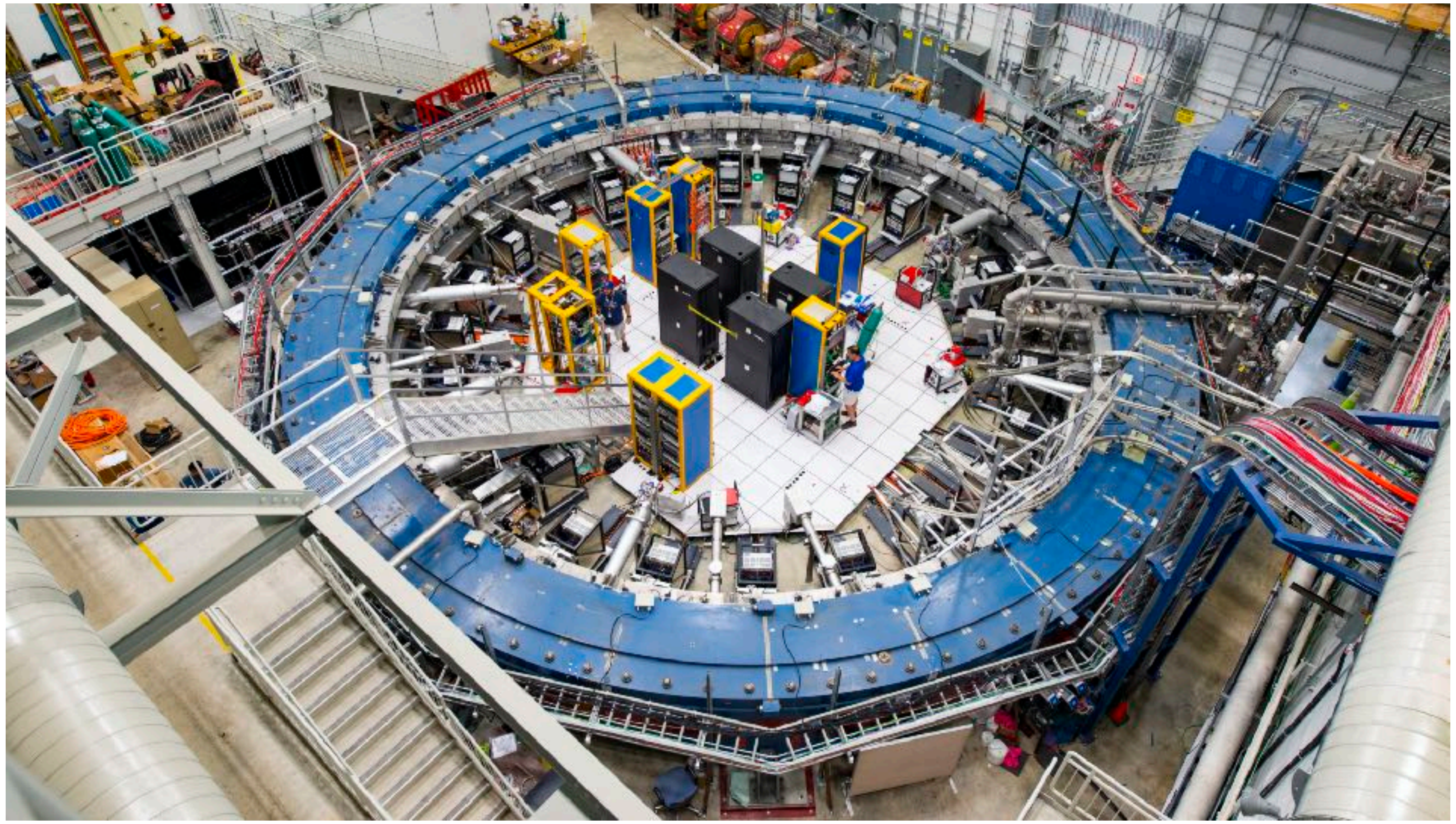


First Results from the Fermilab Muon g-2 Experiment

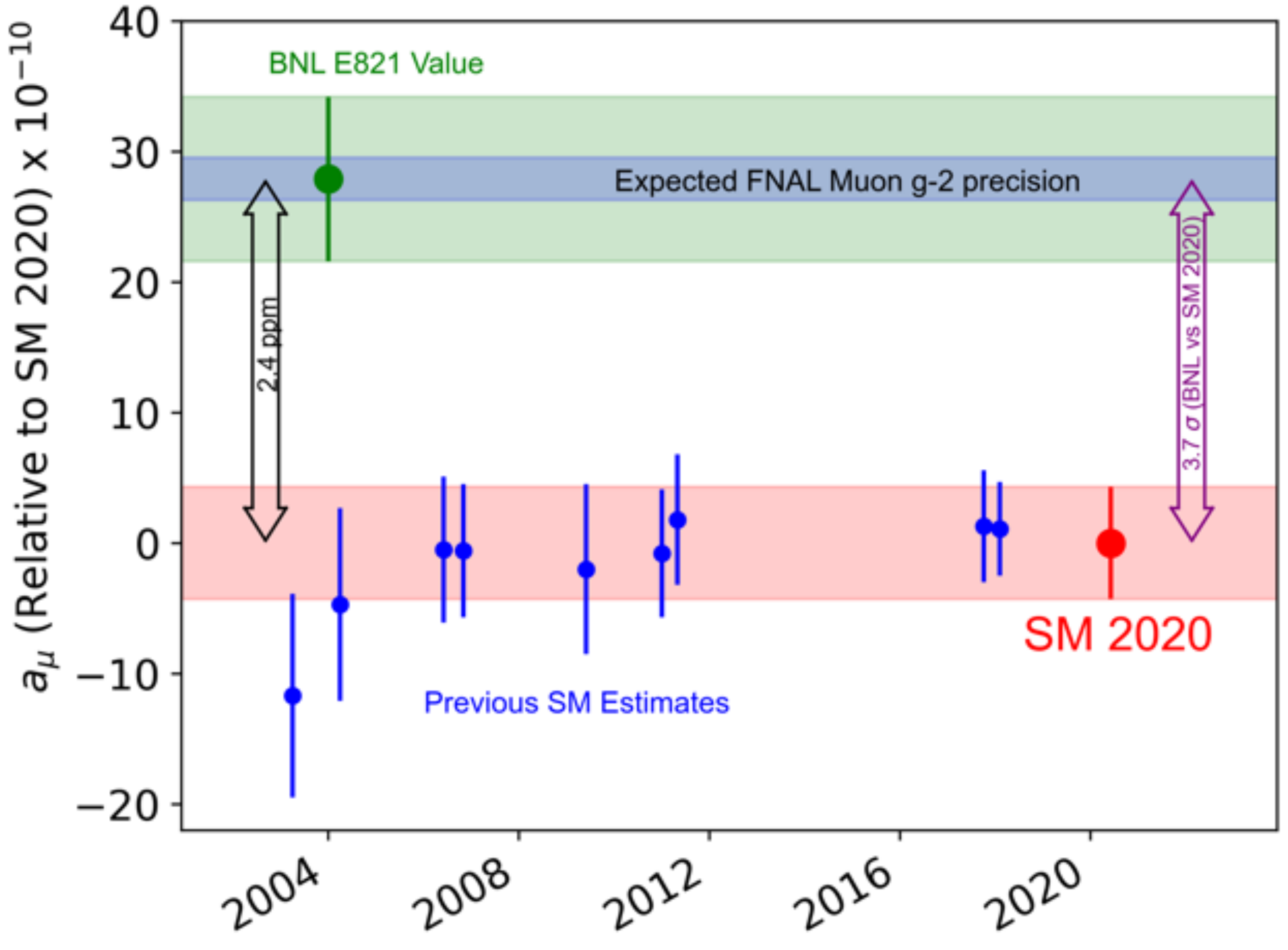
RAL HEP Seminar

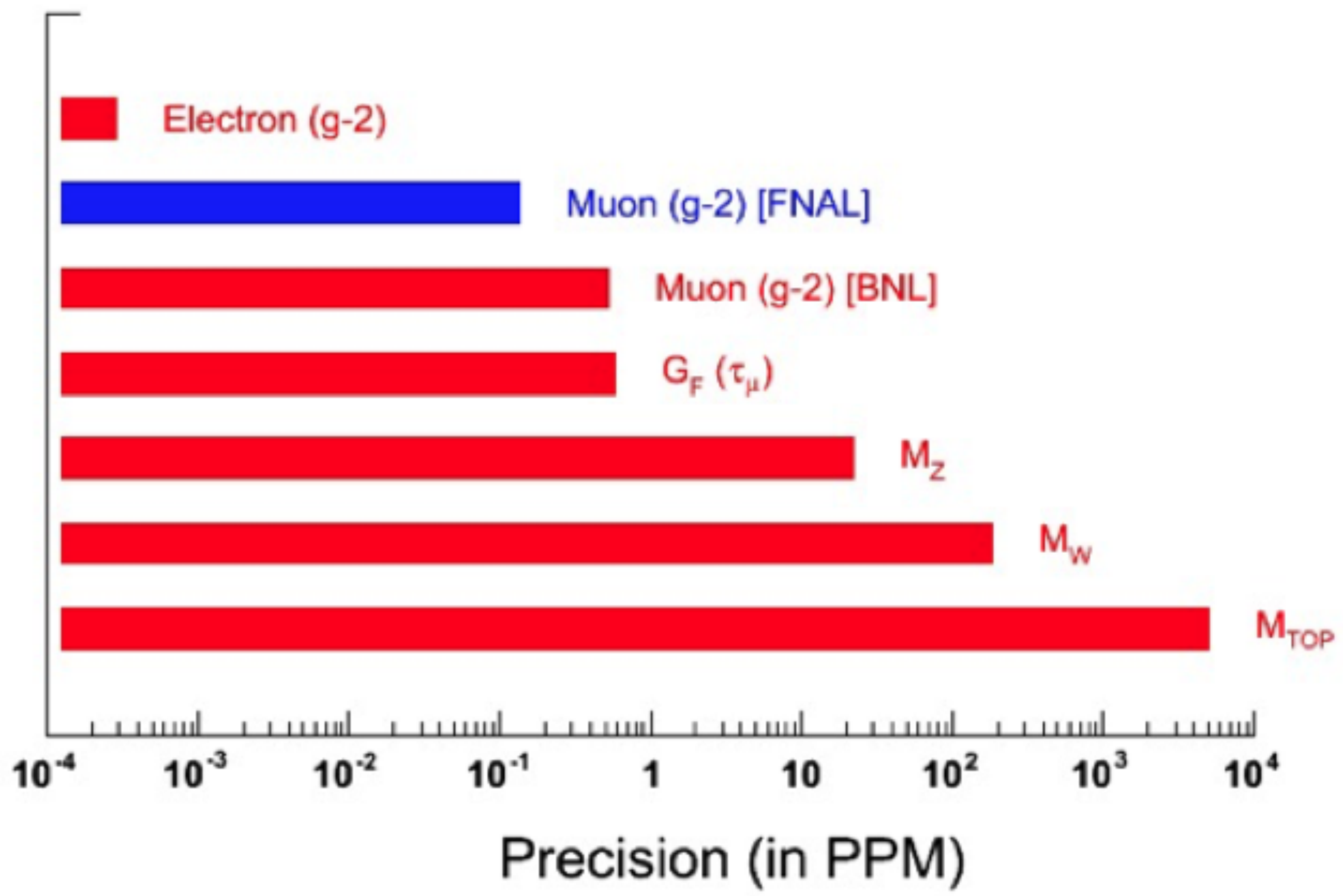
Saskia Charity (FNAL)

02 June 2021

History of muon g-2 discrepancy

- The BNL E821 measurement had a 0.54 ppm (540 ppb) uncertainty





- BNL-SM discrepancy: 2.4 ppm

- FNAL target is 100 ppb stat. ⊕ 100 ppb syst.

- Today's talk is on a dataset of similar size to BNL (~10 billion μ^+)

Fermilab

Magnetic moments

- The muon has a magnetic moment that couples to its spin via the gyromagnetic ratio, *g*

$$\vec{\mu} = g\frac{q}{2m}\vec{s}$$

$$\boxed{a_\mu = \frac{g-2}{2}}$$

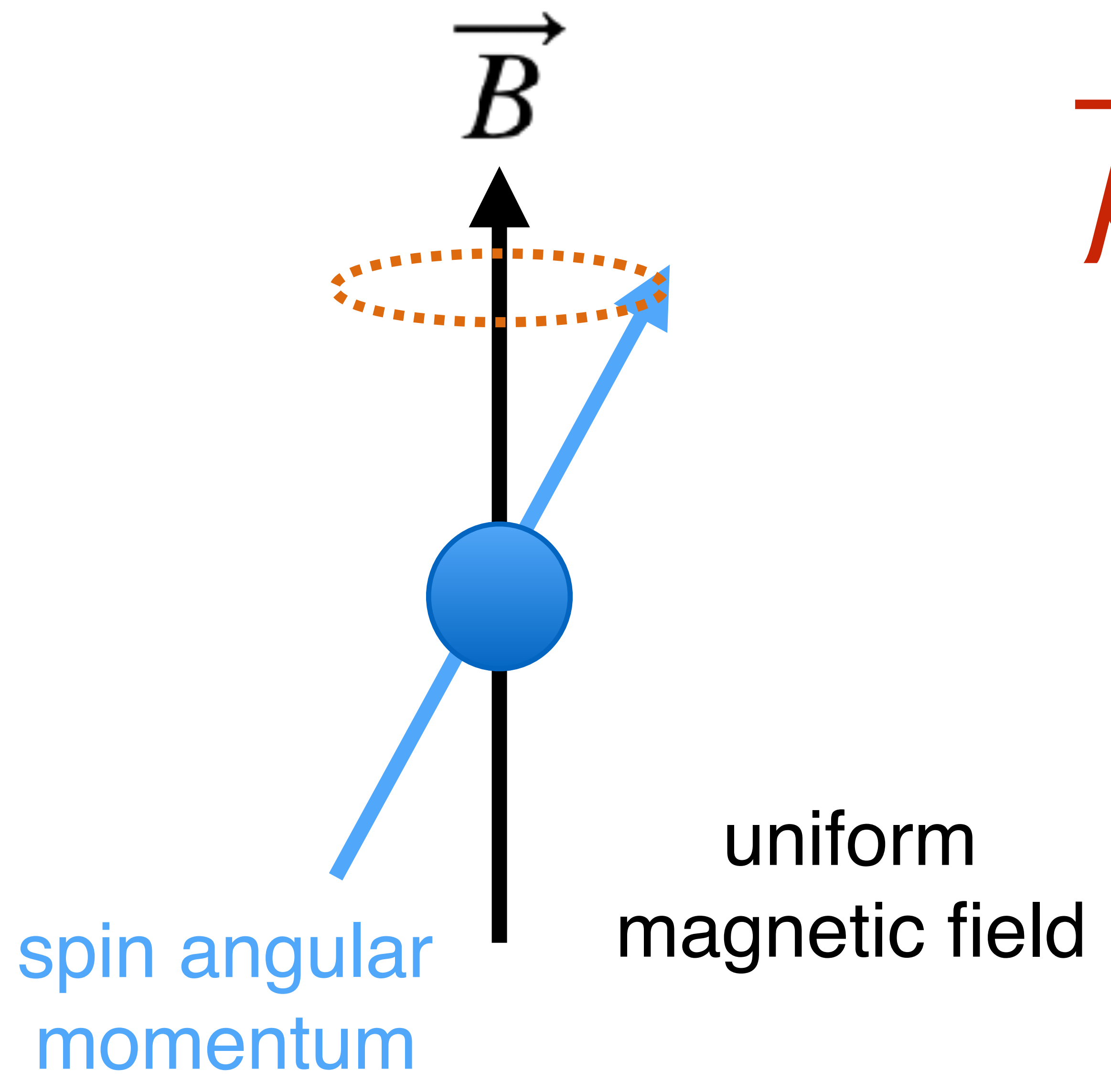
g = gyromagnetic ratio

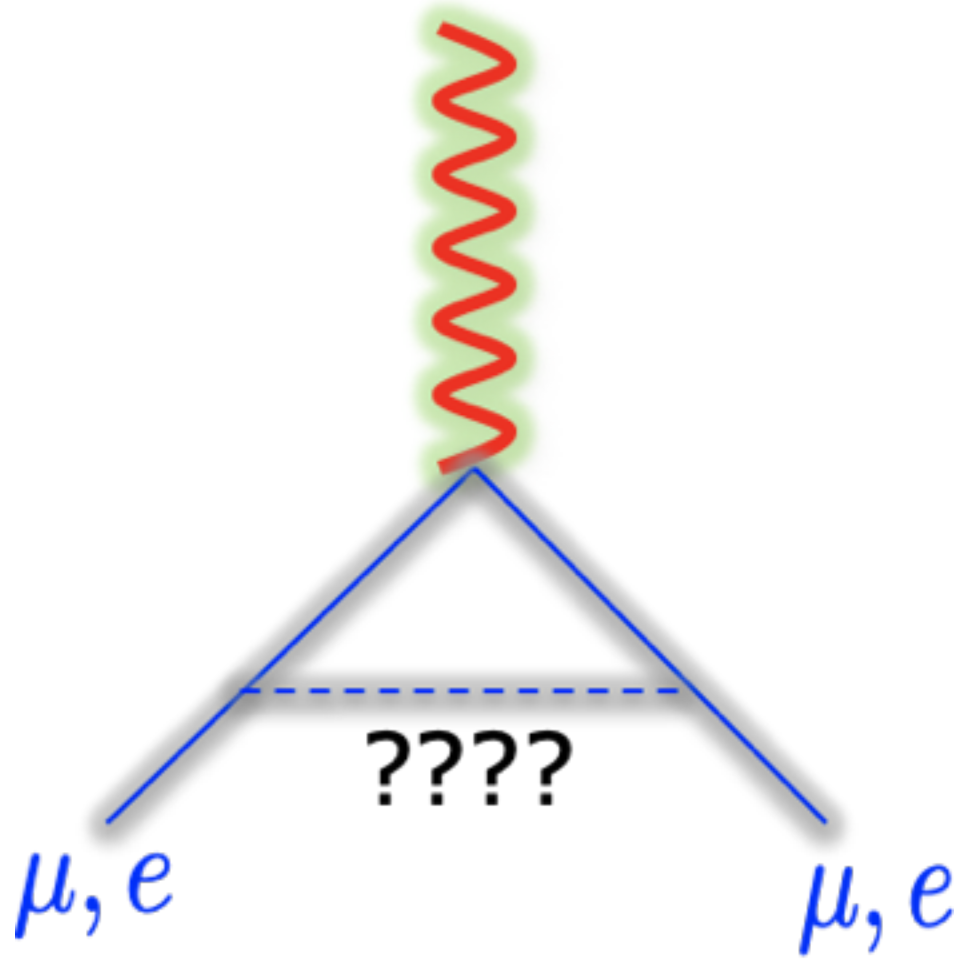
μ = magnetic moment

- Magnetic moment (spin) interacts with external magnetic fields

- Spin precesses at a rate determined by *g*

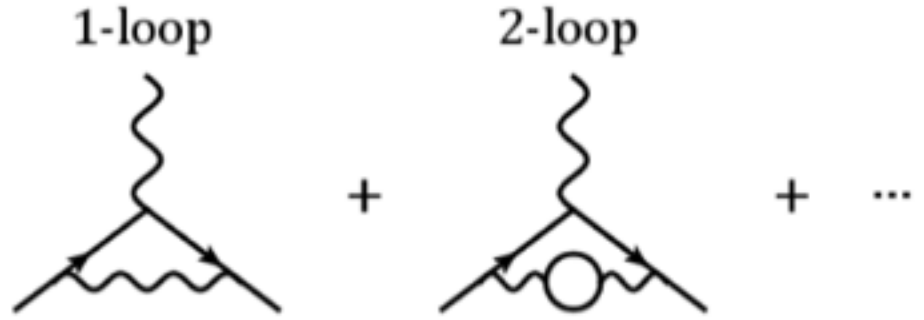
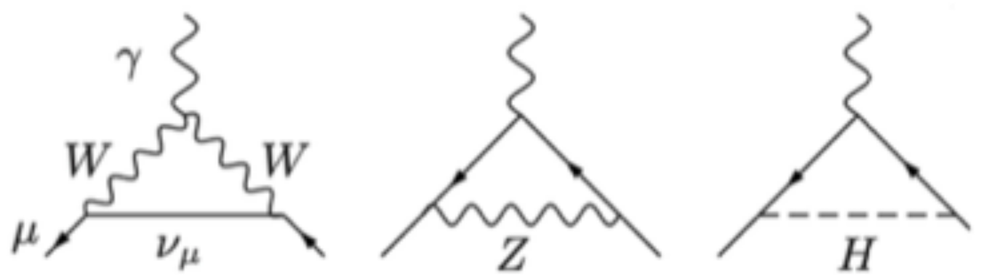
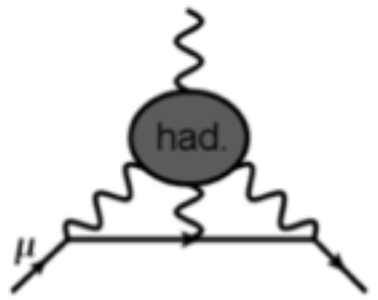
$$\vec{\mu} \times \vec{B}$$

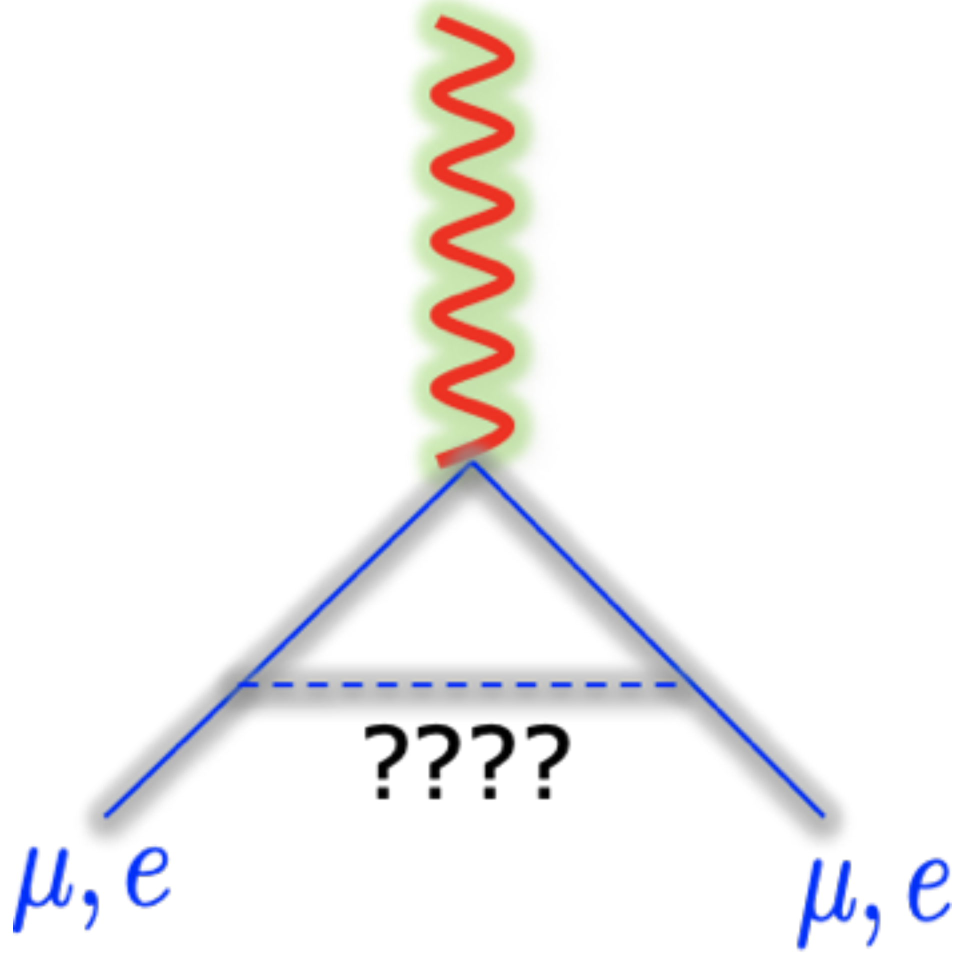




Theory

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{HVP}} + a_\mu^{\text{HLbL}}$$

			a_μ^{SM} portion	δa_μ^{SM} portion
QED		Perturbative (Known to five-loop)	$\sim 99.99\%$	$\sim 0.001\%$
EW		Perturbative (Known to two-loop)	~ 1 ppm	$\sim 0.2\%$
HVP		Non-perturbative (Data-driven & lattice)	~ 59 ppm	**$\sim$84%**
HLbL		Non-perturbative (Data-driven & lattice)	~ 1 ppm	**$\sim$16%**



Muons at Fermilab

- Lower instantaneous rate but larger integrated rate than BNL

- ~10,000 μ^+ (from 10^{12} p) at 3.1 GeV every 10 ms
- (g-2): 1/3 of proton cycles, neutrino experiments 2/3
- Extra 900m of instrumented beamlines

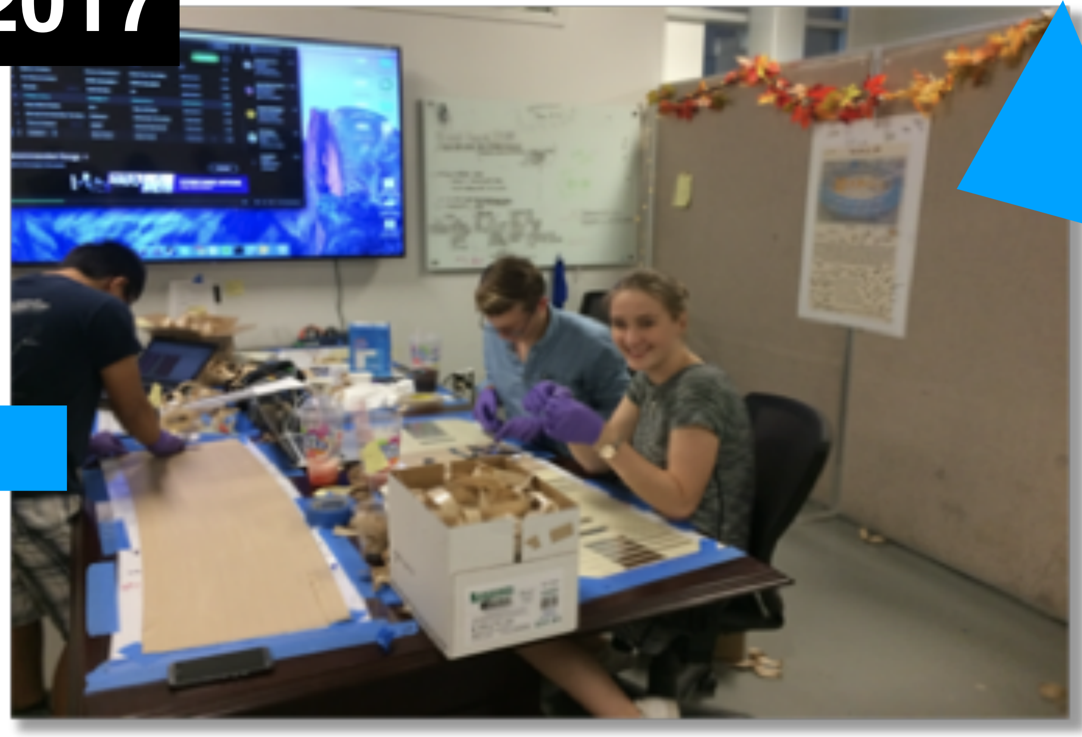
4 years to build (2 years magnet “shimming”)

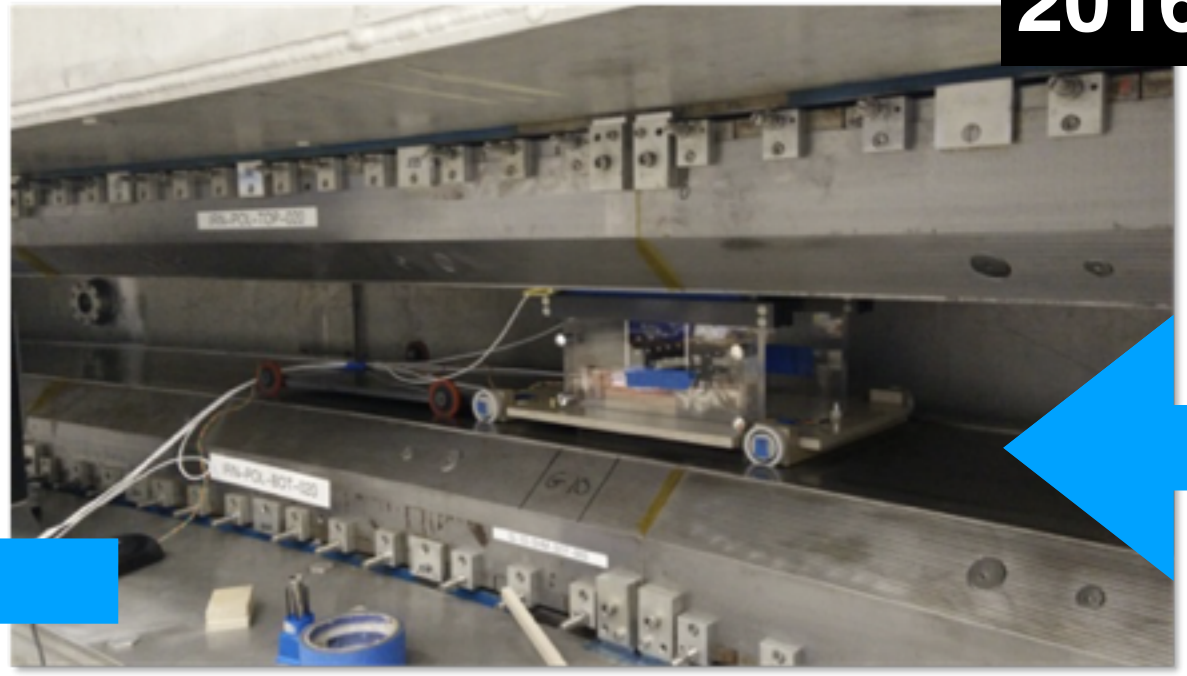
May 2013

2013

2015

2016 - 2017

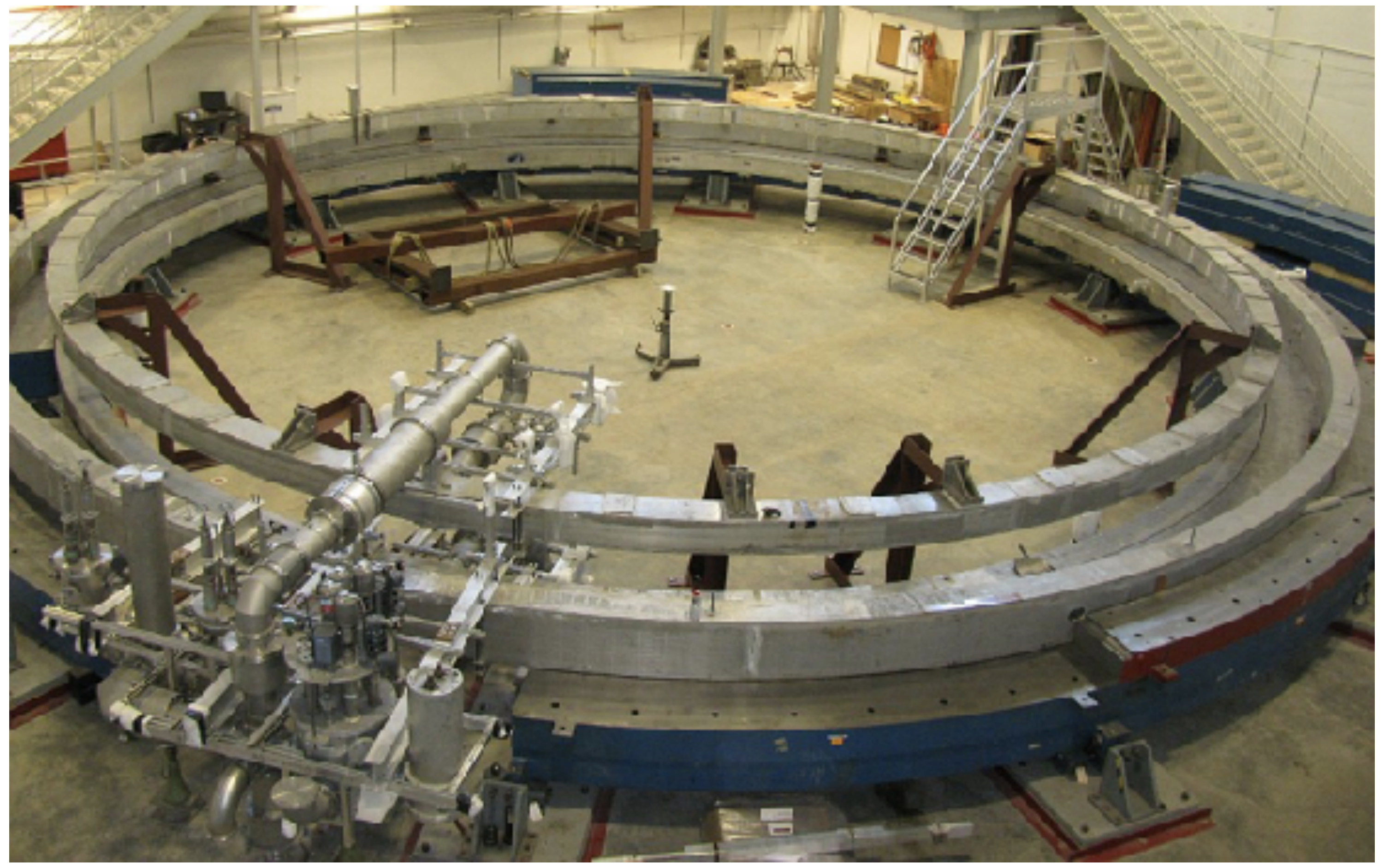


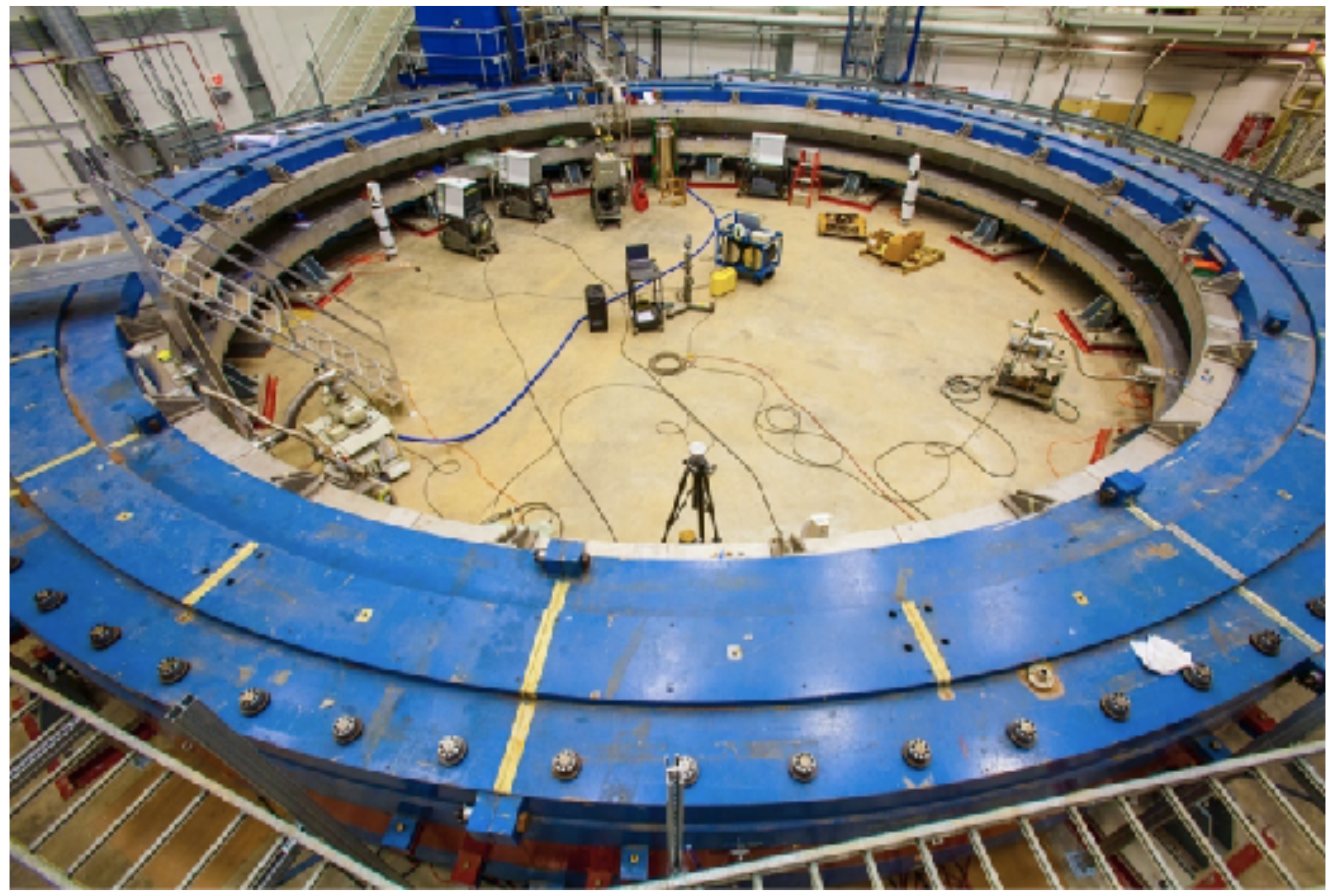


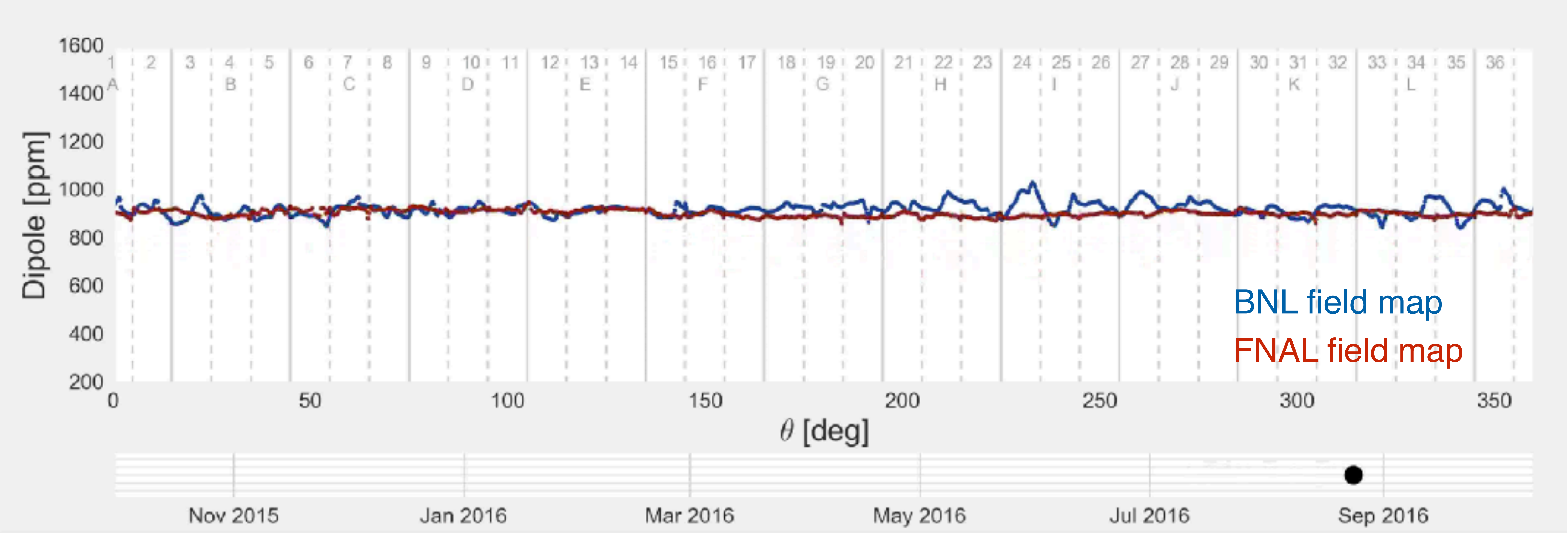
May 31 2017

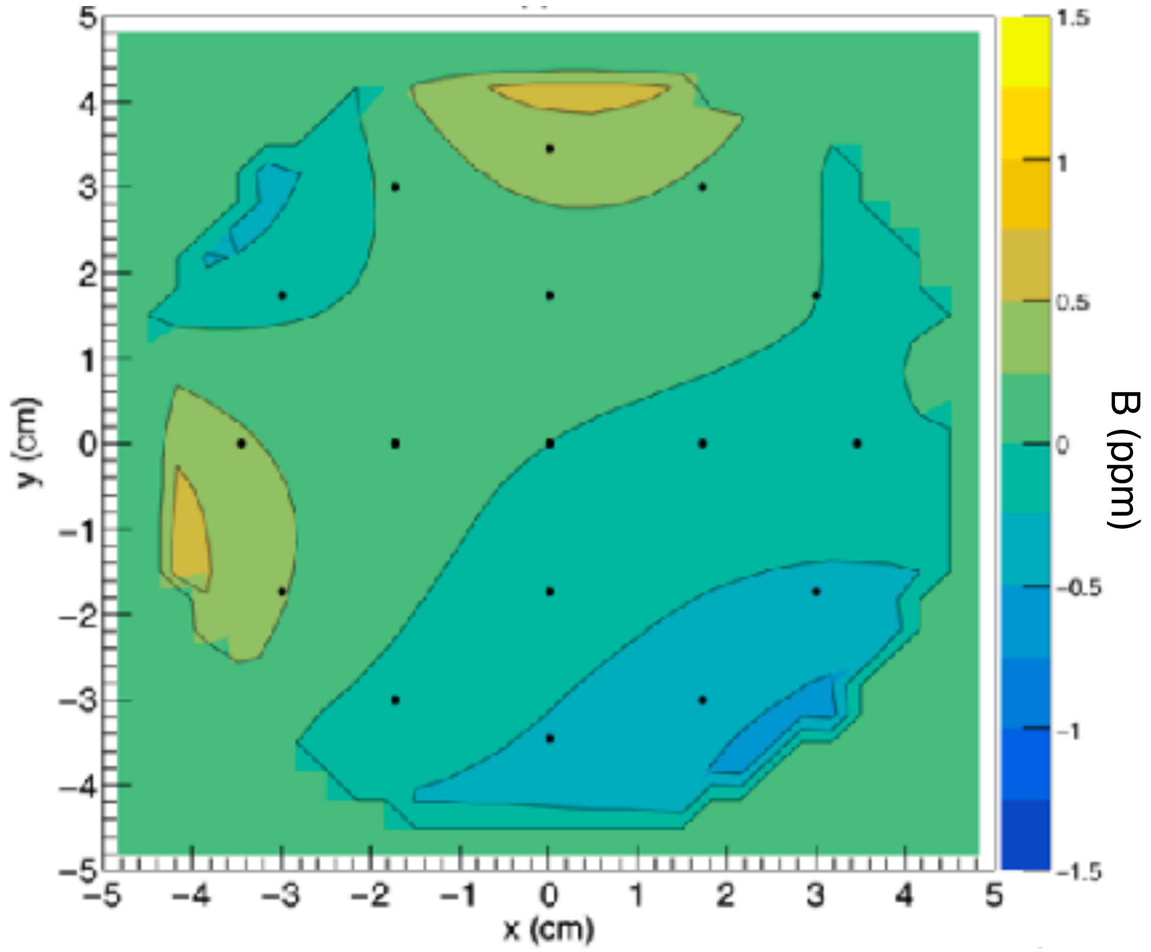
Run-1 data taking began Feb 2018

The magnetic storage ring









Magnetic field 3 times better than goal (BNL)

Measuring a_μ

spin precession frequency ω_s

$$\vec{\omega_s} = \boxed{\frac{ge\vec{B}}{2m_\mu c}} + \boxed{(1-\gamma)\frac{e\vec{B}}{\gamma m_\mu c}}$$

