The Electric Dipole Moment of the Muon: Prospects

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On Behalf of the Muon g-2 Collaboration

Electric and Magnetic Dipole Moment Workshop

September 17th, 2020

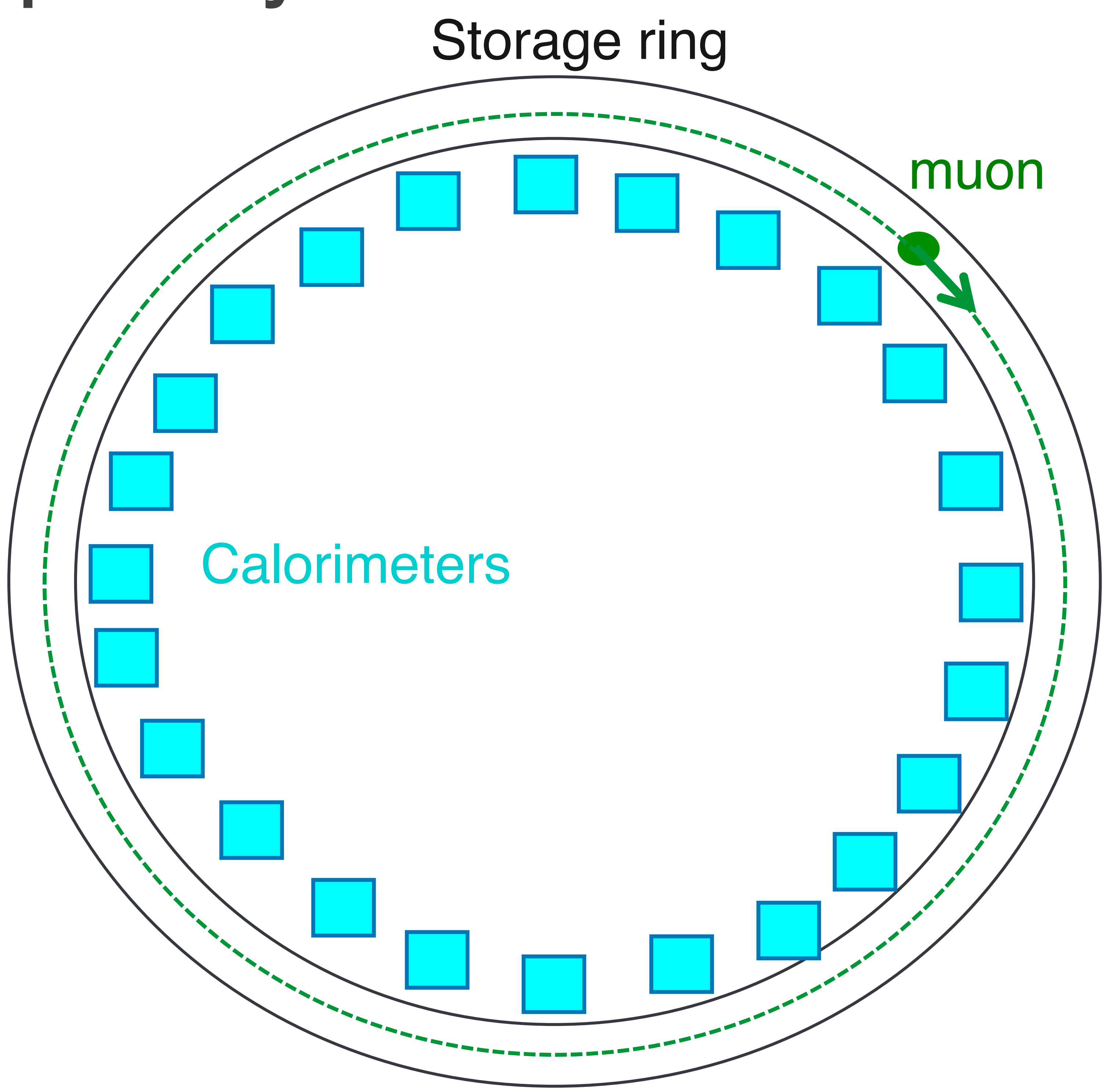
Outline

- Brief overview of g-2 measurement principle
- Effect of a muon EDM on g-2 experiments
  - BNL measurement
  - E989 EDM measurement techniques: Improvements since BNL
- Overview of data taking at Fermilab
- Prospects for Fermilab EDM measurement
- Dedicated muon EDM measurement at PSI

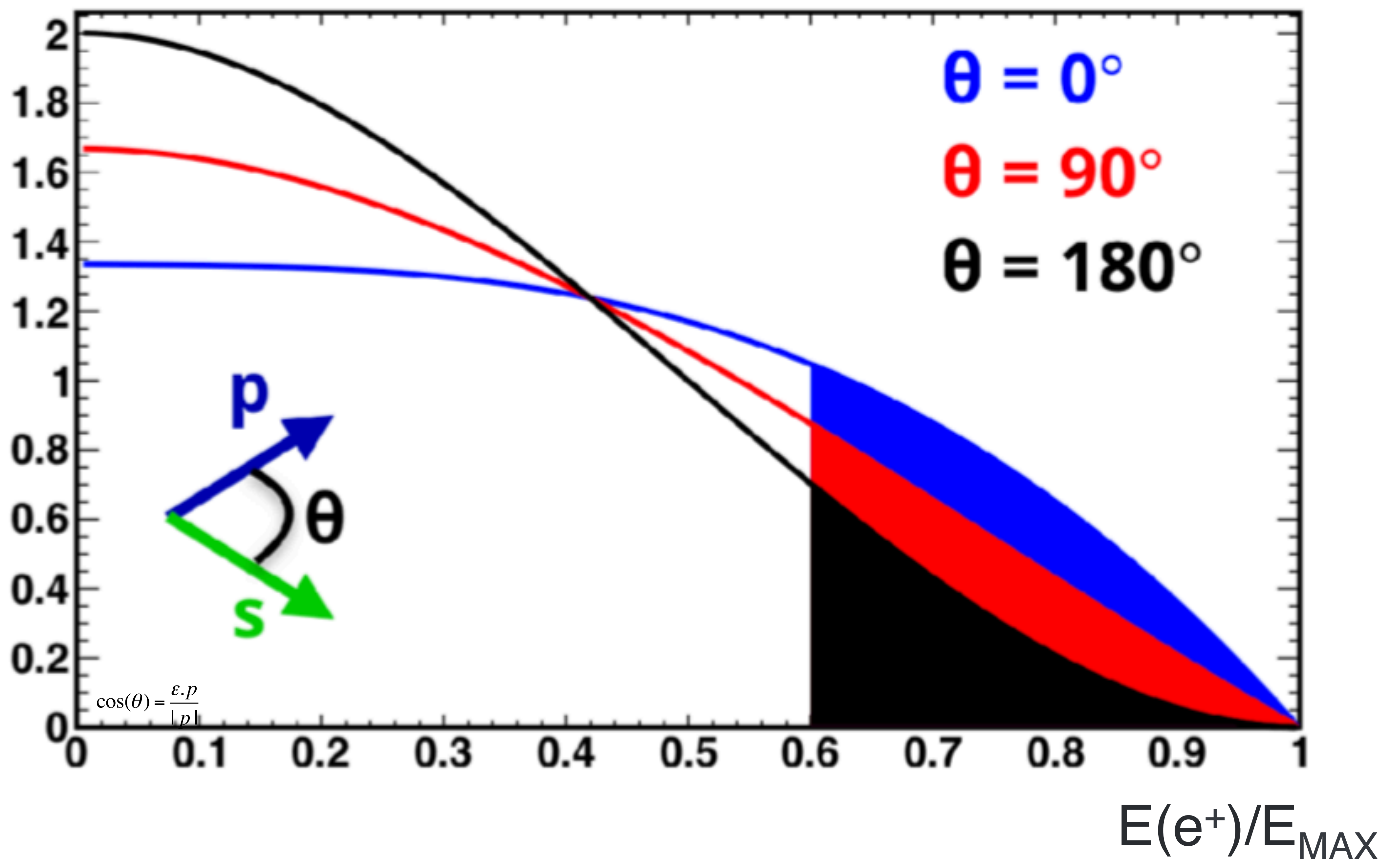
- Note that J-PARC EDM prospects in later talk by T. Mibe

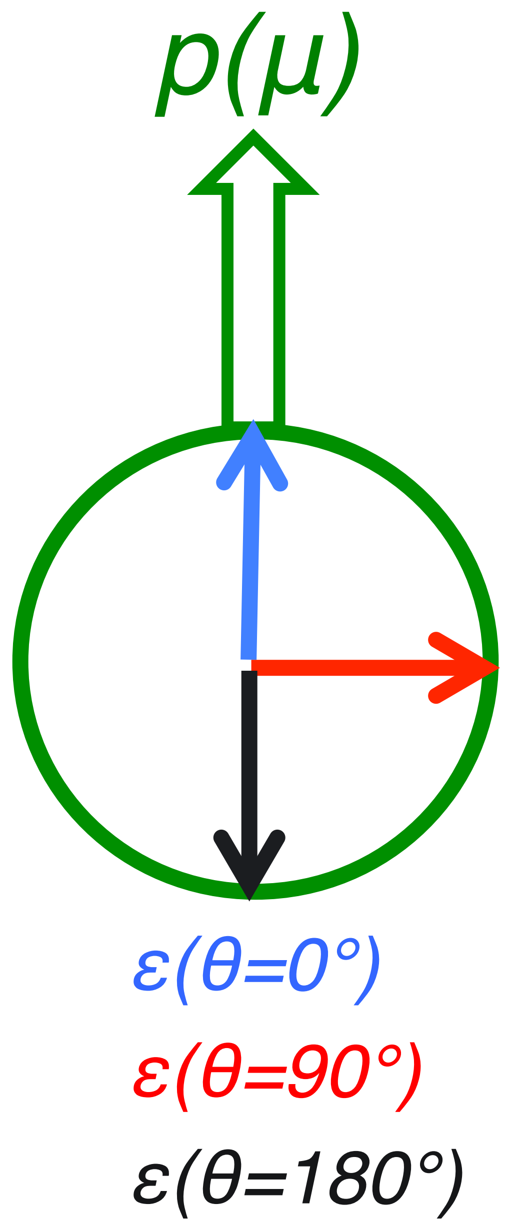
Measuring ω_a

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



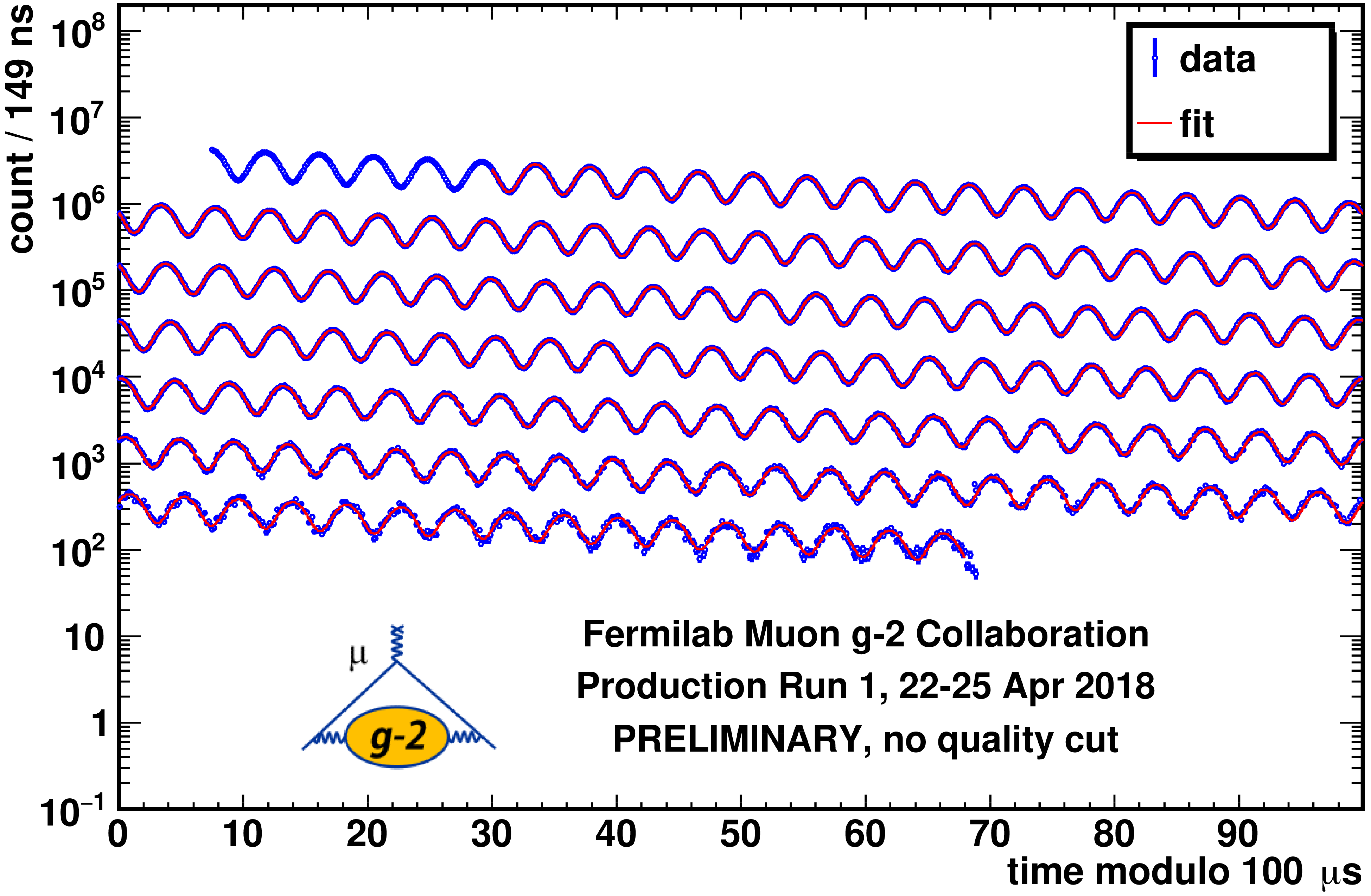
$$\cos(\theta) = \frac{\varepsilon . p}{|p|}$$





- 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 $\theta \approx 0°$
- Minima at $\theta \approx 180°$
- Amplitude determined by energy threshold

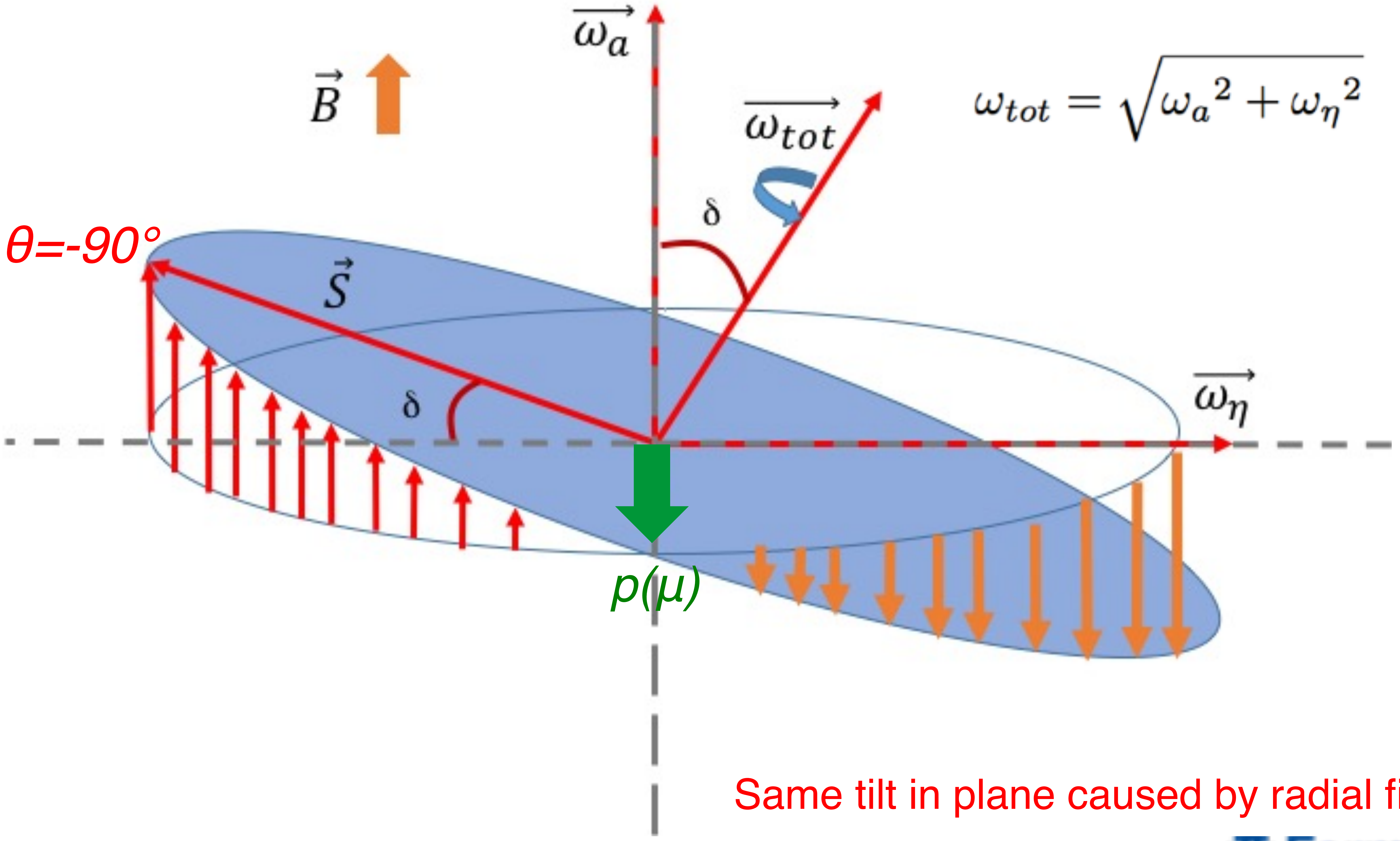
- But what happens when an EDM is introduced?...

