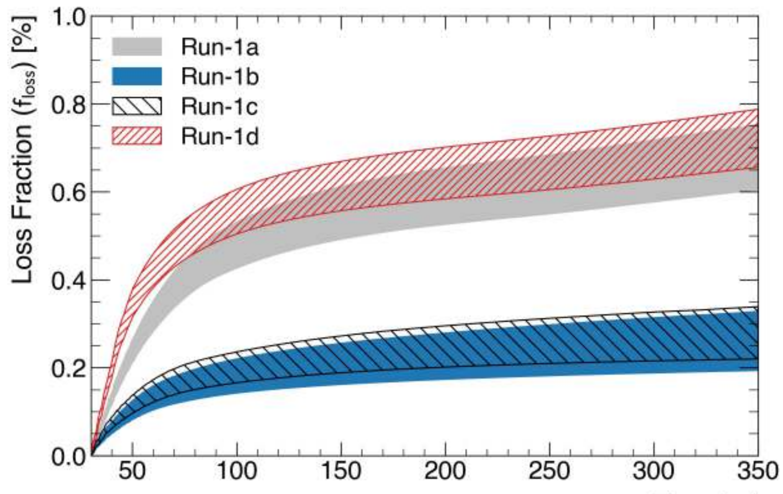
$$\frac{f_{\text{clock}}\ \omega_a^m\ (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega'_p(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$

