Status of muon EDM measurement at the Muon g-2 experiment in Fermilab

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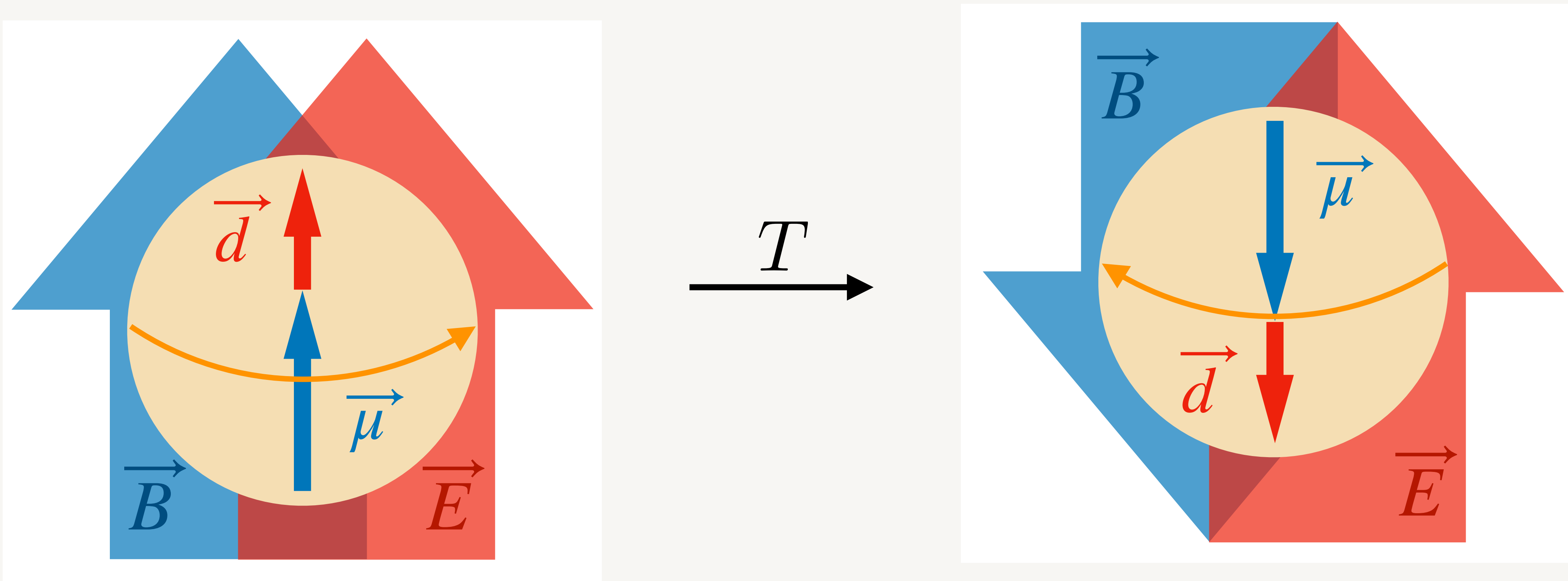
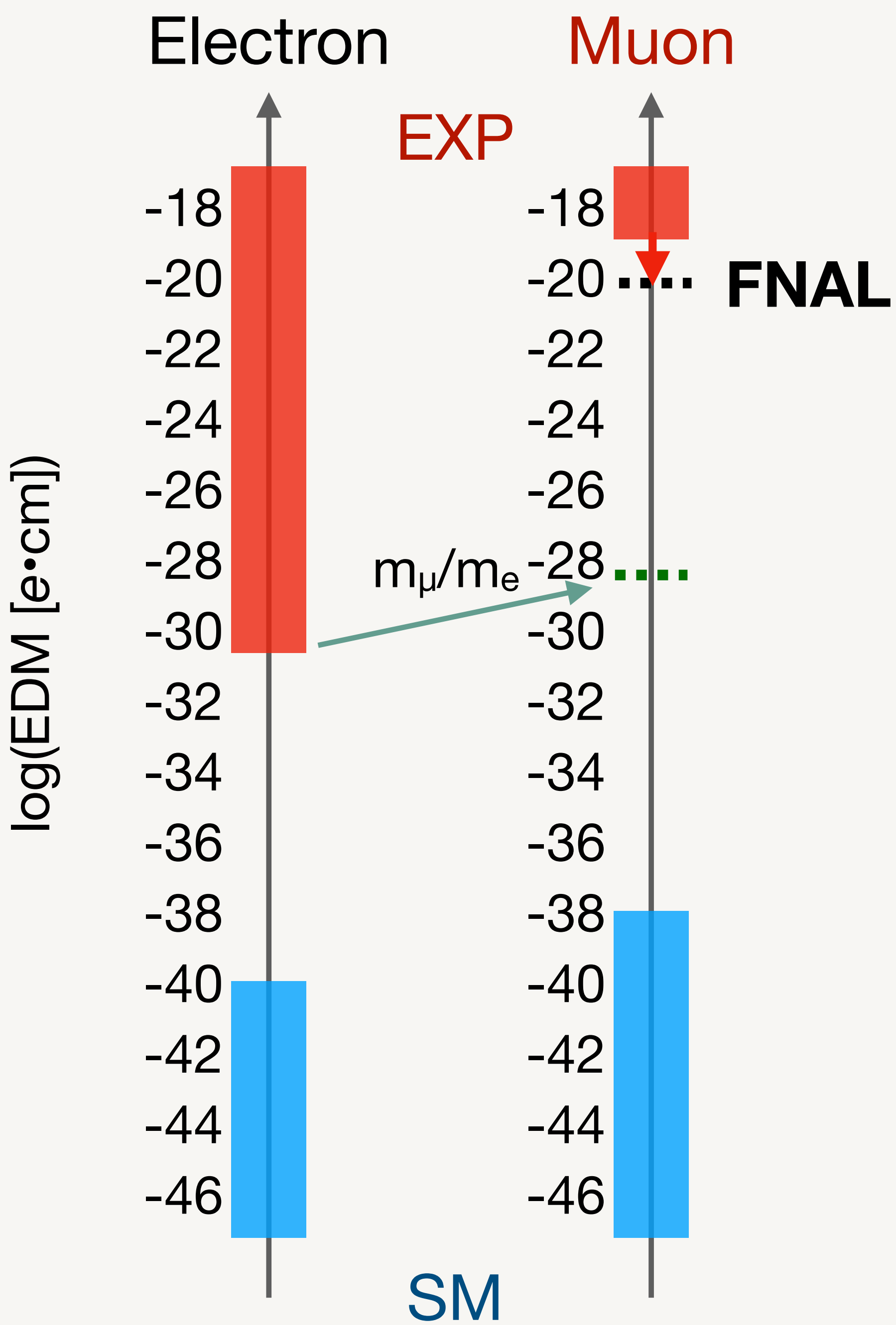
EDM and CP violation



$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E} \qquad \mathcal{H}^T = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$

- If $\vec{d} = 0$, $H = H^T$
- If $\vec{d} \neq 0$, $H \neq H^T$ → T violation ⇒ CP violation assuming CPT invariance