EDM in a storage ring

$$\vec{\omega}_{a\eta} = \vec{\omega}_a + \vec{\omega}_\eta = -\frac{Qe}{m}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] - \eta\frac{Qe}{2m}\left[\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right]$$

$$\vec{d} = \eta\left(\frac{Qe}{2mc}\right)\vec{s}$$

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



Same tilt in plane caused by radial field

EDM experimental signature

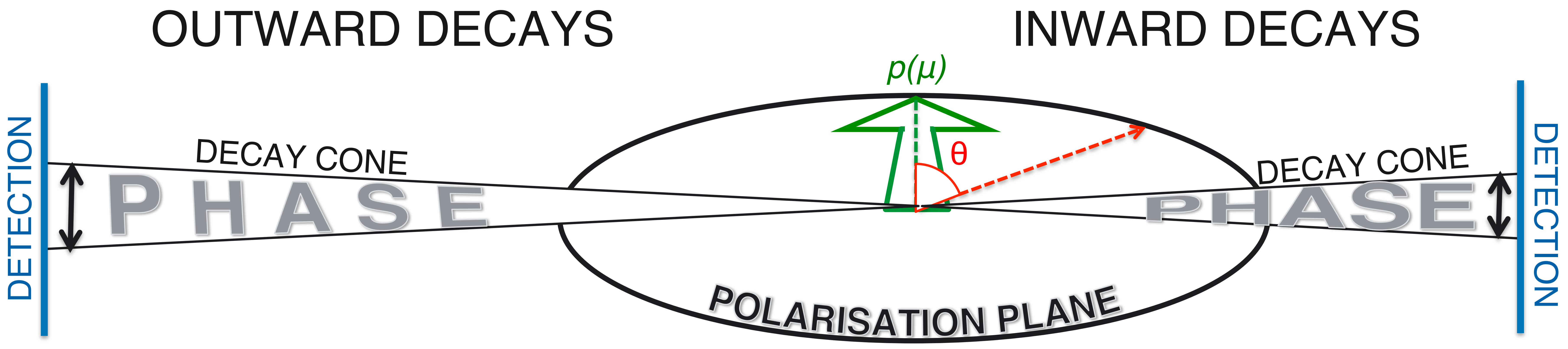
- For a 'large' EDM can look for increase in precession frequency
  - For scale, the BNL measured ω_a - ω_{SM} gives $d_\mu \approx 2.5 \times 10^{-19}$ e.cm

- To go beyond that, there are 2 approaches:

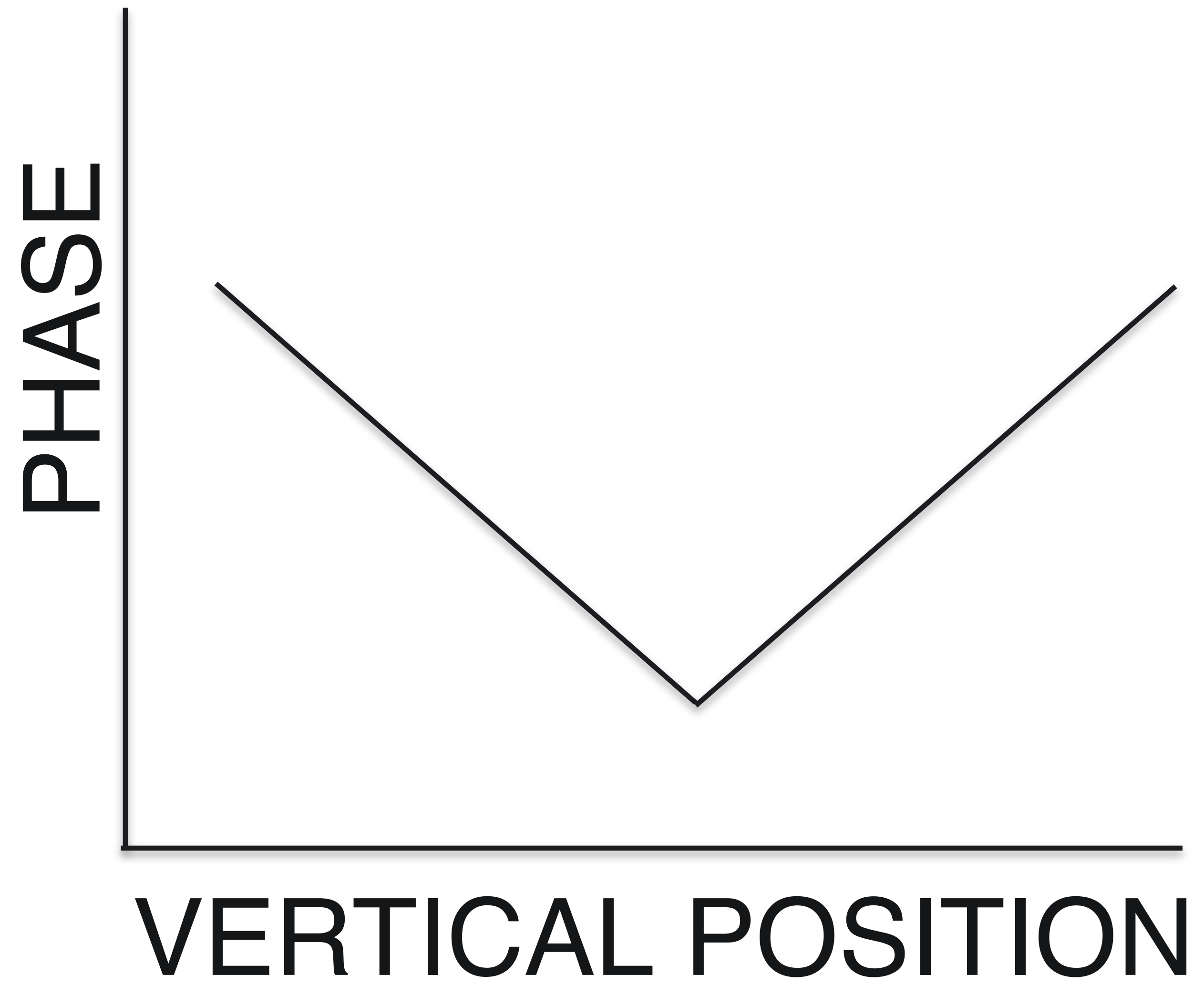
1. Asymmetry in phase of measured ω_a vs vertical position

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

Phase Asymmetry

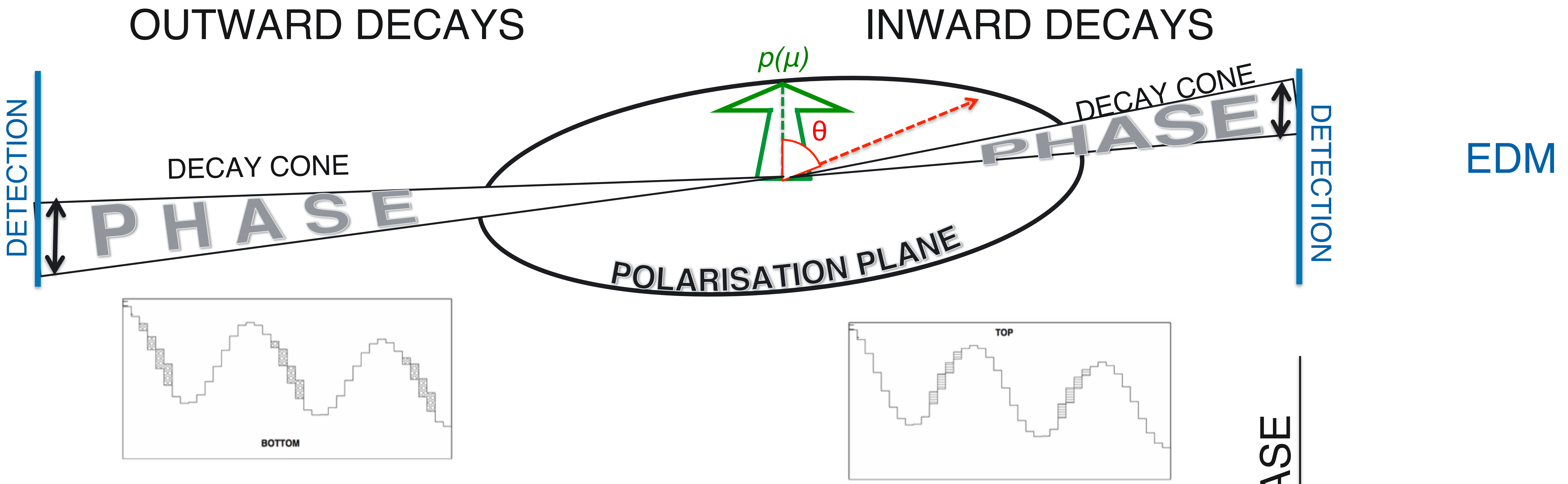


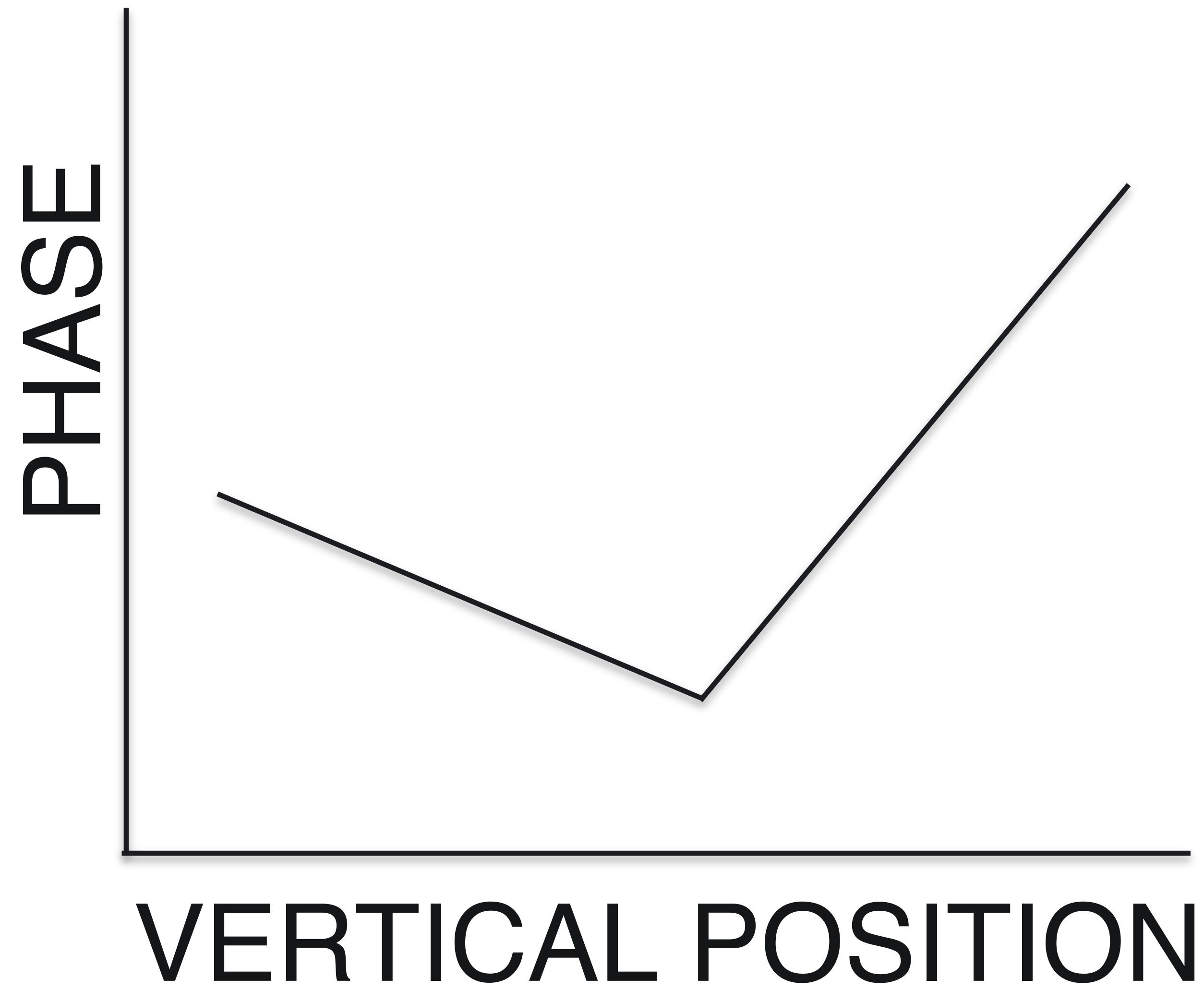
No EDM



- 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

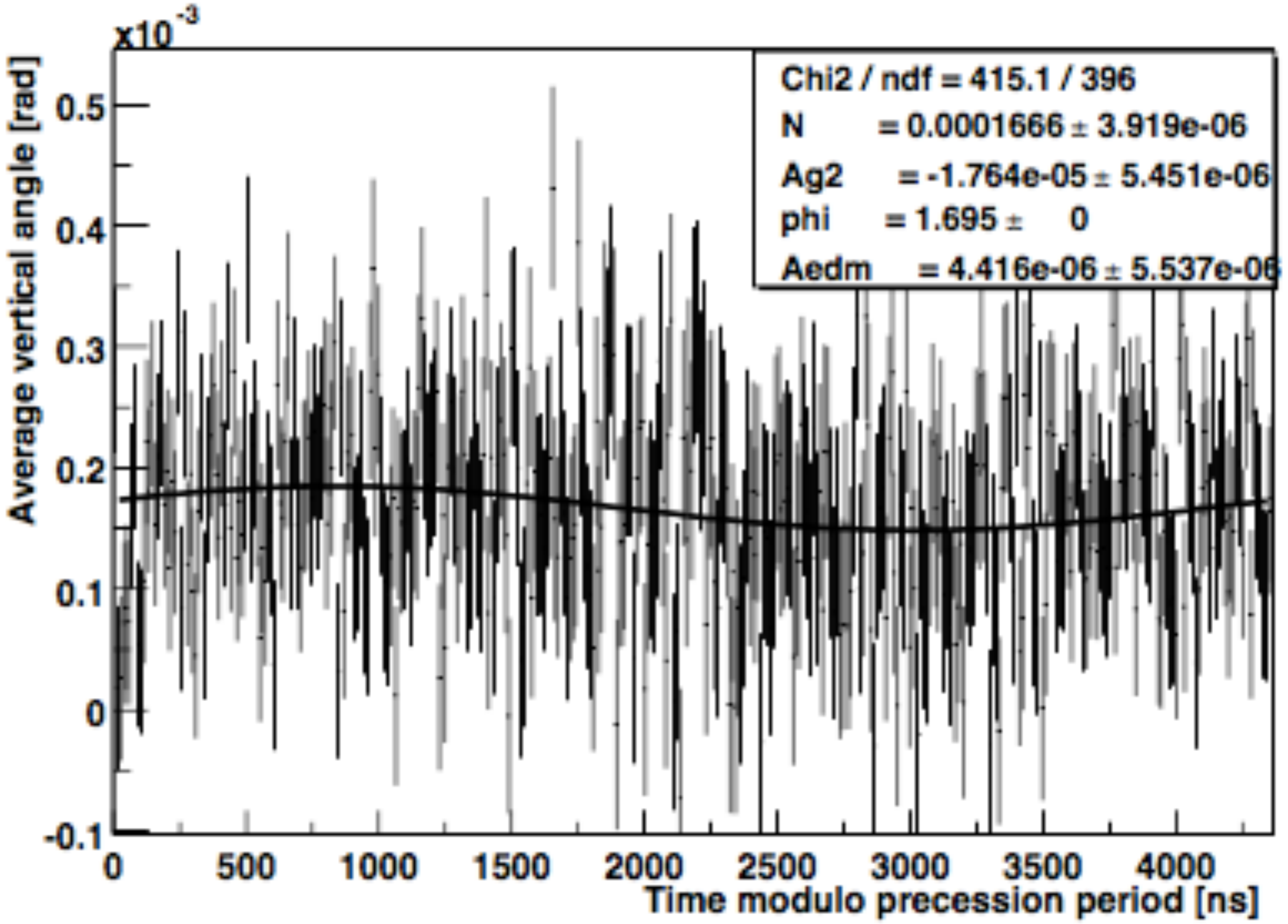




- Inward (towards calorimeter) decays travel a shorter distance than outward
- When there is an EDM, the polarisation plane is tilted, and there is a vertical asymmetry
- Dominant systematic uncertainty is detector alignment

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

arxiv: 0811.1207

BNL results

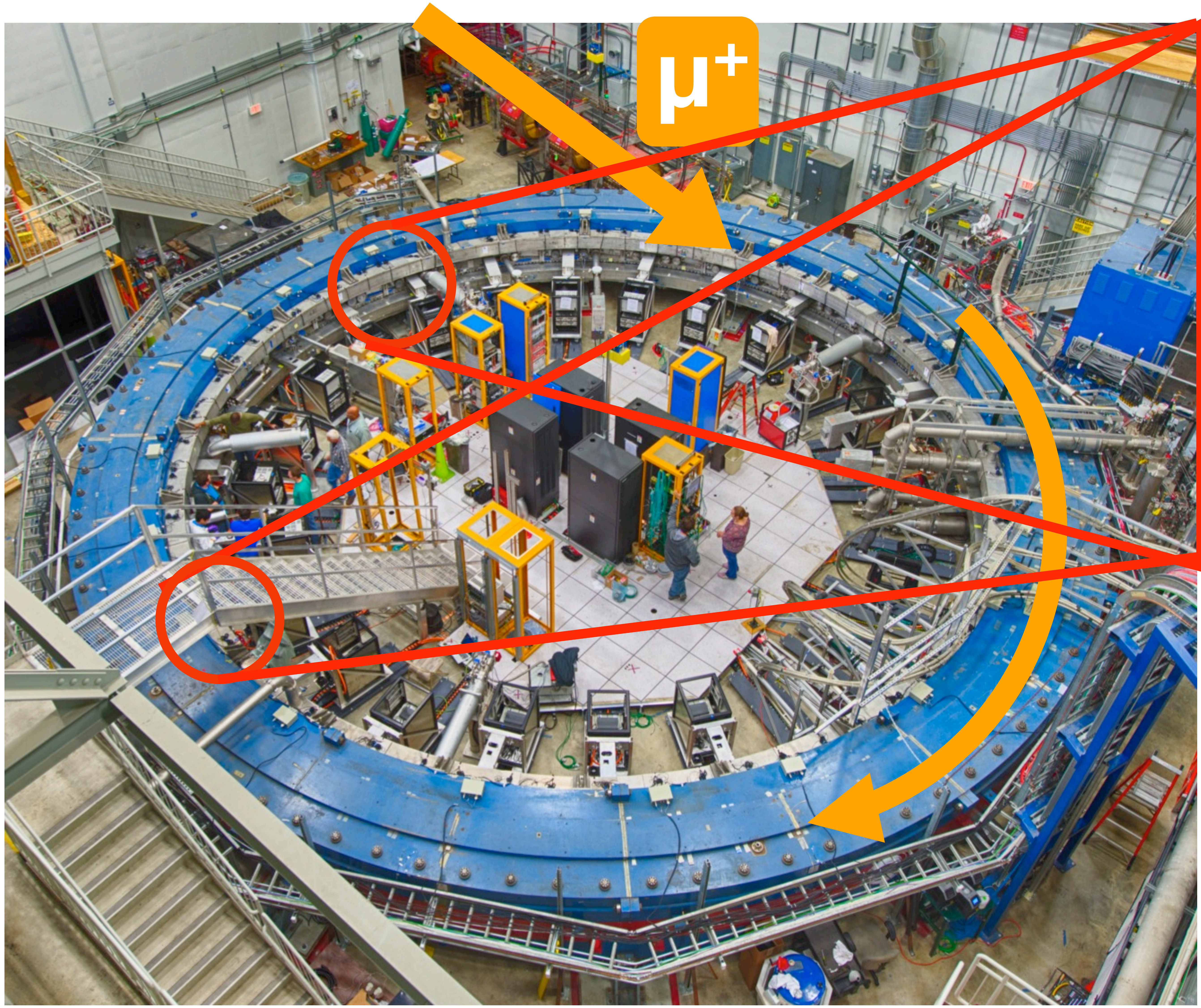
- Summary of BNL results:

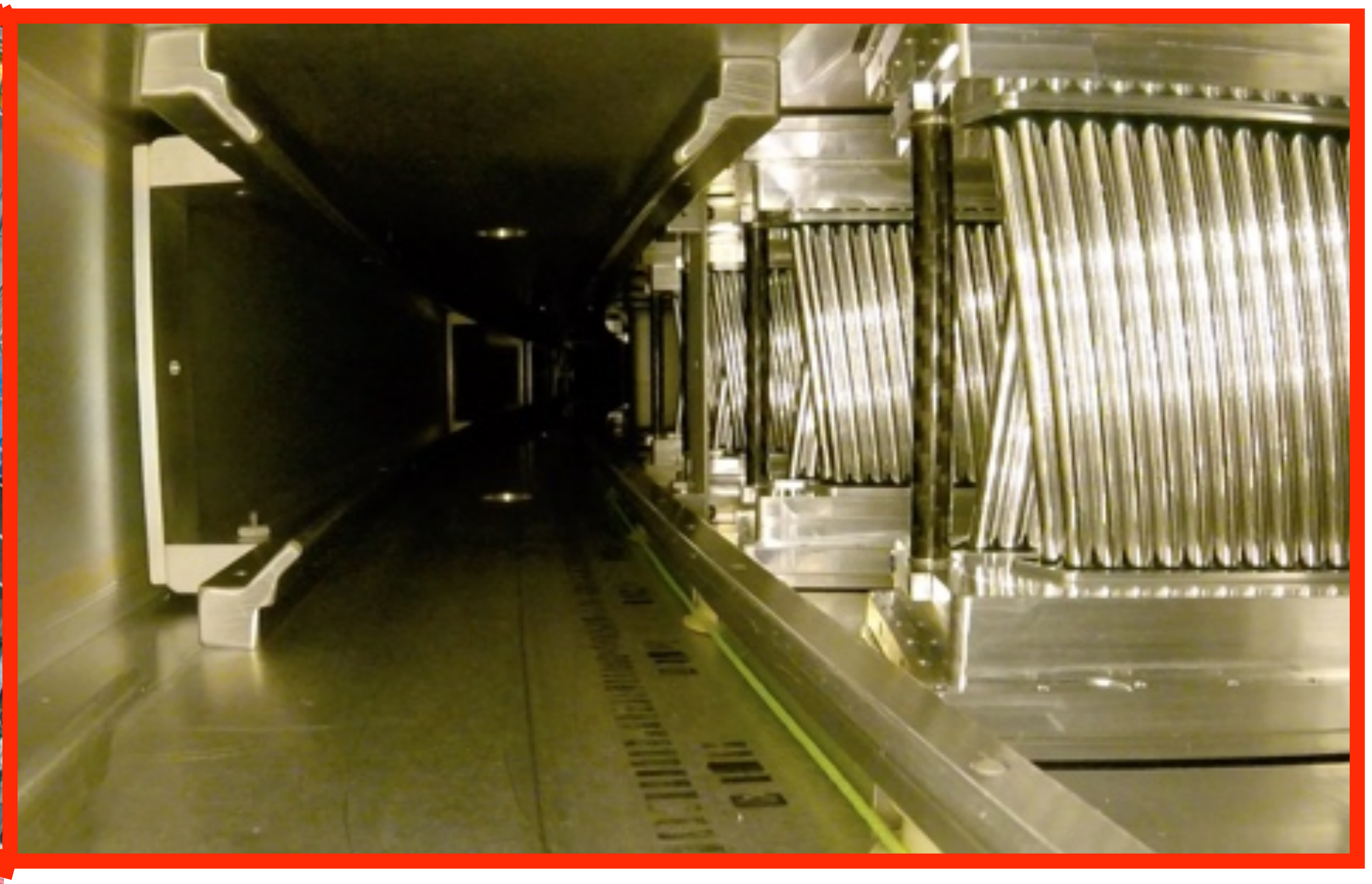
Method	Dataset	Particle	Measurement (10^{-19} e.cm)	$\|d_\mu\|$ e.cm (95% CL)
Tracking $\langle y' \rangle$	1999, 2000	μ^+	$-0.04 \pm 1.6 \pm 0.0\ (\ll 1.6)$	$< 3.2 \times 10^{-19}$
Phase vs y	2000	μ^+	$-0.1 \pm 0.34 \pm 1.36$	$< 2.9 \times 10^{-19}$
Phase vs y	2001	μ^-	$-0.1 \pm 0.28 \pm 0.70$	$< 1.9 \times 10^{-19}$
Phase vs y	2001	μ^-	$-0.48 \pm 0.73 \pm 1.09$	

- Direct tracker method only available for 1999, 2000 dataset
  - Statistically limited ~ 4.8 + 4.6 million high quality tracks in total BNL dataset
- Position and phase measurements systematically limited
  - Detector alignment is dominant source of uncertainty

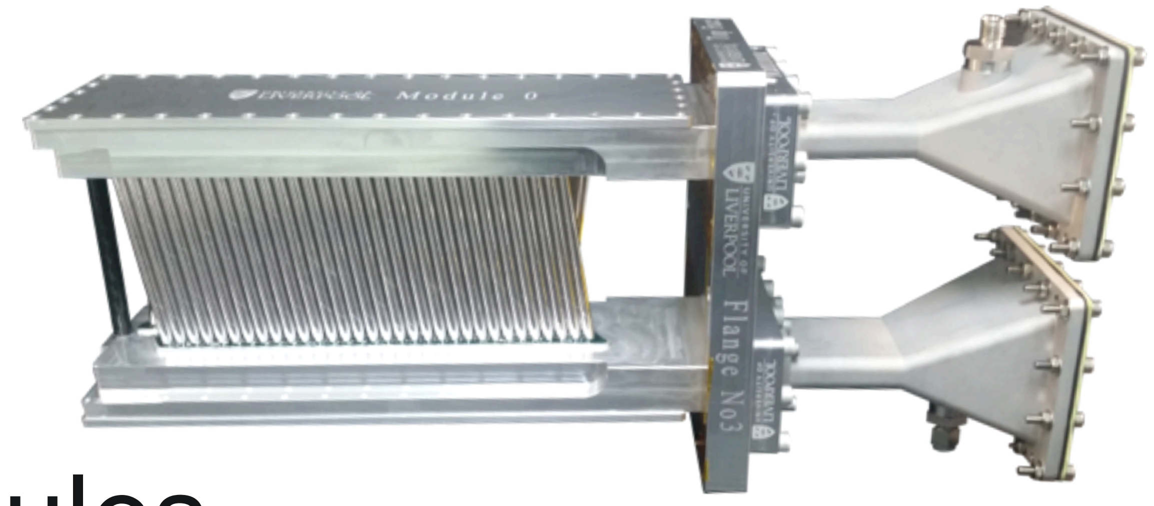
arxiv: 0811.1207, UMI-29261, UMI-31-13195

FNAL Trackers





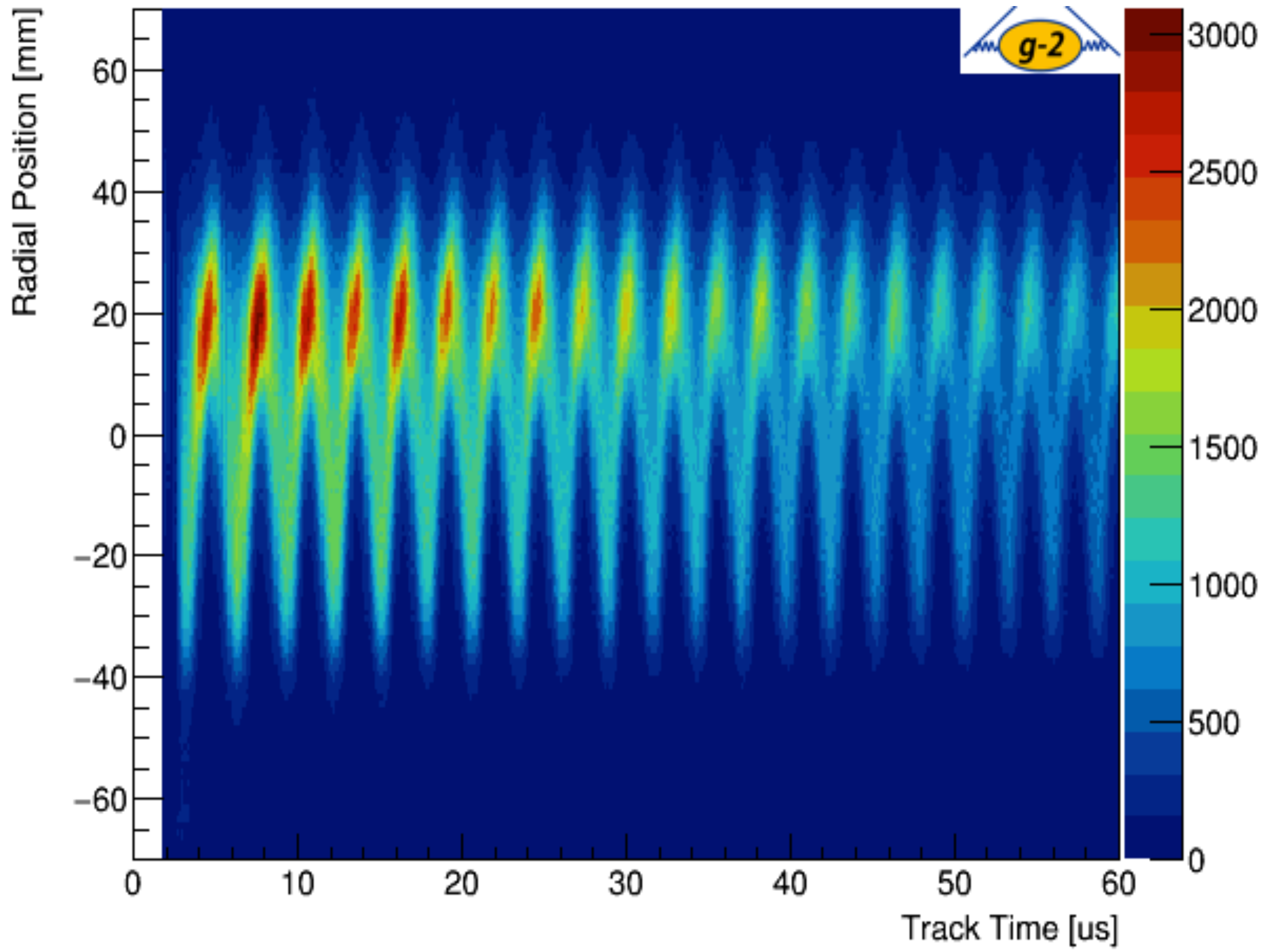
2 Tracking stations

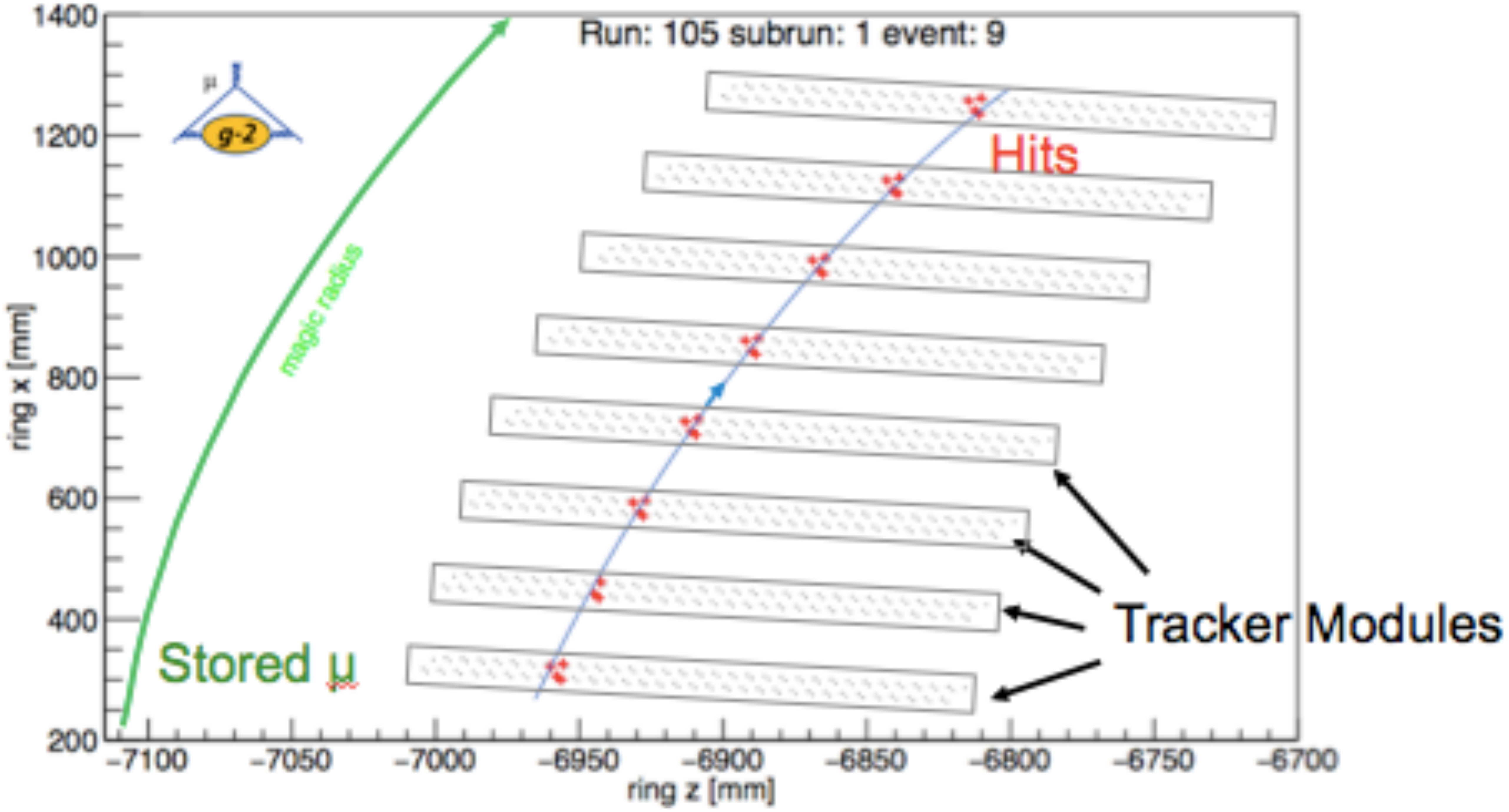


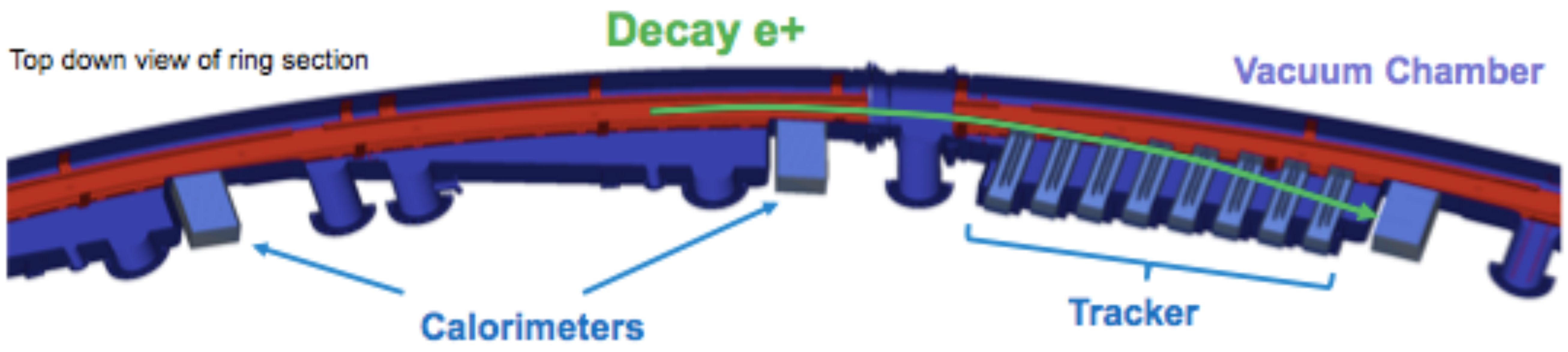
- Each contain 8 modules
- 128 gas filled straws in each module
- Traceback positrons to their decay point

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







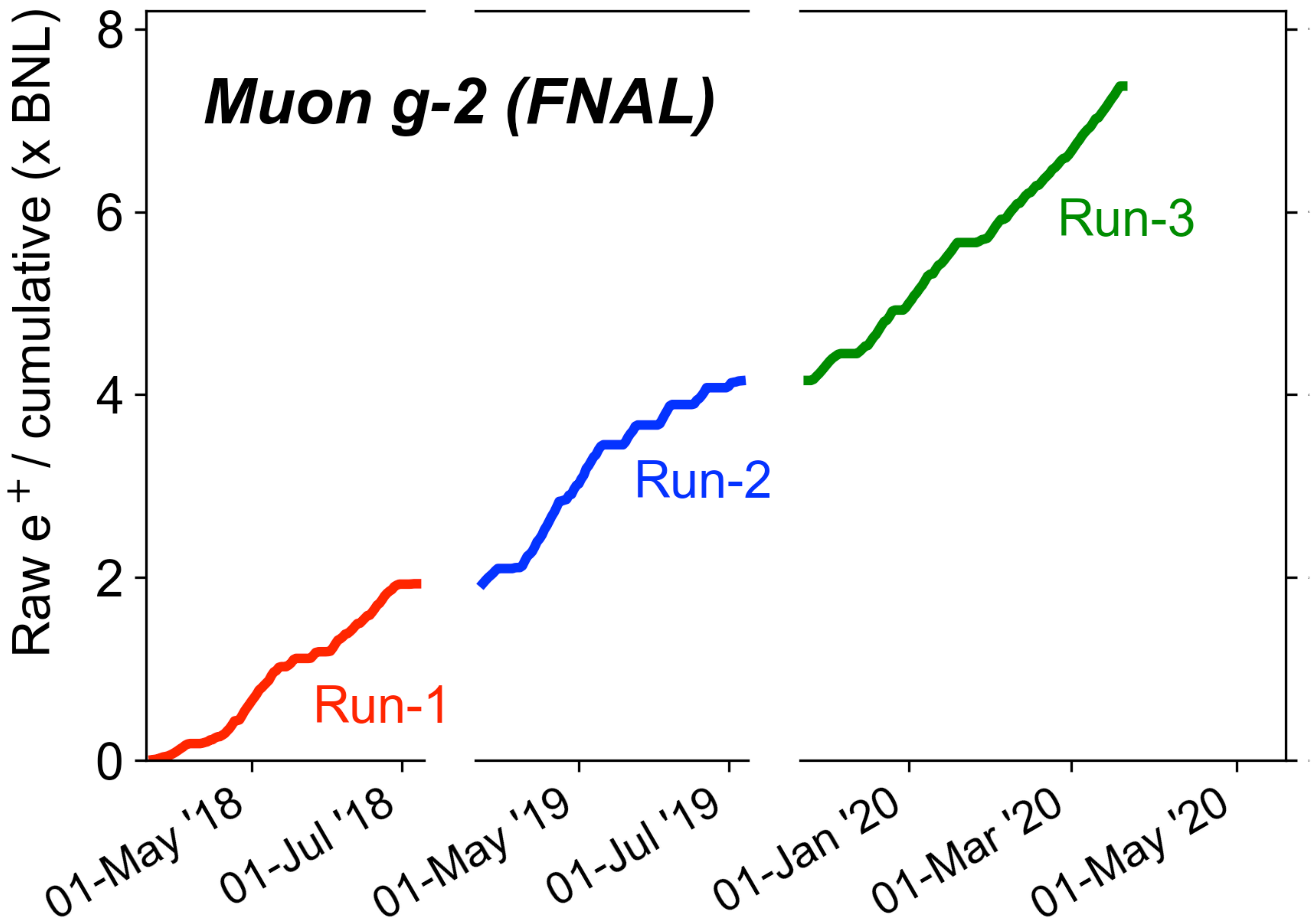
Data taking overview

Run 1:

- Data taking period: April—July 2018
- Accumulated ~ 1.1 x BNL statistics (after data quality cuts) — **$\delta\omega_a$(stat) ~ 400 ppb**
- Field uniformity ~ 2x better than BNL

Run 2 and 3:

- More data taken in 2019 and 2020
- Field uniformity expected to be similar to run 1



Can take 5% of a BNL per day!