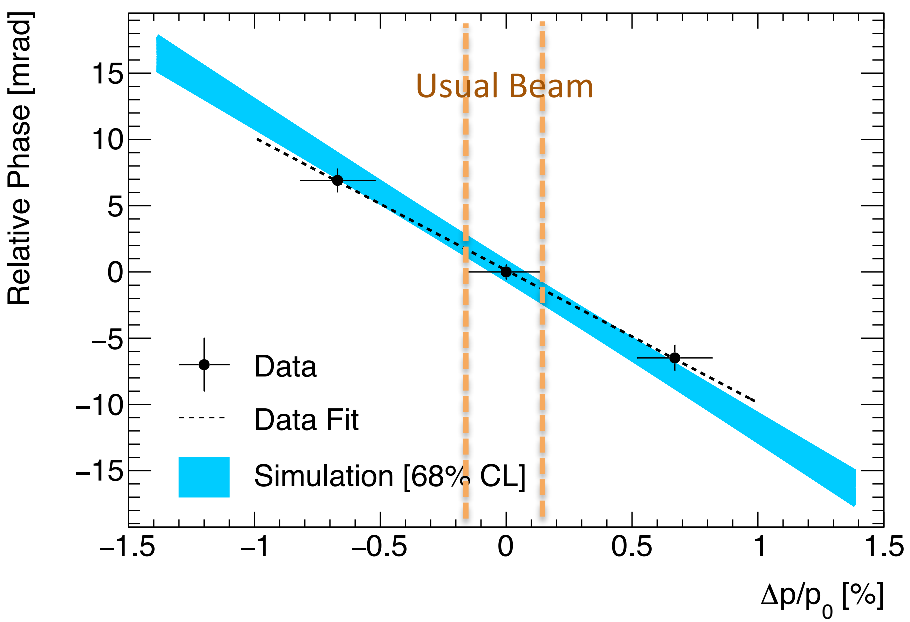
p-phase correlation

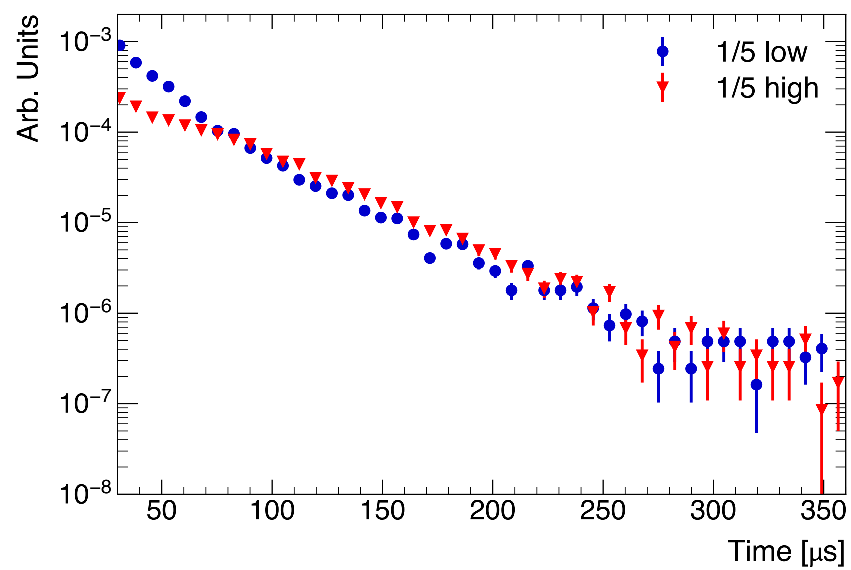
+ preferential loss of low-p muons

= bias

Dataset	Run-1a	Run-1b	Run-1c	Run-1d
Correction [ppb]	-14 ± 6	-3 ± 2	-7 ± 4	-17 ± 6







Full fit function

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

$$N_x(t) = 1 + e^{-1t/\tau_{\mathrm{CBO}}} A_{N,x,1,1} \cos(1\omega_{\mathrm{CBO}} t + \phi_{N,x,1,1}) + e^{-2t/\tau_{\mathrm{CBO}}} A_{N,x,2,2} \cos(2\omega_{\mathrm{CBO}} t + \phi_{N,x,2,2}), \quad (27)$$

$$N_y(t) = 1 + e^{-1t/\tau_y} A_{N,y,1,1} \cos(1\omega_y t + \phi_{N,y,1,1}) + e^{-2t/\tau_y} A_{N,y,2,2} \cos(1\omega_{\mathrm{VW}} t + \phi_{N,y,2,2}), \quad (28)$$

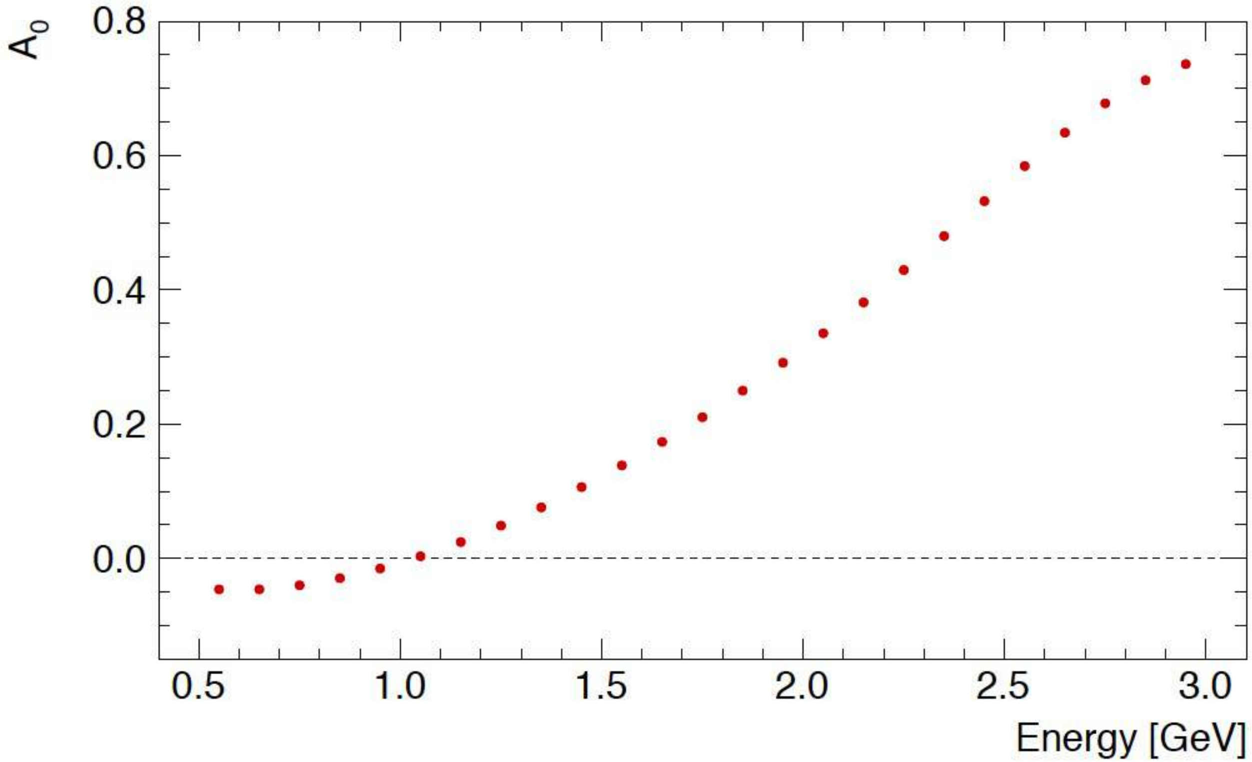
$$A_x(t) = 1 + e^{-1t/\tau_{\mathrm{CBO}}} A_{A,x,1,1} \cos(1\omega_{\mathrm{CBO}} t + \phi_{A,x,1,1}), \quad (29)$$

