The Electric Dipole Moment of the Muon at Fermilab

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On Behalf of the Muon g-2 Collaboration

EDM workshop, PSI

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Outline

- Brief overview of g-2 measurement principle
- Effect of a muon EDM on g-2 experiments
  - BNL measurement
  - EDM measurement Improvements since BNL
- Overview of data taking at Fermilab
- Prospects for Fermilab EDM measurement

Measurement Principle

- Inject polarized muon beam into magnetic storage ring
- Measure **difference** between spin precession and cyclotron frequencies
- If $g = 2$, $\omega_a = 0$
- $g \neq 2$, $\omega_a \cong (e/m_\mu)a_\mu B$

Spin precession freq.

$$\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

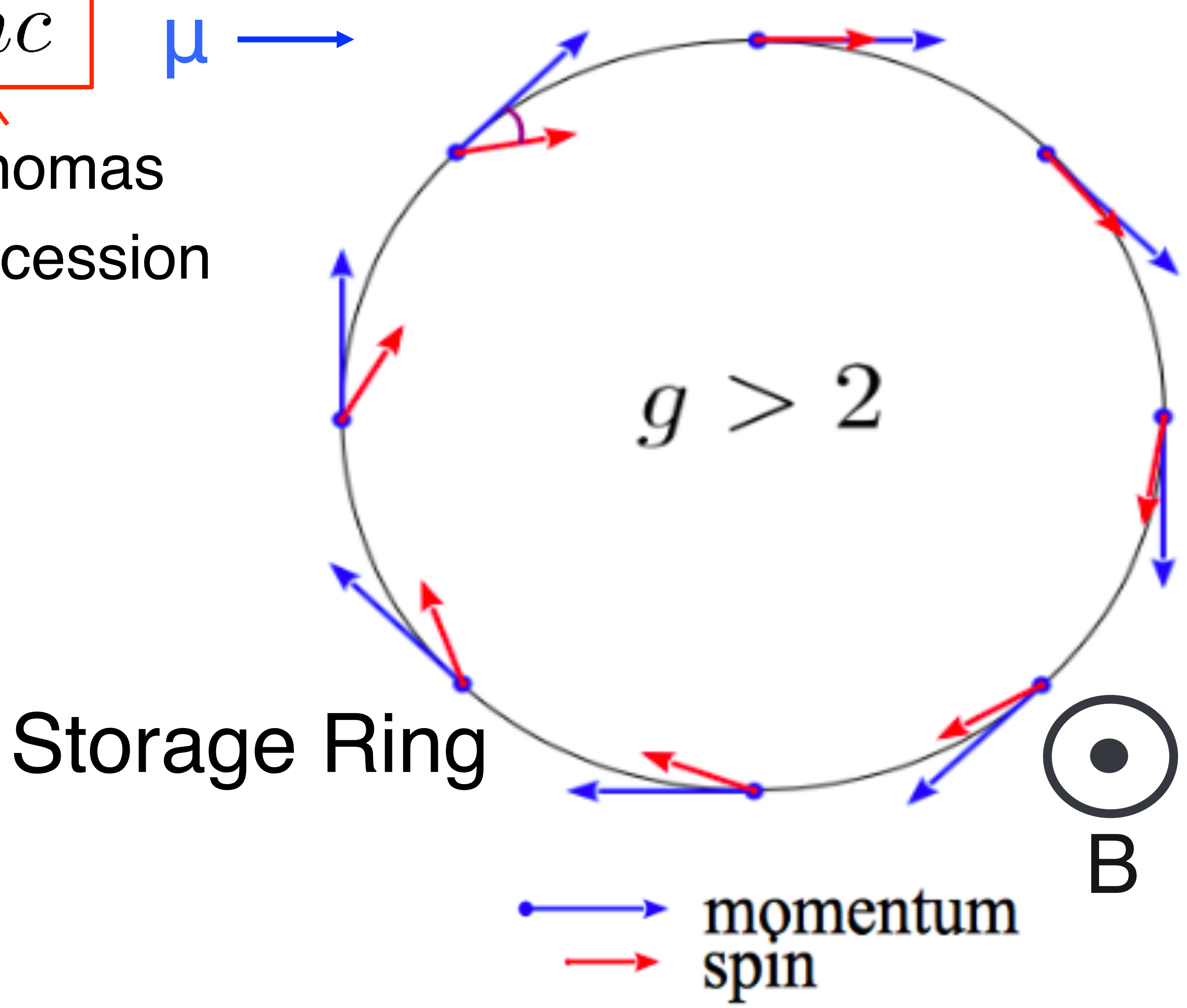
Larmor precession

Thomas precession

Cyclotron freq.

$$\omega_c = \frac{eB}{\gamma mc}$$

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



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

3 ppb 22 ppb 0.3 ppt

Rev. Mod. Phys. **88**, 035009 (2016)

- We measure ω_a and ω_p separately
- Aiming for 70 ppb precision on each (systematic)
- **Target: δa_μ(syst) = 140 ppb; factor of 4 improvement over BNL**

Real World Considerations

- Muon beam has a small vertical component
- We need to use Electric fields to focus the beam so we can store the muons

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

- This introduces an unwanted $\beta \times E$ term…
- …unless γ = 29.3, then E-field term vanishes: we call this the "magic" momentum (3.094 GeV)
- Leaves 2 effects that we can't ignore:
  - Not all muons are exactly at magic momentum
  - Some small degree of vertical motion of muons (reduces effective B-field)
- Need to use tracking and beam dynamics models to calculate the small corrections for these (< 1 ppm)

Beam Dynamics Corrections

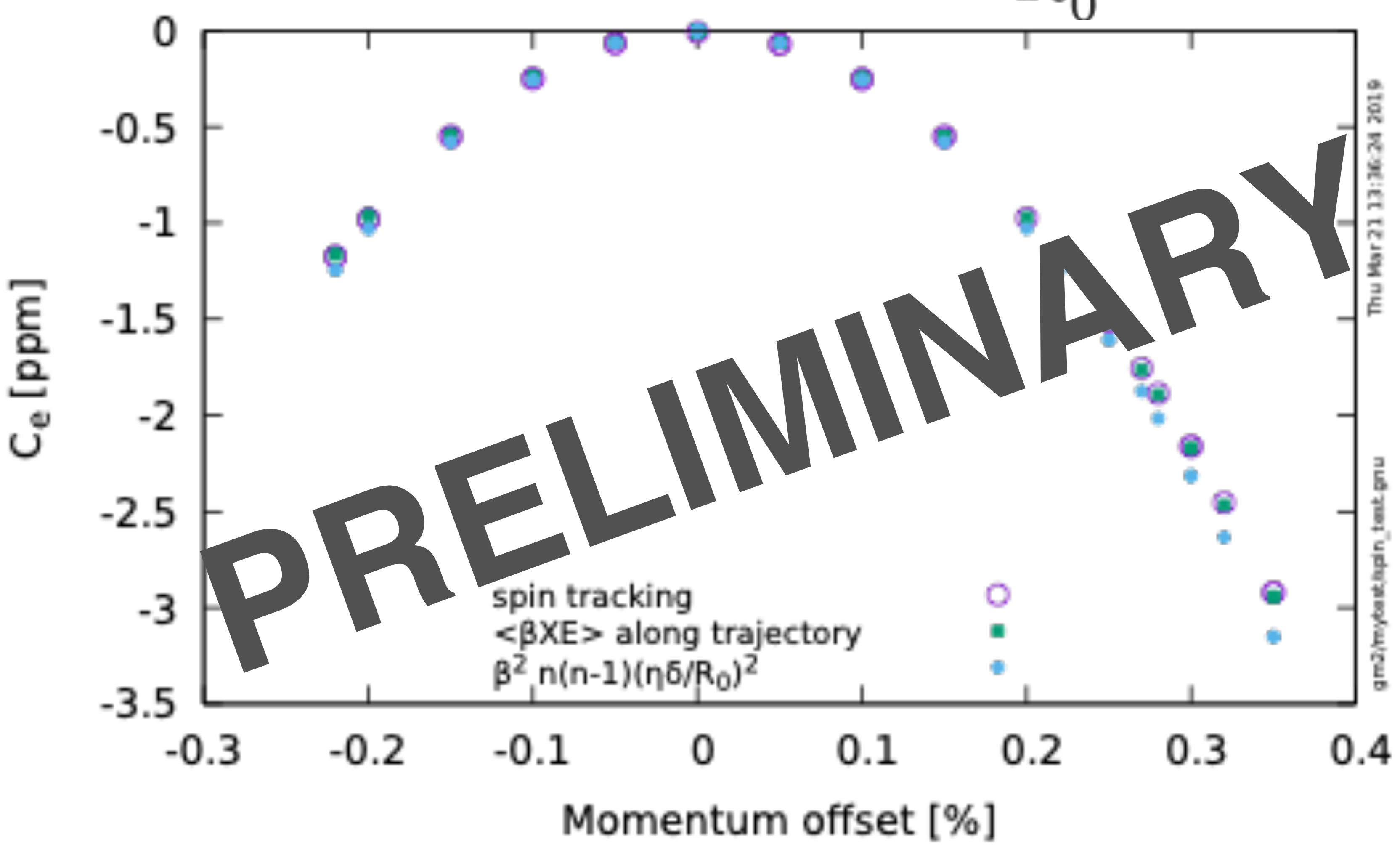
- Full expression for ω_a:

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

- Choose $\gamma = 29.3$ ($p_\mu = 3.094$ GeV/c)

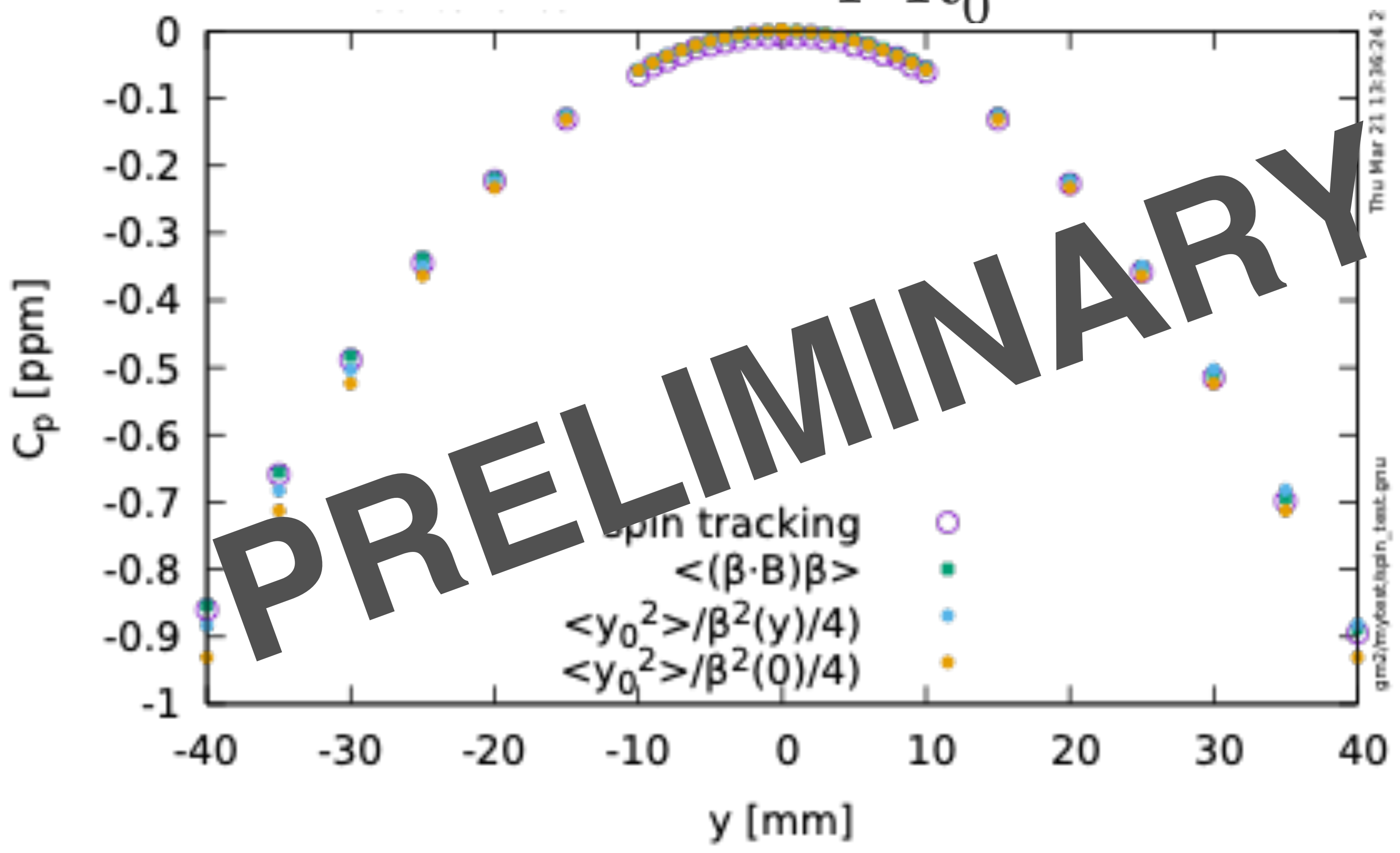
Not all μ^+ at this γ → **E-field correction**

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



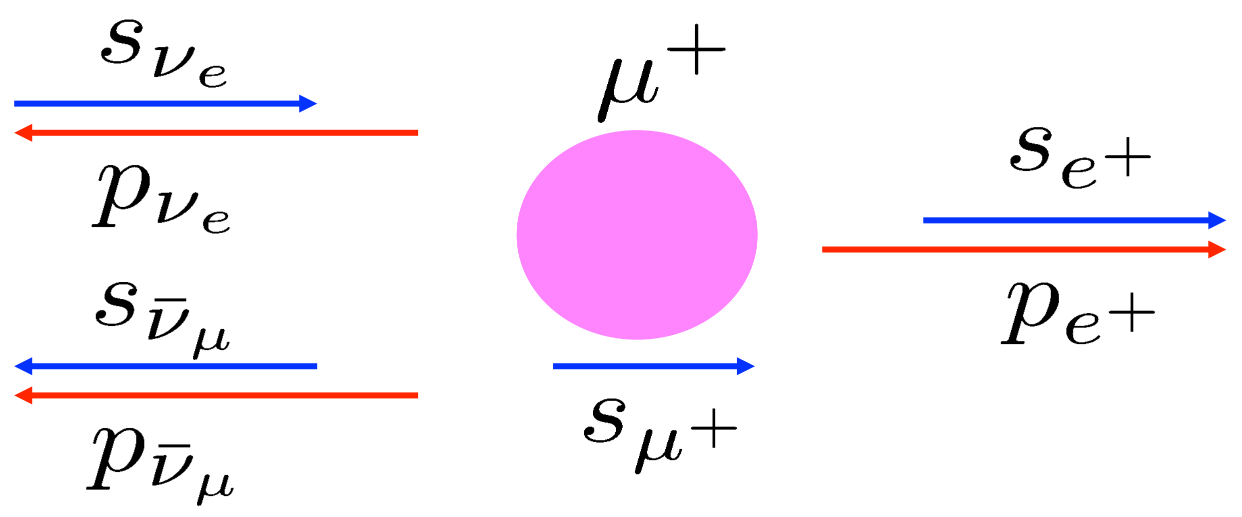
Vertical beam oscillations → **pitch correction**

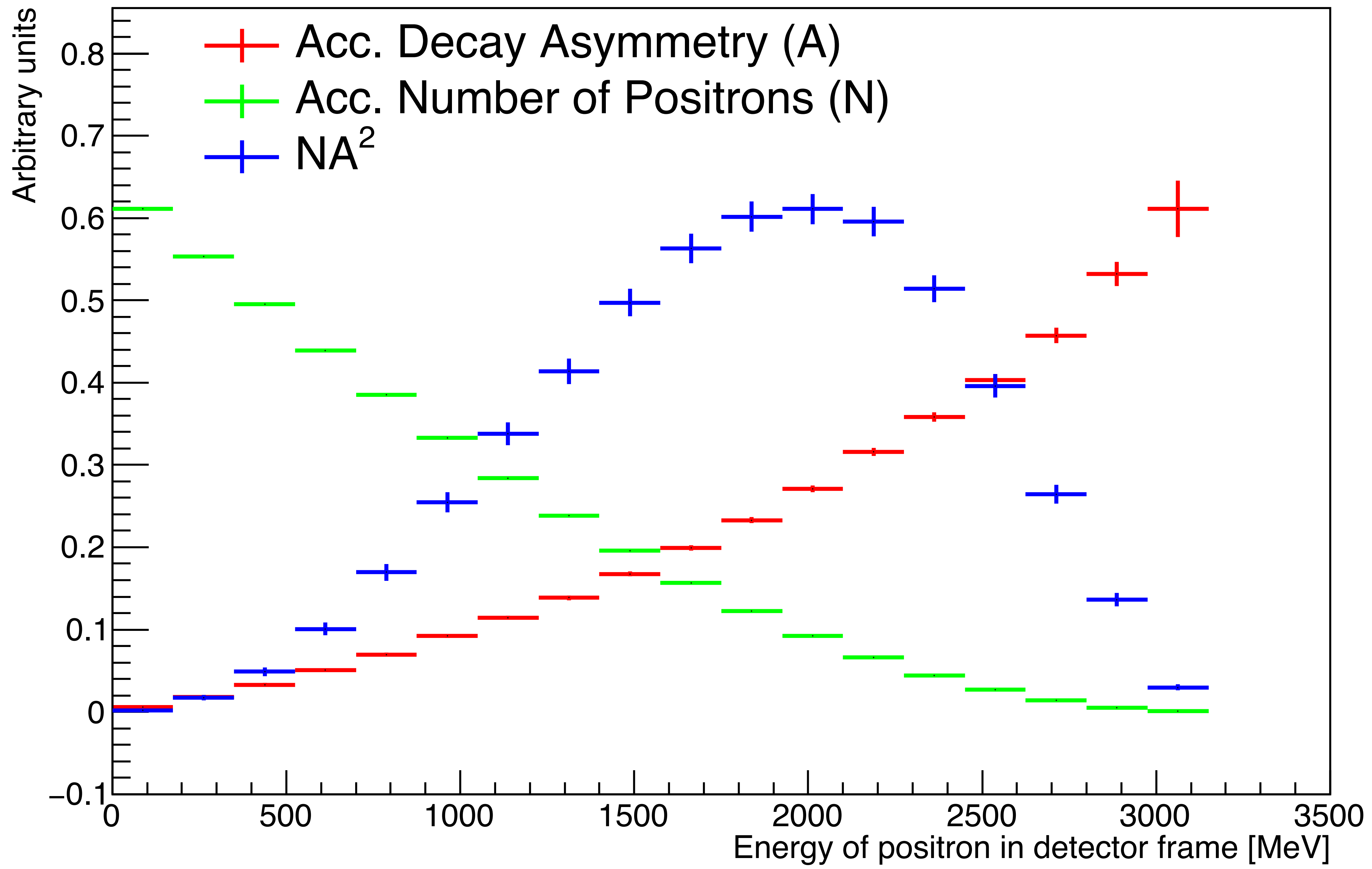
$$C_p = -\frac{n}{4}\frac{\langle y^2\rangle}{R_0^2}$$

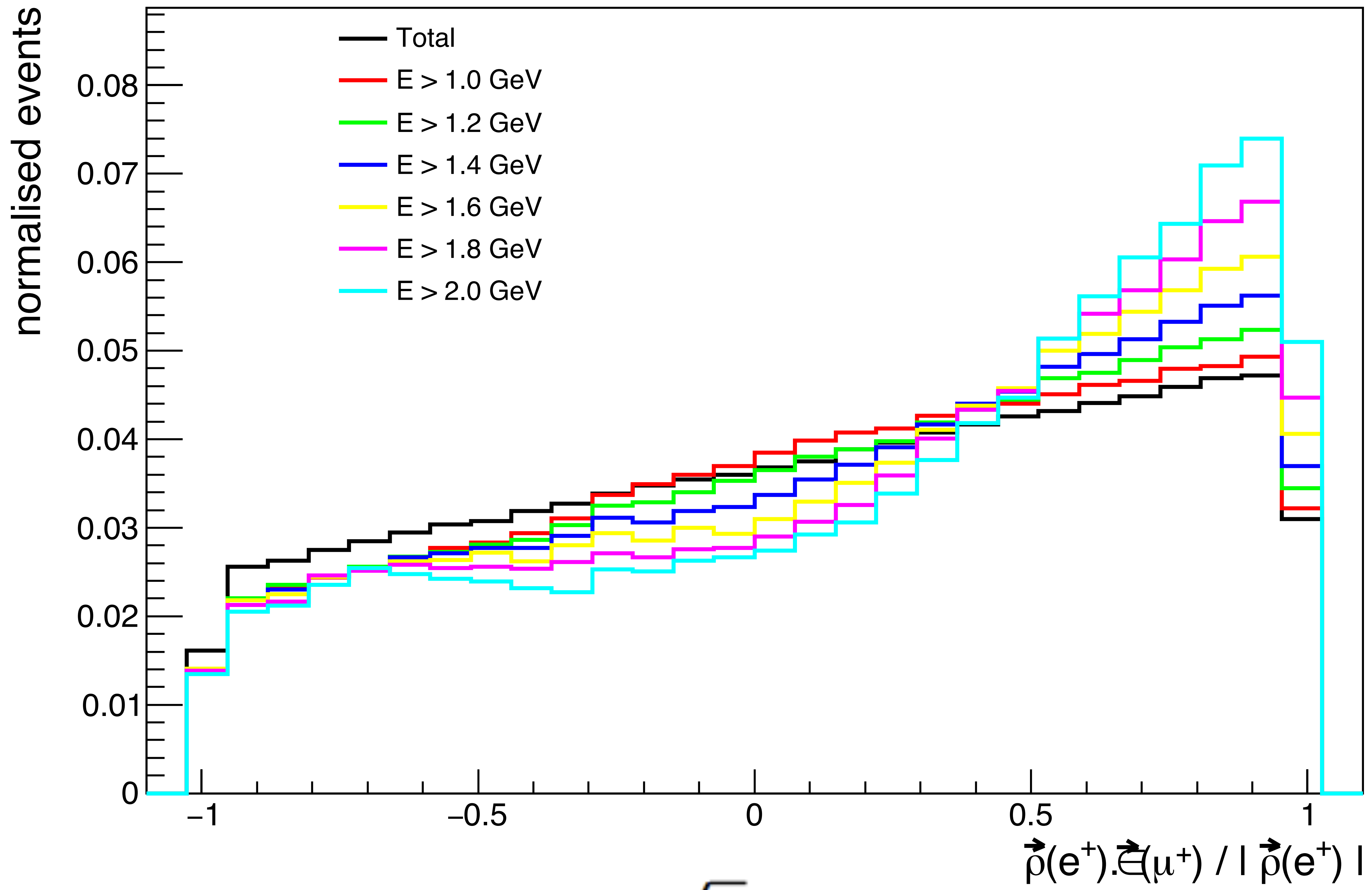


Measuring the muon spin…

- e⁺ preferentially emitted in direction of muon spin





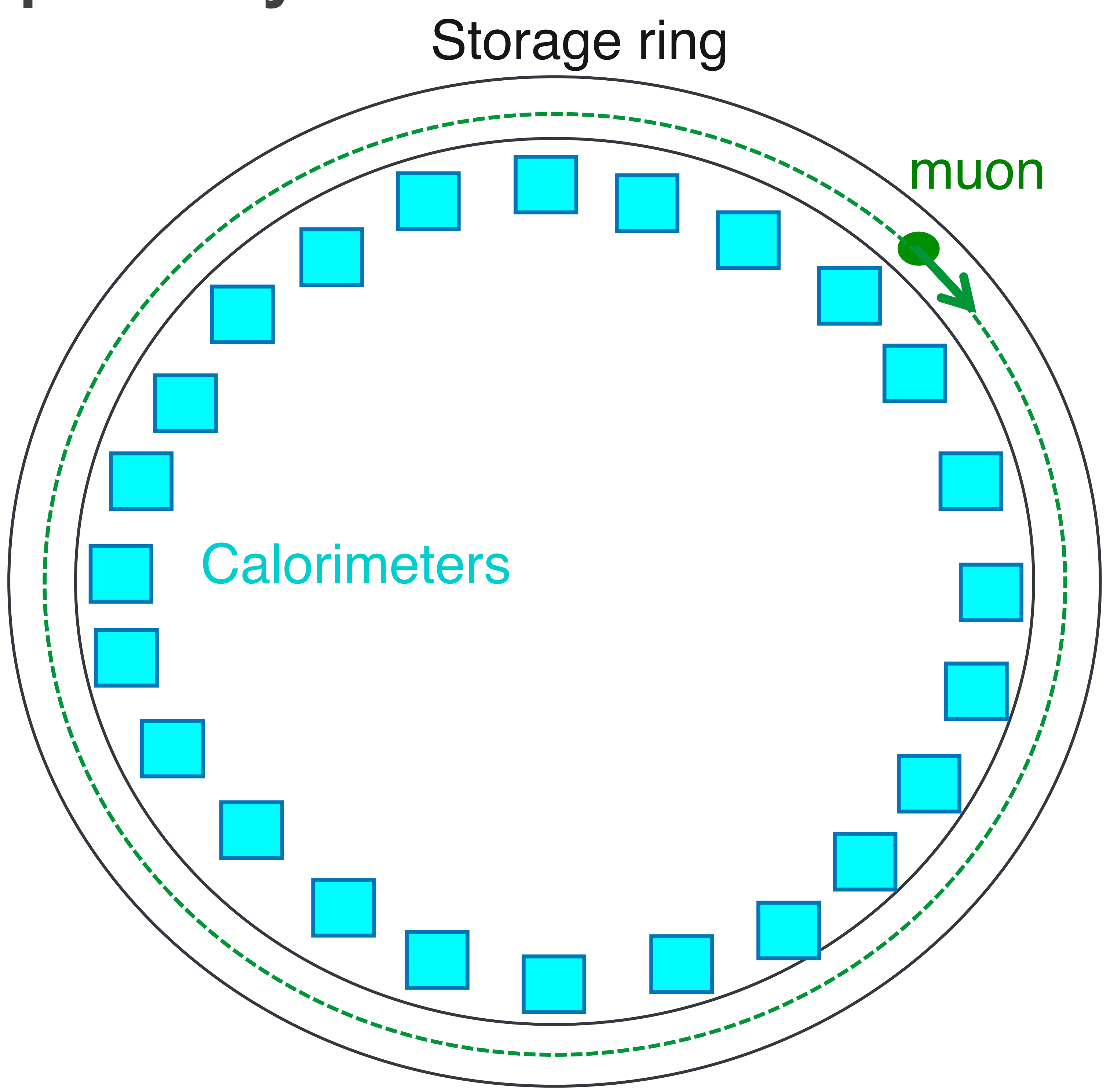


$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{2\pi f_a \tau_\mu \sqrt{NA^2}}$$

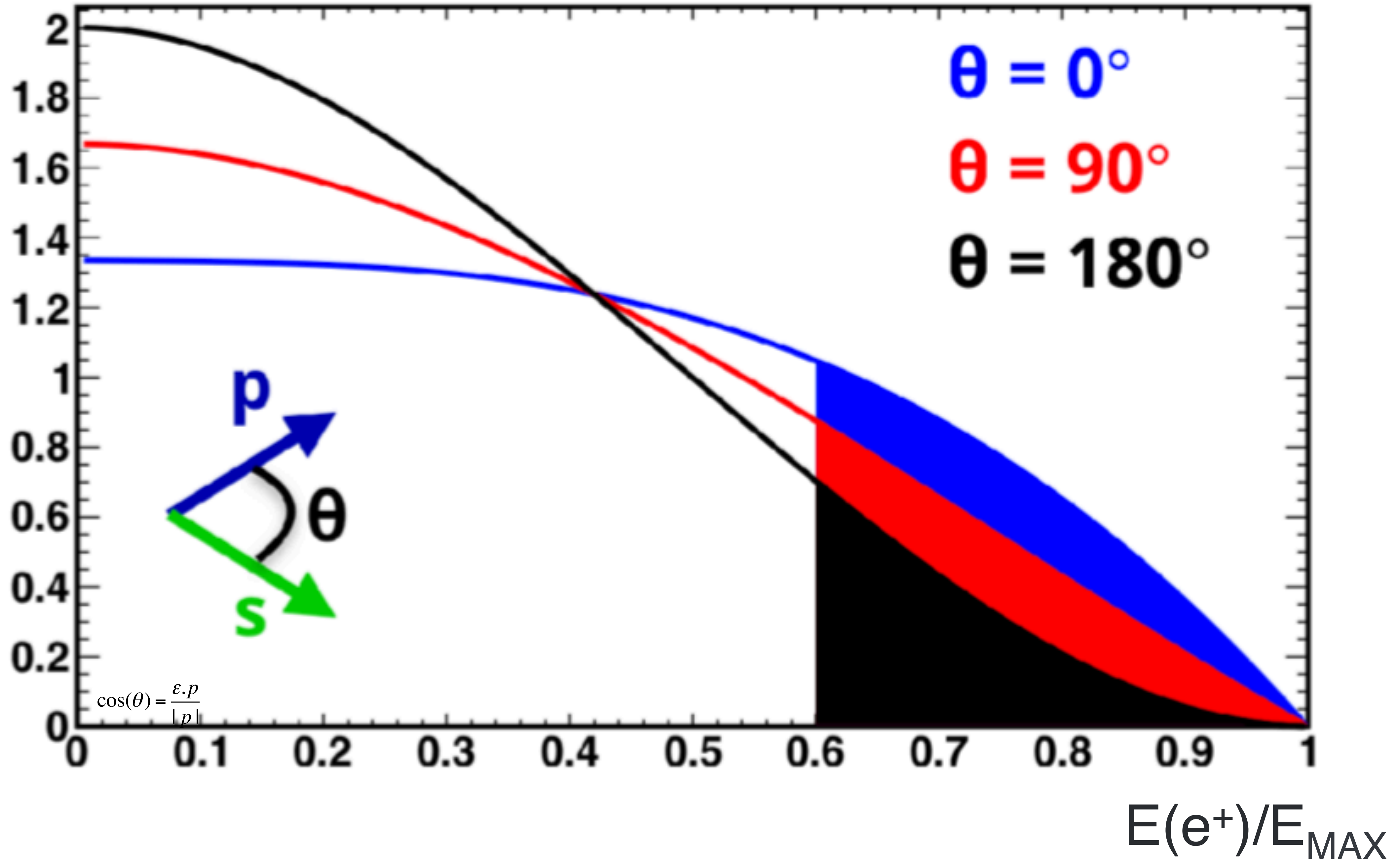
- Asymmetry is larger for high momentum e+
- Optimal cut at E~1.8 GeV

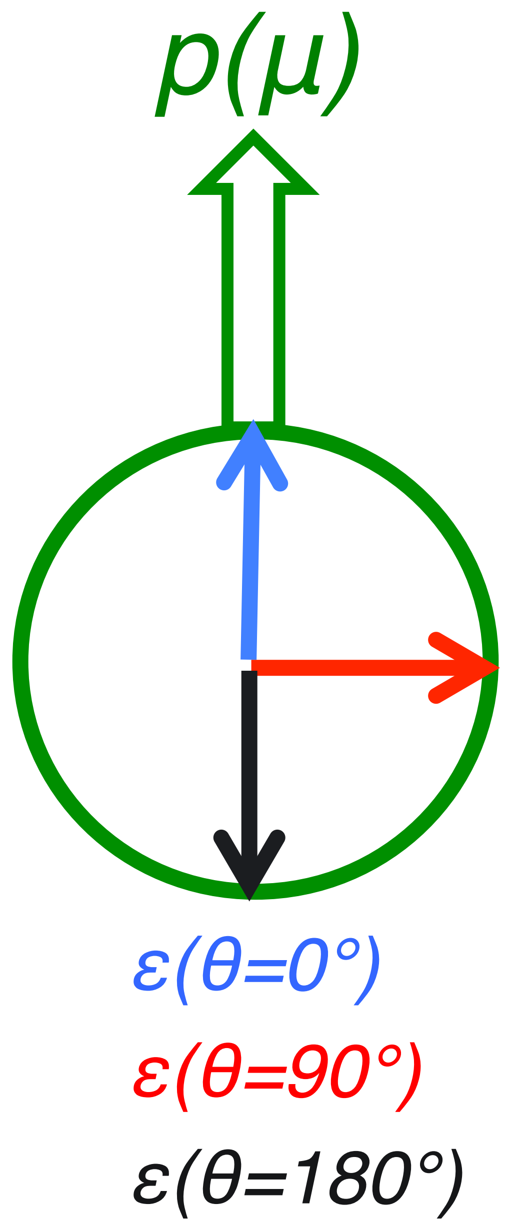
Measuring ω_a

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



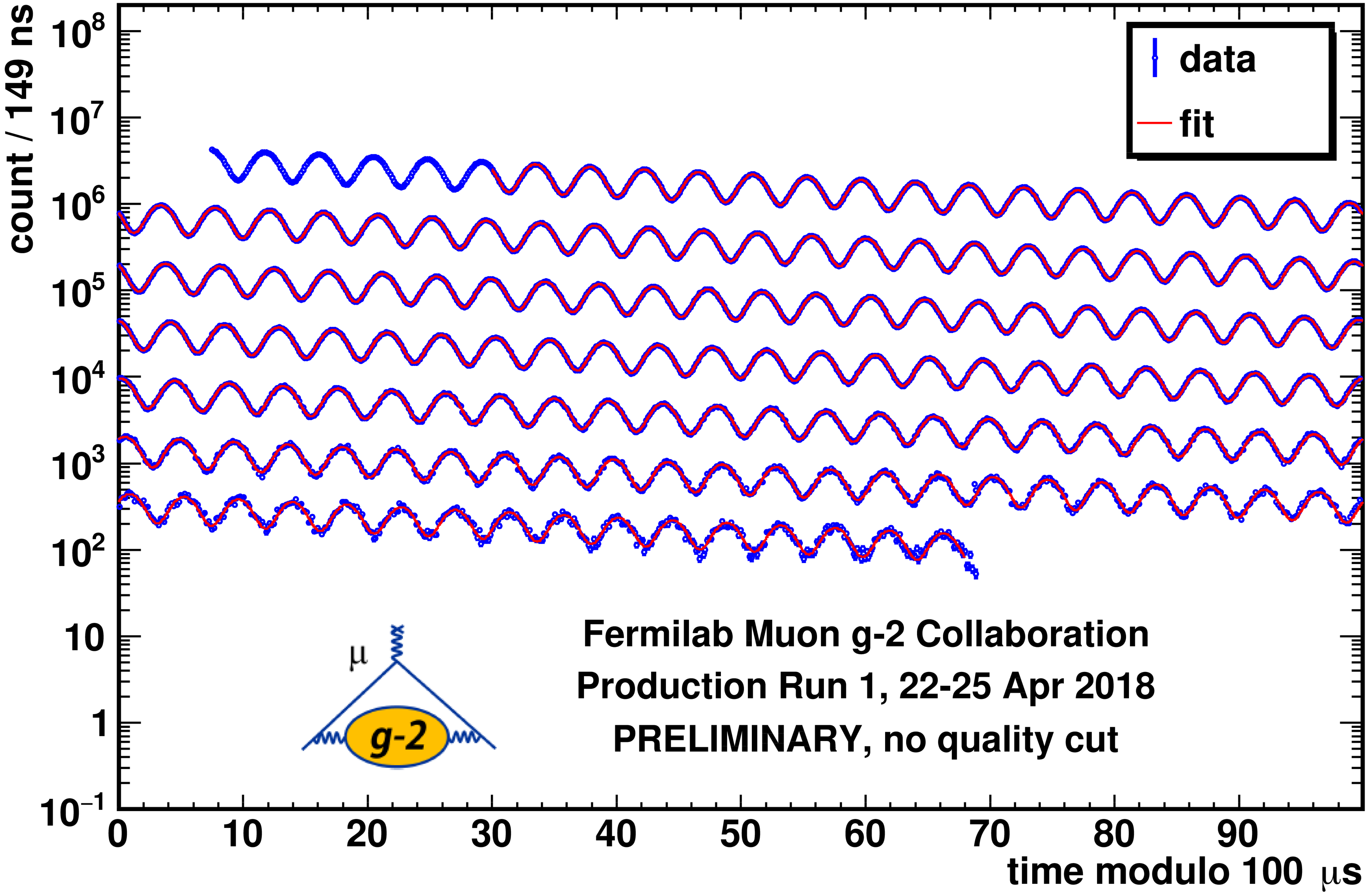
$$\cos(\theta) = \frac{\varepsilon . p}{|p|}$$





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

Example 'wiggle' plot

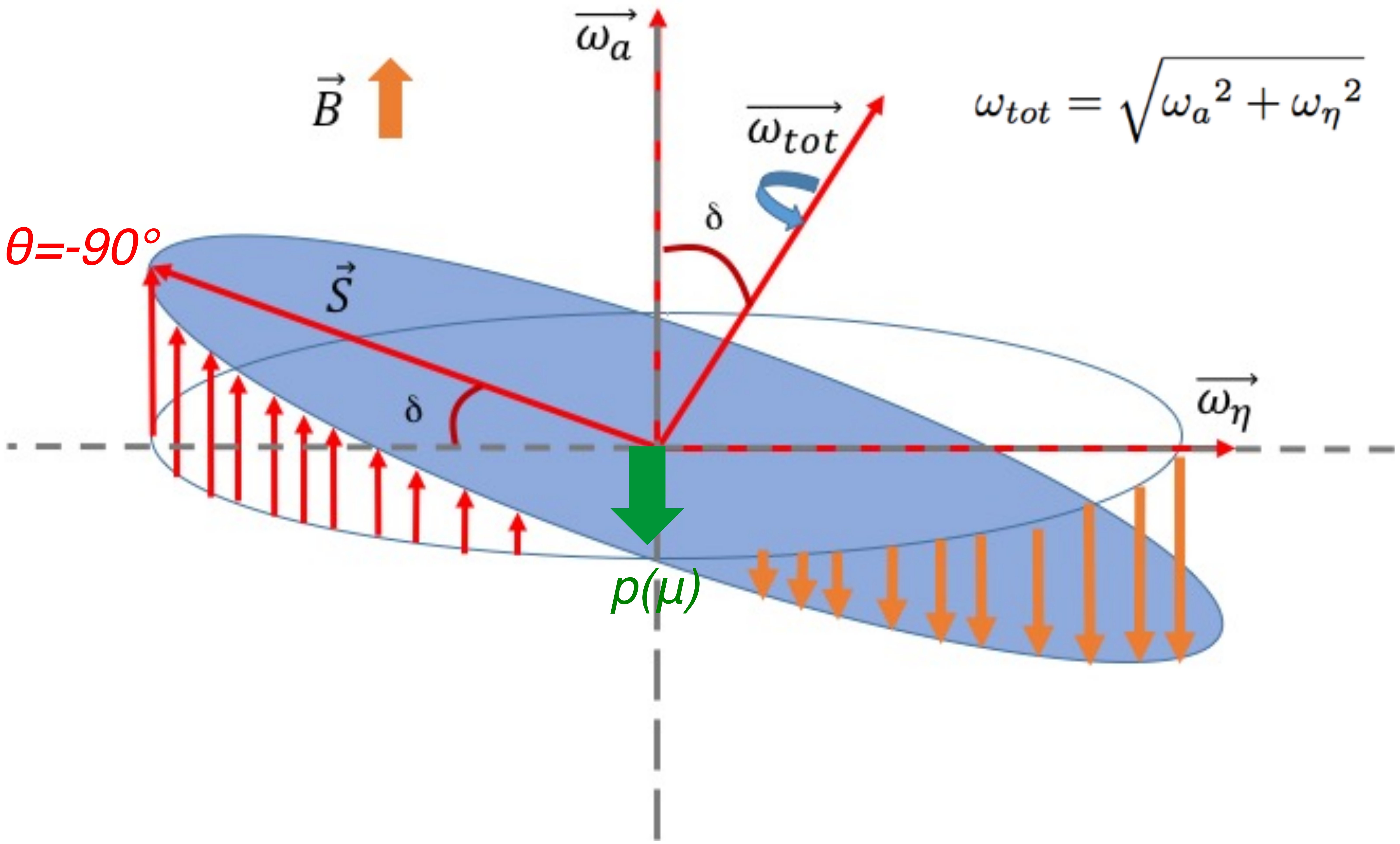


- Exponential decay of μ^+ with boosted lifetime $\tau \approx 64.4\mu s$
- ω_a oscillation with $T_a \approx 4.4\mu s$
- Maxima corresponds to $\theta=0°$
- Minima at $\theta=180°$
- Amplitude determined by energy threshold

- But what happens when an EDM is introduced?...