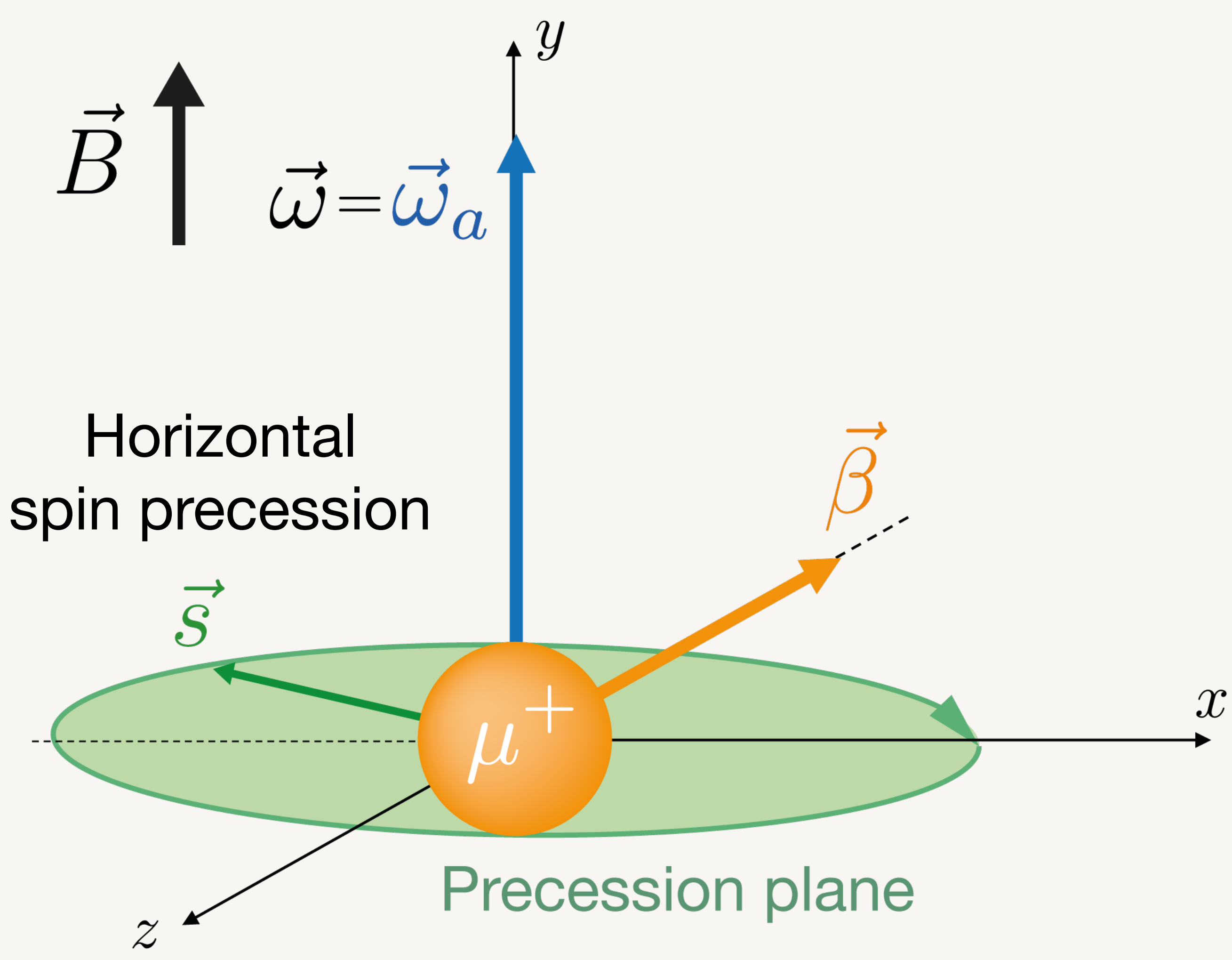
Muon EDM

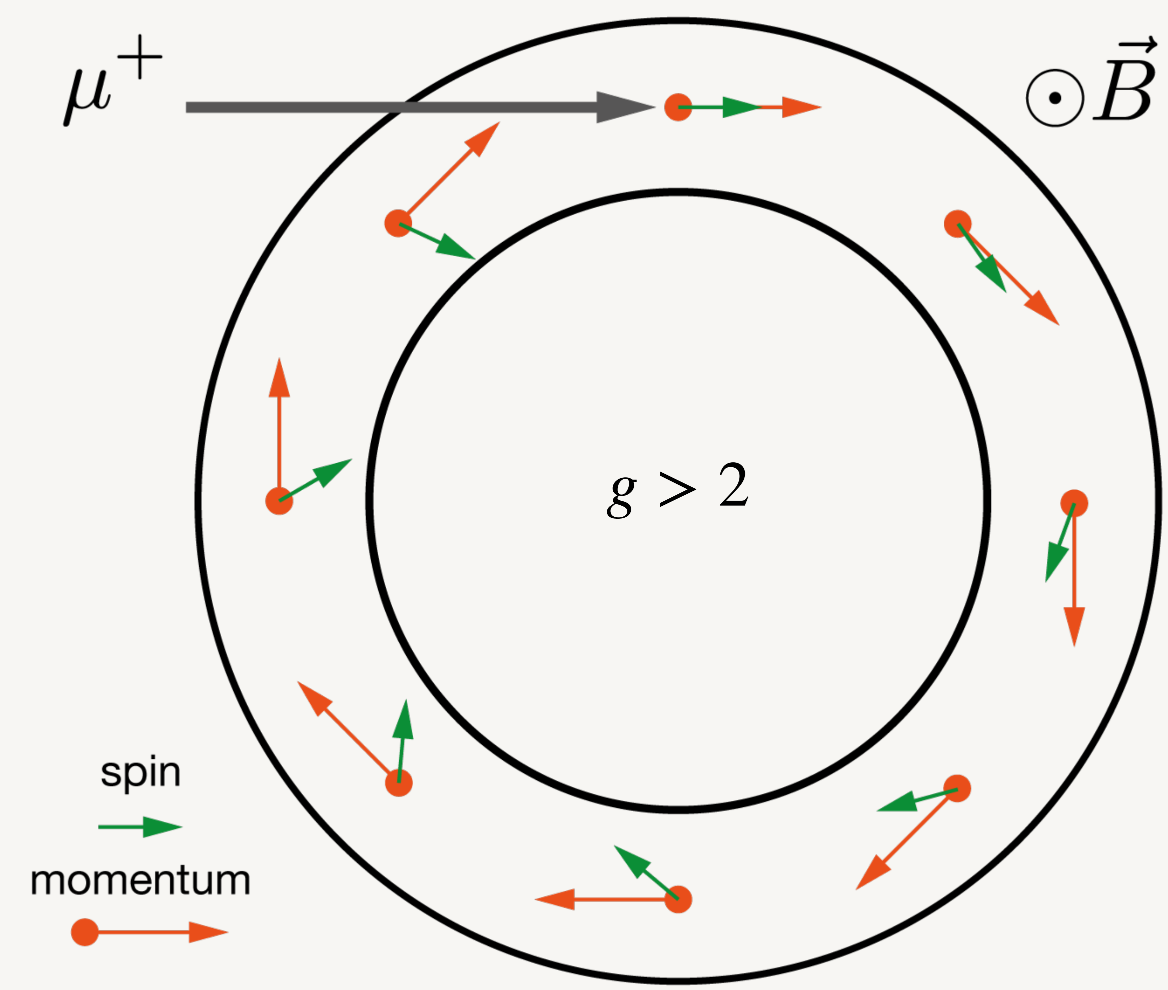


SM: M. Pospelov *et al.*, PRD 89, 056006 (2014)
Y. Yamaguchi *et al.*, PRL 125, 241802 (2020)

- Muon EDM has been measured in conjunction with muon g-2 over the past decades
- The current best direct limit was set at BNL:
  $d_\mu < 1.8 \times 10^{-19}\ e \cdot \mathrm{cm}$ (95% C. L.)
  G. W. Bennett *et al.*, PRD 80, 052008 (2009)
- Indirect limits
  - Electron (m_μ/m_e): $d_\mu < 8.5 \times 10^{-28}\ e \cdot \mathrm{cm}$
    electron EDM: T. S. Roussy *et al.*, Science 381,46-50 (2023)
  - ^{199}Hg: $d_\mu < 6 \times 10^{-20}\ e \cdot \mathrm{cm}$
    Y. Ema *et al.*, PRL 128, 131803 (2023)
- Key opportunity to further push EDM searches together with other experimental efforts (e, p, n…)
- Probing the role of lepton flavour universality

Muon spin precession in a storage ring



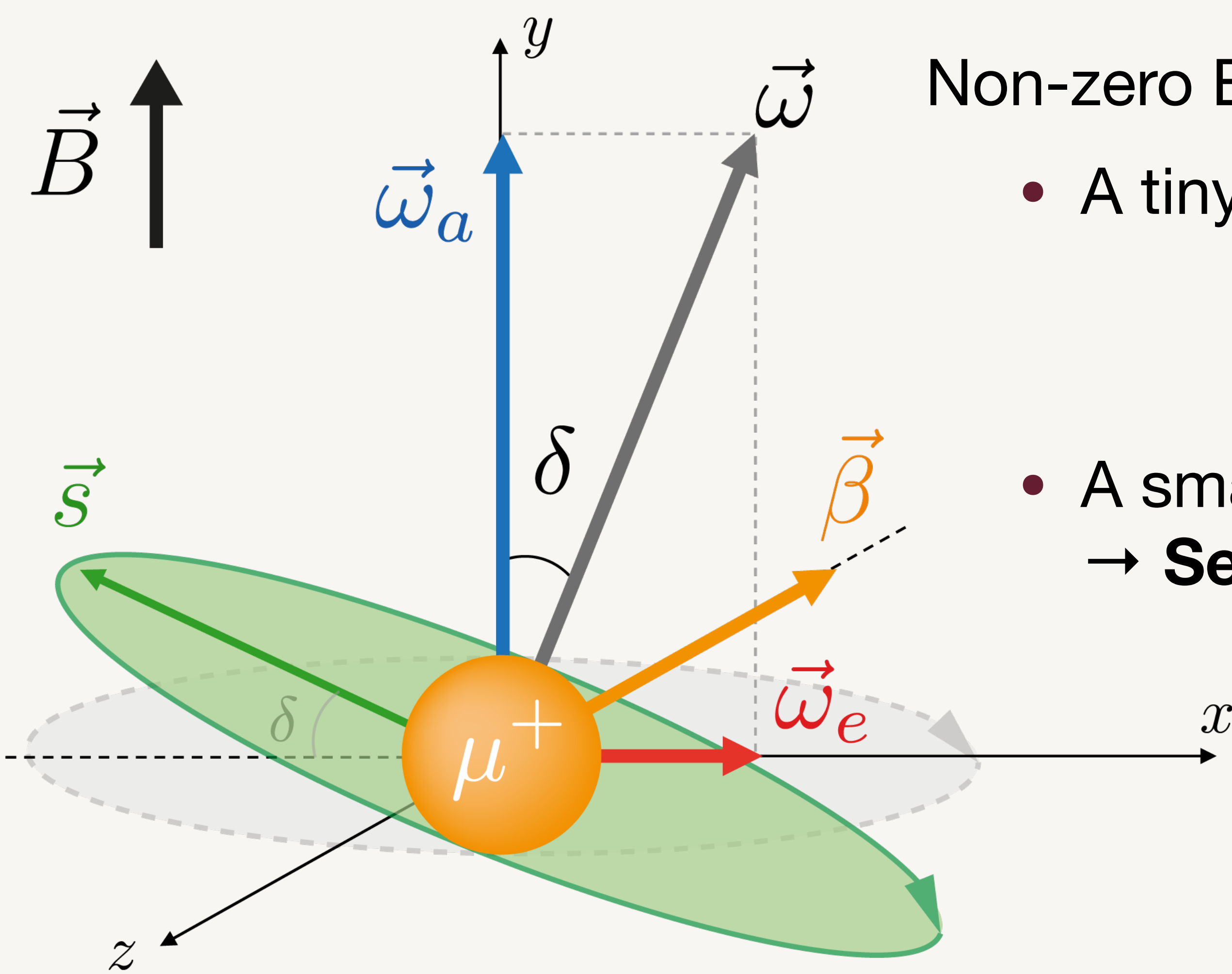


0 for $\gamma = 29.3$ (p = 3.09 GeV/c)