$$\phi_x(t) = 1 + e^{-1t/\tau_{\mathrm{CBO}}} A_{\phi,x,1,1} \cos(1\omega_{\mathrm{CBO}} t + \phi_{\phi,x,1,1}). \quad (30)$$

Asymmetry method

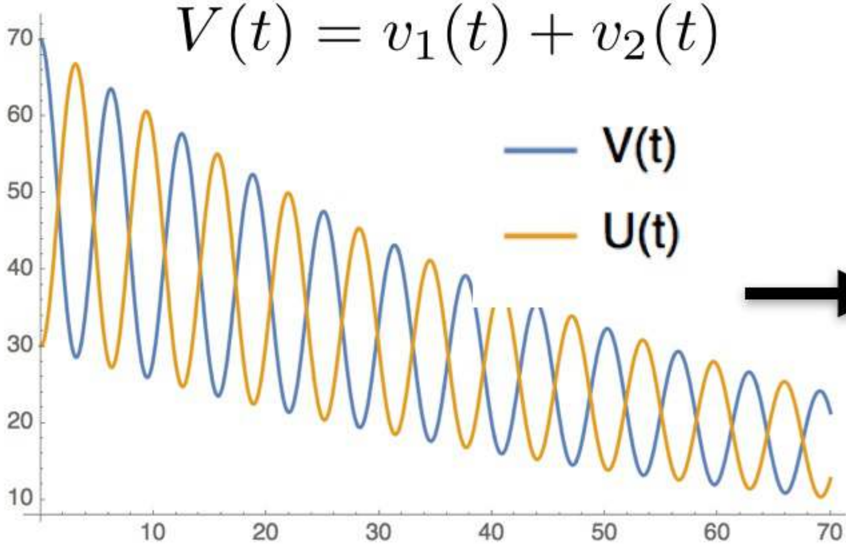
Asymmetry estimated from the data

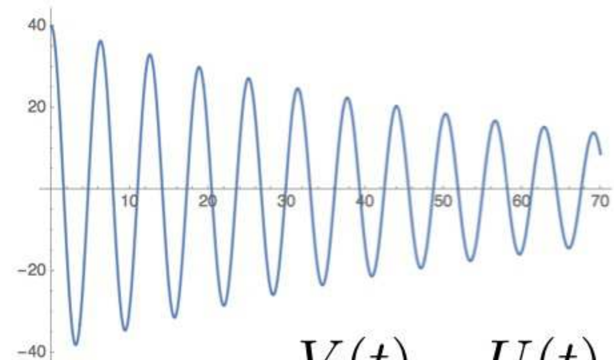
Weighting each count by A(E) known to be most sensitive approach