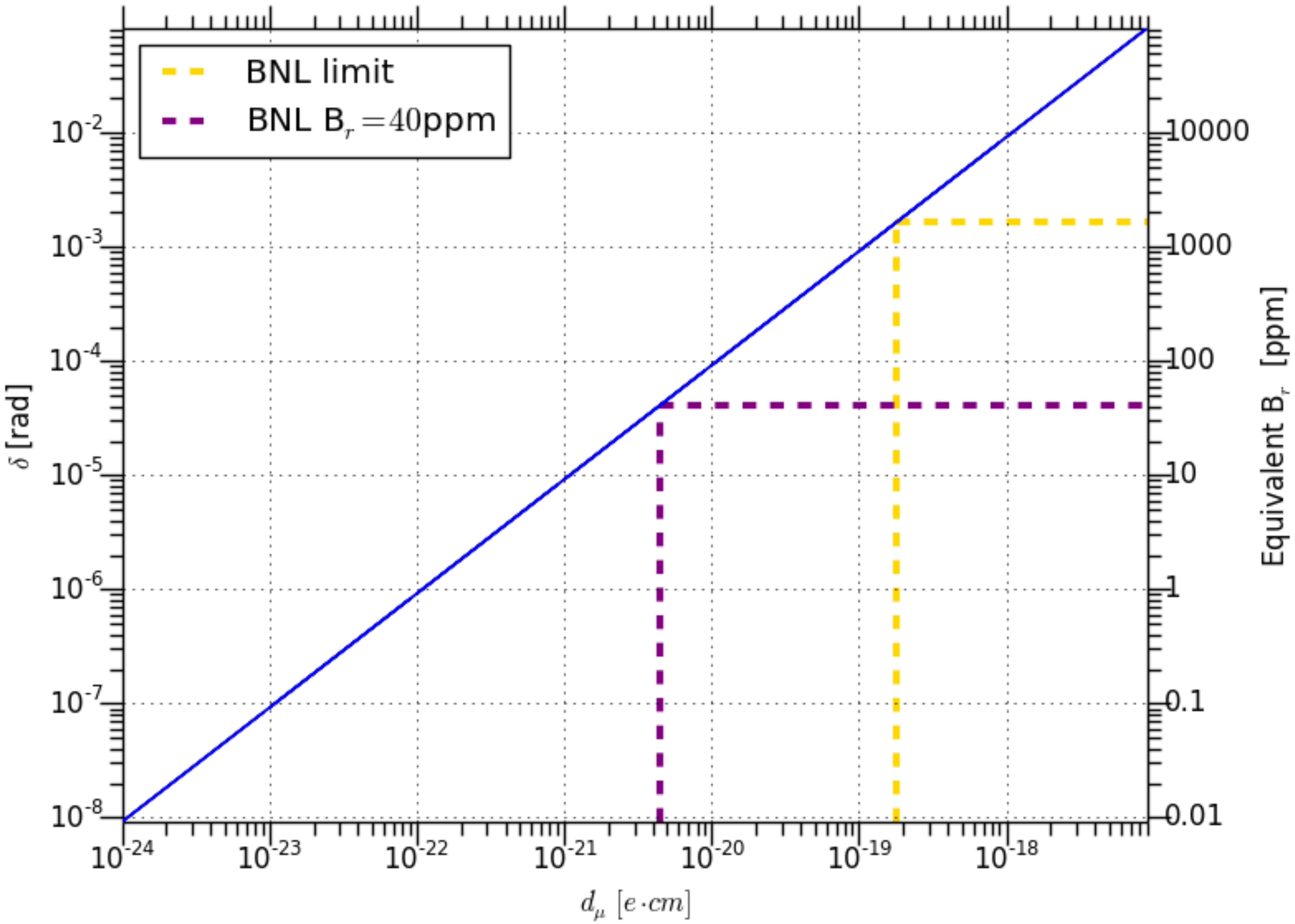
Tracking overview

- BNL tracking based EDM analysis statistically limited
- Applying the same momentum selection criteria as BNL:

	BNL Tracking	FNAL Run 1	FNAL Run 1+2+3 (projected)	FNAL total (projected*)
High quality tracks ($1.5 < p < 2.5$GeV)	9.4M	100M	~500M	~5B

- FNAL major tracker improvements:
  - Placed closer to beam (better vertical angle acceptance)
  - Turn on time at 4us instead of 130us
- Expecting to get near systematically limited EDM measurement for E989…

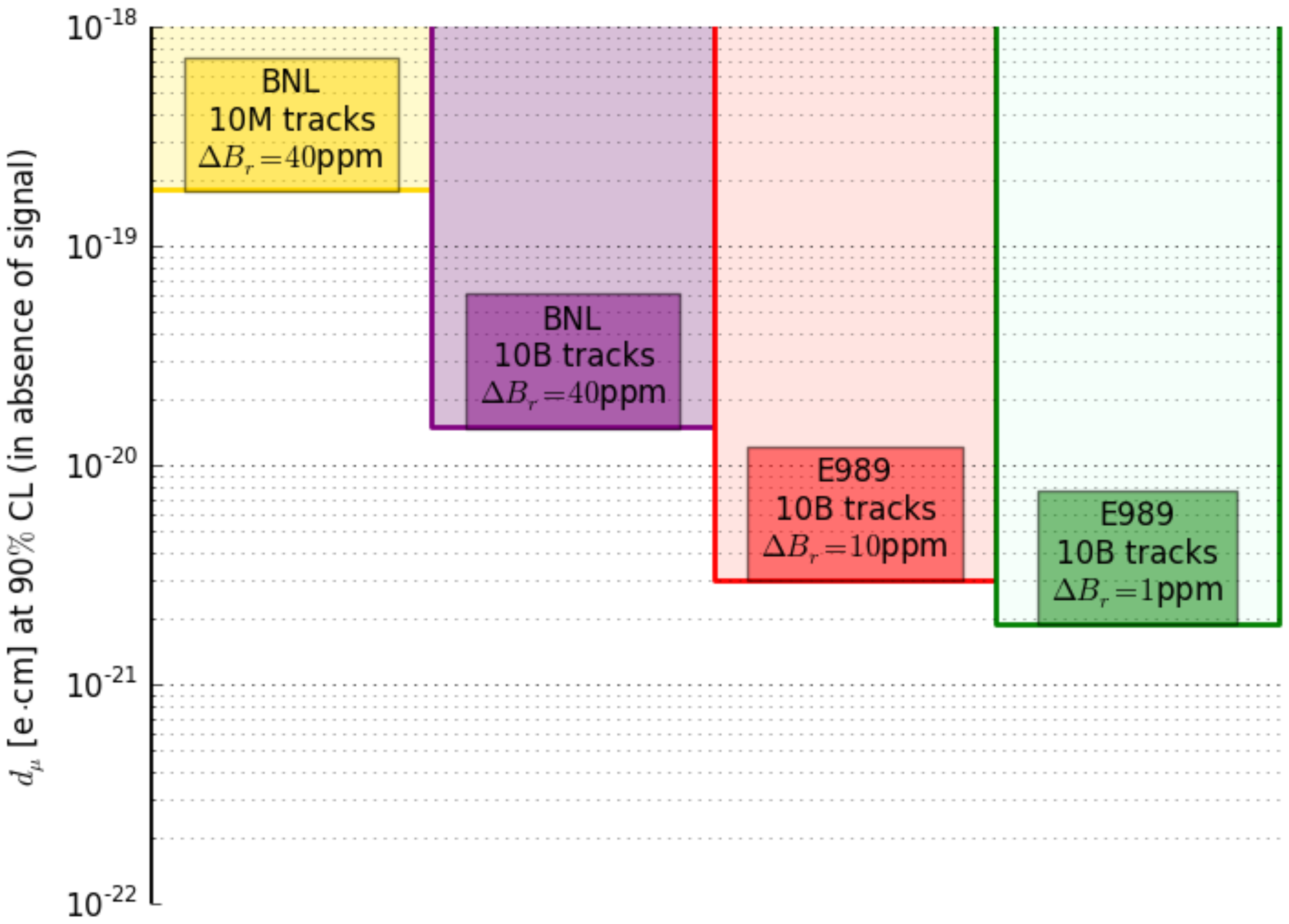
Radial field - Limiting the EDM sensitivity



S. Charity, B. Kiburg

- BNL EDM limit is equivalent to **1468ppm** radial field
- The BNL radial field precision was estimated to be around **40ppm**
- 40ppm radial field gives an oscillation equivalent to: $|d_\mu| \approx 4.5 \times 10^{-21}$ e.cm
- In the absence of signal the limit of course would not have reached this…

E989 - Projected limits



D. Vasilkova

- Had BNL had enough tracking statistics would have been set: $|d_\mu| \approx 2 \times 10^{-20}$ e.cm
- With $\sigma_{|Br|}$ = 10ppm FNAL can improve the EDM limit: $|d_\mu| \approx 3.0 \times 10^{-21}$ e.cm
- Target of $\sigma_{|Br|}$ = 1ppm is difficult, and requires new dedicated B_r apparatus
- Would improve E989 the limit: $|d_\mu| \approx 1.9 \times 10^{-21}$ e.cm

PSI - Dedicated muon EDM experiment

$$\vec{\omega} = \frac{q}{m}\left[a\vec{B} + \left(\frac{1}{1-\gamma^2} - a\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta_d}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

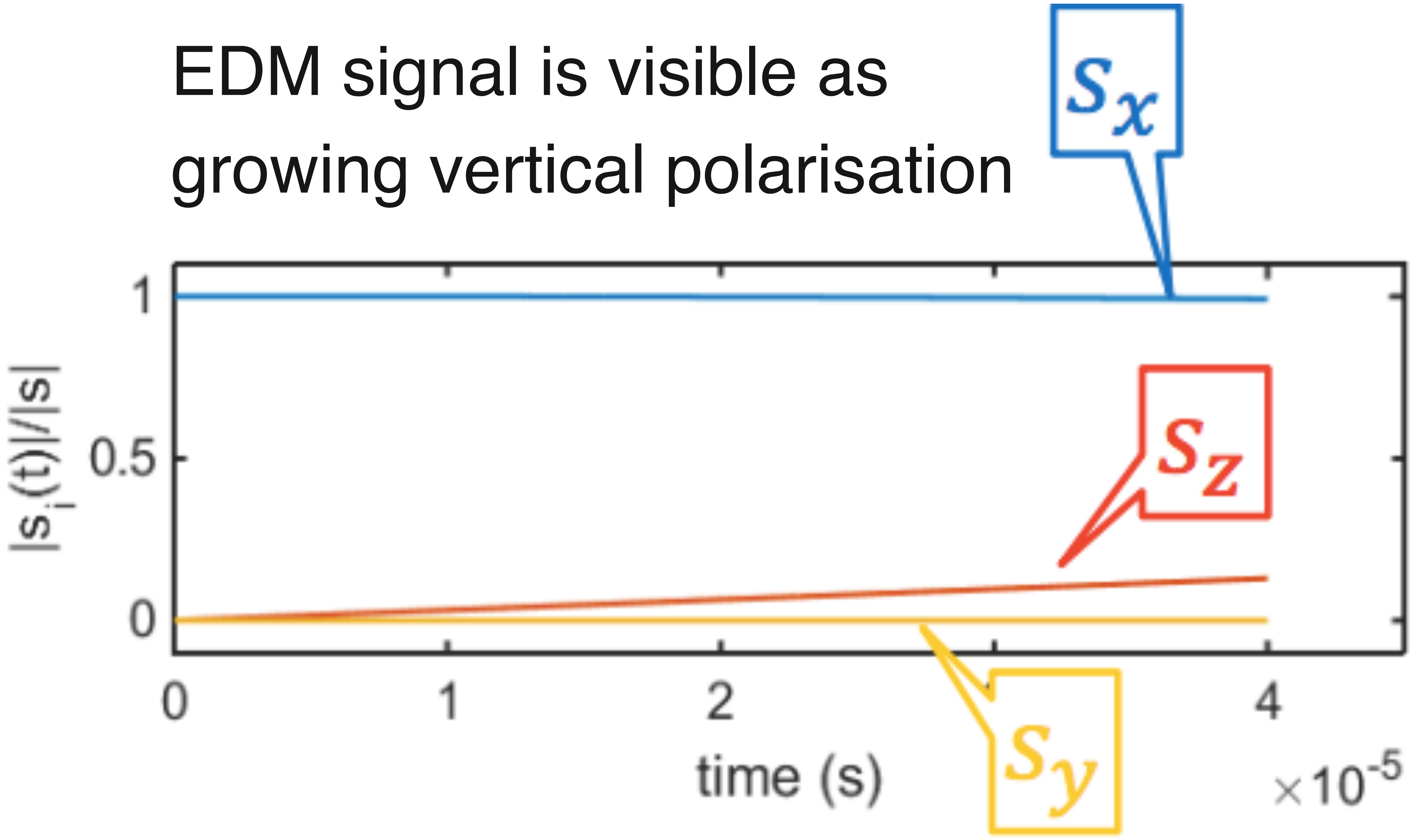
- Cancel anomalous precession with matched E-field:

$$E \cong aBc\beta\gamma^2$$

- Spin remains parallel to orbit
- No "contamination" from anomalous spin precession

$$s_z \propto \eta E^* \cdot t$$

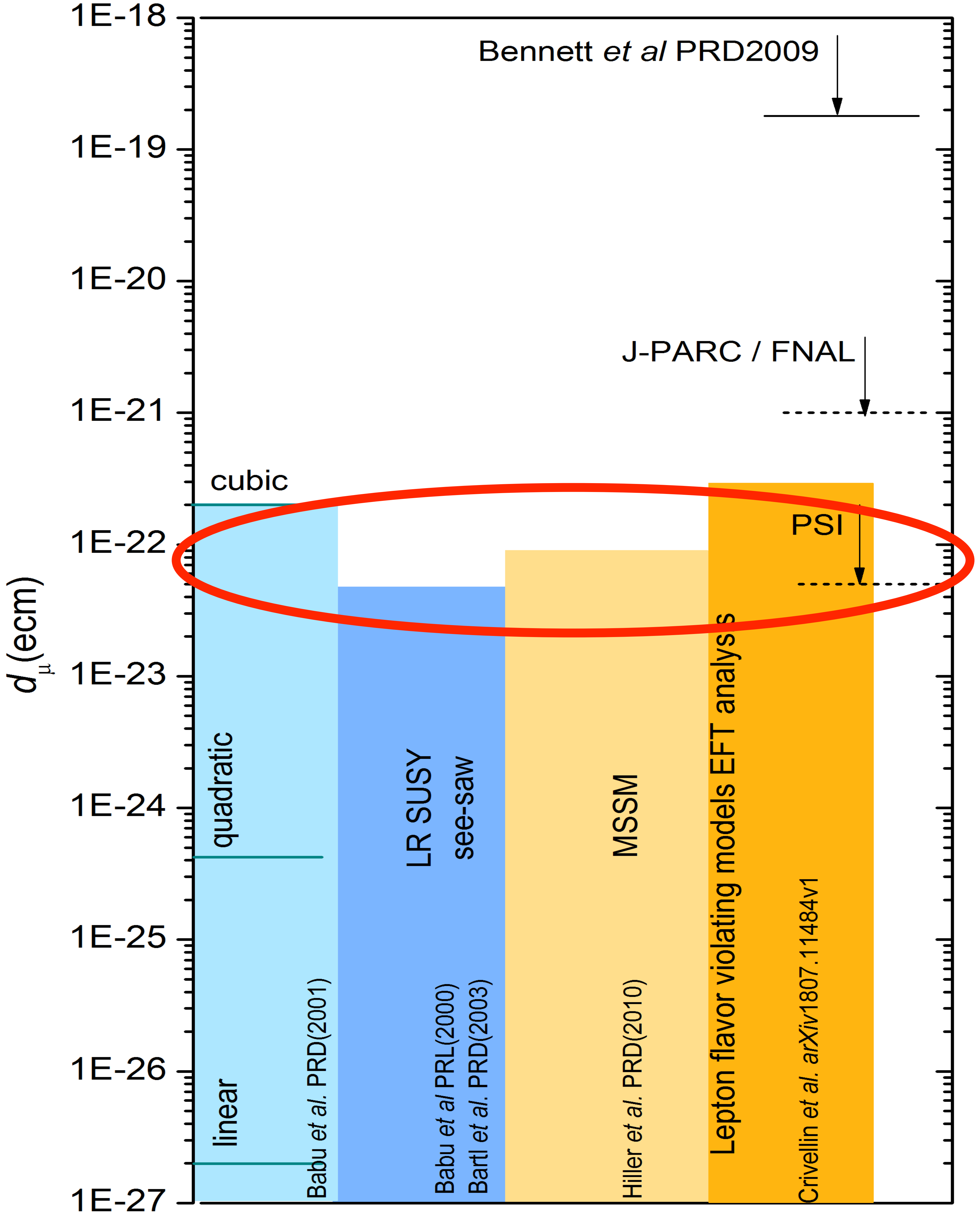
EDM signal is visible as growing vertical polarisation



Slide courtesy of Philipp Scmidt-Wellenburg

PRL93 (2004), JPG37 (2010)

Prospects for compact μ-EDM at PSI



- Apply frozen spin technique
  - PSI μE1: *2×10^8 μ^+/s, **γ=1.57***
  - Polarisation from pion decay: ***P=0.9***
  - Mean asymmetry of muon decay: ***a=0.3***
  - Compact conventional magnet:
    - ***B = 1.5 T ➡ R=0.28m, E = 10 MV/m***

  - Detection rate 200kHz
  - Run time 2×10^7s ➡ N = 4×10^{12} e^+ *per year*

- PSI Sensitivity (1 year):

  $\sigma(d_\mu) < 5 \times 10^{-23}$ e.cm

Slide courtesy of Philipp Scmidt-Wellenburg

Summary

- E989 Data taken with ~ 5 x BNL stats total
- Demonstrated ability to take 5% BNL per day, on course for 21 BNLs over next few years
- Radial field measurement uncertainty expected to limit EDM sensitivity
  - Can achieve $\sim |d_\mu| \approx 3.0\times10^{-21}$ *e.cm* with targeted measurement of B_r
  - Dedicated apparatus needed to reach 1ppm B_r uncertainty for $|d_\mu| \approx 1.9\times10^{-21}$ *e.cm*
- See T. Mibe's J-PARC talk for EDM limit
- Planned muon EDM experiment at PSI in design phase
  - 2 possible scenarios being investigated
  - Target EDM limit of 5×10^{-23} *e.cm*

Thank you!