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

$\vec{\omega}_a$: horizontal precession

Addition of a non-zero EDM



Non-zero EDM introduces

- A tiny increase in the precession frequency

$$\omega = \sqrt{\omega_a^2 + \omega_e^2}$$

- A small tilt to the spin precession plane
  → **Search for an EDM by looking for this tilt**

0 for $\gamma = 29.3$ (p = 3.09 GeV/c)

$$d_\mu = \eta \frac{e\hbar}{4mc} \neq 0$$

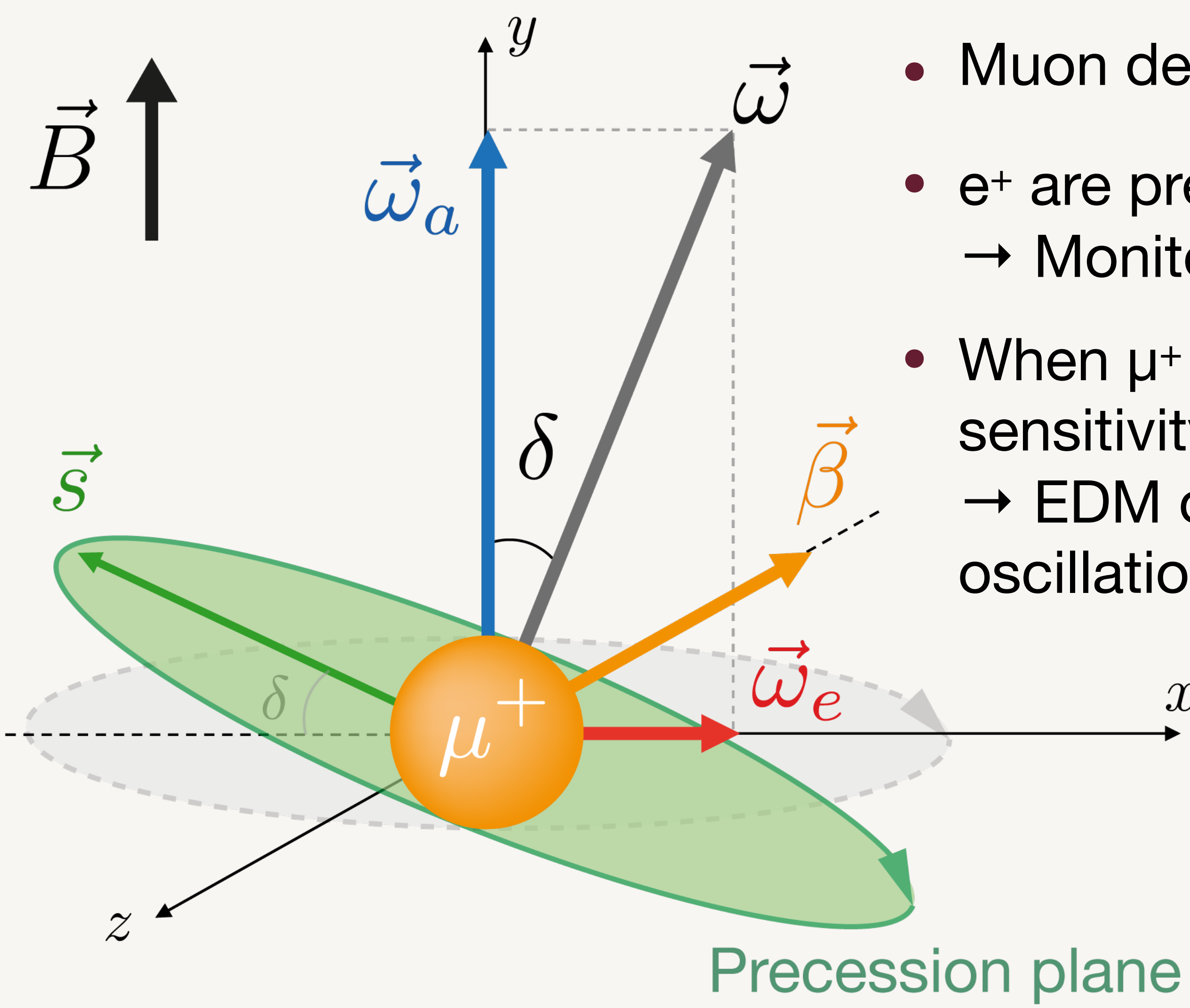
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] - \frac{e}{m}\left[\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

$\vec{\omega}_a$: horizontal precession

$\vec{\omega}_e$: vertical precession

Measuring the muon EDM

UCL



- Muon decay: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
- e^+ are preferentially emitted in μ^+ spin direction
  → Monitor μ^+ spin precession by detecting e^+
- When μ^+ spin aligns with its momentum vector, no sensitivity to EDM and maximal sensitivity to EDM at π/2
  → EDM oscillation is π/2 out of phase with the g-2 oscillation

0 for $\gamma = 29.3$ (p = 3.09 GeV/c)

$d_\mu = \eta \frac{e\hbar}{4mc} \neq 0$

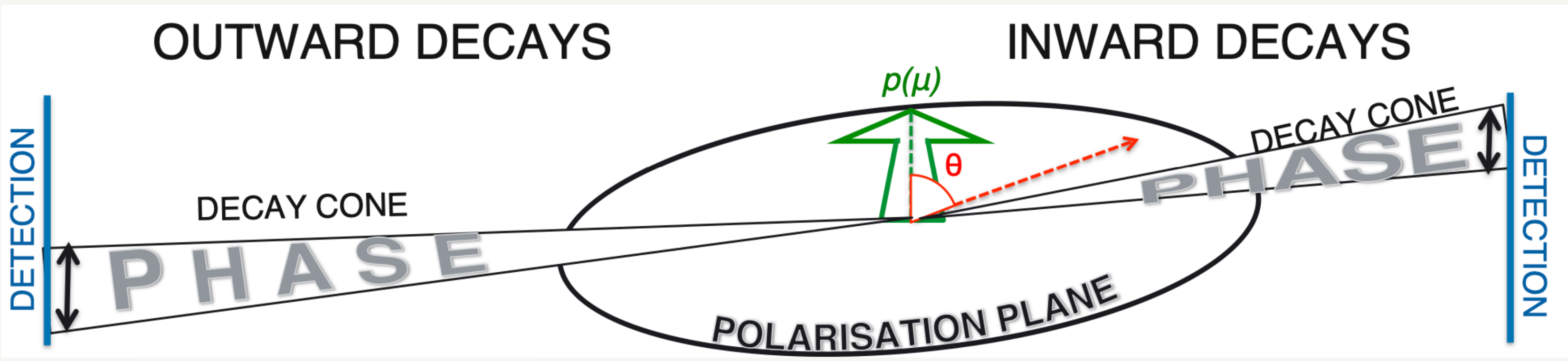
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] - \frac{e}{m}\left[\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