Larmor precession　　Thomas precession

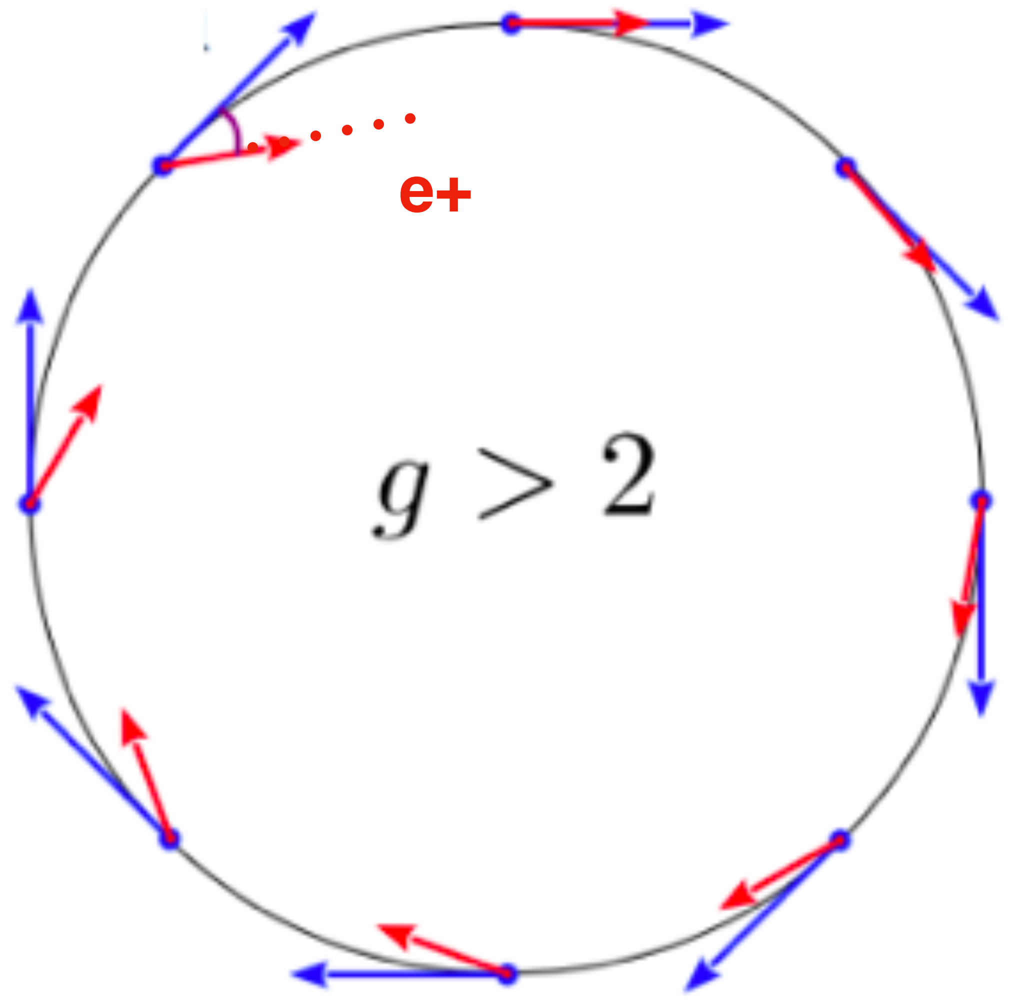
cyclotron frequency ω_c

$$\boxed{\vec{\omega_c} = \frac{e\vec{B}}{\gamma m_\mu c}}$$

$$\vec{\omega_a} = \vec{\omega_c} - \vec{\omega_s}$$

Measure difference between ω_c and ω_s :
anomalous precession frequency, ω_a

$$\boxed{\vec{\omega_a} = a_\mu \frac{e\vec{B}}{m_\mu c}}$$



Measuring a_μ

To extract a_μ we need to know both ω_a and B to high precision

$$\hbar\omega_p' = 2\mu_p|\vec{B}|$$

Larmor frequency of a proton in a spherical water sample

$$\vec{\omega_a} = a_\mu \frac{e\vec{B}}{m_\mu c}$$

3 ppb 22 ppb 0.0003 ppb

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

We measure this ratio

Measuring a_μ

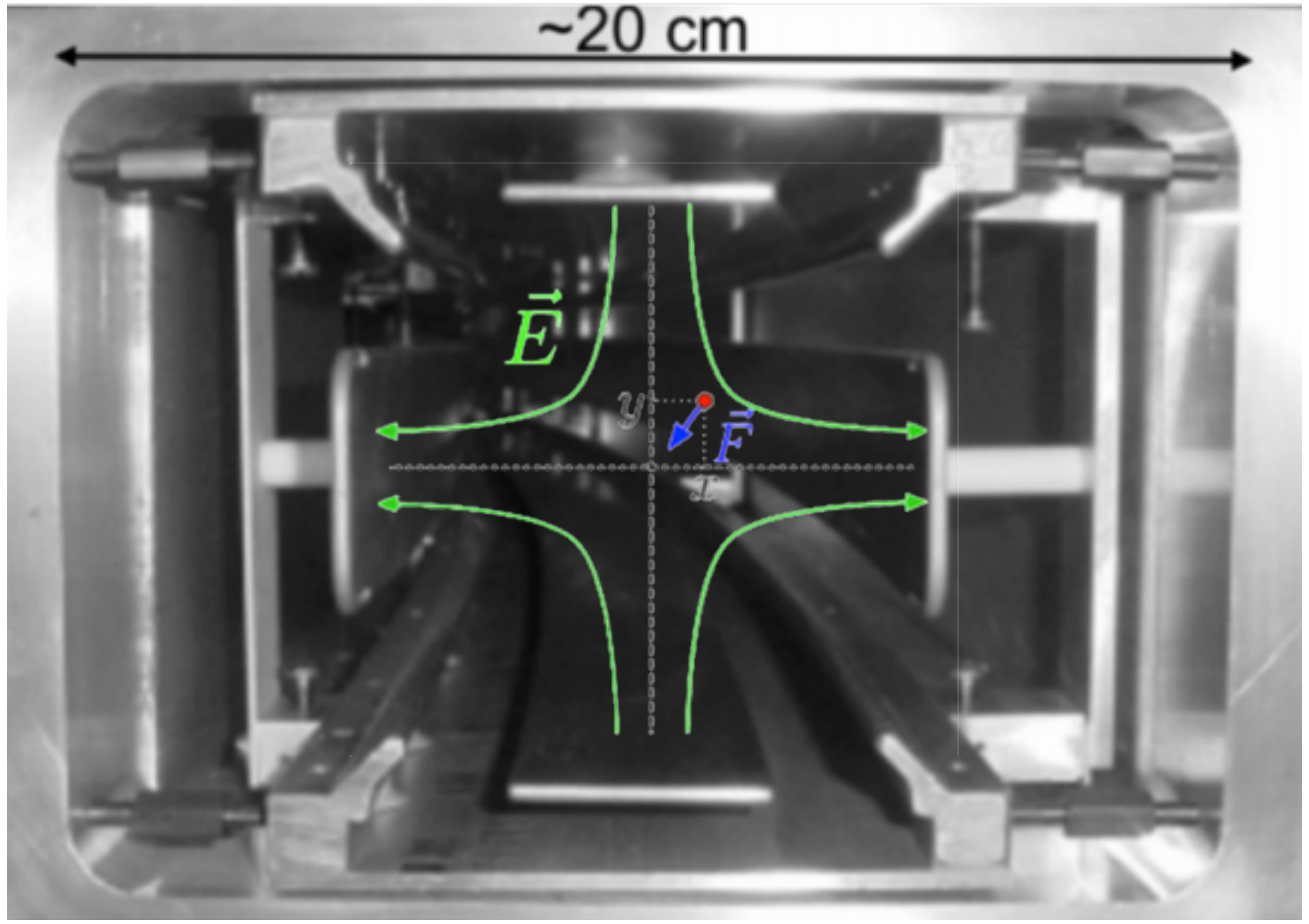
Unblinding conversion factor

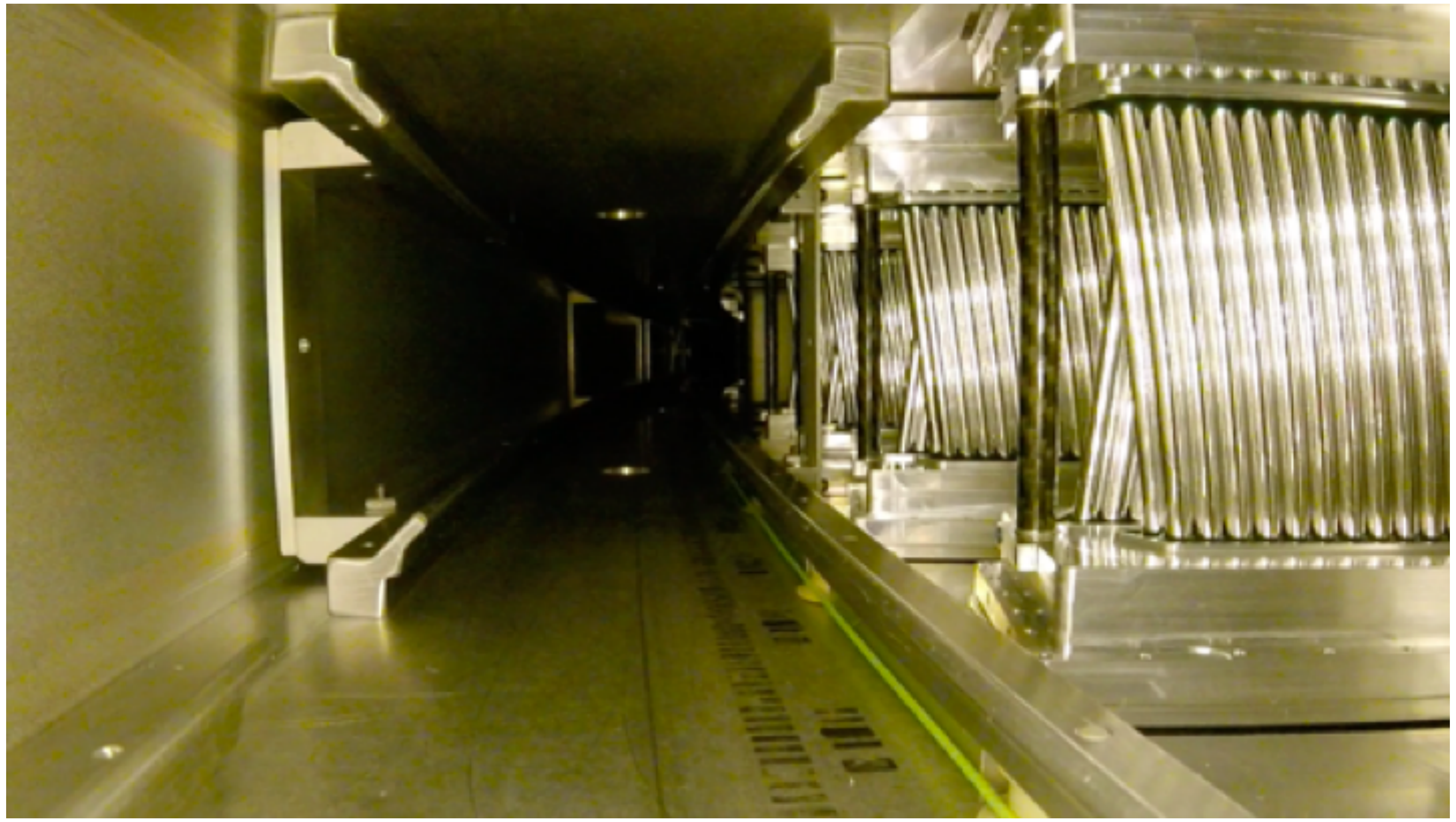
Measured $g-2$ frequency

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\;\omega_a^m\,(1+\overbrace{C_e+C_p+C_{ml}+C_{pa}}^{\text{Corrections from the beam dynamics systematic effects}})}{f_{\text{calib}}\;\underbrace{\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle}_{\text{Magnetic field weighted over the muon distribution and azimuthally averaged}}(1+\underbrace{B_k+B_q}_{\text{Corrections from the transient magnetic field}})}$$

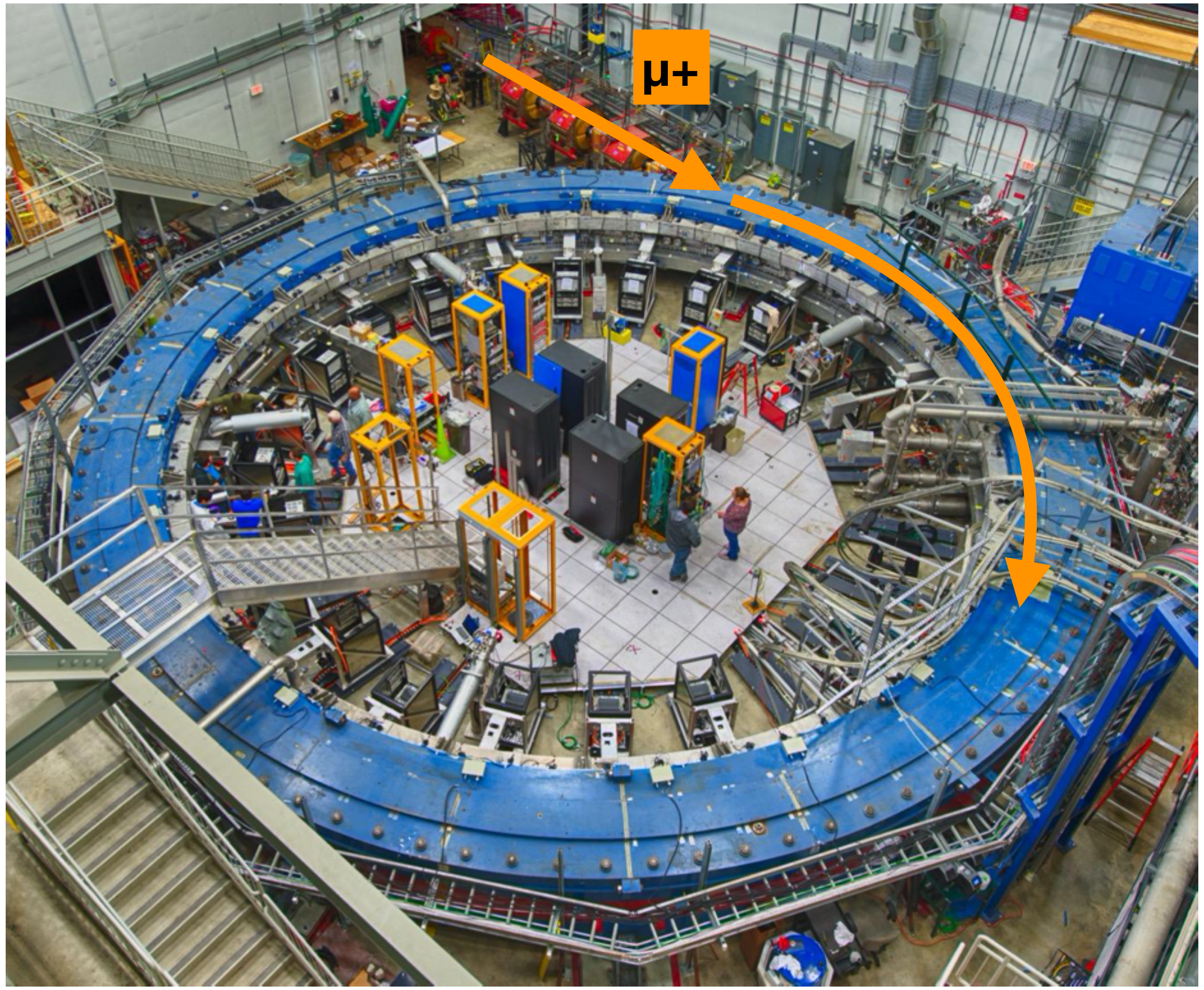
NMR probe calibration factor

Storing and detecting the beam

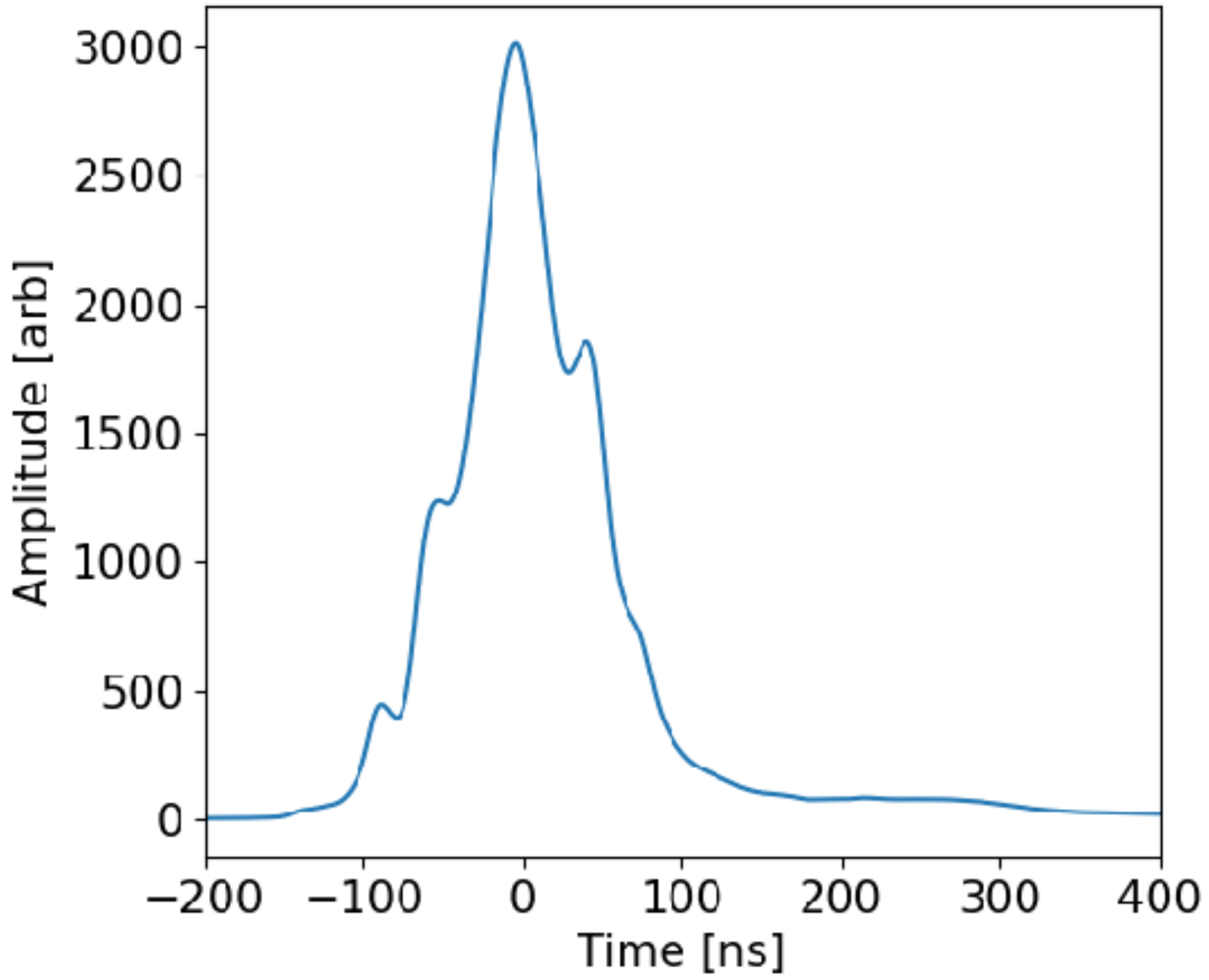




Beam Injection



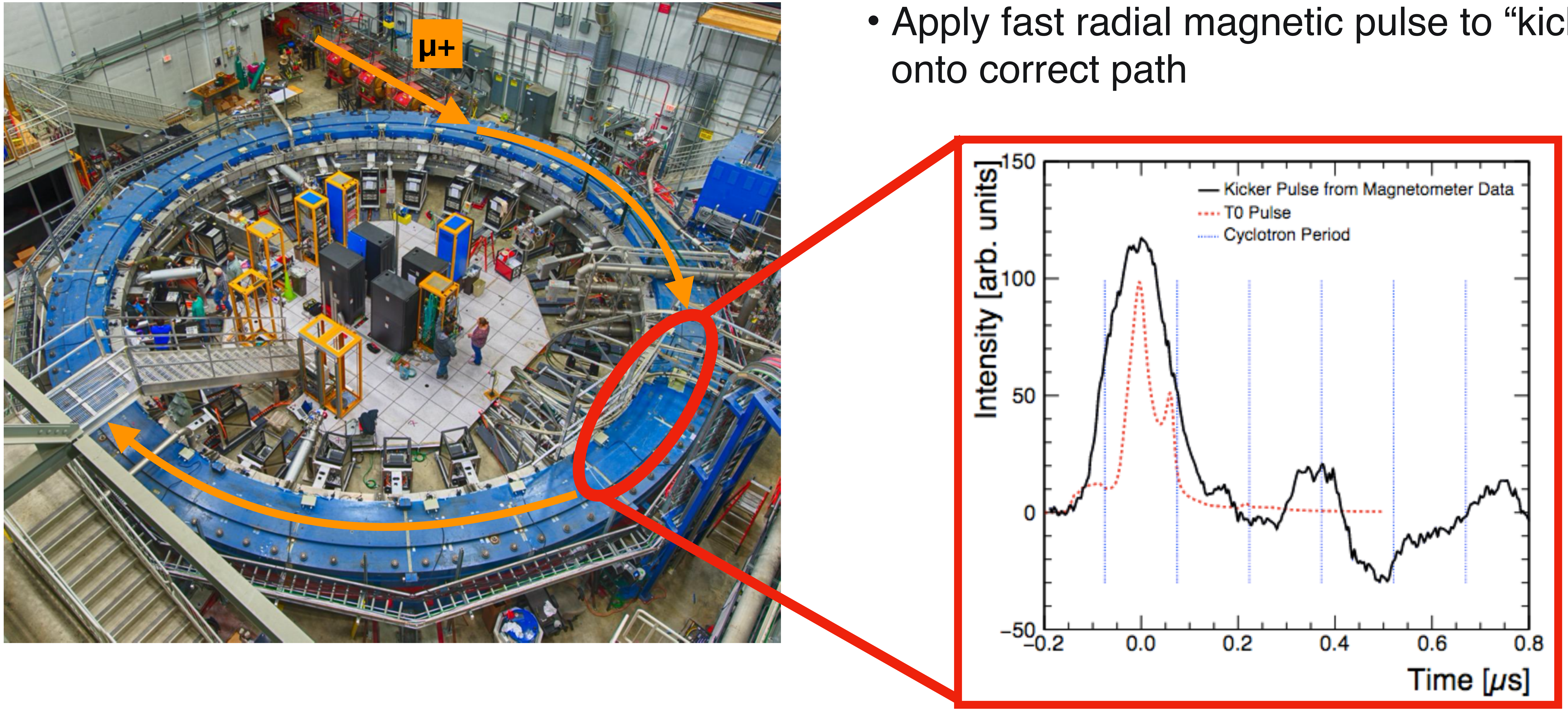
- Monitor beam profile before entrance with scintillating X and Y fibres
- Get time profile of beam using scintillating pad
- ~125 ns wide



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

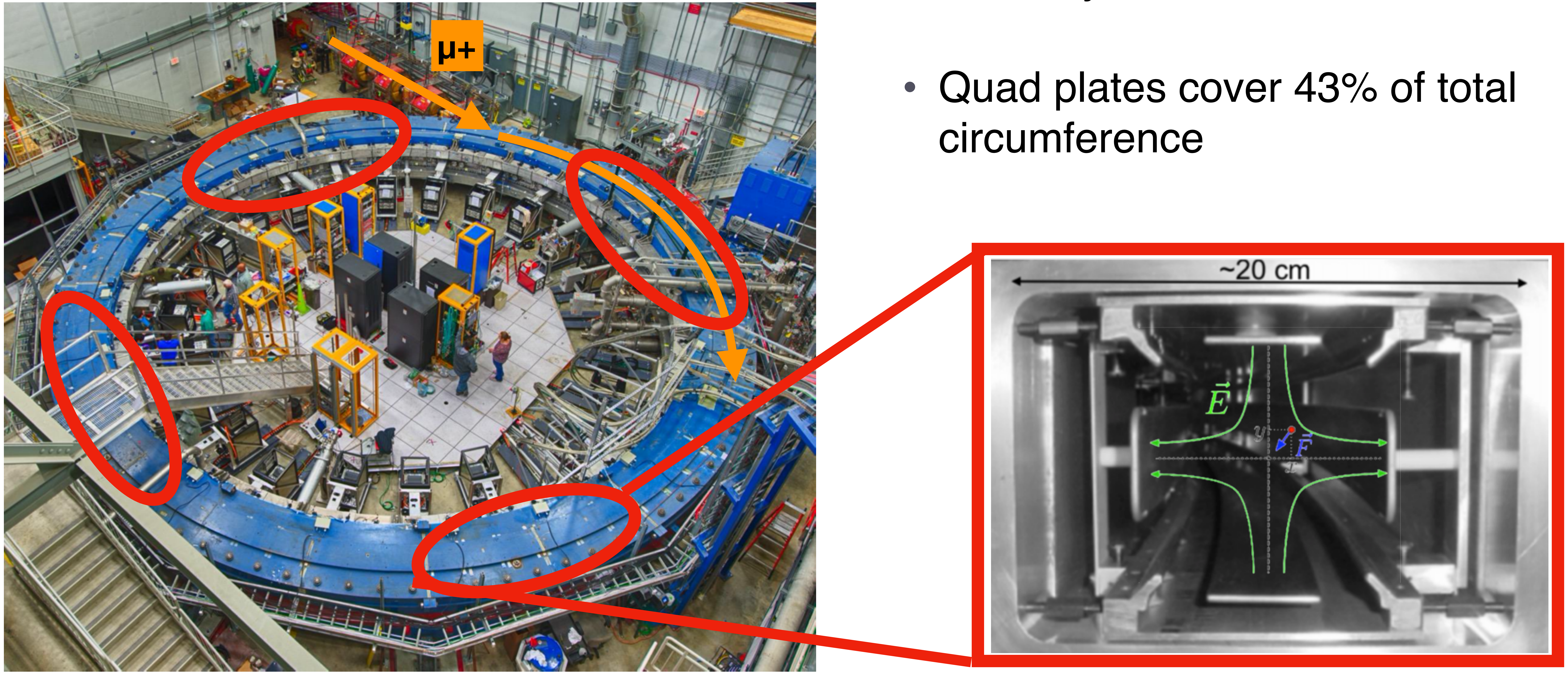
‘Kick’ onto correct orbit

- Injected muons are 77 mm away from the ideal orbit radius
- Apply fast radial magnetic pulse to “kick” muons onto correct path



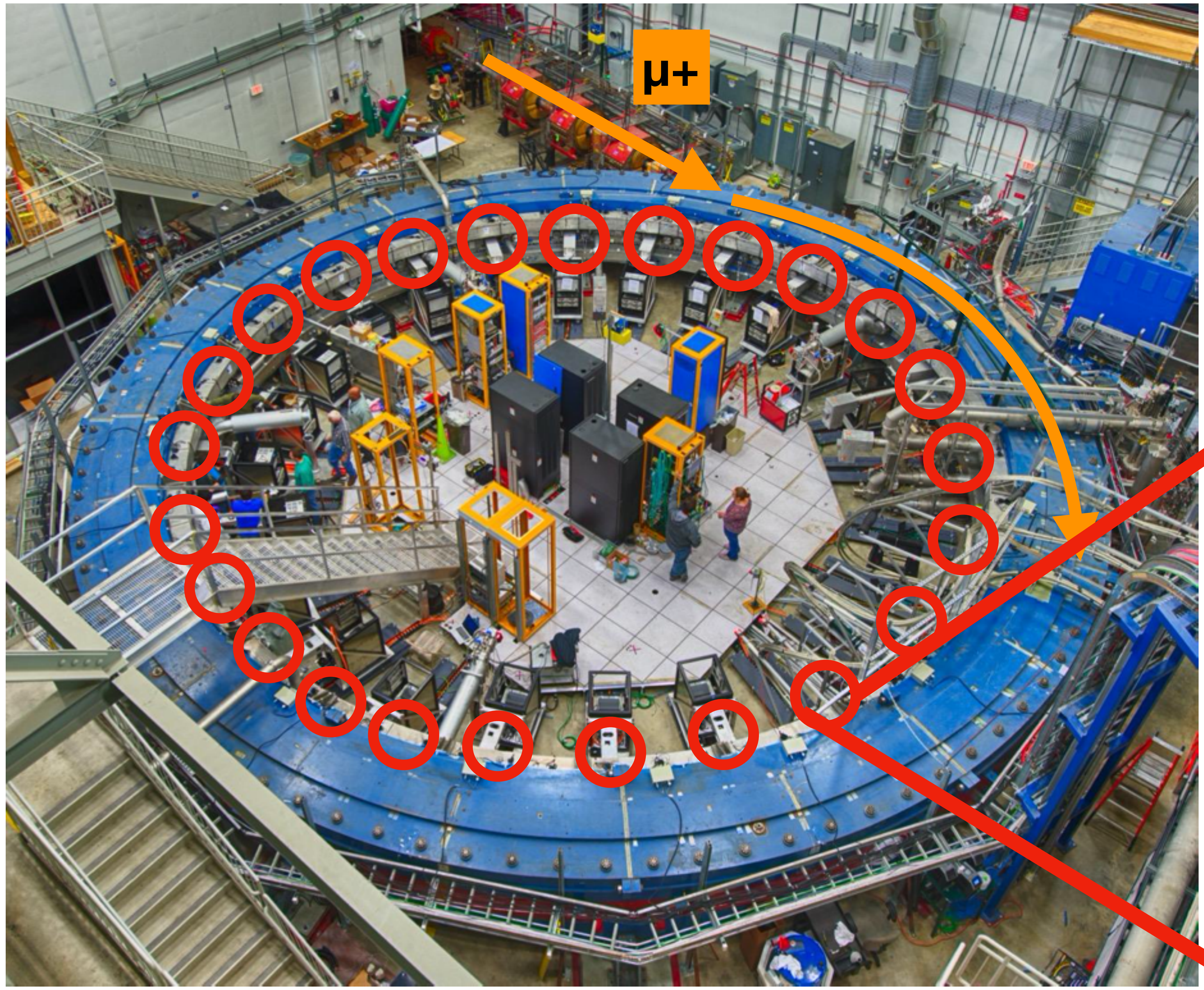
Beam focusing

- Electrostatic quadrupoles focus the beam vertically
- Quad plates cover 43% of total circumference

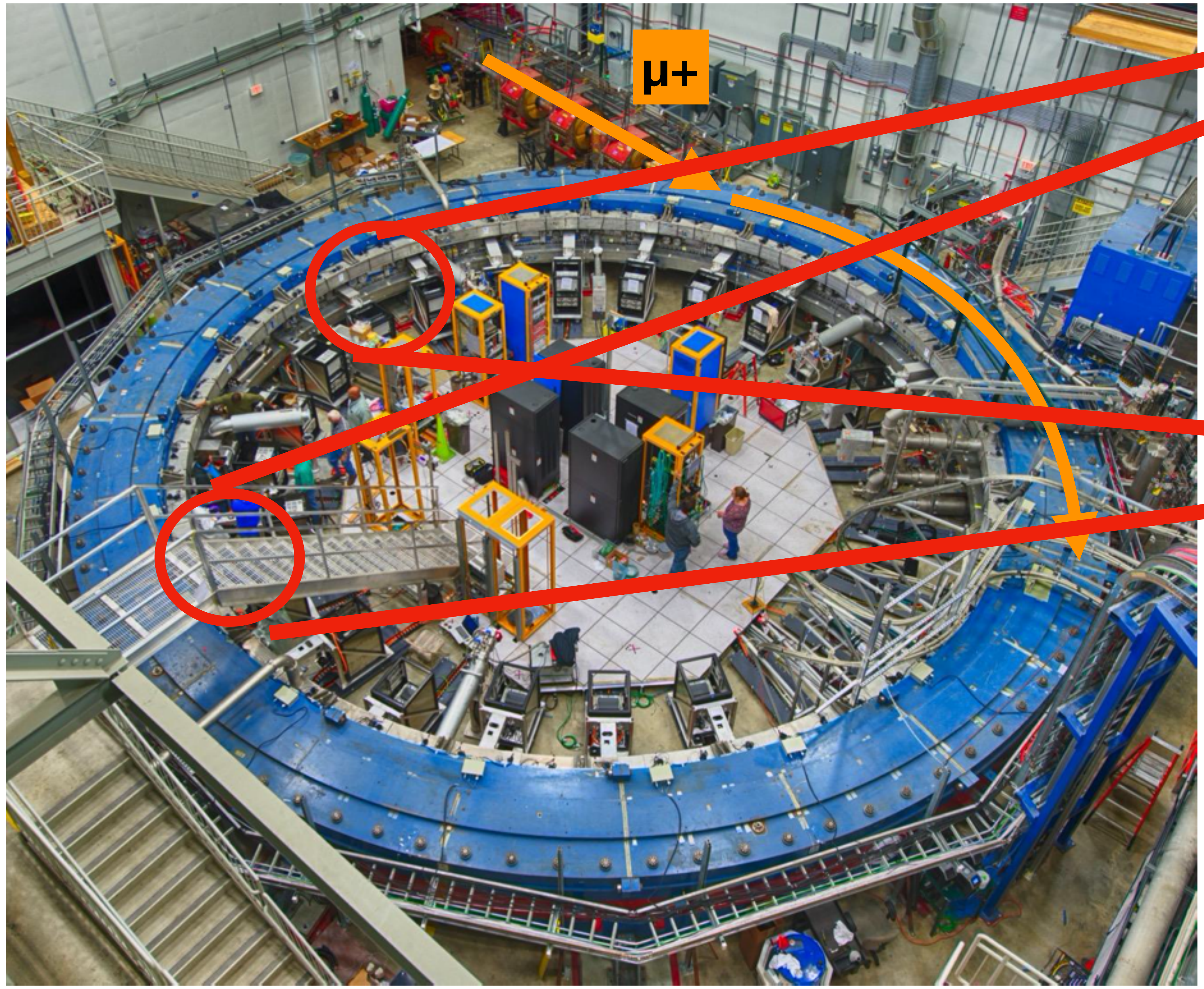


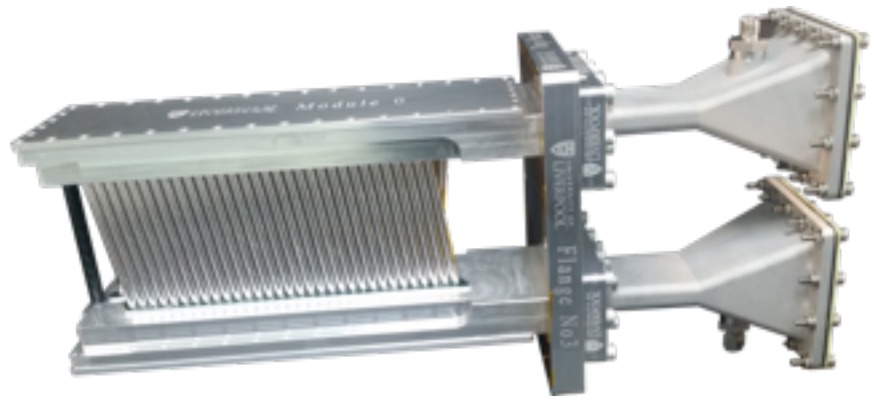
Calorimeters

- 24 electromagnetic calorimeters
- Arrays of 6x9 PbF_2 crystals (2.5 x 2.5 cm^2 x 14 cm) (15 X0)
- Readout by SiPMs to 800 MHz WFDs



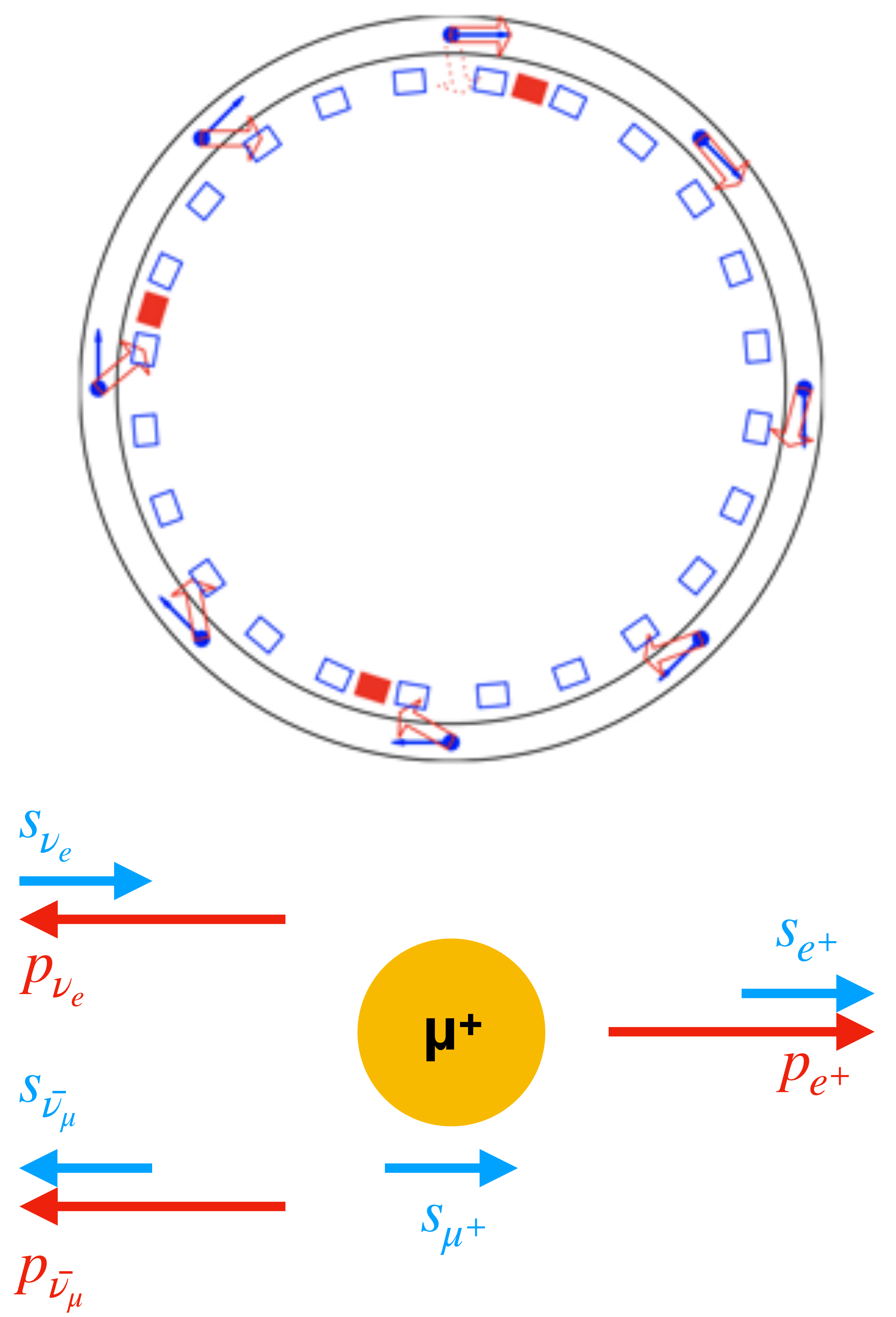
Tracking Detectors



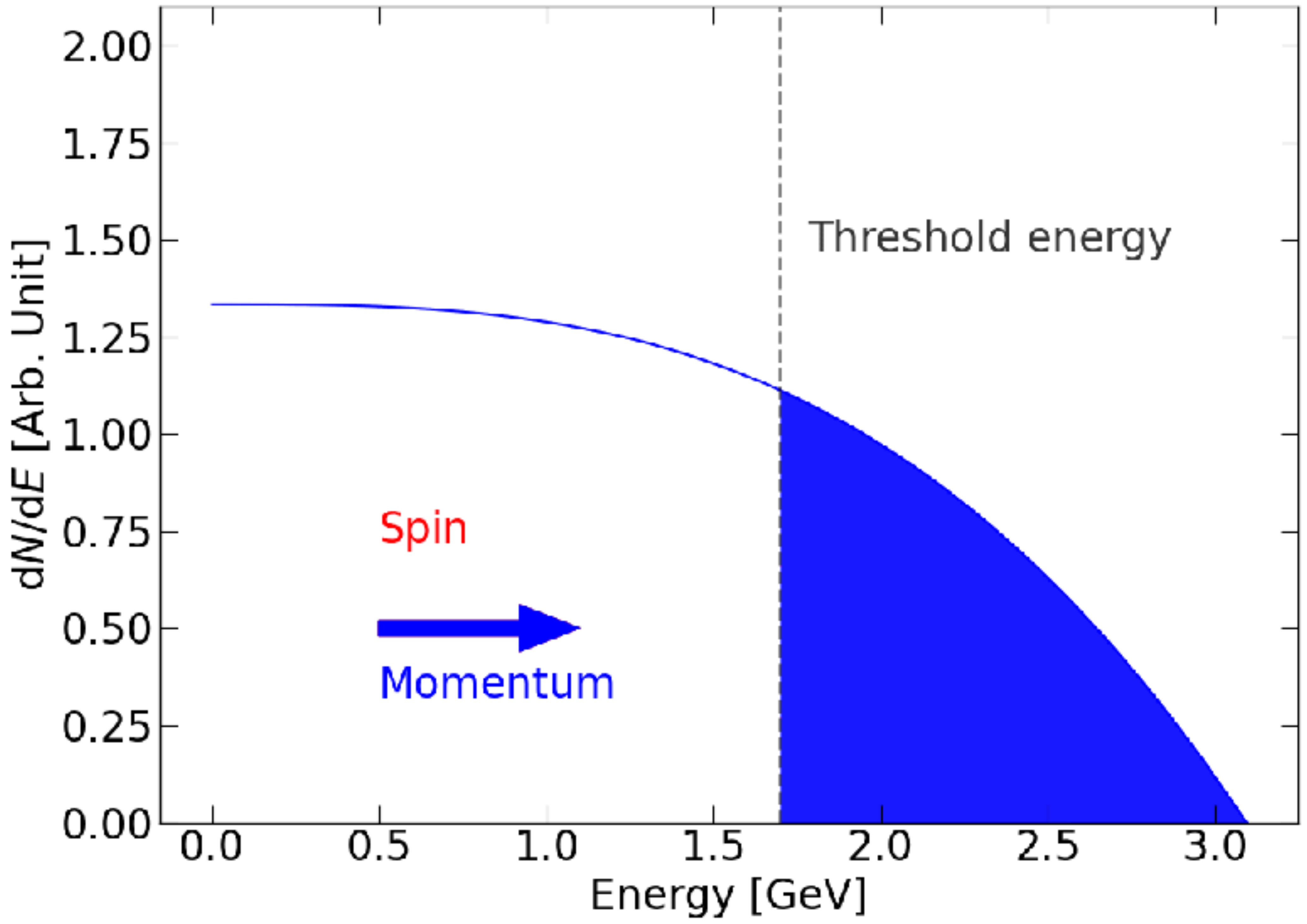


- Two tracking stations, each with 8 modules
- 128 gas-filled straws per module
- Track the decay e^+ trajectories back to their decay point