Backup

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.

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

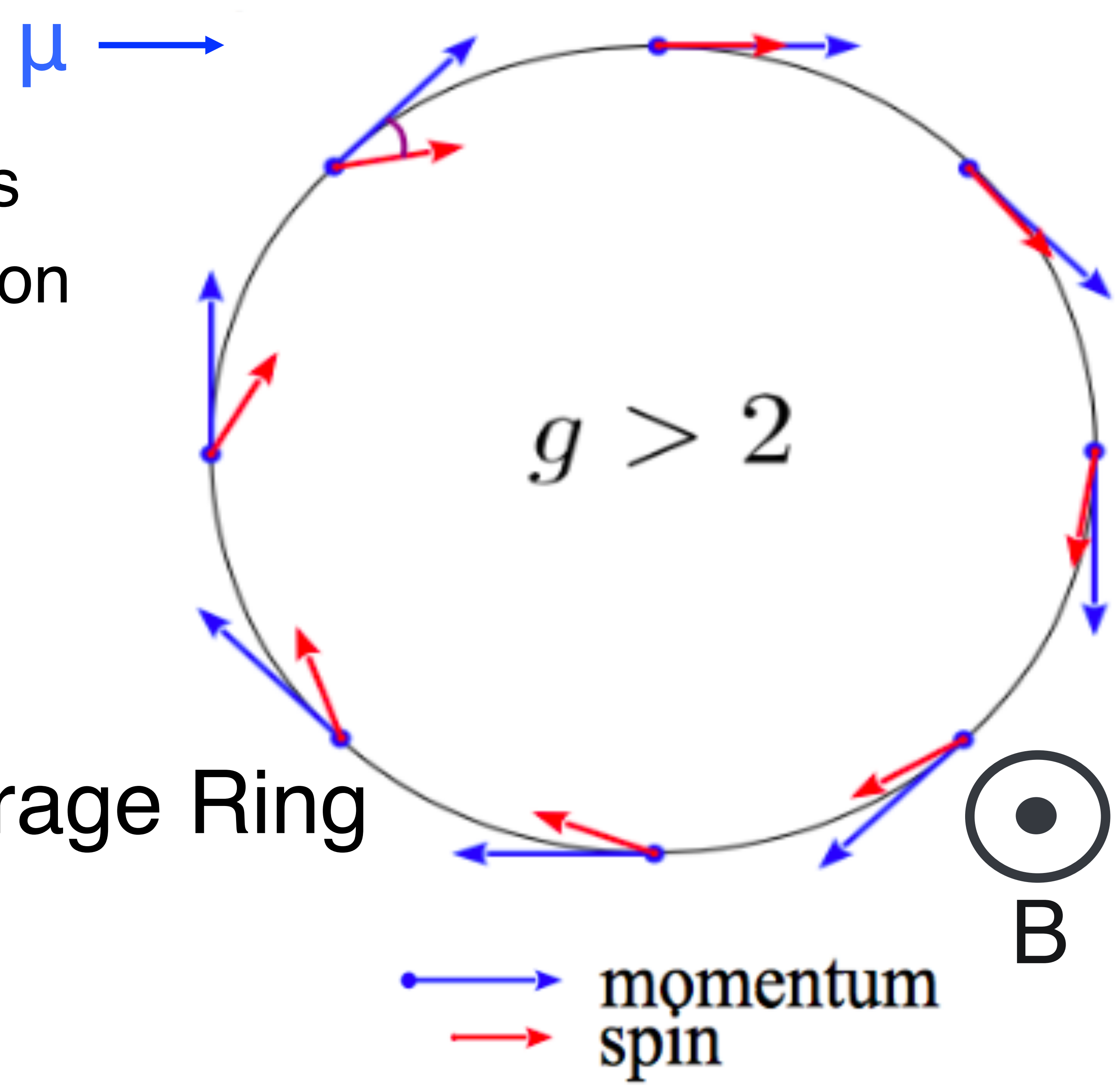
Larmor precession

Thomas precession

Cyclotron freq.

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

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



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

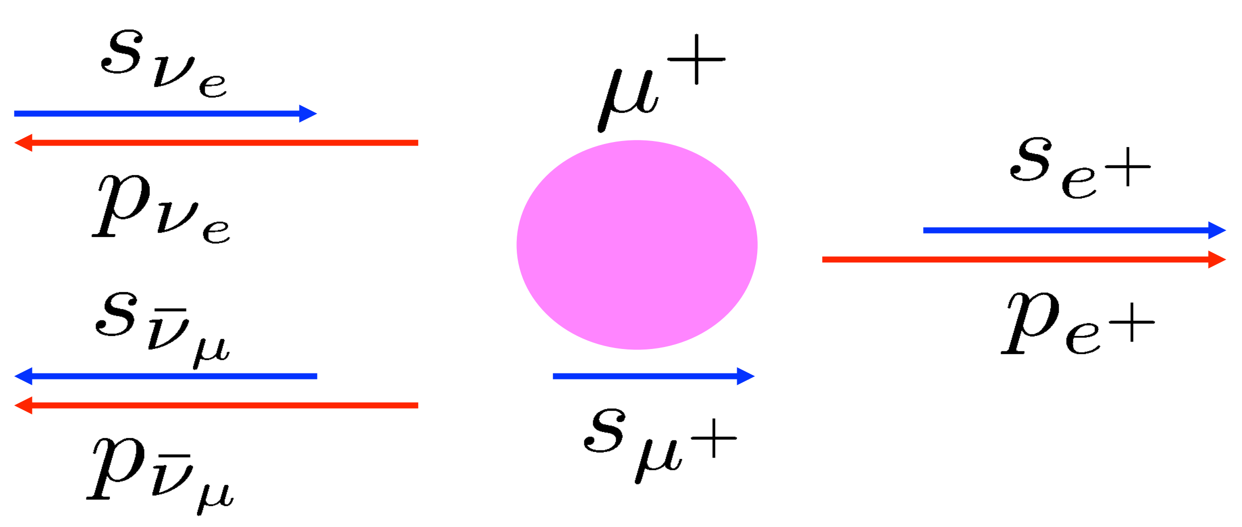
3 ppb | 22 ppb | 0.3 ppt

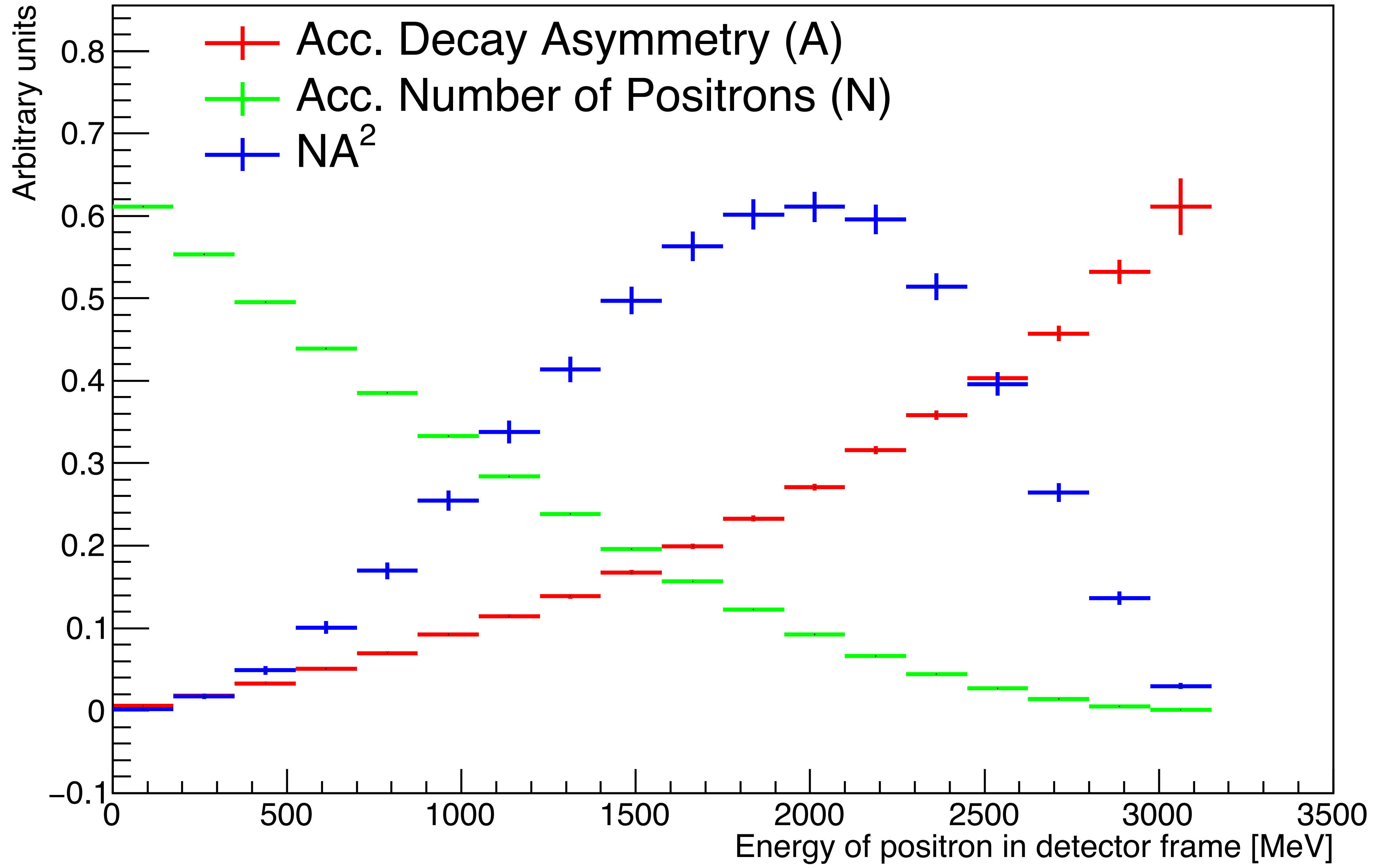
Rev. Mod. Phys. **88**, 035009 (2016)

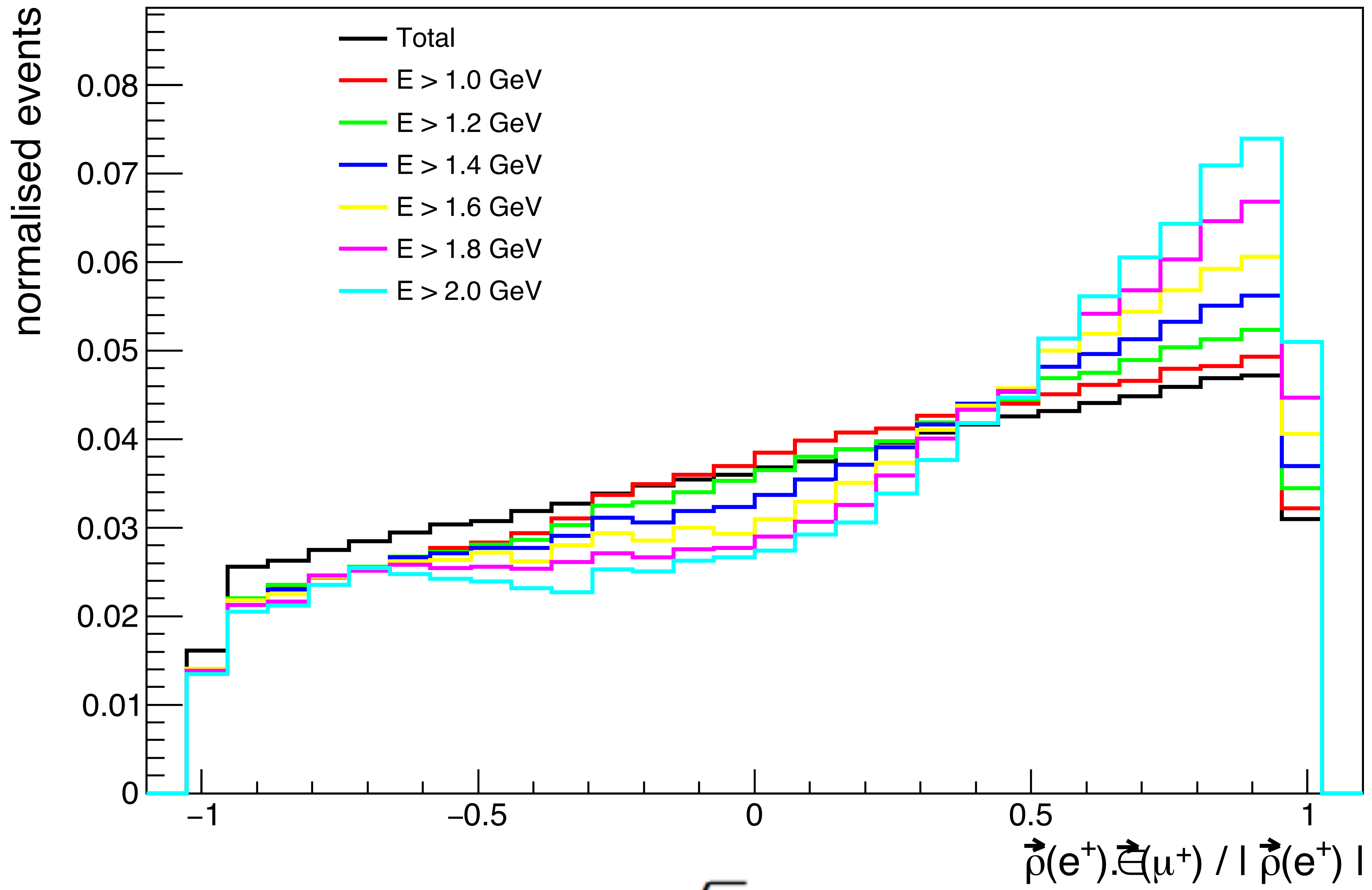
- We measure ω_a and ω_p separately
- Aiming for 70 ppb precision on each (systematic)
- **Target: δa_μ(syst) = 140 ppb; factor of 4 improvement over BNL**

Measuring the muon spin…

- e^+ preferentially emitted in direction of muon spin







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

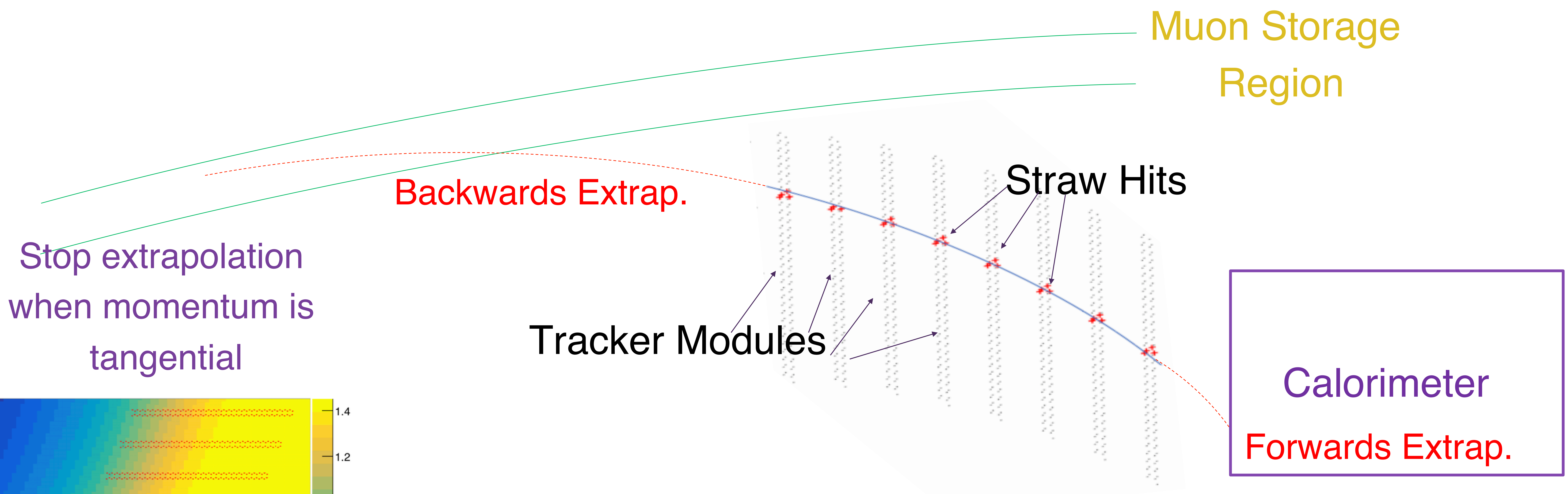
- Asymmetry is larger for high momentum e+
- Optimal cut at E~1.8 GeV