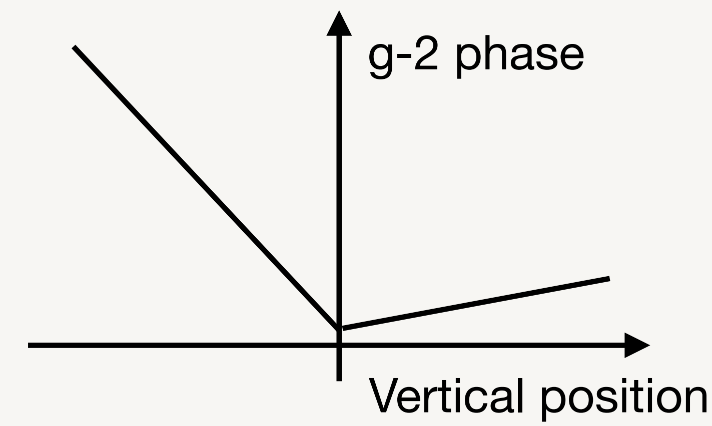
$\vec{\omega}_a$: horizontal precession

$\vec{\omega}_e$: vertical precession

Measuring the muon EDM at FNAL

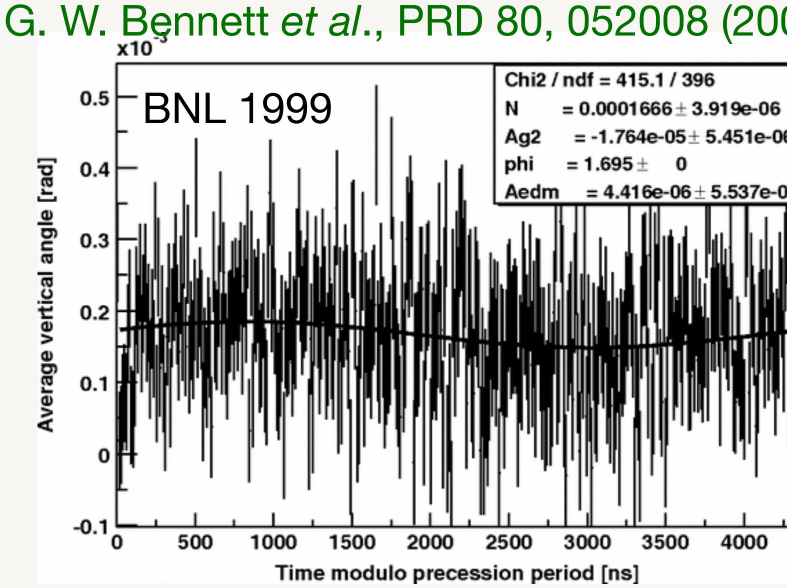
- Phase asymmetry





  - Look for a phase asymmetry in vertical position caused by inward/outward decay positrons
  - Calorimeter-based approach used at BNL → systematically limited
- Vertical decay angle
  - Direct measurement of positron decay angle by tracker
  - Statistically limited at BNL
- @FNAL: stats improved but calorimeter-based approach is still systematically limited

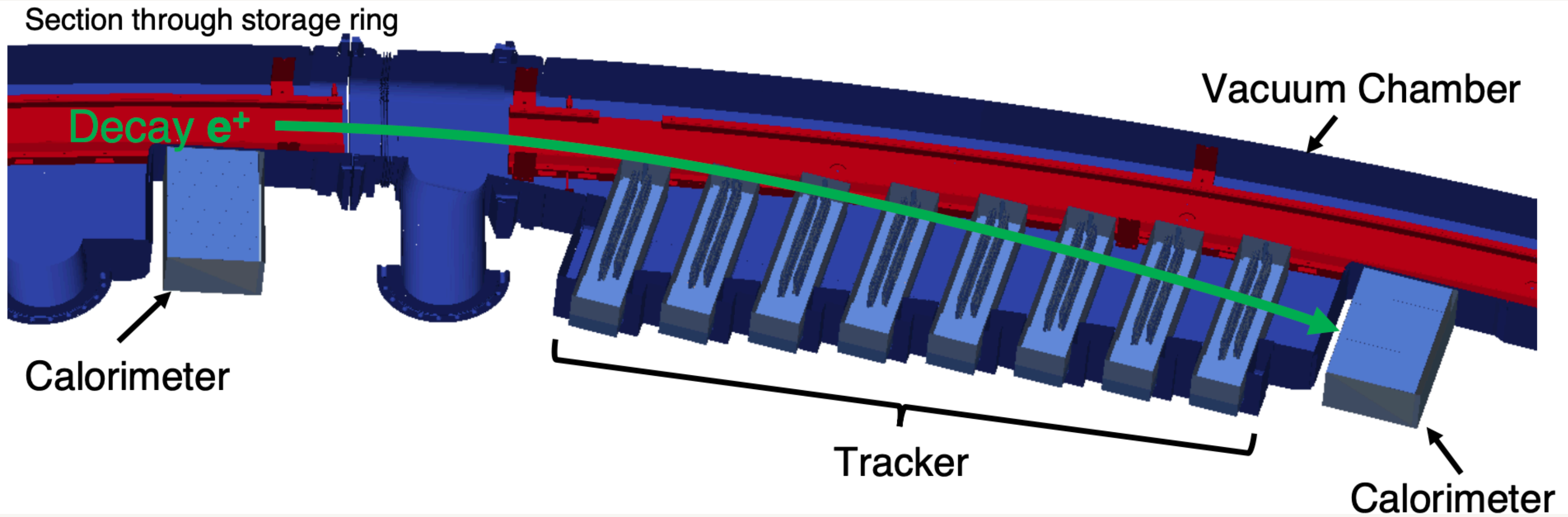
G. W. Bennett *et al.*, PRD 80, 052008 (2009)

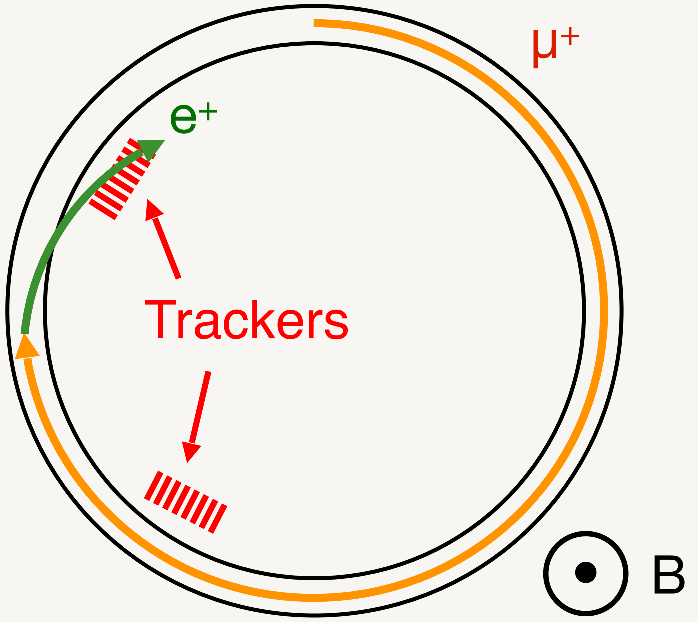


- FNAL muon EDM search focuses on the **tracker-based approach, measuring vertical decay angle**

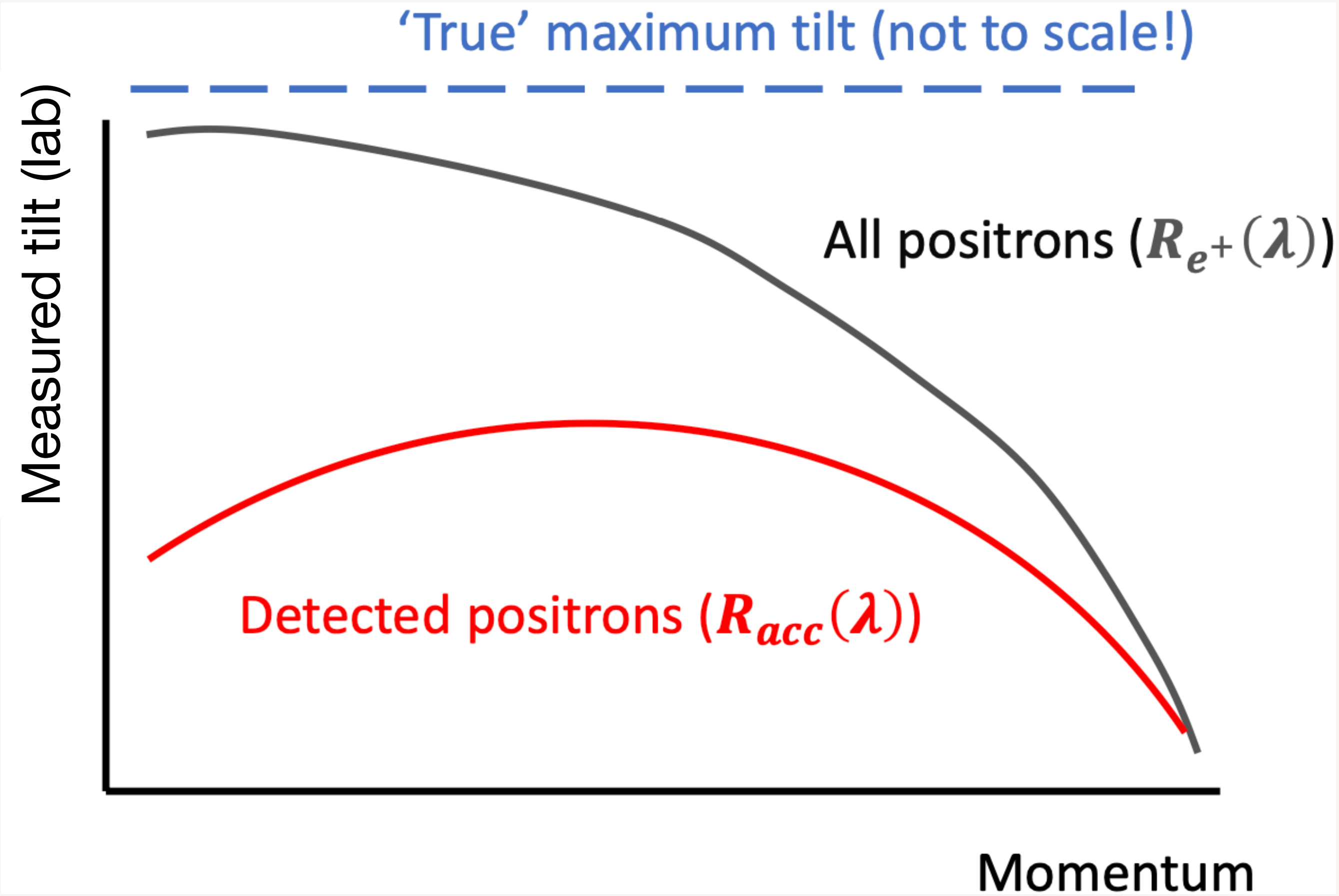
Straw trackers at FNAL

- 2 straw tracker stations (12 and 18) around the ring
  - 8 Argon-Ethane straw module per station with hit resolution ~100 μm
  - Operation inside the vacuum chamber
- Hits are fitted into tracks, which are then extrapolated backwards to the decay vertex
  → Used for the EDM analysis to measure the vertical decay angle