EDM in a storage ring

- Causes an increase in muon precession frequency
- Precession plane tilts towards center of ring
- Oscillation is 90° out of phase with the a_μ oscillation

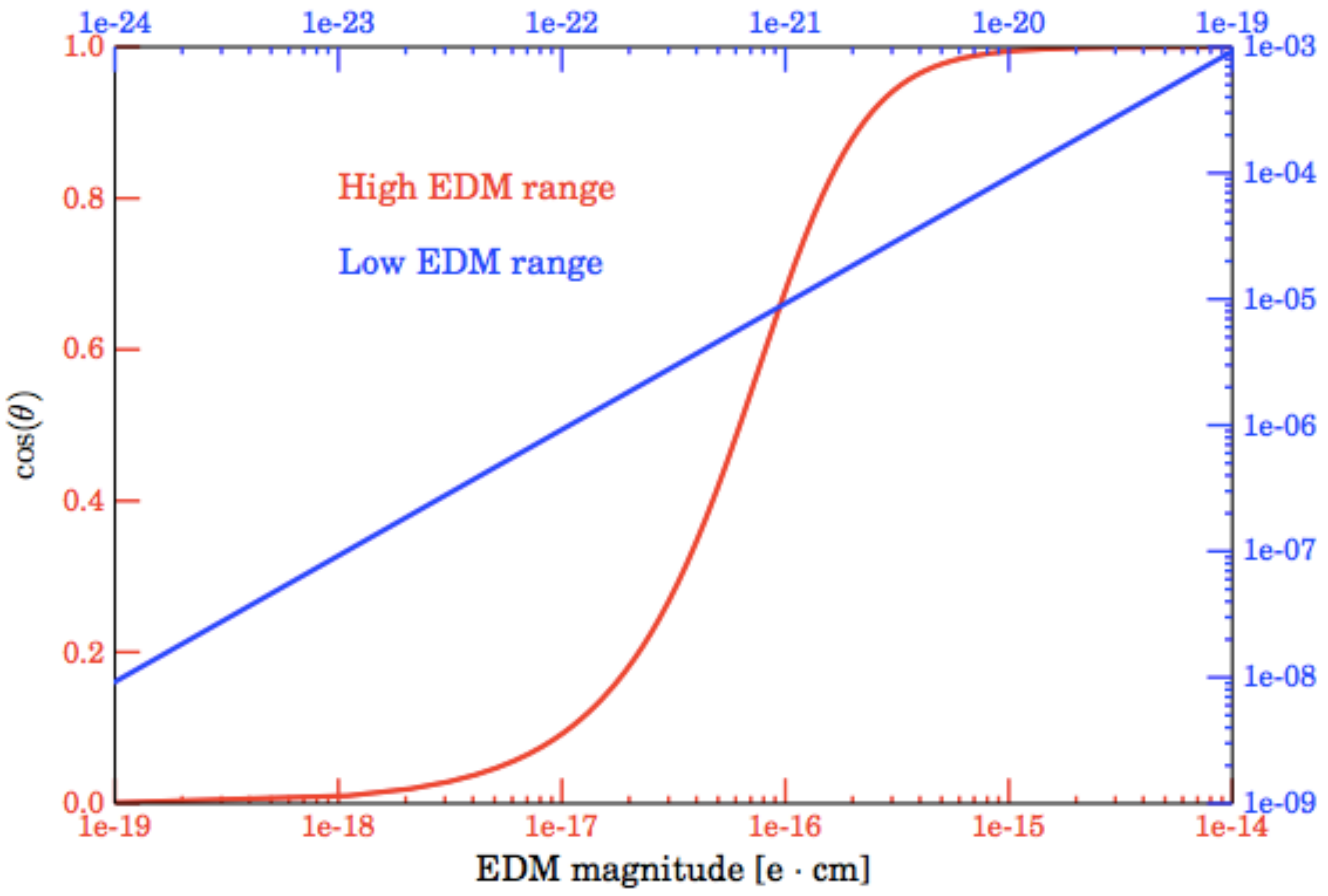


Effect of tilted plane

- Tilt of the precession plane (δ) is determined by the size of the EDM, and is given by

$$\delta = \tan^{-1}\left(\frac{\omega_\eta}{\omega_a}\right) = \tan^{-1}\left(\frac{\eta\beta}{2a_\mu}\right)$$

Lorentz boost: $$\delta' = \tan^{-1}\left(\frac{\tan\delta}{\gamma}\right)$$



- Further reduction by ~10% due to the fact that not all positrons are emitted aligned with the polarisation vector

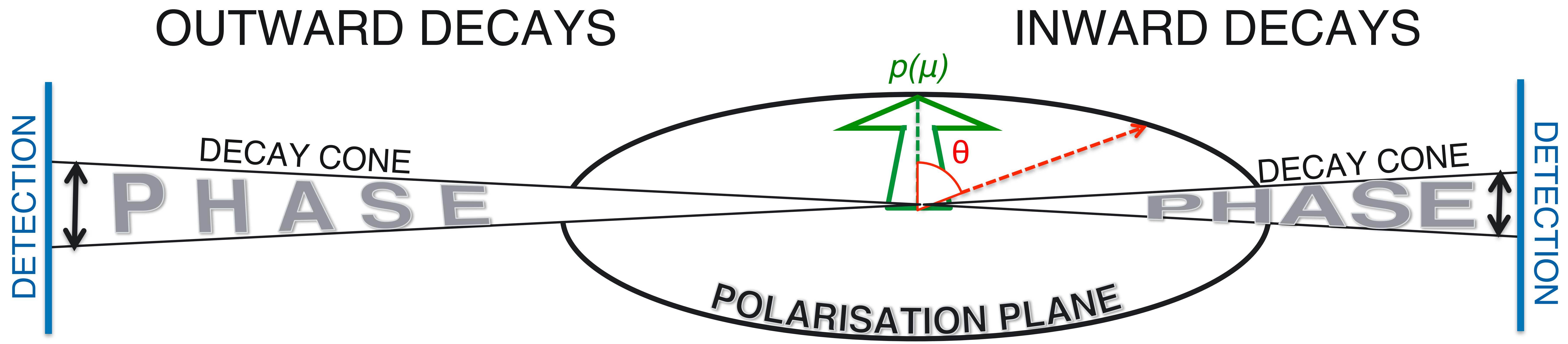
EDM experimental signature

- For a 'large' EDM can look for increase in precession frequency
  - For scale, the BNL measured ω_a - ω_{SM} gives $d_\mu \approx 2.5 \times 10^{-19}$ e.cm
- To go beyond that, there are 2 approaches:

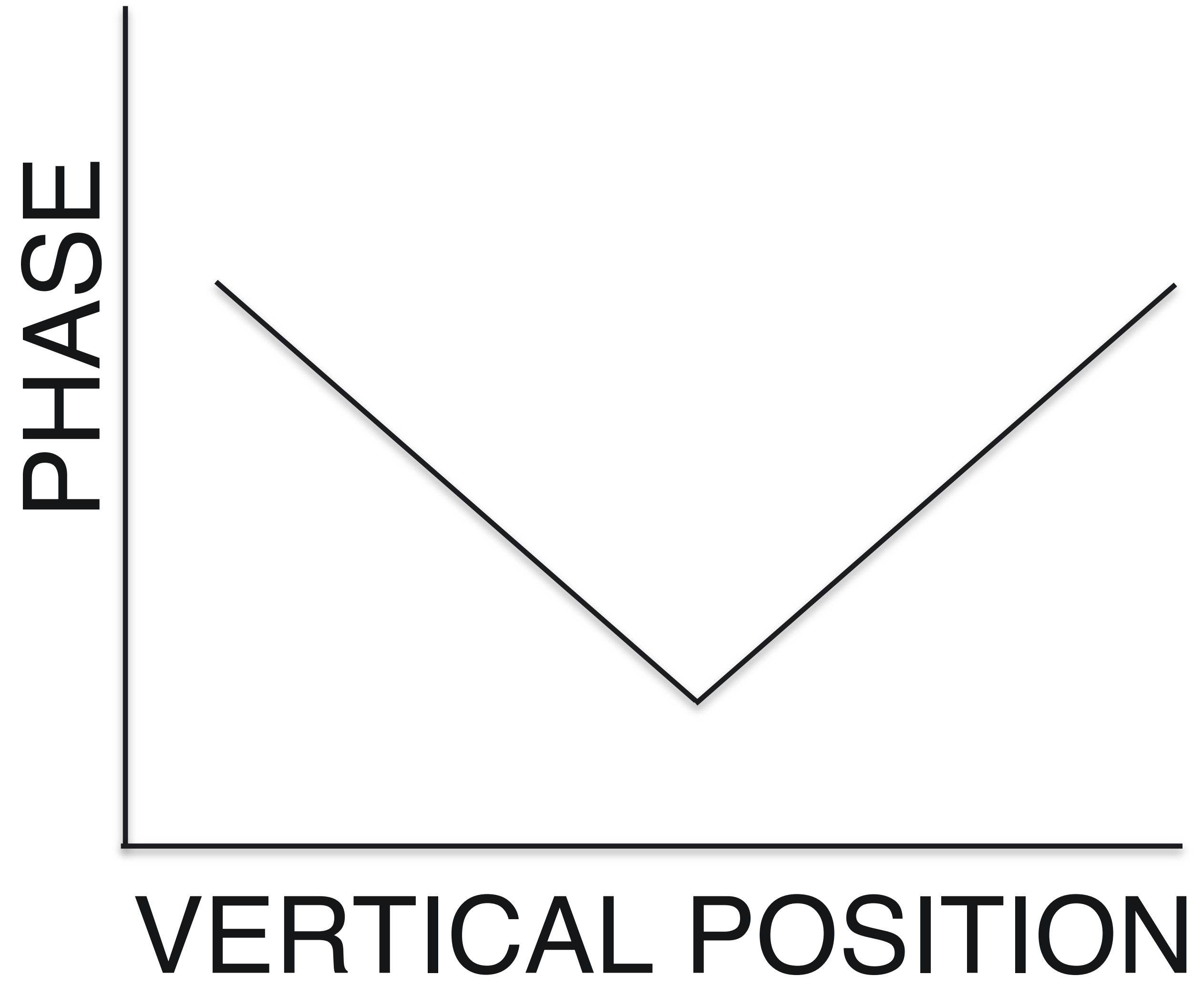
1. Asymmetry in phase of measured ω_a vs vertical position

2. Oscillation of detected positrons vertical position/angle
   - At same frequency as ω_a
   - $\pm 90^\circ$ out of phase with ω_a (depending on sign of d_μ)

Phase Asymmetry

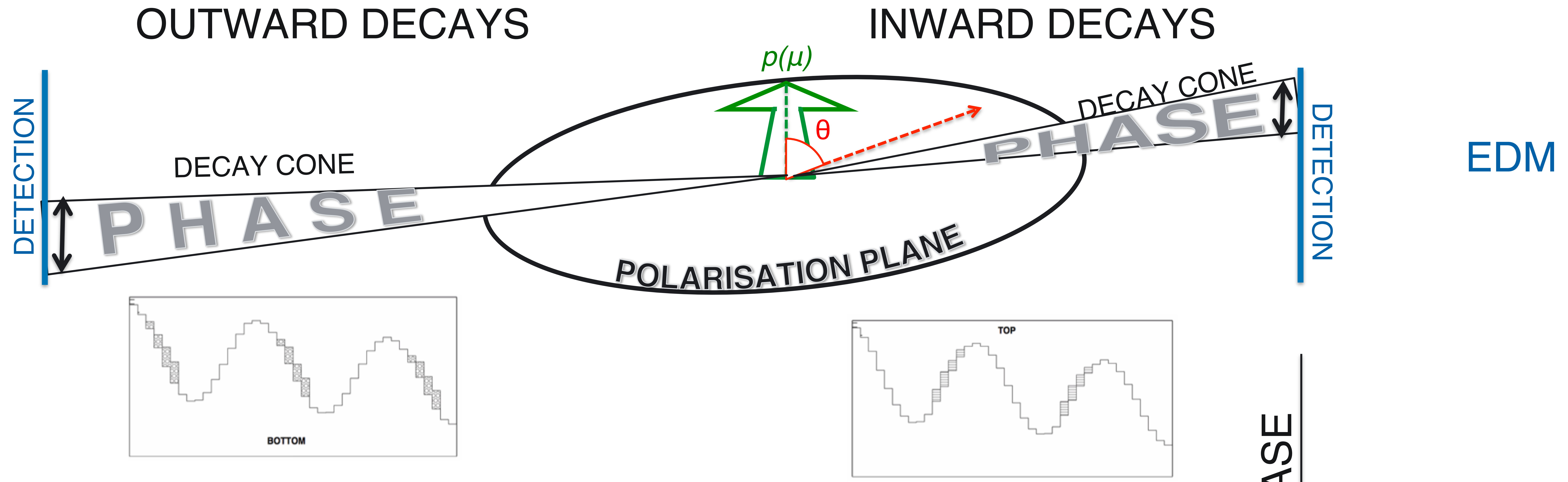


No EDM

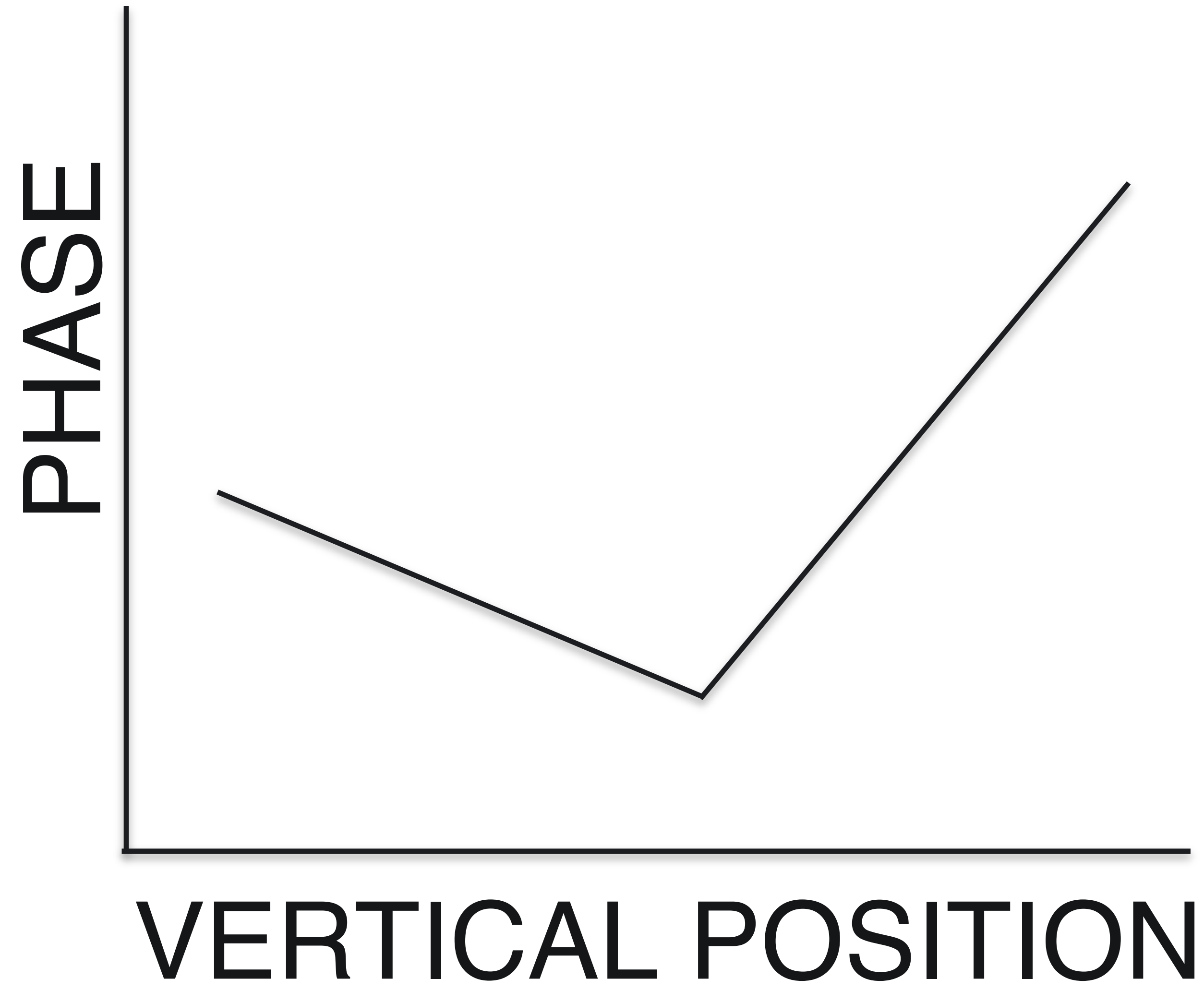


- Inward (towards calorimeter) decays travel a shorter distance than outward
- When there is no EDM, the polarisation plane is flat, and there is no vertical asymmetry

Phase Asymmetry

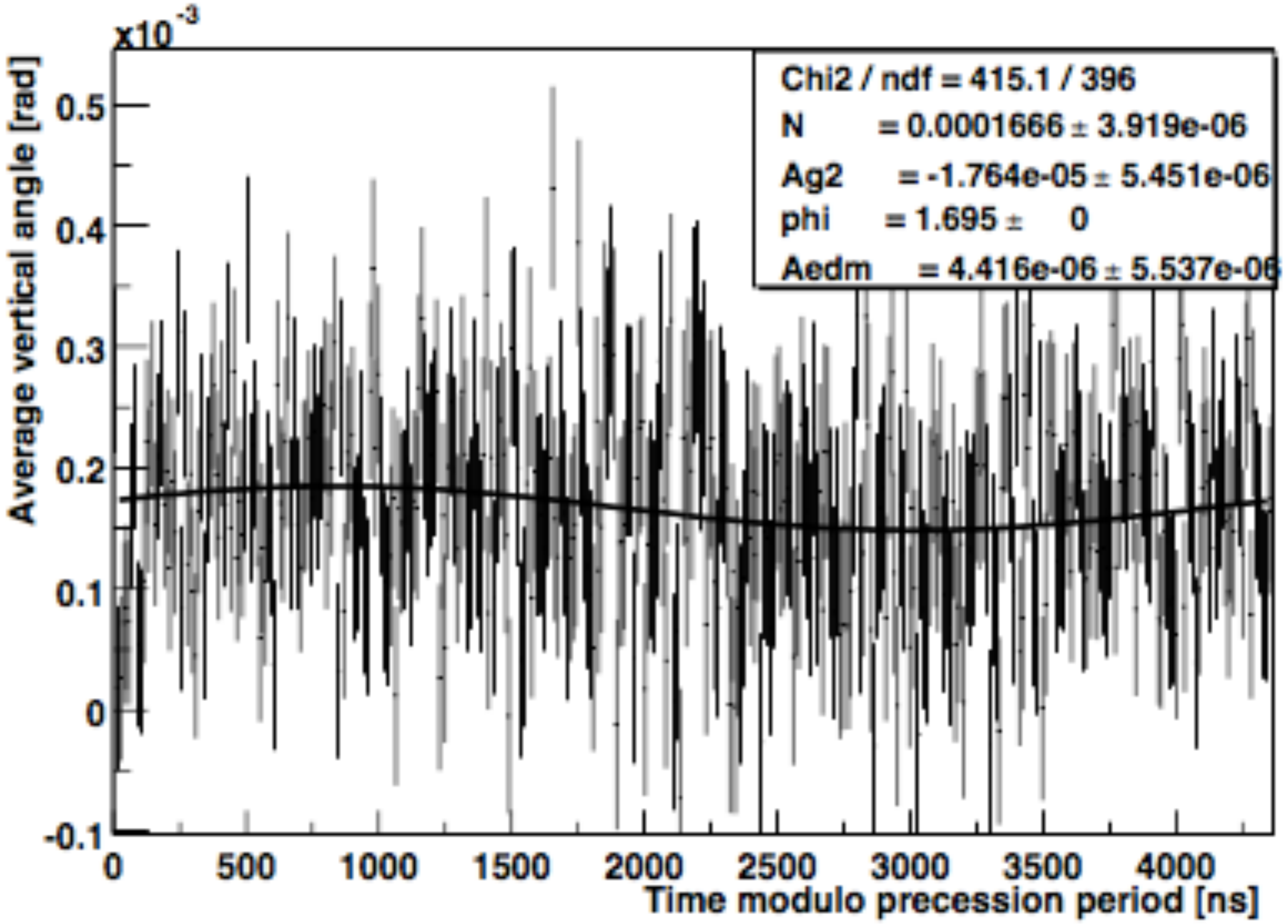


- Inward (towards calorimeter) decays travel a shorter distance than outward
- When there is an EDM, the polarisation plane is tilted, and there is a vertical asymmetry



Vertical oscillations

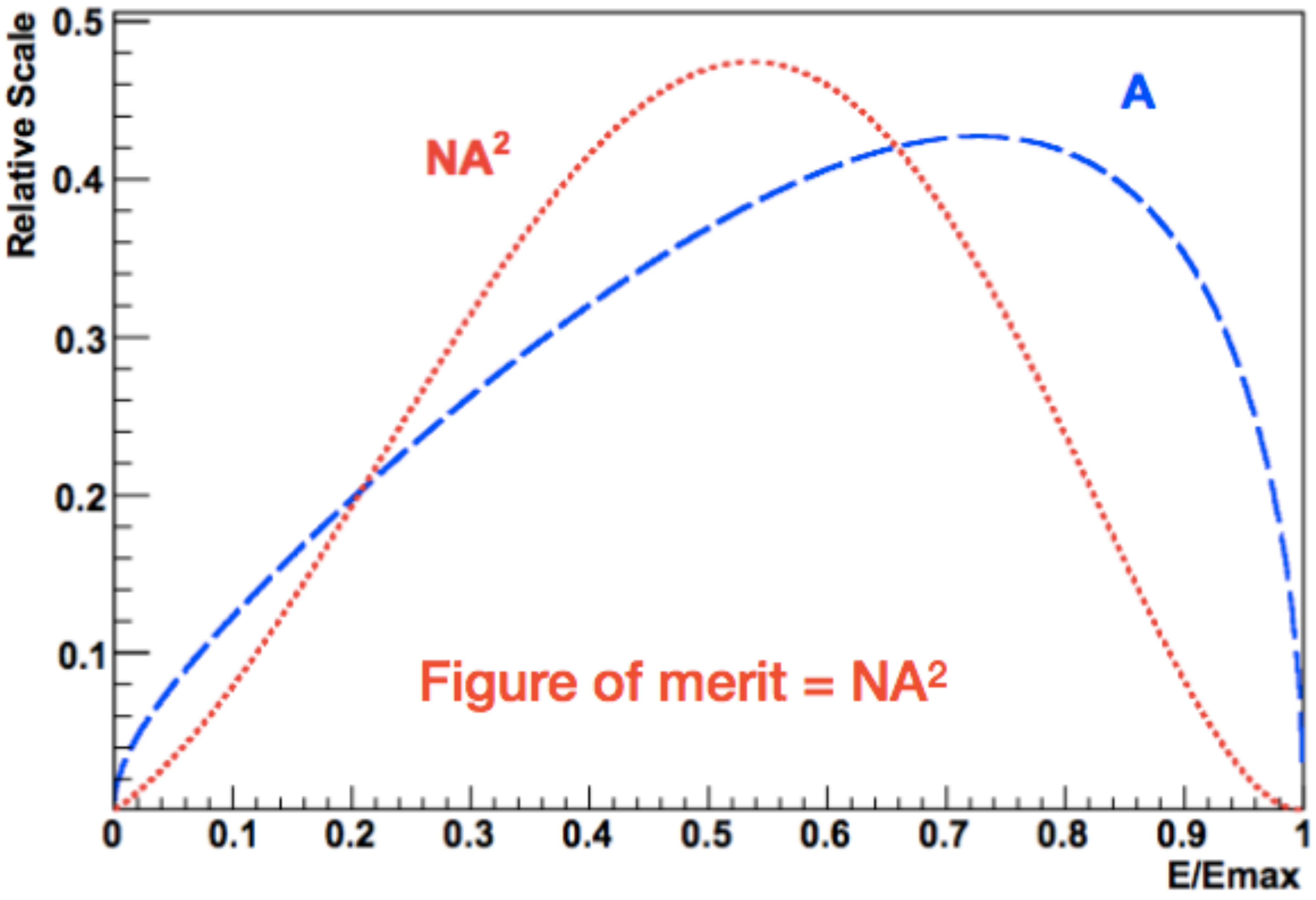
- Can also look directly at vertical position and angle measurement
- Angular measurement less dependent on detector misalignment

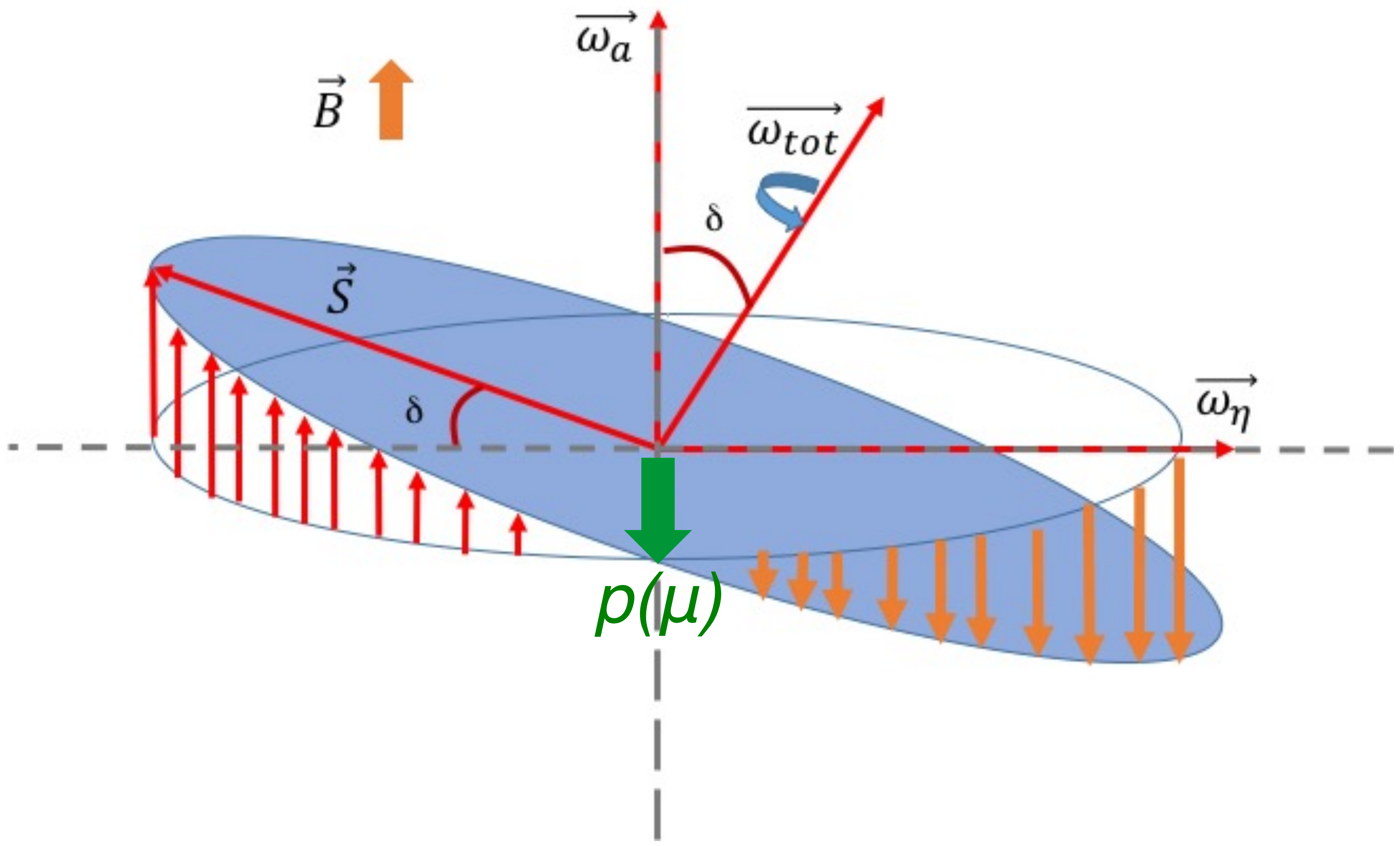


- Get phase and period from ω_a fit
- Fold data over at precession period
- Directly look for sinusoidal oscillation out of phase with ω_a

EDM signal

- Tilt in precession plane is instantaneously 0 when polarisation vector is pointing along muon momentum vector - no sensitivity to EDM
- Maximal sensitivity at 90°, for mid-range momenta