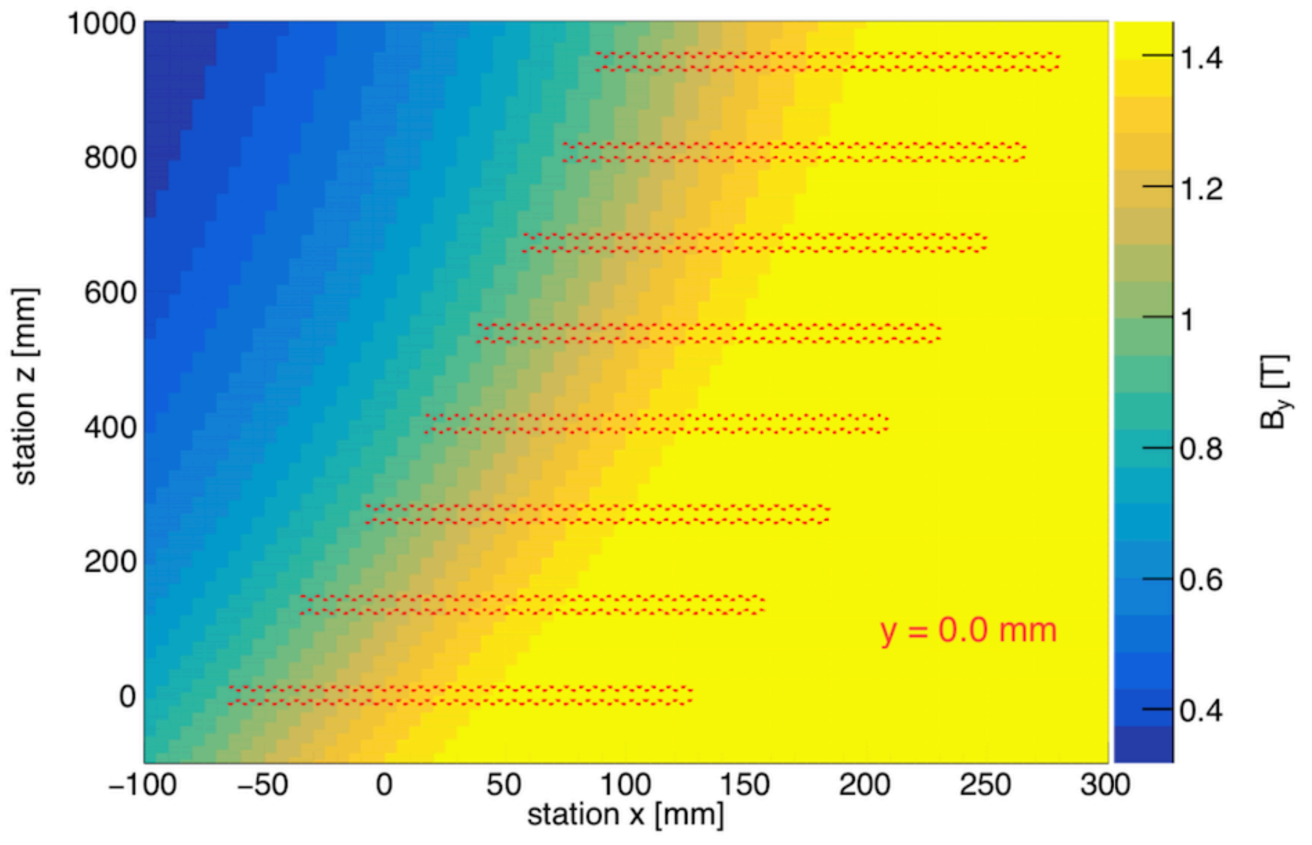
BNL Phase based method: systematics

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·cm)
Total statistical		28 μrad/mm (0.73×10^{-19} e·cm)
Total		50 μrad/mm (1.3×10^{-19} e·cm)

Track Extrapolation

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

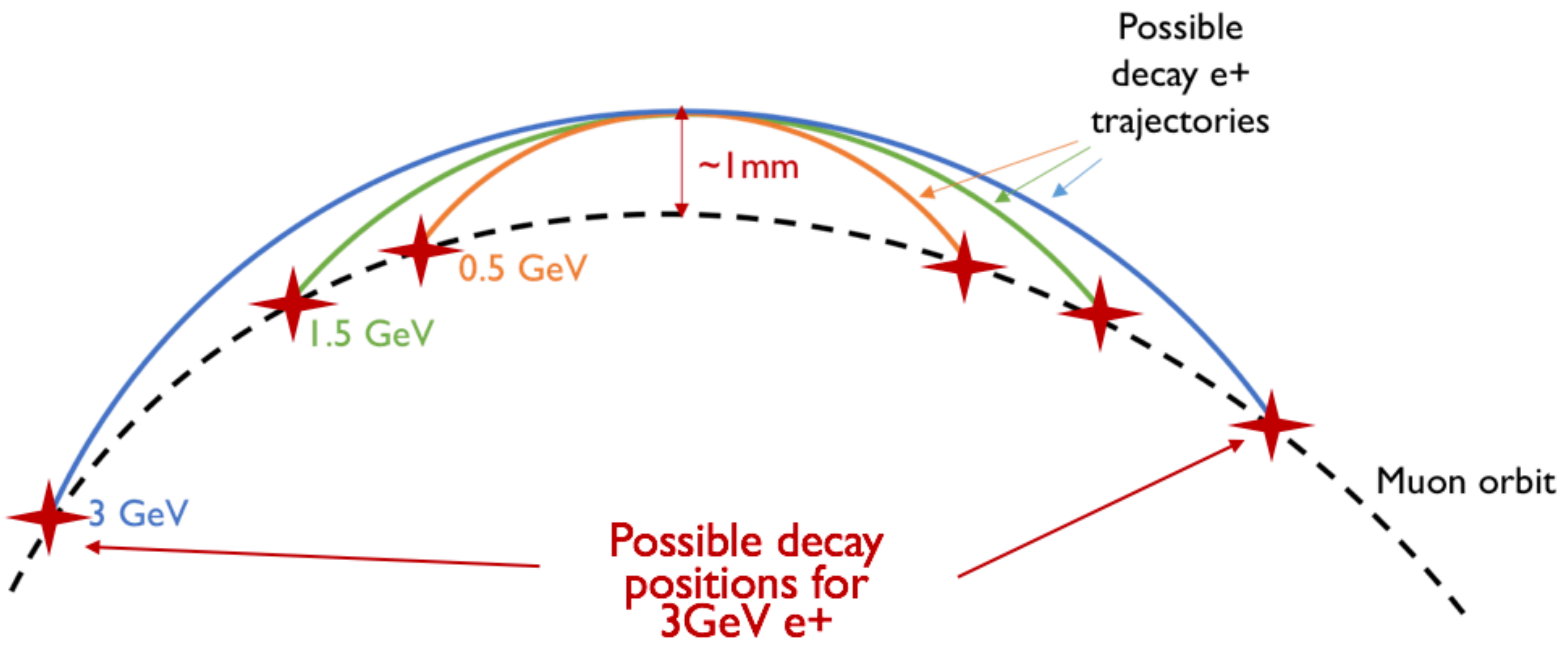




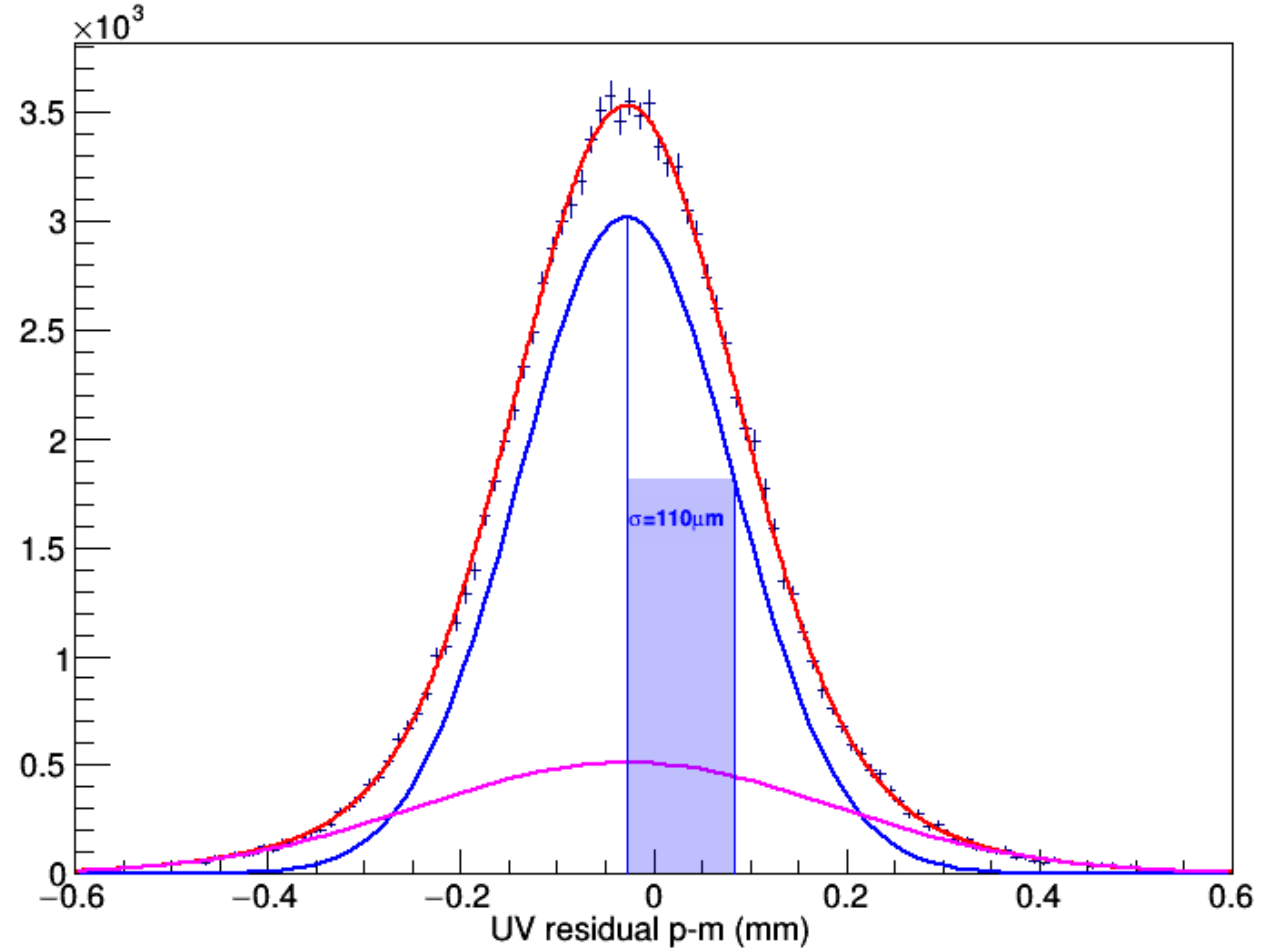
- Straws placed in varying fringe field
- Challenging environment for tracking

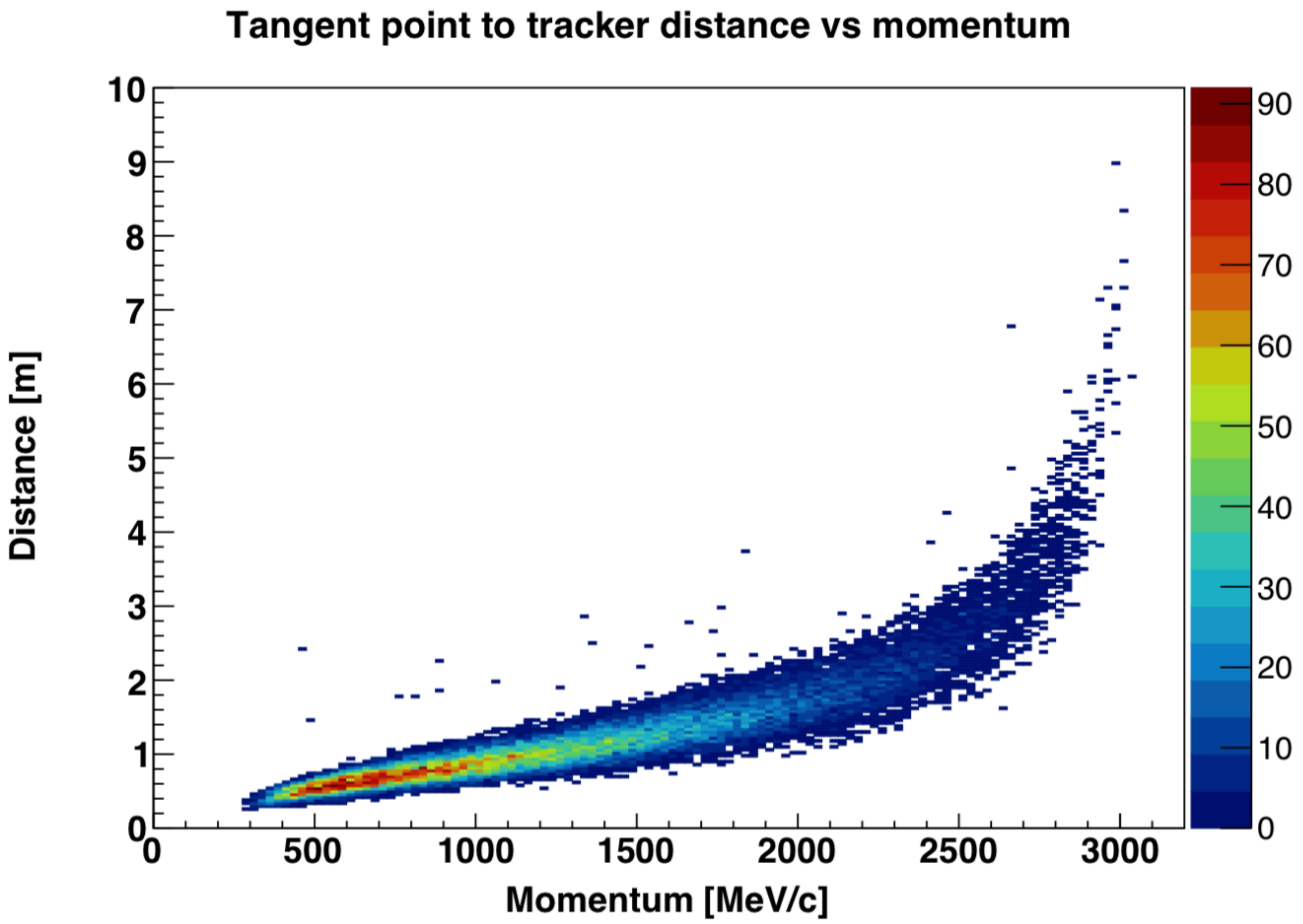
Radial Tangency

- 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

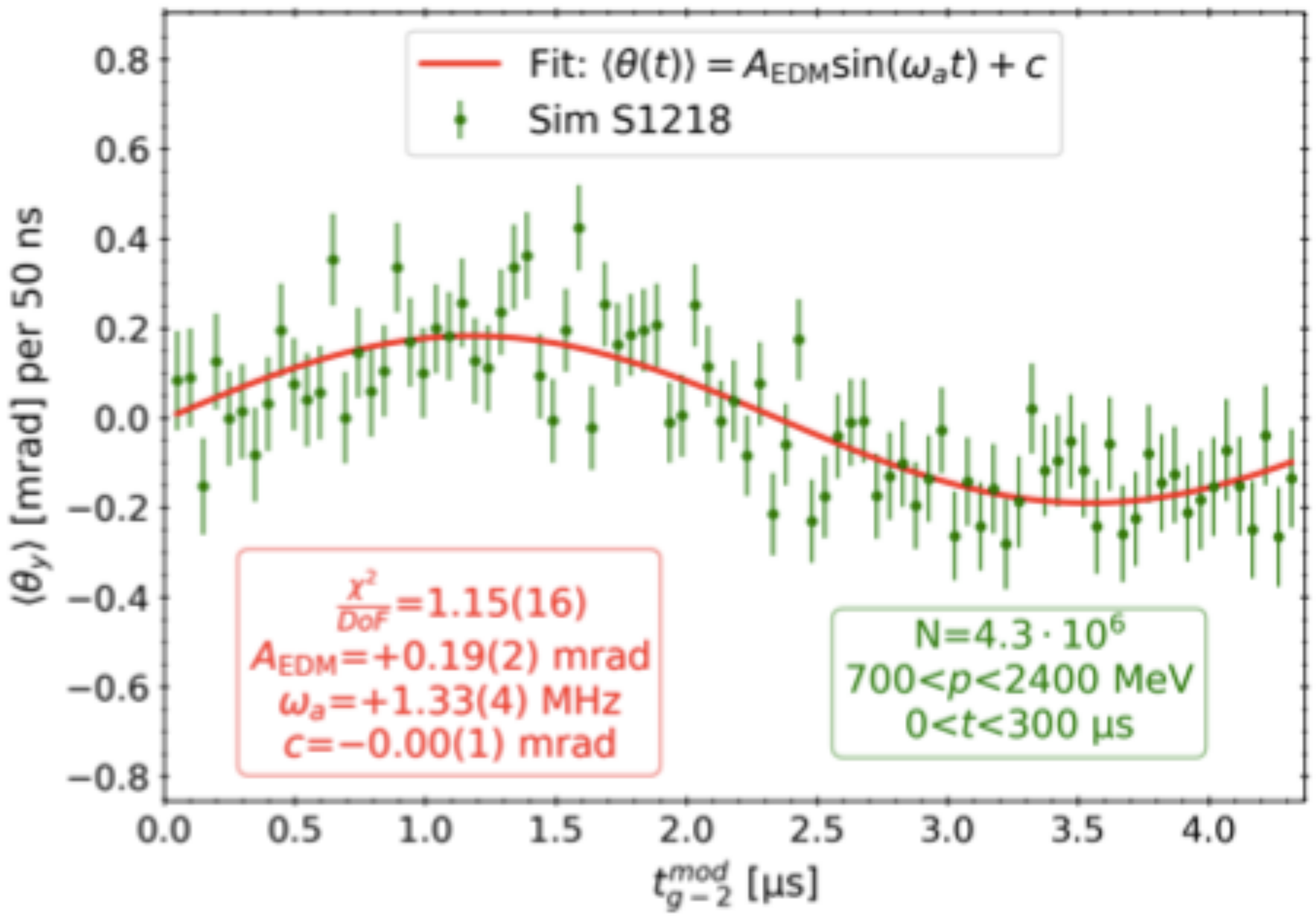




- Per hit resolution ~100μm
- At decay vertex, per track resolution of ~3mm
- Per track vertical angle resolution ~1mrad: error on mean is what matters