Reduction factors for the measured vertical angle



- Measured tilt in trackers is reduced from the rest frame tilt via

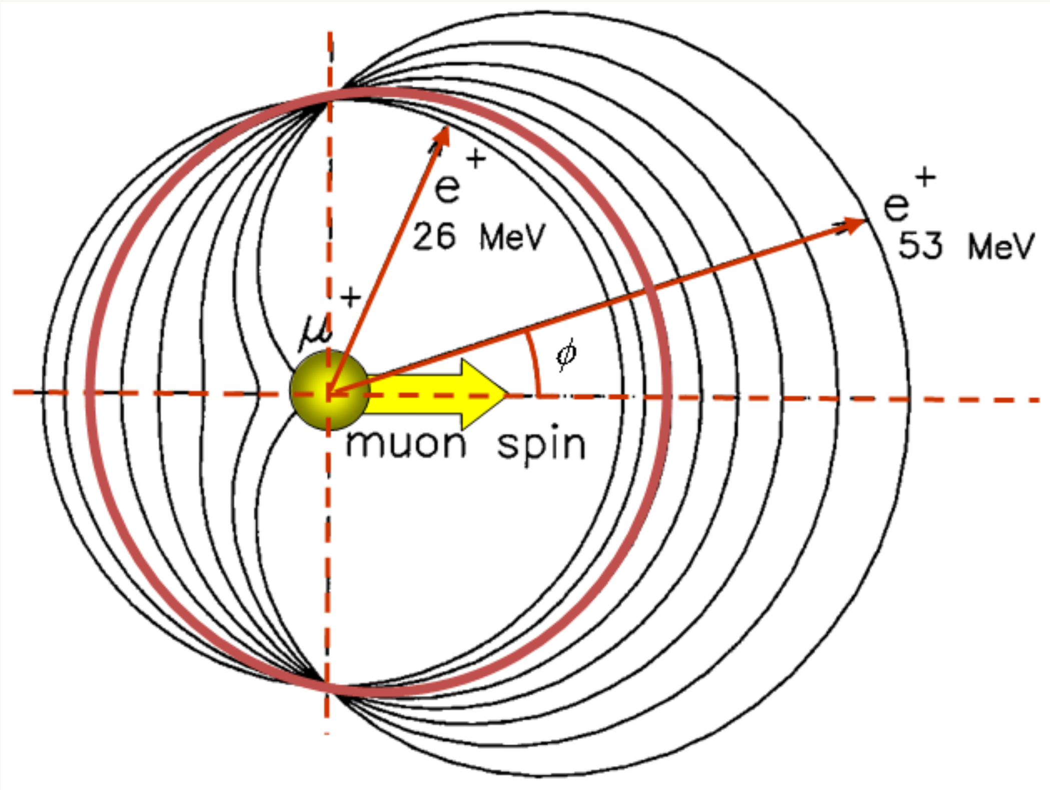
Measured tilt (lab) = $R_\gamma \; R_P \; R_{e^+}(\lambda) \; R_{\text{acc}}(\lambda)$ **True tilt (rest)**

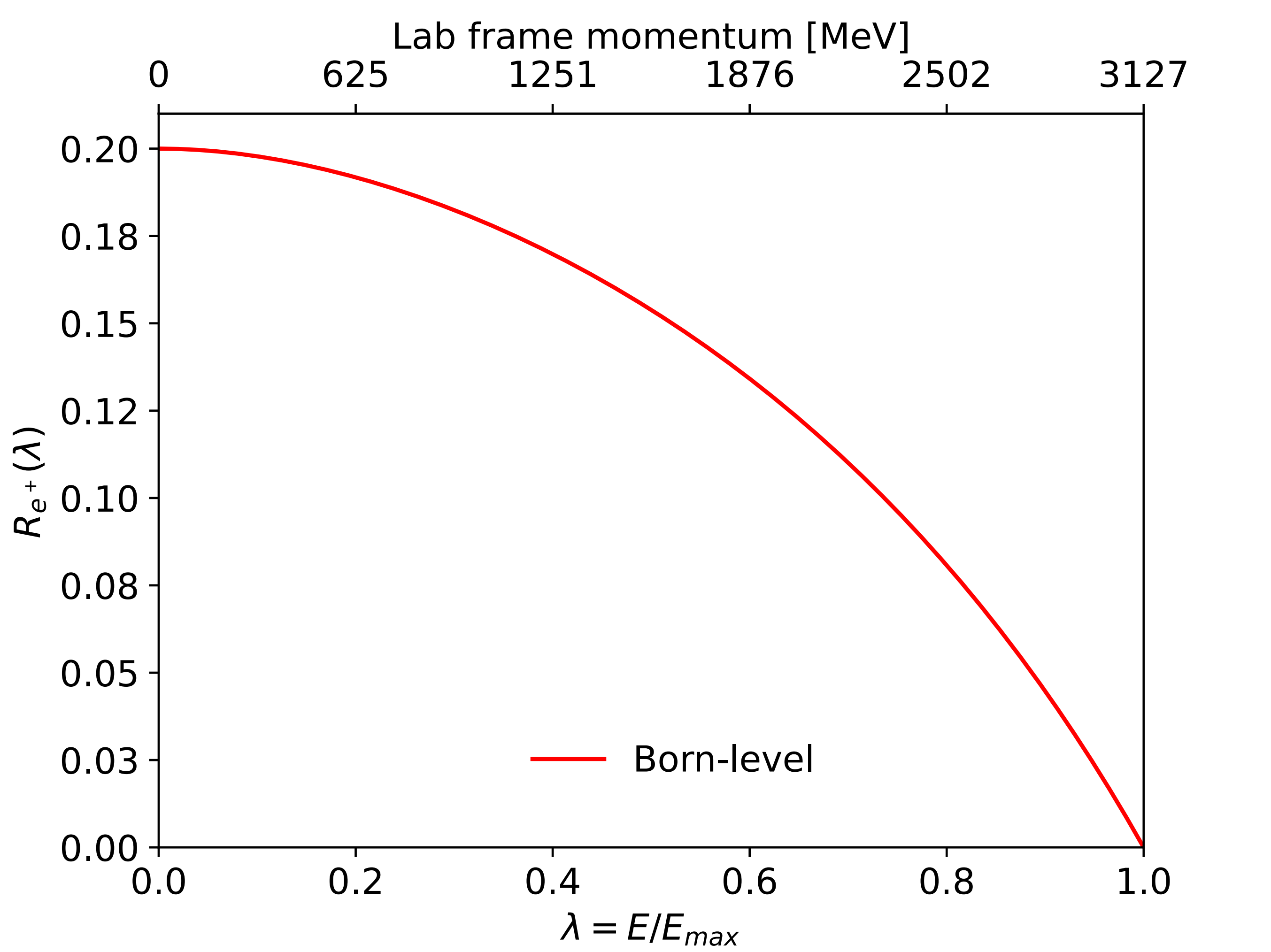
  - R_γ : Lorentz boost 1/γ ~ 1/29
  - R_P : average beam polarisation ~0.96
  - $R_{e^+}(\lambda)$: momentum-dependent asymmetry in muon decay property
  - $R_{\text{acc}}(\lambda)$: momentum-dependent tracker acceptance

Momentum dependent $R_{e^+}(\lambda)$ factor

- Positrons are preferentially emitted along muon spin direction
  → 'Boosted' Michel spectrum