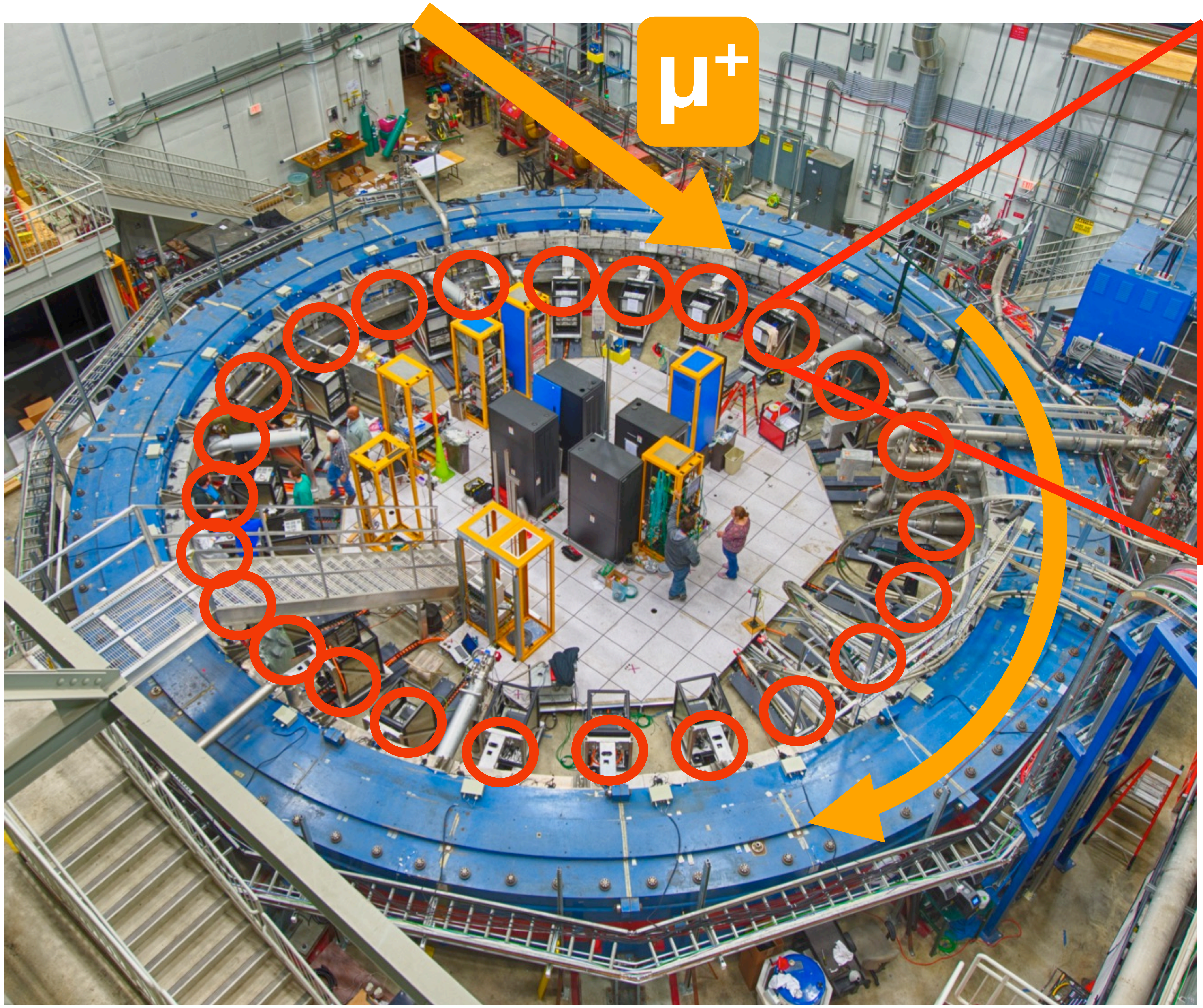
BNL results

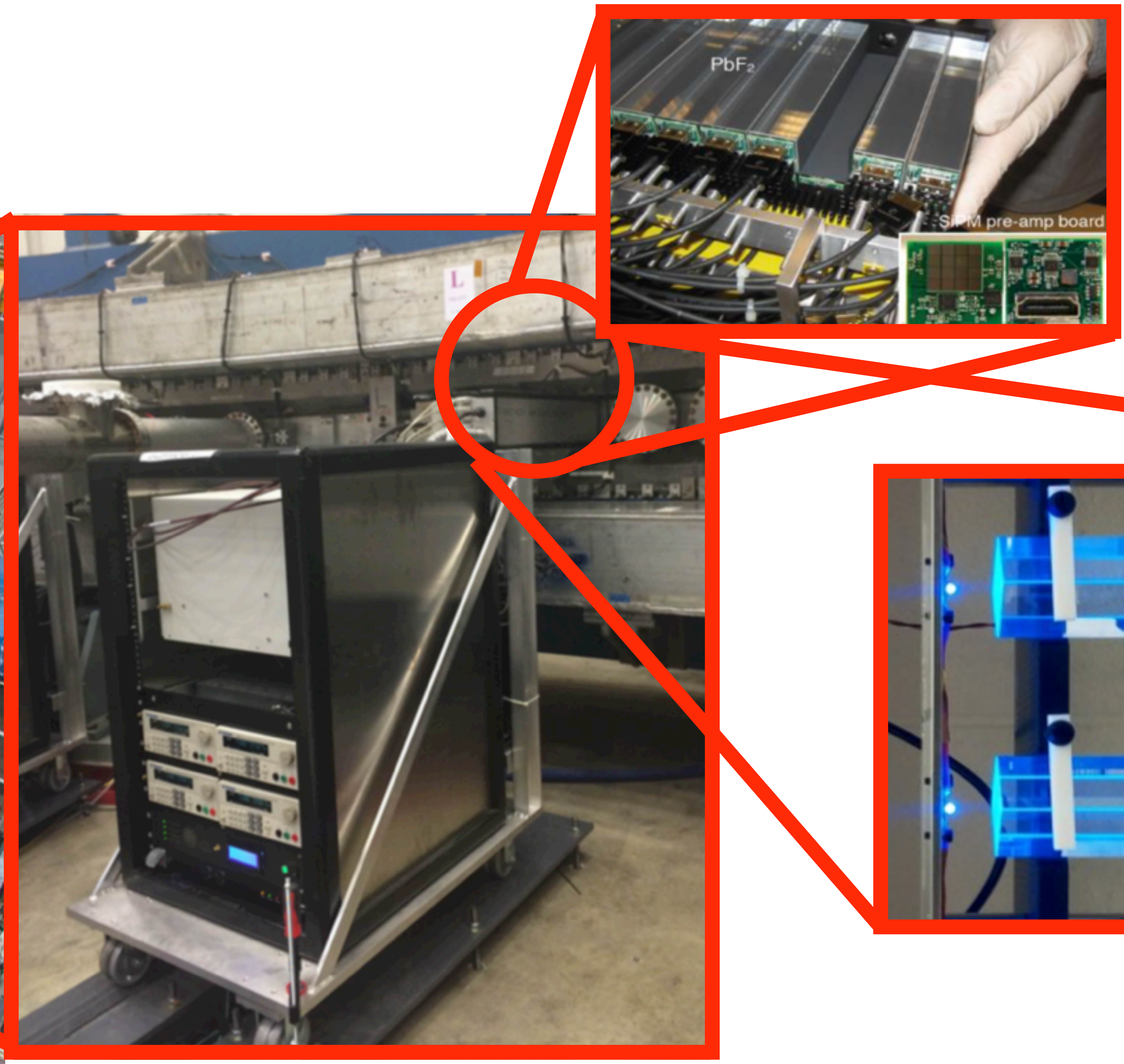
- Summary of BNL results:

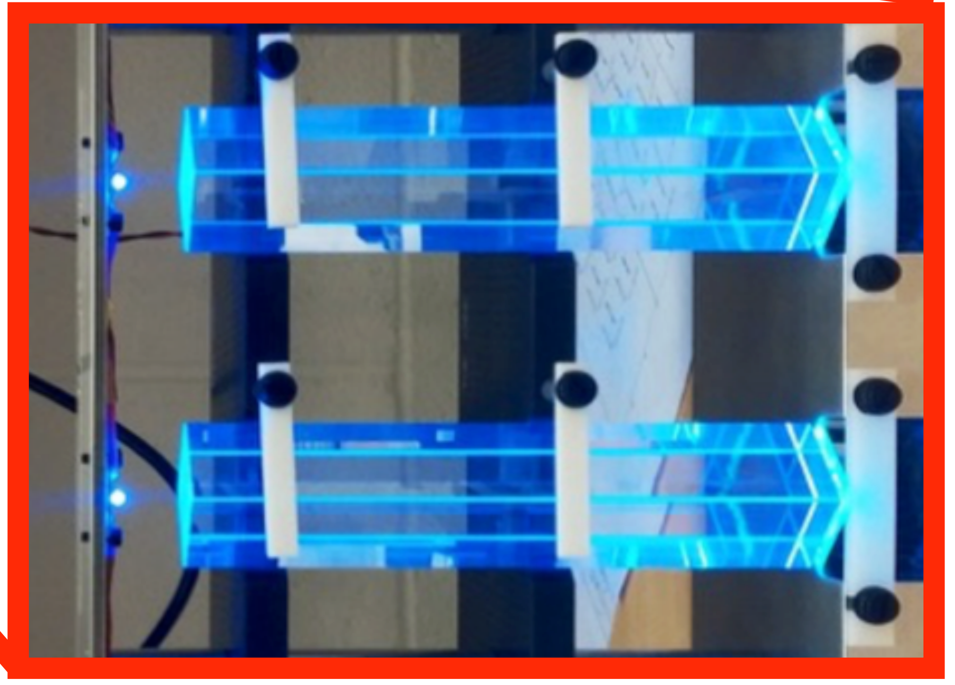
<table>
<tr><th>Method</th><th>Dataset</th><th>Particle</th><th>Measurement (10^{-19} e.cm)</th><th>$|d_\mu|$ e.cm (95% CL)</th></tr>
<tr><td>TWC <y’></td><td>1999, 2000</td><td>μ^+</td><td>$-0.04 \pm 1.6 \pm 0.0$ ($\ll 1.6$)</td><td>$< 3.2 \times 10^{-19}$</td></tr>
<tr><td>FSD <y></td><td>2000</td><td>μ^+</td><td>$-0.1 \pm 0.34 \pm 1.36$</td><td>$< 2.9 \times 10^{-19}$</td></tr>
<tr><td>PSD <y></td><td>2001</td><td>μ^-</td><td>$-0.1 \pm 0.28 \pm 0.70$</td><td rowspan="2">$< 1.9 \times 10^{-19}$</td></tr>
<tr><td>PSD [phase]</td><td>2001</td><td>μ^-</td><td>$-0.48 \pm 0.73 \pm 1.09$</td></tr>
</table>

- Direct tracker method only available for 1999, 2000 dataset
  - Statistically limited ~ 4.7 million high quality tracks in total BNL dataset
- Position and phase measurements systematically limited
  - Detector alignment is dominant source of uncertainty

FNAL Calorimeters



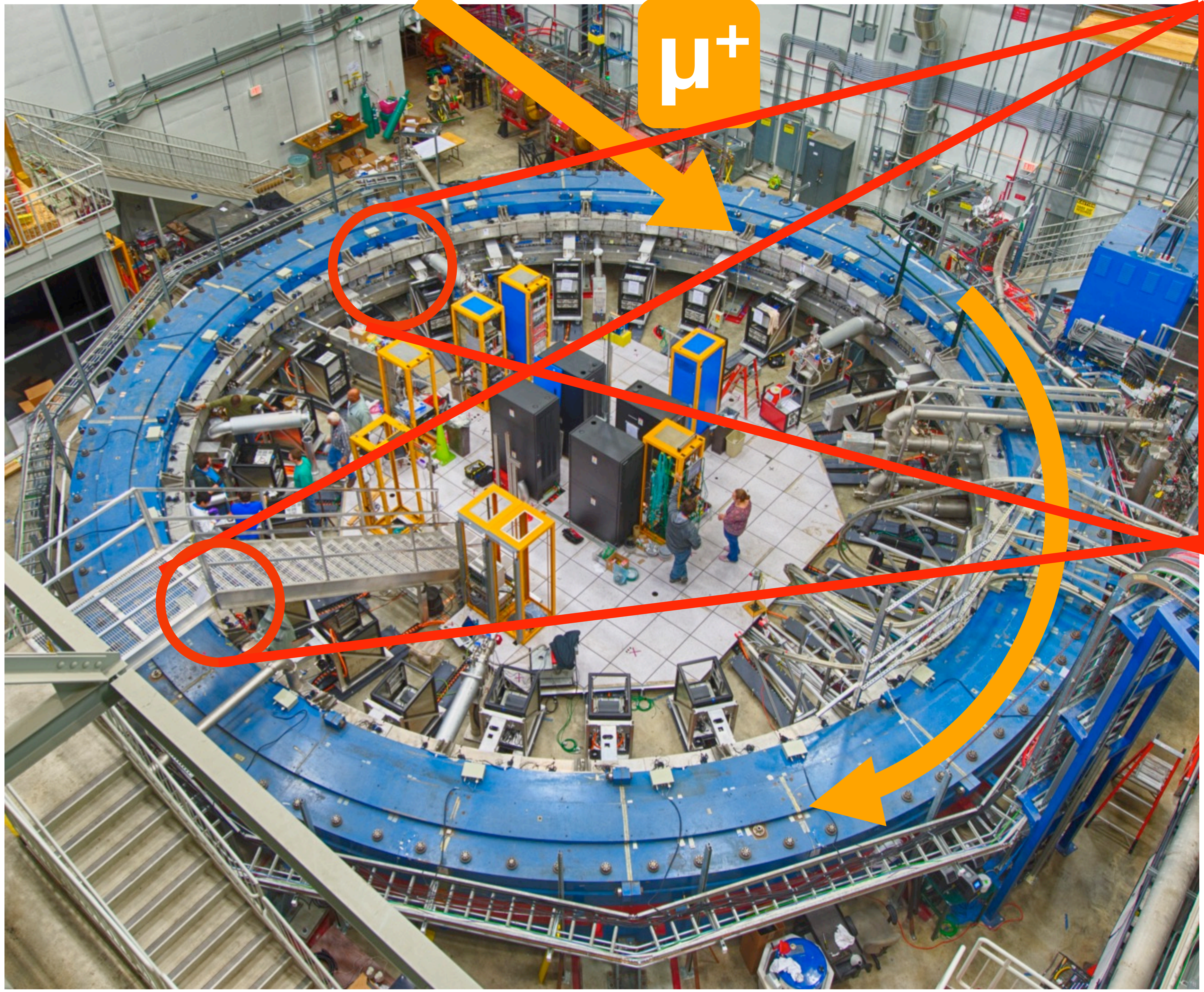


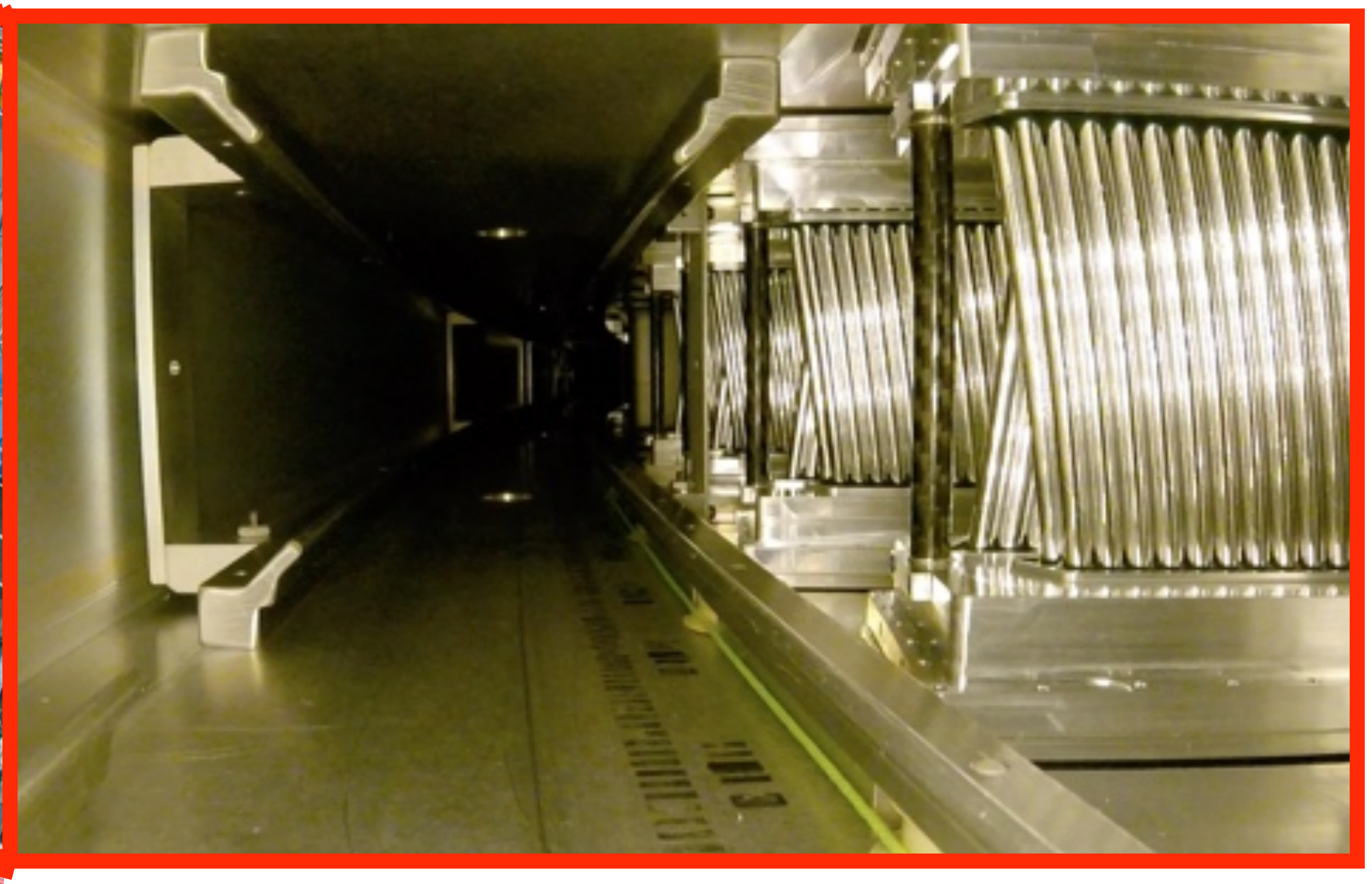


24 segmented PbF_2 crystal calorimeters

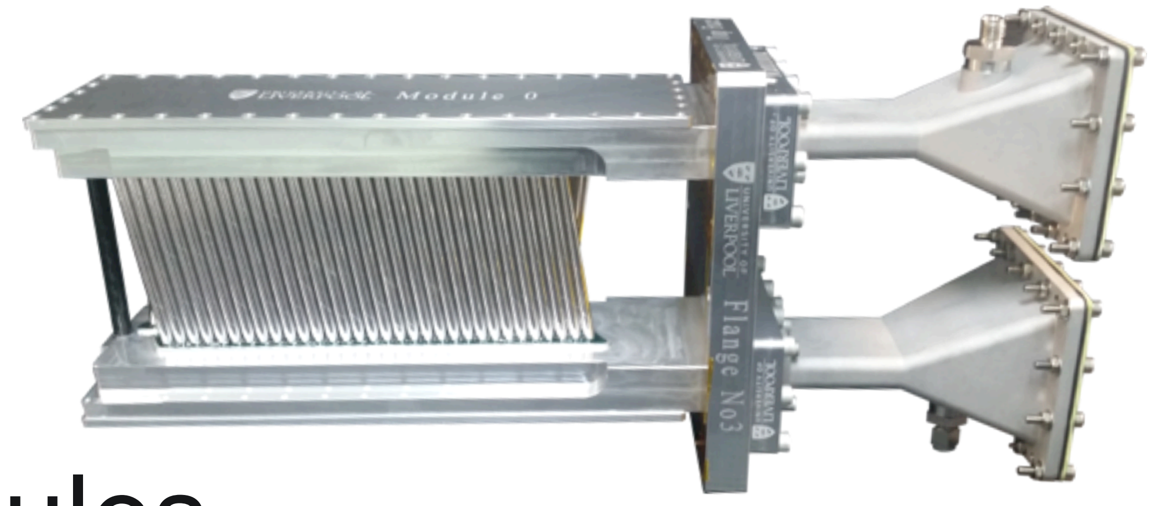
- Each crystal array of 6 x 9 PbF_2 crystals
  - 2.5 x 2.5 cm^2 x 14 cm ($15X_0$)
- Readout by SiPMs to 800 MHz WFDs (1296 channels in total)

FNAL Trackers





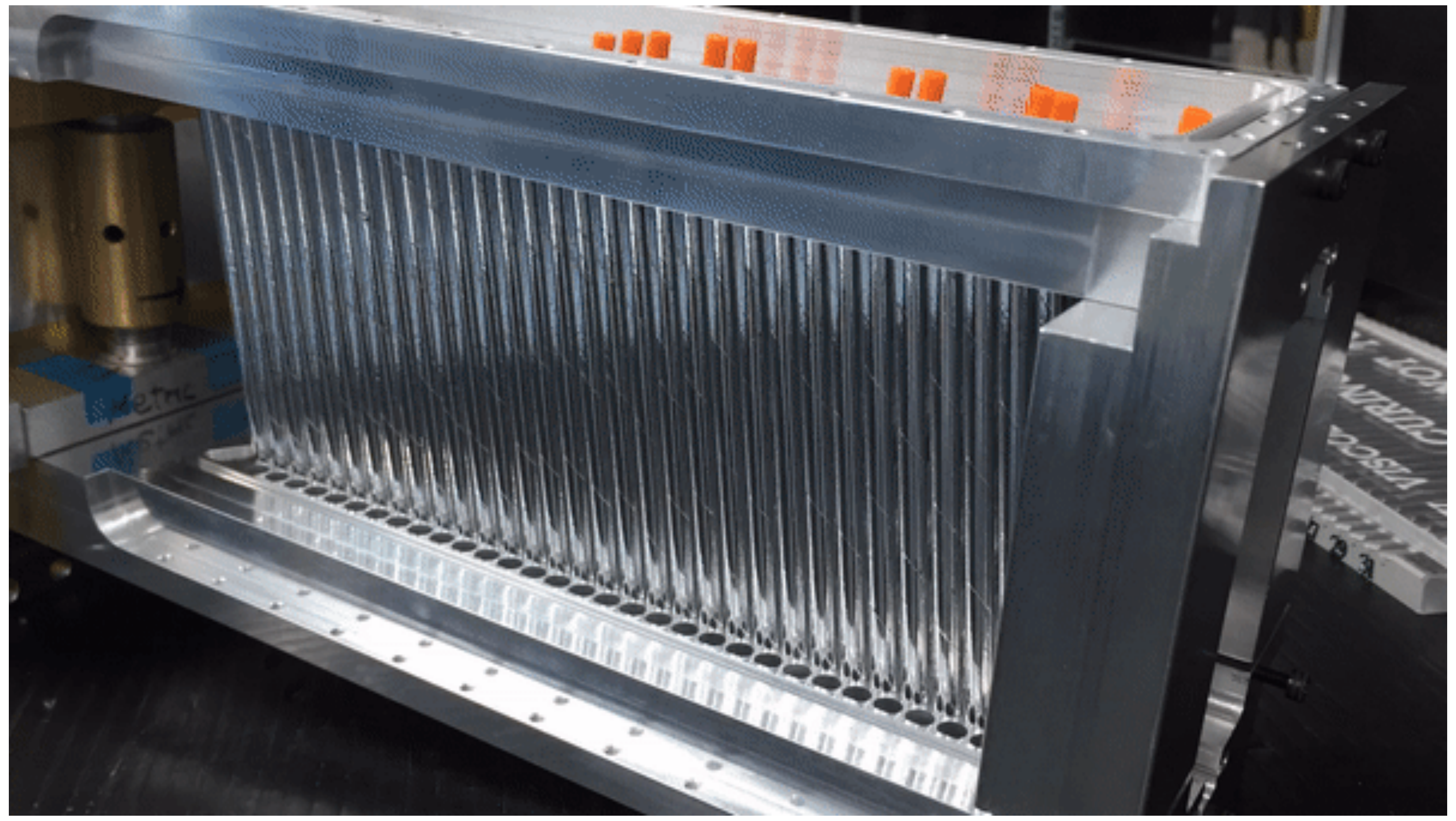
2 Tracking stations

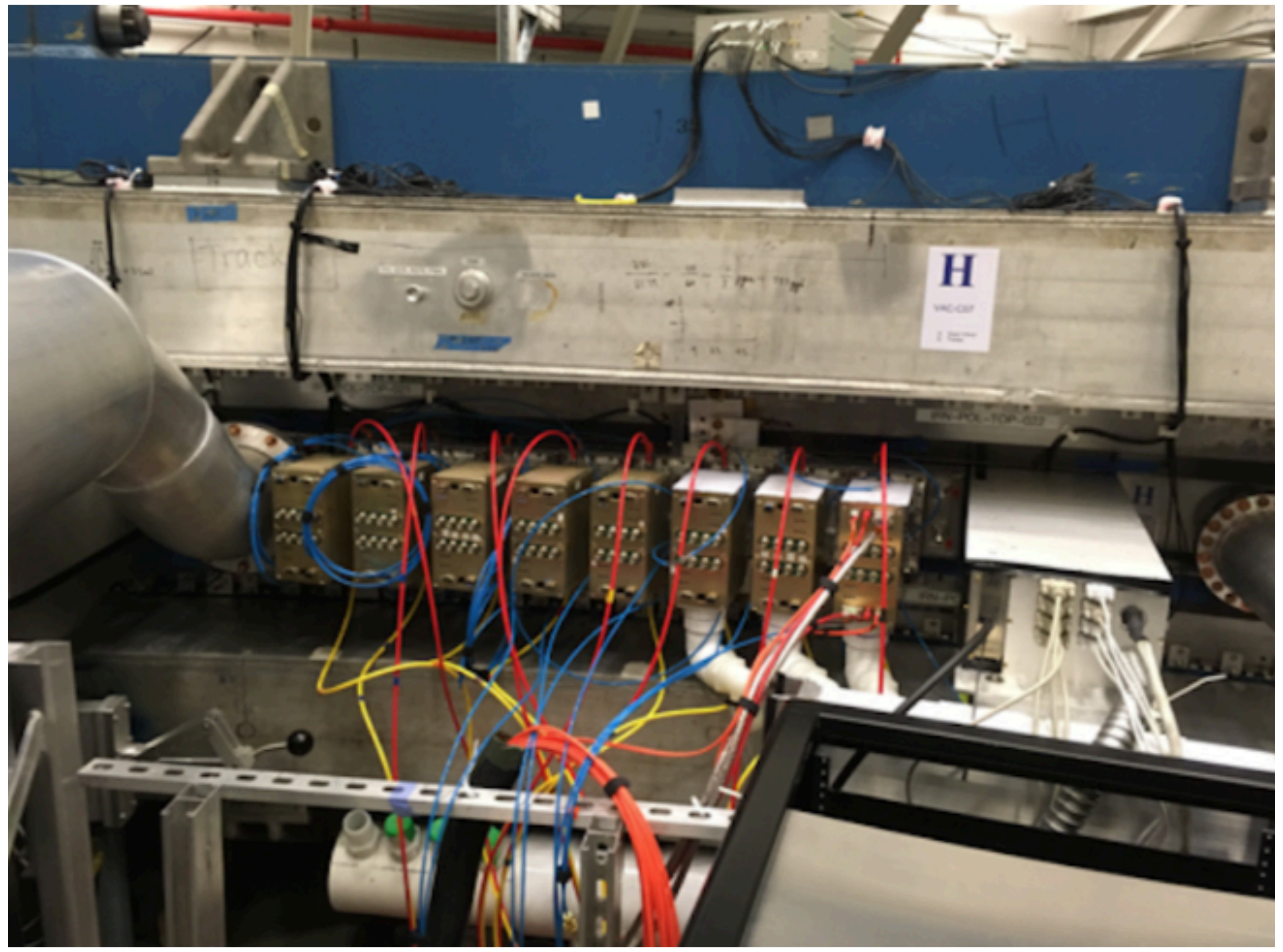


- Each contain 8 modules
- 128 gas filled straws in each module
- Traceback postrons to their decay point

Tracking detectors

- 2 × 8 modules placed at 180° and 270° location
- Each module 32 mylar straws (15μm thick)
- 4 layers per module
- 2 layers place with ±7.5° stereo angle

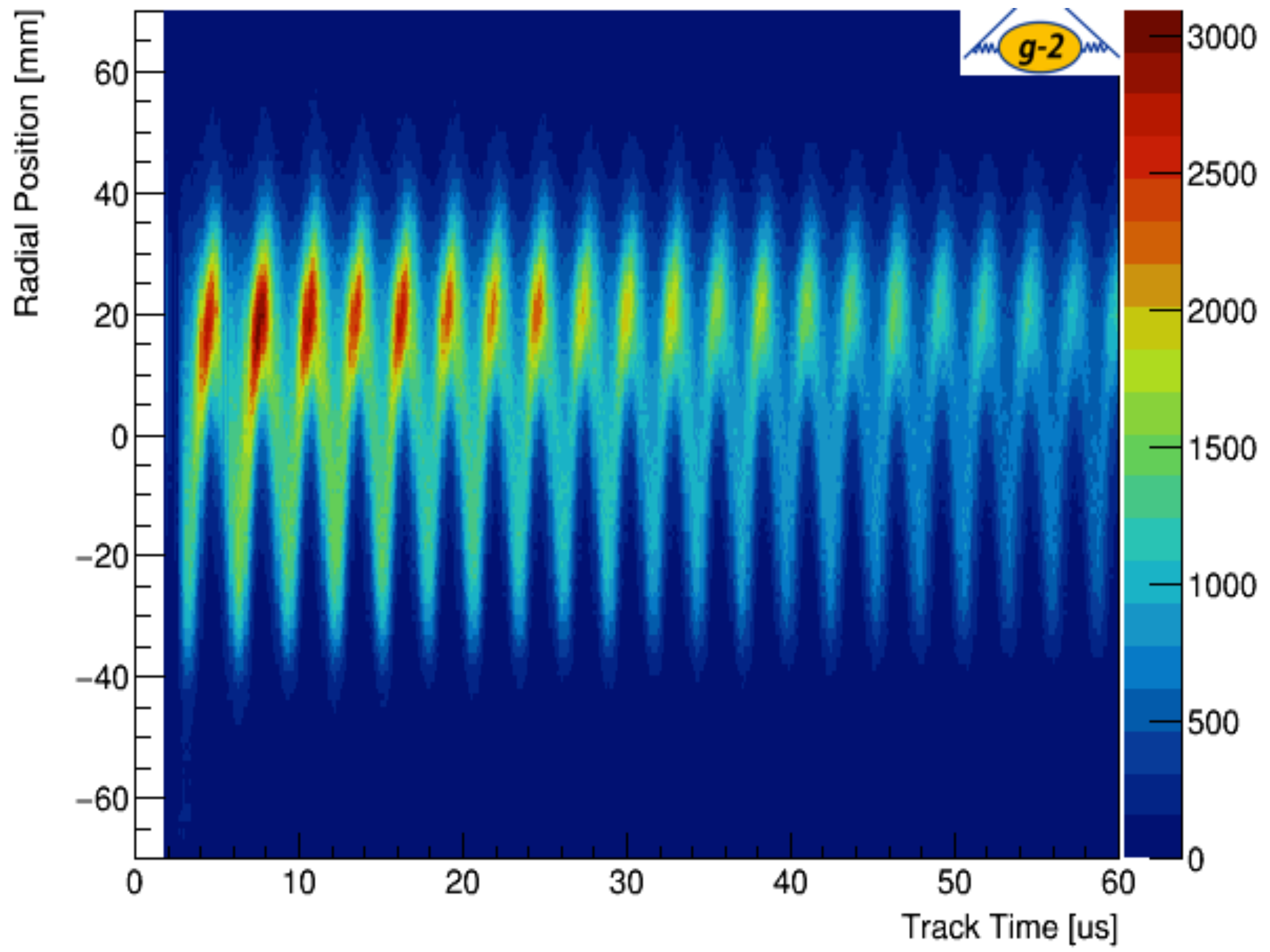


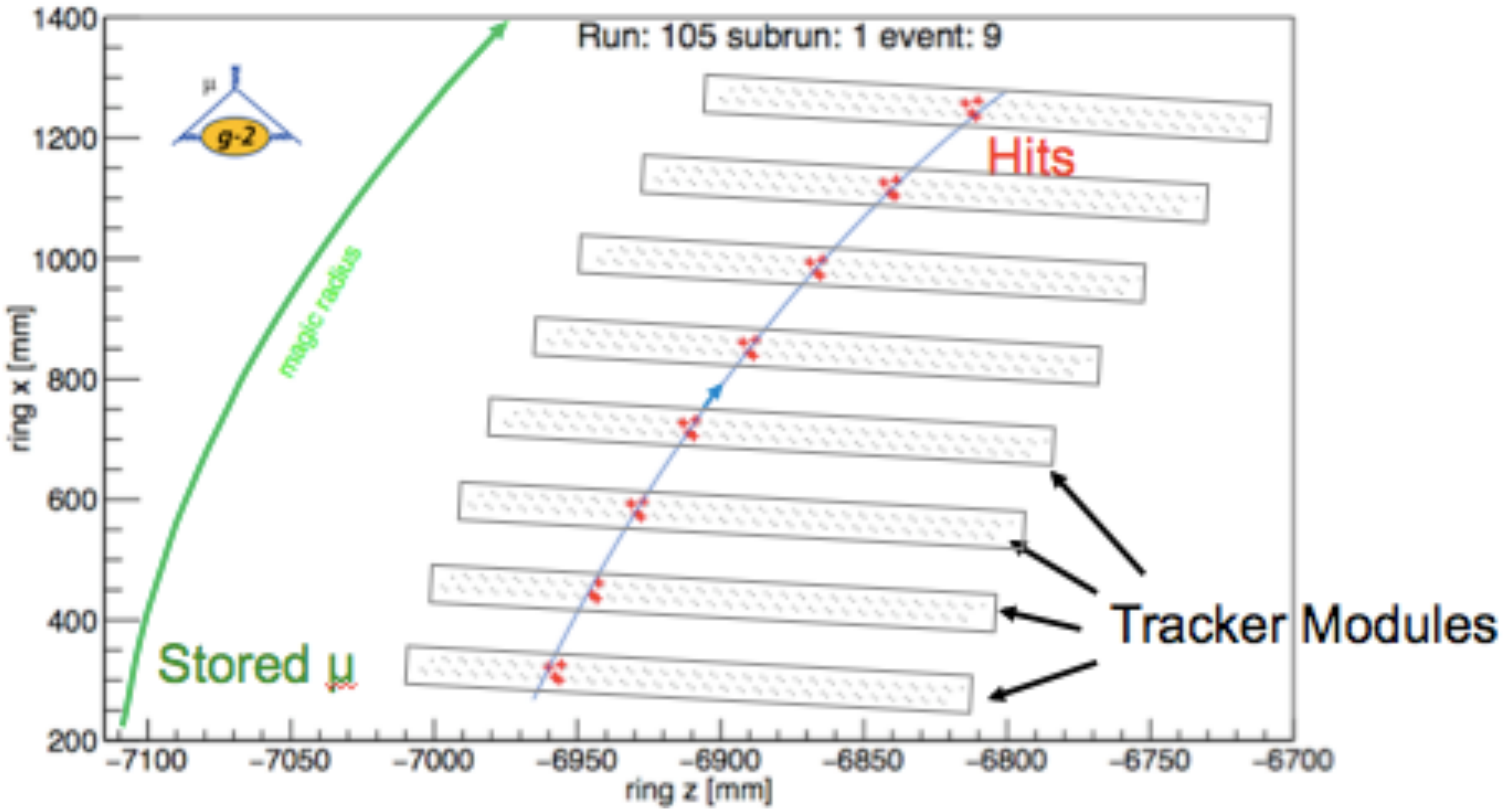


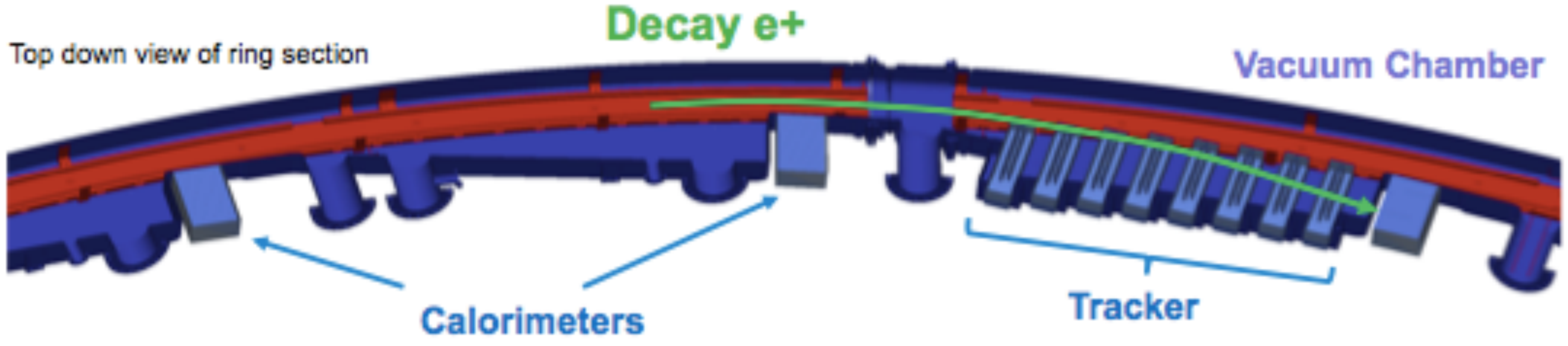
- Filled with 50:50 Argon ethane
- Able to operate at vacuum < 1×10^{-7} torr
- Closer to beam w.r.t. BNL trackers
- Able to track 2μs after beam injection

Position of the beam

- Use Trackers to measure the beam
- Extrapolate tracks back through B-field to point of radial Tangency
- Observe beam moving in time
- Use Trolley-Fixed probe interpolation to tell us the field at these positions