Measuring ωa



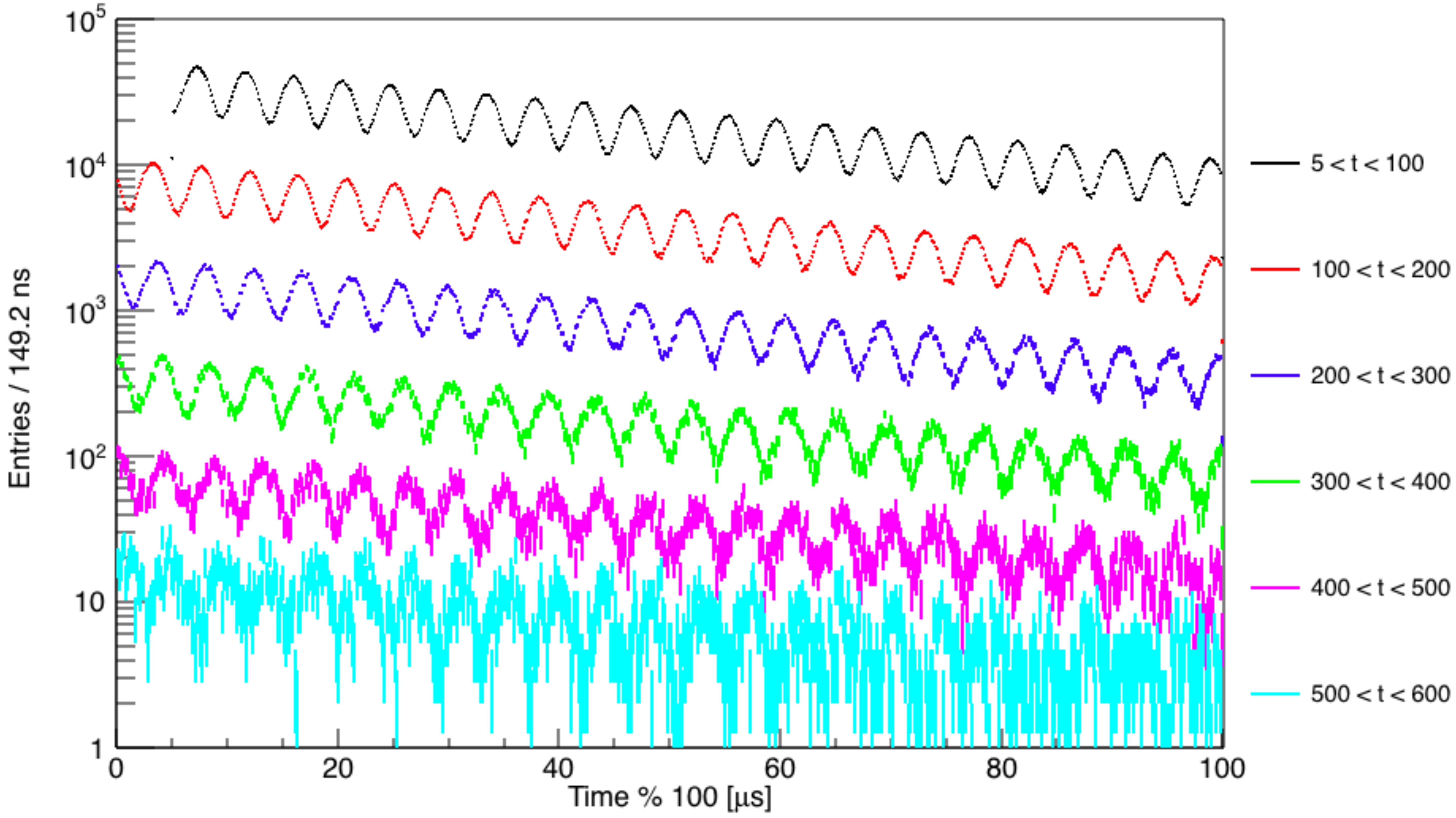
e+ preferentially emitted in direction of the muon spin



Number of e+ above threshold energy oscillates with frequency ωa

Simply count number of e+ above threshold vs time

Precession in one hour of data



$$N_e(t) \simeq N_0 e^{-\frac{t}{\gamma\tau}}[1 - A\cos(\omega_a t + \phi_a)]$$

Beam corrections

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

Injected beam has a small vertical component

- focus vertically with quads
- introduces two additional terms which reduce the precession frequency

Minimize the first by choosing ɣ = 29.3

- p_μ = 3.1 GeV ("magic" momentum)
- radius of ring = 7.11 m for 1.45 T field

Need to apply two corrections to a_μ…

E-field correction

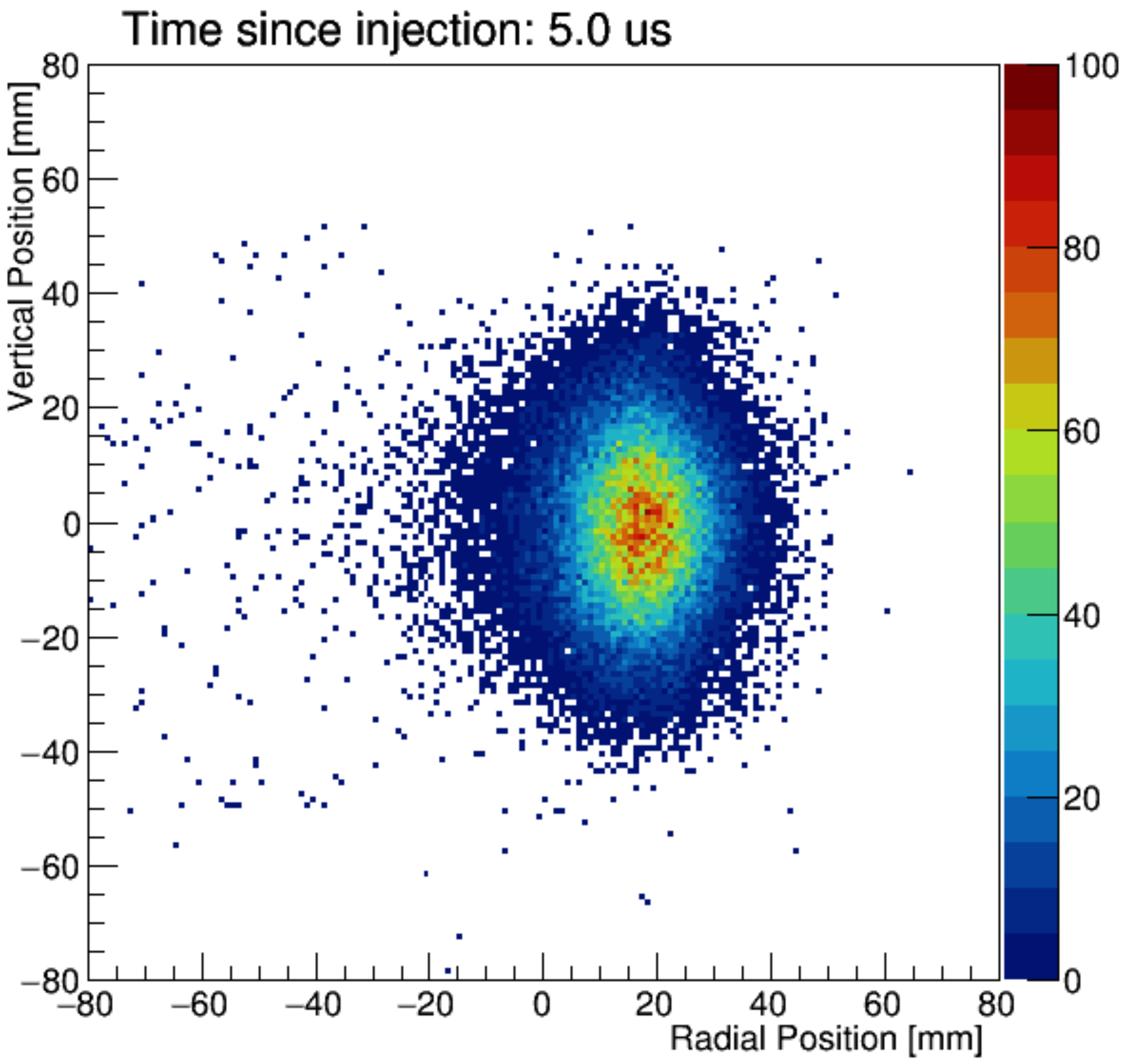
Not all muons at magic momentum $C_E = \frac{\Delta\omega_a}{\omega_a}$

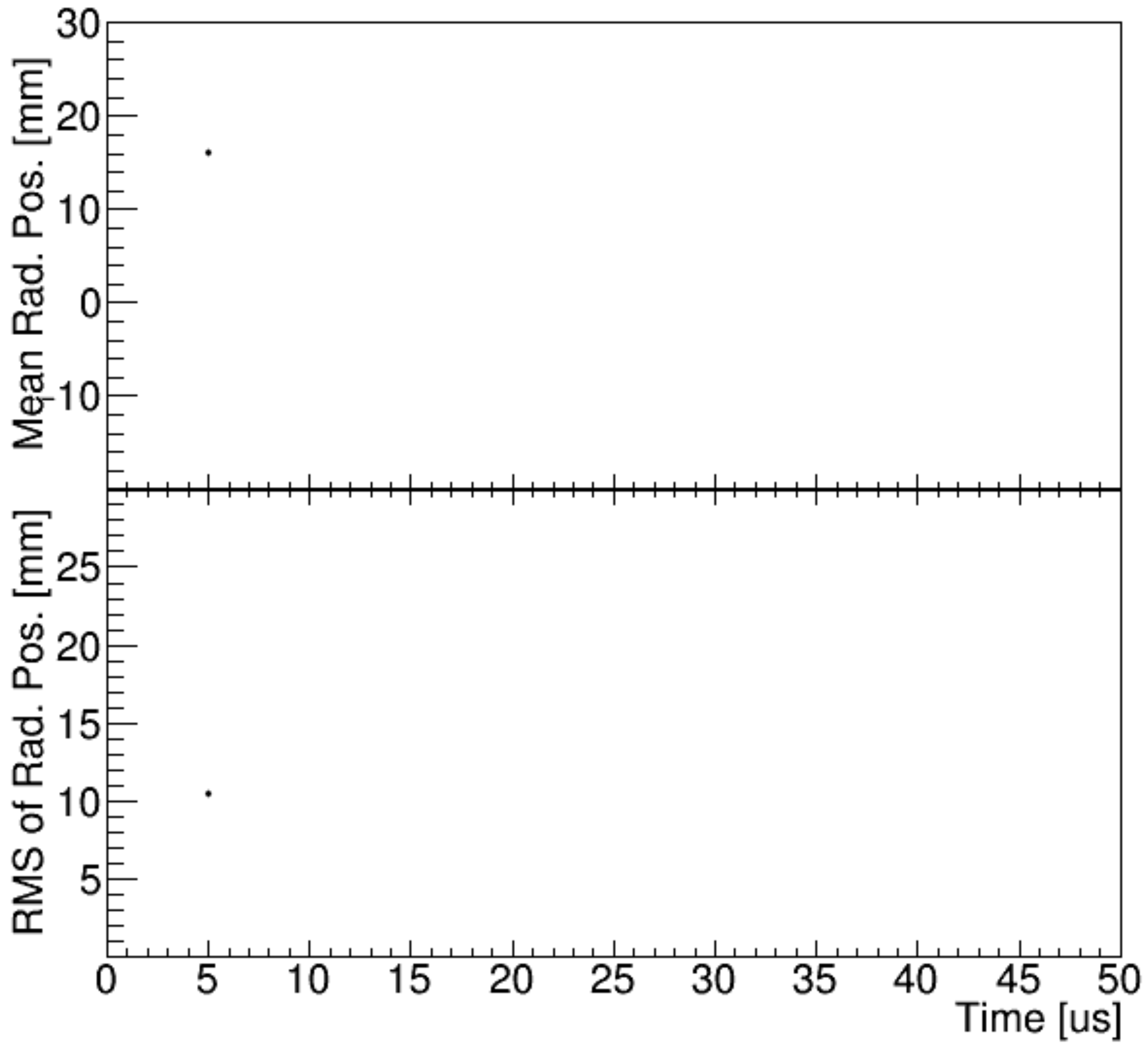
Vertical momentum component aligned with B field $C_p = \frac{\Delta\omega_a}{\omega_a}$

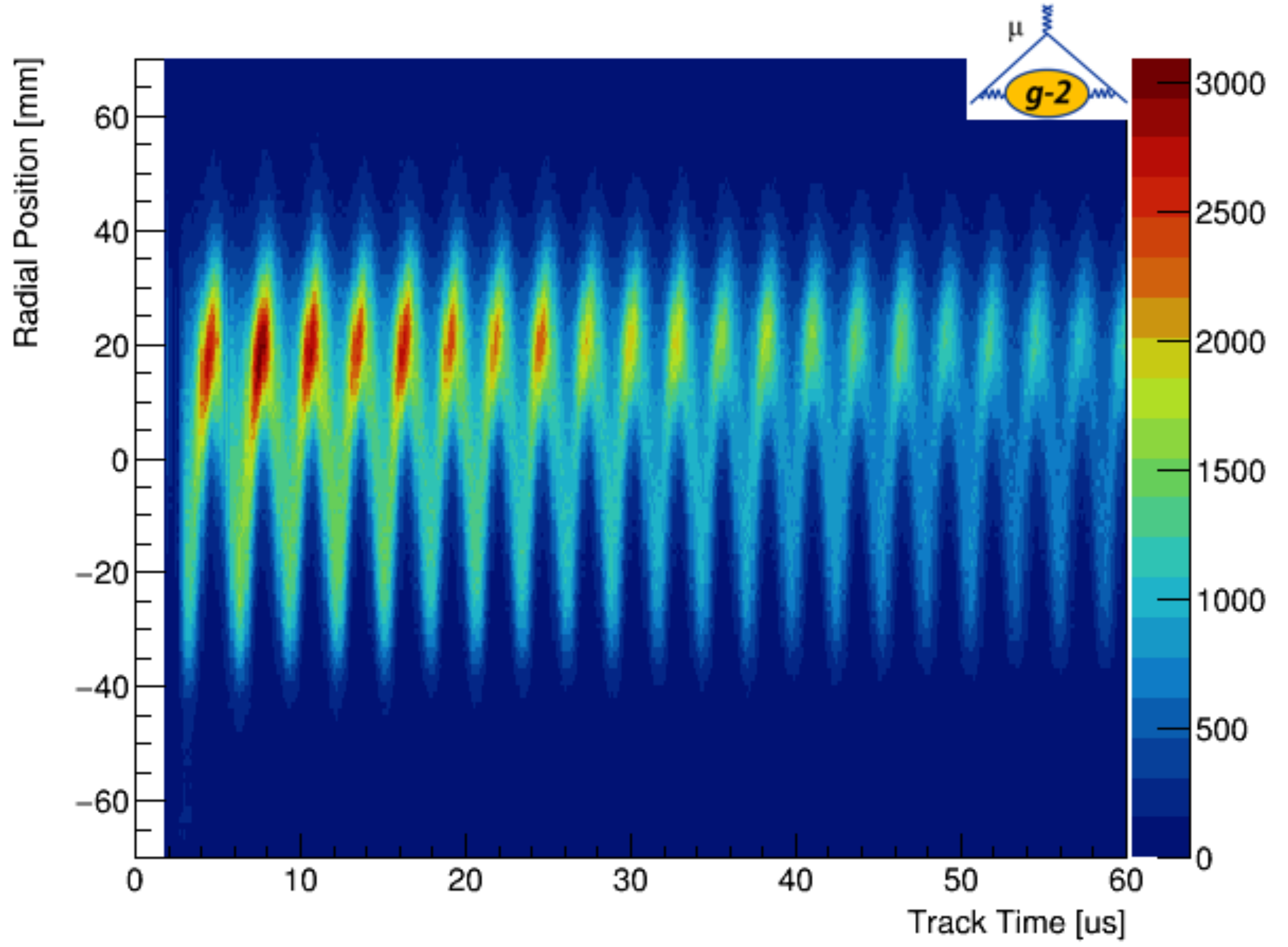
Pitch correction

Both corrections depend on quadrupole field strength and are < 0.5 ppm

Beam measurements







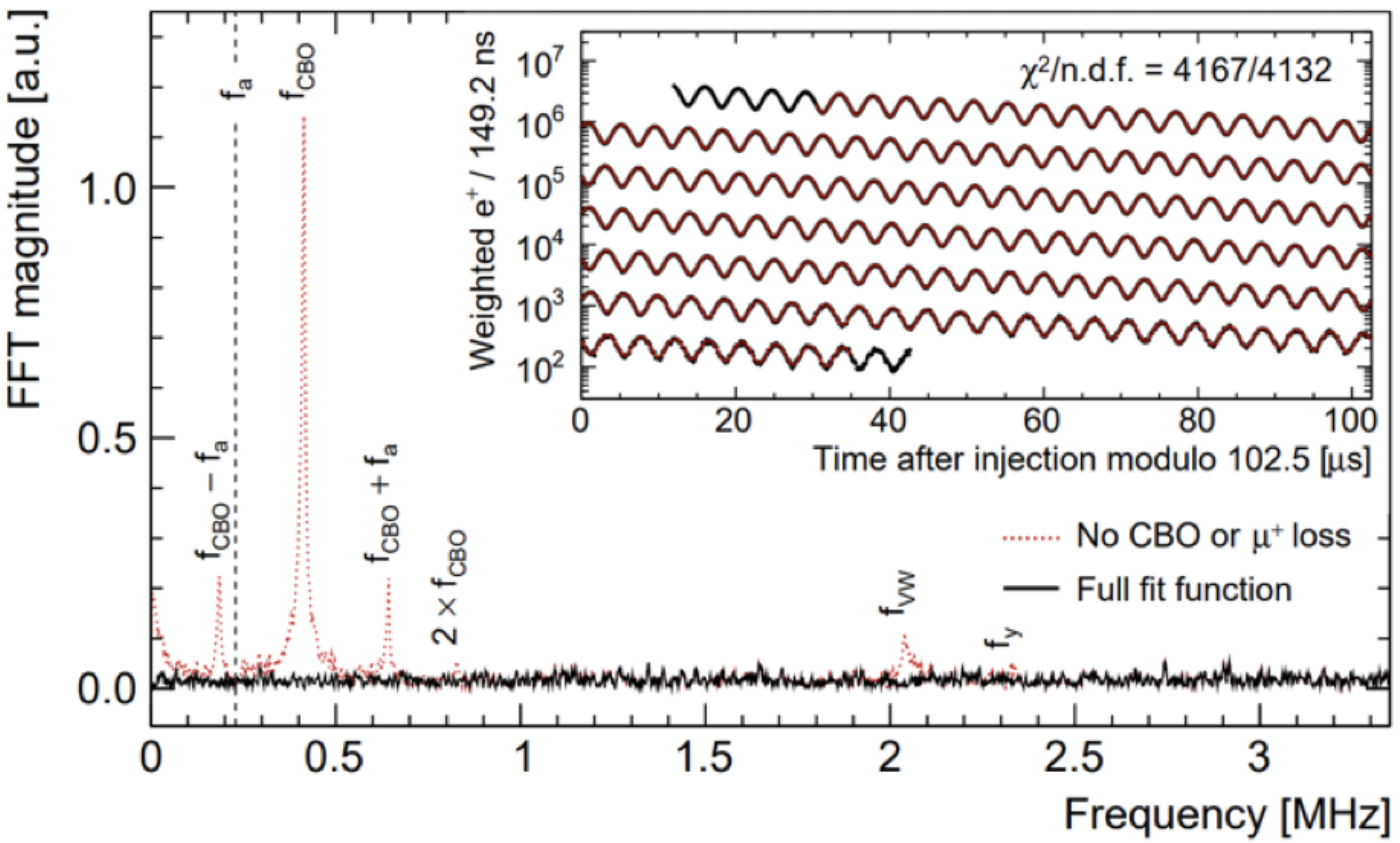
- Use tracking detectors to measure the decay e+ and infer decay position

- Muons oscillate radially and vertically at different frequencies, according to the quadrupole strength

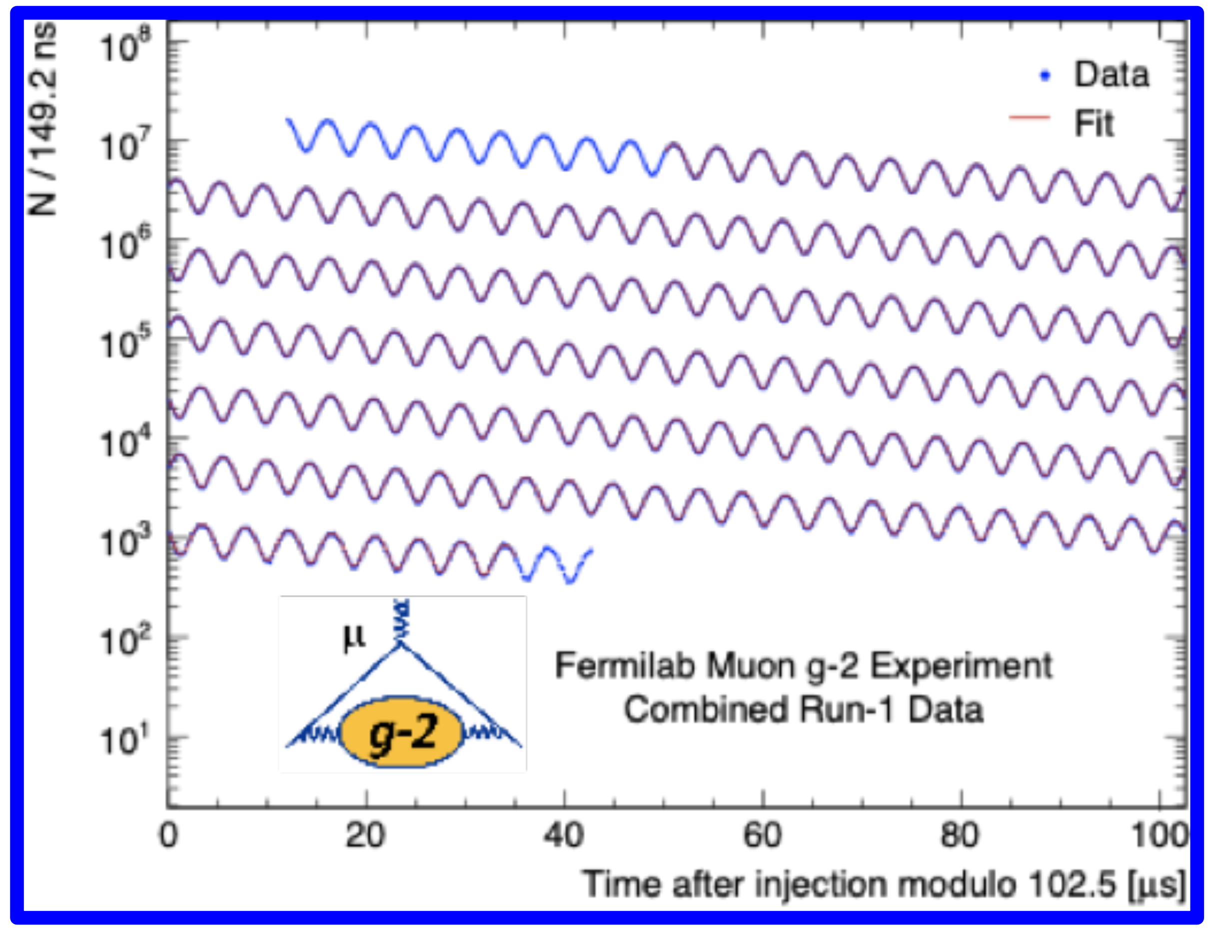
Fitting for ω_a

- Fourier transform of the residuals to the fit shows contributions from the movements of the beam, pileup and muon losses

- To account for these effects, additional terms included in the final fit function (24 parameters)

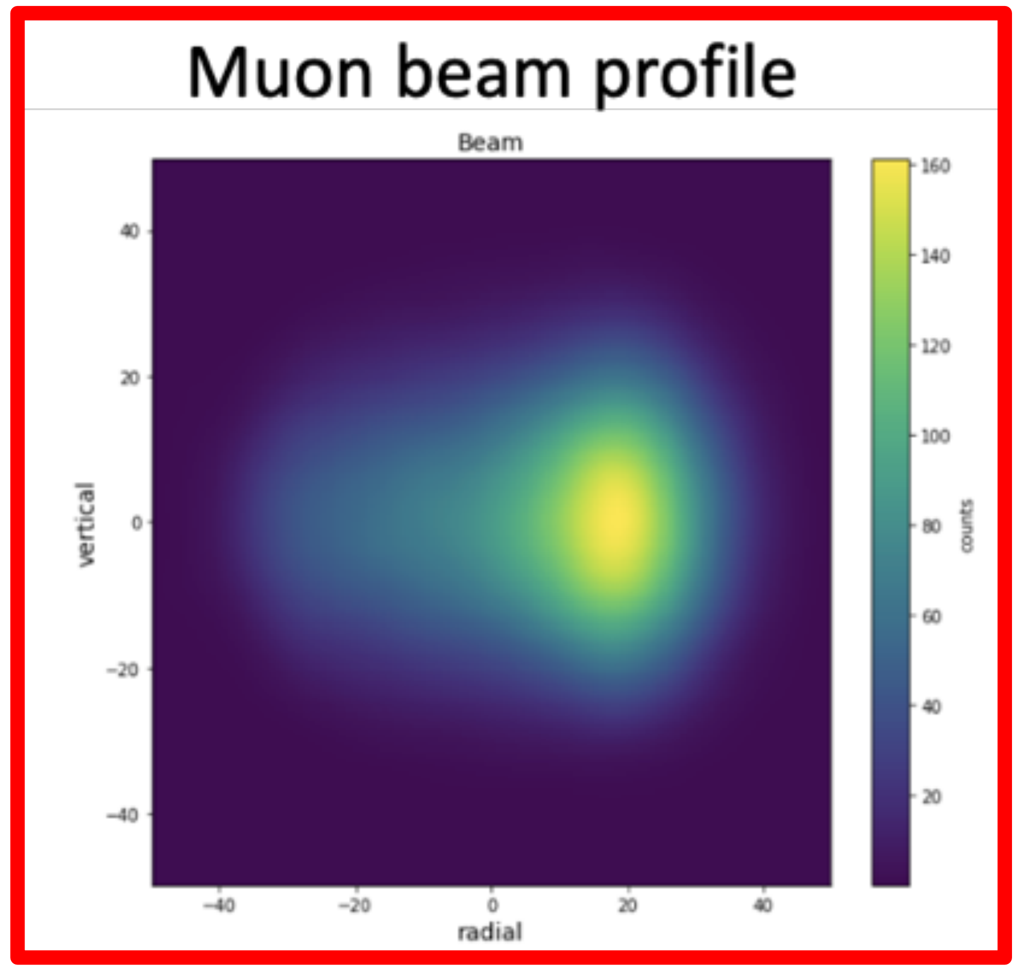


Field measurement



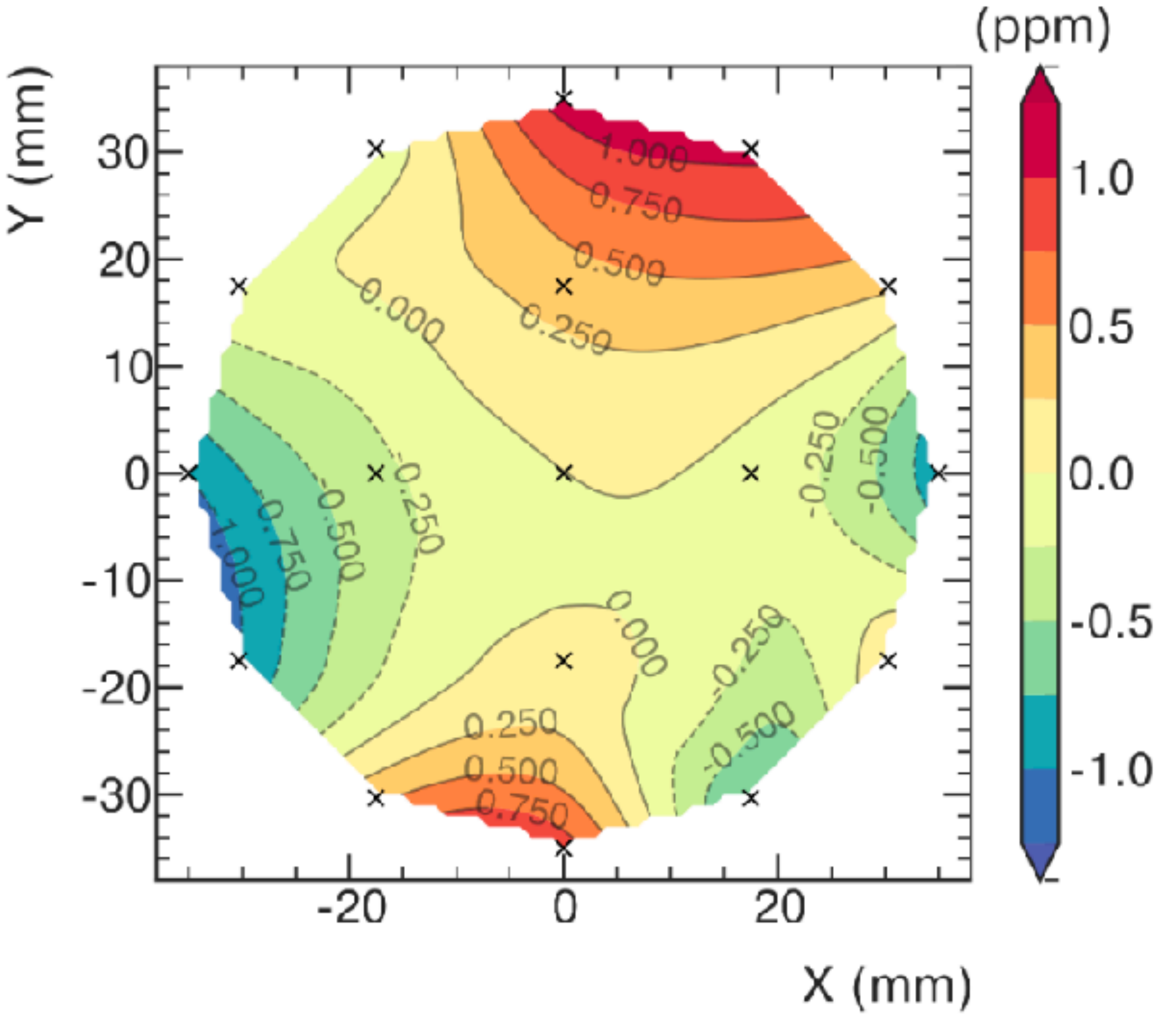
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\, \boxed{\omega_a^m}\,(1 + C_e + C_p + C_{ml} + C_{pa})}{\boxed{f_{\text{calib}}\ \langle \omega_p(x, y, \phi)} \times \boxed{M(x, y, \phi)}\rangle (1 + B_k + B_q)}$$

Magnetic field measurement



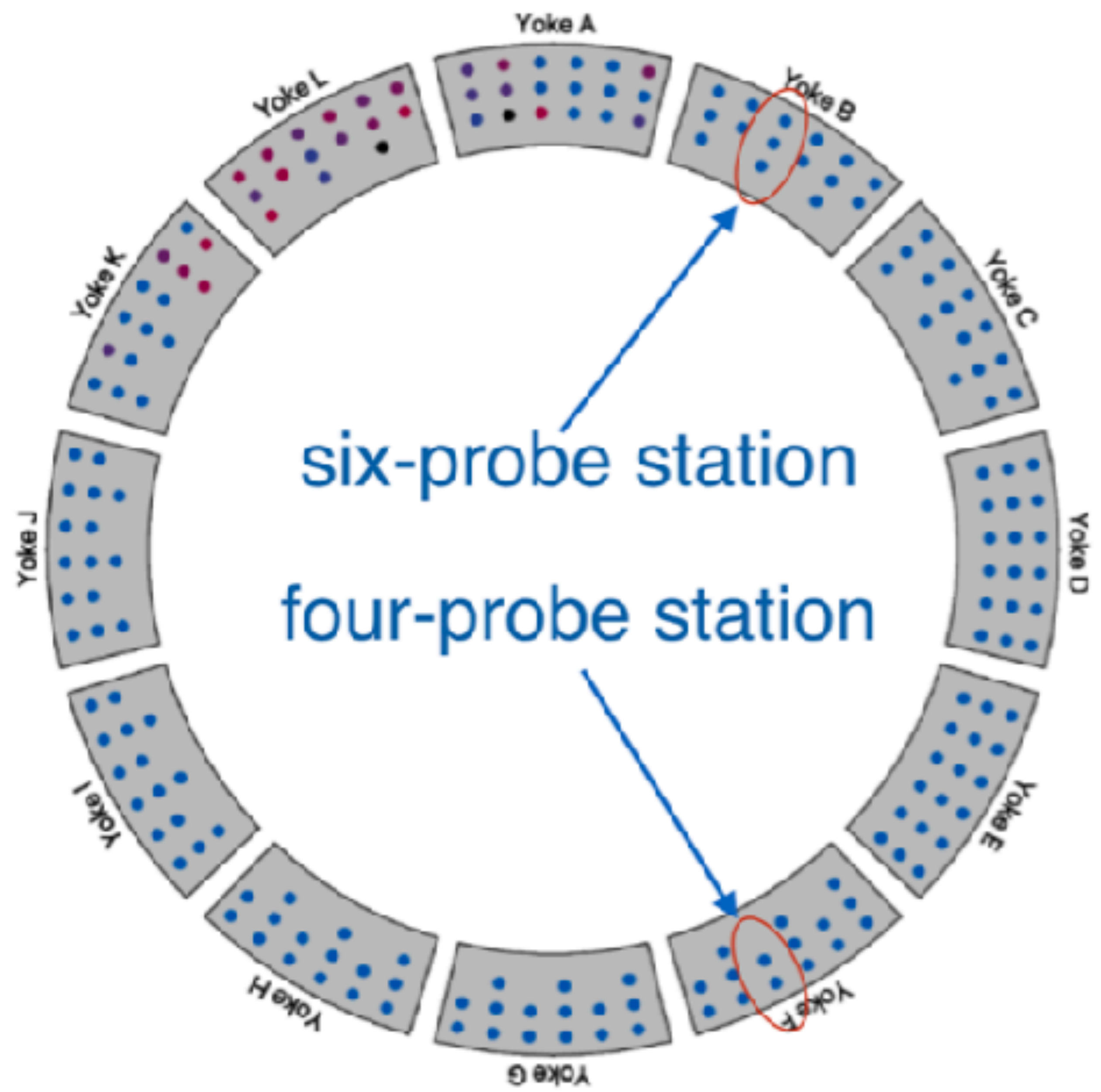
Fermilab

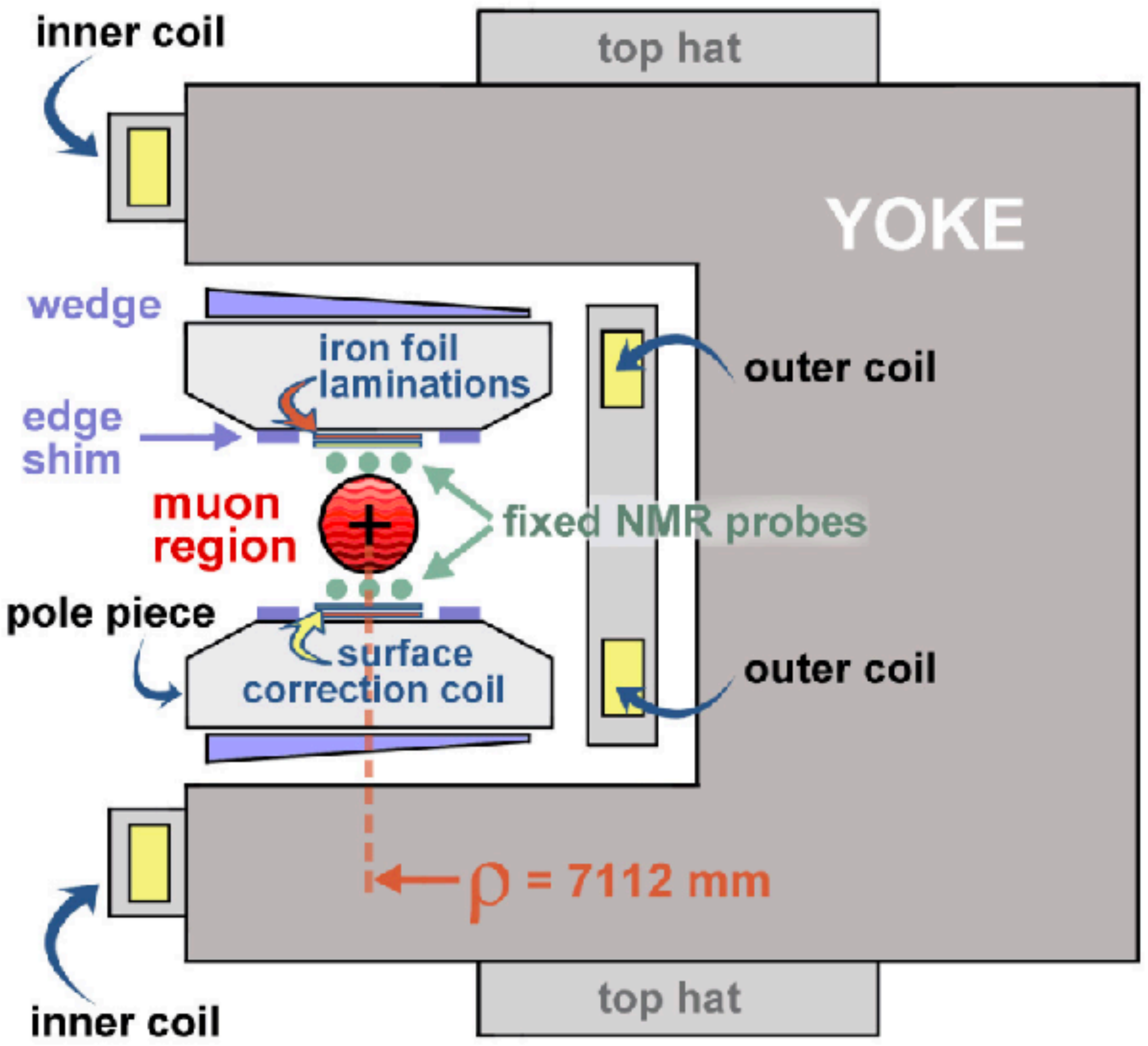
Measuring the magnetic field



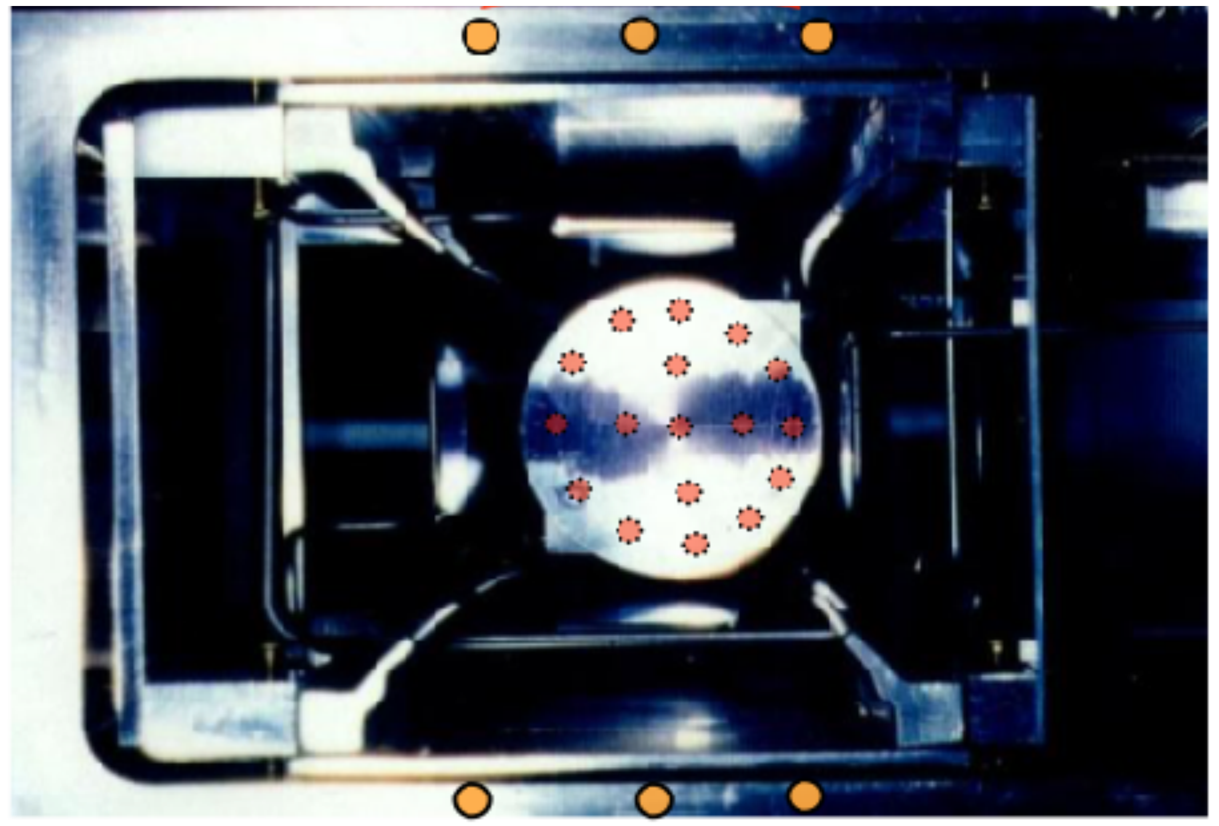
The Storage Ring Magnet

Field changes monitored continuously by 378 fixed NMR probes





Field in storage region mapped out by NMR trolley



B = 1.45 T

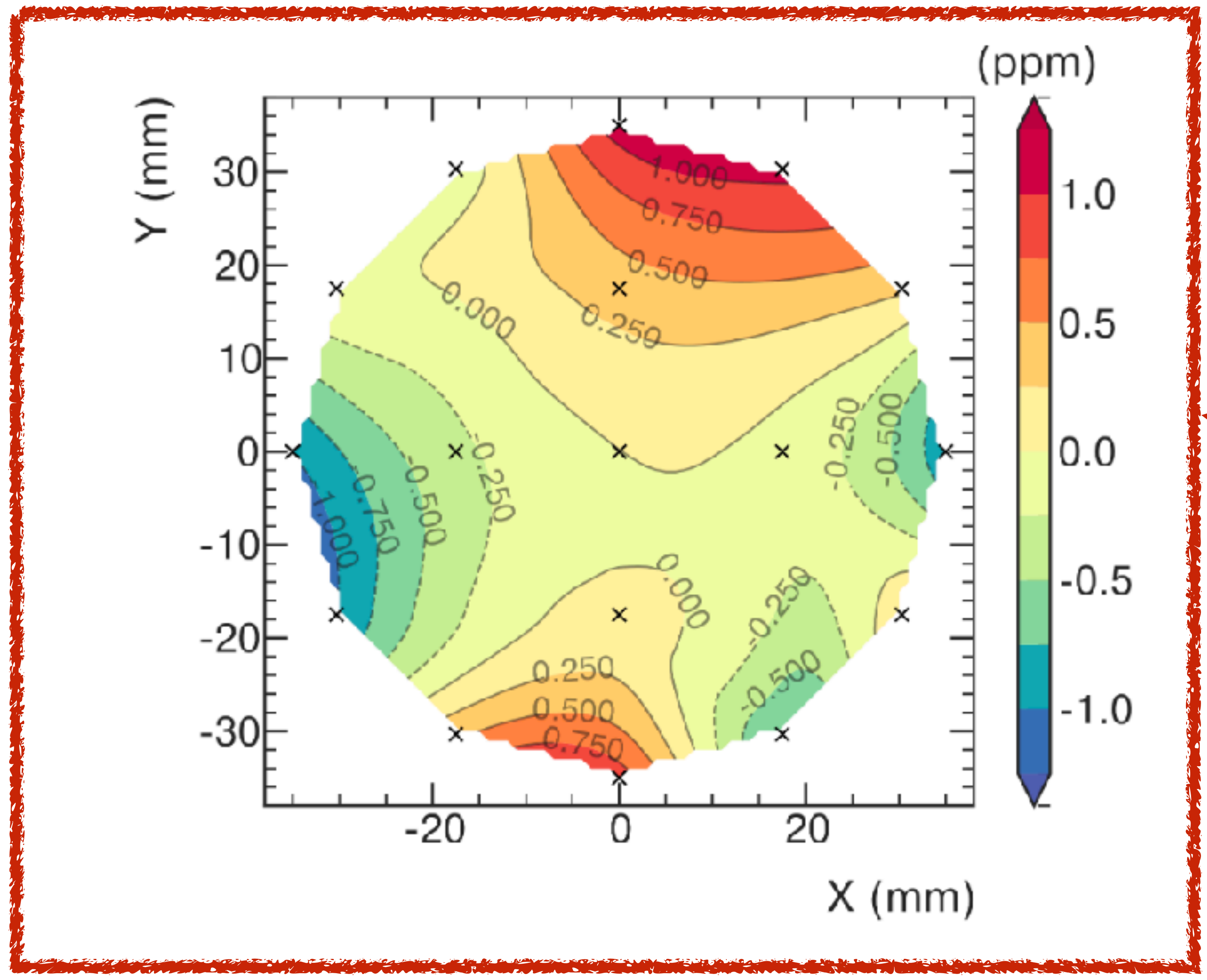
12 C-shaped yokes

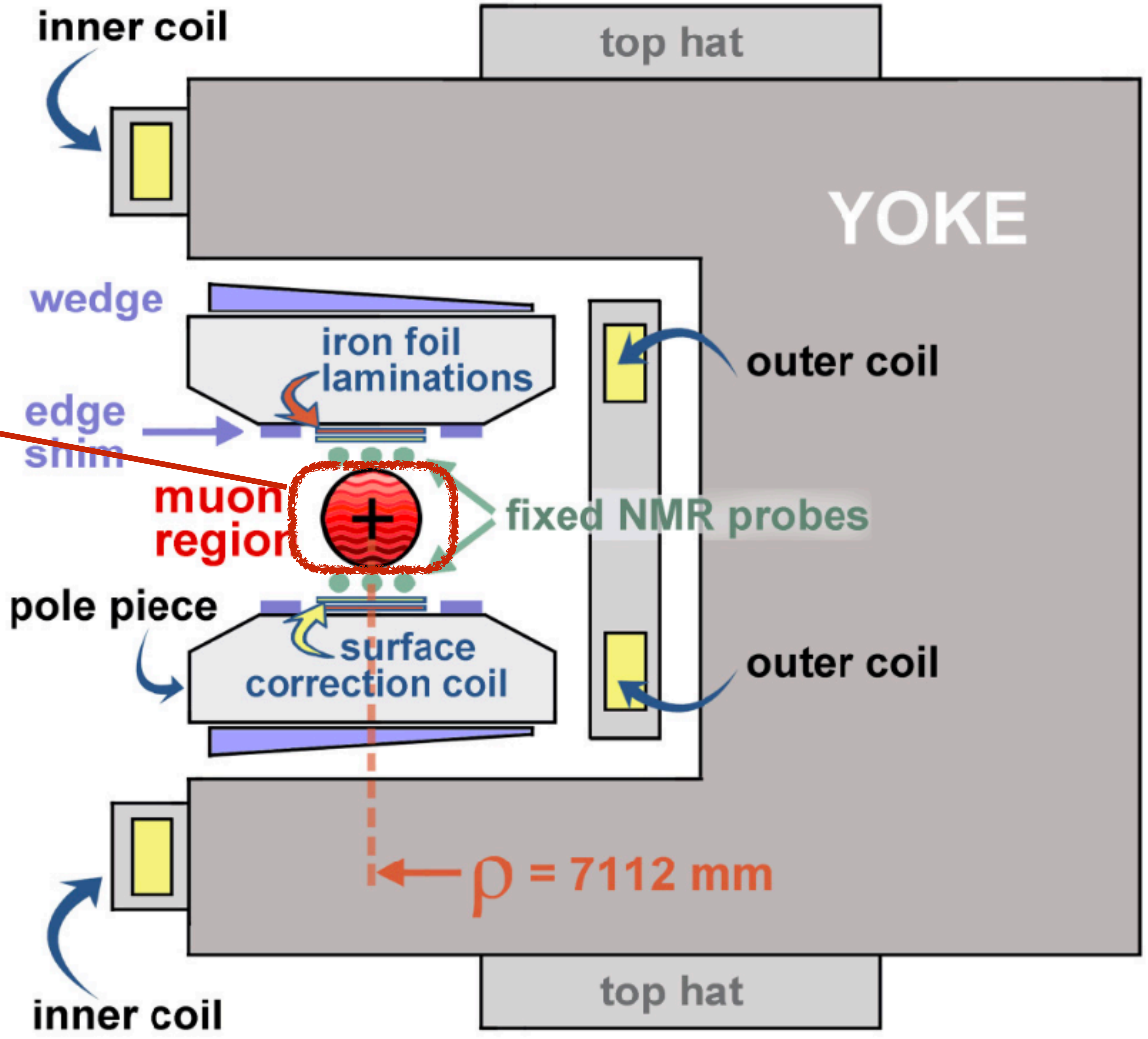
6 poles per yoke (3 upper, 3 lower)