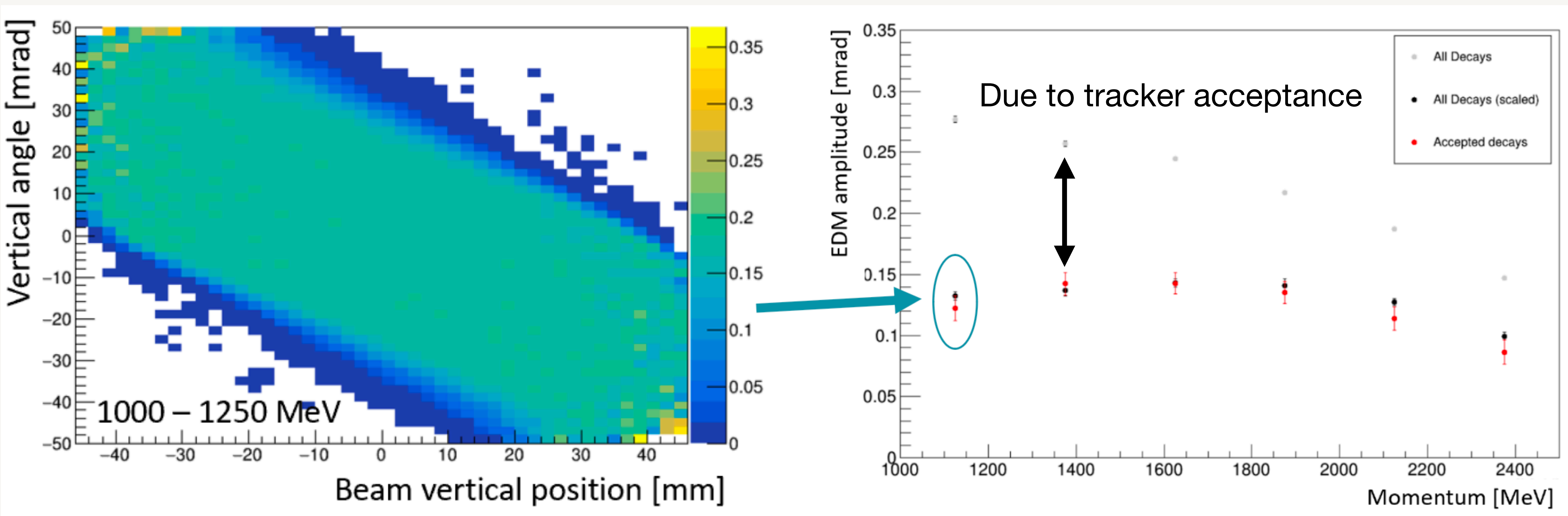
- Can be described analytically but misses radiative corrections leading to a small reduction in the tilt seen
  → Determine $R_{e^+}(\lambda)$ factor using MC to take account for the higher-order effects



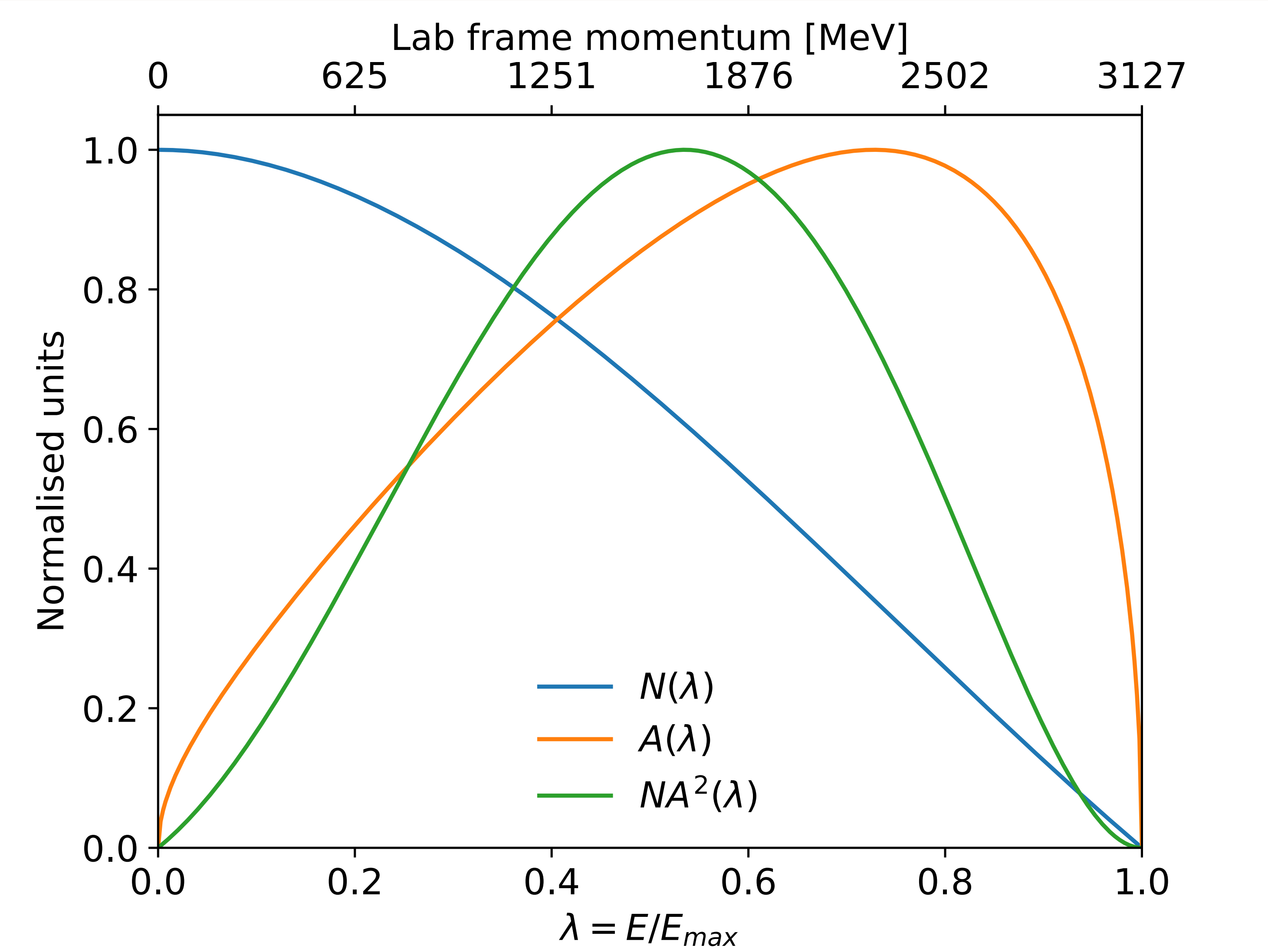


Momentum dependent acceptance $R_{acc}(\lambda)$ factor

- Due to the finite size of the detector, a fraction of decay positrons can be detected
- The ratio of detected decays to all decays in MC gives $R_{acc}(\lambda)$ factor
  → Statistically limited due to the low numbers of detected decays
- 2D acceptance probability maps in each momentum bin to shape the ideal all decays MC without reducing its statistical power for correction evaluation

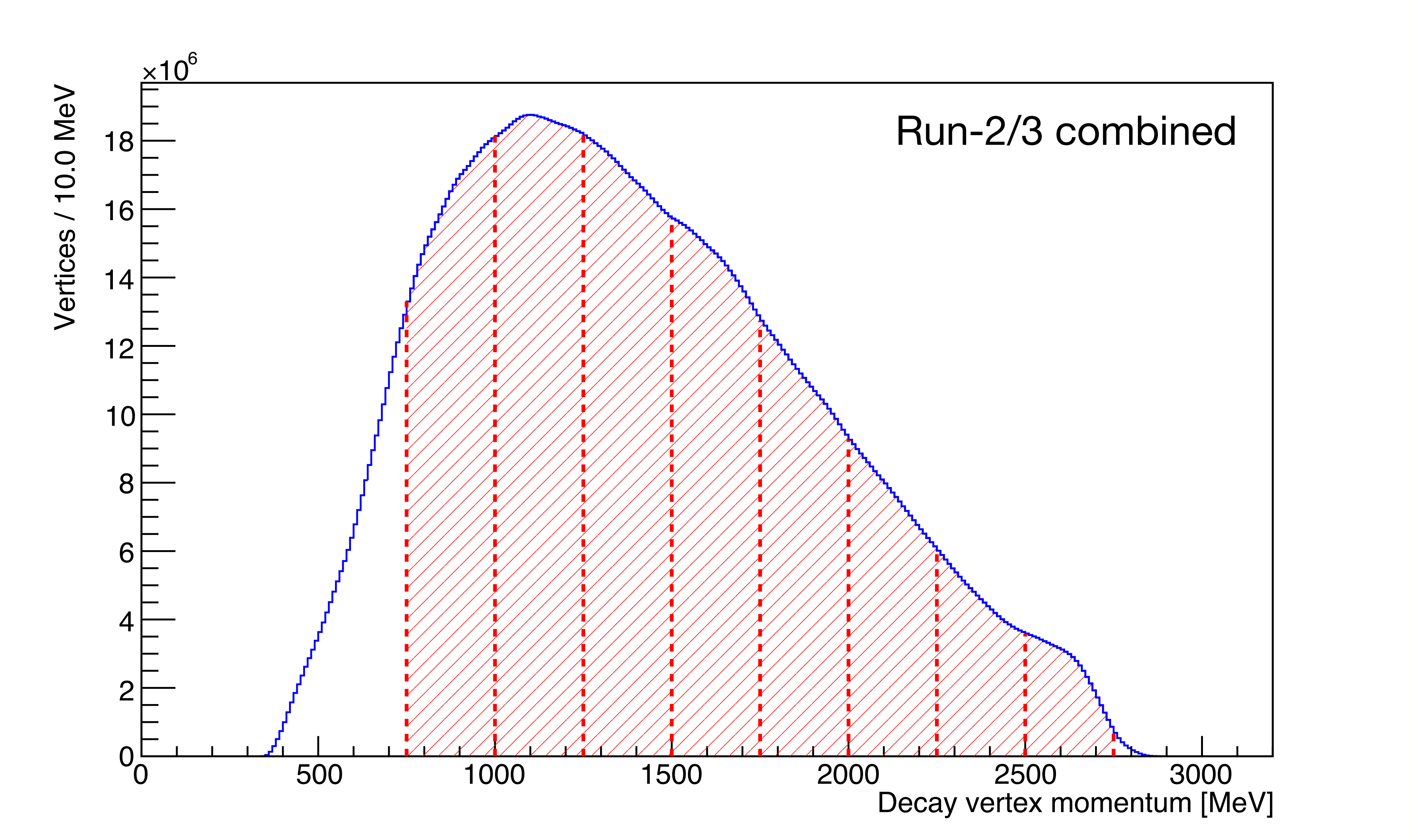


FNAL EDM figure of merit



- Statistical sensitivity: $\sigma(d_\mu) \propto 1/\sqrt{NA^2}$
- Mid-momentum range muons carry more sensitivity