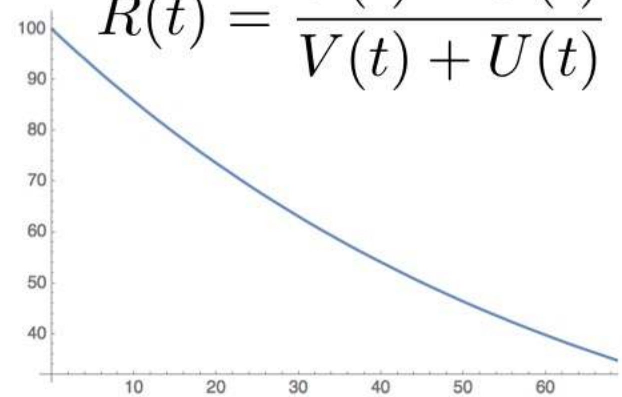
Ratio method

$$U(t) = u_+(t) + u_-(t)$$
$$V(t) = v_1(t) + v_2(t)$$





$$R(t) = \frac{V(t) - U(t)}{V(t) + U(t)}$$

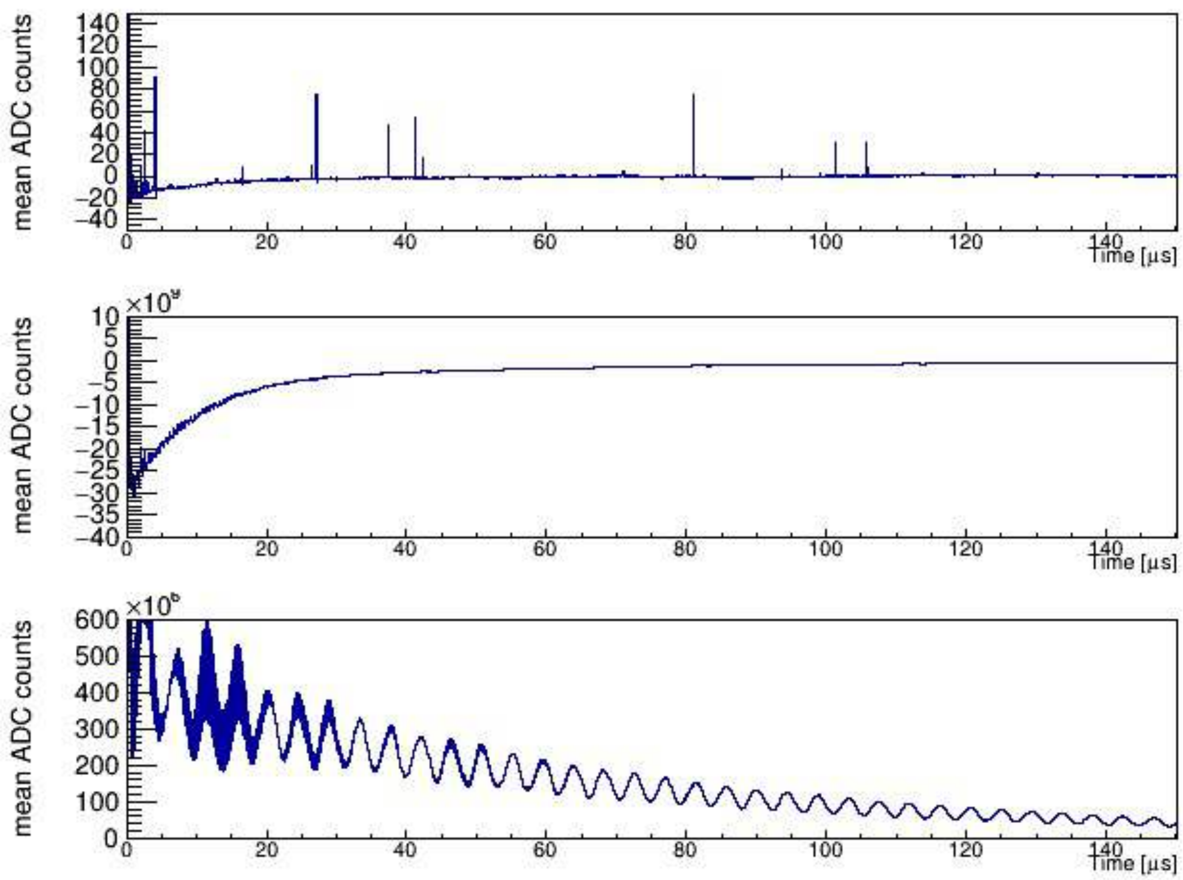


Integrated energy method

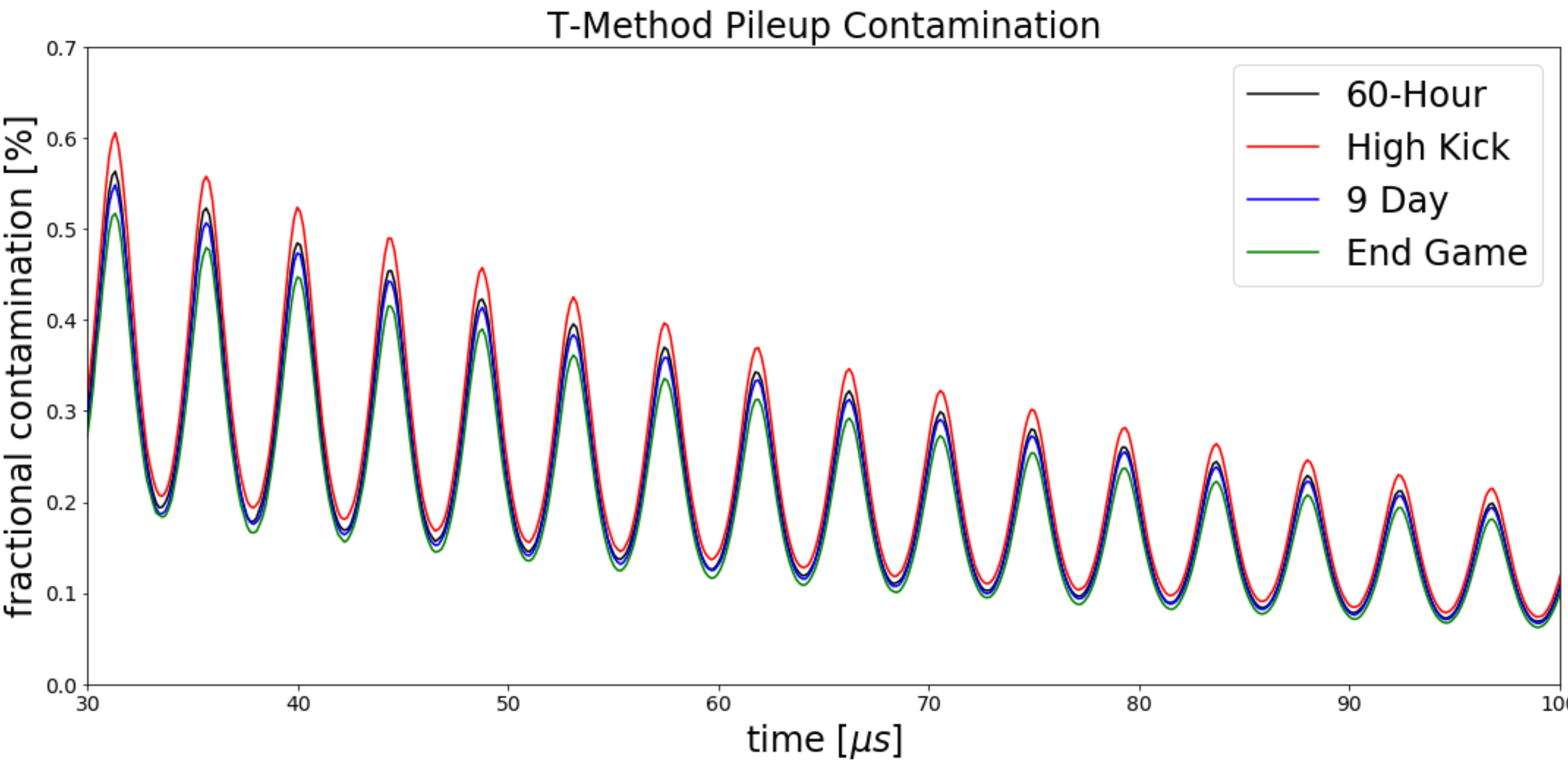
Independent data set, only 50% correlated