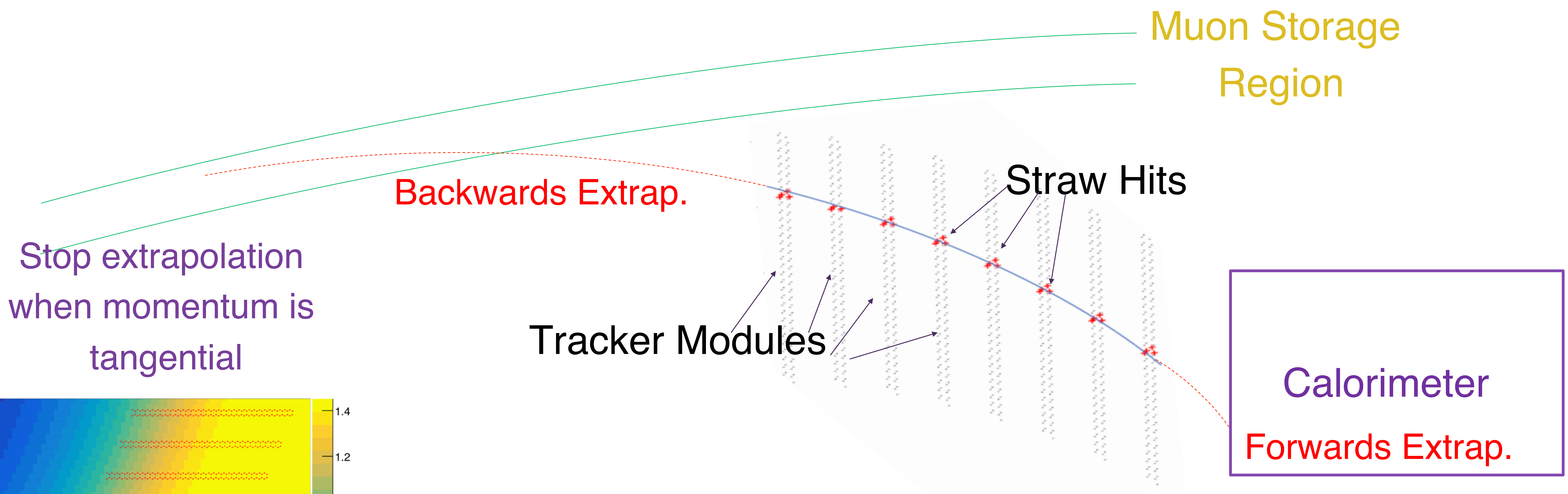


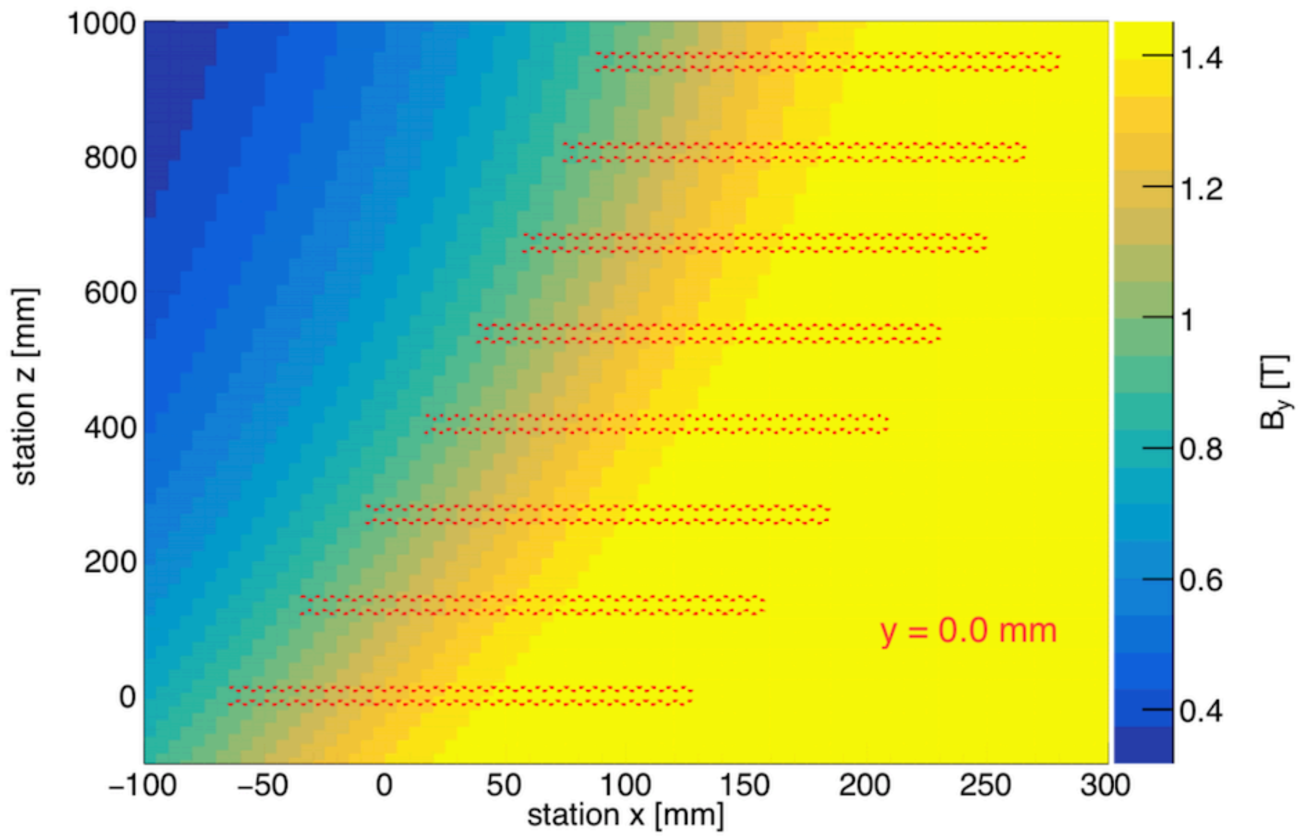




Track Extrapolation

- We extrapolate our tracks through the magnetic field forwards and backwards

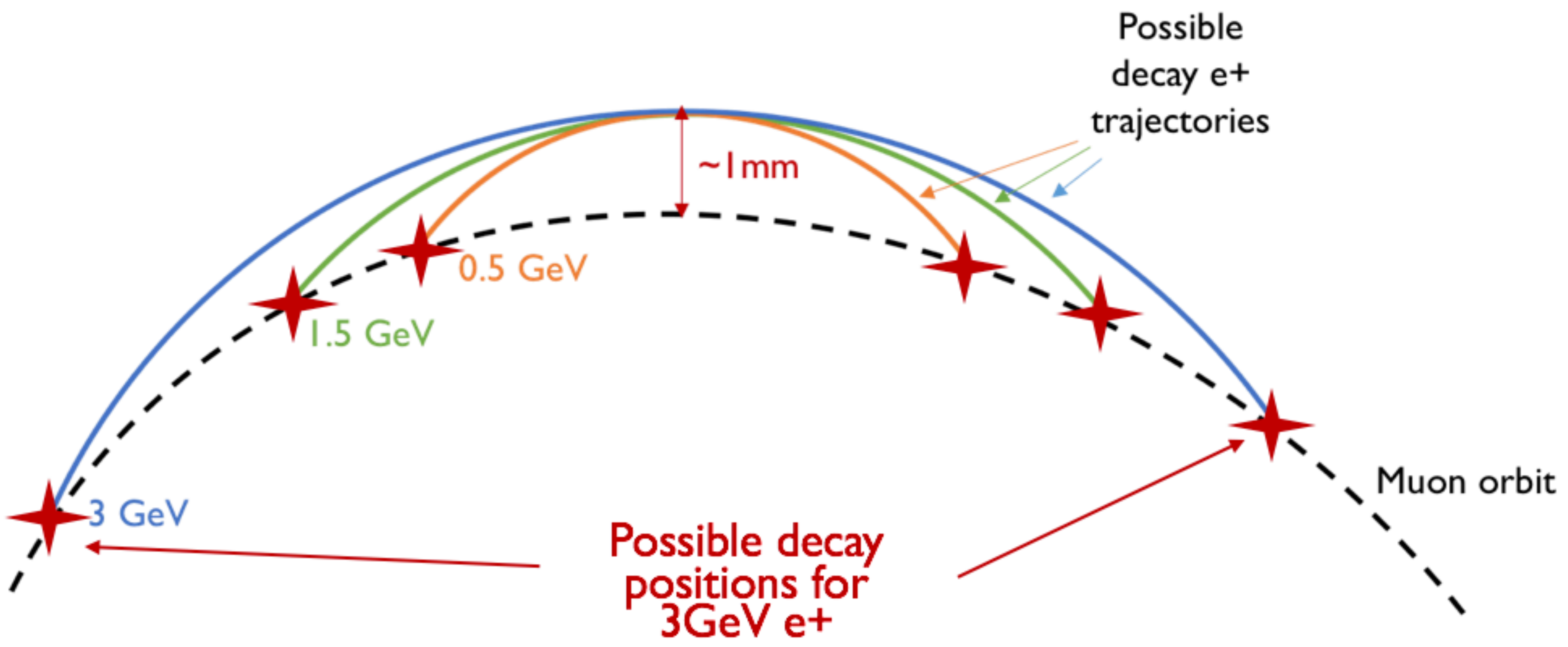




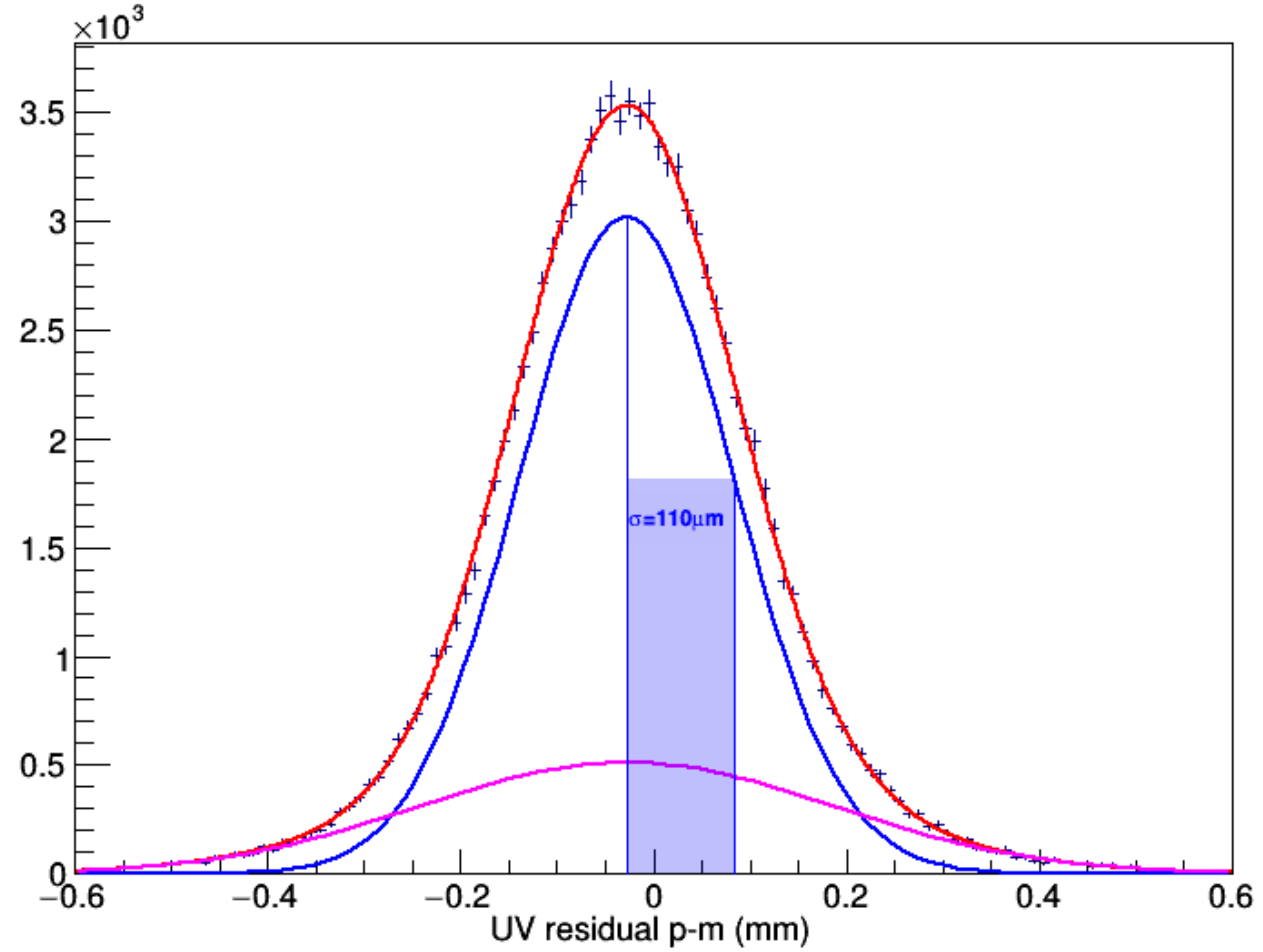
- Straws placed in varying fringe field
- Challenging environment for tracking

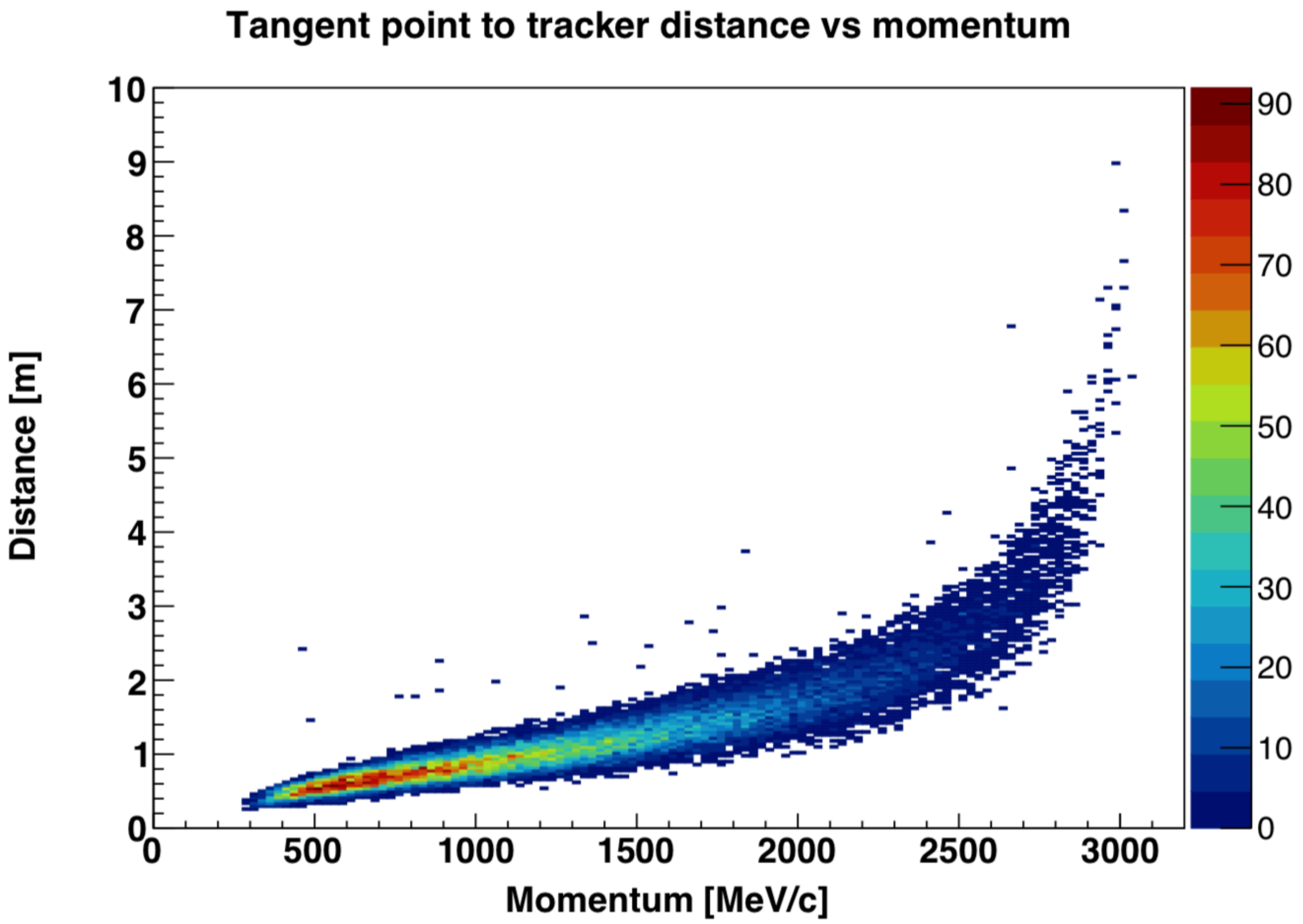
Radial Tangency

- No interaction point to stop tracking at
- Choose point of radial tangency (parallel to magic momentum oribit) as proxy for decay position
- Consistently overestimate radial decay position by ~1mm
- Degeneracy between 2 possible decay points



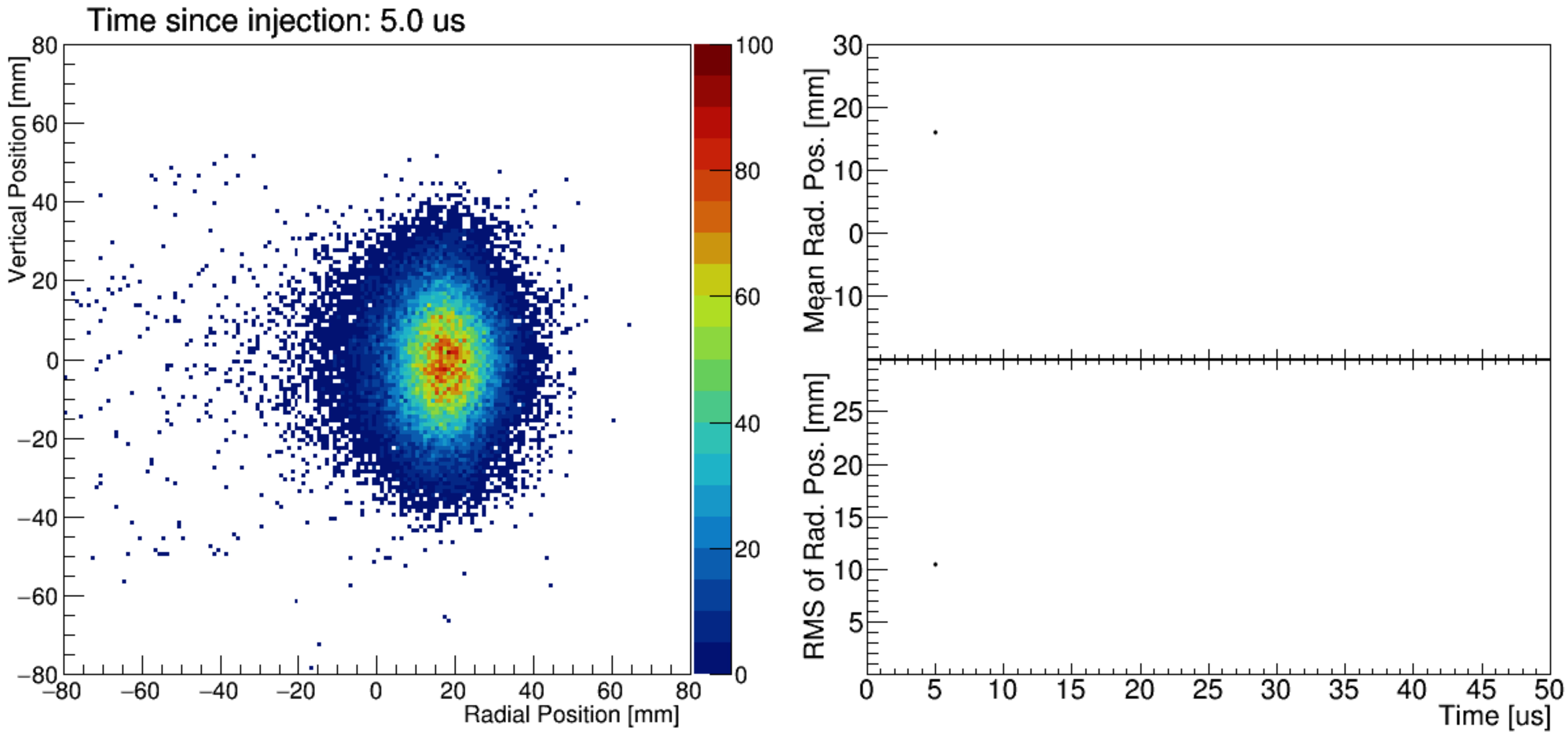
Tracker resolution





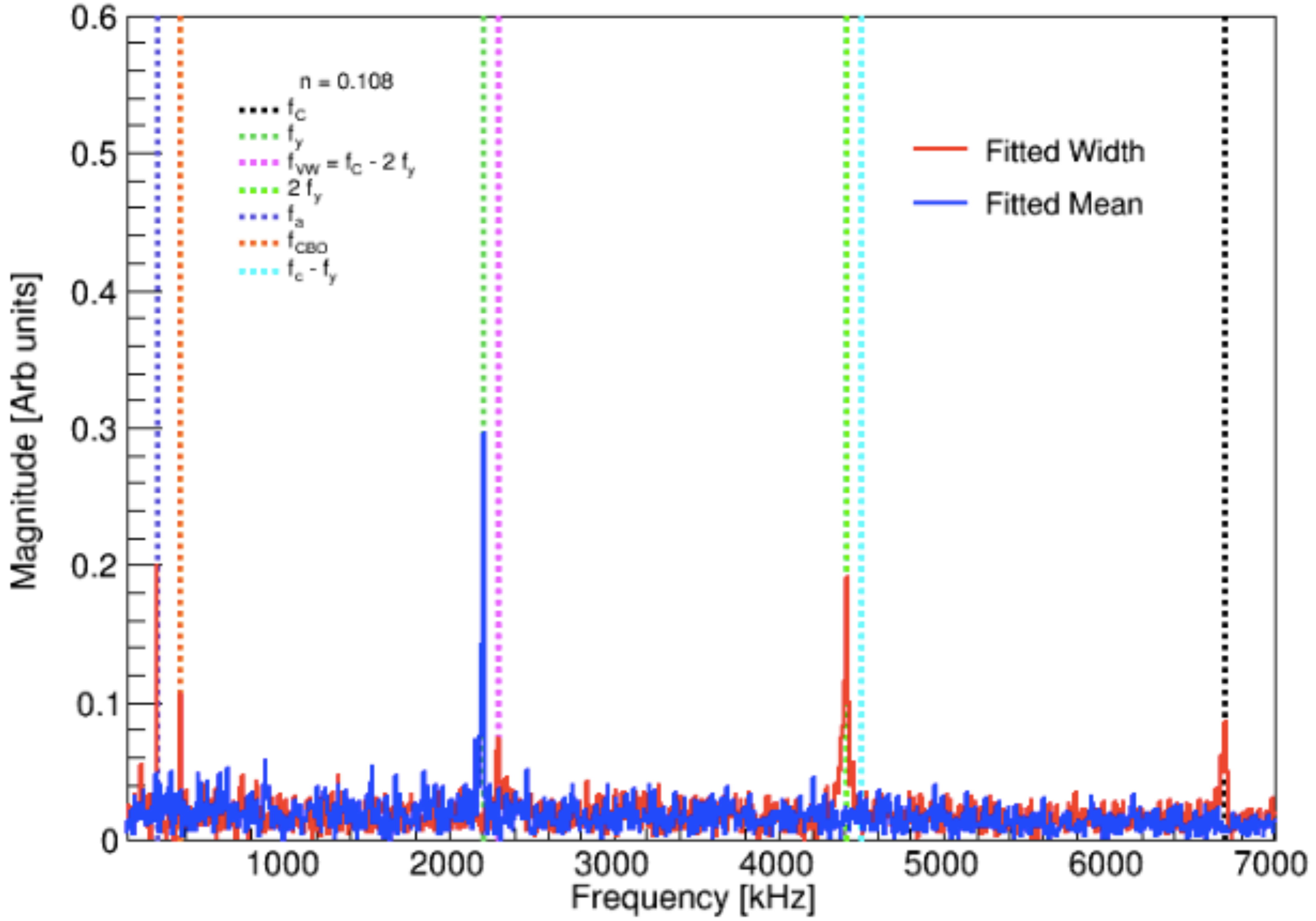
- Per hit resolution ~100μm
- At decay vertex, per track resolution of ~3mm
- Per track vertical angle resolution ~1mrad: error on mean is what matters

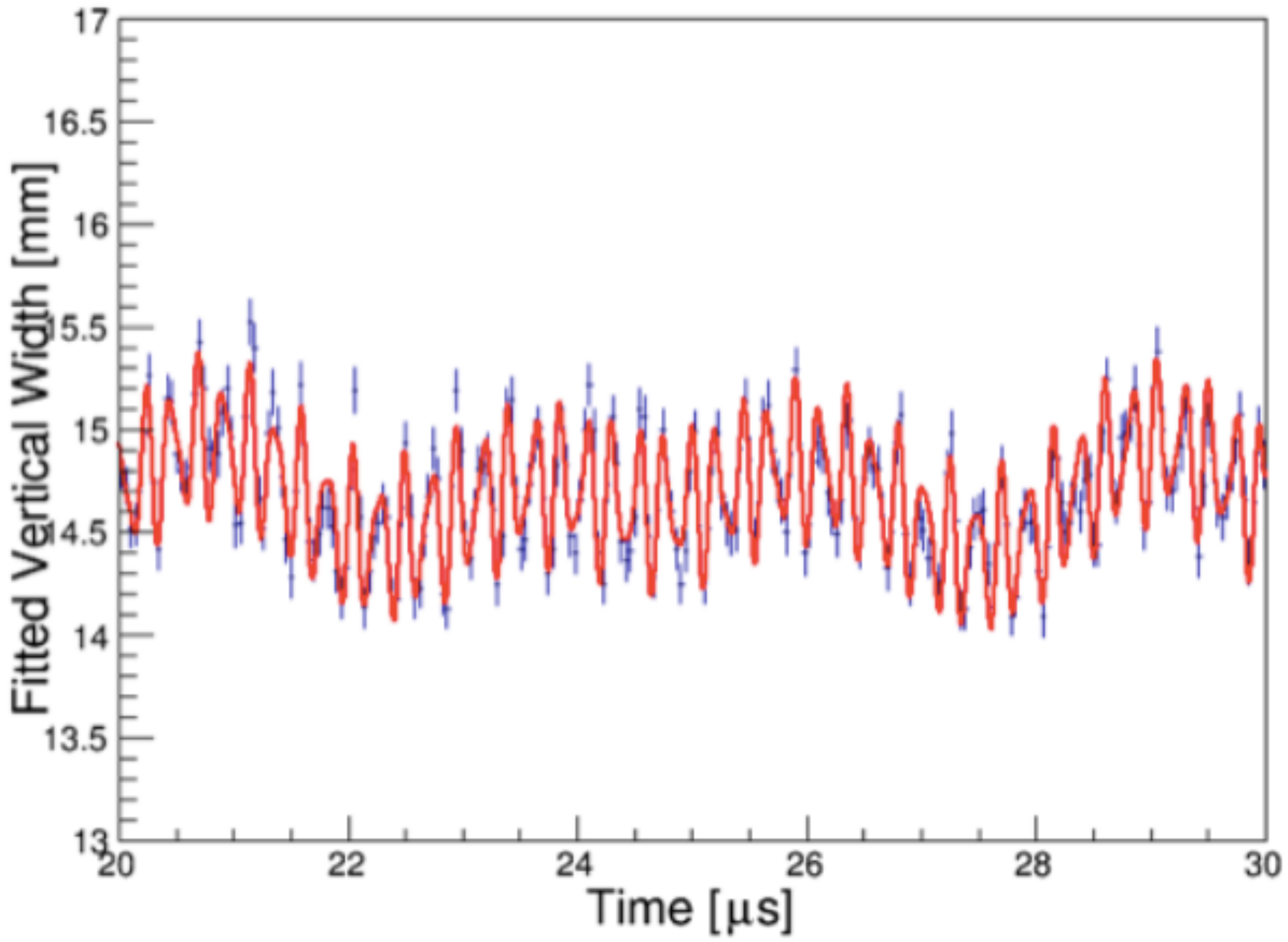
Beam position vs time



- Radial and vertical width oscillate vs time due to momentum acceptance of beam

Vertical Beam Frequencies

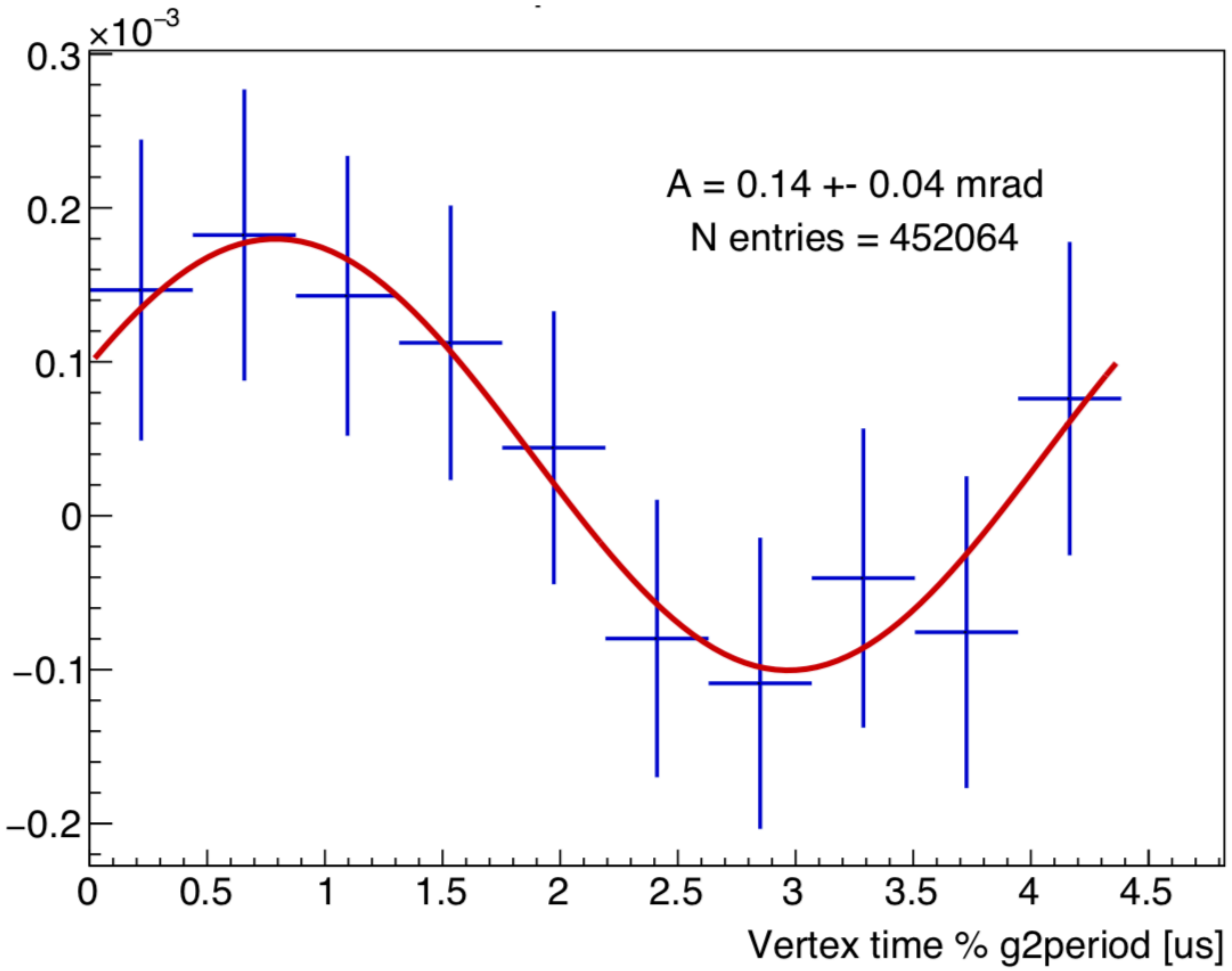




- Can look at Fourier transform of vertical position and width vs time
- Fit for expected beam frequencies and acceptance oscillations
- Proof that trackers are capable of measuring vertical oscillations!

EDM in simulation

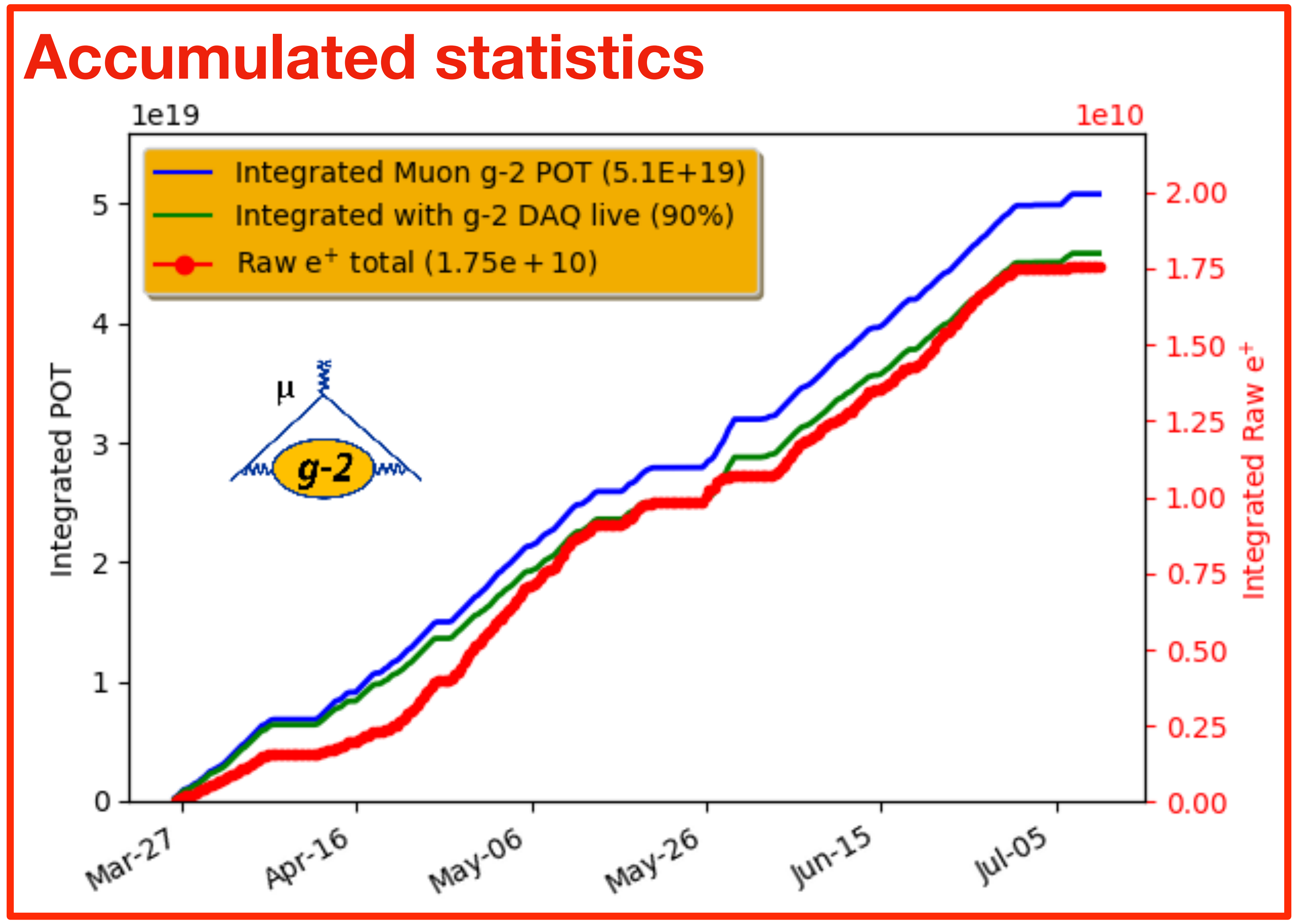
- Input EDM of ~30 x BNL limit (5.4×10^{-18} e.cm)
- Plot oscillation in the vertical angle at the tangent point as a function of time, modulo the g-2 period

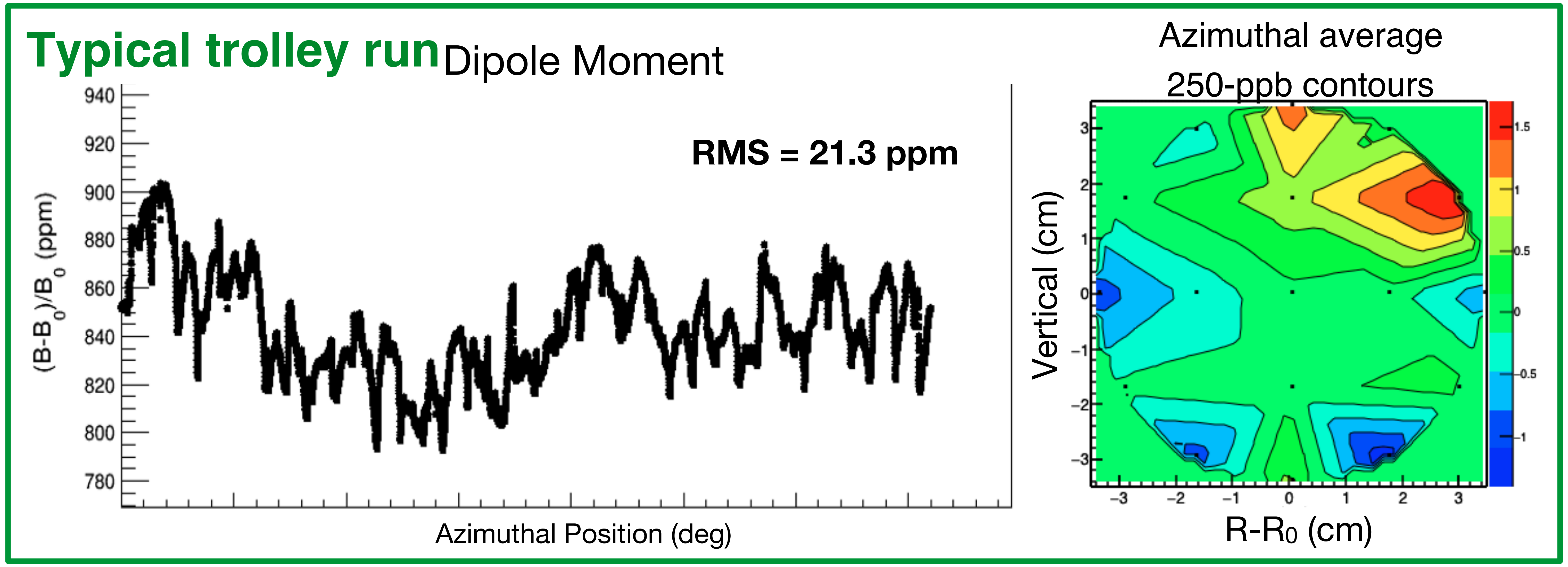


- Expected tilt angle in MRF:
  - δ = 49 mrad
- Expected reduced angle in detectors:
  - δ' = ~0.15 mrad
- Trackers capable of EDM measurement with very low stats!