Field determined by pole separation

Fermilab

The field inside the storage ring





Ideally, the field would be uniform everywhere inside the storage region

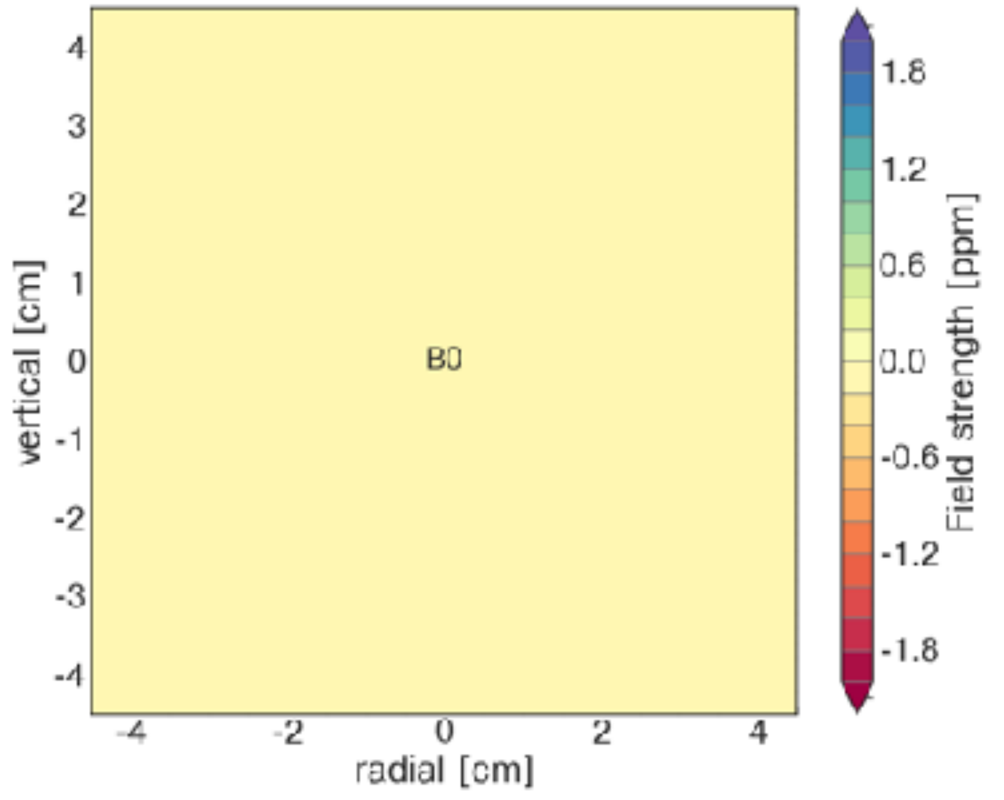
In practice, we have gradients — slight variations in the field over the storage region

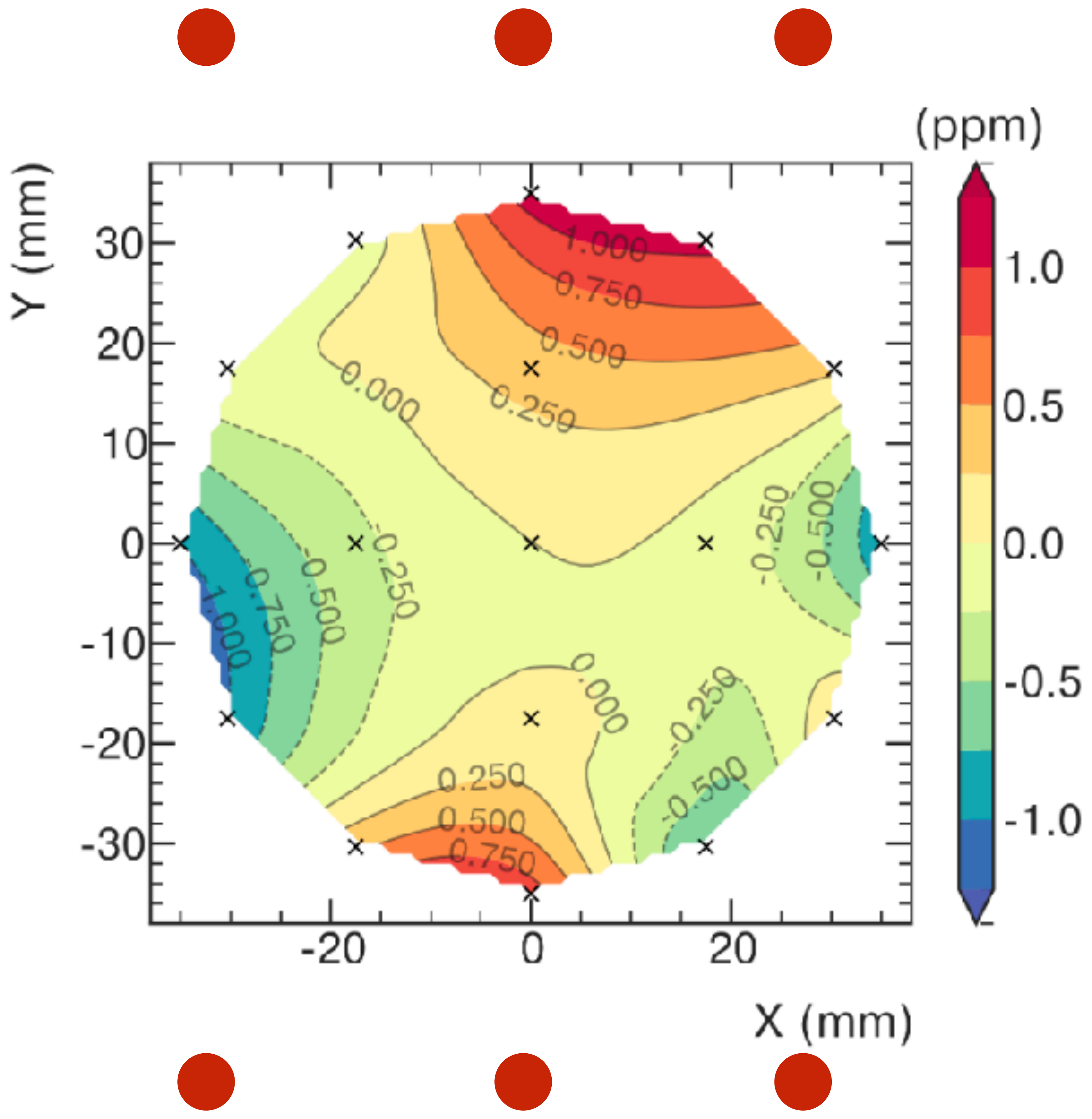
Spatial dependence of the B-field

2D B-field contour map can be described by the terms in a multipole expansion of B in r and θ

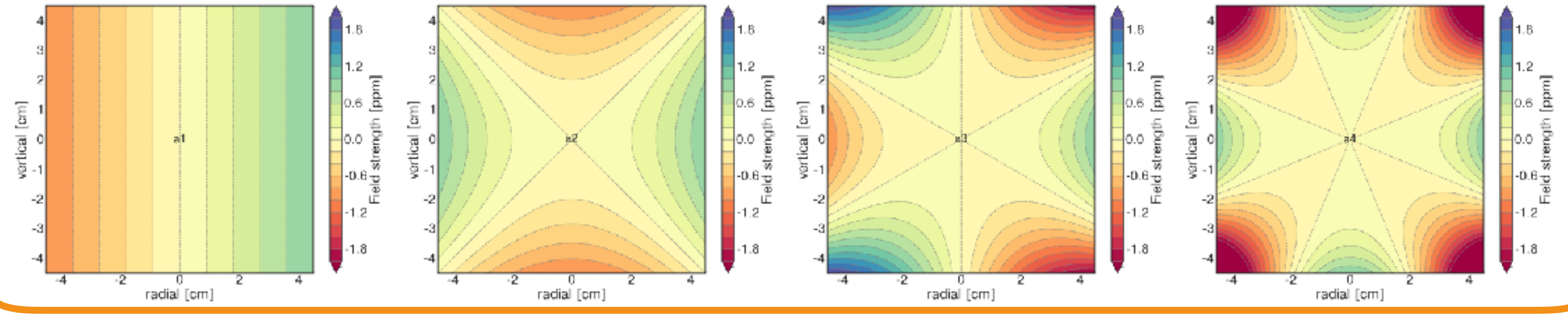
$$B(r,\theta) = \boxed{B_0} + \sum_{n=0}^{4} \left(\frac{r}{r_0}\right)^n \left[\boxed{a_n \cos(n\theta)} + \boxed{b_n \sin(n\theta)}\right]$$

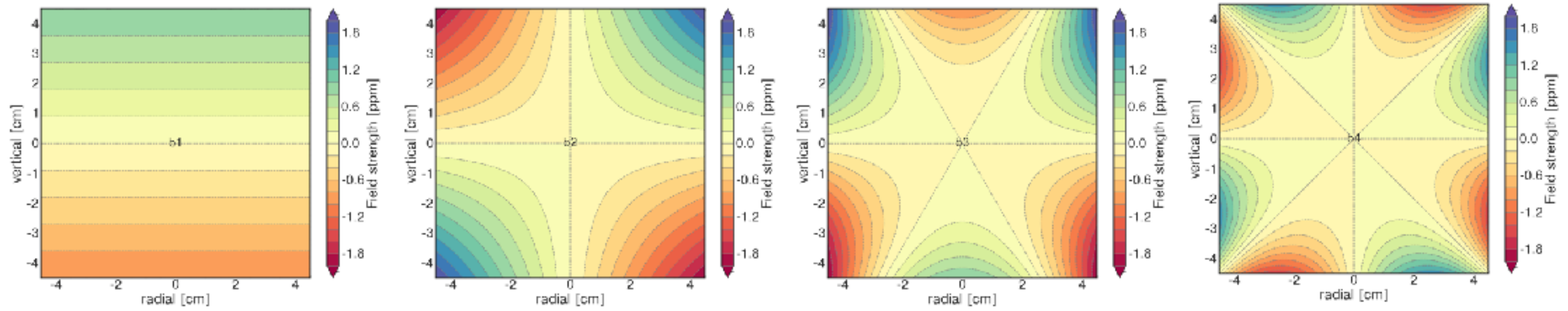
Dipole





‘normal’ terms





‘skew’ terms

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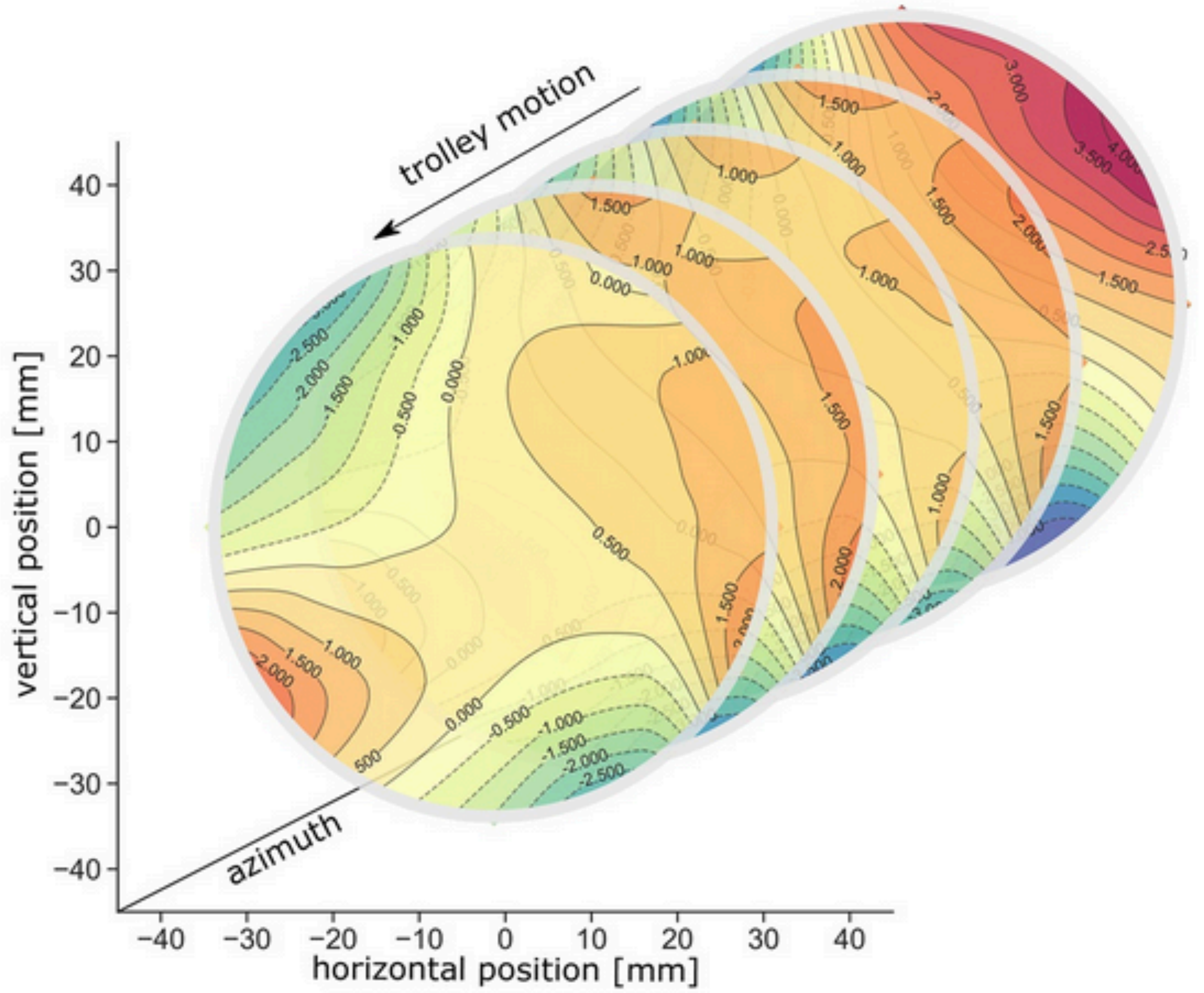
Measurement procedure

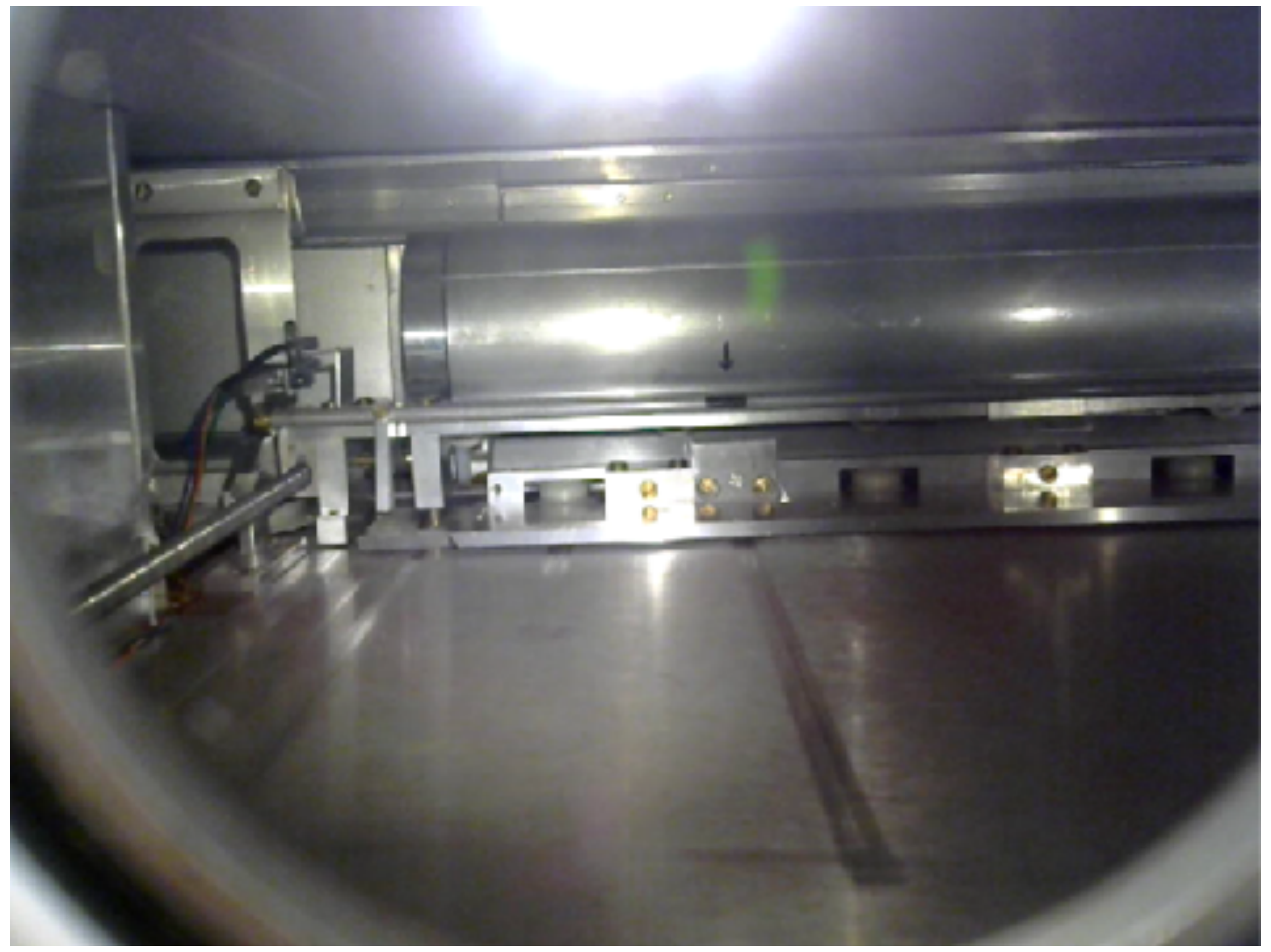
$$\tilde{\omega}_p{}'(T_r) = \underbrace{f_{calib}}_{\text{NMR probe calibration factor}} \underbrace{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle}_{\text{Magnetic field weighted by the muon beam distribution}} \underbrace{(1 + B_k + B_q)}_{\text{Corrections from transient magnetic fields}}$$

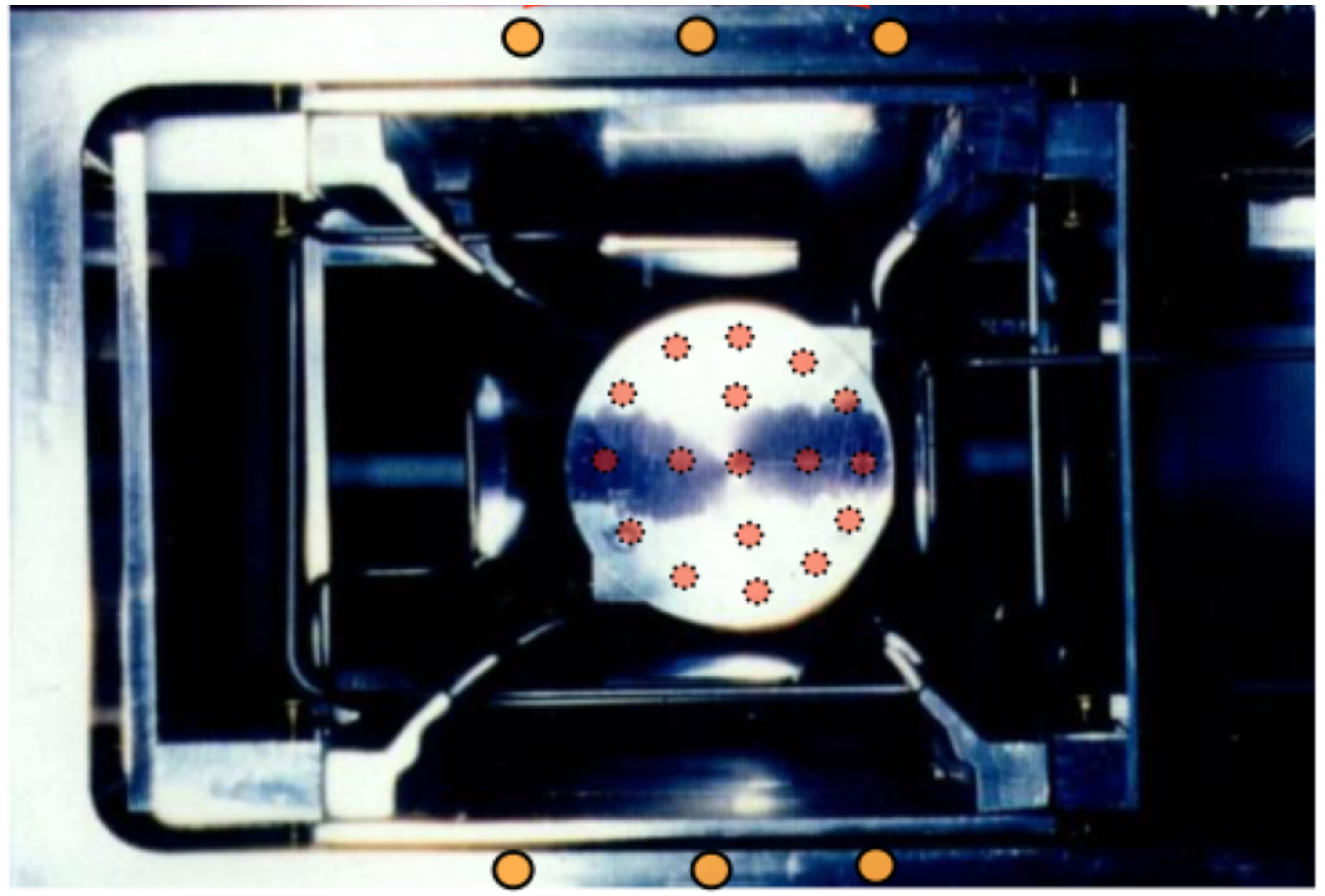
- B field measurement:
  - Measure the spatial distribution of the field components everywhere in the storage ring
  - Track field changes over time
  - Weight by muon intensity and distribution to obtain average field experienced by the muons

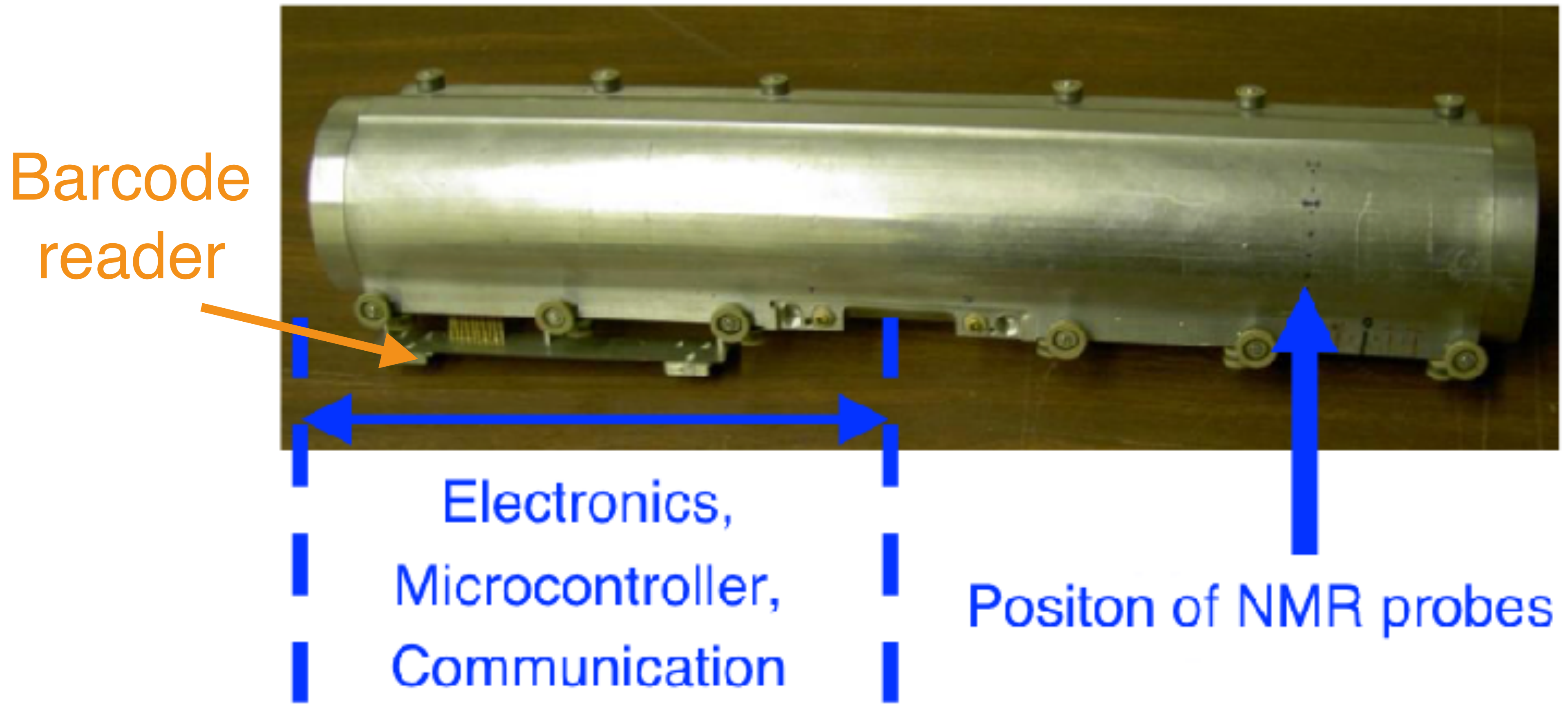
The in-vacuum trolley

- The trolley is a cylindrical shell housing 17 NMR probes
- Every ~3 days, stop the beam for 3 hours and perform trolley run to precisely map field gradients around ring
- > 8000 azimuthal ‘slices’ measured in one trolley run



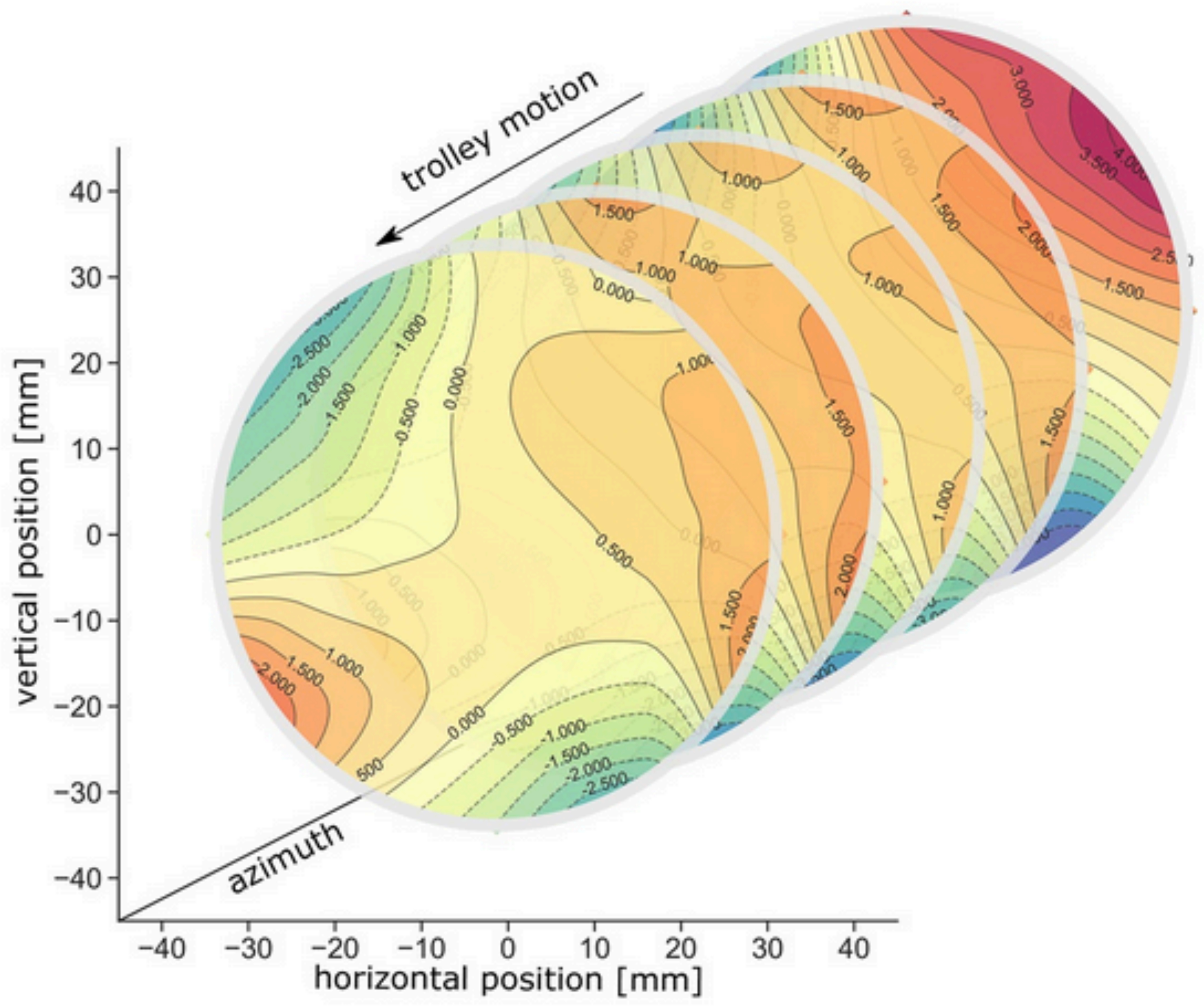


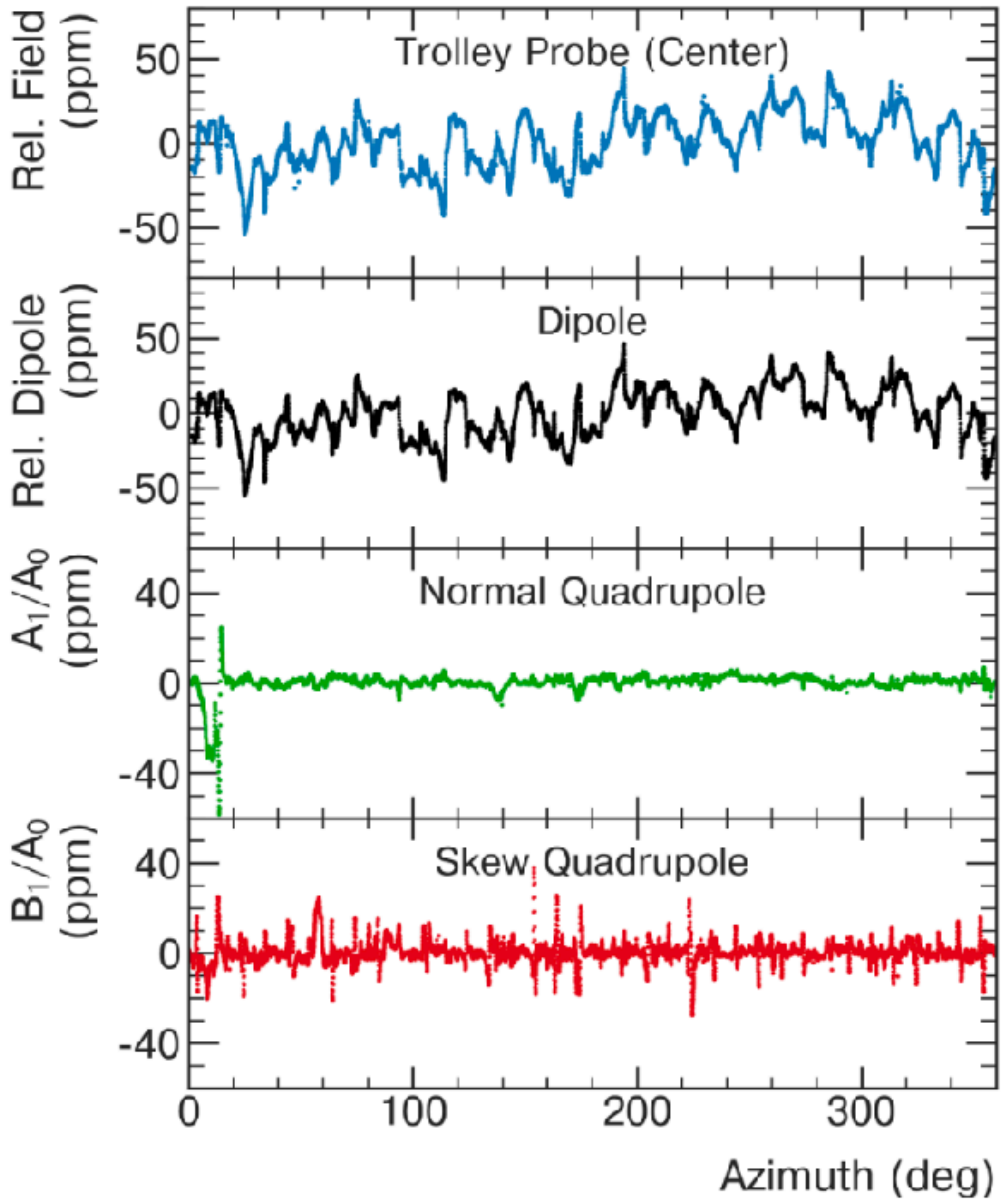




Fermilab

A typical trolley run

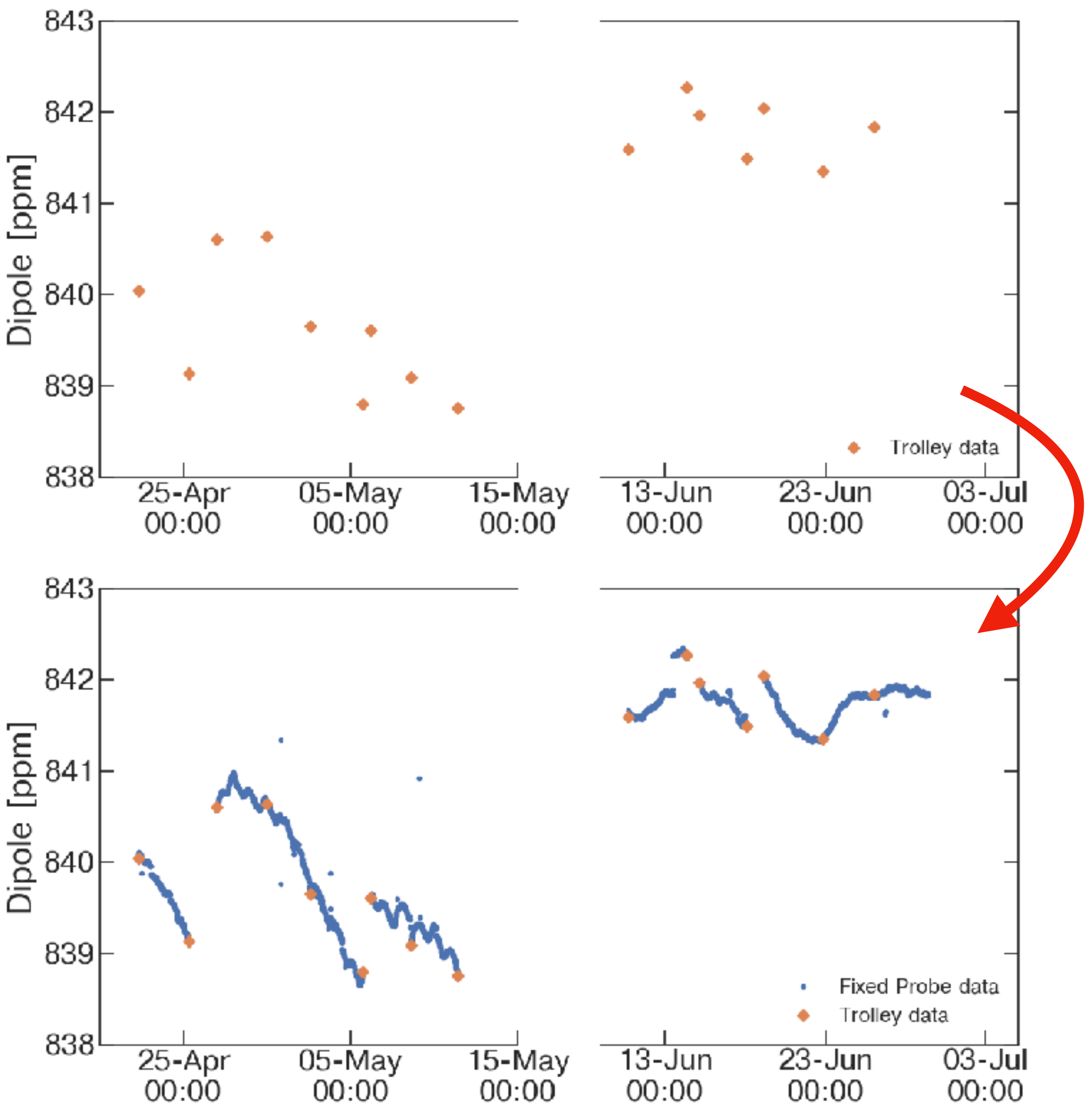


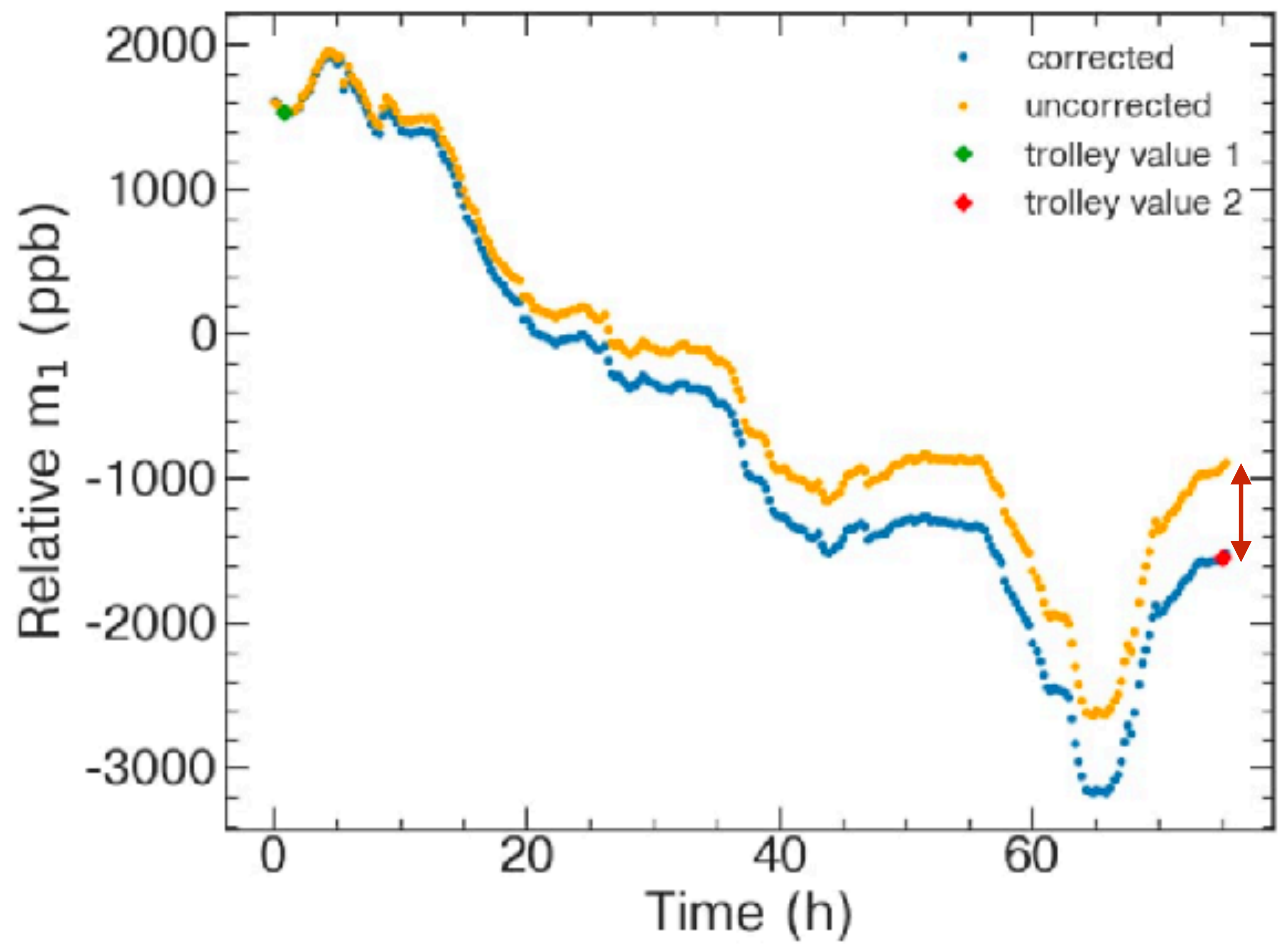


Trolley measures field gradients at >8000 azimuthal slices

Terms describing different field gradients are extracted from a 2D fit to the slice