Very different systematics

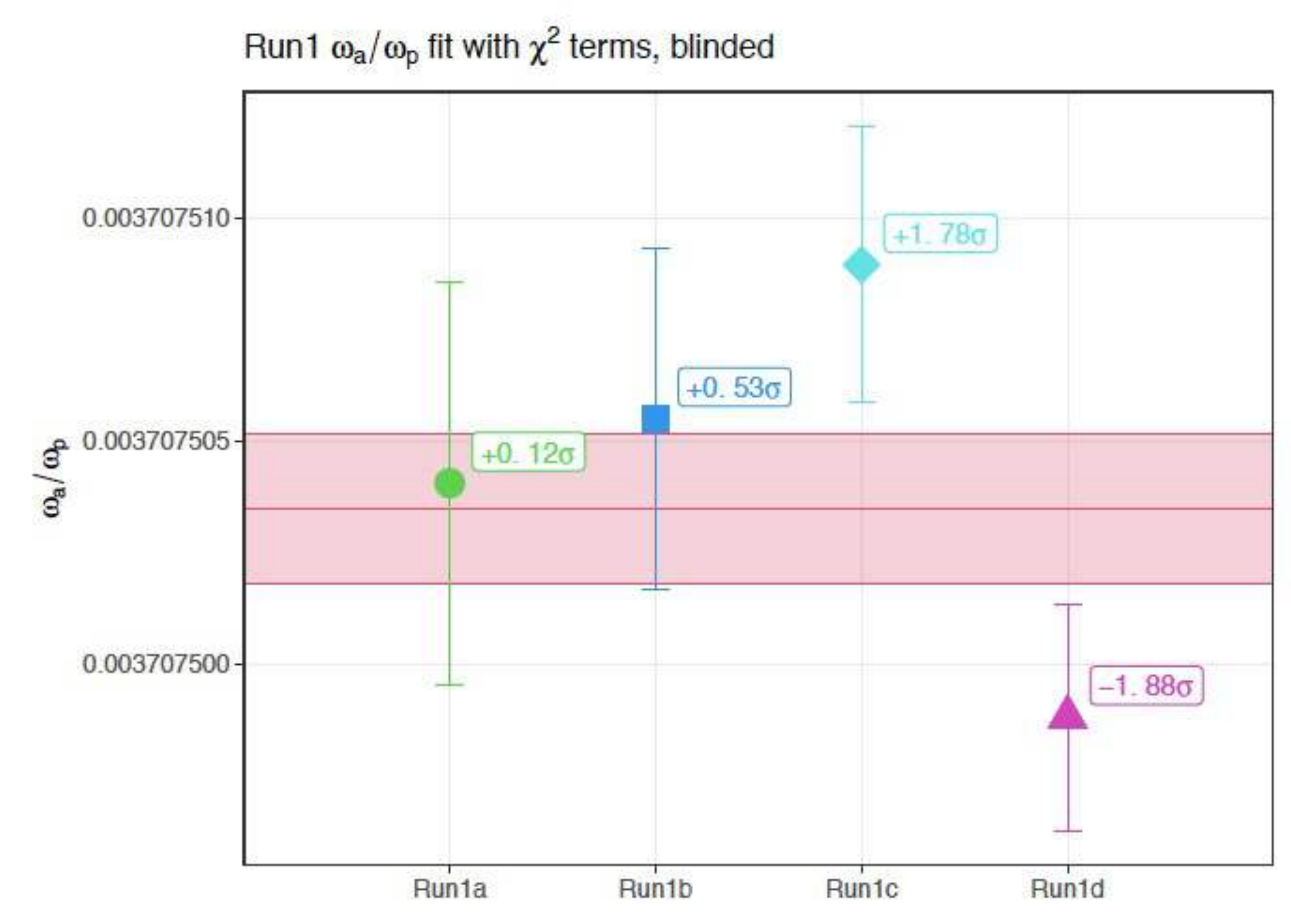
Shorter data collection period, lower statistical precision



Pileup in time



Four dataset results



External Constants

1. Proton to electron magnetic moment ratio
   W.D. Phillips, W.E. Cooke, D. Kleppner, Metrologia 13 179 (1977)
2. Electron magnetic moment
   D. Hanneke, S.F. Hoogerheide, G. Gabrielse, Phys. Rev. A 83 052122 (2011)
3. Muon to electron mass ratio
   W. Liu et al., PRL 82 711 (1999) (muonium hyperfine splitting)
4. H bound state electron magnetic moment (from QED)
   P.J. Mohr, D.B. Newell, B.N. Taylor, Rev. Mod. Phys. 88(3):035009 (2016)