Run 1 Overview

- Data taking period: April—July 2018
- Accumulated ~ 1.4 x BNL statistics (after data quality cuts) — **$\delta\omega_a$(stat) ~ 350 ppb**
- Field uniformity ~ 2x better than BNL

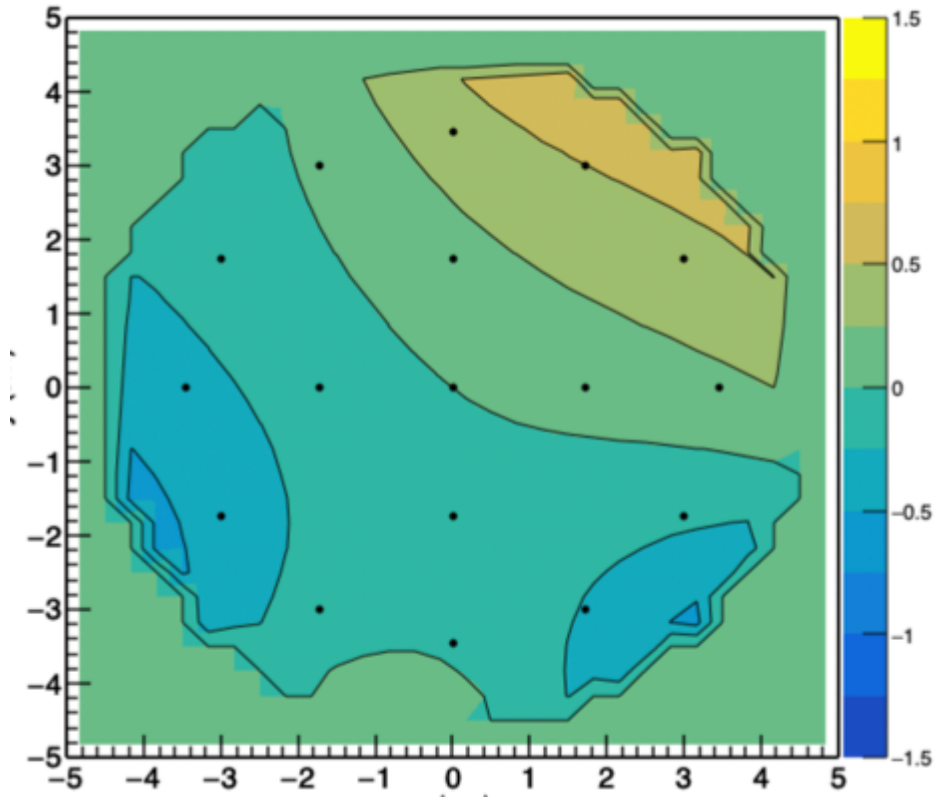




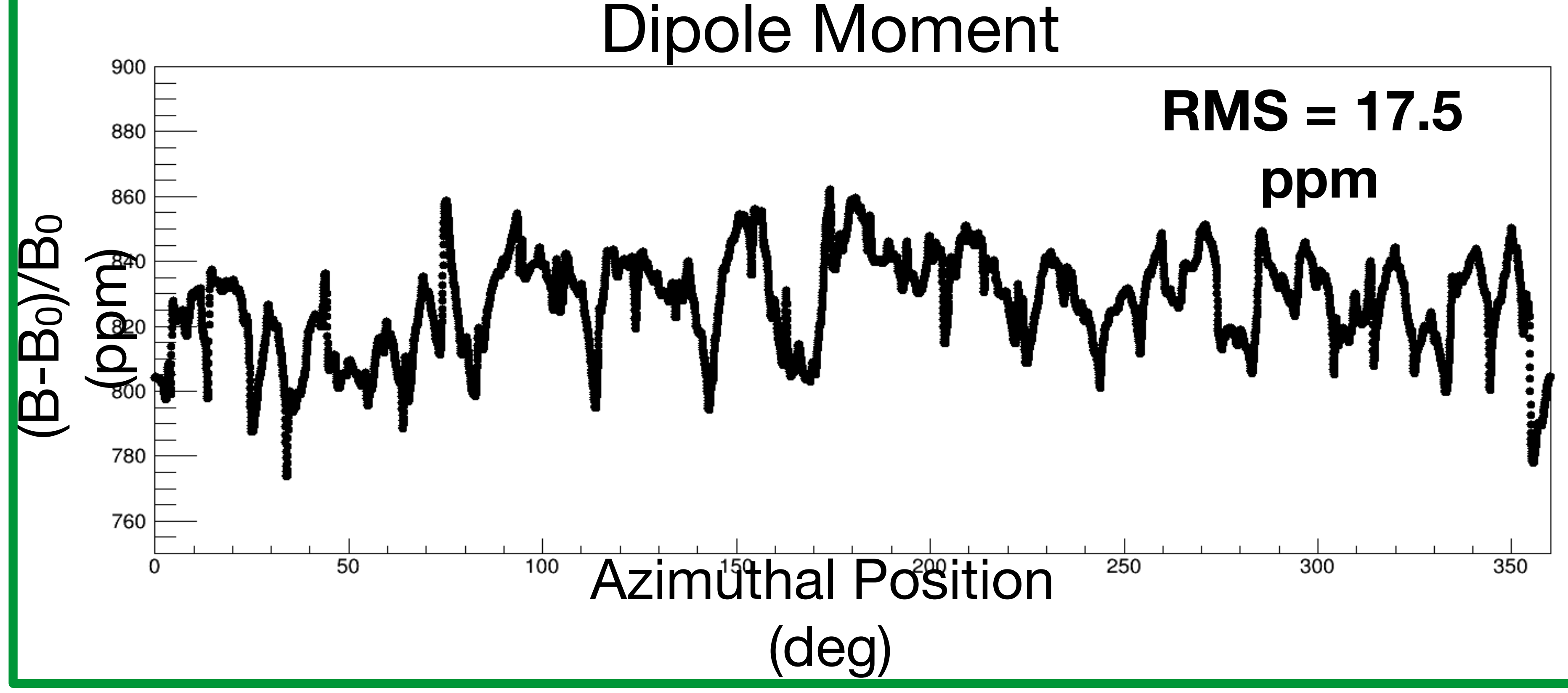
Data taking overview

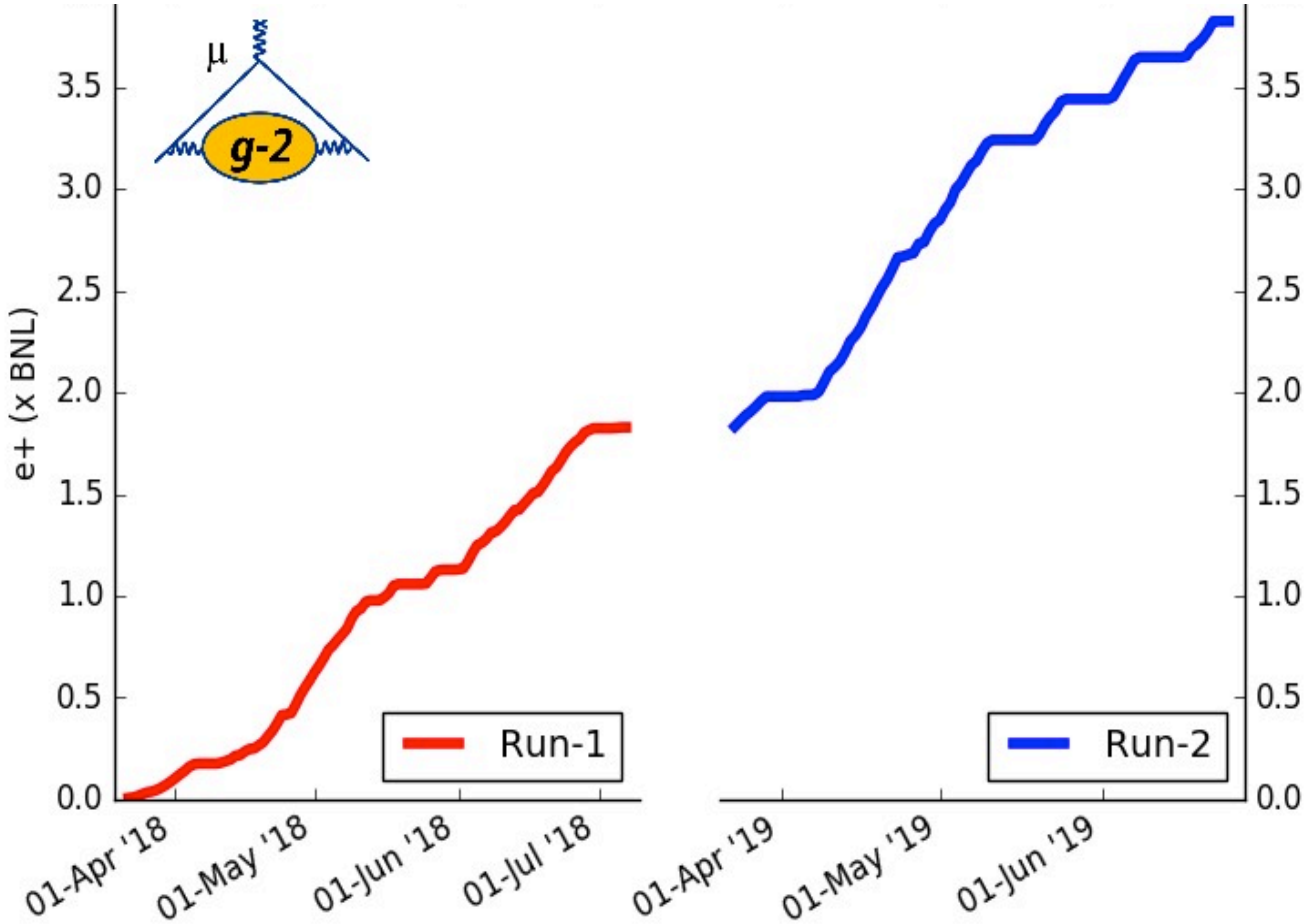
- More data taken during 2019
- Field uniformity expected to be similar to run 1

Azimuthal average
250-ppb contours



Recent trolley run



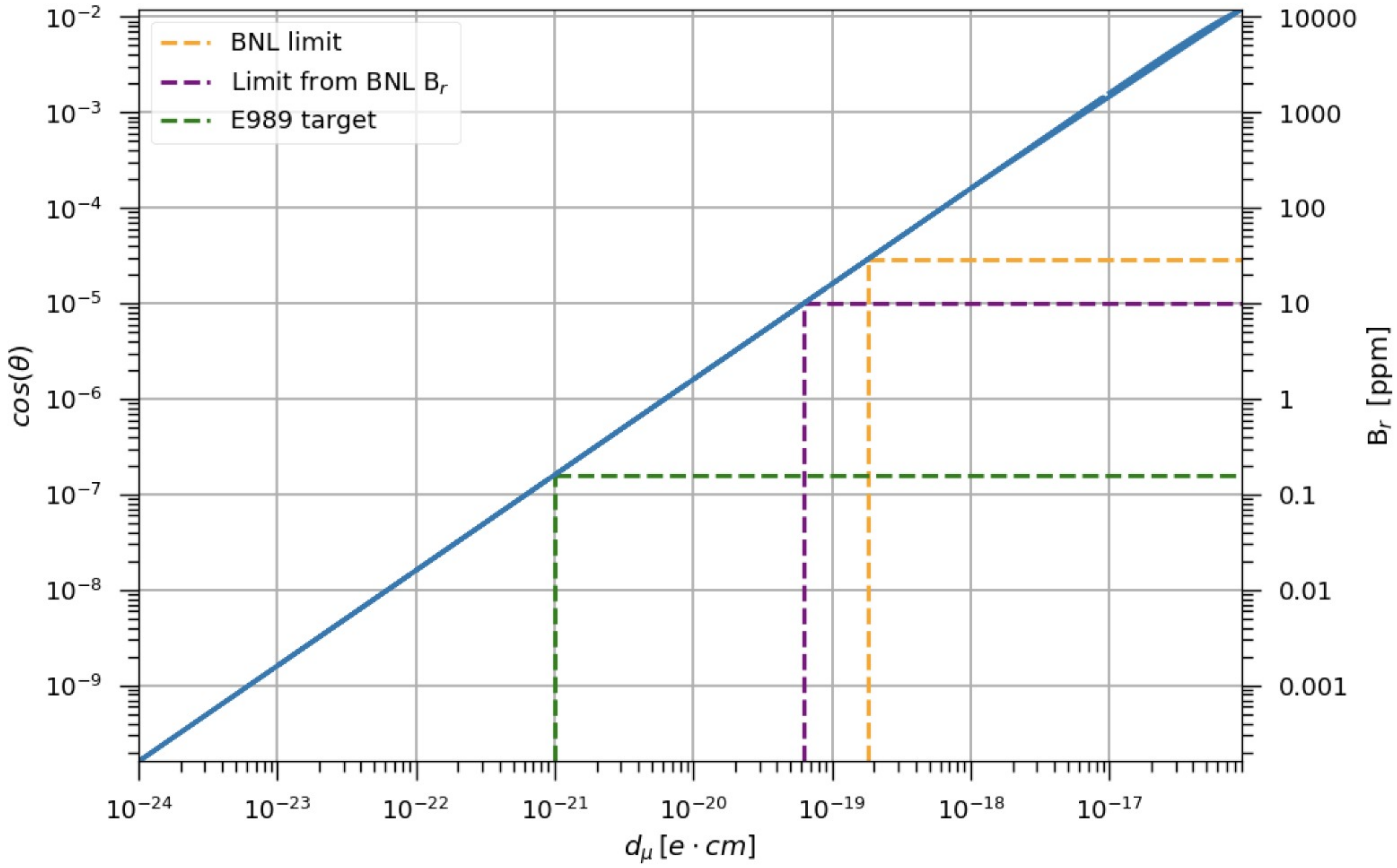


Can take 5% of a BNL per day!

Tracking overview

- BNL tracking based EDM analysis statistically limited
- We have accumulated ~100 million tracks ($t > 30\mu s$) in run 1 dataset
- At least that many again in run 2
- Tracking improvements (potential reprocessing) expected to improve statistics

Radial field



- BNL EDM limit is equivalent to 30ppm radial field
- The BNL radial field precision was estimated to be around 10ppm
- Had they had enough tracking statistics would have been limited at:
  - $|d_\mu| \approx 4.5 \times 10^{-20}$ e.cm

- Saw Martin's talk yesterday outlining improved radial field measurement
- Average field of 30ppm reduced using surface coils

Summary

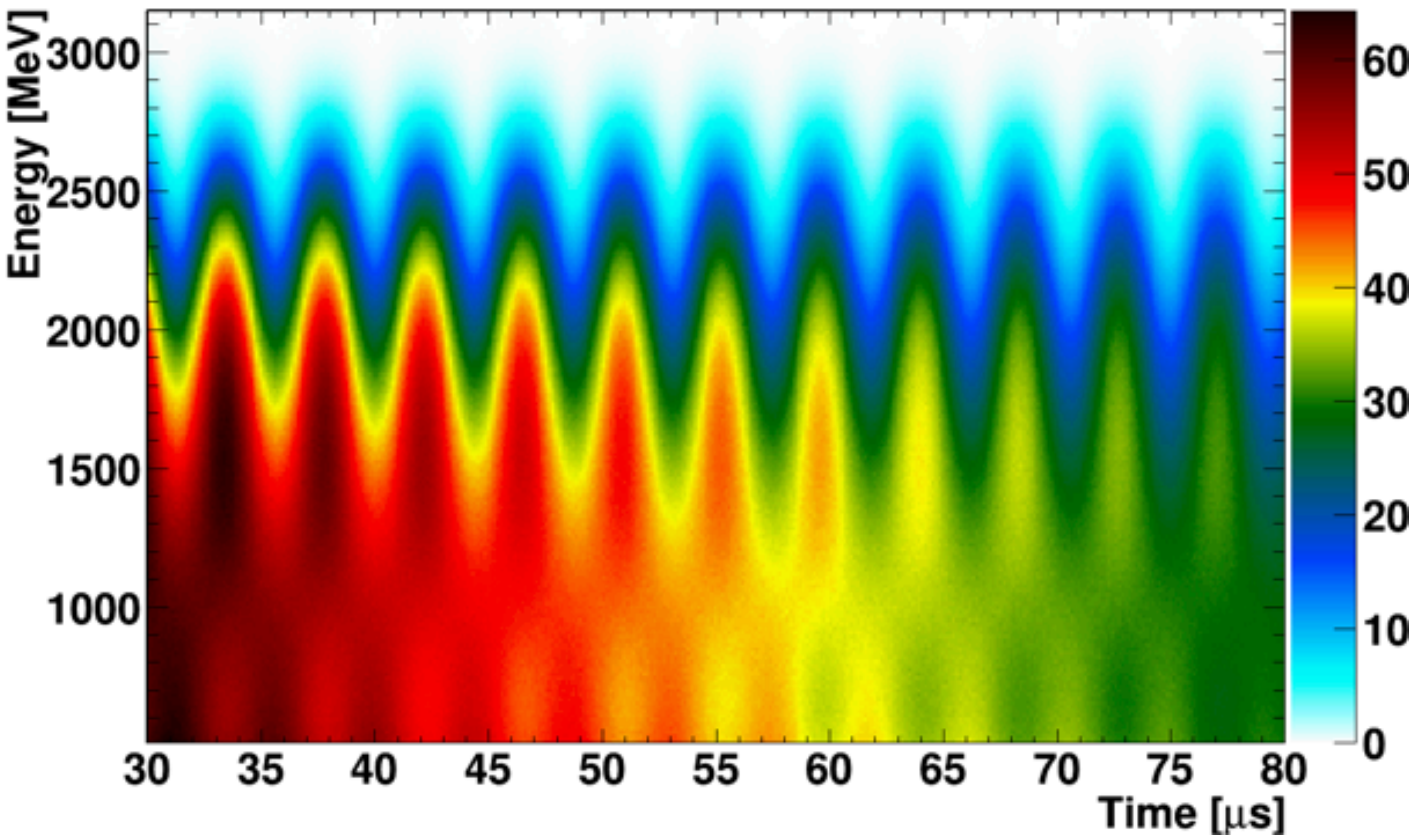
- Completed run 1 ω_a with dataset ~ 1 x BNL
- Run 2 data taken with at least as much again
- Demonstrated ability to take 5% BNL per day, on course for 21 BNLs over next 2 years
- Run 3 has ~ 4 x BNL and counting…

- Improvements from BNL for EDM
  - Segmented calorimeters for phase based measurement
  - Trackers with 20 x BNL stats in run 1, 100 x BNL total tracking stats
  - Radial field measured with finer granularity
- Radial field measurement expected to limit EDM sensitivity - dedicated measurement possible (100ppb challenging…)

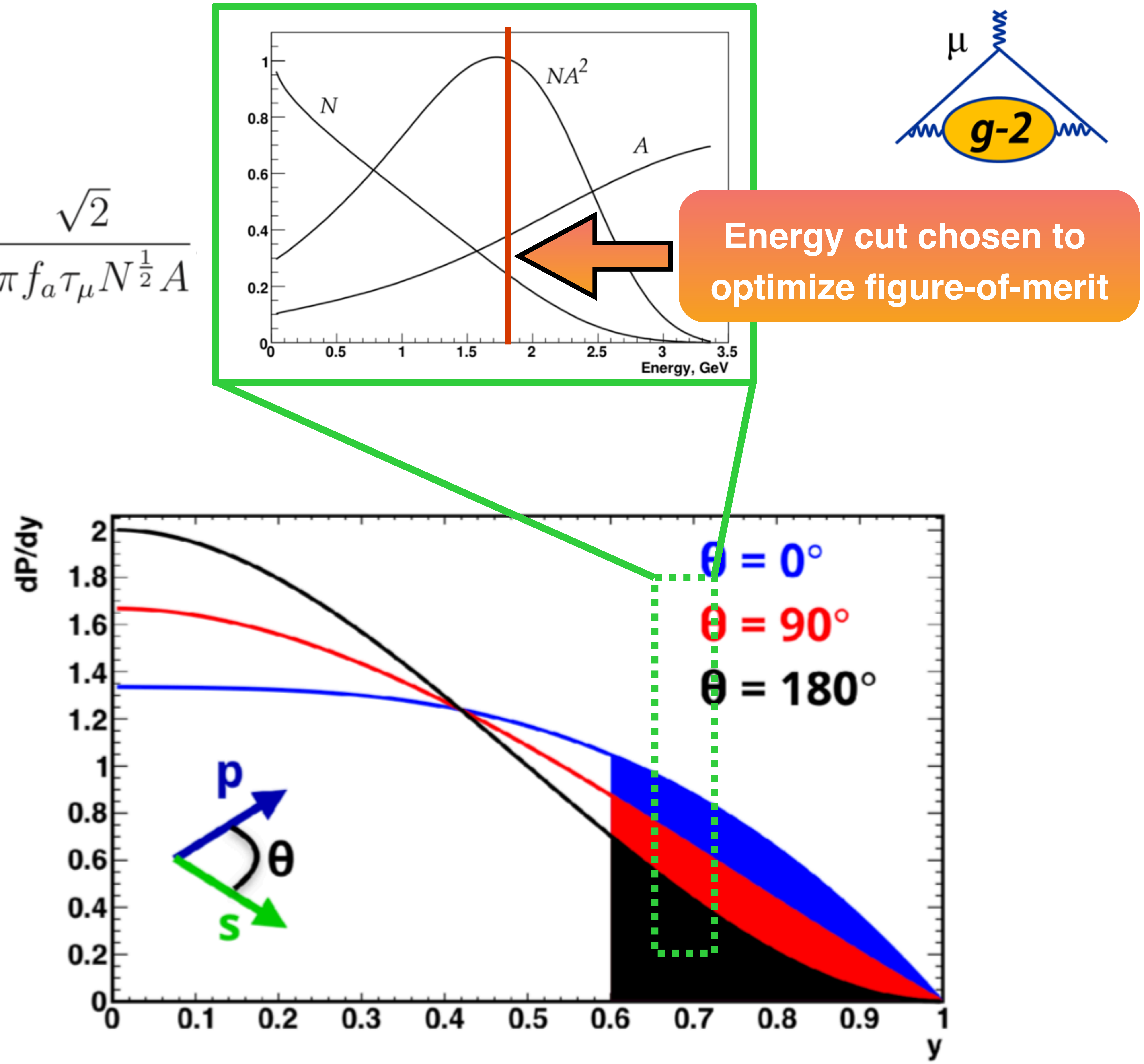
Thank you!

Backup

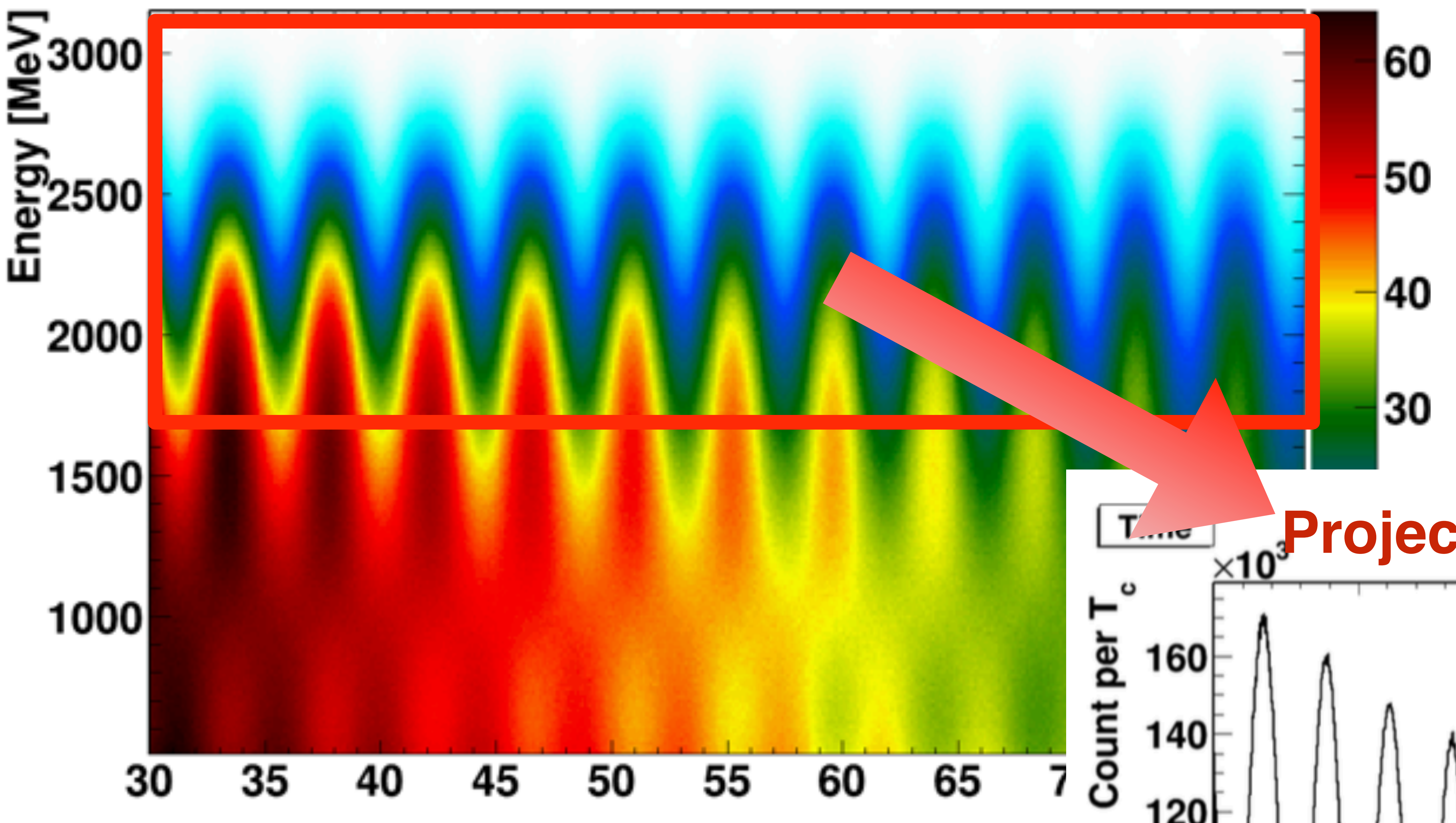
Run 1 Analysis Status: ω_a



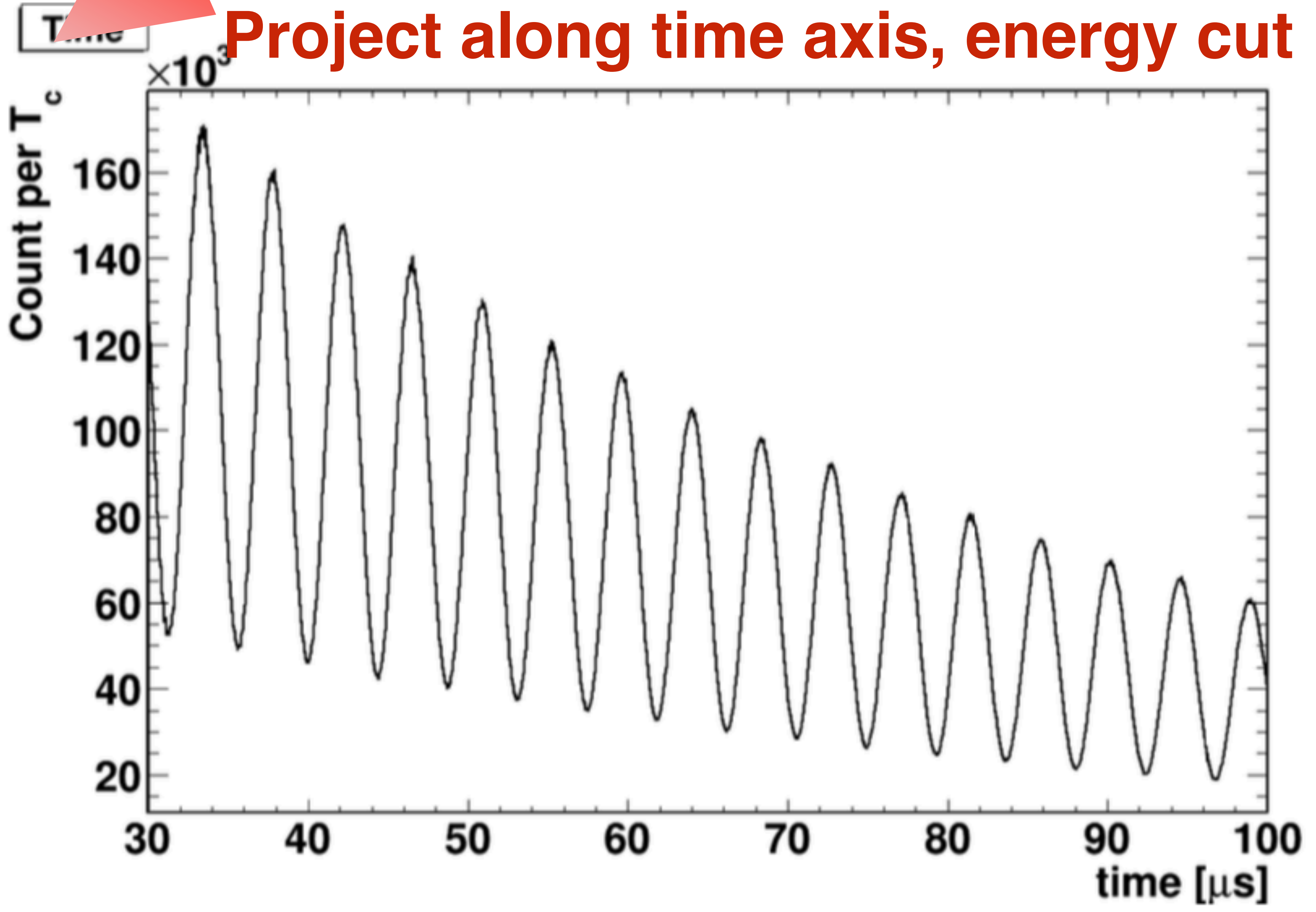
$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{2\pi f_a \tau_\mu N^{\frac{1}{2}} A}$$