Interpolating between trolley runs





- Between trolley runs, use fixed probes to track changes in the field over time
- Synchronize trolley and fixed probe measurements
- Synchronization drifts over time due to drifts in higher-order terms

Measurement procedure

$$\tilde{\omega}_p{}'(T_r) = \underbrace{f_{calib}}_{\text{NMR probe calibration factor}} \underbrace{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle}_{\text{Magnetic field weighted by the muon beam distribution}} (1 + \underbrace{B_k + B_q}_{\text{Corrections from transient magnetic fields}})$$

NMR probe calibration factor

Magnetic field weighted by the muon beam distribution

Corrections from transient magnetic fields

Relate protons in our NMR probes (petroleum jelly) to those in **spherical water sample**

$$\tilde{B} = \frac{\hbar \tilde{\omega}_p{}'(T)}{2\mu_p{}'(T)} = \frac{\hbar \tilde{\omega}_p{}'(T)}{2} \boxed{\frac{\mu_e(H)}{\mu_p{}'(T)}} \frac{\mu_e}{\mu_e(H)} \frac{1}{\mu_e}$$

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

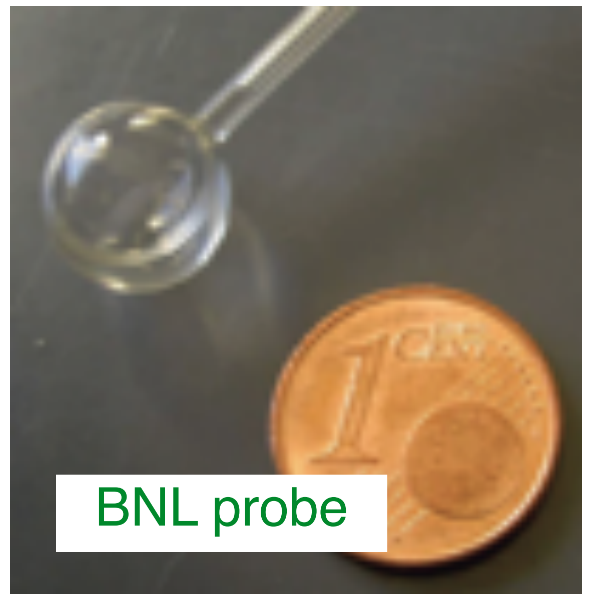
proton shielded in spherical water sample

This ratio measured to 10.5 ppb at a water temperature $T_r = 34.7°C$

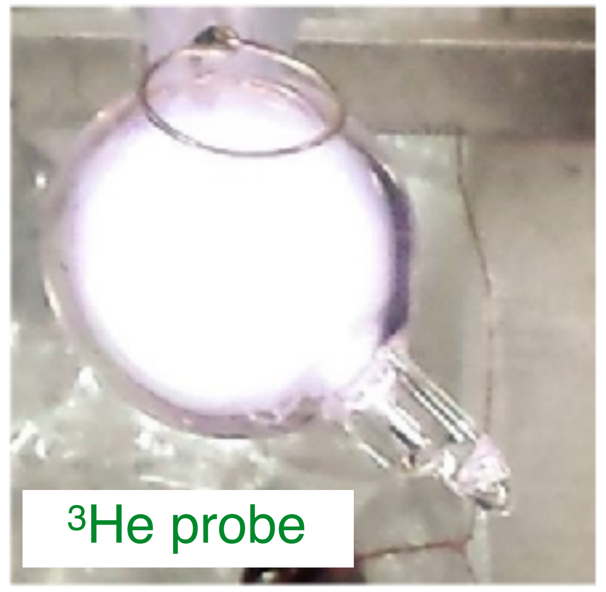
Magnetic Field Calibration

Convert trolley measurements to the measurement standard

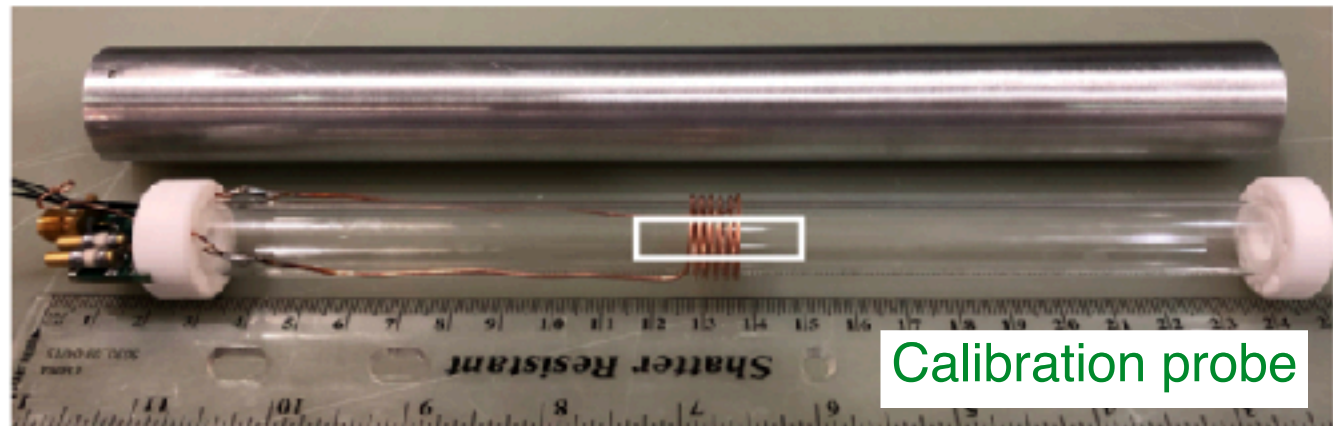
Absolute calibration: cross-check the calibration probe in MRI magnet at ANL



spherical water sample, known to high precision

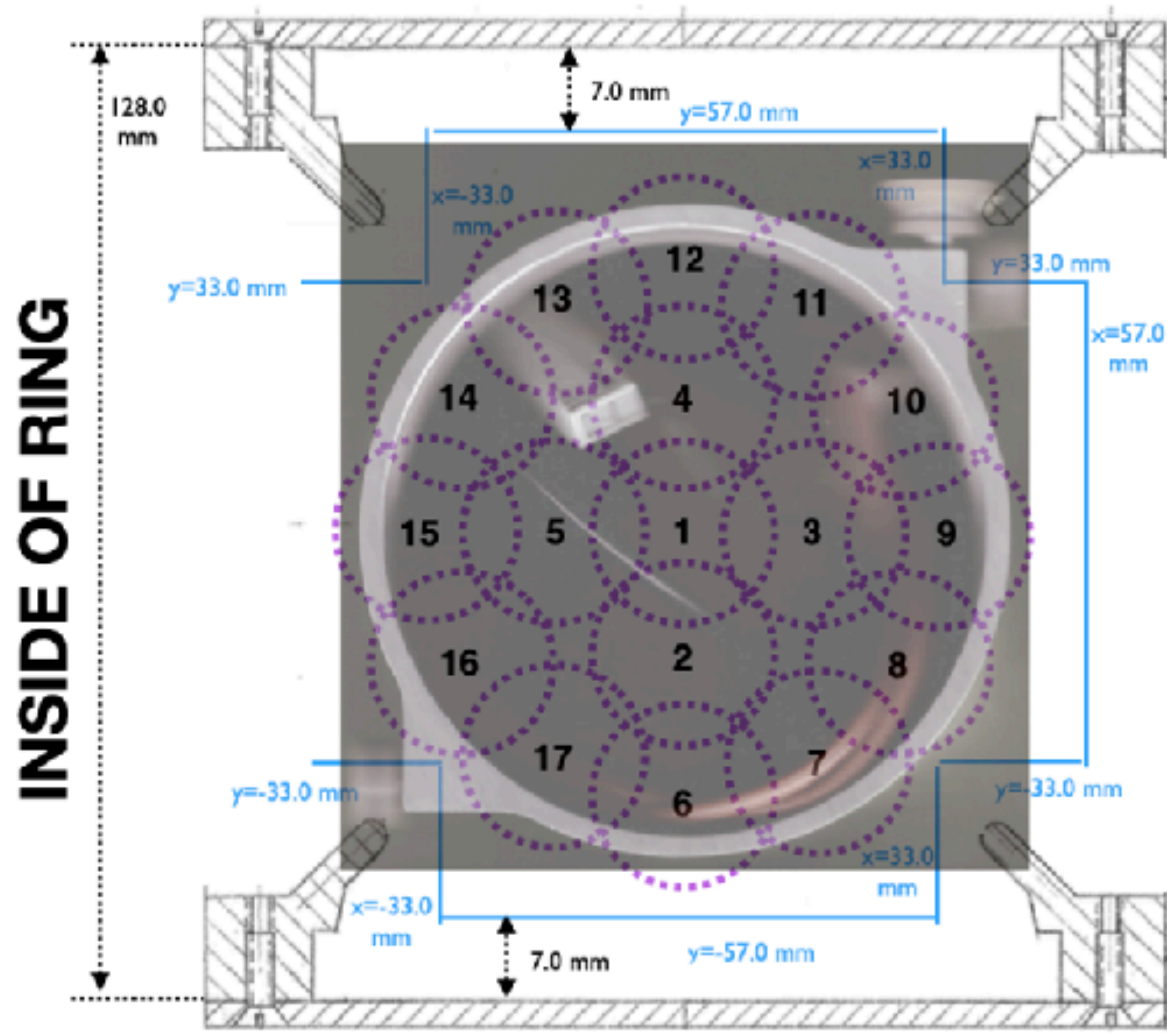


novel ^{3}He sample, different systematics



Cylindrical water sample, highly symmetric

Trolley calibration: transfer the measured calibrations to the trolley probes (protons in petroleum jelly) using the calibration probe



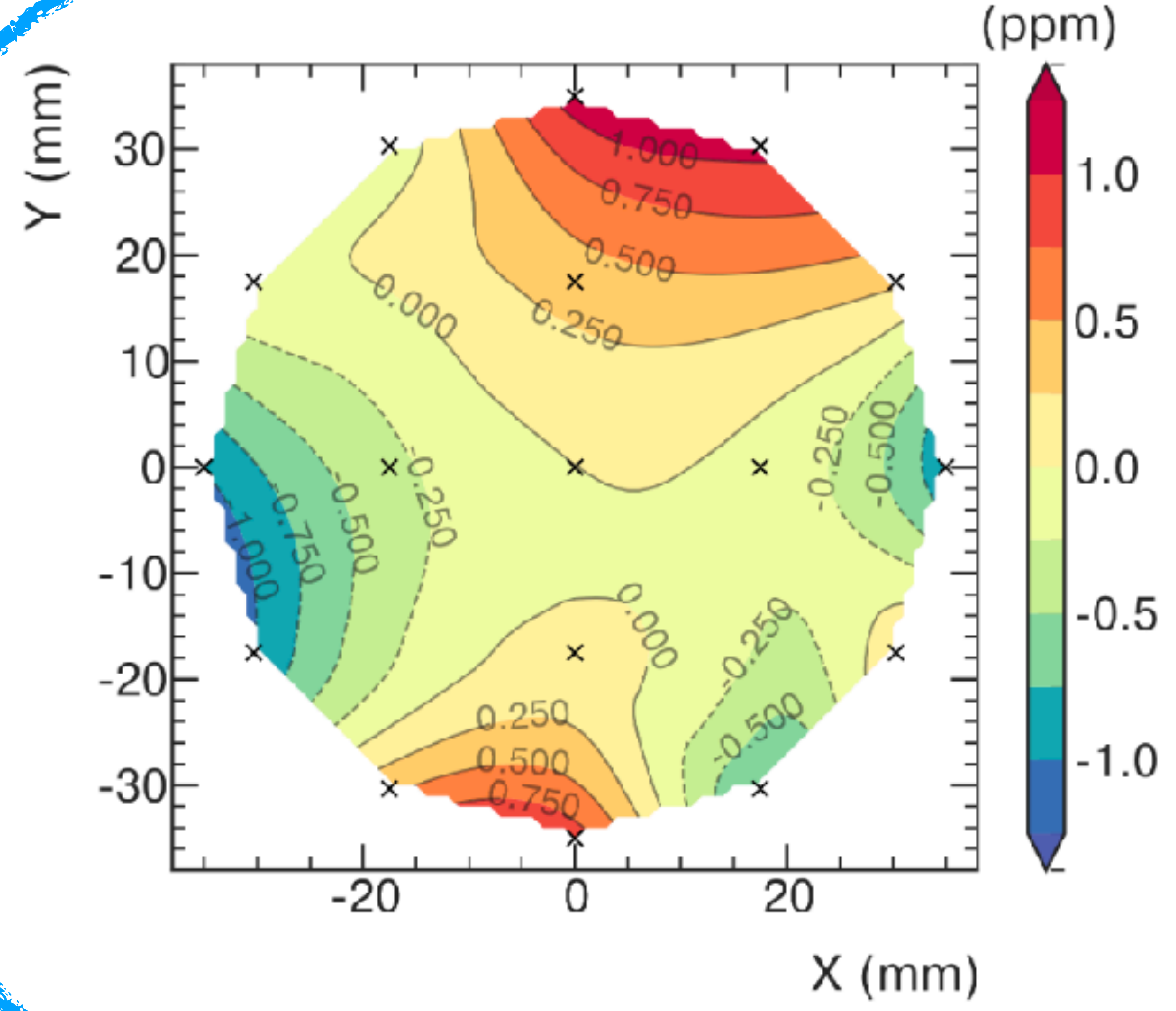
Measurement procedure

$$\tilde{\omega}_p{}'(T_r) = \underbrace{f_{calib}}\underbrace{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle}(1 + \underbrace{B_k + B_q})$$

NMR probe calibration factor

Magnetic field weighted by the muon beam distribution

Corrections from transient magnetic fields



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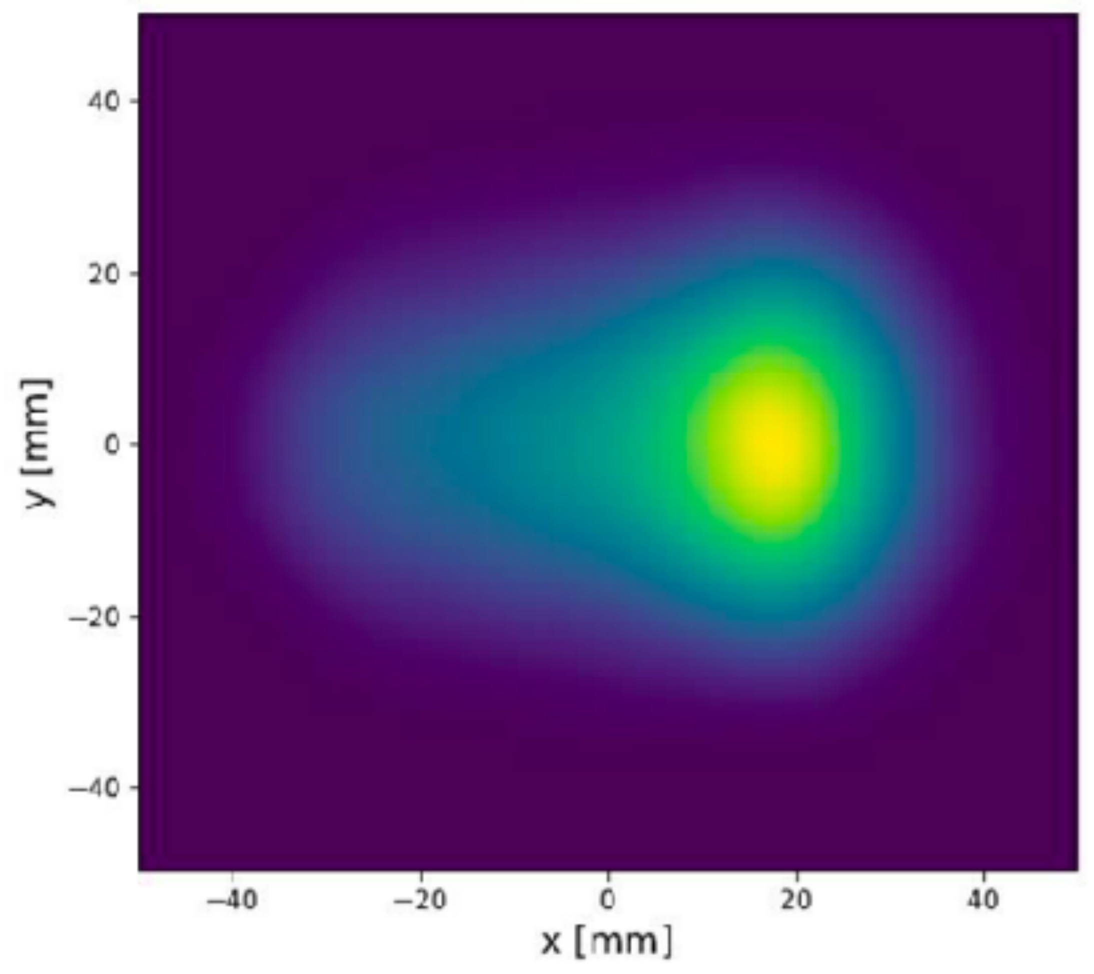

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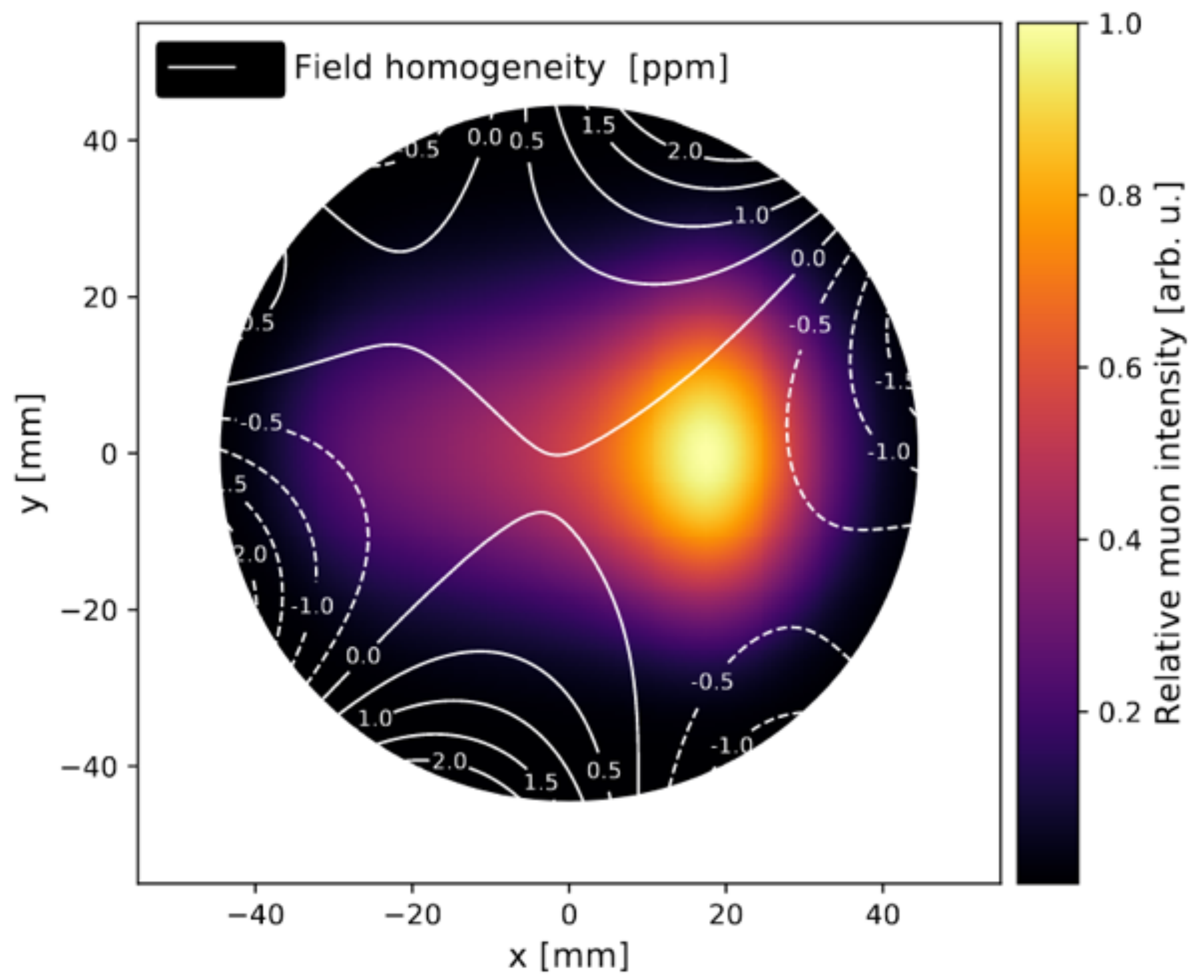
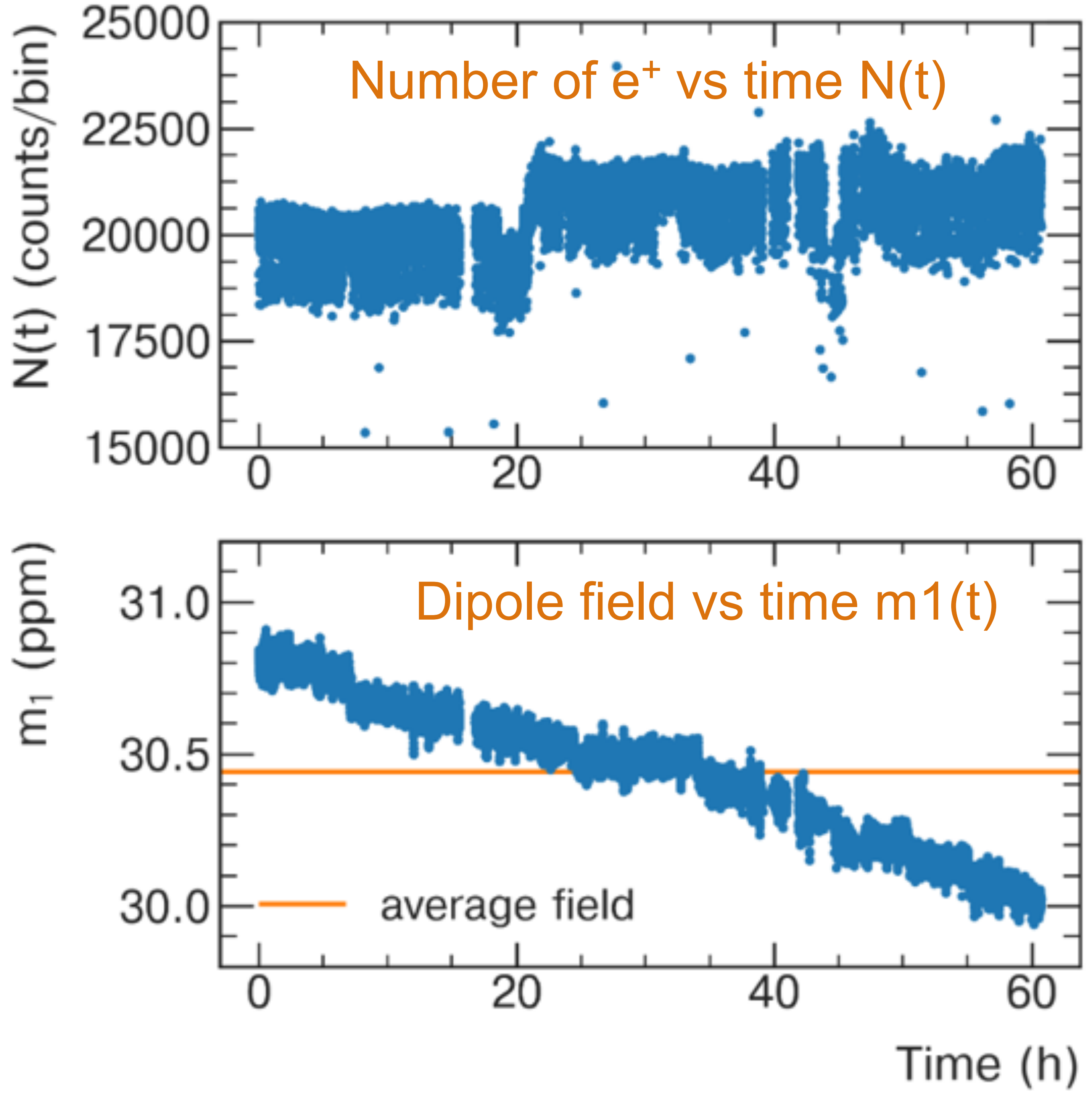
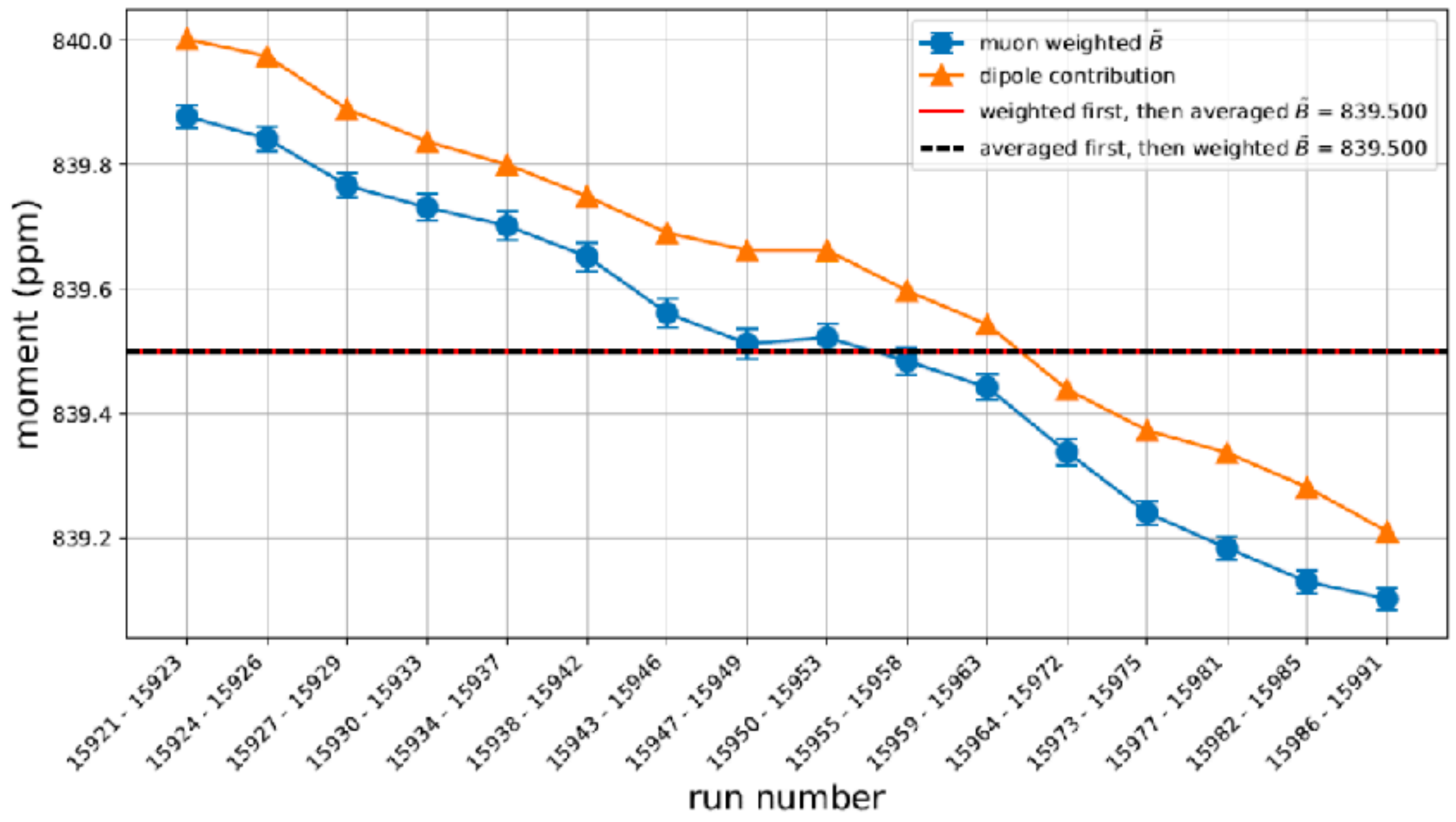


The Muon-Weighted Field

Obtain the average field experienced by the muons





- Weight the magnetic field distribution as a function of time by
  - The number of muons as a function of time, N(t)
  - The beam distribution as a function of time

- Weighted field is ~120 ppb smaller than the unweighted dipole field (dominated by the size of the largest field gradient)

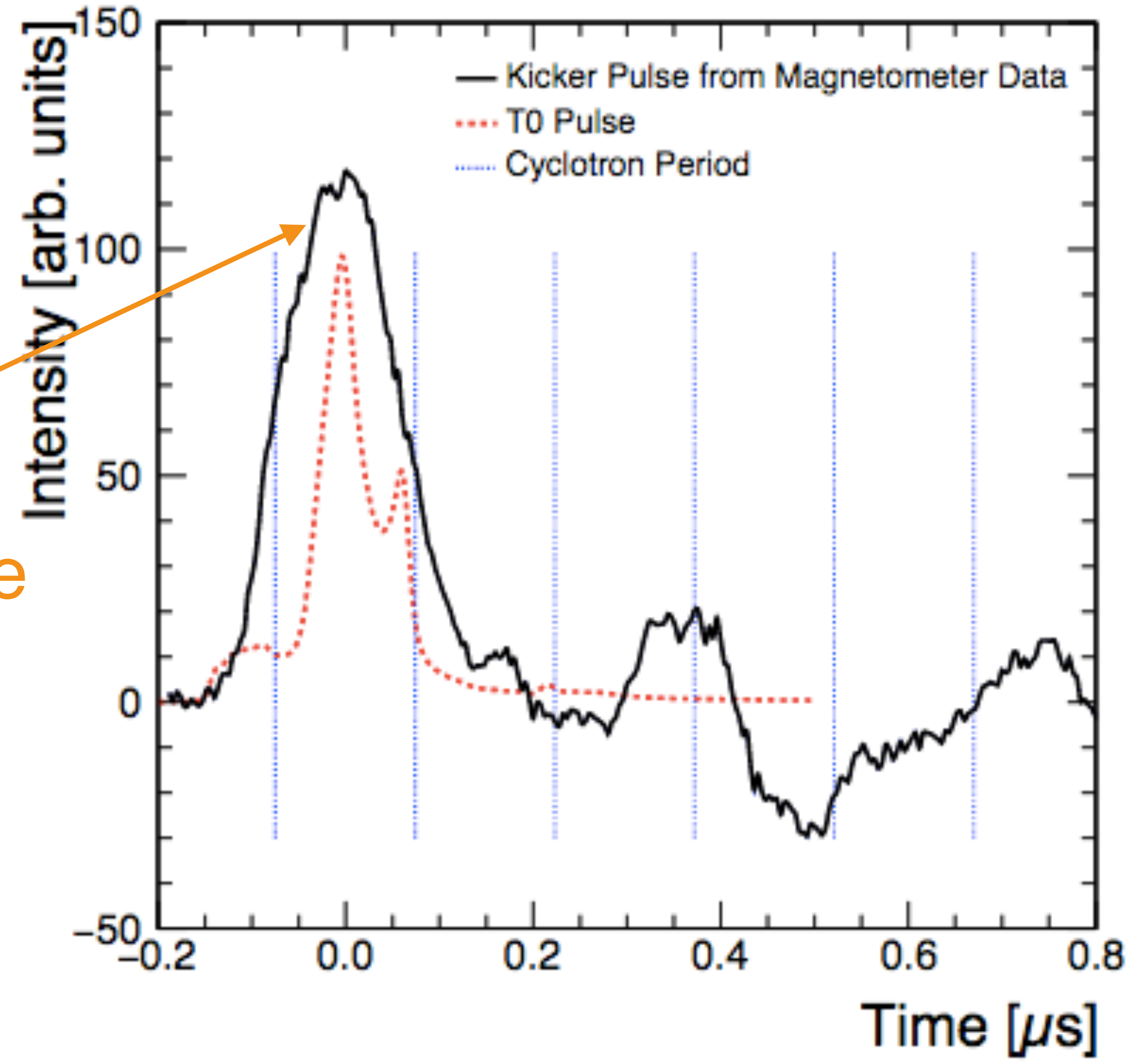
Measurement procedure

$$\tilde{\omega}_p{}'(T_r) = \underbrace{f_{calib}}_{\text{NMR probe calibration factor}} \underbrace{\langle \omega_p(x, y, \phi) \times M(x, y, \phi) \rangle}_{\text{Magnetic field weighted by the muon beam distribution}} \underbrace{(1 + B_k + B_q)}_{\text{Corrections from transient magnetic fields}}$$

- Corrections from transient magnetic fields
  - Two pulsed systems in the experiment for beam storage: kickers and quads
  - Their pulsing introduces transient magnetic fields during muon storage times
  - Fixed probes do not see the full effect due to shielding; need to apply corrections to the measured field
  - Dedicated measurement campaigns to quantify transient corrections

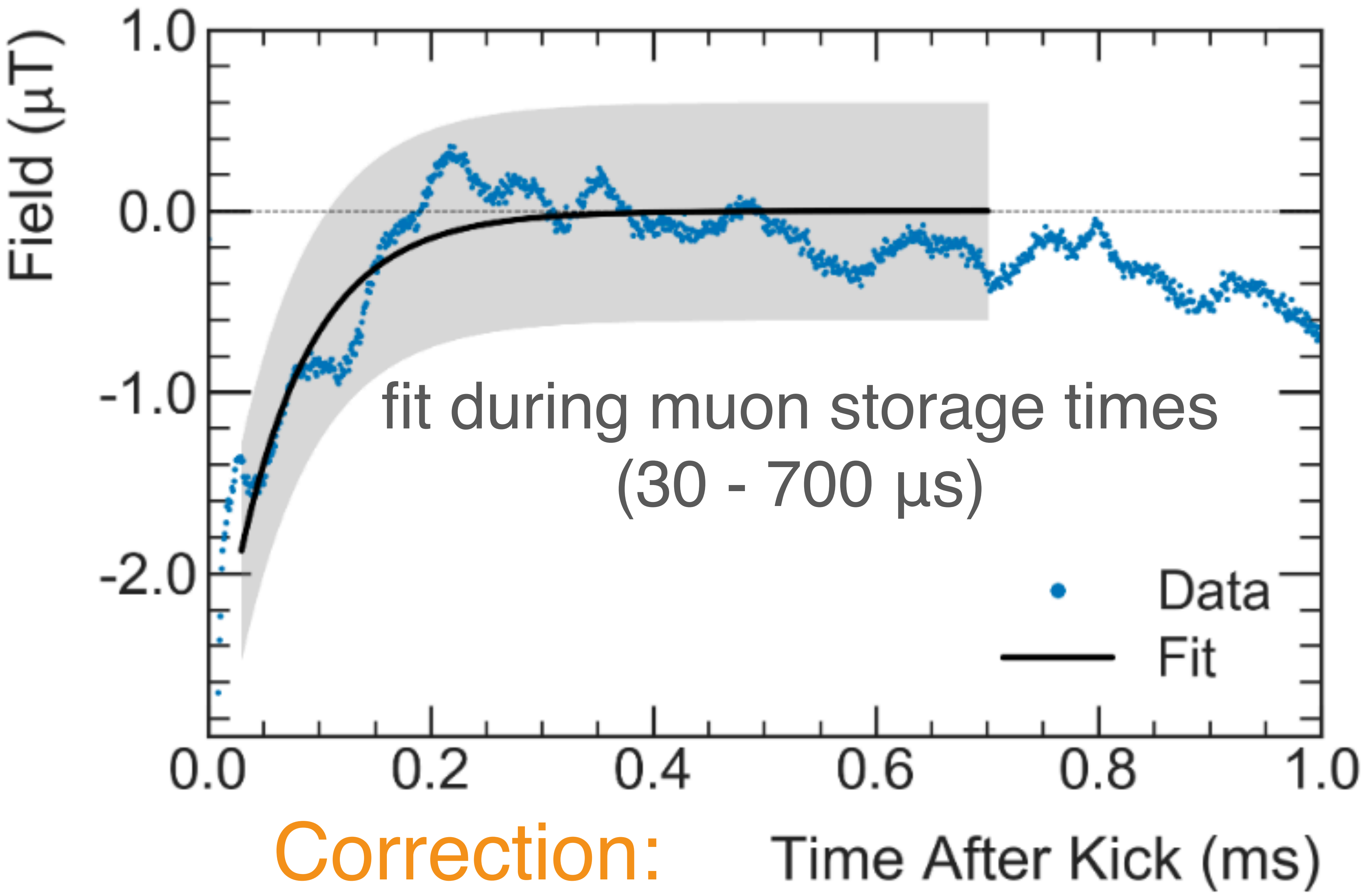
Kicker transients

Kicker pulse of 22 mT applied in radial direction for 150 ns at muon injection



Peak of kicker pulse is 22 mT

Residual pulse at μT level during muon muon storage induces eddy currents

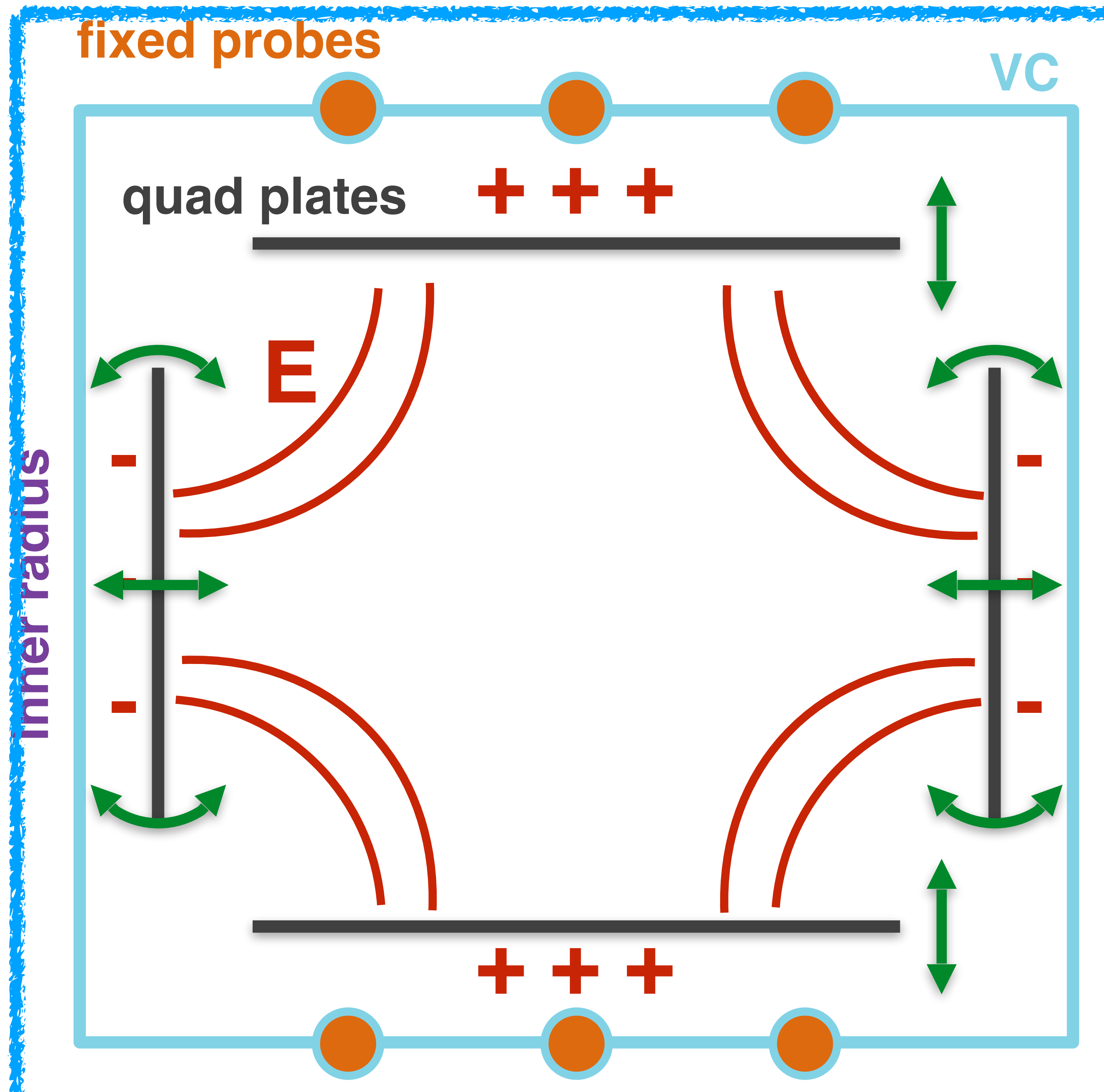


Correction: -27 (37) ppb

Fixed probes see reduced effect due to shielding — dedicated measurement to determine correction

Uncertainty dominated by knowledge of baseline
Anticipate reduction with further study