EDM in simulation

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

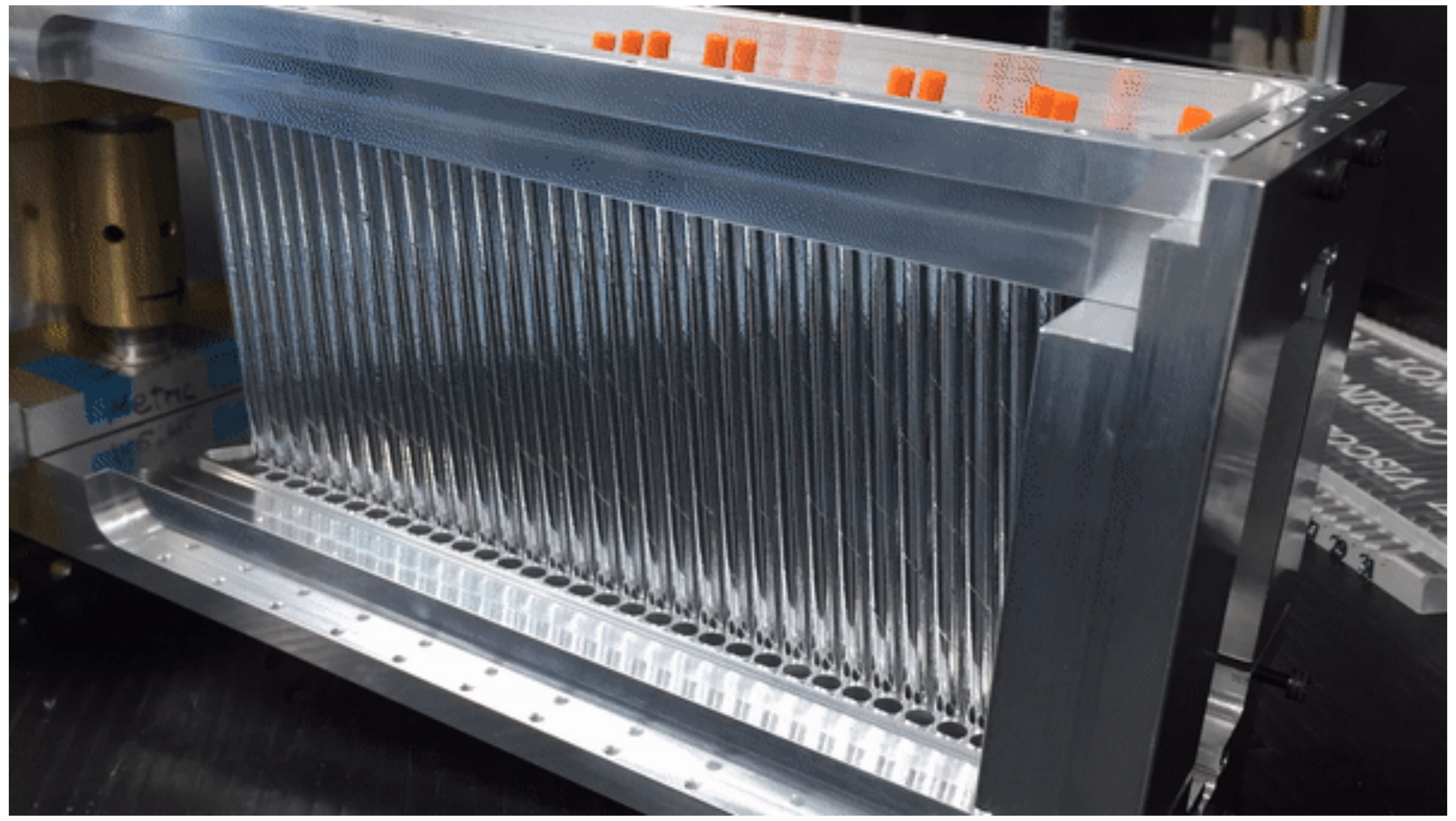


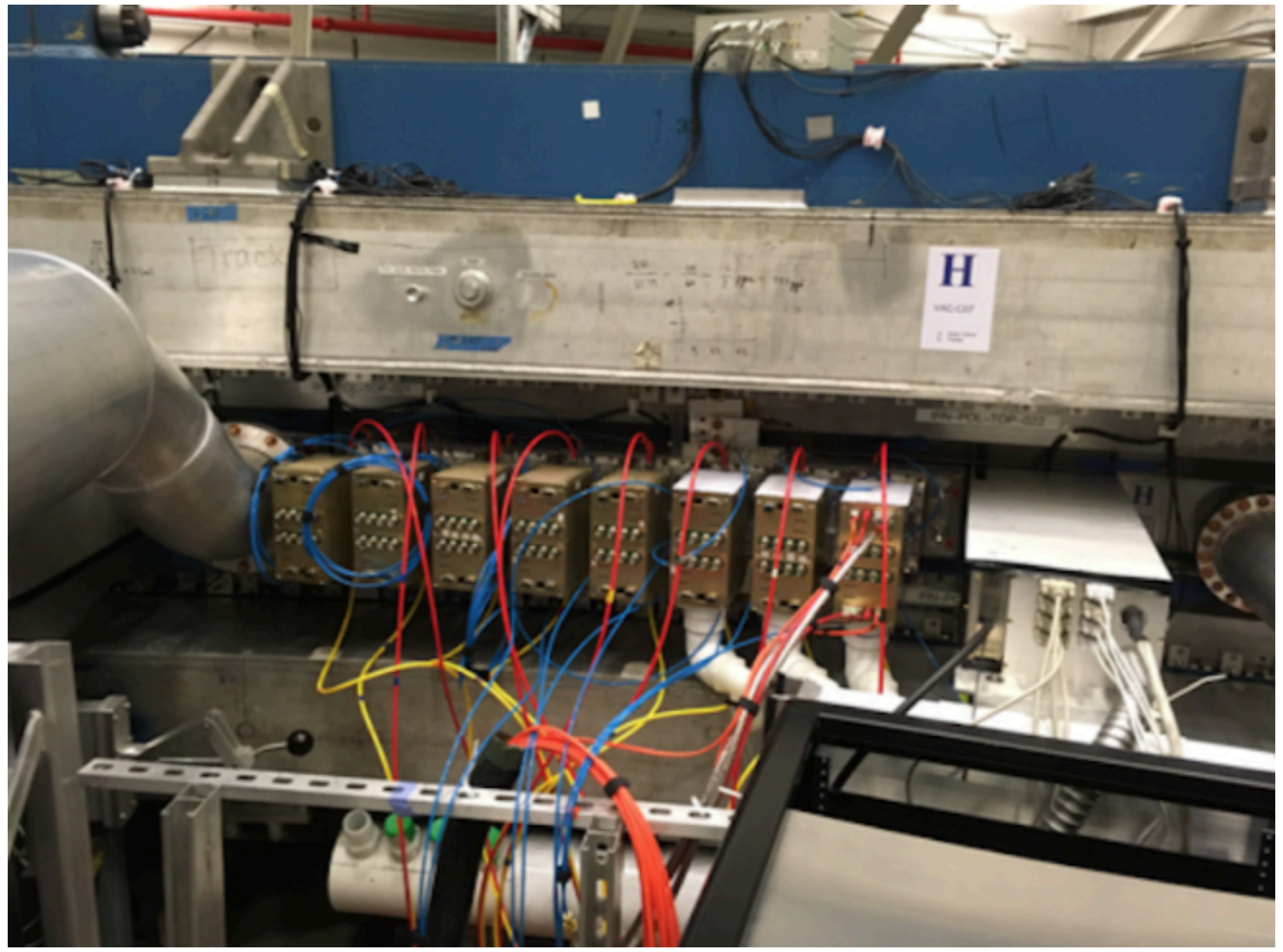
Gleb's thesis (forthcoming)

- Expected tilt angle in MRF:
  - δ = 49 mrad
- Expected reduced angle in detectors:
  - δ' = ~0.22 mrad
- Trackers capable of EDM measurement with very low stats!

Tracking detectors

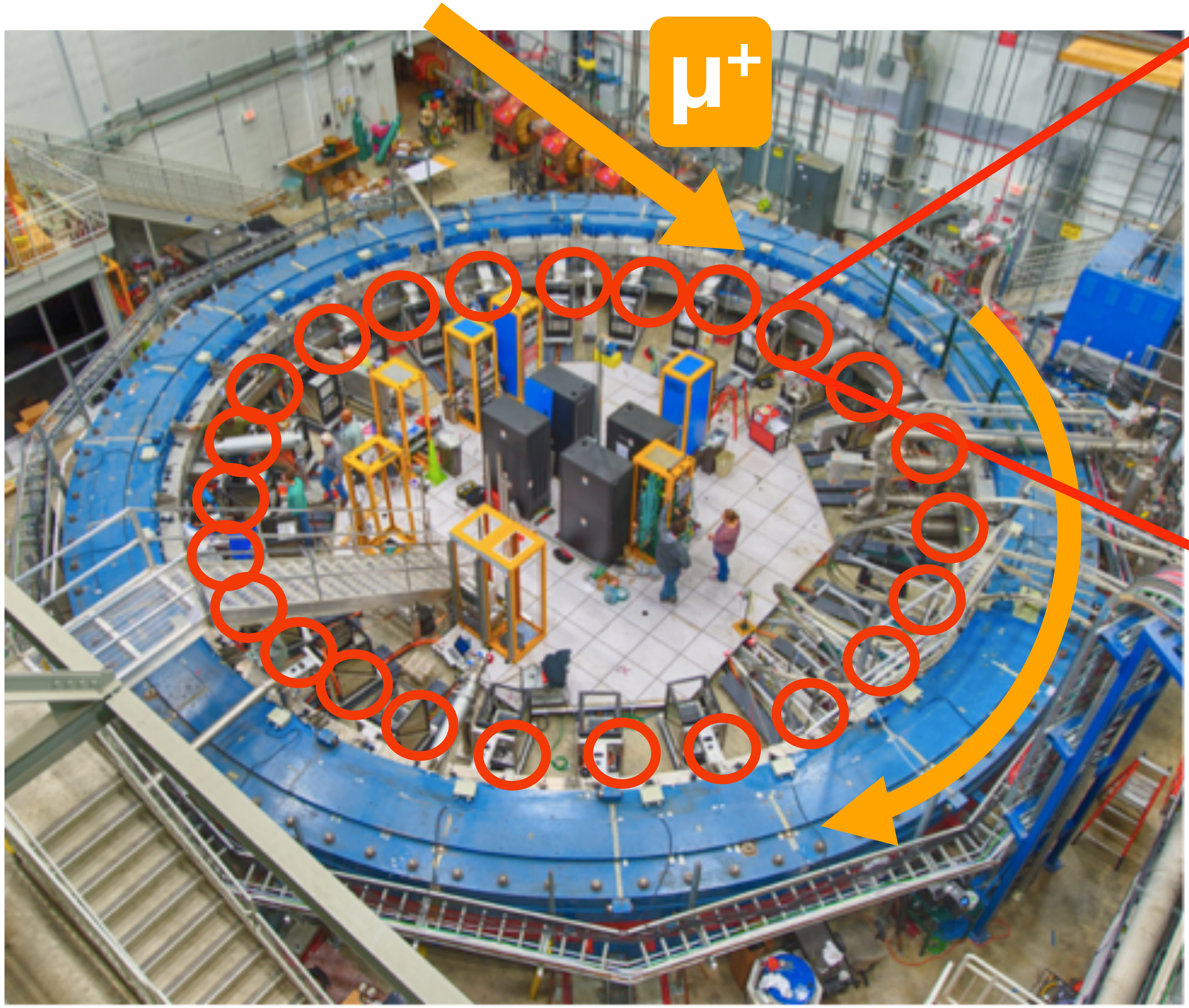
- 2 × 8 modules placed at 180° and 270° location
- Each module 32 mylar straws (15μm thick)
- 4 layers per module
- 2 layers place with ±7.5° stereo angle

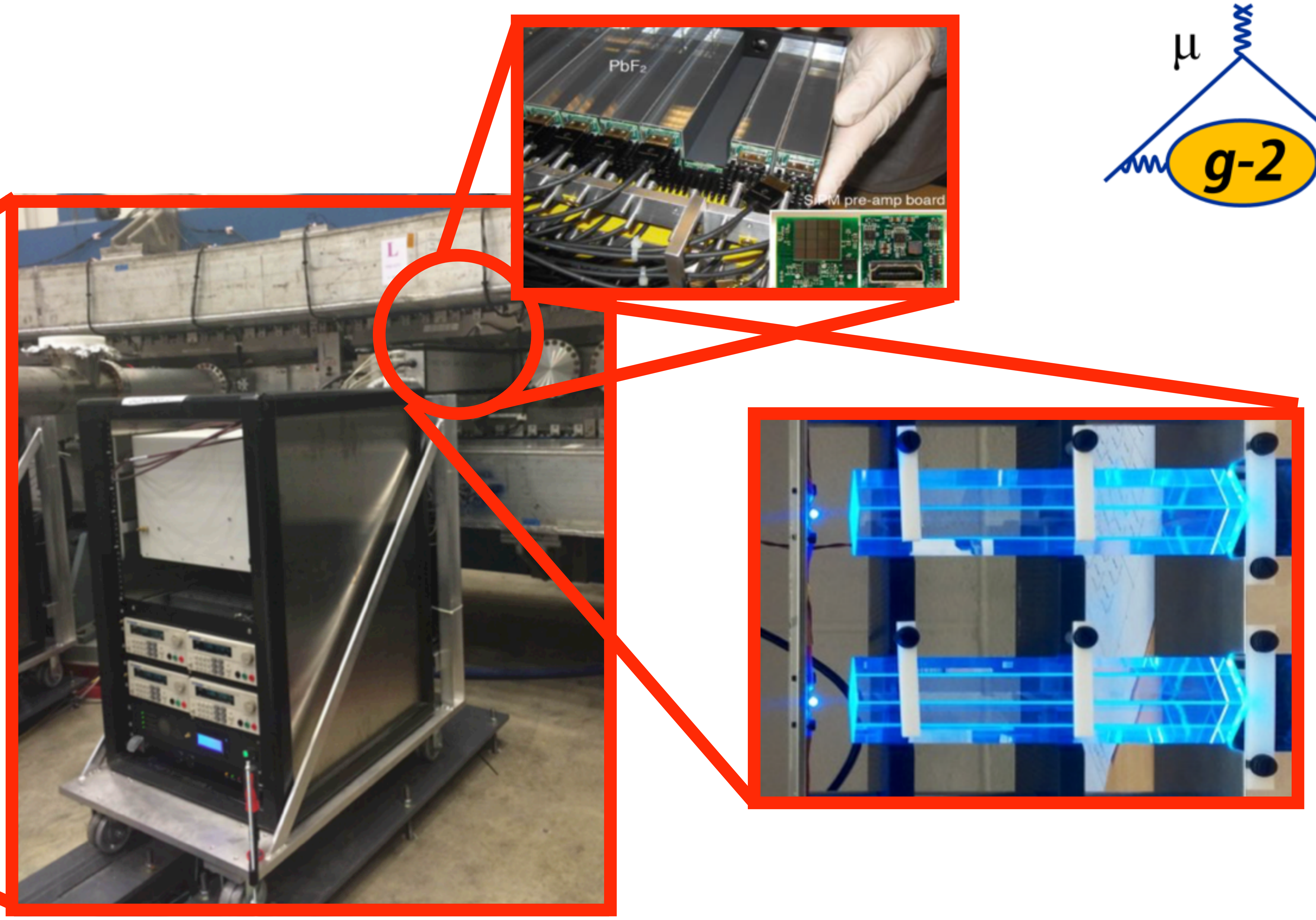




- Filled with 50:50 Argon ethane
- Able to operate at vacuum < 1×10^{-7} torr
- Closer to beam w.r.t. BNL trackers
- Able to track 2μs after beam injection