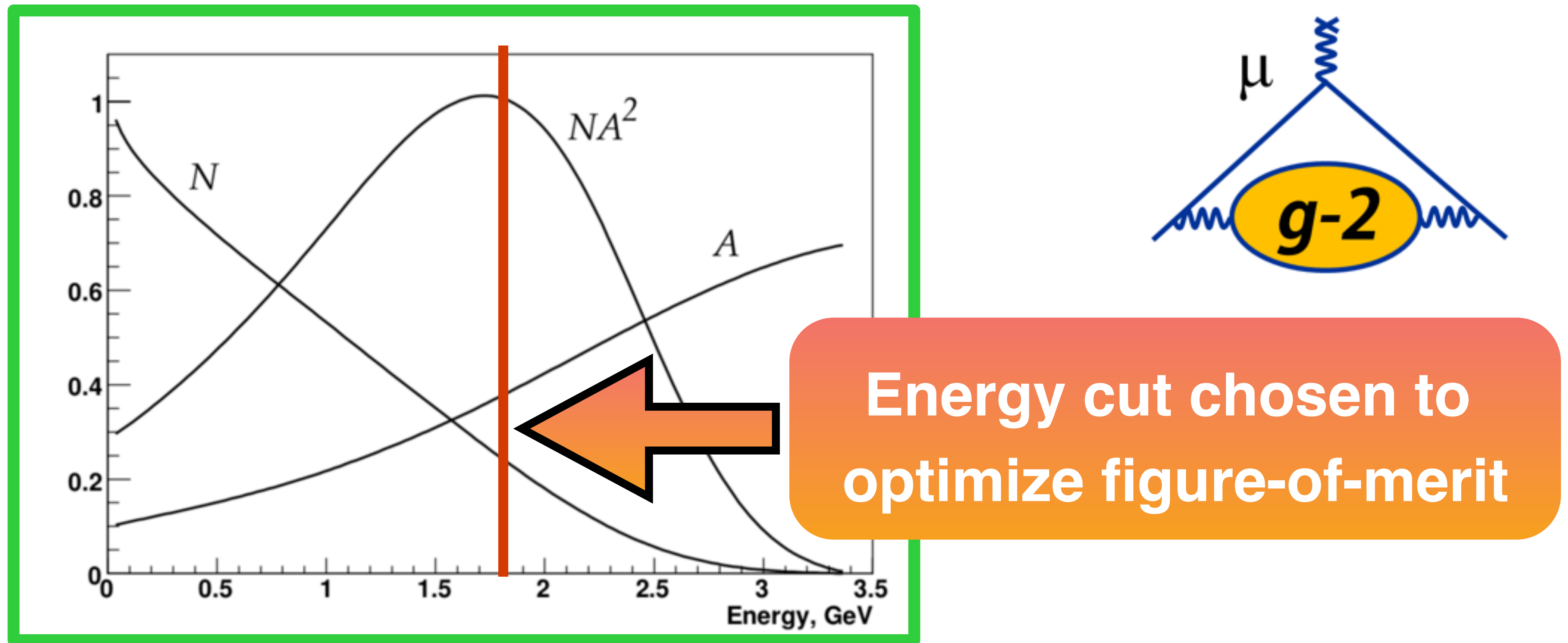


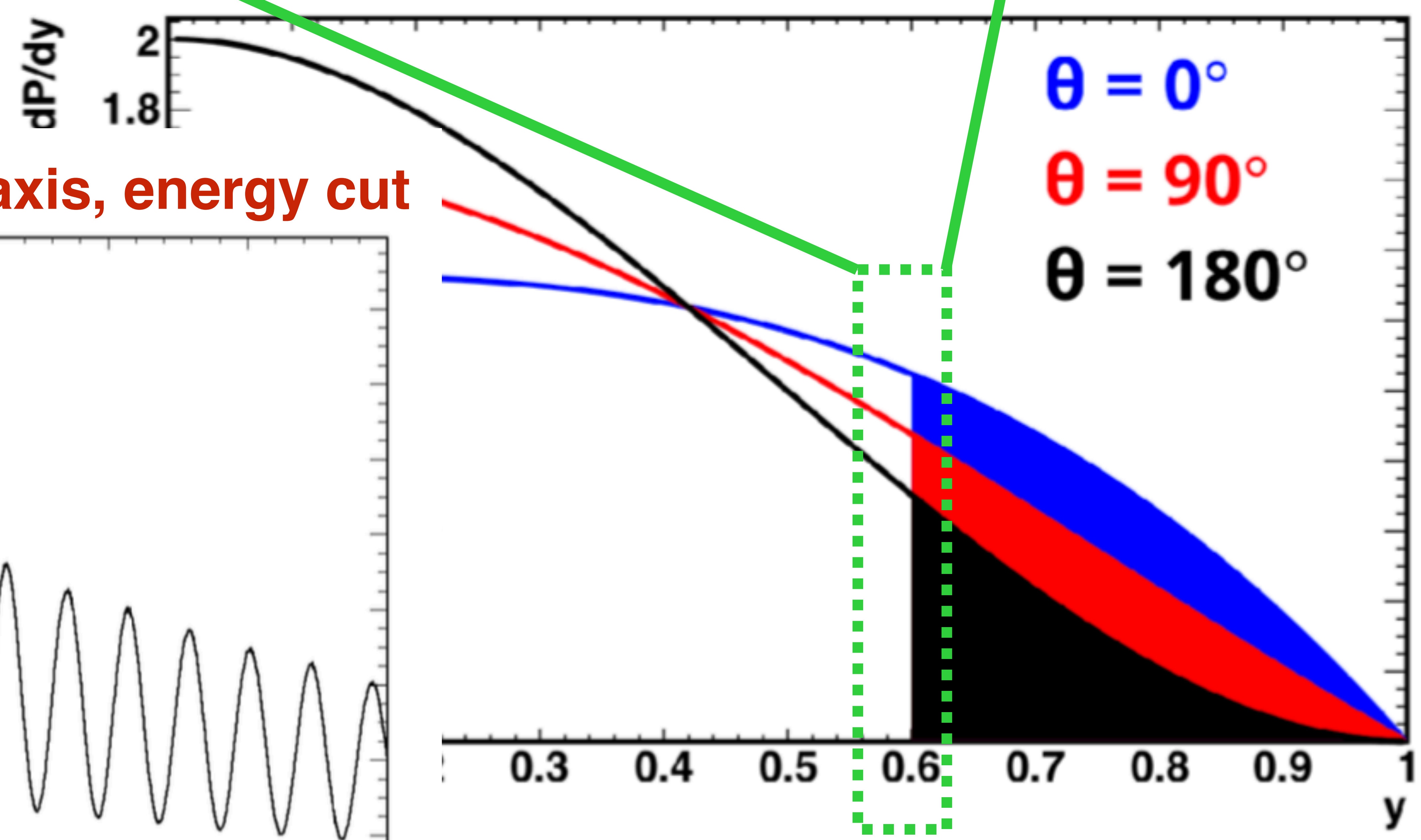
Run 1 Analysis Status: ω_a



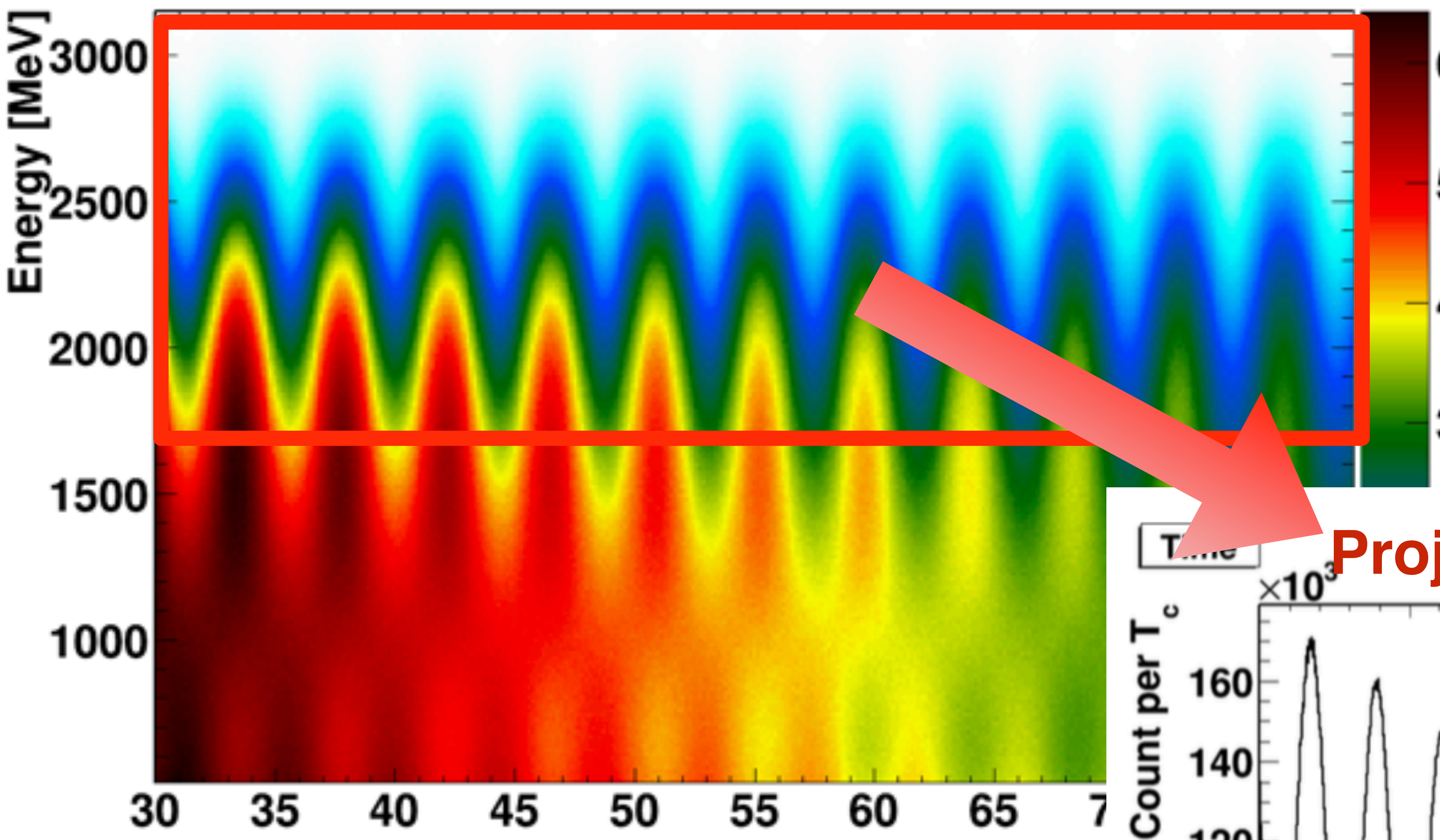
$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{2\pi f_a \tau_\mu N^{\frac{1}{2}} A}$$



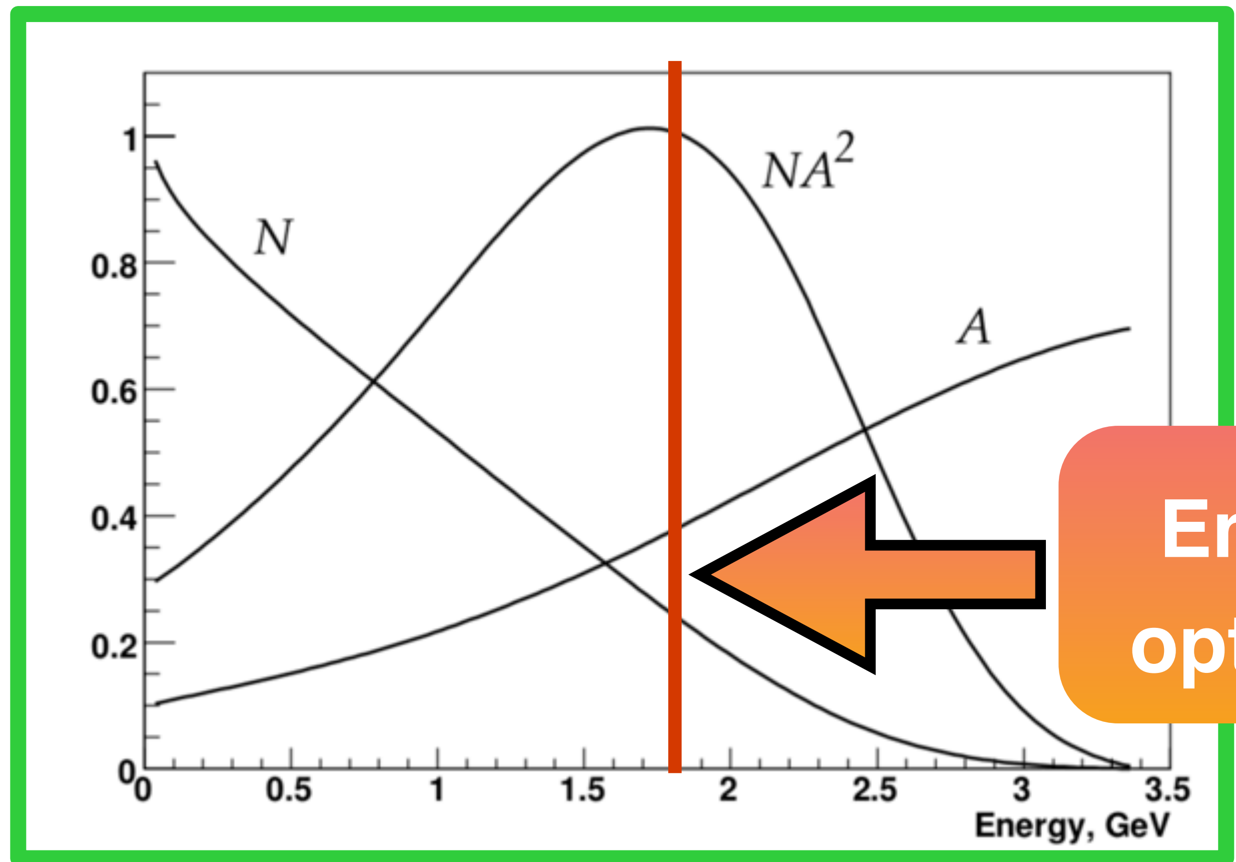




Run 1 Analysis Status: ω_a

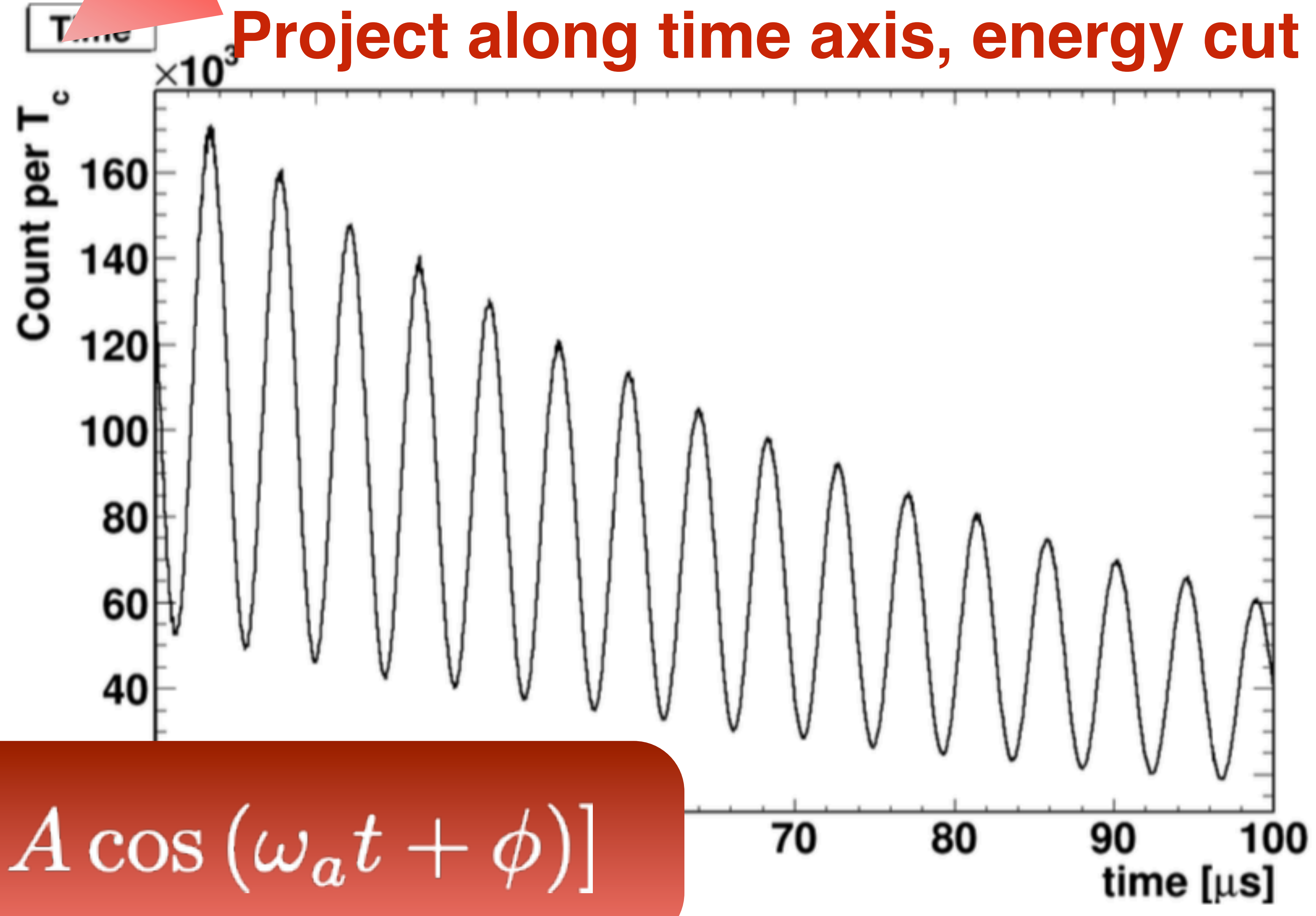


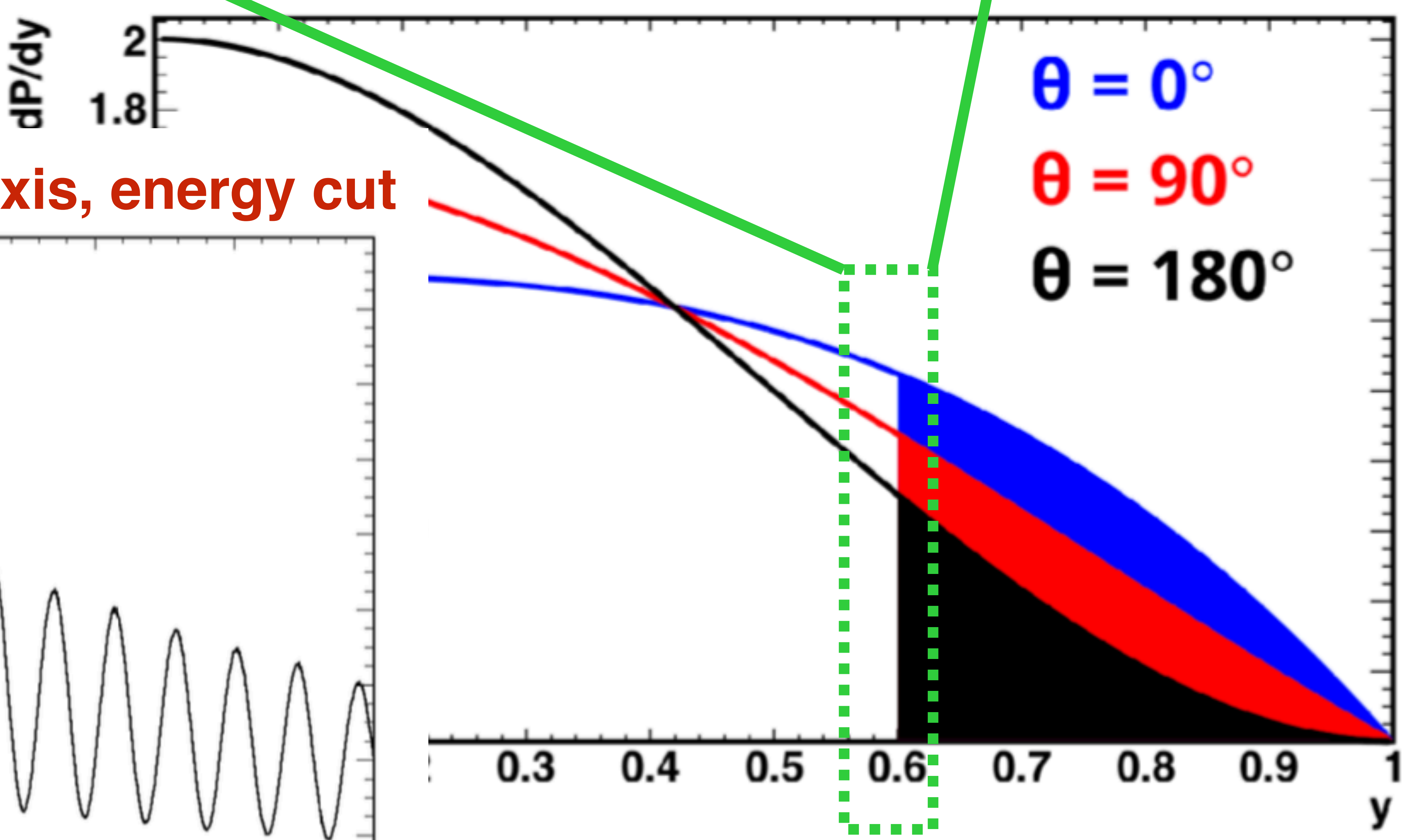
$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{2\pi f_a \tau_\mu N^{\frac{1}{2}} A}$$



Energy cut chosen to optimize figure-of-merit

Project along time axis, energy cut





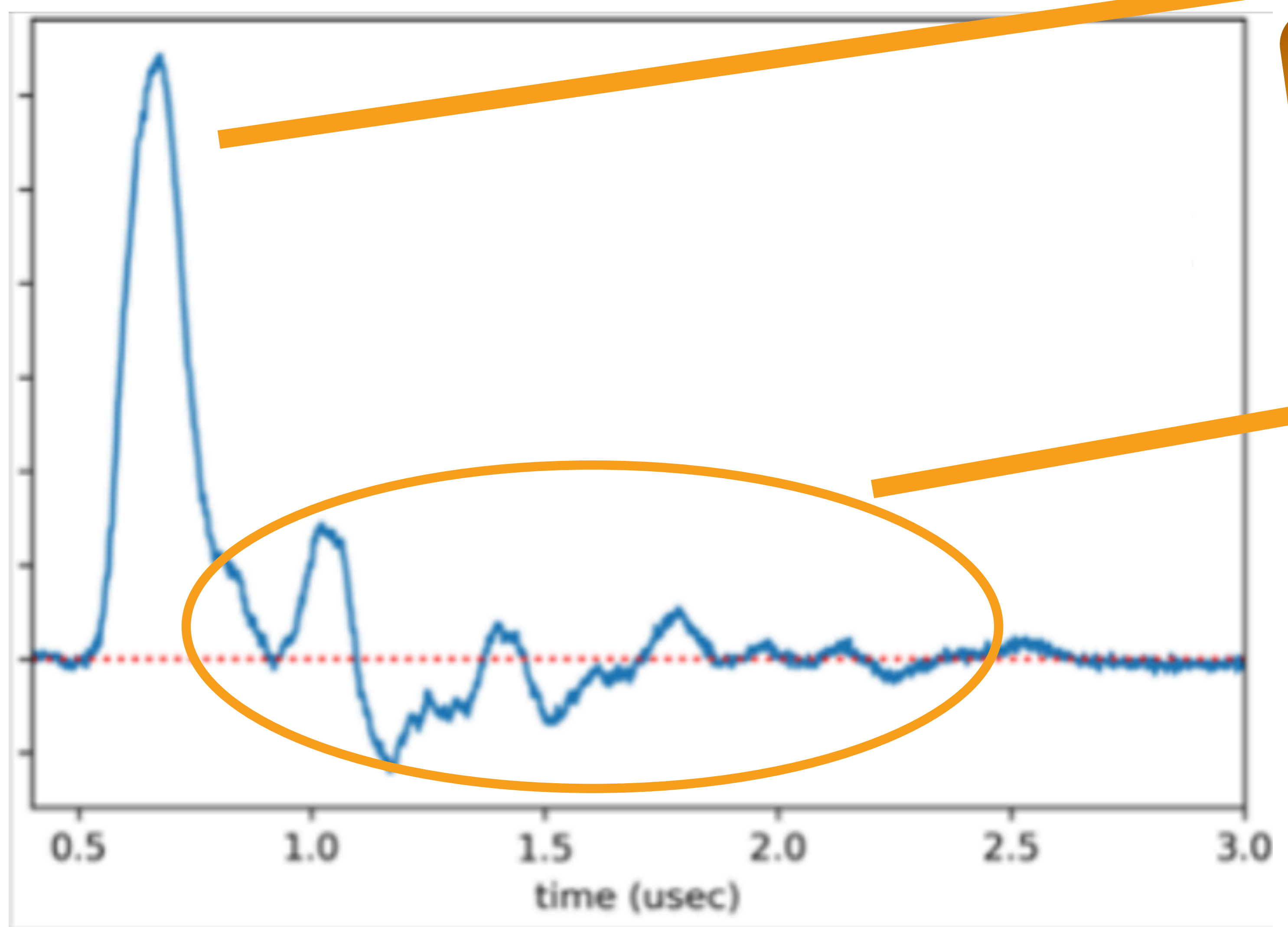
Fit to: $N(t) = N_0 e^{-t/\tau}\left[1 - A\cos\left(\omega_a t + \phi\right)\right]$

Fermilab

What Affects the Beam Shape?

- **Kicker pulse** strength, shape affects structure of beam
- **Beam width** affected by dynamics

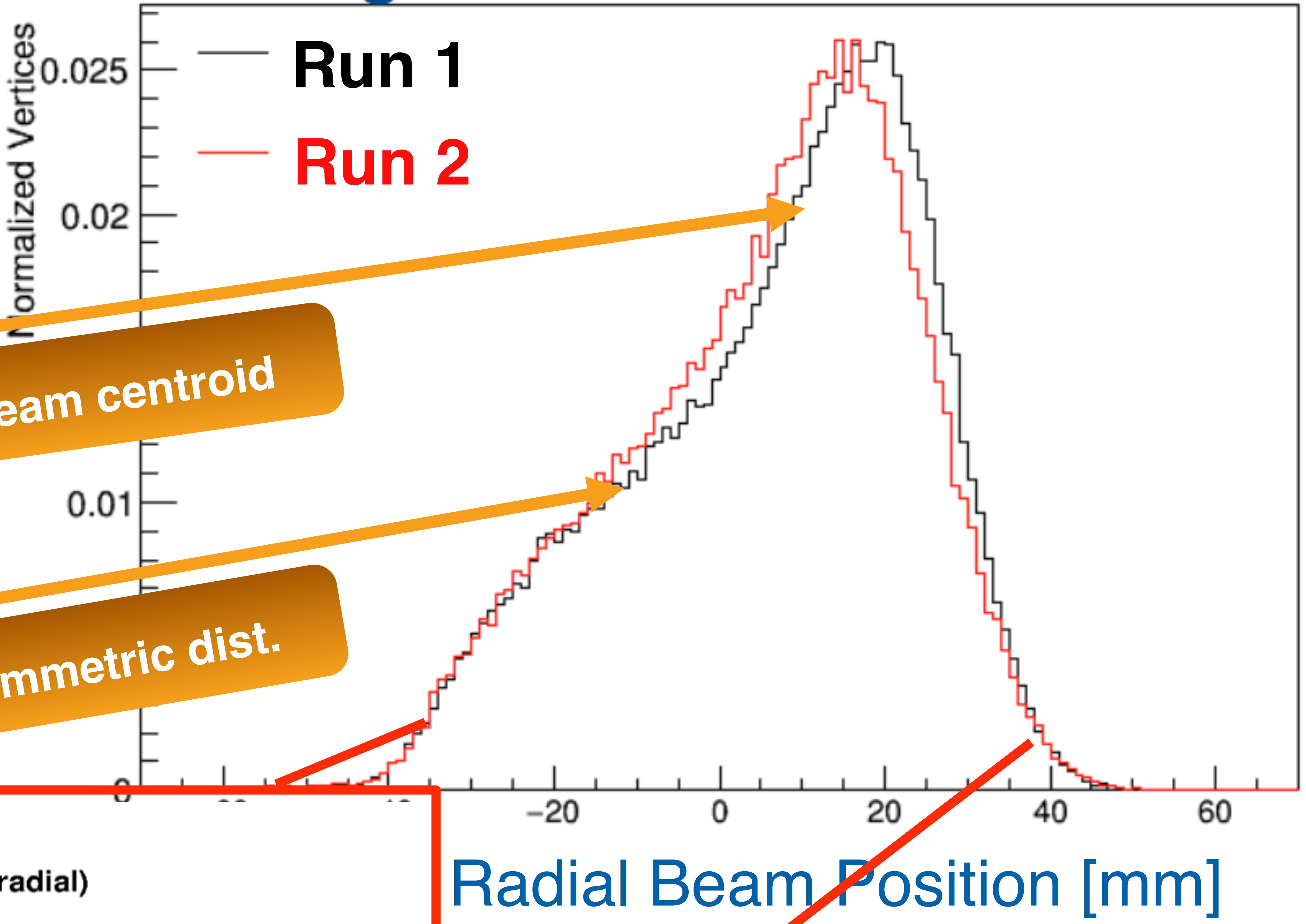
Kicker Pulse

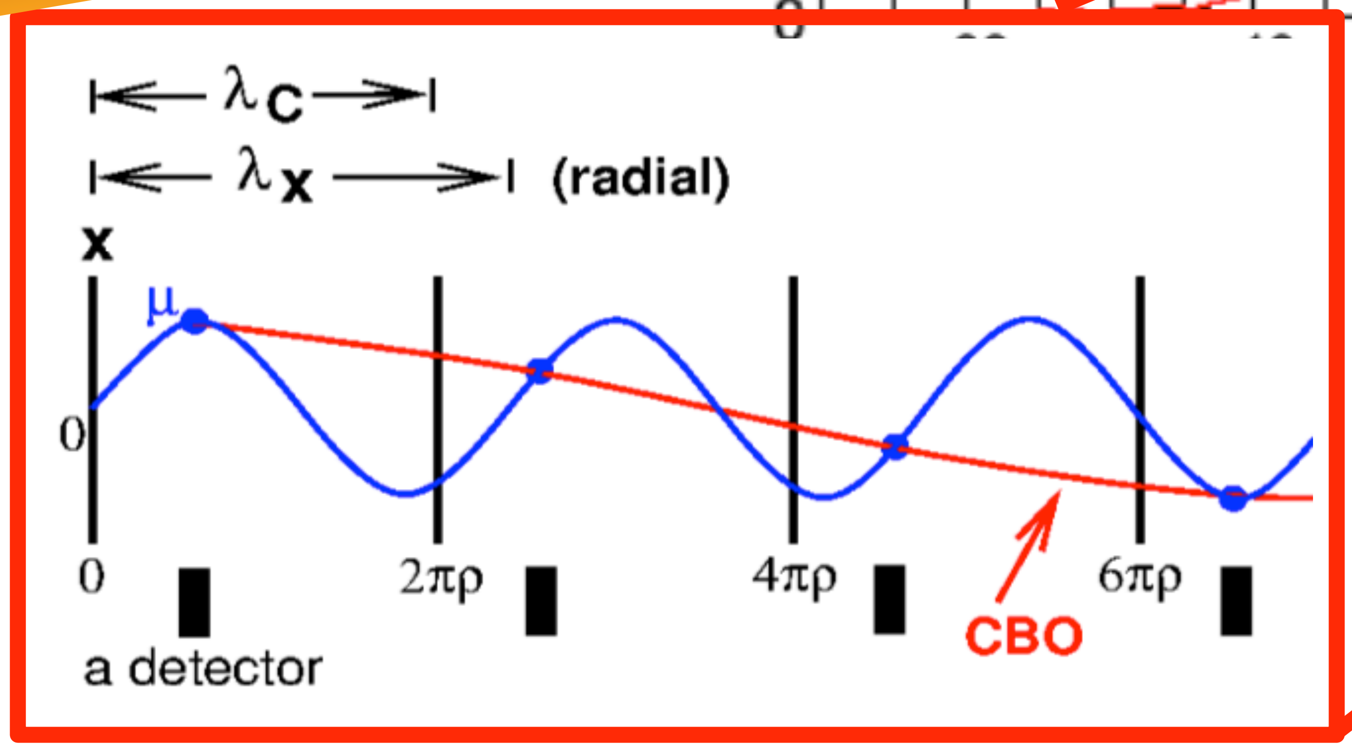


kick strength → beam centroid

ringing kick → asymmetric dist.

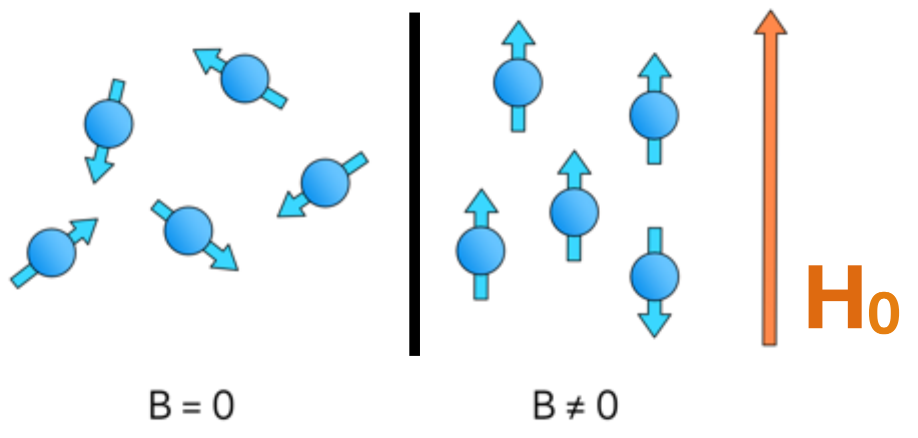
Higher kick → lower radius

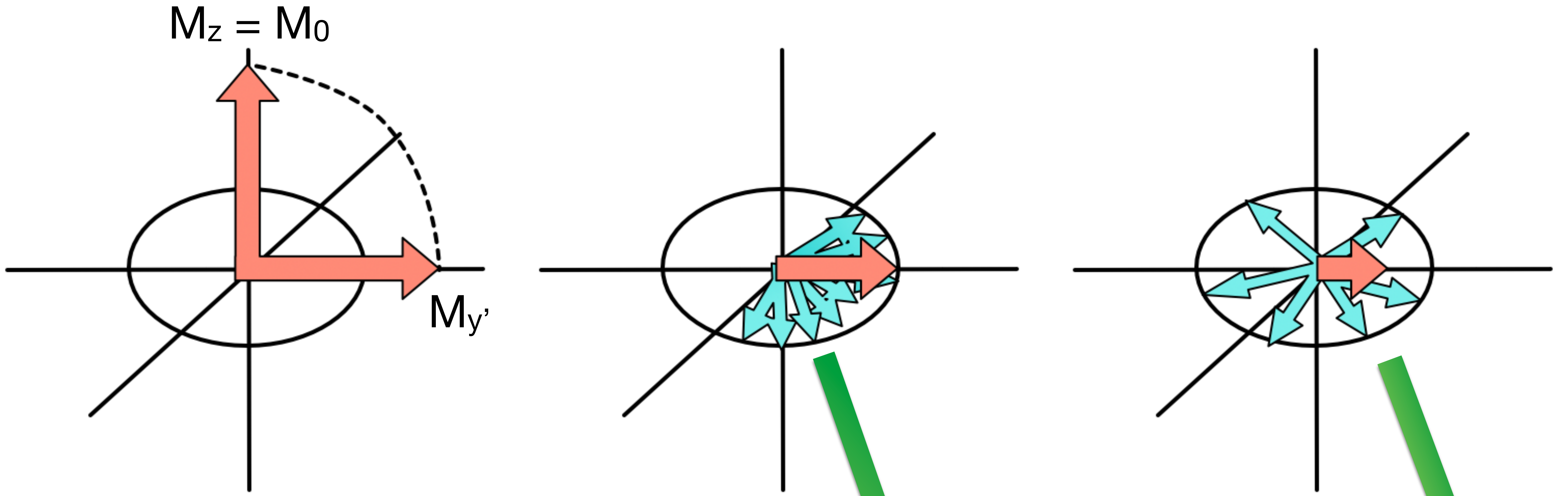




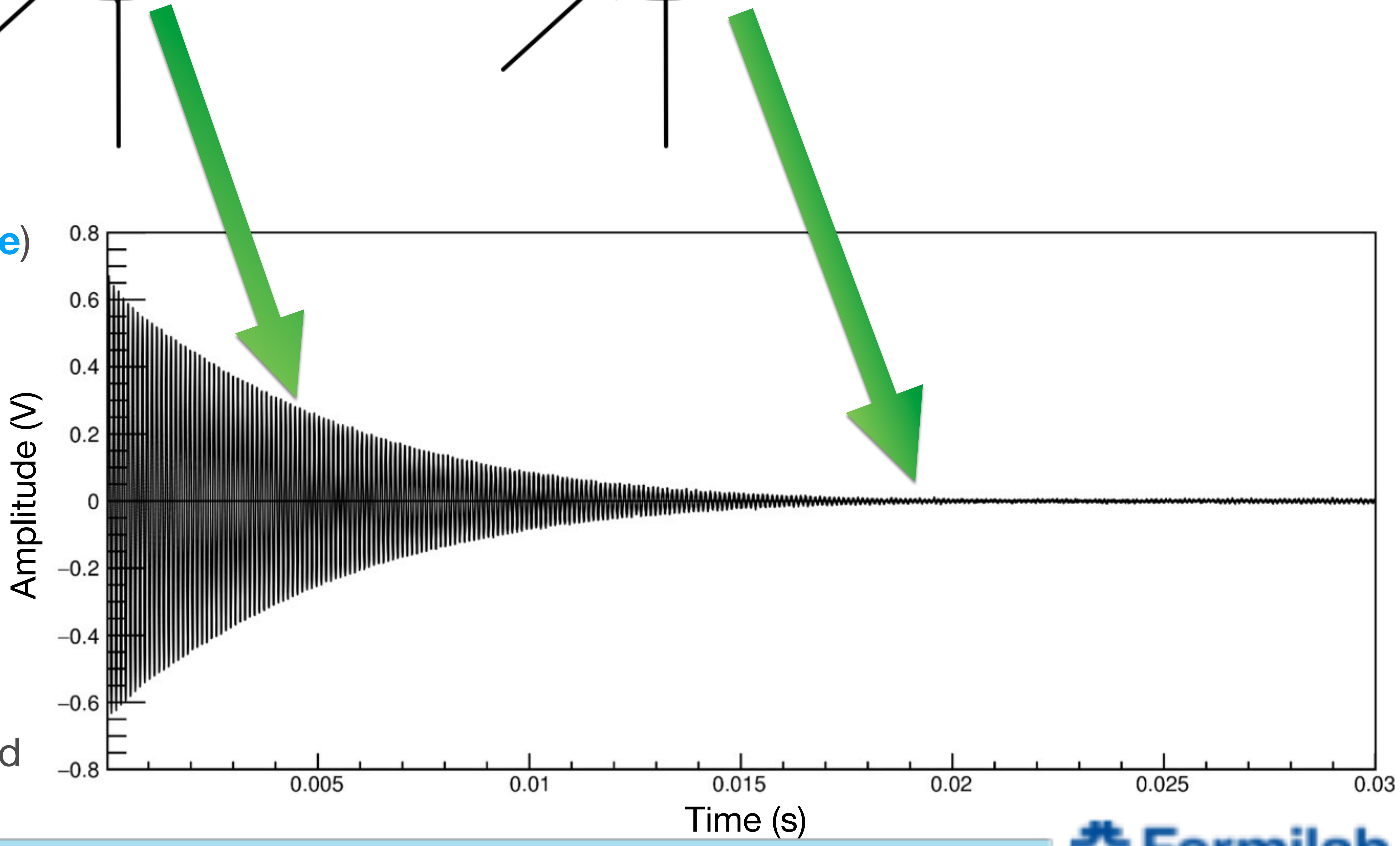
CBO → radial width

Pulsed Nuclear Magnetic Resonance





- Apply an RF pulse for a short time to the sample at Larmor frequency — tips spins perpendicular to external B field (**π/2 pulse**)
- Spin precession induces an EMF in the pickup coil
  - So-called **Free-Induction Decay** (**FID**)
- Decay of signal driven by:
  - Spin-spin interactions (dephasing) (pure T_2)
  - Field inhomogeneities (T_2^*)
  - Simultaneously, spins relax back to alignment with holding field (spin-lattice relaxation, T_1)



Magnetic Circuits

$$\mathcal{E} = \oint \vec{f}_s \cdot d\vec{\ell} = V = IR$$

Can write a similar equation for magnets

$$\mathcal{F} = \oint \vec{H} \cdot d\vec{\ell} = NI$$

Magnetomotive Force (mmf)