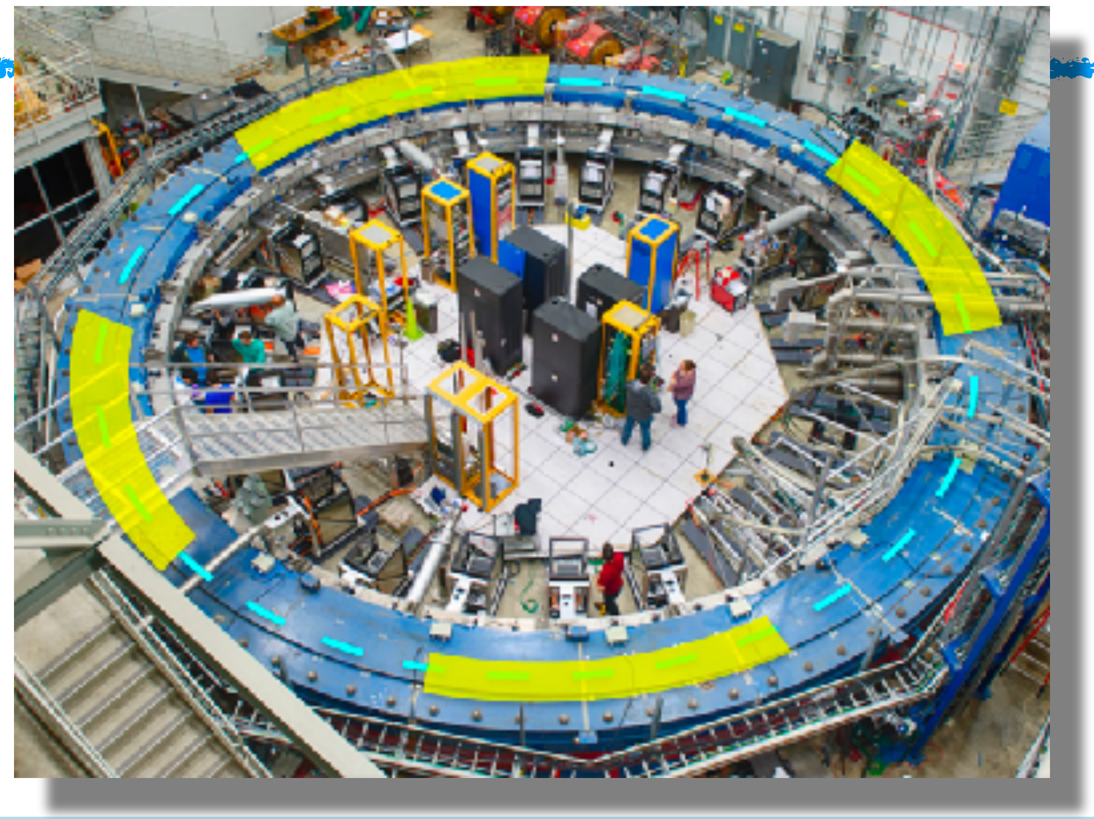
Quad transients



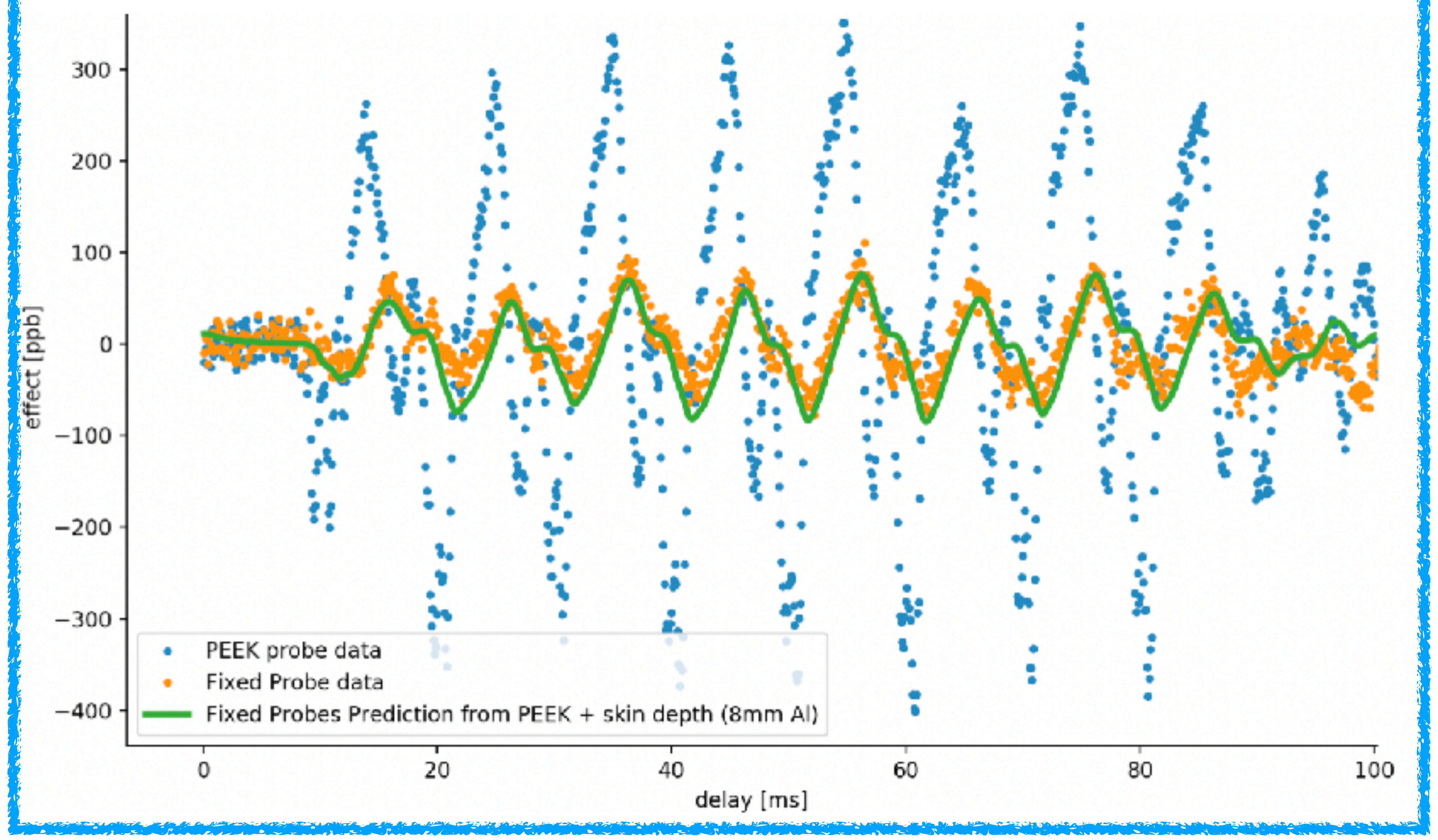
Pulsing the Quads

- Side plates bend, oscillate radially
- Top/bottom plates oscillate vertically
- Motion causes a field perturbation
- Distinct oscillation in **fixed probe** measurements

43% of ring covered by quads



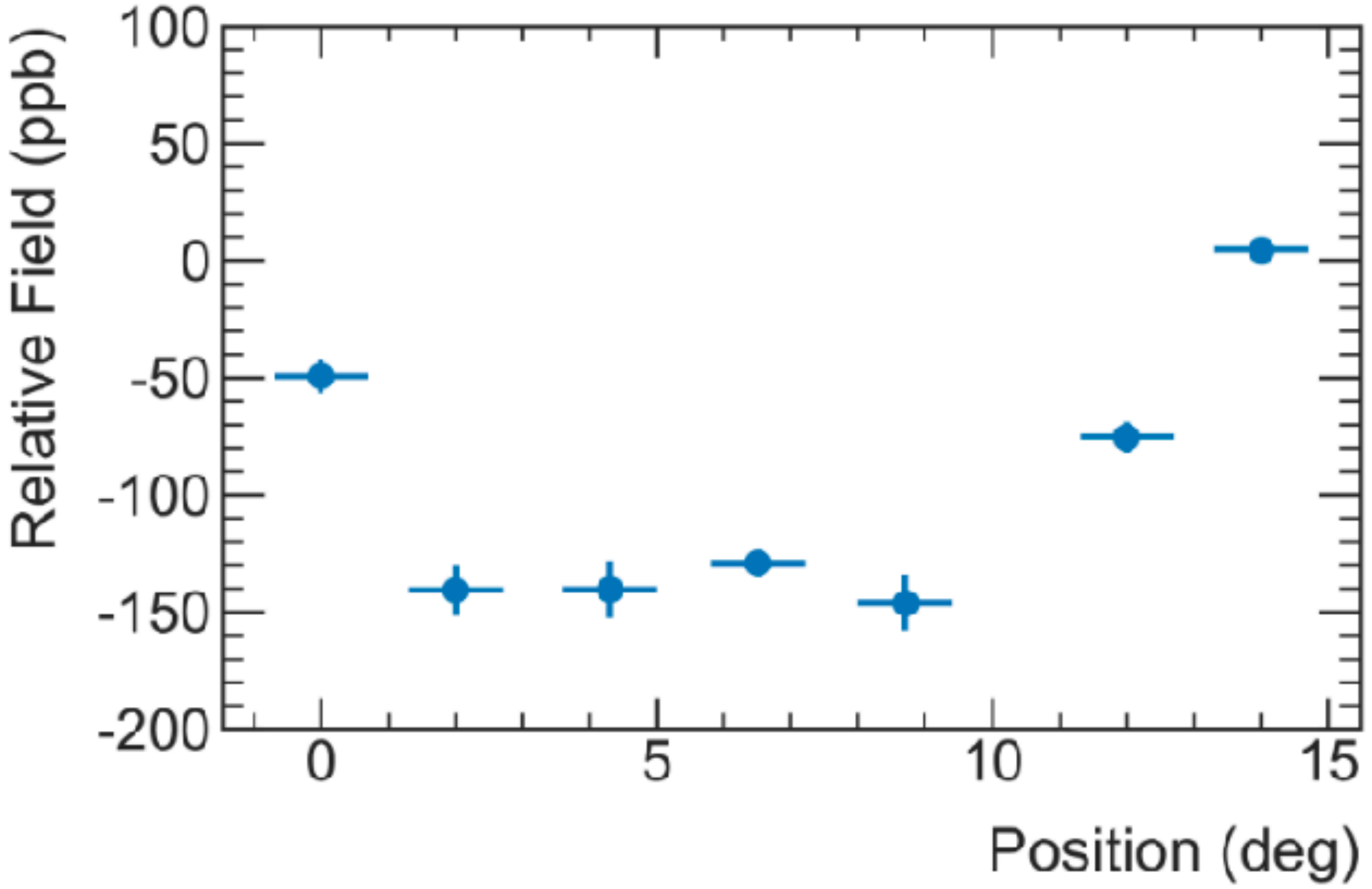
Fixed probes are shielded by the vacuum chambers, so they do not see the full effect that the muons experience

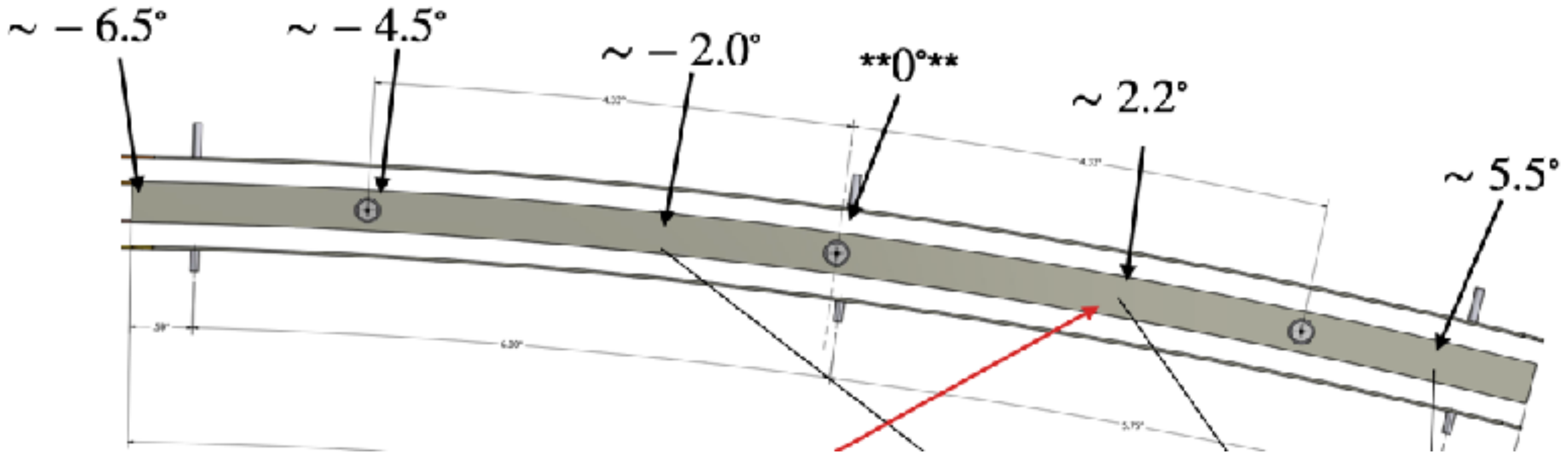


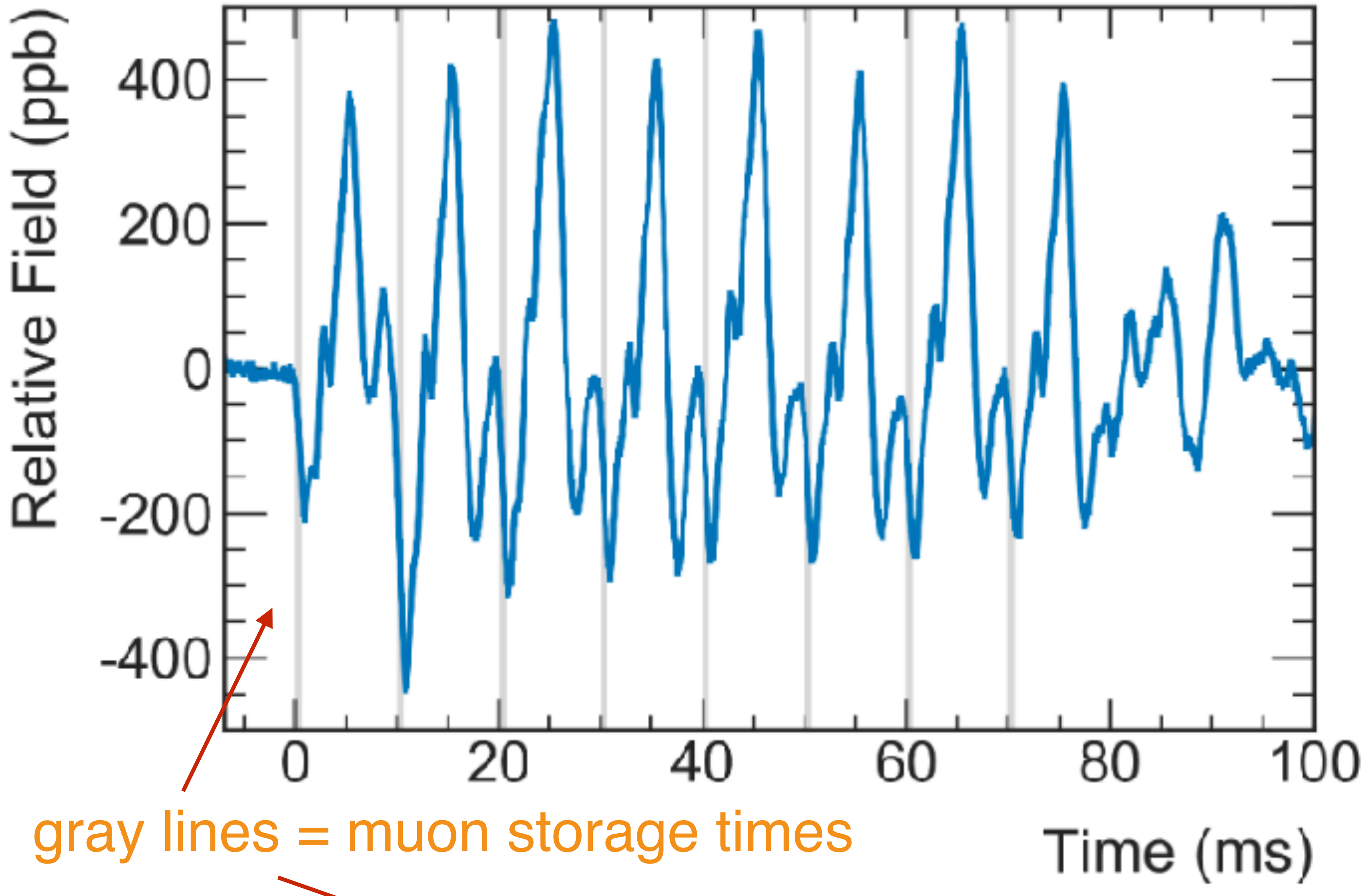
Fermilab

Quad transients

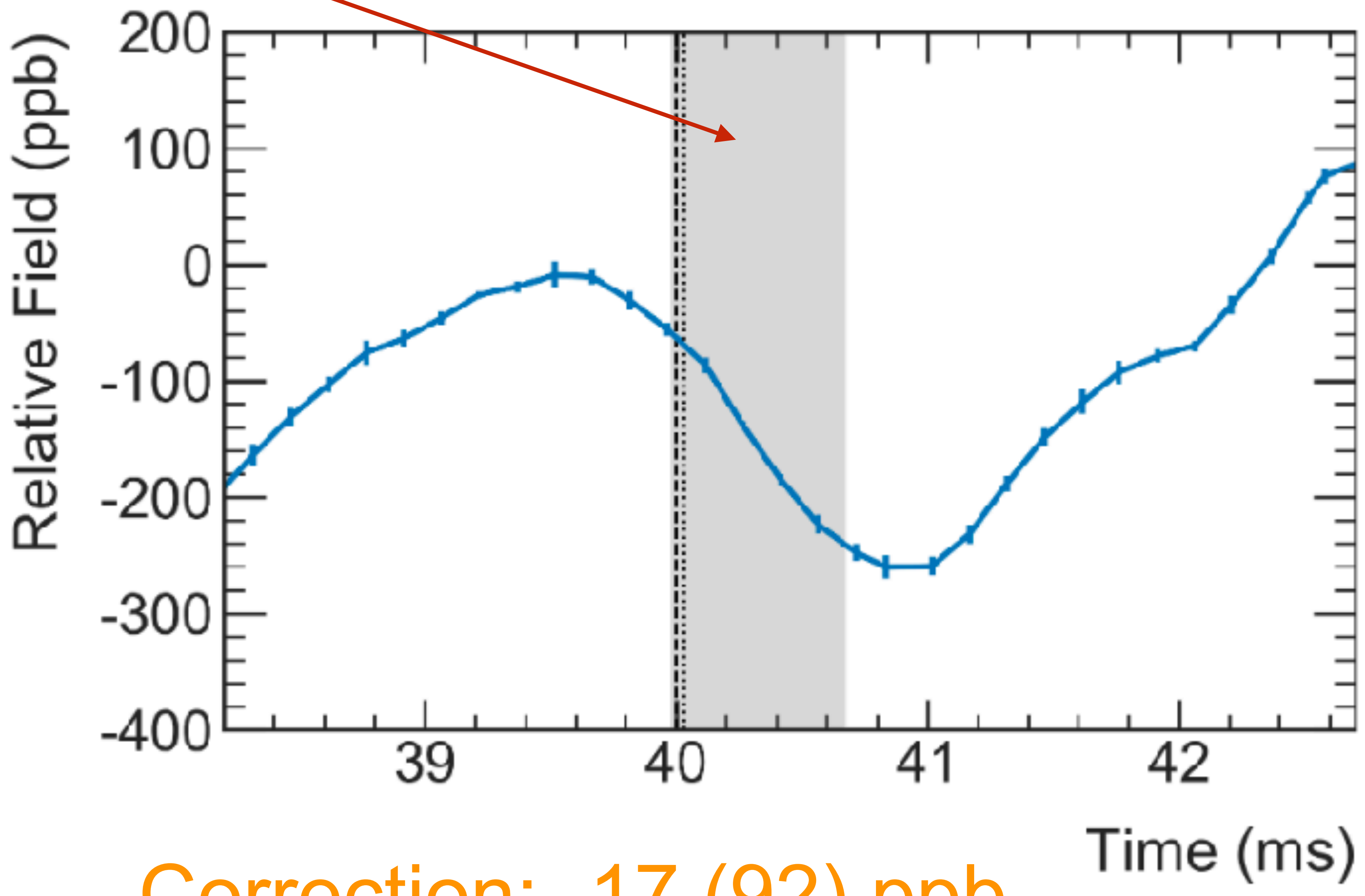
Azimuthal dependence: relative field change caused by the transient varies depending on position inside the quad plates





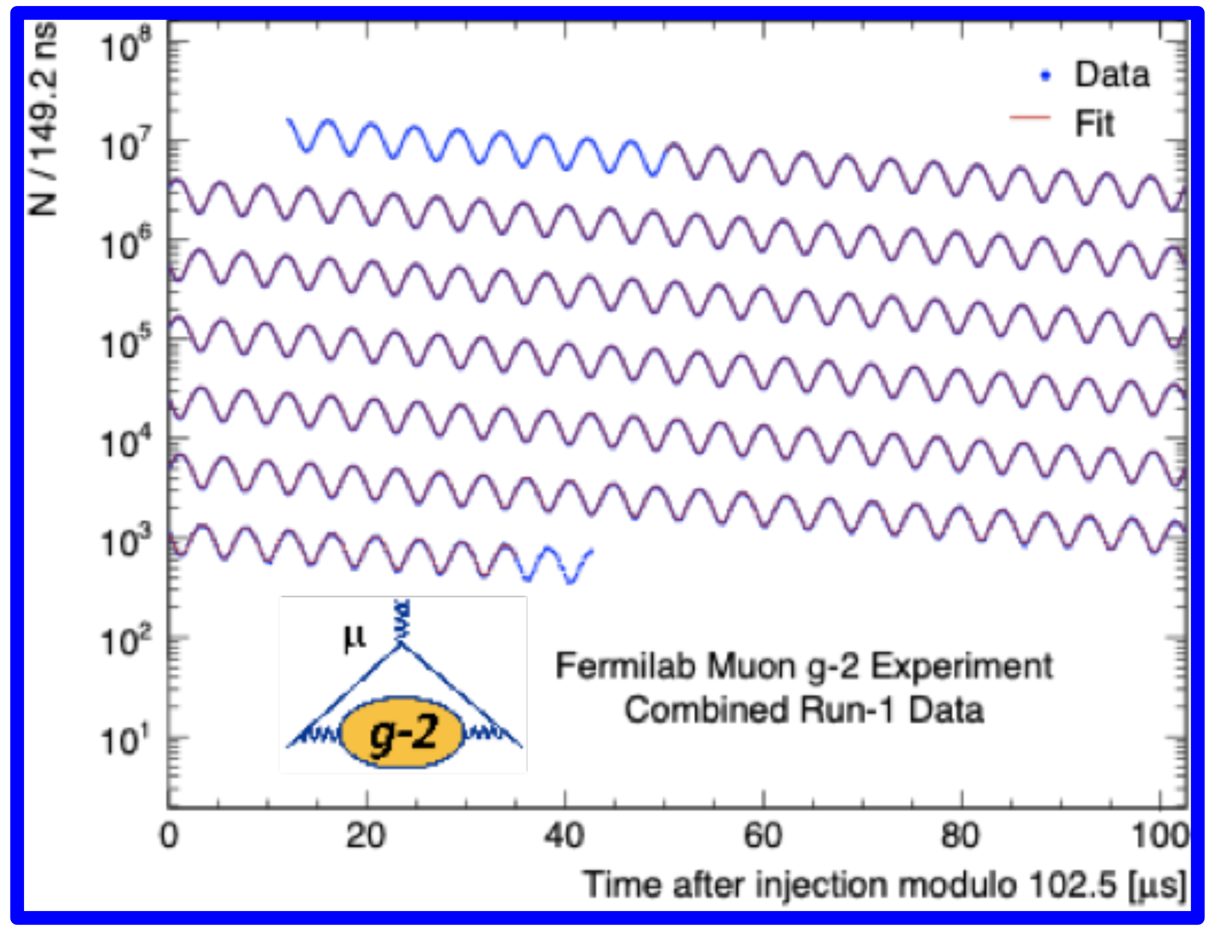


gray lines = muon storage times



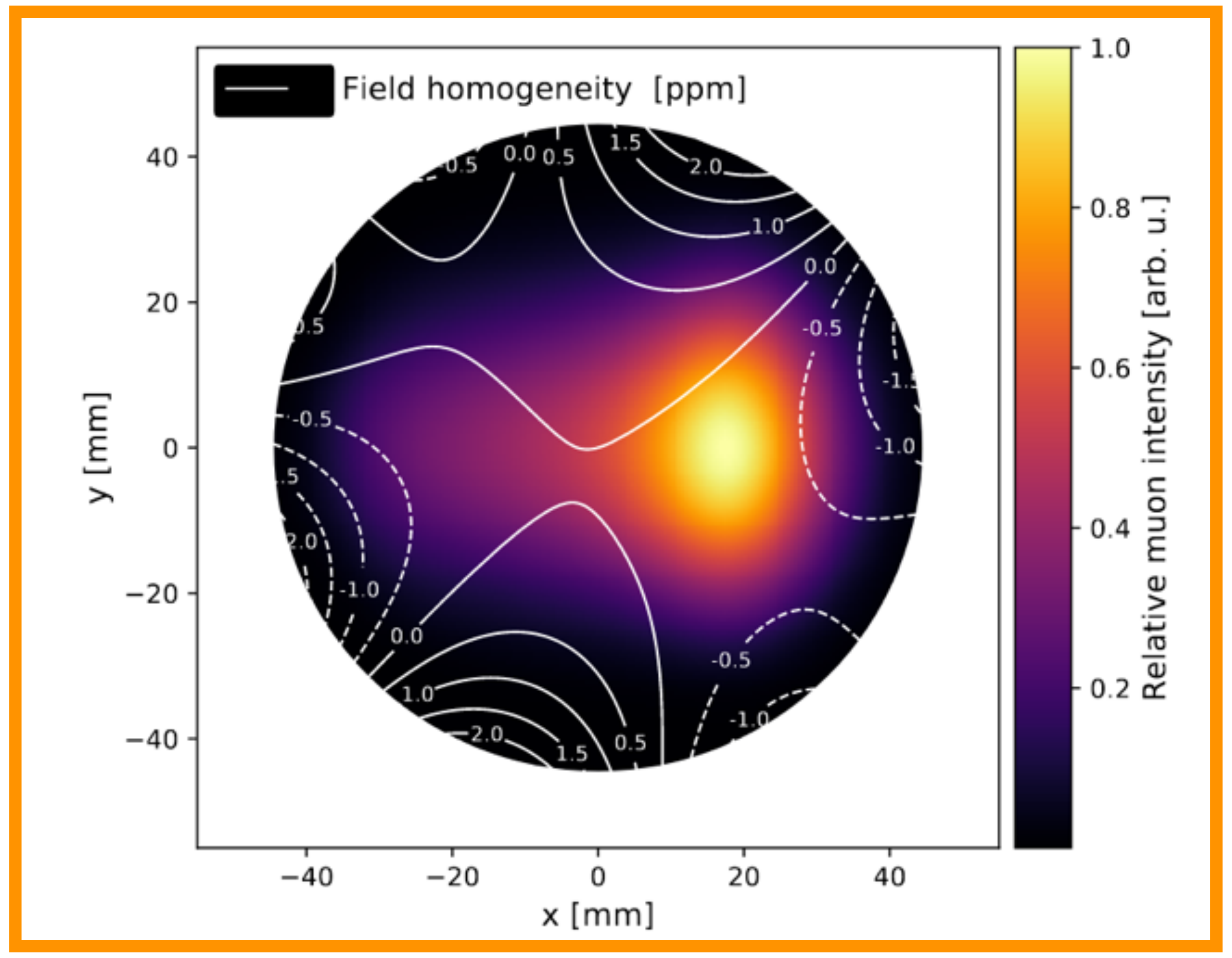
Correction: -17 (92) ppb

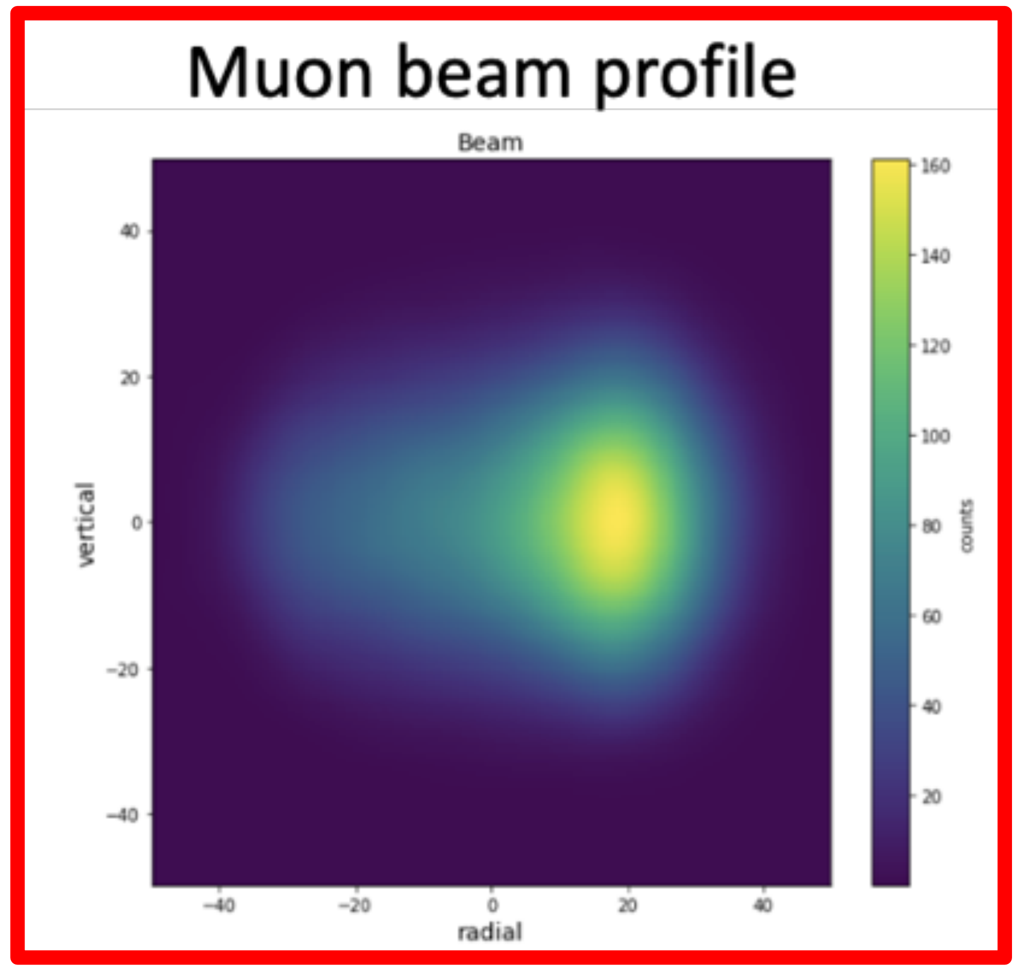
More corrections



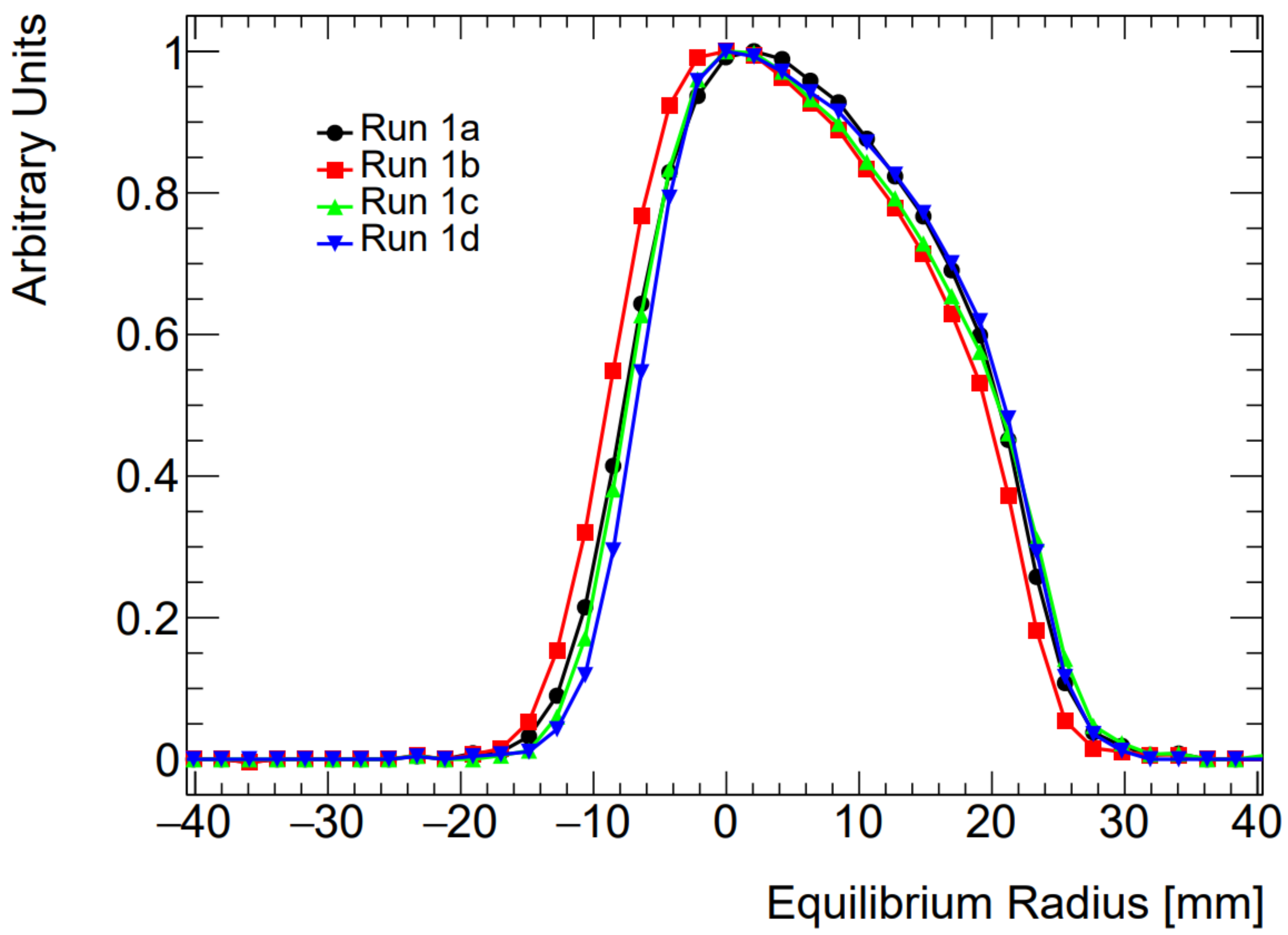
Beam dynamics corrections

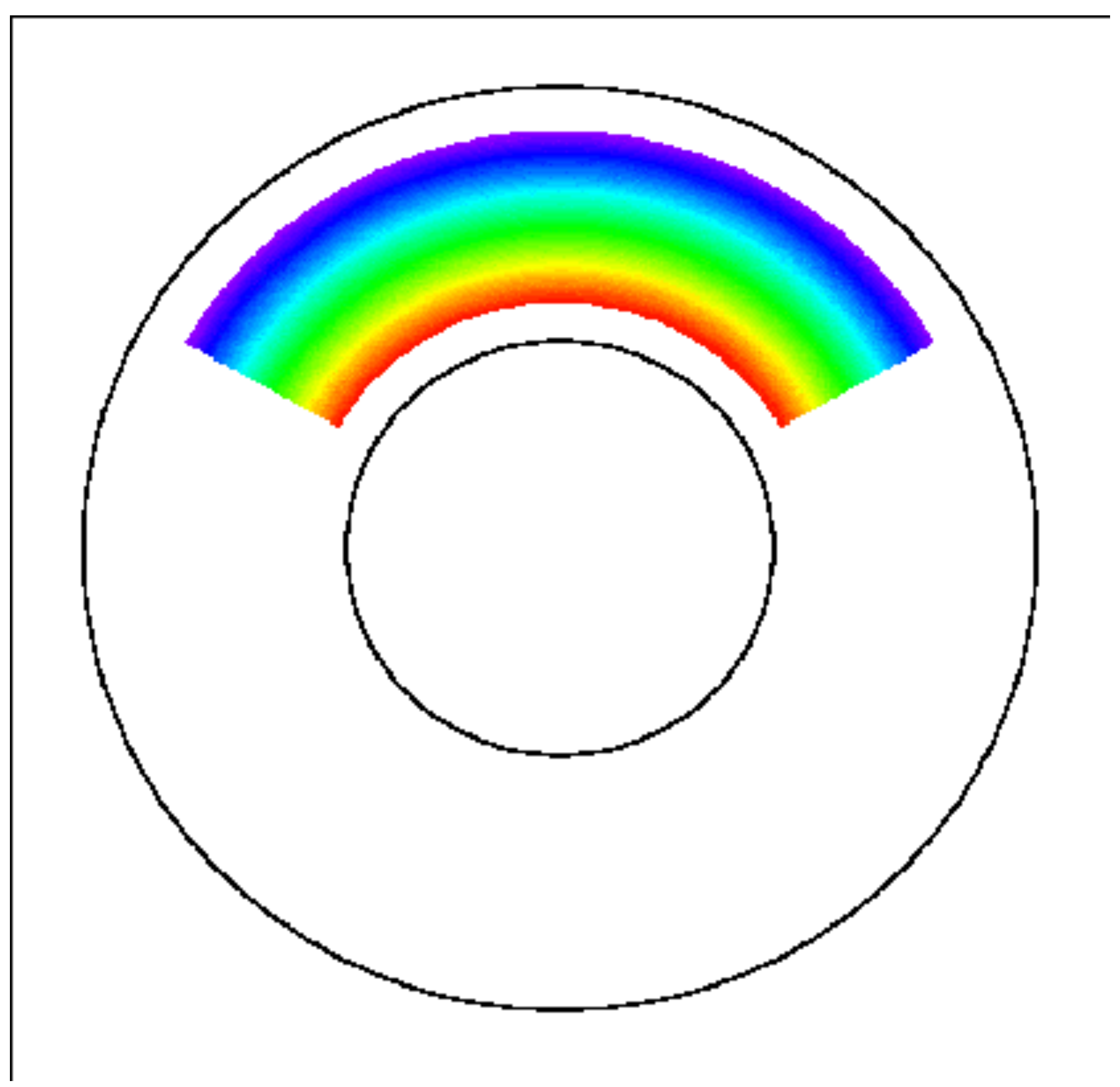
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

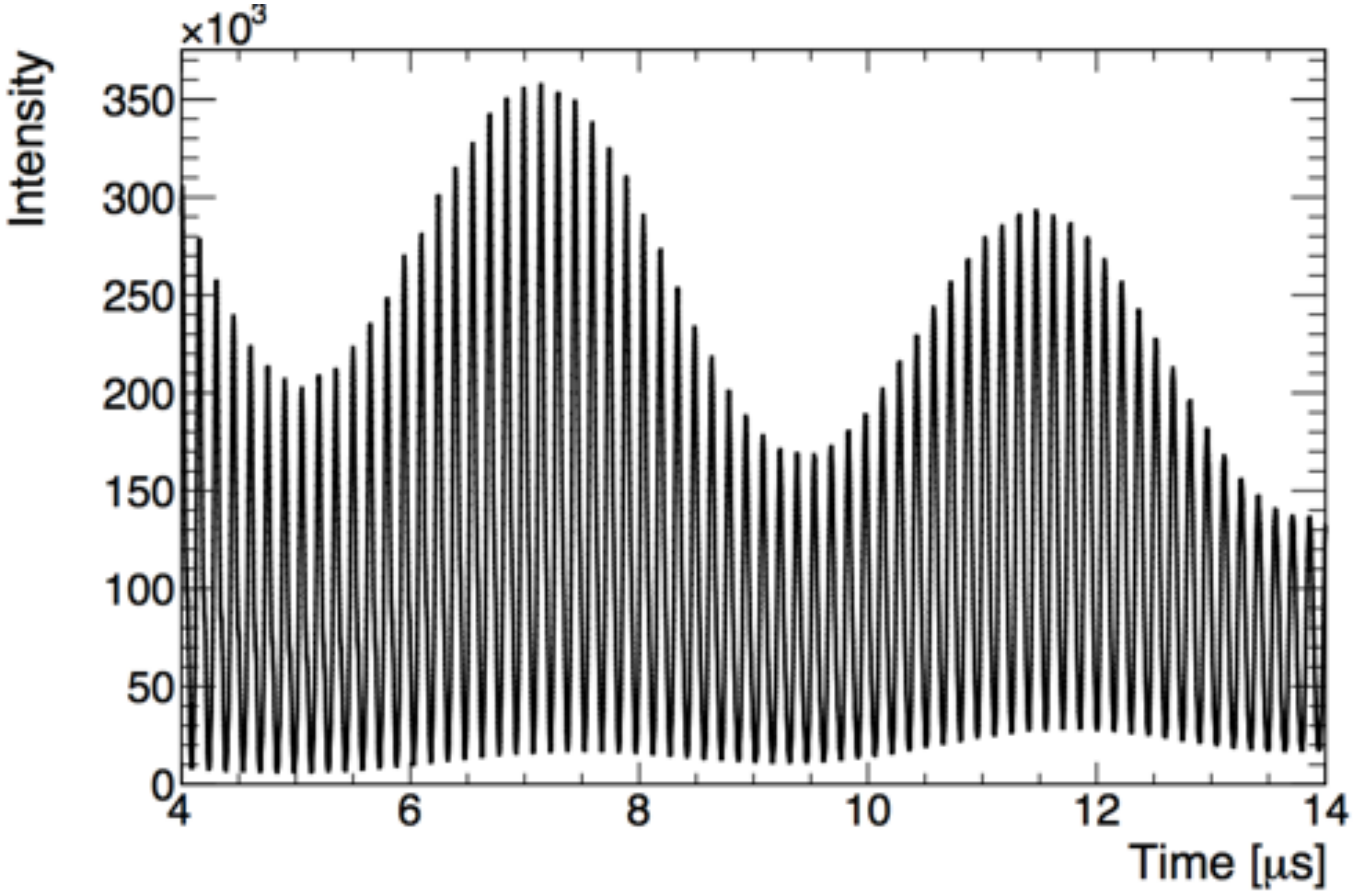




Beam Dynamics Corrections





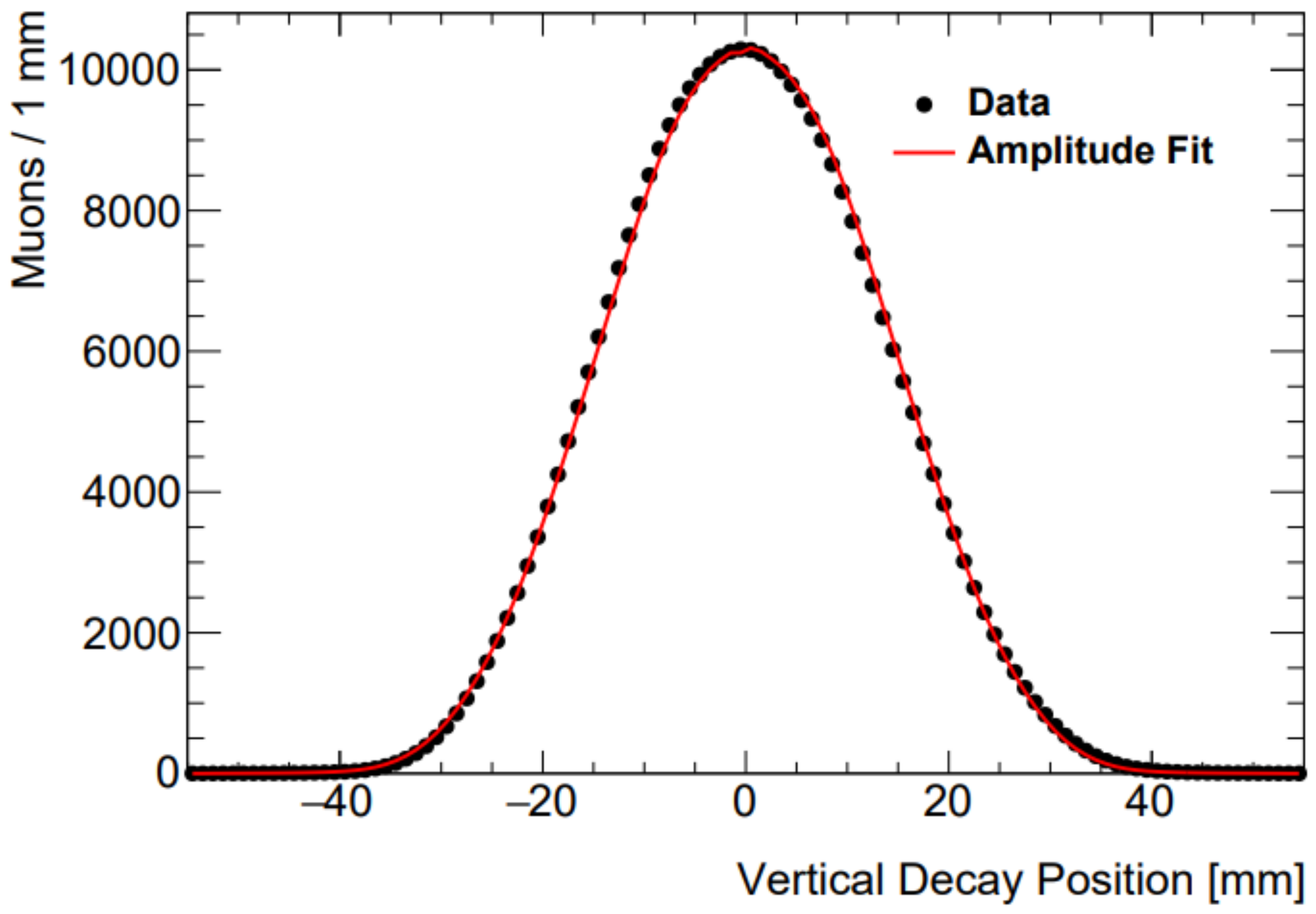


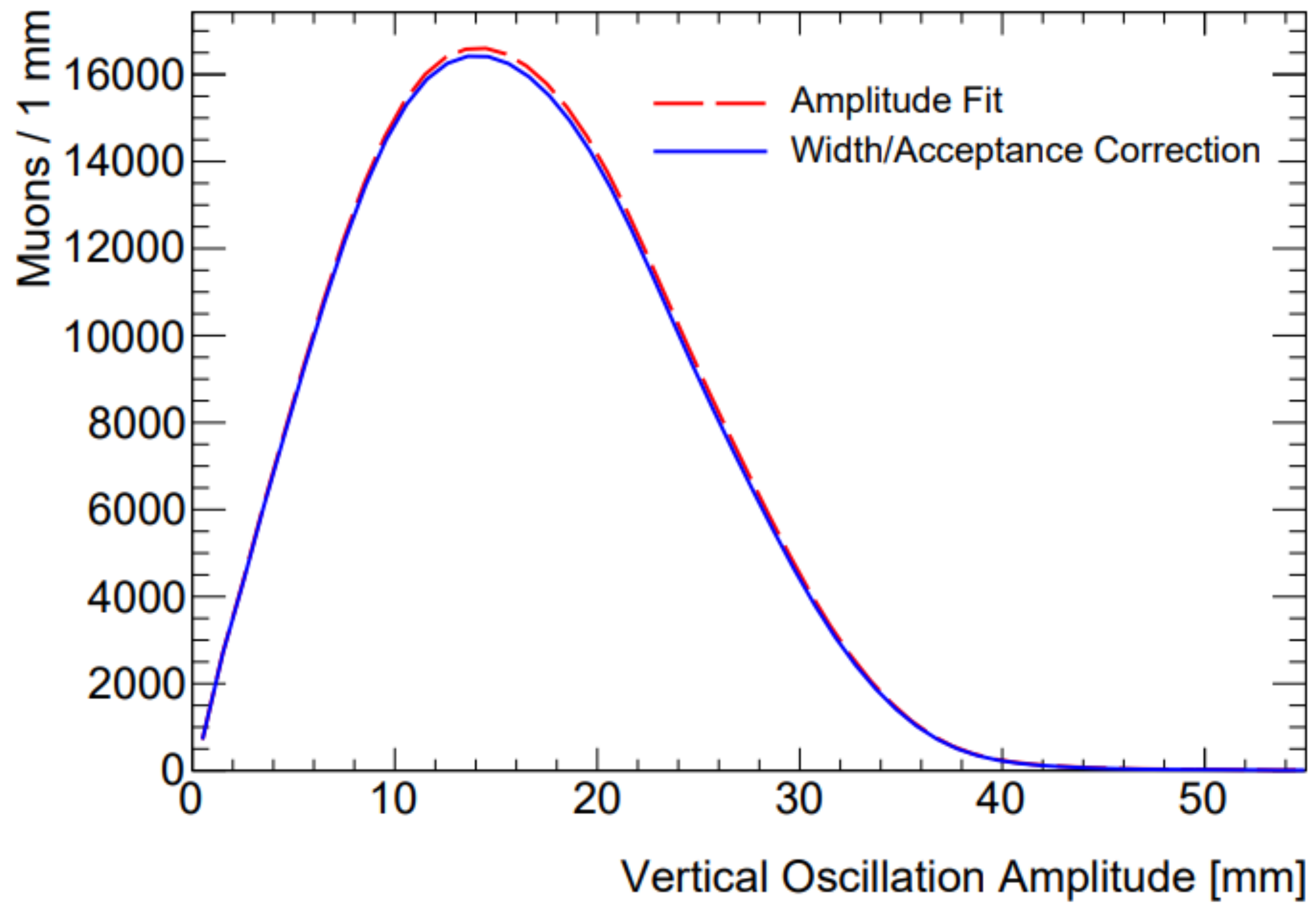
- Beam has 0.1% momentum spread
- <R> of stored muons depends on p
- Fourier analysis to determine equilibrium positions