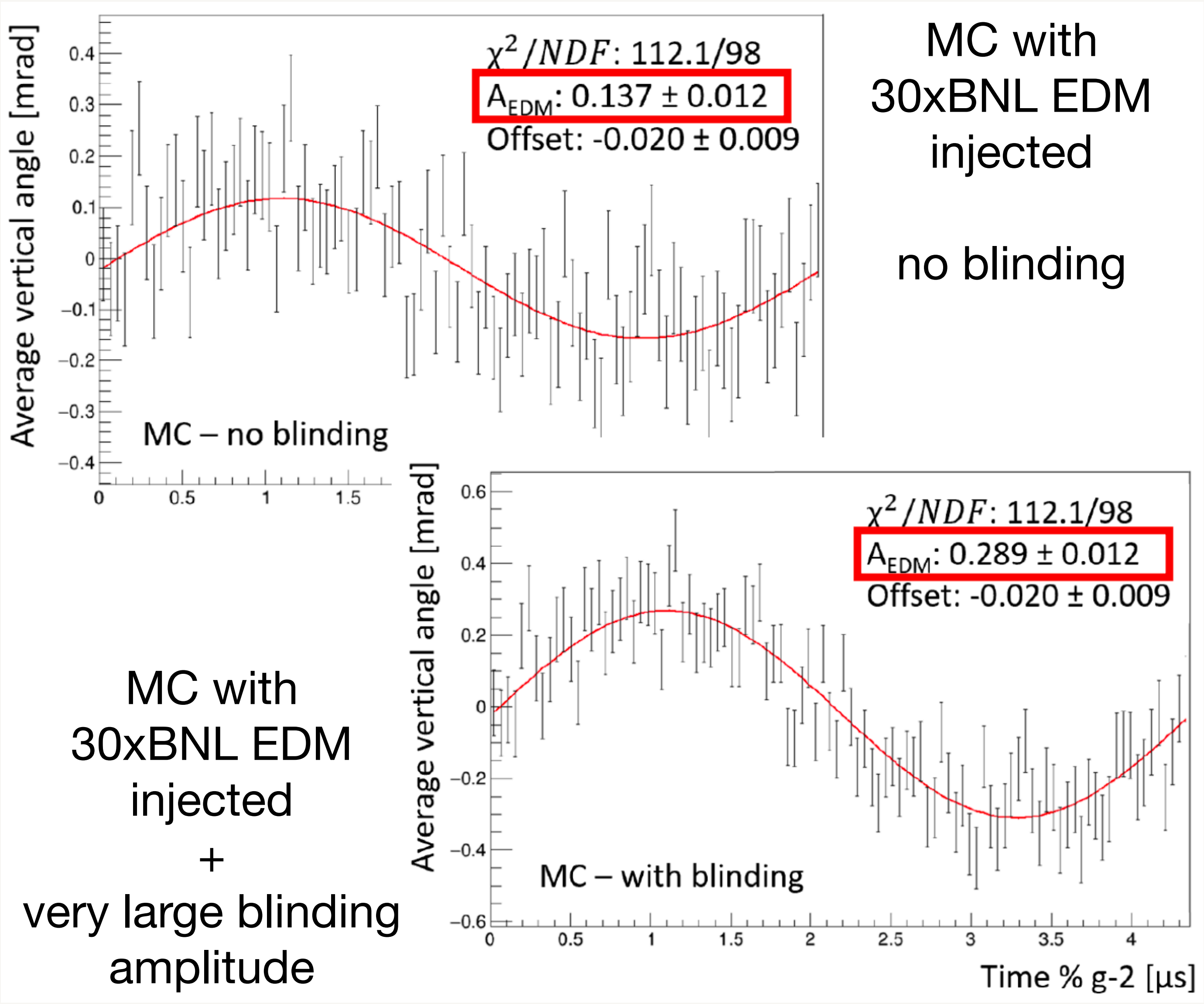
Momentum-binned analysis



- Momentum range 750 – 2750 MeV are used for the EDM analysis
- Total 8 momentum bins, each 250 MeV wide
  → can increase overall sensitivity to the EDM by allowing more accurate application of momentum-dependent correction factors

Blinding

- Need to blind the vertical angle oscillation to prevent bias in the analysis
- Inject a very large fake signal into the oscillation in phase with EDM
  - Amplitude is sampled randomly from a gaussian distribution, chosen to be >> BNL limit
  - Applying per momentum bin
  - Only blind A_{EDM} without changing the fit quality