FNAL Calorimeters

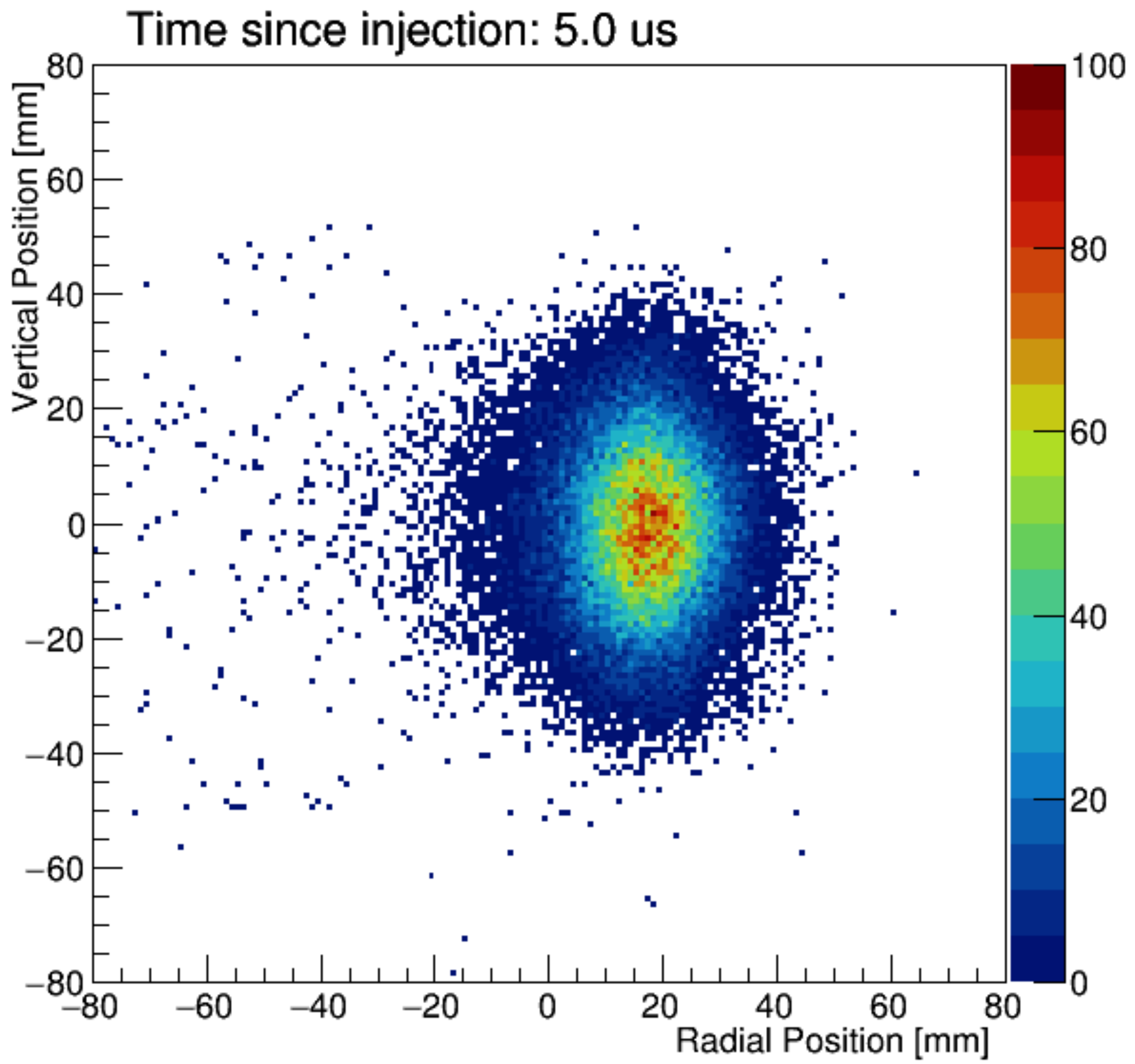


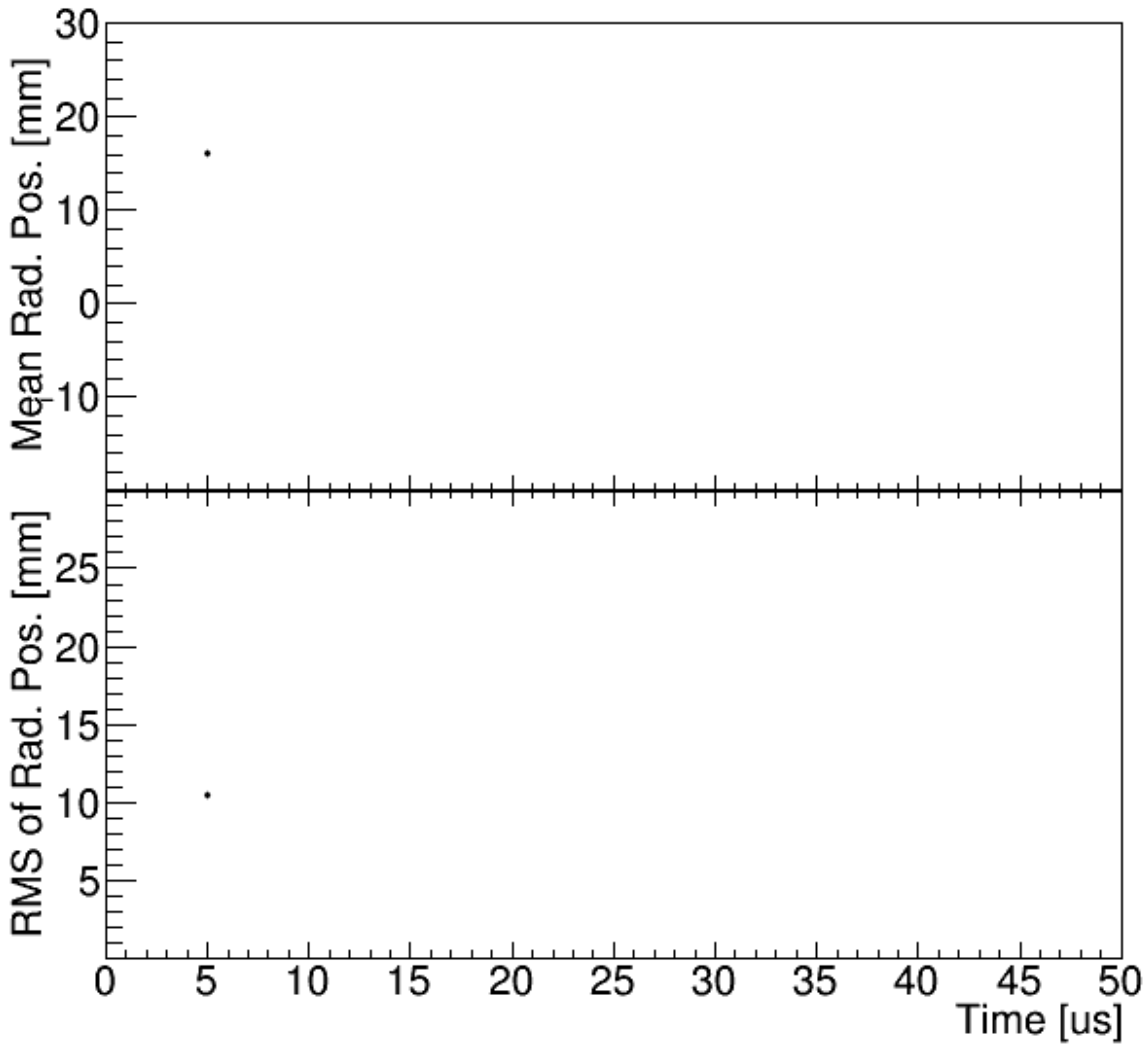


24 segmented PbF_2 crystal calorimeters

- 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)

Beam position vs time

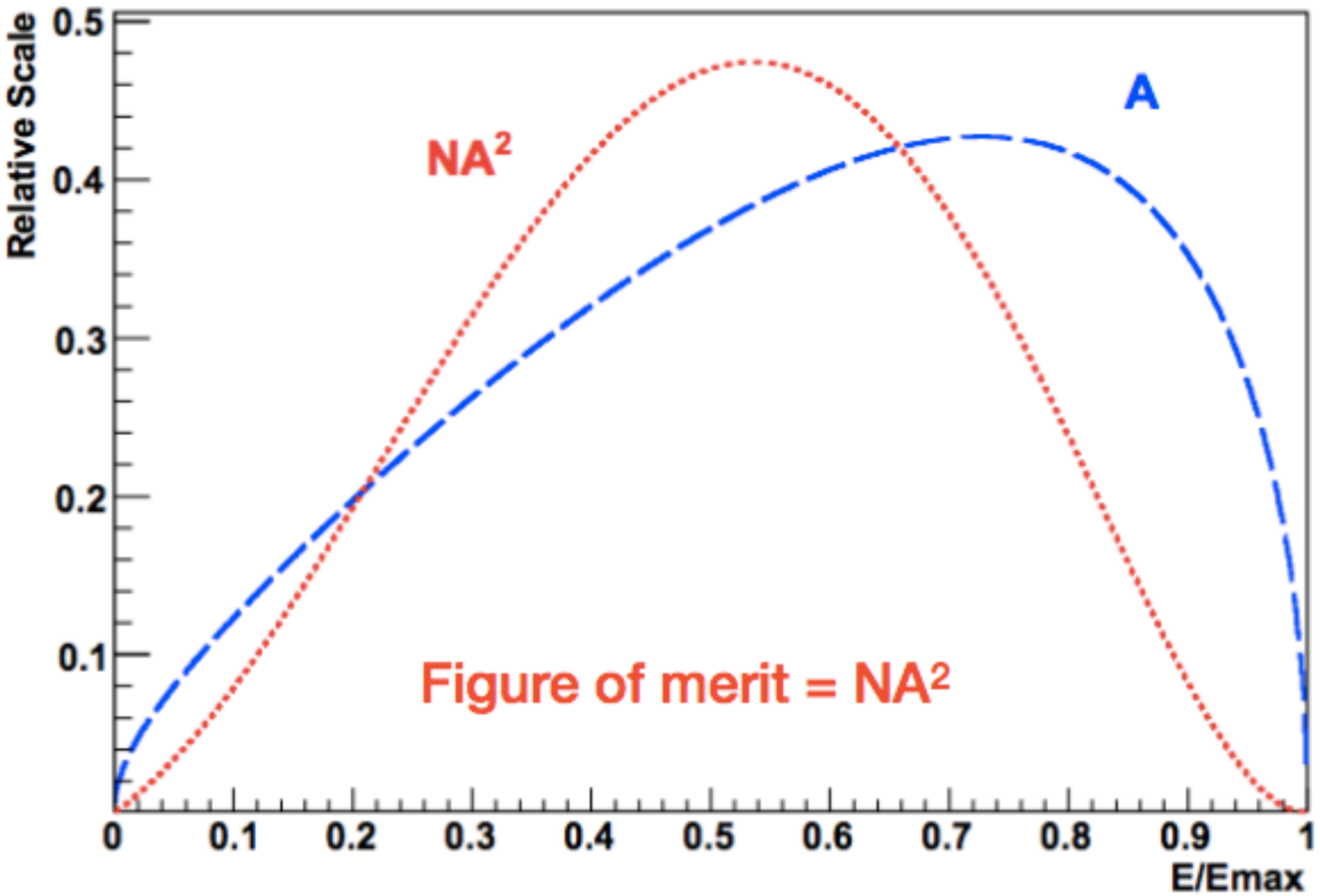


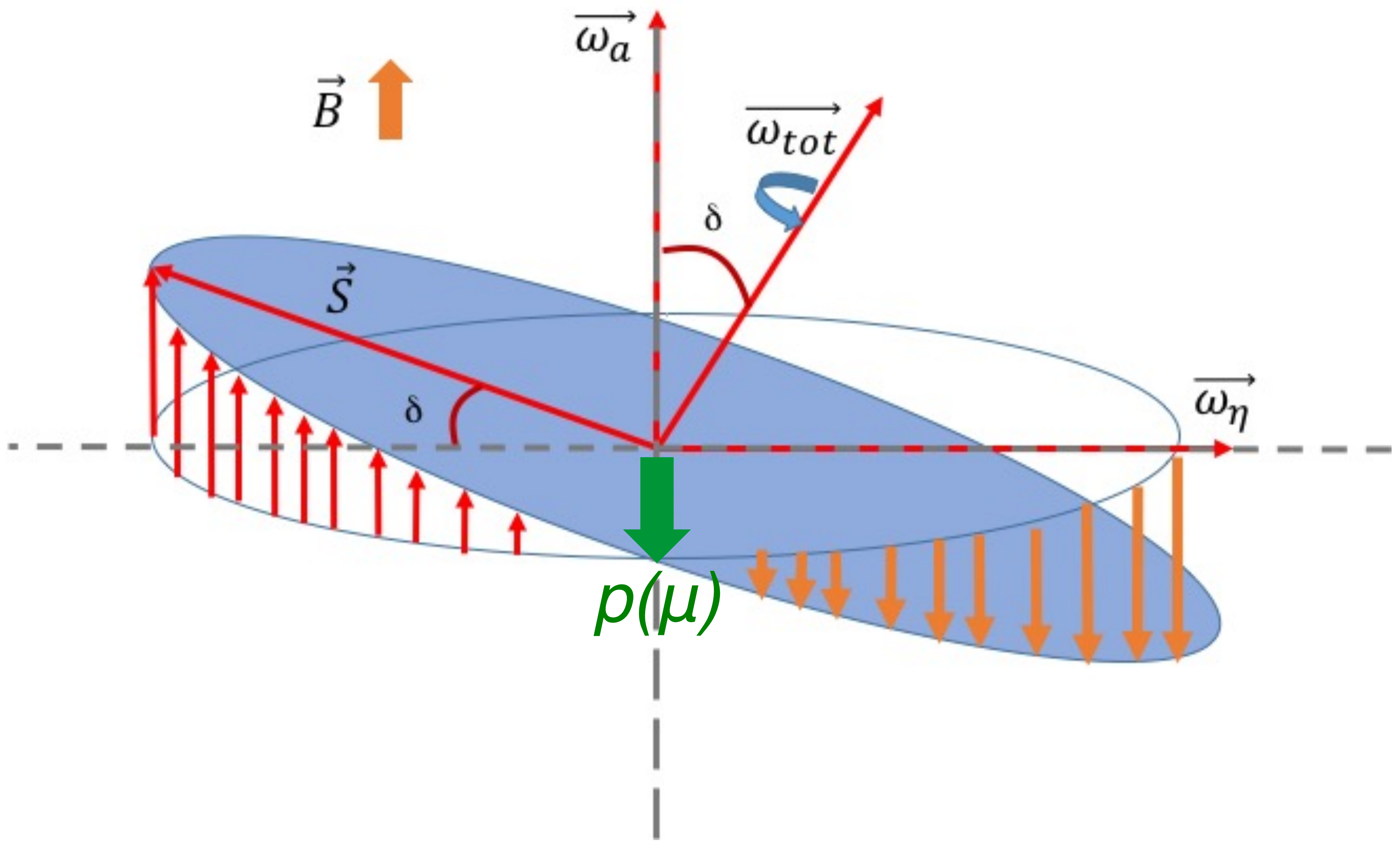


- Radial and vertical width oscillate vs time due to momentum acceptance of beam

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





arxiv: 0811.1207

Effect of tilted plane

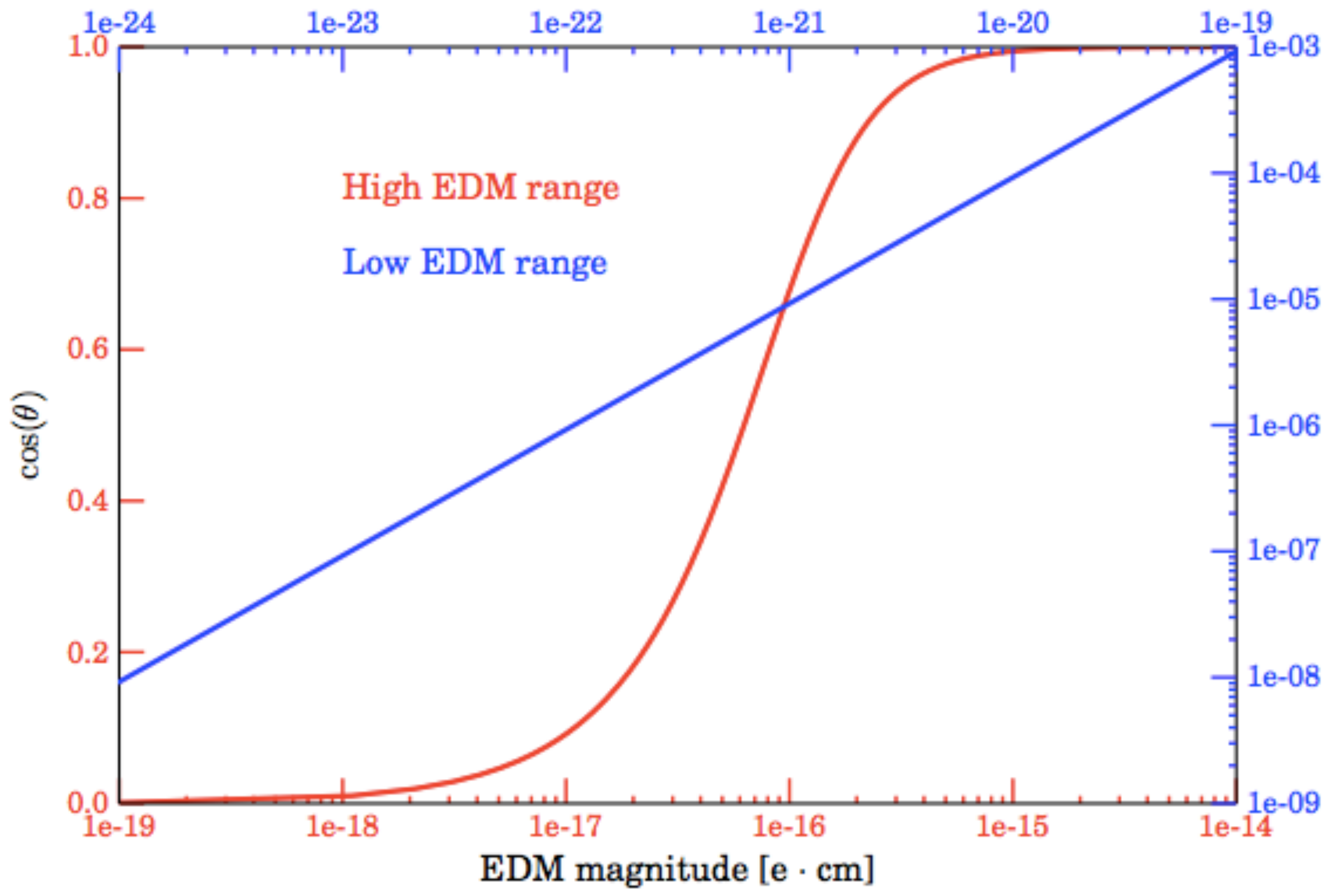
- Tilt of the precession plane (δ) is determined by the size of the EDM, and is given by

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

Lorentz boost:

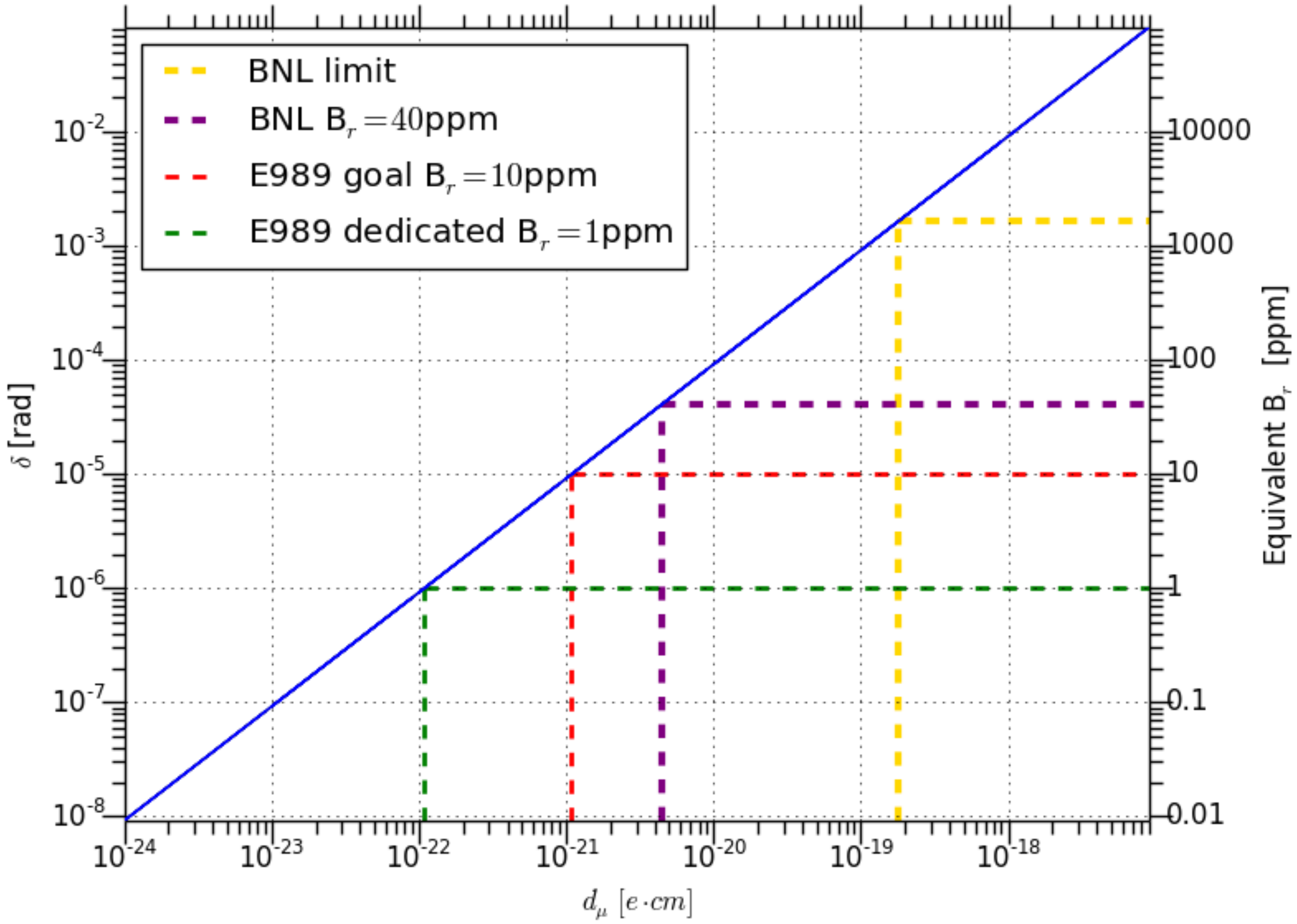
$$\delta' = \tan^{-1}\left(\frac{\tan\delta}{\gamma}\right)$$

θ = π/2 - δ



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

Equivalent Radial Fields



- These are the false EDMs that a radial field can mimic