Beam Dynamics Corrections: Pitch Correction

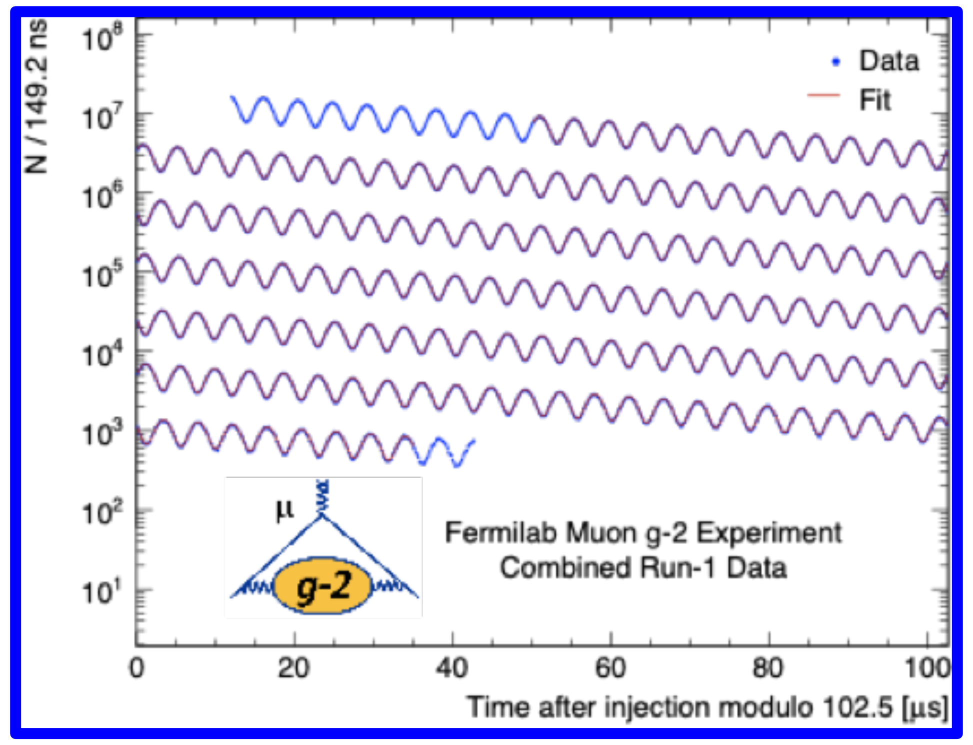
- Muon beam has a vertical spread
- Reduced precession frequency measured for muons with momentum component parallel to B field
- Trackers measure the vertical decay position distribution
- Use the measured vertical beam width to quantify correction

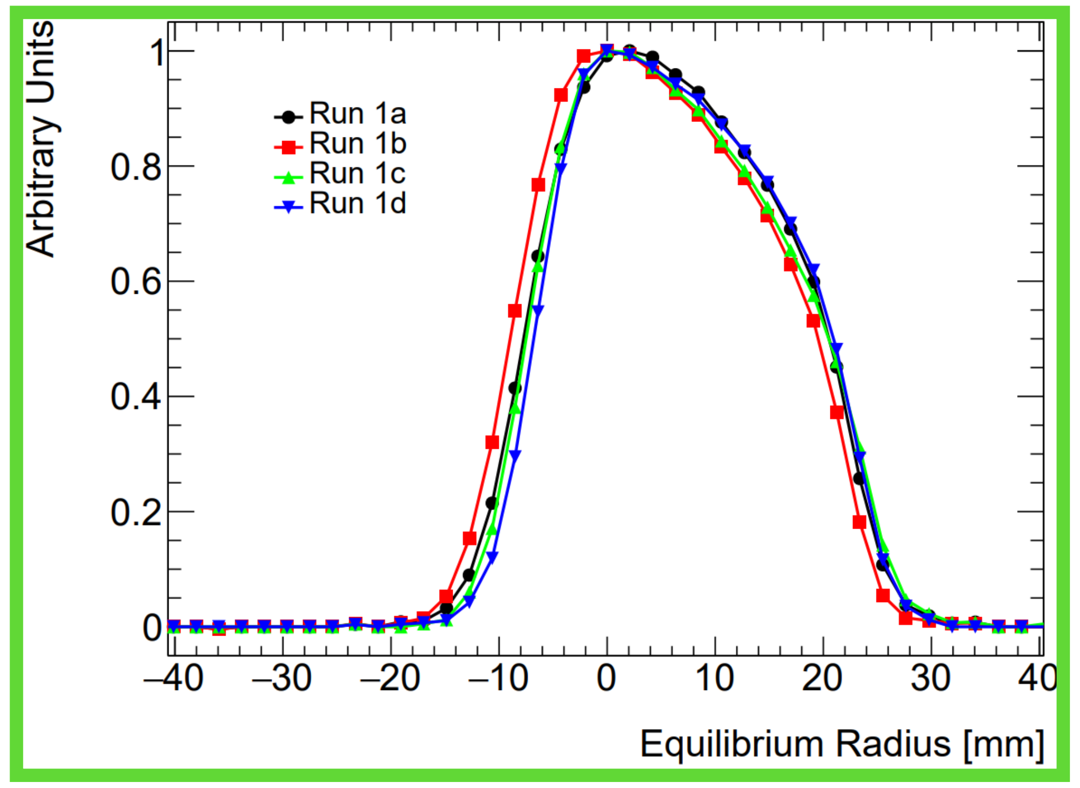
$$C_p = \frac{n}{2}\frac{\langle y^2 \rangle}{R_0^2} = \frac{n}{4}\frac{\langle A^2 \rangle}{R_0^2}$$



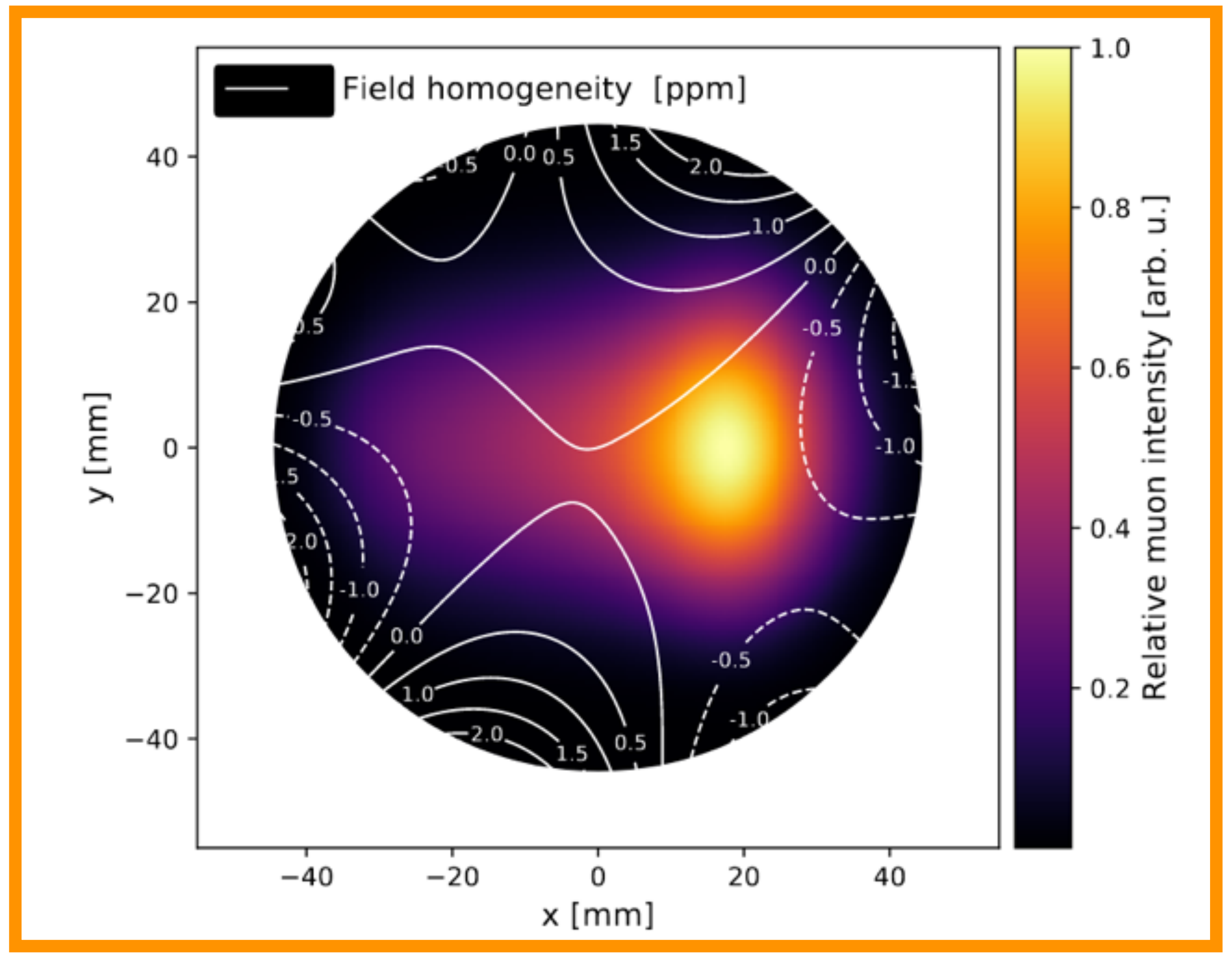


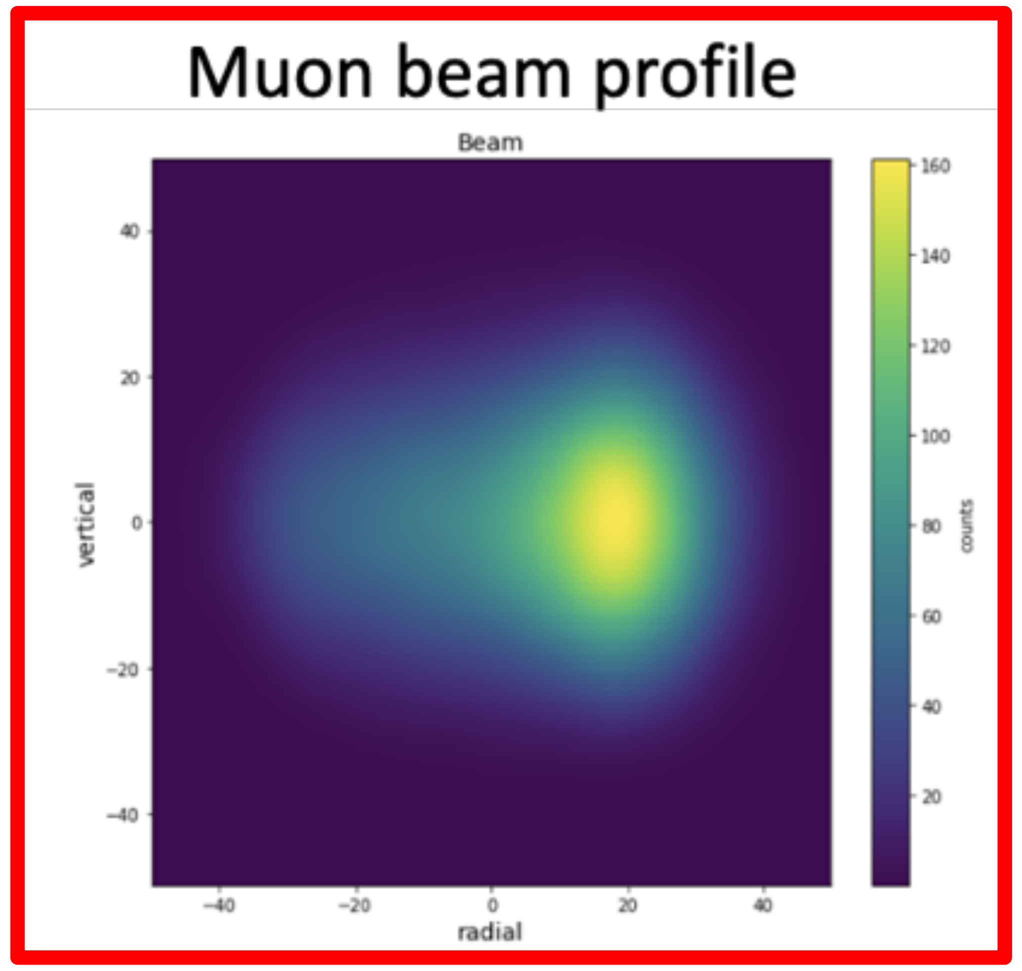
Bringing it all together





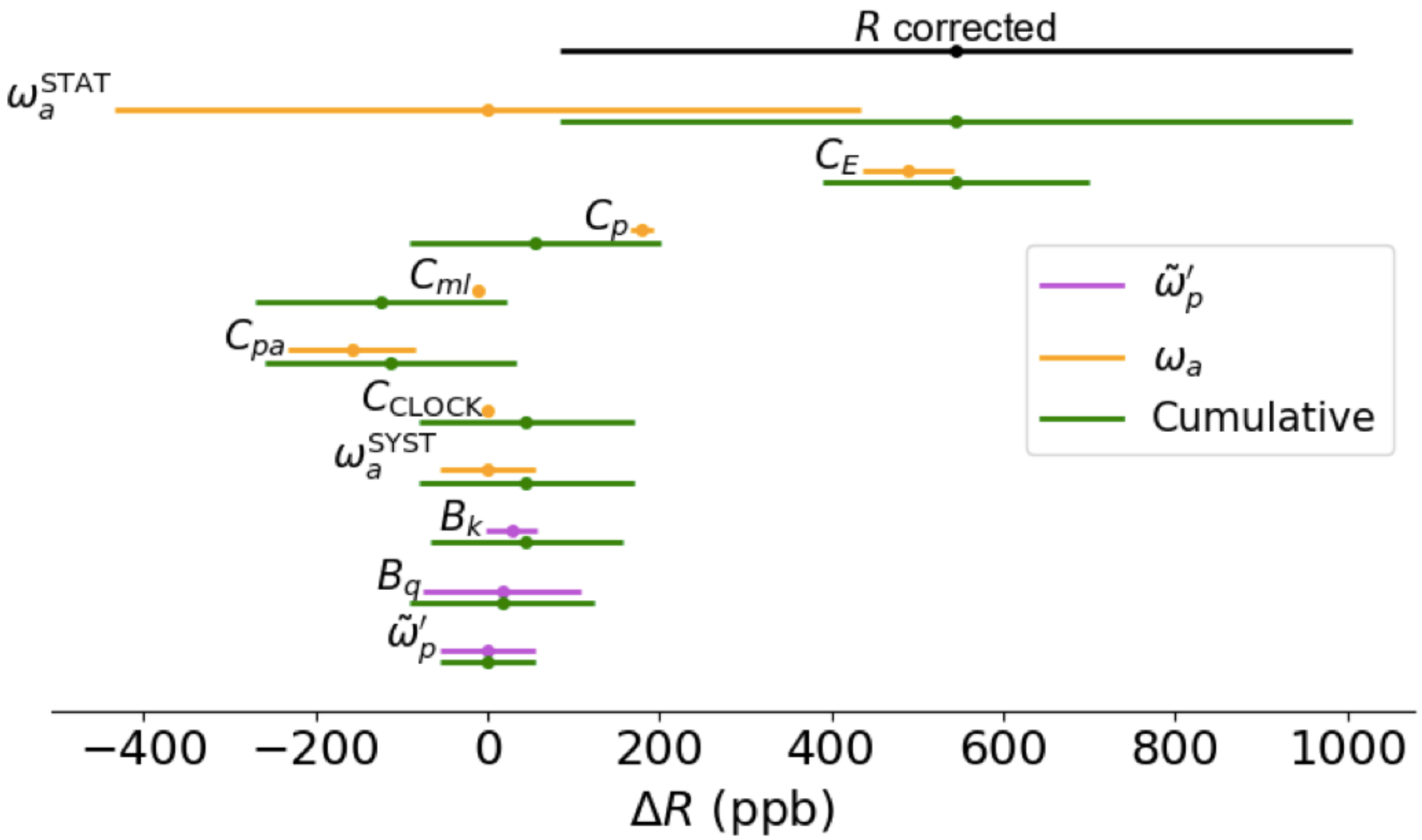
$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \boxed{\omega_a^m}\ \boxed{(1 + C_e + C_p + C_{ml} + C_{pa})}}{\boxed{f_{\text{calib}}\ \langle\omega_p(x,y,\phi)} \times \boxed{M(x,y,\phi)}\rangle(1 + B_k + B_q)}$$





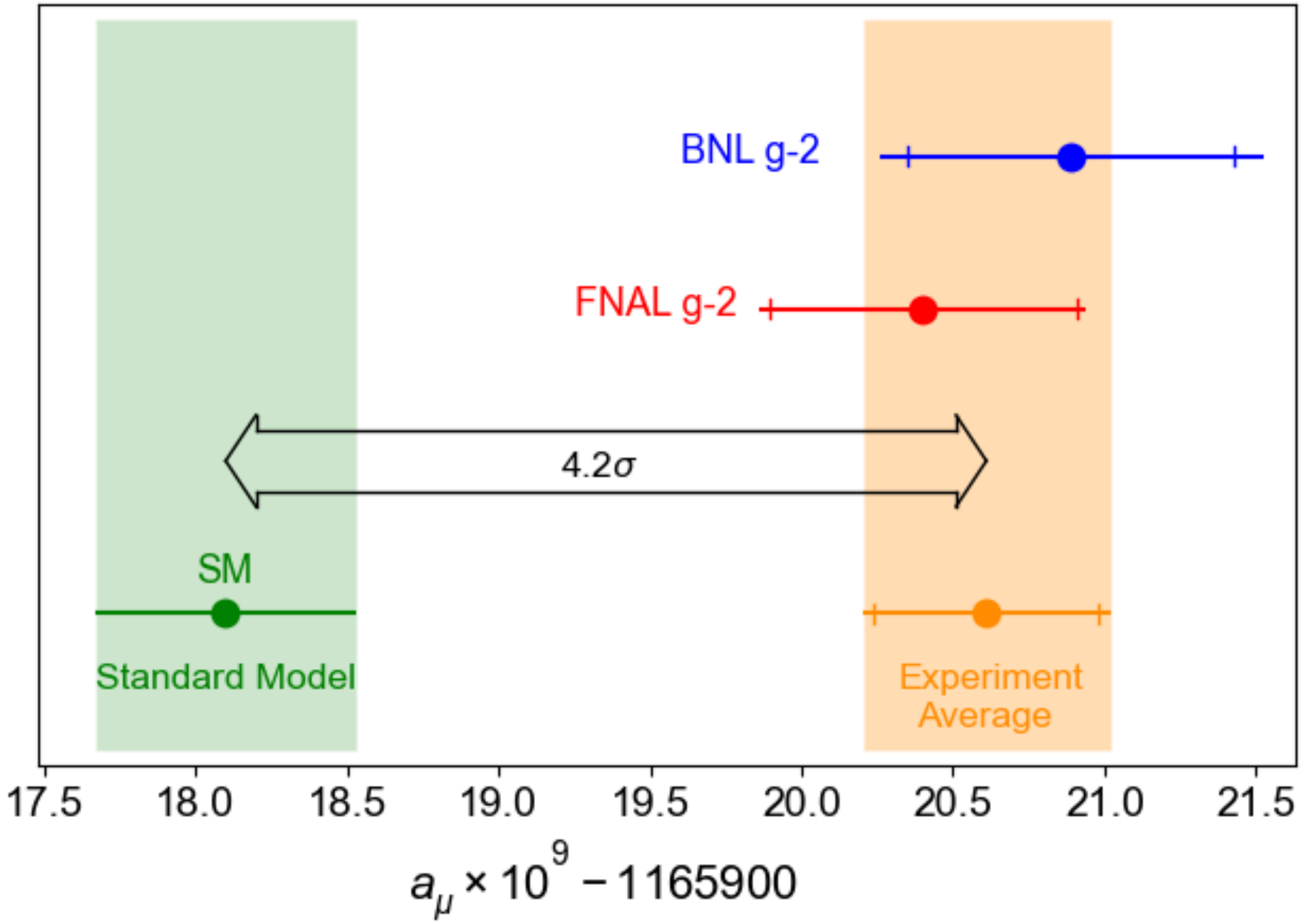
Correcting measured R

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



The Run-1 Result

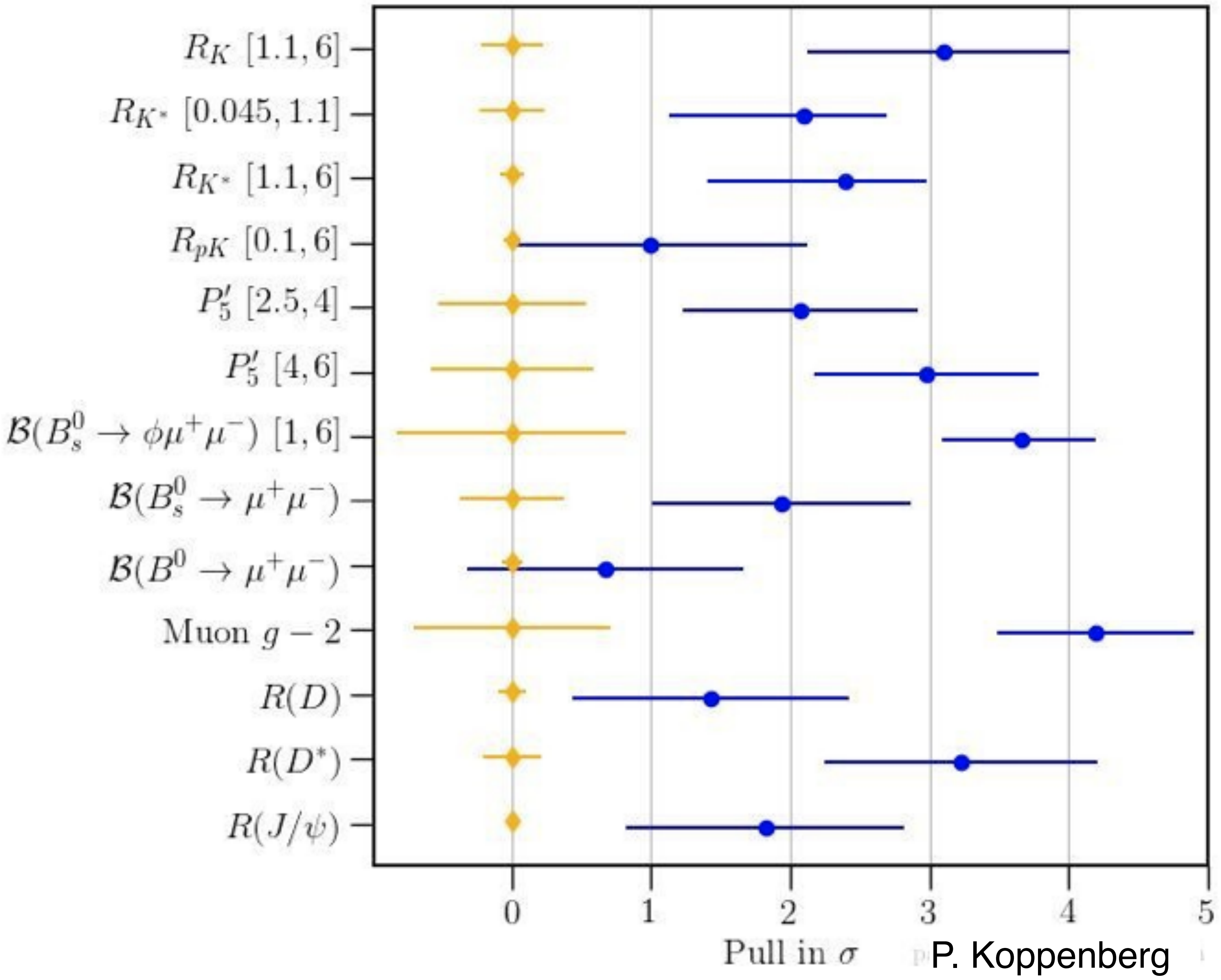
- Analysis of Run-1 data produced result with 460 ppb precision
- 4.2 σ discrepancy with Theory Initiative recommended SM prediction



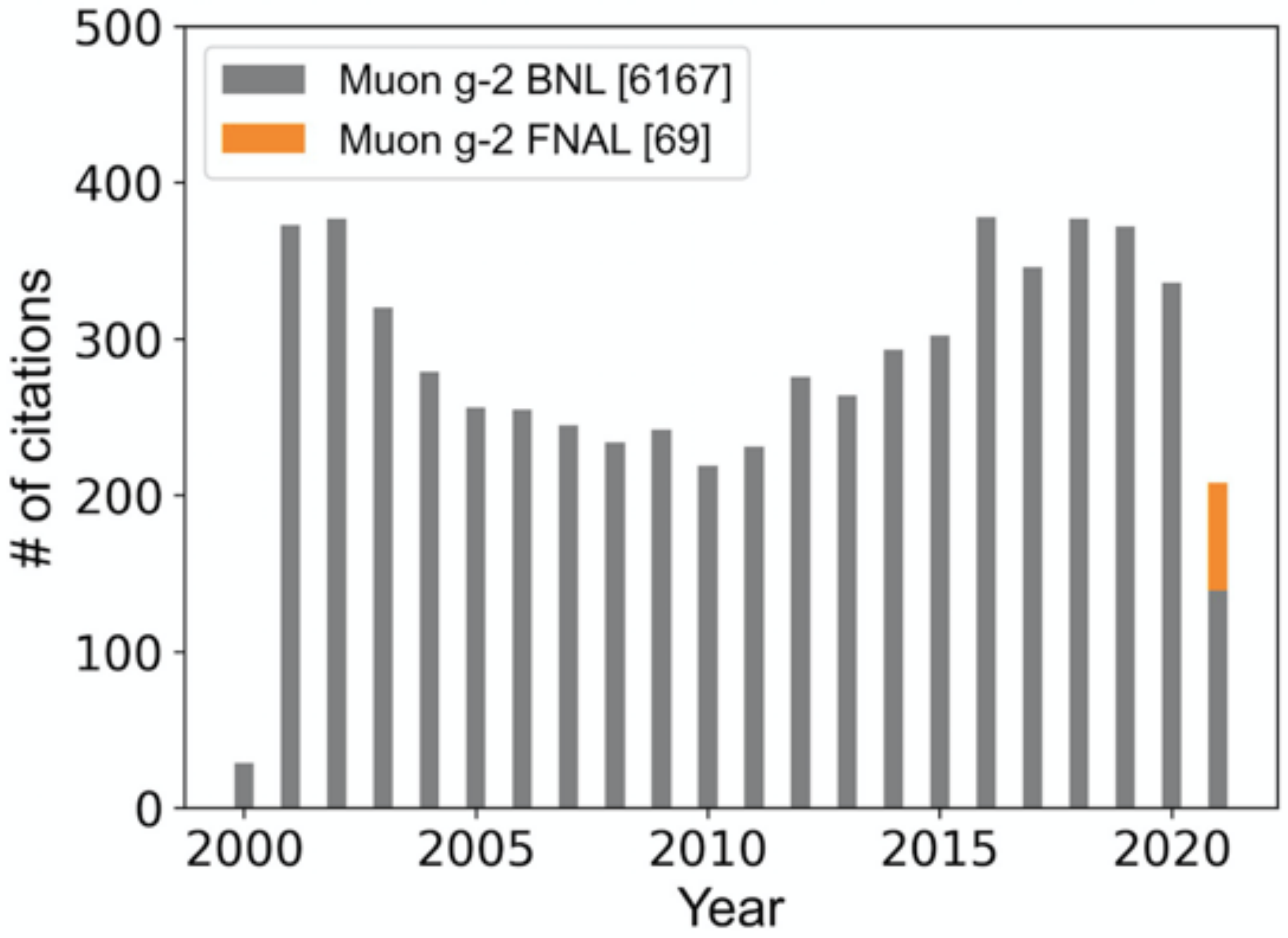
Fermilab

Interpretation

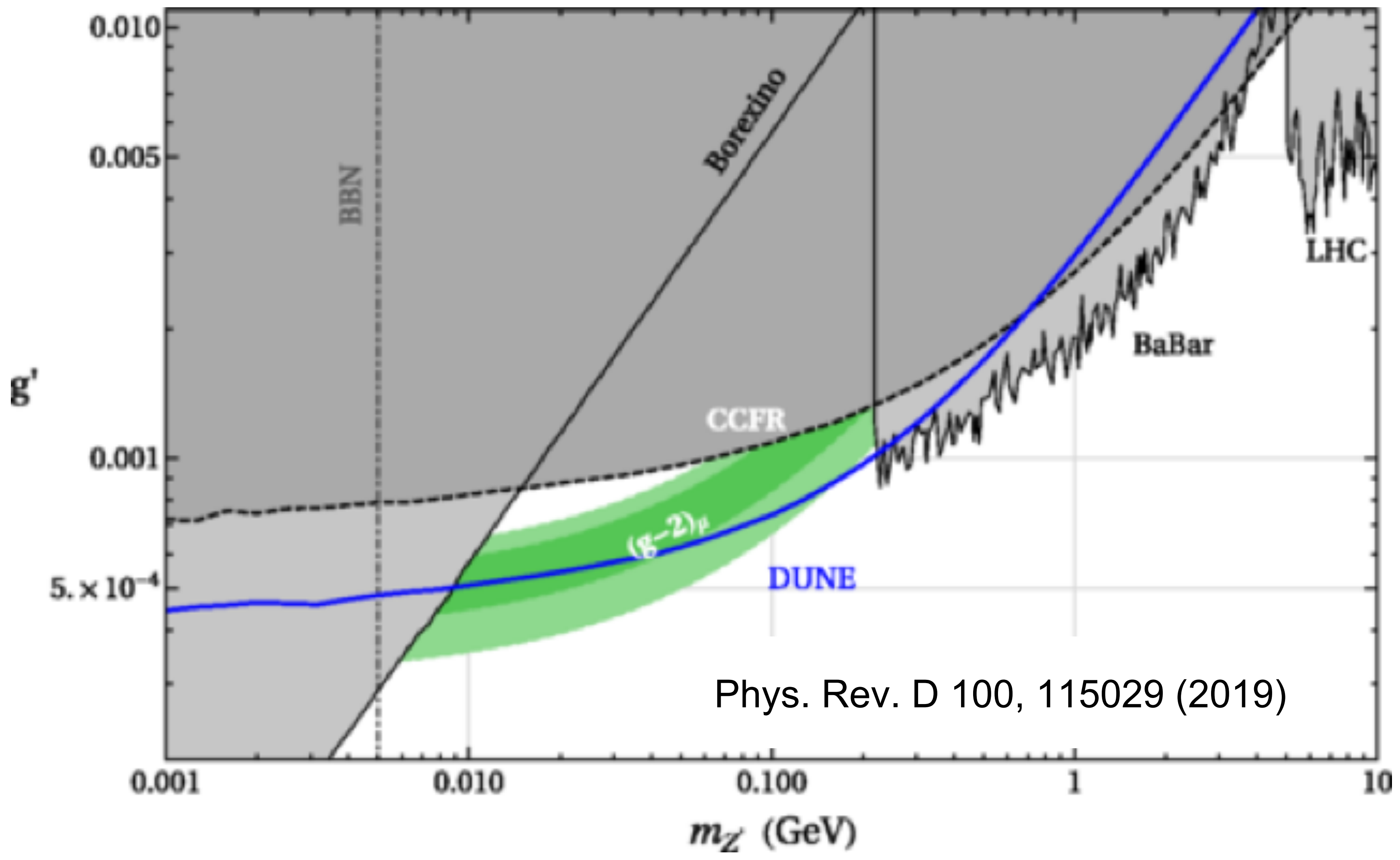
- More precision needed



P. Koppenberg



1 week after announcement



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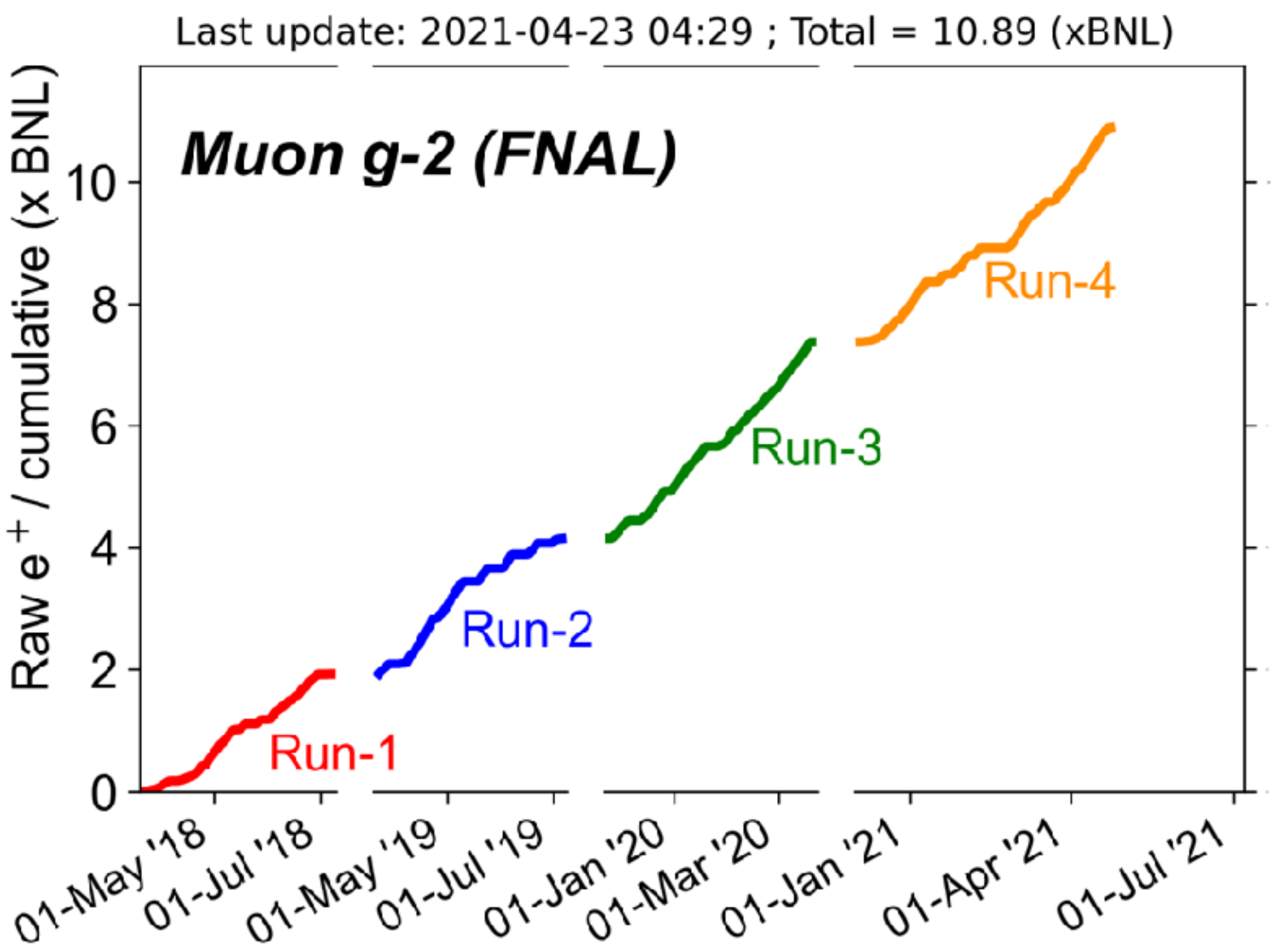
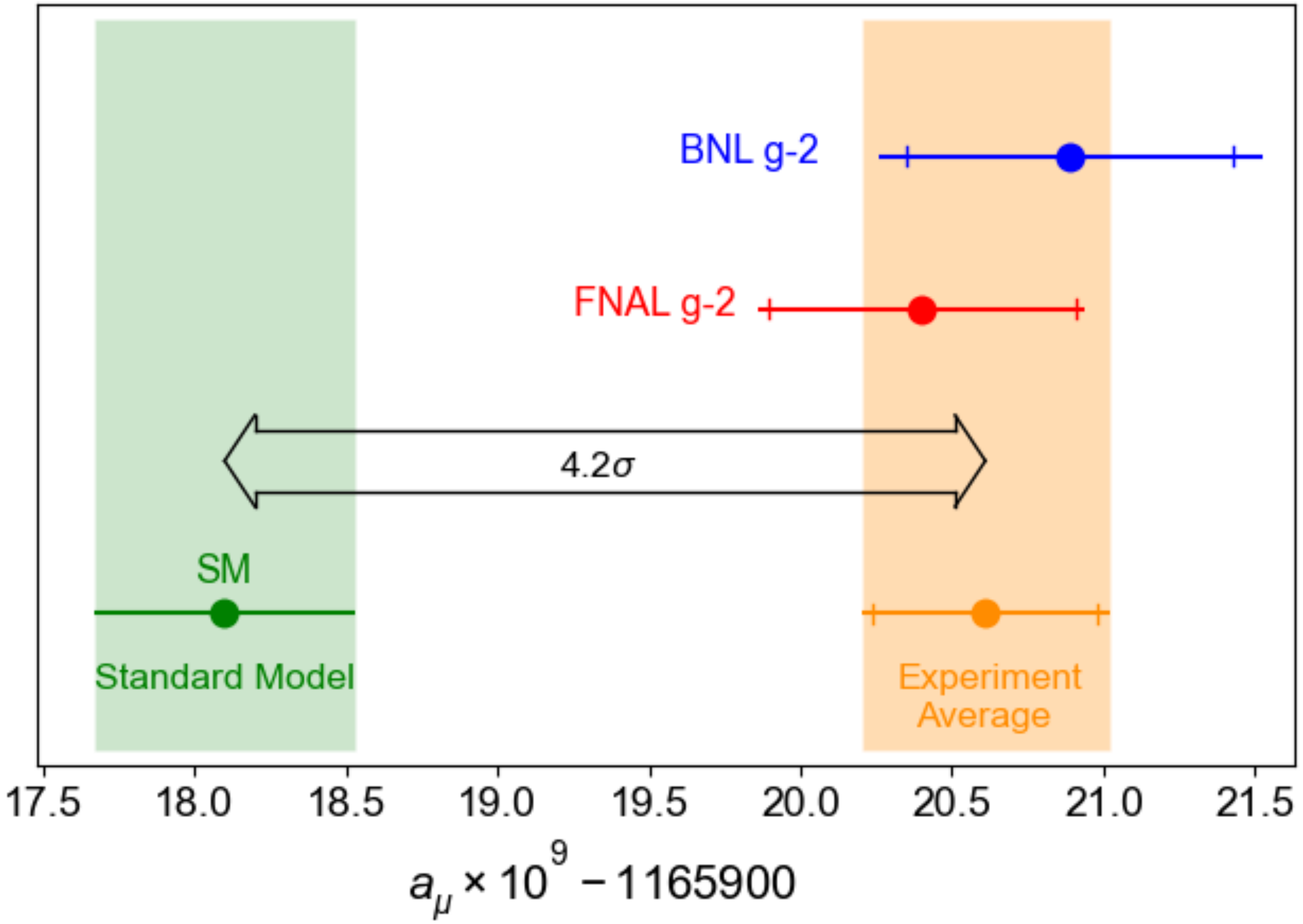
The Future

- Reduced beam dynamics systematics
- Increased kick strength to put muons on central orbit and reduce C_E
- More detailed measurements of B_q and B_k
- Magnet insulation and better temperature control for less variations in the B field and reduced field tracking uncertainty
- More data! Expect factor of ~2 times better precision with the Run-2/3 dataset