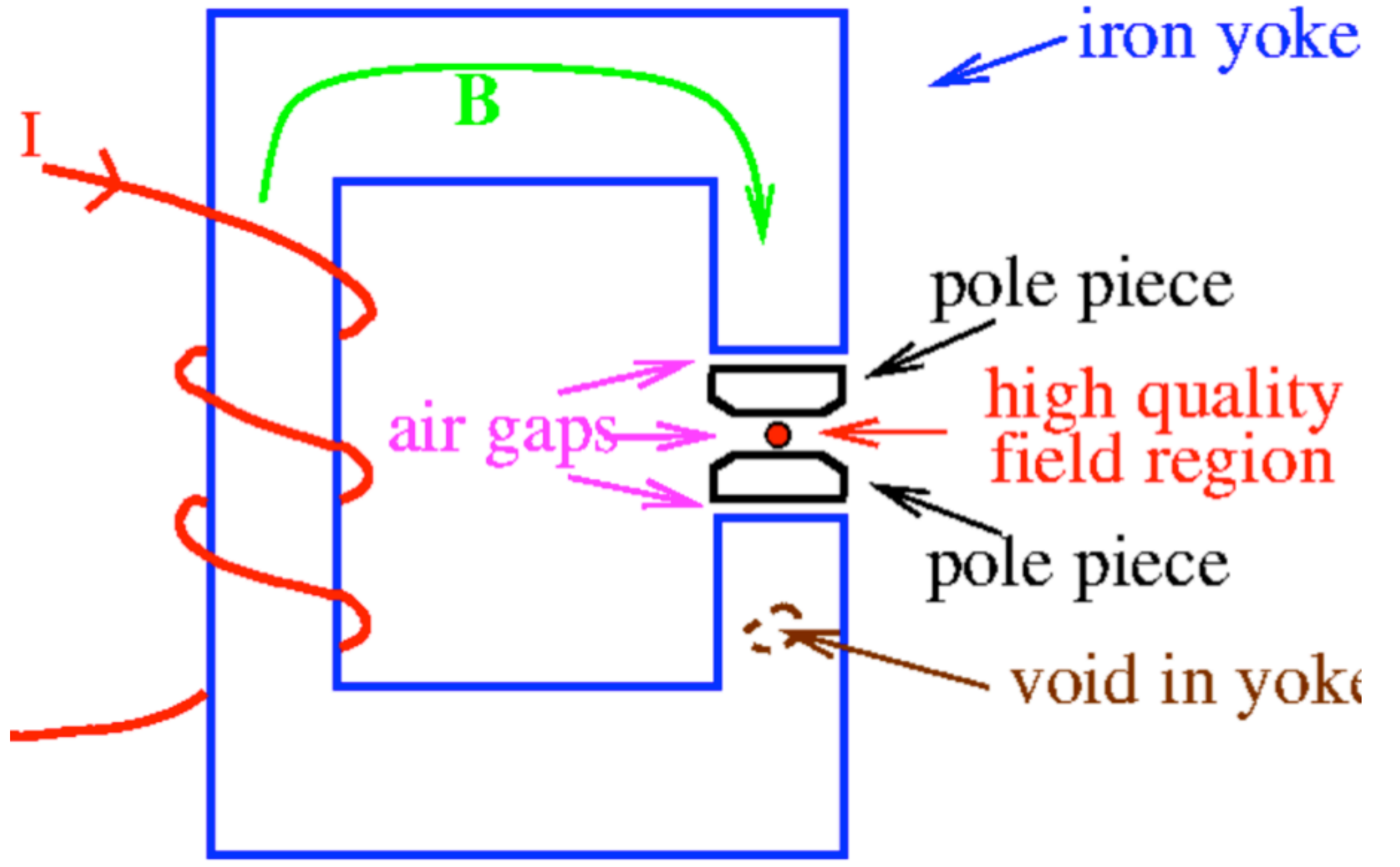
$$\vec{B} = \mu_0 (1 + \chi_m) \vec{H} = \mu \vec{H}$$

Rewrite H in terms of B

$$\Phi = \vec{B} \cdot \vec{A} = \mu \vec{H} \cdot \vec{A}$$

Consider magnetic flux

$$\Phi \oint \frac{d\ell}{\mu A} = \mathcal{F} \Rightarrow \boxed{\mathcal{R} = \oint \frac{d\ell}{\mu A} = \frac{\mathcal{F}}{\Phi}}$$

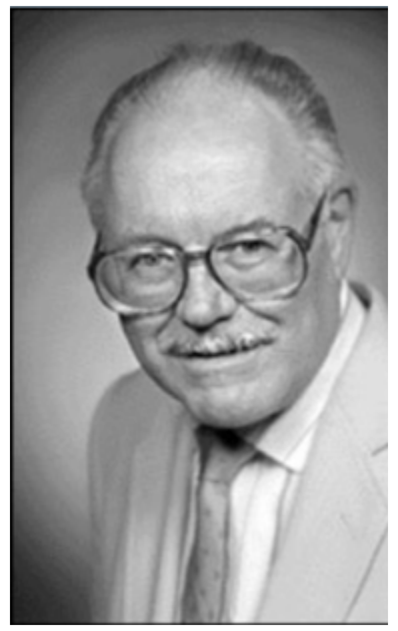


Magnetic Reluctance

- Analogous to resistance in an electrical circuit $\boxed{V = IR \Leftrightarrow \mathcal{F} = \Phi \mathcal{R}}$
- Current flows along a path of least resistance while field lines will take a path of least reluctance
- While the emf drives electric charges (Ohm's Law), the mmf "drives" magnetic field lines (Hopkinson's Law)

Magnet Anatomy

- For E821, Gordon Danby had a brilliant magnet design



B = 1.45 T (~5200 A)

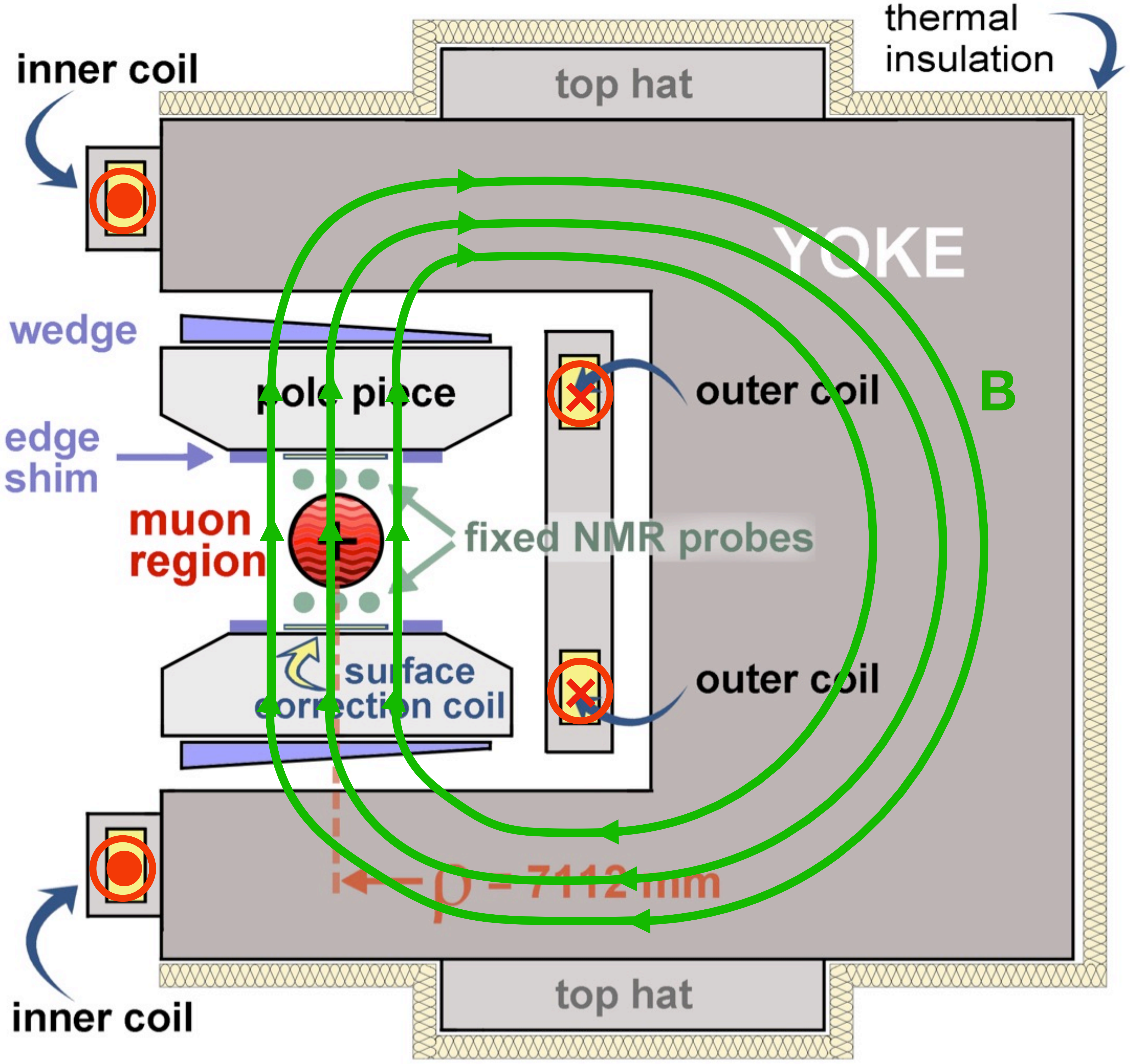
- Non-persistent current: fine-tuning of field in real time

12 C-shaped yokes

- 3 upper and 3 lower poles per yoke
- 72 total poles

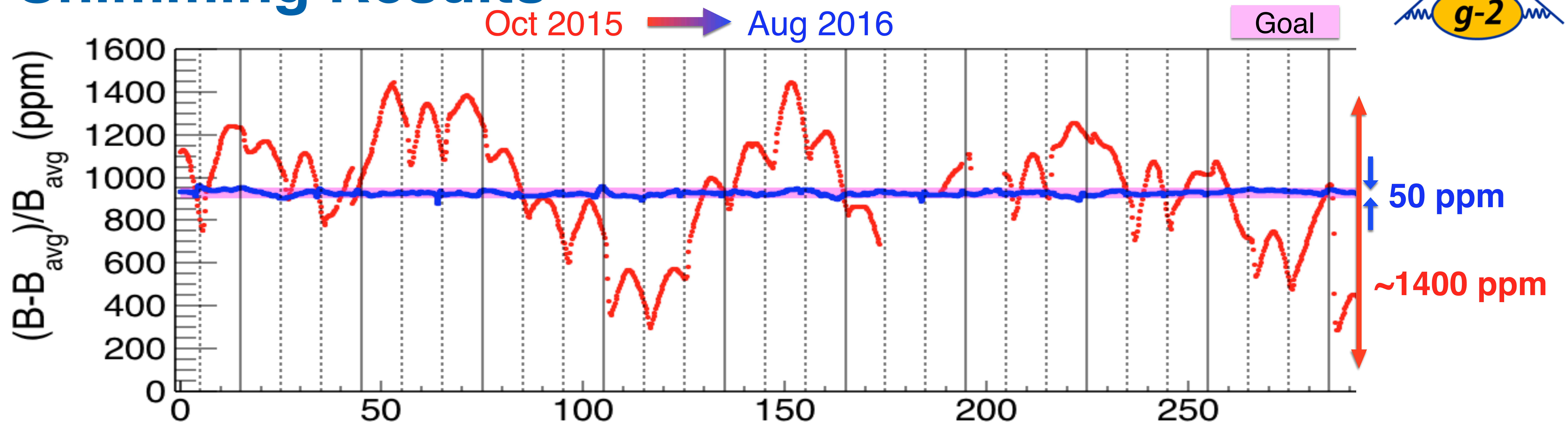
Shimming knobs

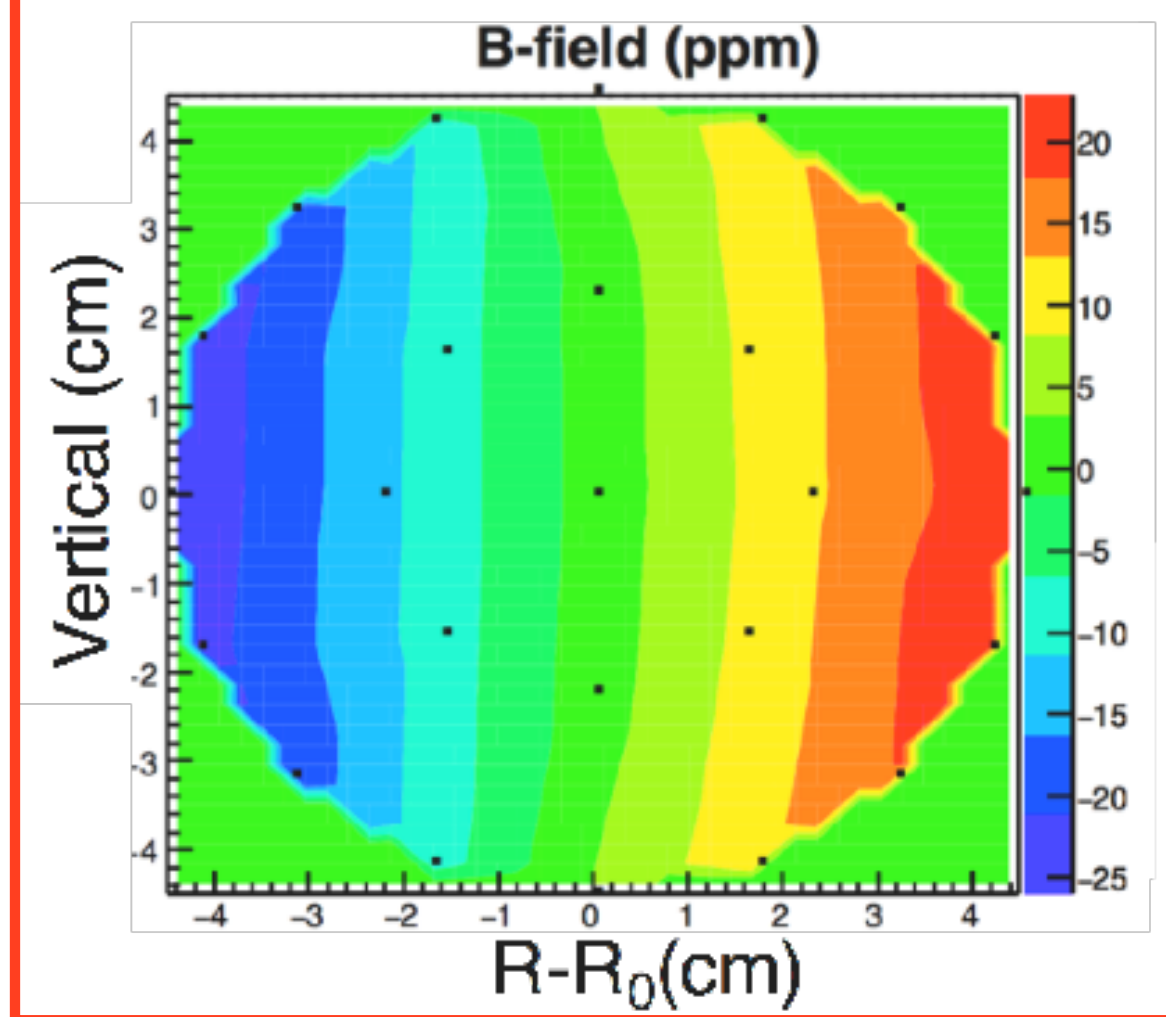
- Pole separation determines field: pole tilts, non-flatness affect uniformity
- Top hats (30 deg effect, dipole)
- Wedges (10 deg effect, dipole, quadrupole)
- Edge shims (10 deg effect, dipole, quadrupole, sextupole)
- Laminations (1 deg effect, dipole, quadrupole, sextupole)
- Surface coils (360 deg effect, quadrupole, sextupole,…)



Current direction indicated by red markers

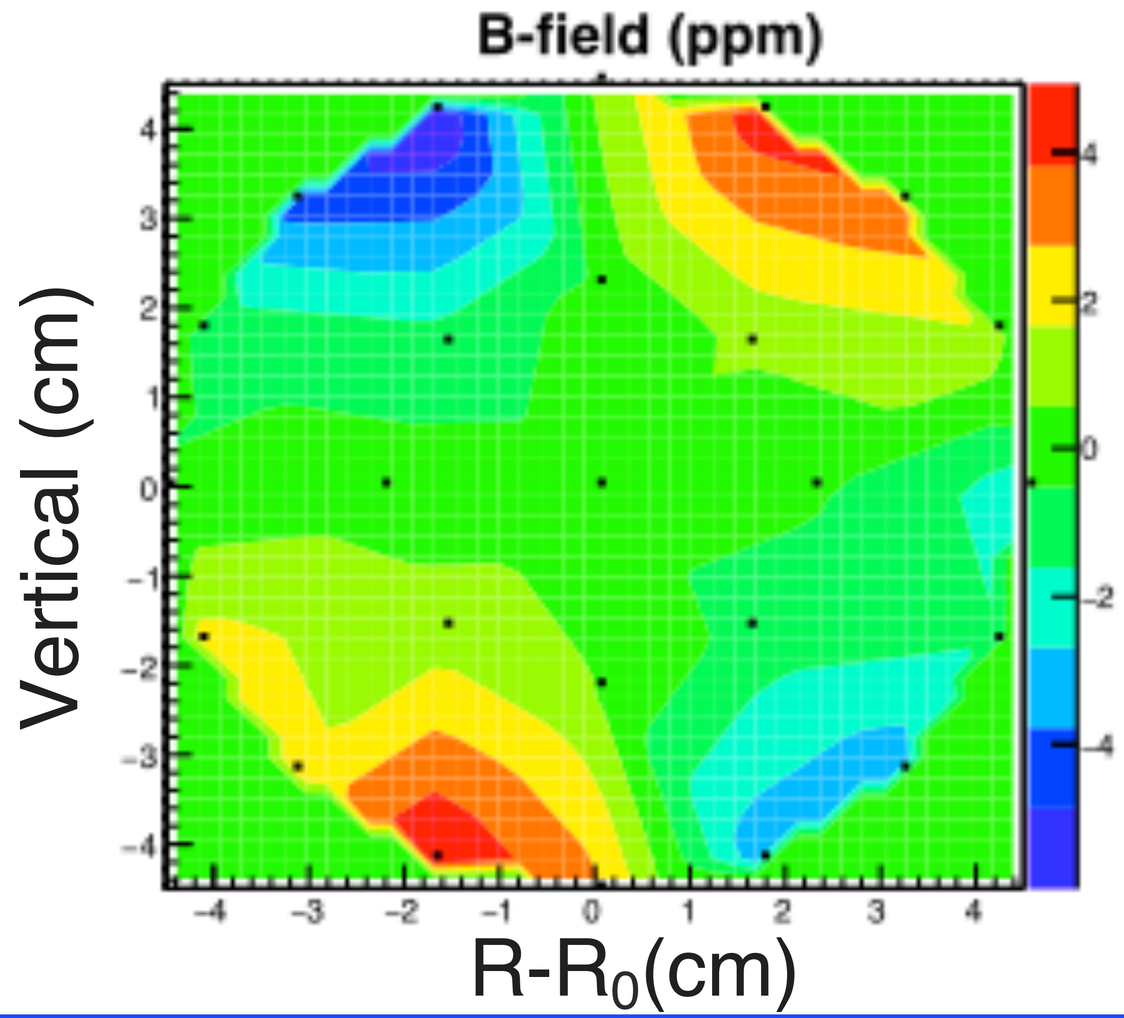
Rough Shimming Results





	Norm	Skew
Quad	25.13	-0.53
Sext	-1.99	-0.11
Octu	-1.16	-0.31
Decu	0.95	-0.07

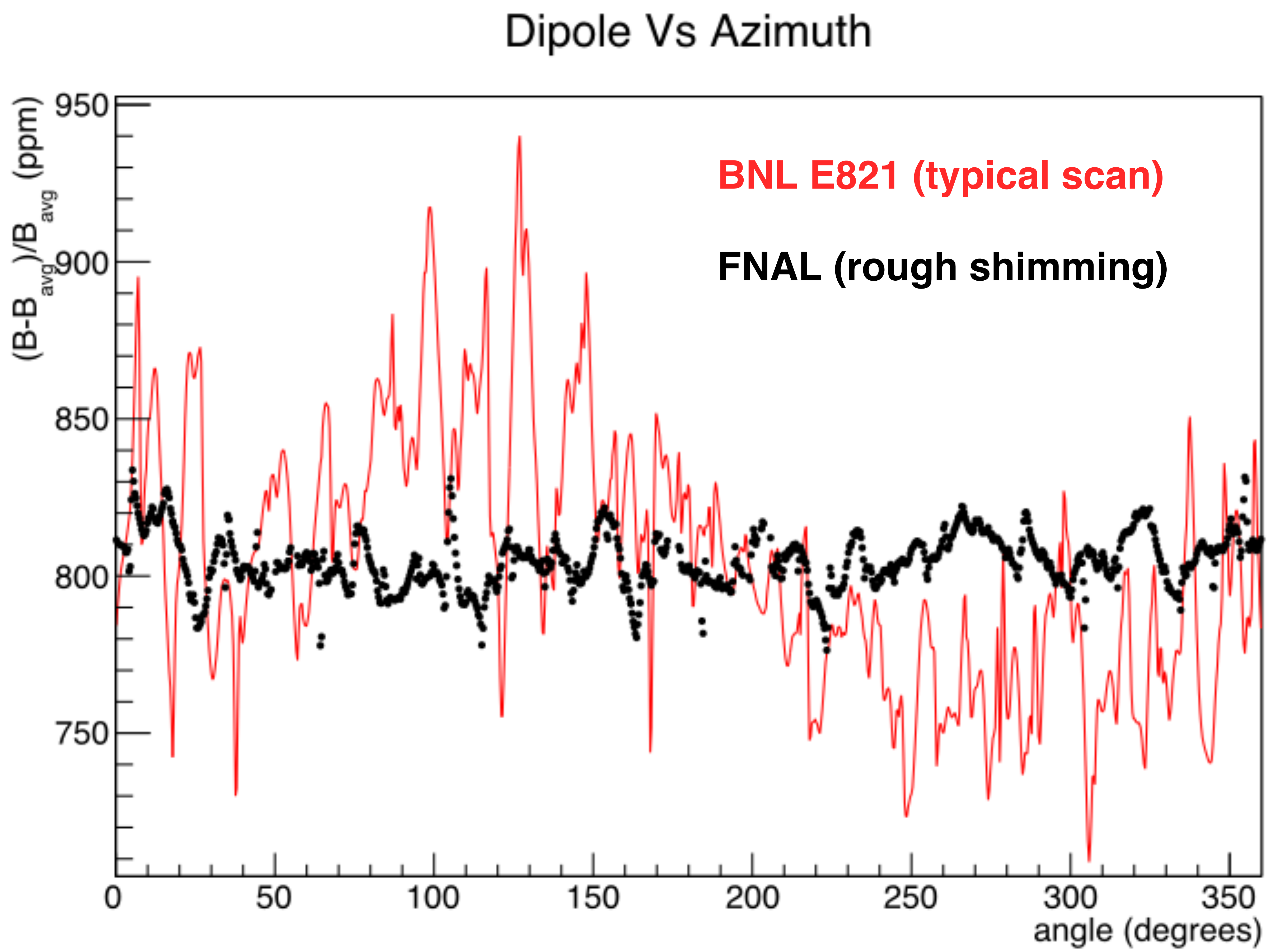
Oct 2015



	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

Aug 2016

Magnetic Field Comparison: BNL 821 and FNAL E989

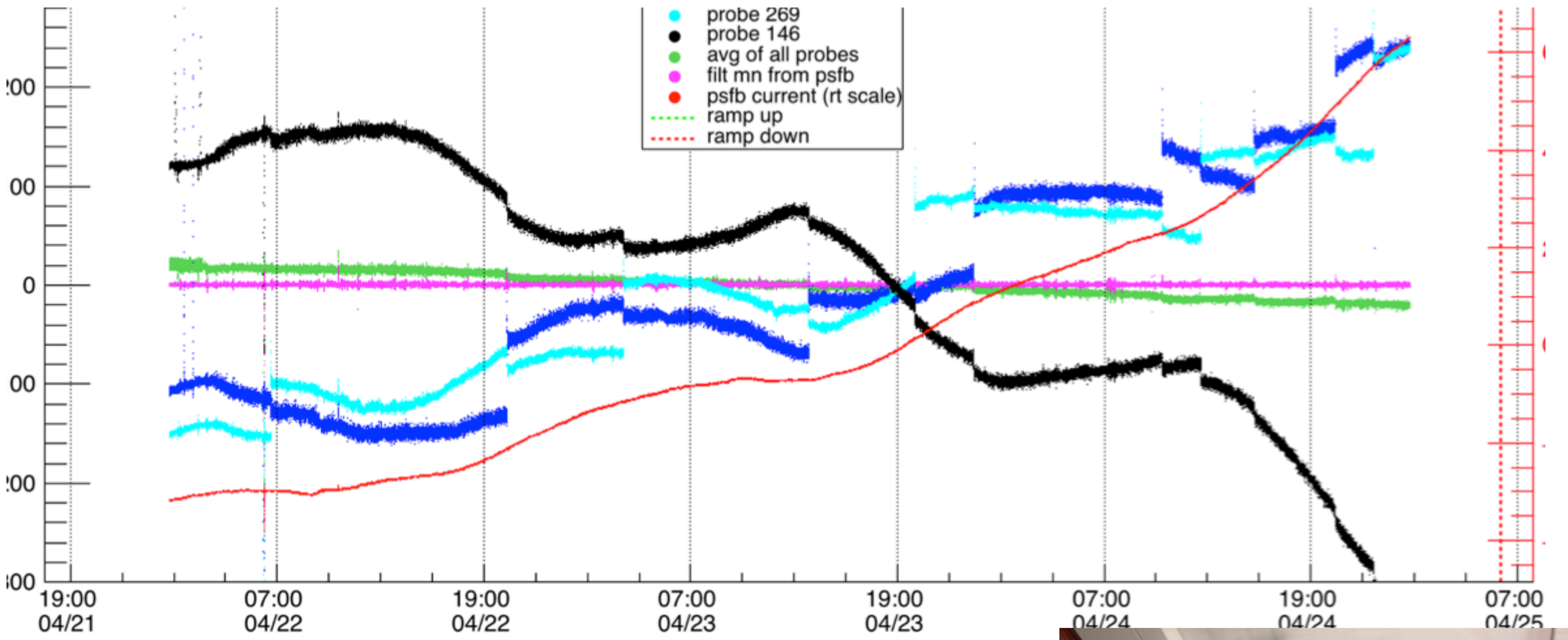


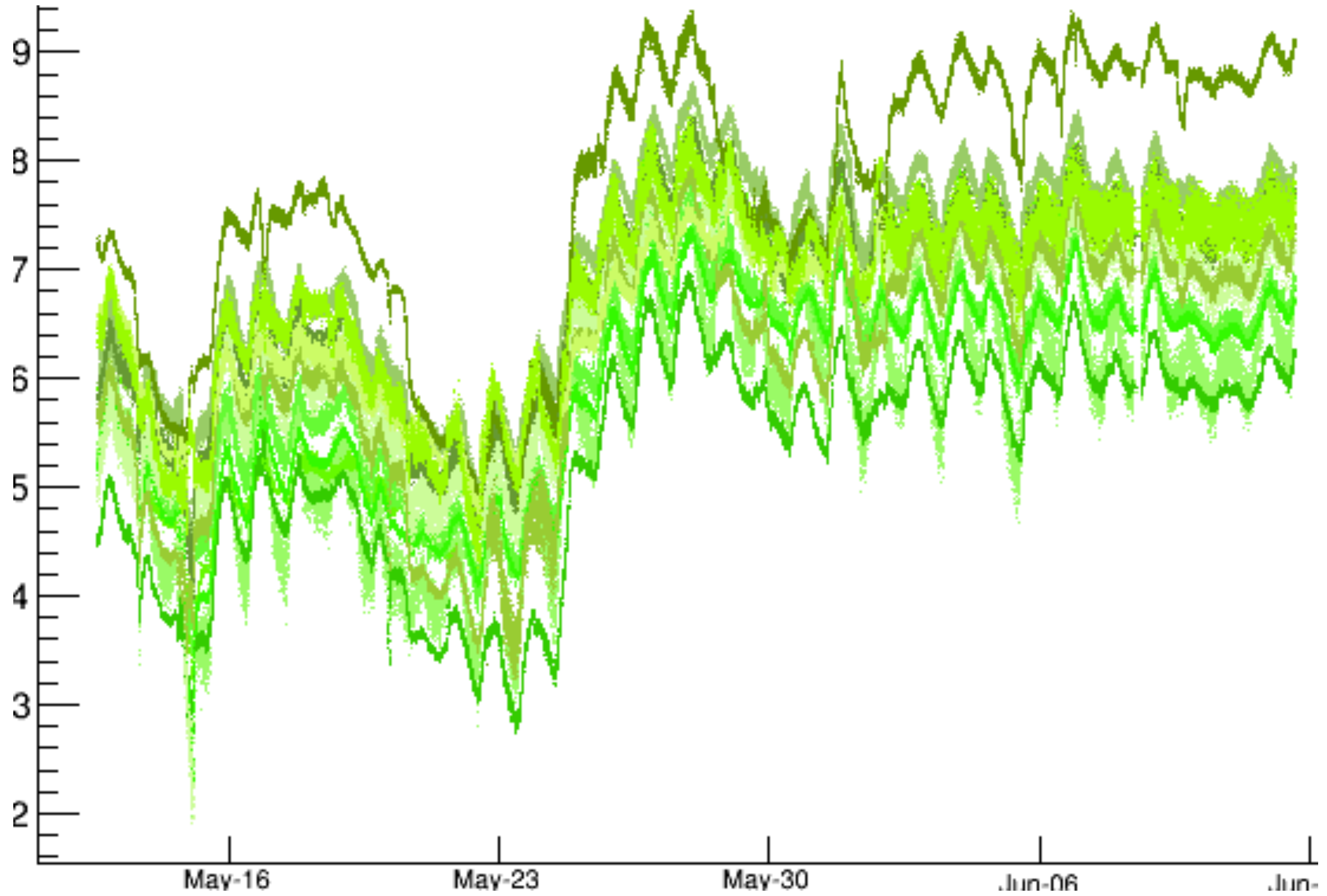
- Laminations very successful in reducing field variations

- BNL E821: 39 ppm RMS (dipole), 230 ppm peak-to-peak
- FNAL rough shimming: 10 ppm RMS (dipole), 75 ppm peak-to-peak

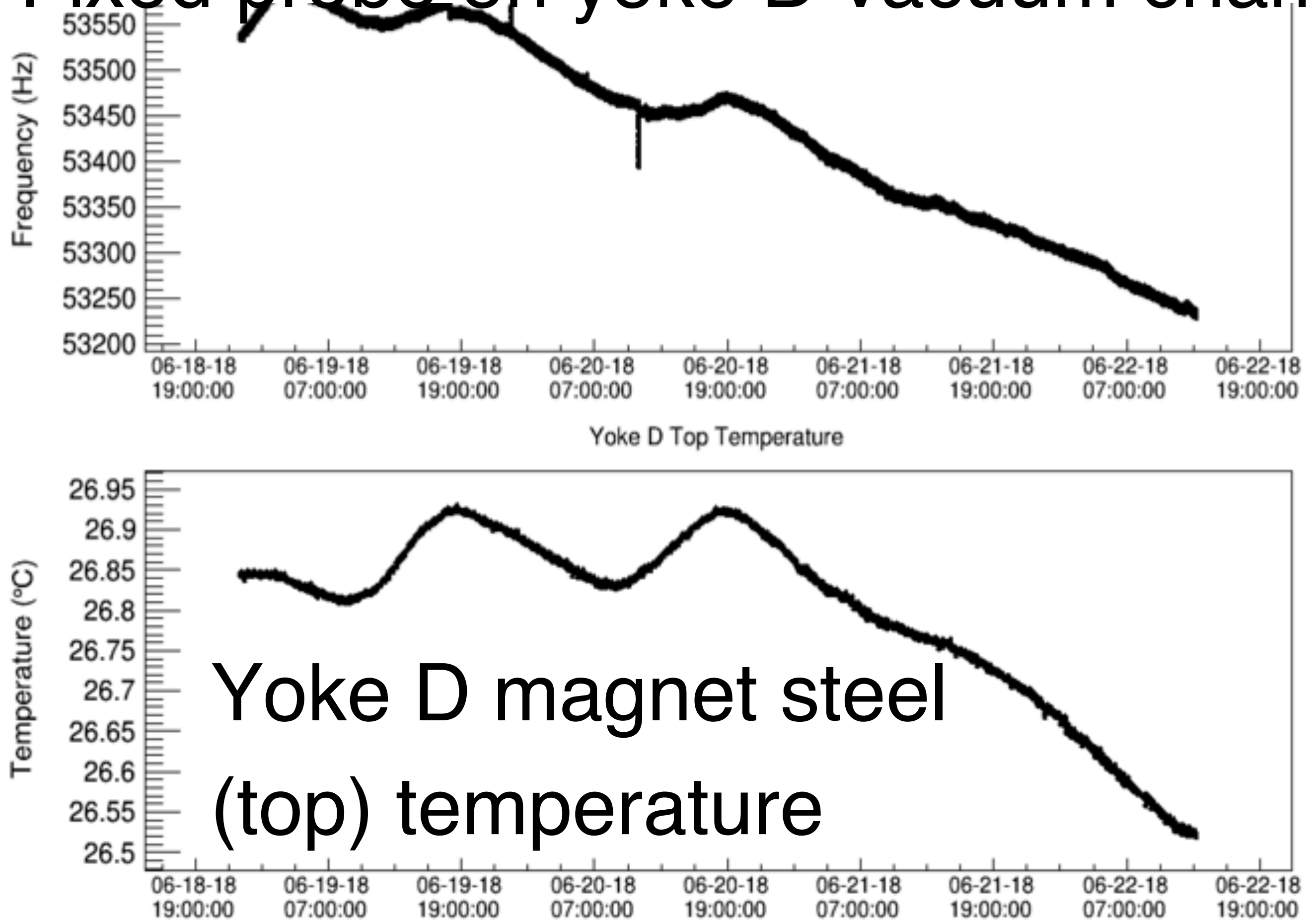
Magnet Insulation

- Temperature variations in the hall affect the quality of the magnetic field
  - Observed ~ 20 ppm/deg C effects on the dipole moment during the run
  - Also affects ability to track higher-order multipoles
- Two main issues
  - Large changes in average temperature over time (2–3°C)
  - Differential changes across the magnet (~3°C)
- Two-pronged solution:
  - Improved cooling system in the hall
  - Install fiberglass insulation blanket on magnet steel

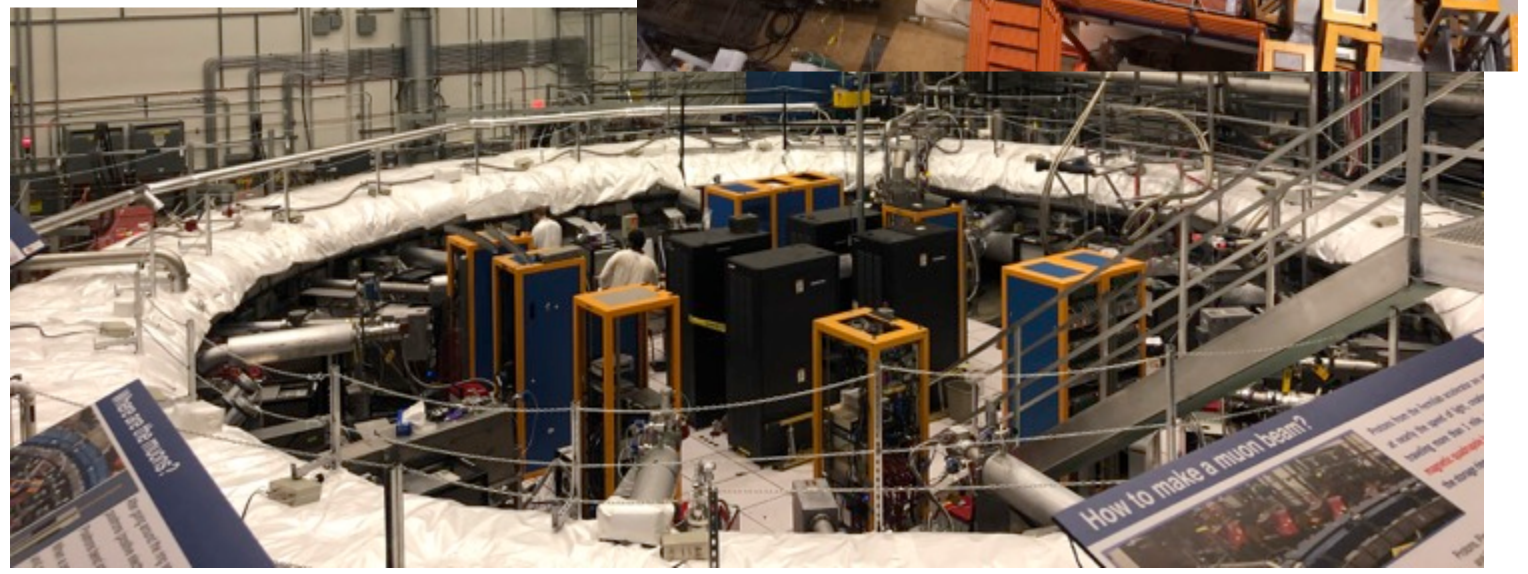




Fixed probe on yoke D vacuum chamber (top)



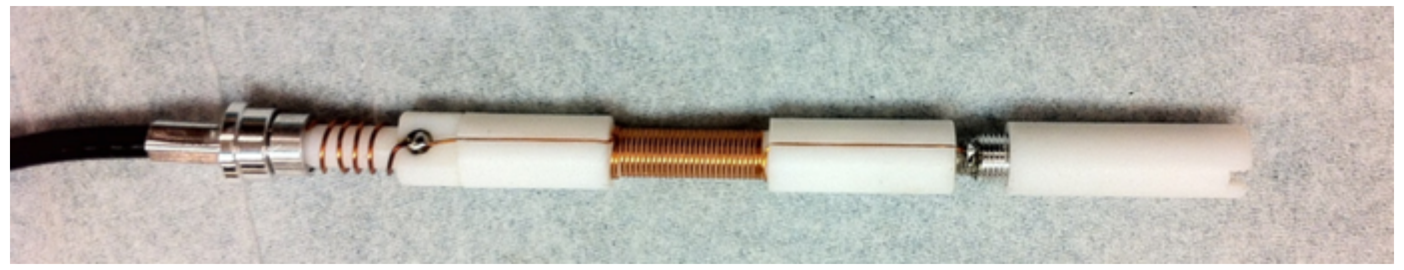
Installed blankets this past summer



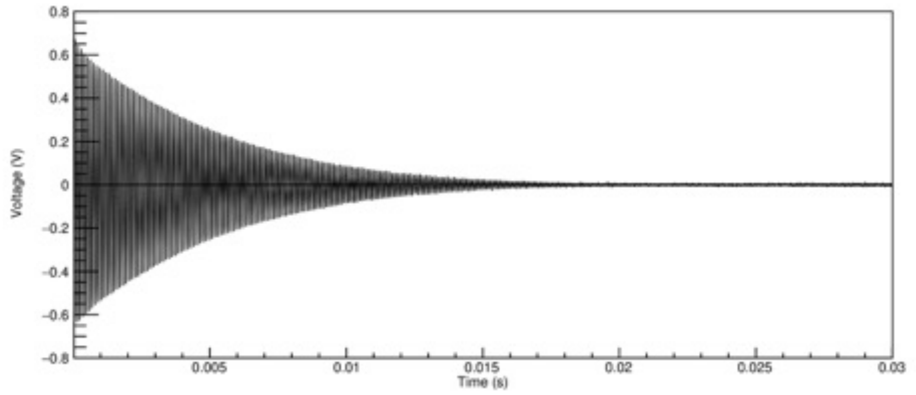
Fermilab

Monitoring and Mapping the Magnetic Field

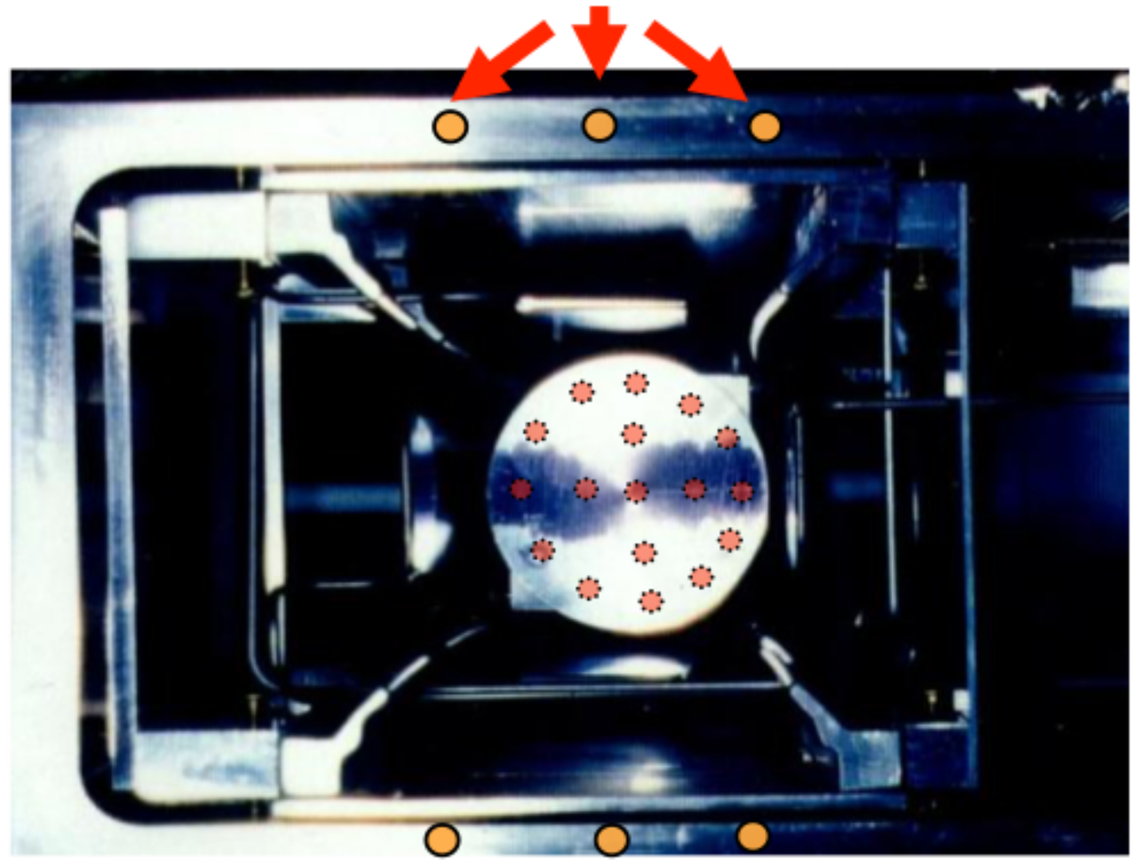
Pulsed NMR



- Deliver π/2 pulse to probe, induce & record the free-induction decay (FID)
- Extracted frequency precision: 10 ppb/FID

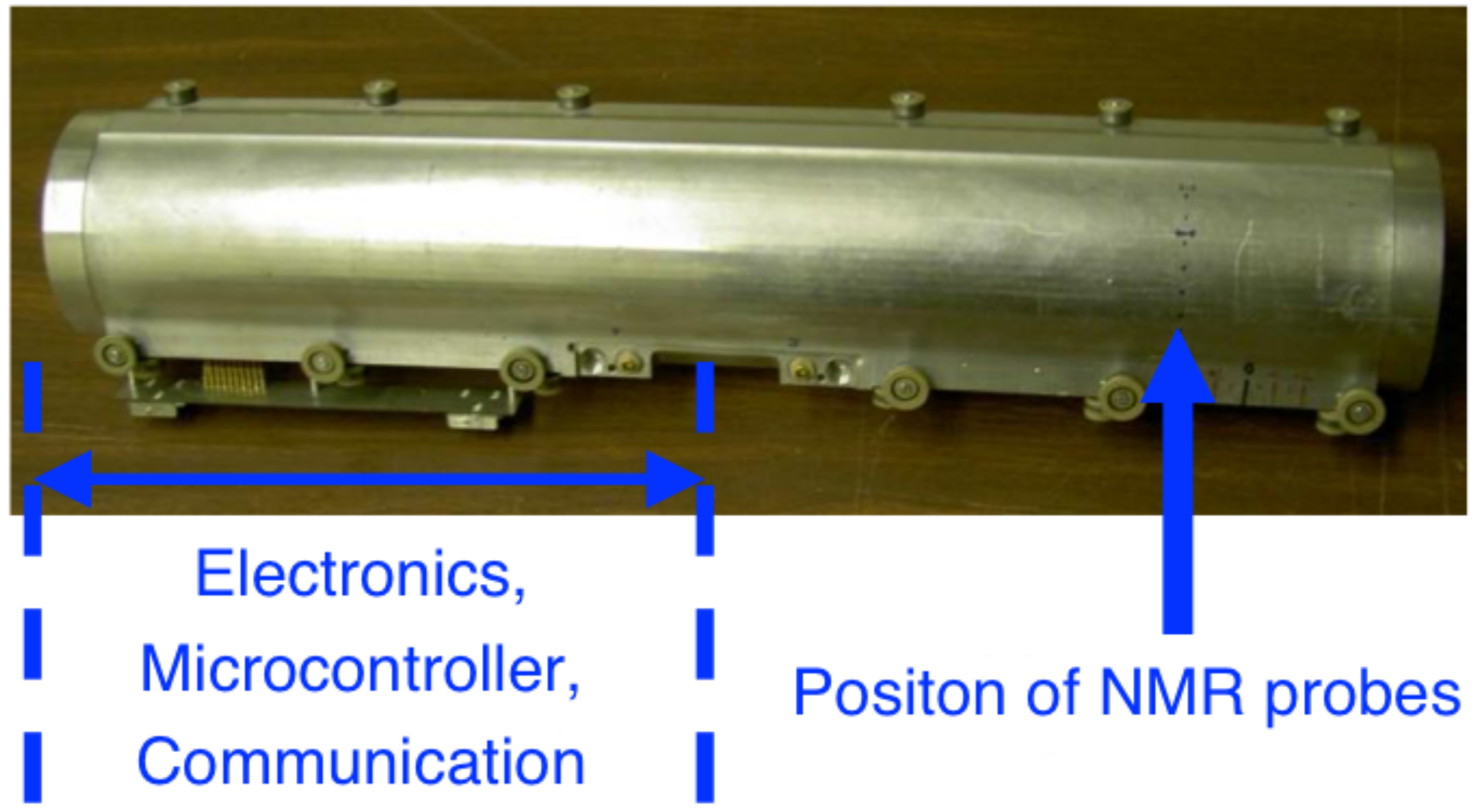


Fixed probes on vacuum chambers



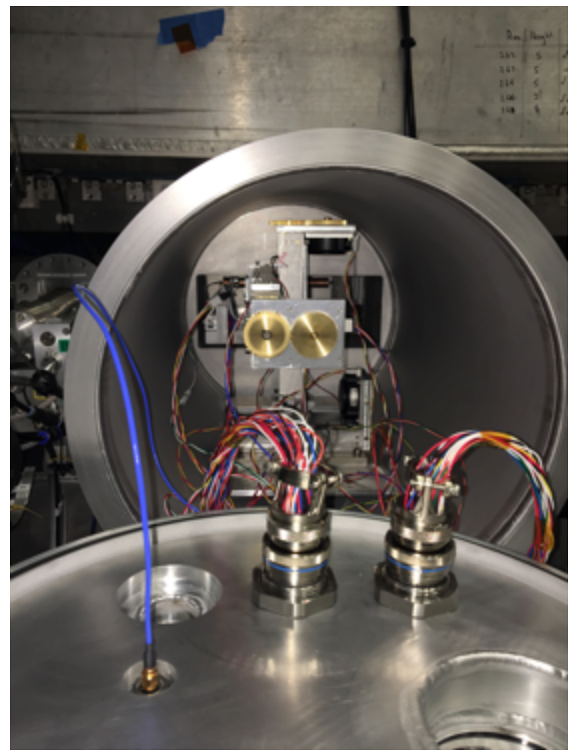
- Measure field while muons are in ring – 378 probes **outside** storage region

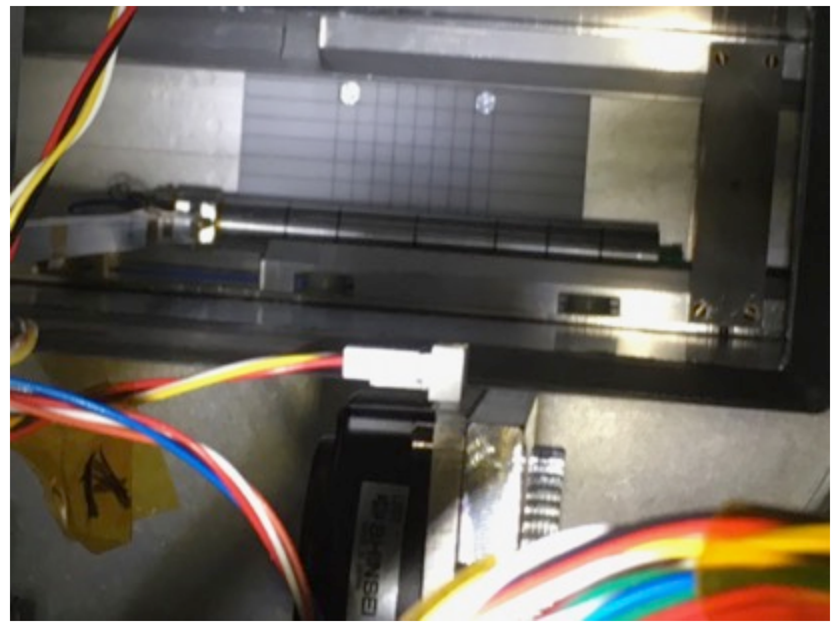
Trolley matrix of 17 NMR probes



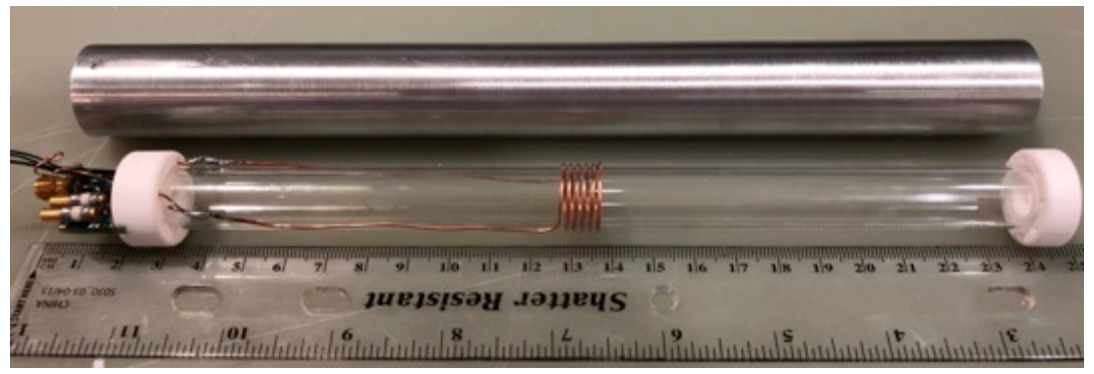
- Measure field in storage region during **specialized runs** when **muons are not being stored**

- **Trolley** probes **calibrated to free-proton Larmor frequency**
  - Calibrate trolley probes using a special probe that uses a water sample
  - Measurements in specially-shimmed region of ring



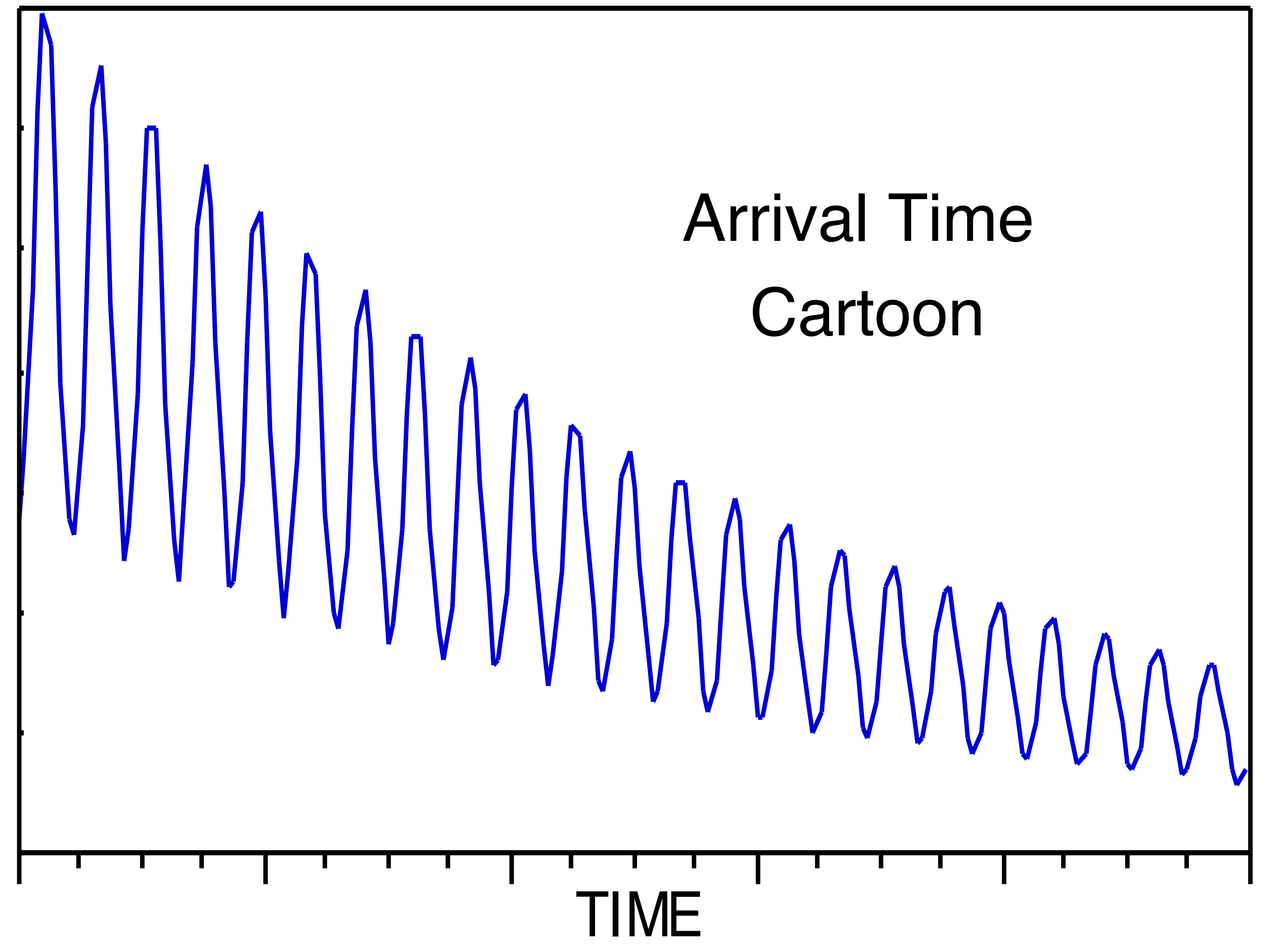


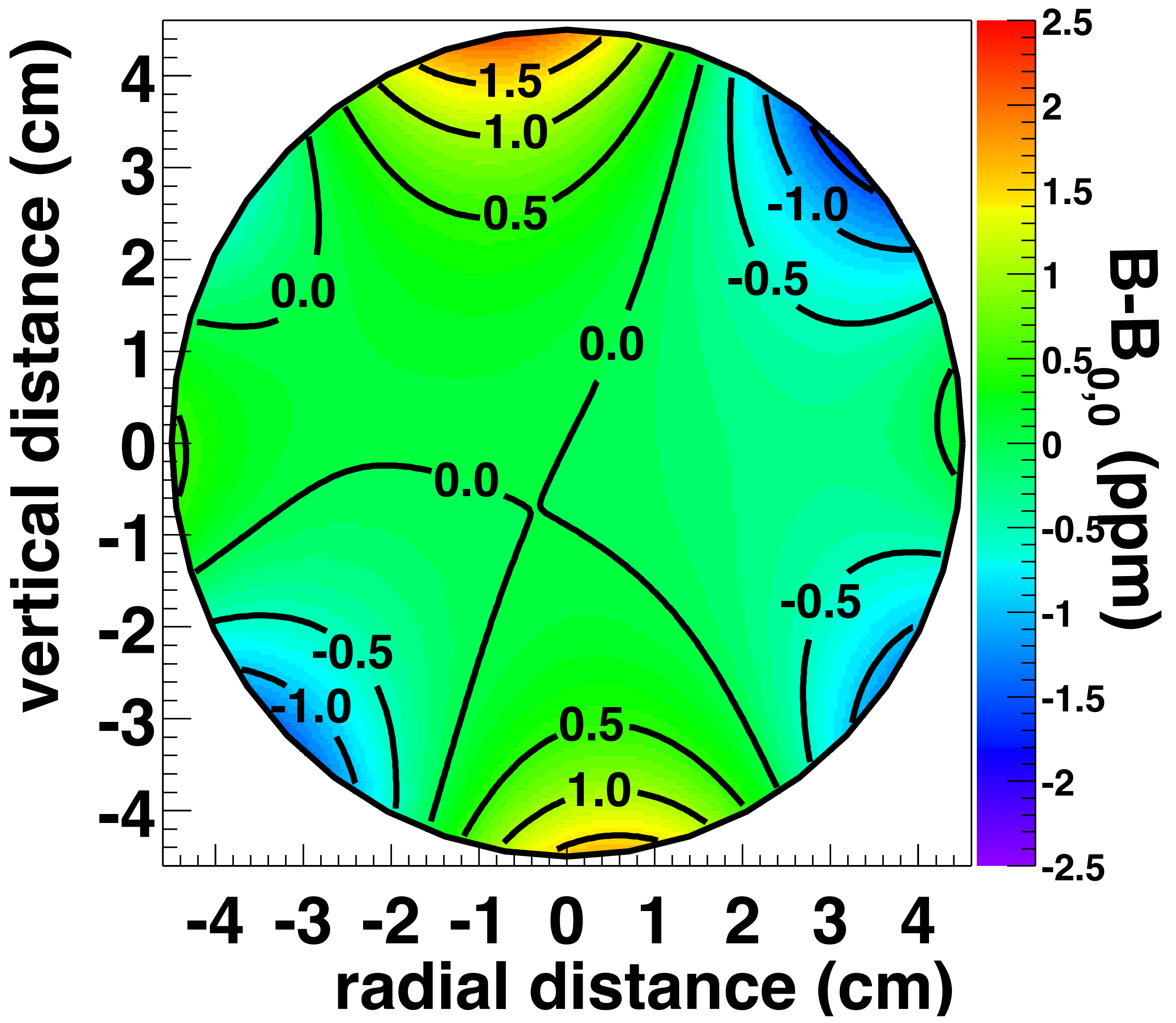
Plunging Probe

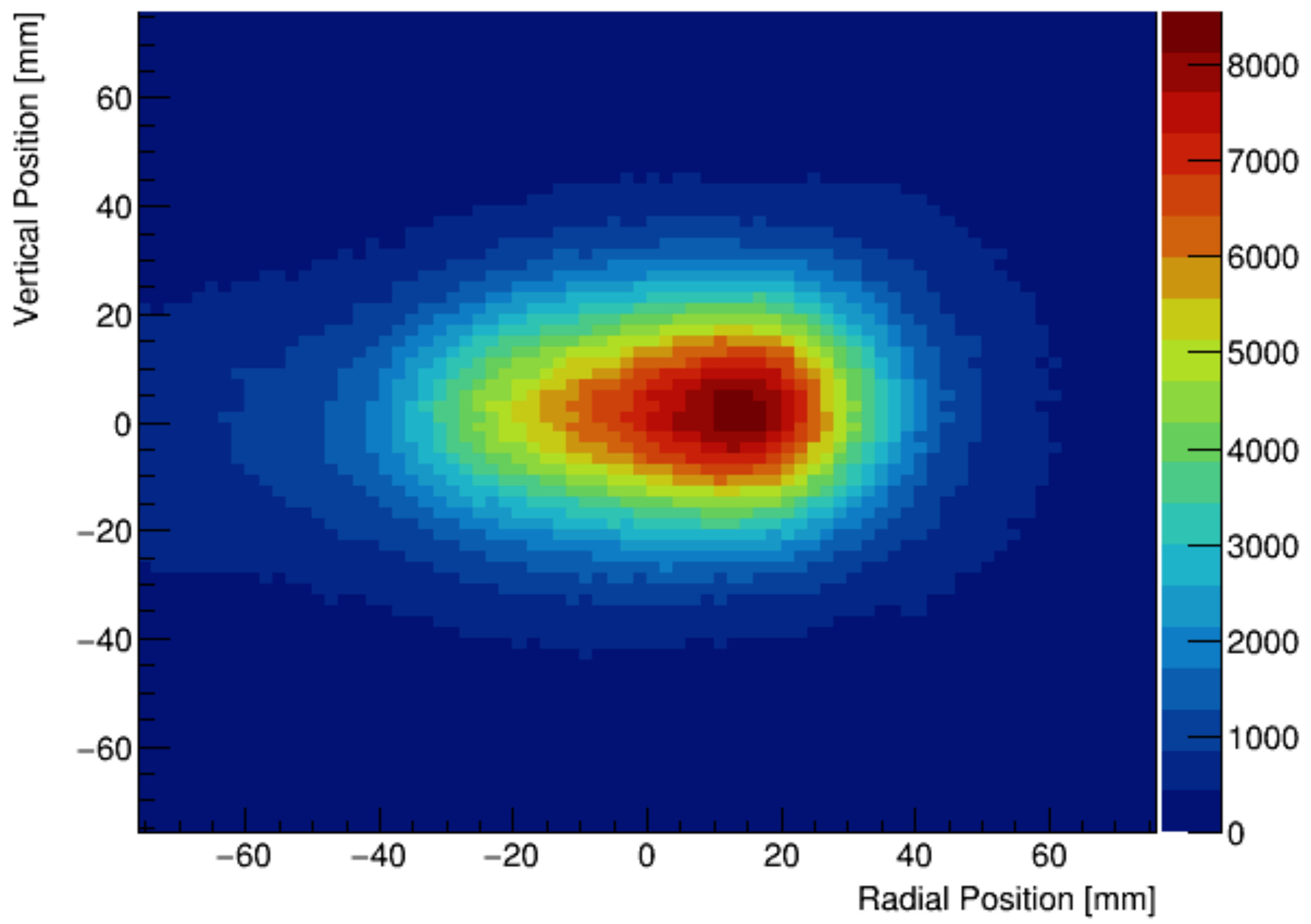


Measurement Principle

- Three ingredients to measure $a_\mu \sim (\omega_a / \tilde{\omega}_p)$
  - ω_a: Arrival time spectrum of high energy positrons
  - ω_p: Magnetic field in storage region measured by proton NMR
  - $\tilde{\omega}_p$: Muon distribution to get weighted magnetic field frequency





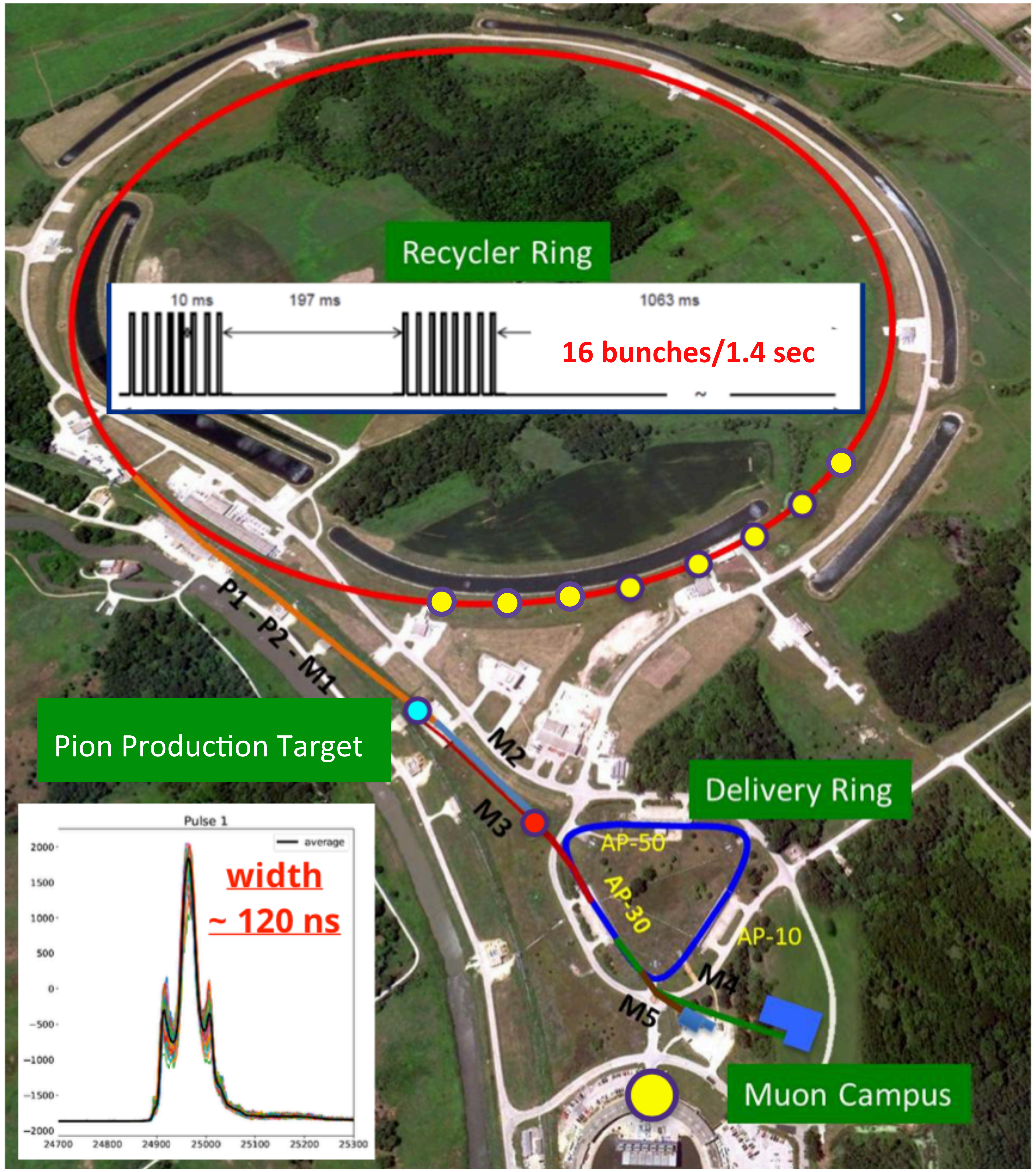


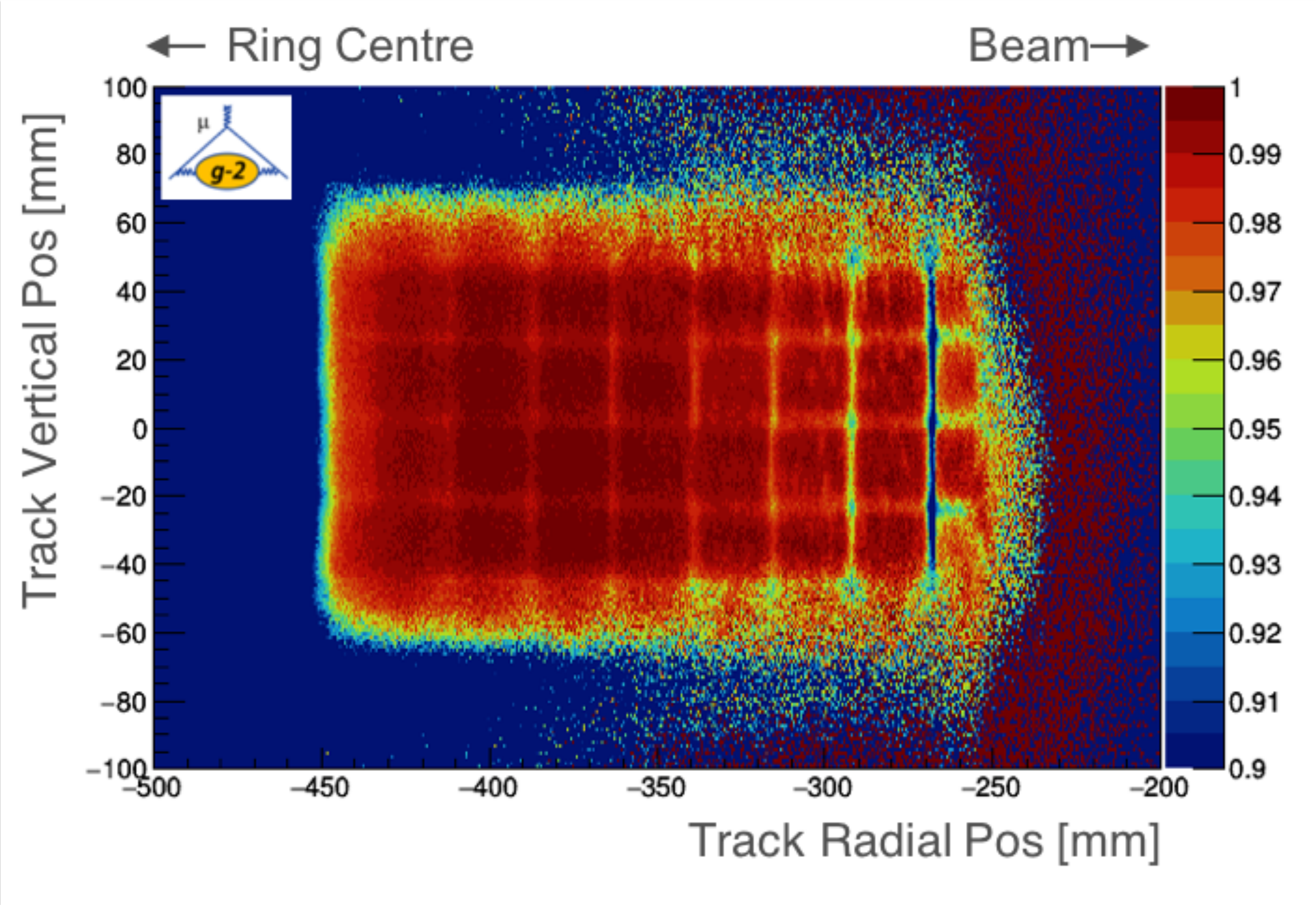
Why Fermilab?

- BNL limited by statistics
  (540 ppb on 9 x 10^9 detected e^+)
- E989 goal: Factor of 21 more statistics
  (2 x 10^{11} detected e^+)

Fermilab advantages

- Long beam line to collect $\pi^+ \rightarrow \mu^+$
- Much reduced amount of p, π in ring
- 4x higher fill frequency than BNL




← Ring Centre
Beam→
Track Vertical Pos [mm]
Track Radial Pos [mm]
100
80
60
40
20
0
−20
−40
−60
−80
−100
−500
−450
−400
−350
−300
−250
−200
1
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.9
μ
g-2

BNL Phase based method: systematics

Source	Sensitivity	Result
Tilt	26 μrad/mm/mrad$\times$ 0.75 mrad	20 μ rad/mm
Detector Misalignment	143 μrad/mm/ mm $\times$ 0.2 mm	29 μ rad/mm
Energy Calibration	43 μrad/mm/ % $\times$ 0.1%	4.3 μ rad/mm
Muon Vertical Spin	1.0 μrad/mm $\times$ 8%	8.0 μ rad/mm
Radial B field	0.72 μrad/mm/ppm $\times$ 20.0 ppm	14.4 μ rad/mm
Timing	17.0 μrad/mm/ns $\times$ 0.2 ns	3.4 μ rad/mm
Total systematic		42 μrad/mm (1.1×10^{-19} $e\cdot$cm)
Total statistical		28 μrad/mm (0.73×10^{-19} $e\cdot$cm)
Total		50 μrad/mm (1.3×10^{-19} $e\cdot$cm)