Fermilab

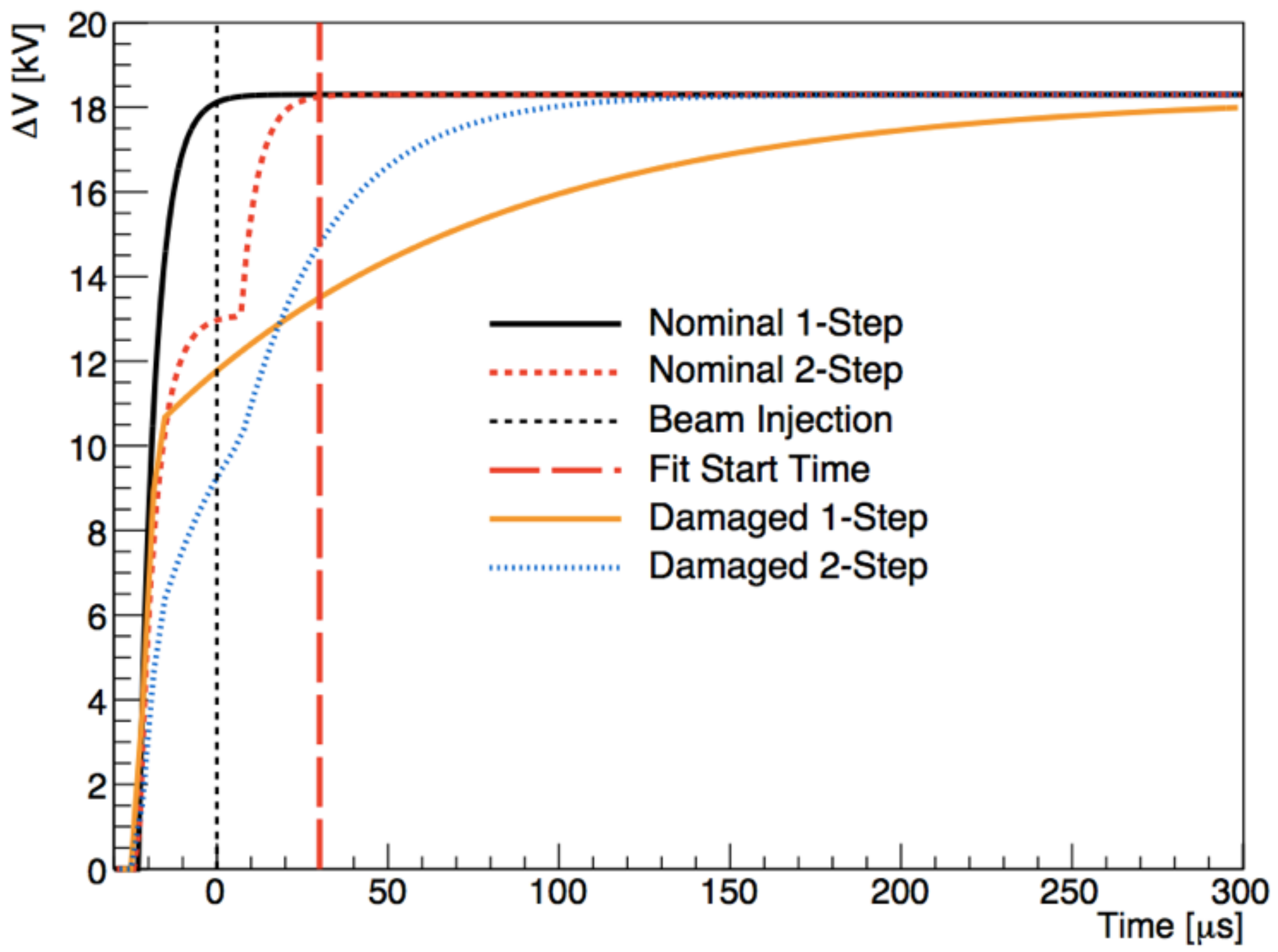
Thank you

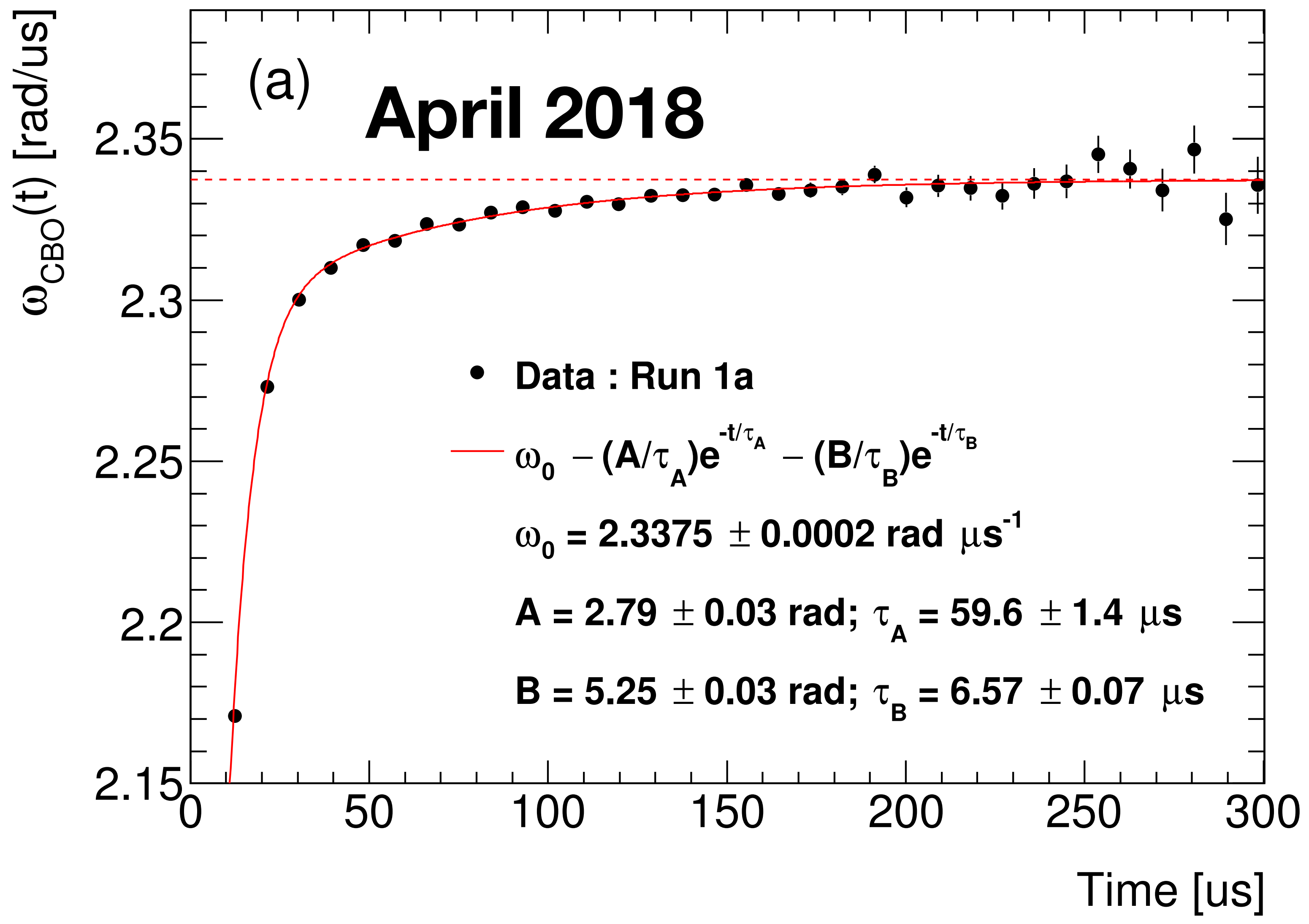


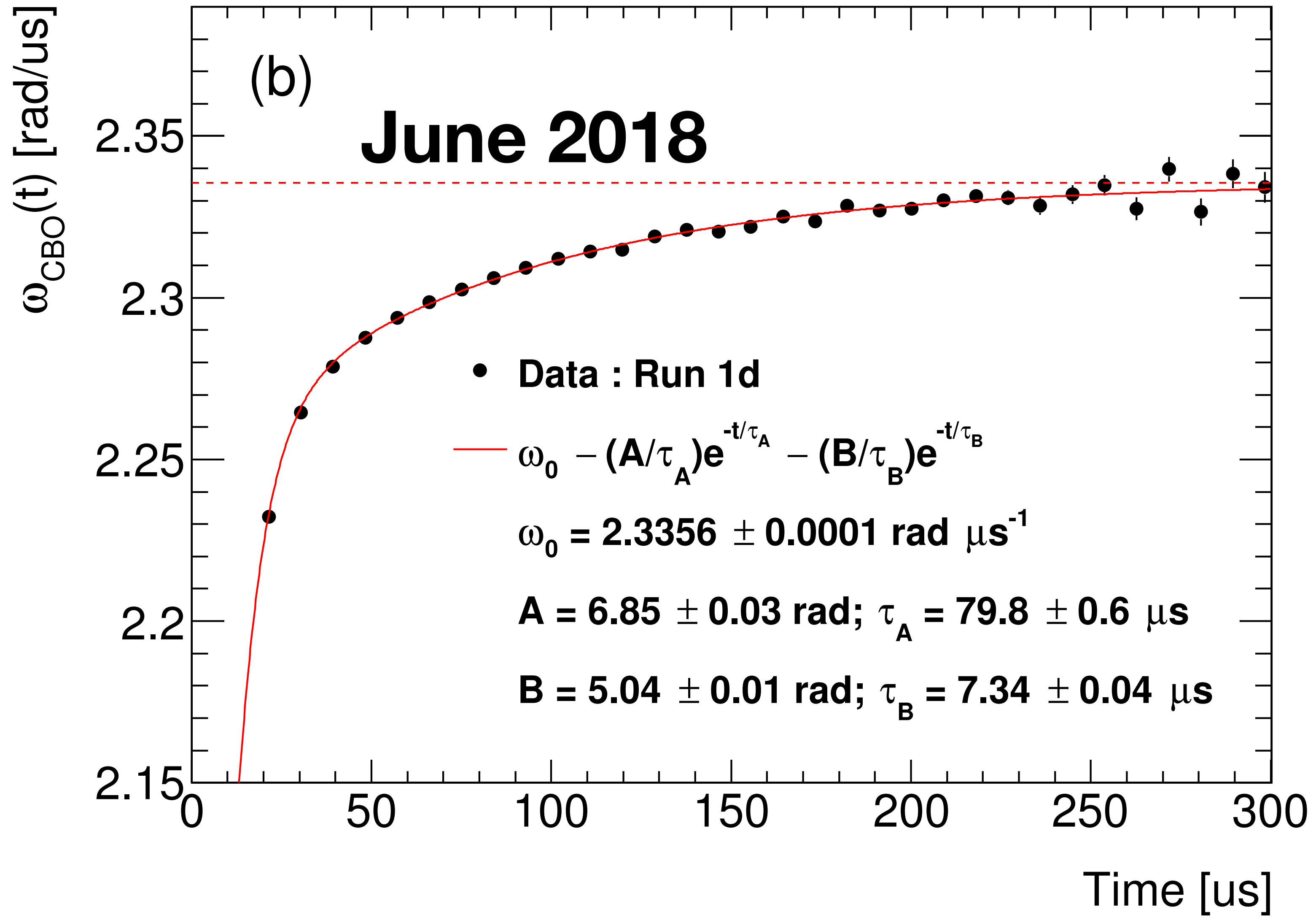
BNL g-2
FNAL g-2
4.2σ
SM
Standard Model
Experiment Average
17.5 18.0 18.5 19.0 19.5 20.0 20.5 21.0 21.5
$a_\mu \times 10^9 - 1165900$

Backup

Phase Acceptance Correction C_{pa}

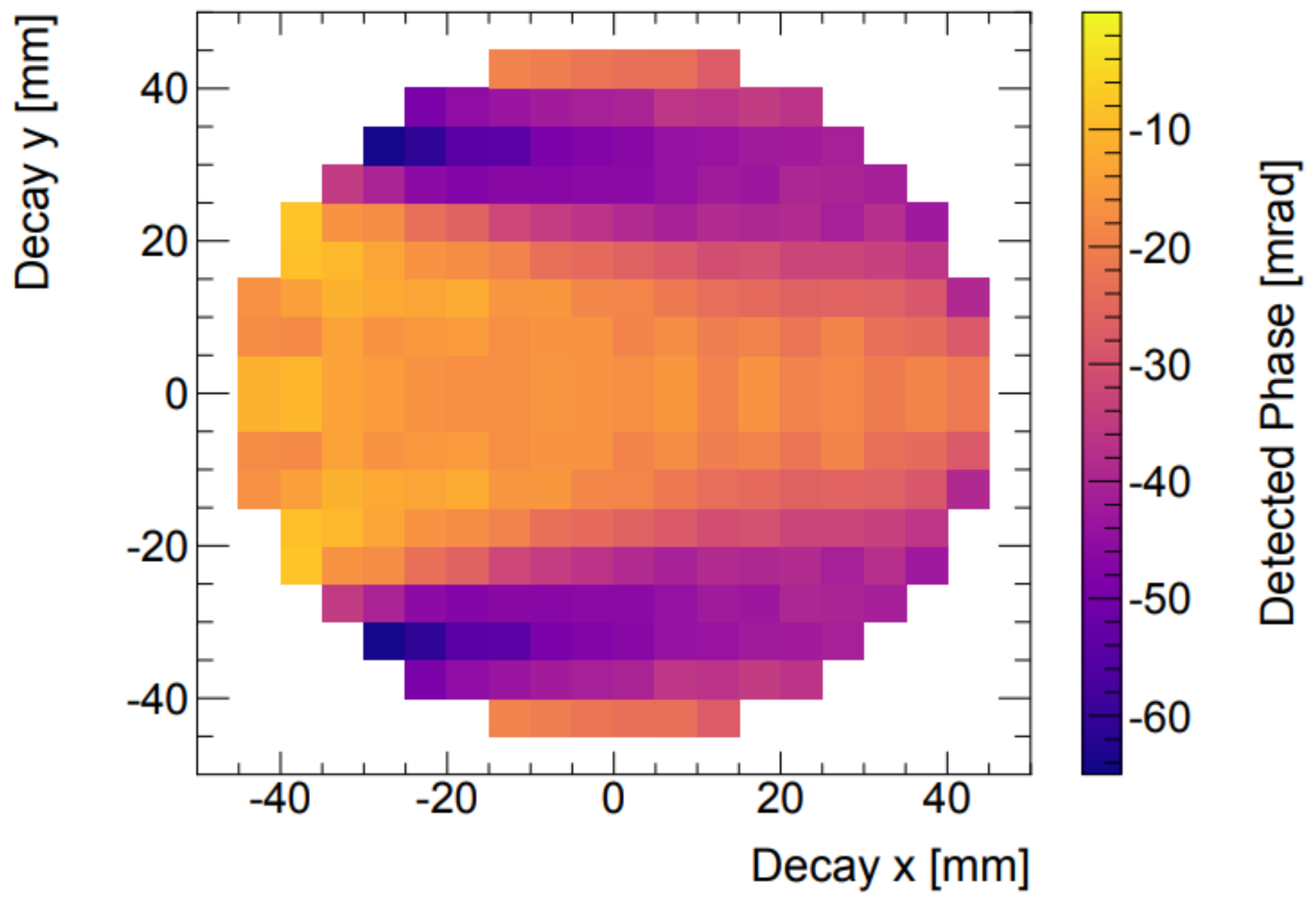


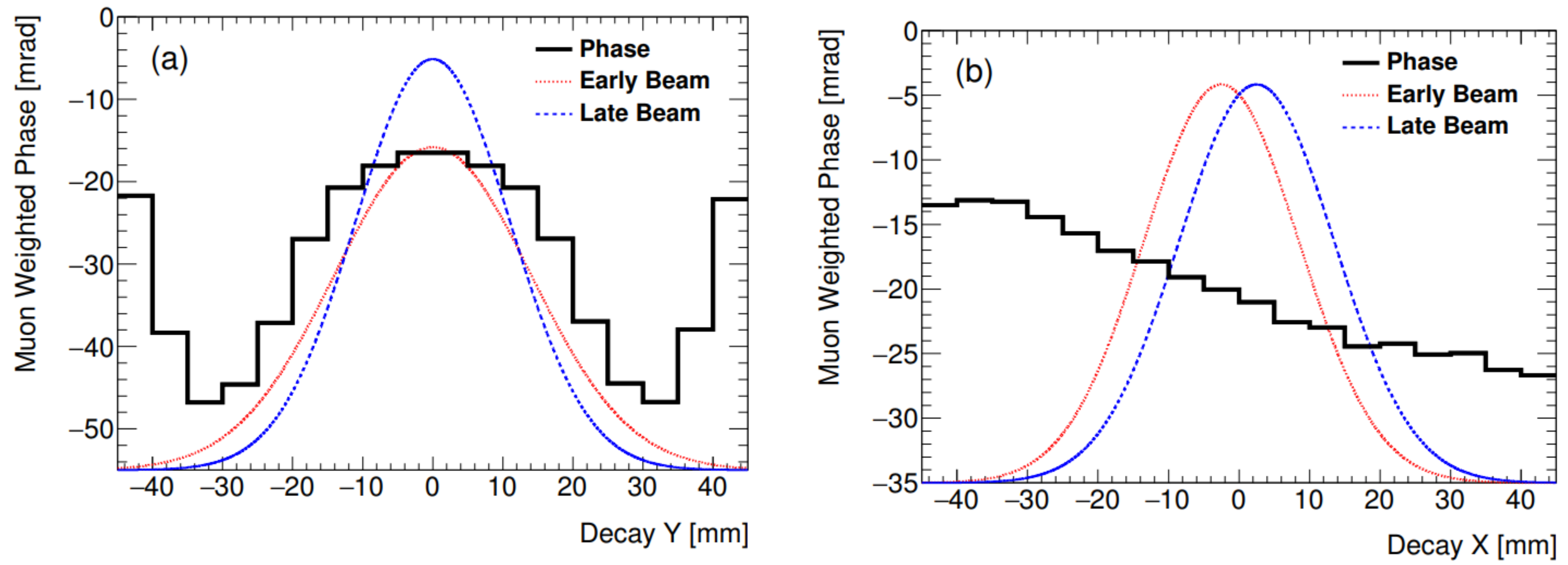




Phase Acceptance Correction C_{pa}

~ 45 +- 90 ppb
Run-1 only (will reduce in future)

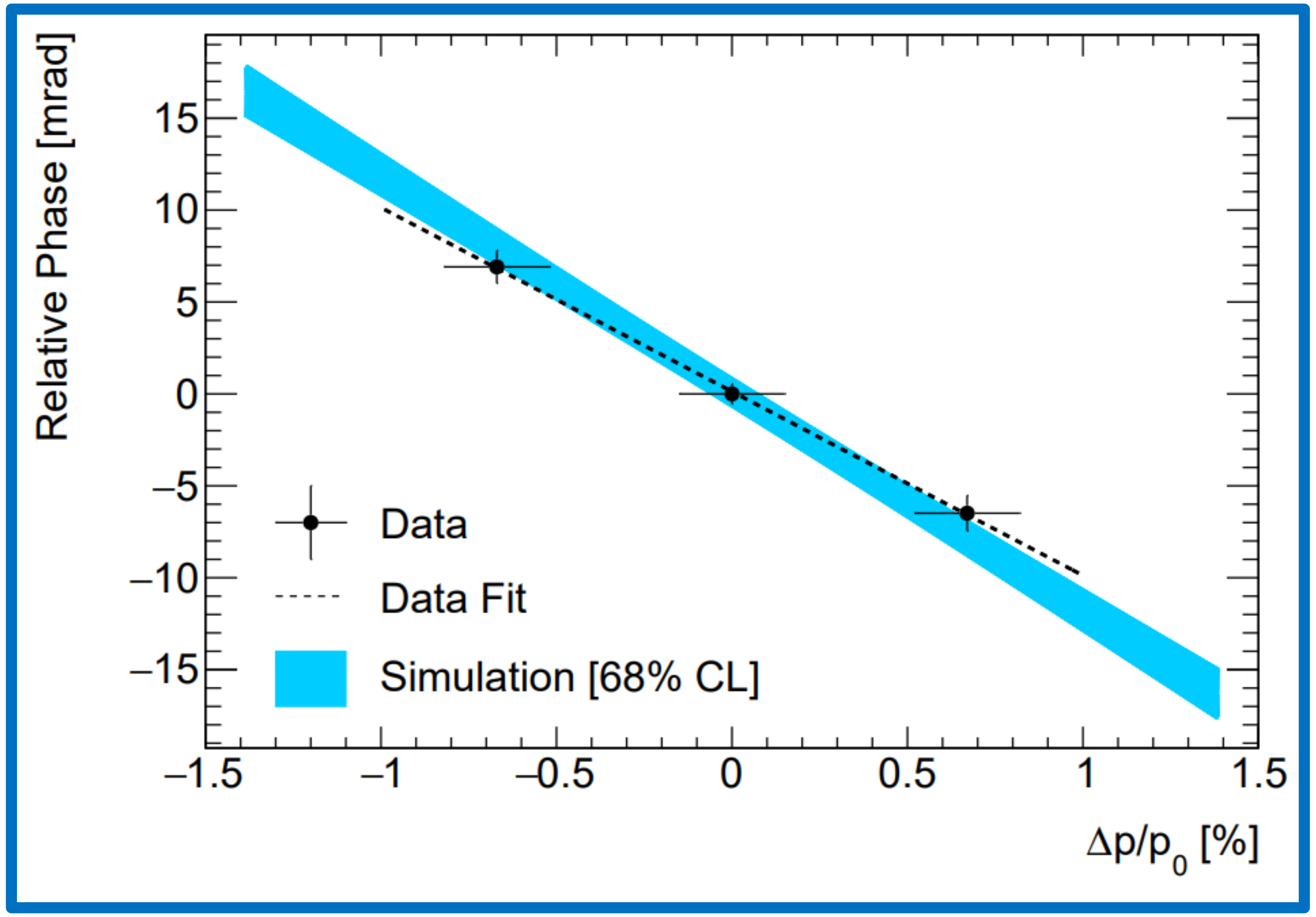


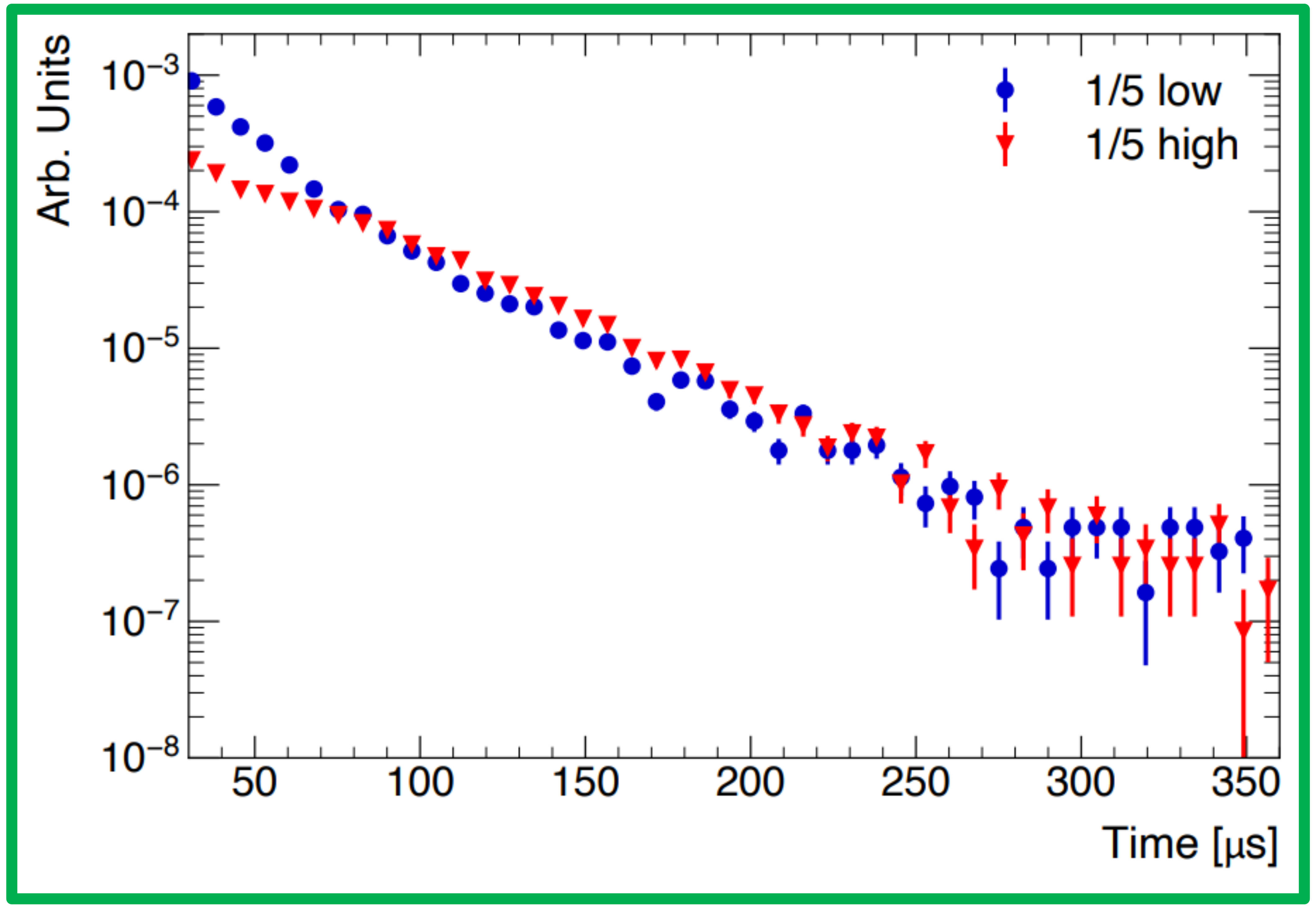


- Focusing strength of the quadrupoles changed during fill
- The non-uniform acceptance of the calorimeters causes the average phase to change during the fill
- Damaged resistors (Run-1 only) enhanced this effect

Muon Loss Correction Cml

< 10 ppb





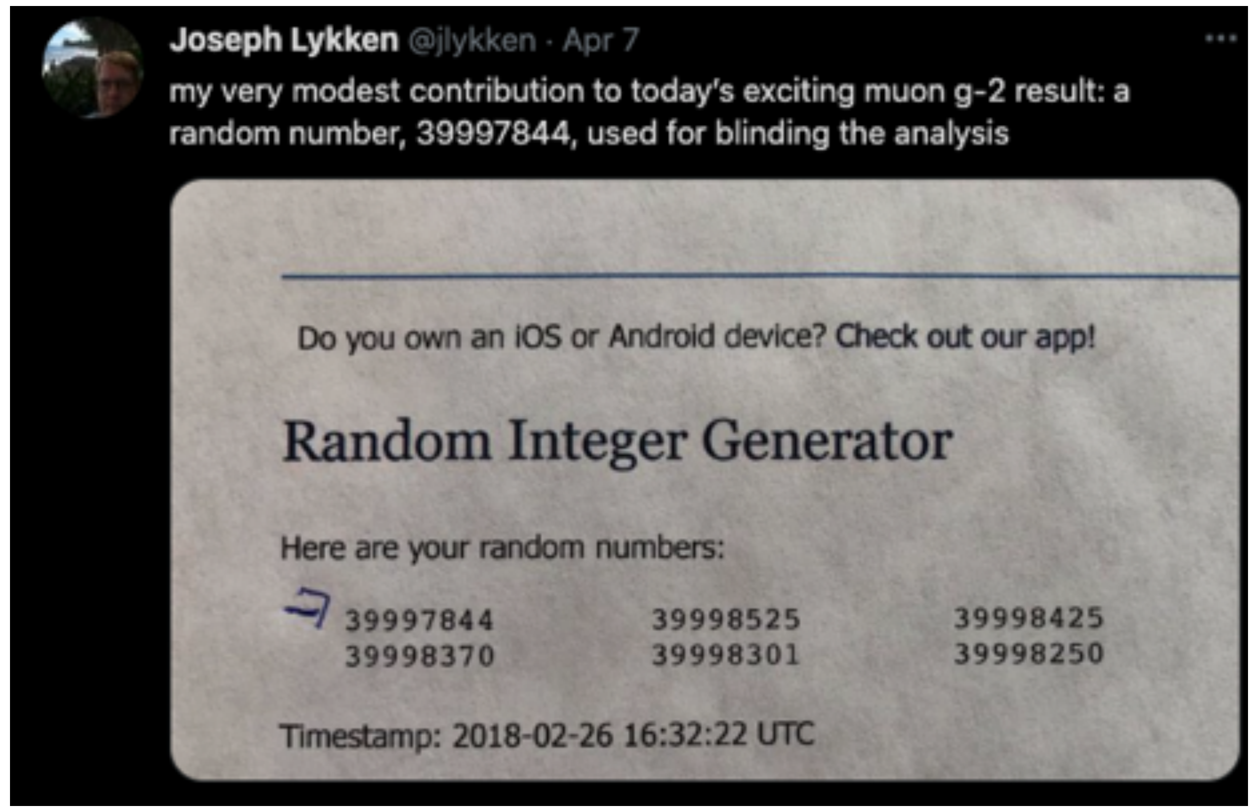
Spin-momentum correlation from delivery ring

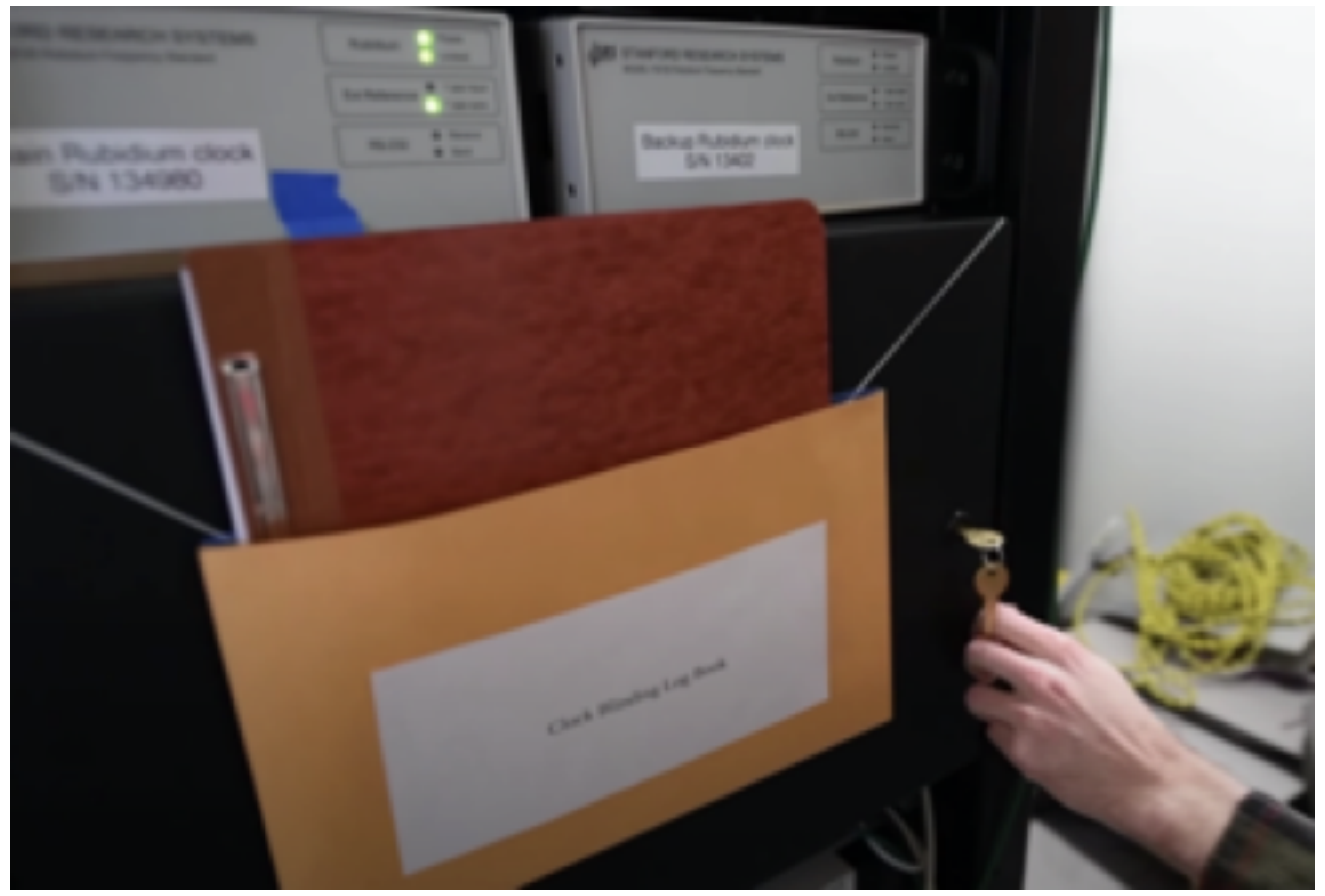
$$\frac{d\varphi_0}{dt} = \frac{d\varphi_0}{d\langle p\rangle}\frac{d\langle p\rangle}{dt}$$

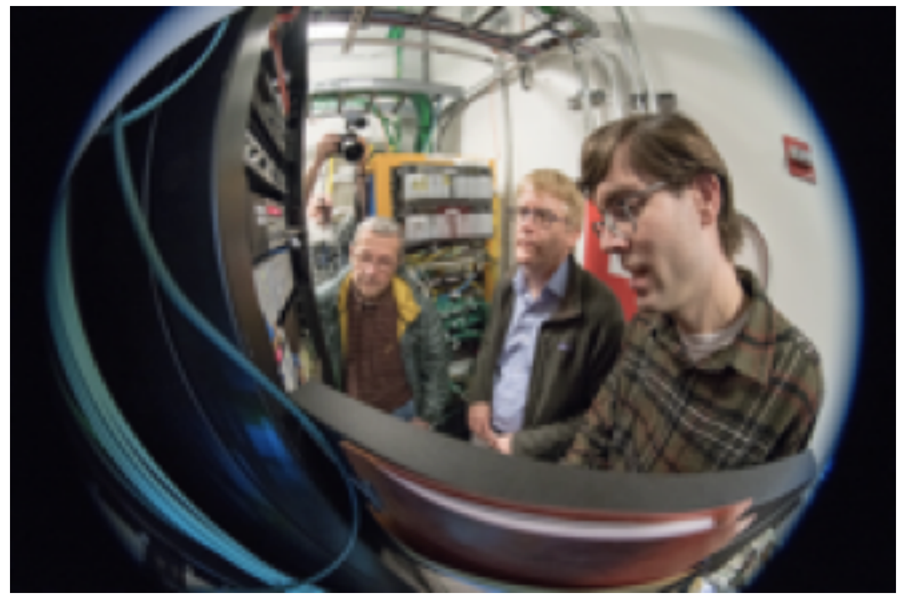
Low mom. muons are lost faster than high mom. at early times

Clock Blinding

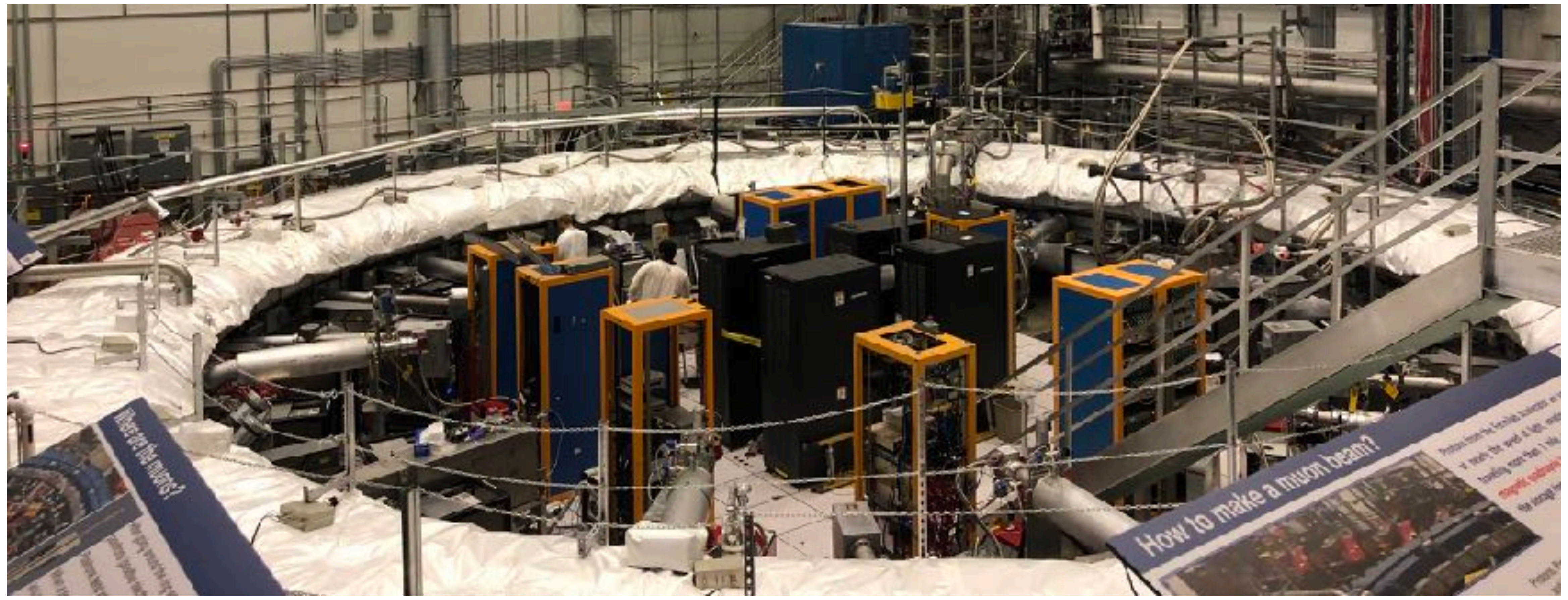
- The clock is hardware blinded to have a frequency of (40 ± ε) MHz
- Only 2 people outside of the collaboration set and know the number
- Blinding offset was ± 25 ppm (approx ×10 BNL-SM difference)
- Additionally, each analysis is blinded in software

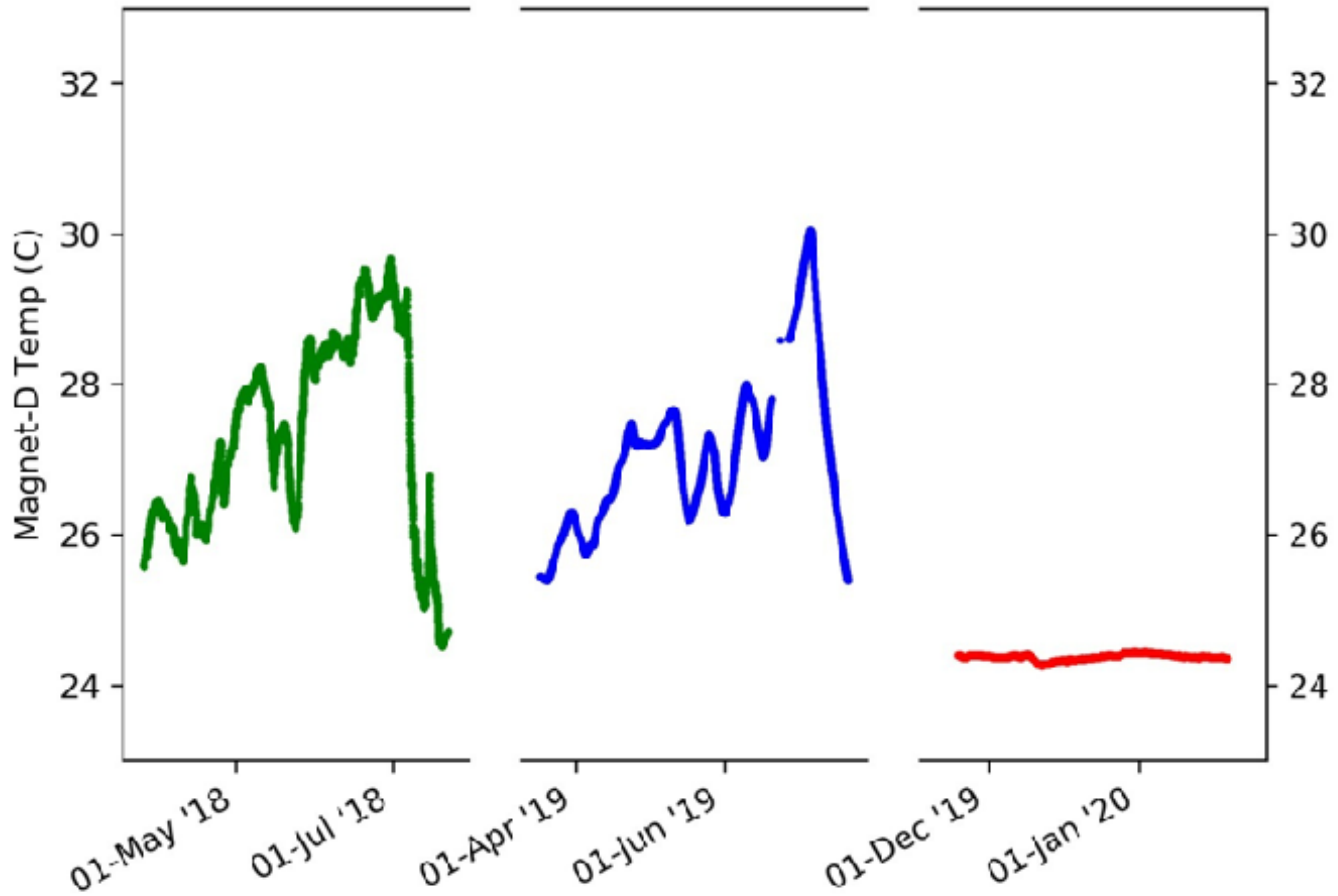


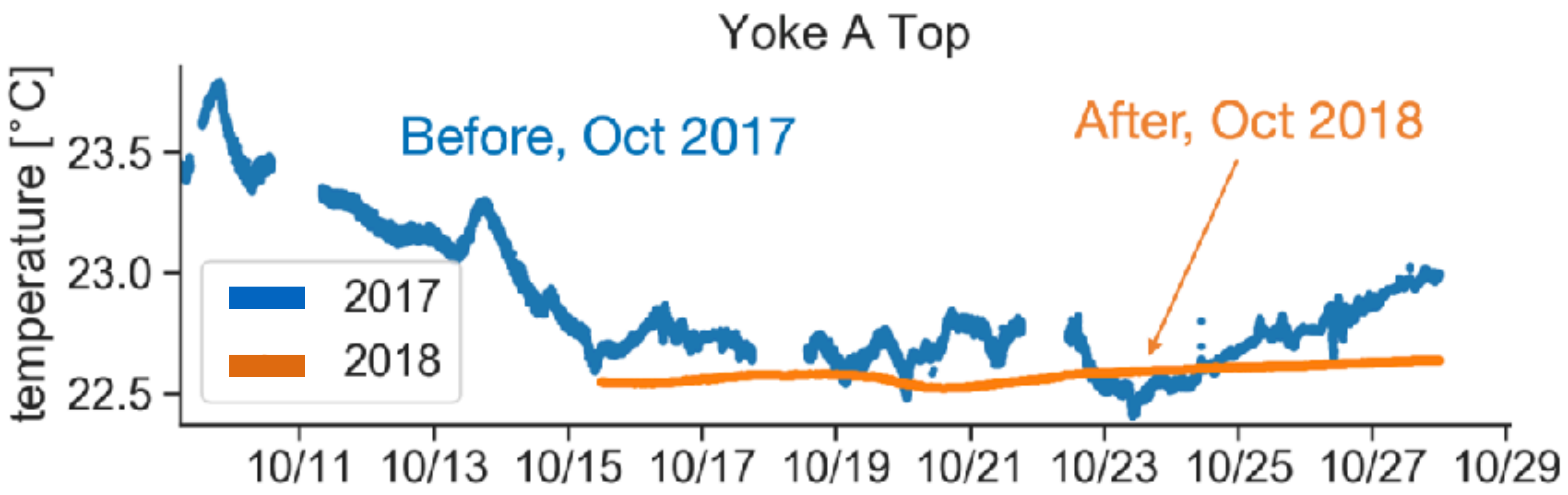




Controlling the magnet temperature







Improved magnet temperature stability in runs 2 and 3 — less variation in the field