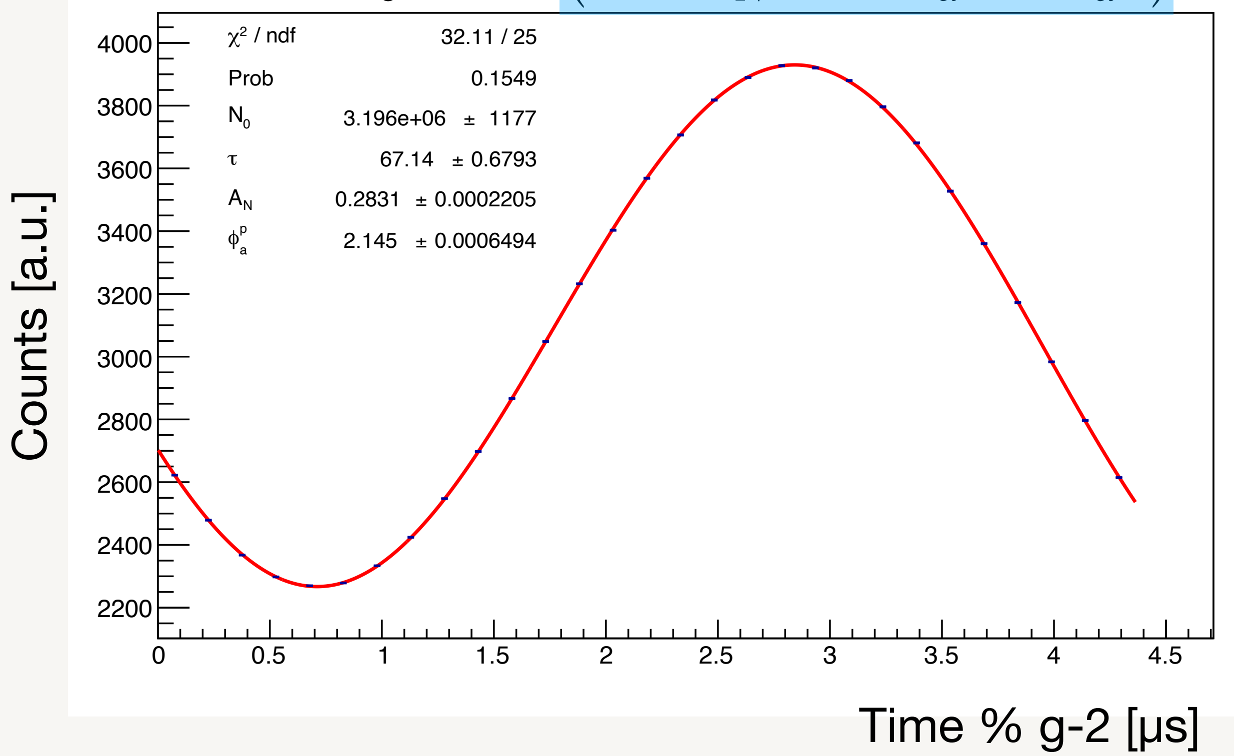


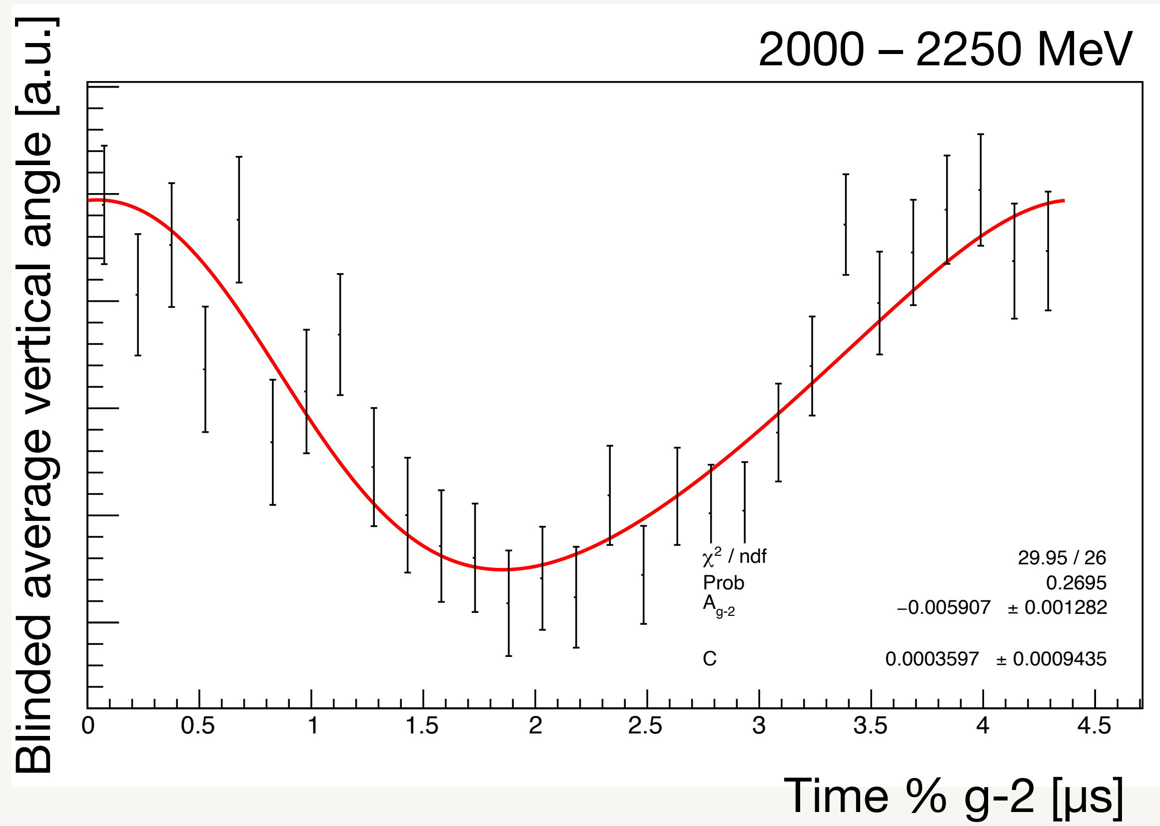
EDM signal extraction

- For each momentum bin, plot average vertical angle vs. time modulo the g-2 period then fit it using

$$\langle\theta_y\rangle = \frac{A_{\mathrm{g}-2}\cos(\omega_a t + \phi_a) + A_{\mathrm{EDM}}\sin(\omega_a t + \phi_a)}{1 + A_N\cos(\omega_a t + \phi_a^p)} + c$$

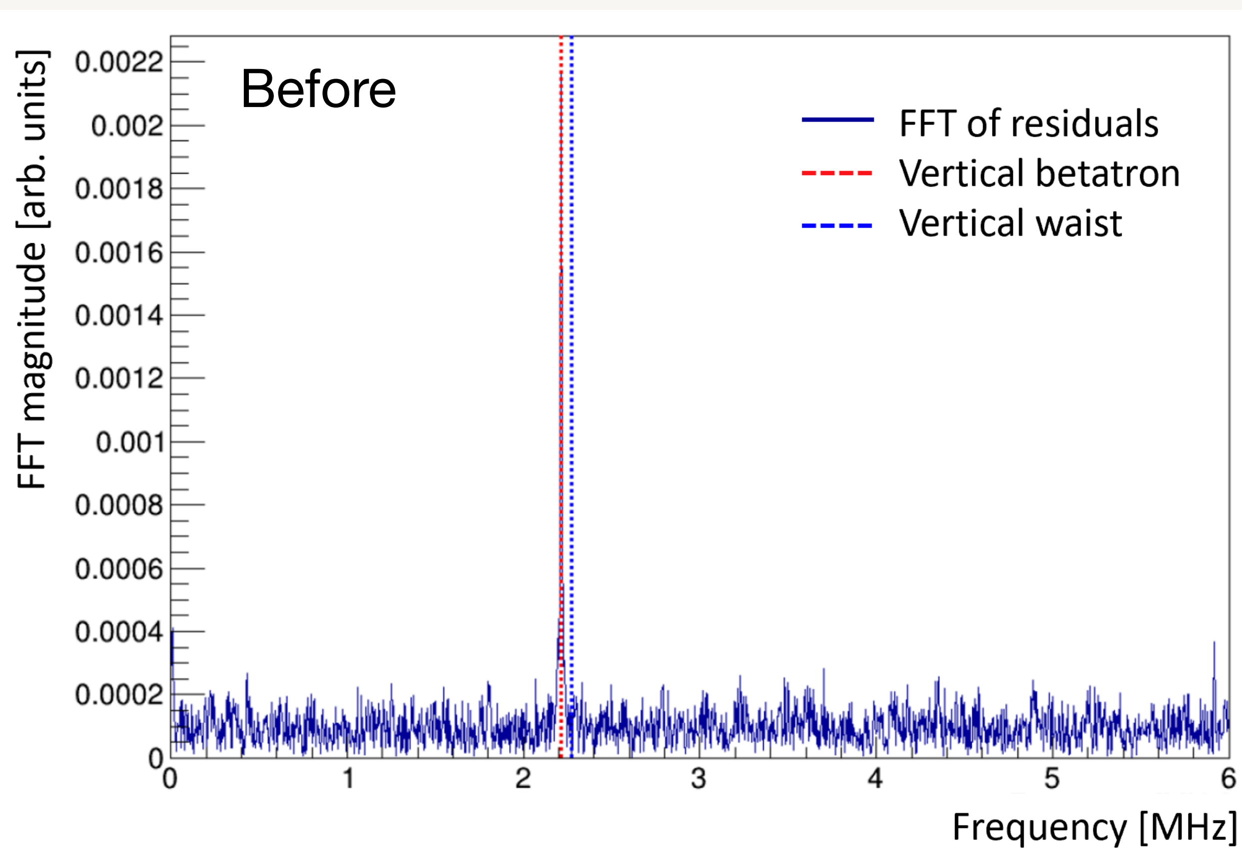
$$N(t) = N_0 e^{-t/\gamma\tau_\mu}\left(1 + A_N\cos(\omega_a t + \phi_a^p)\right)$$

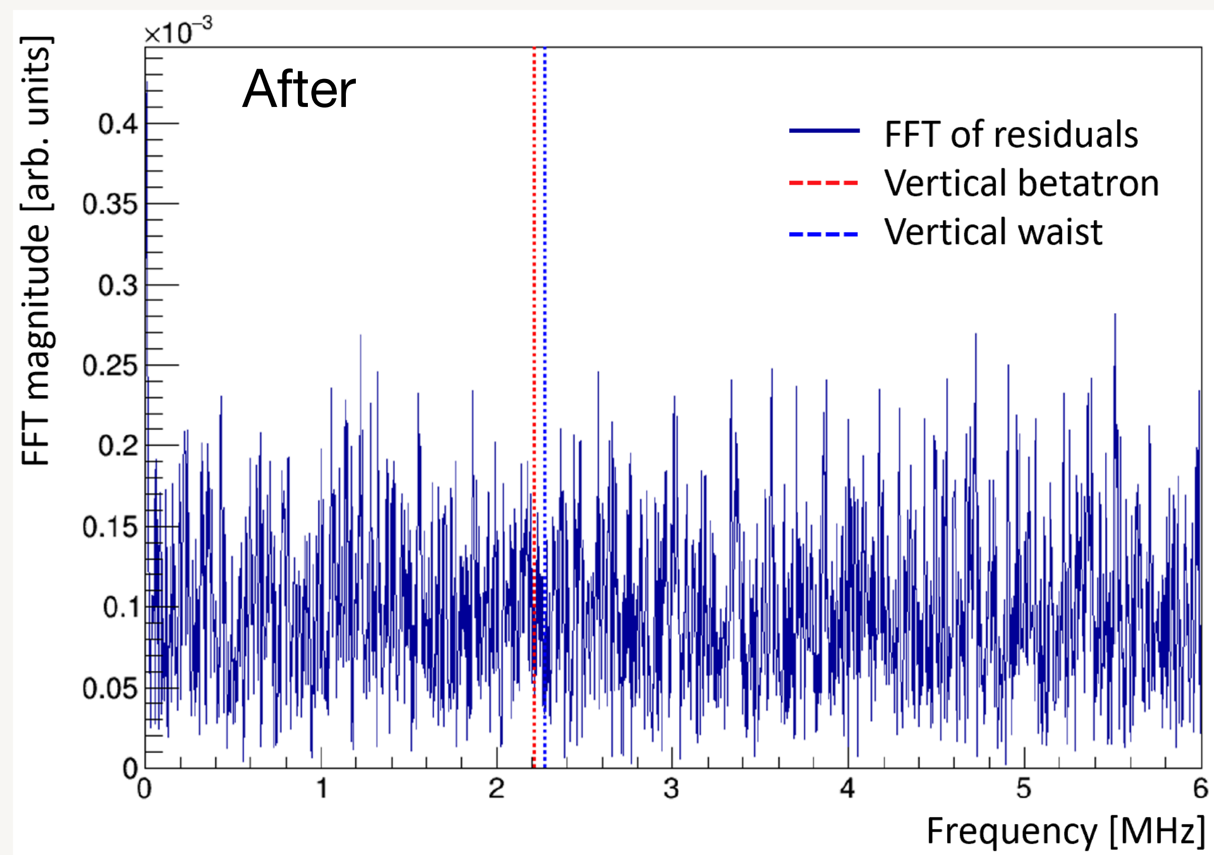




Beam dynamics corrections

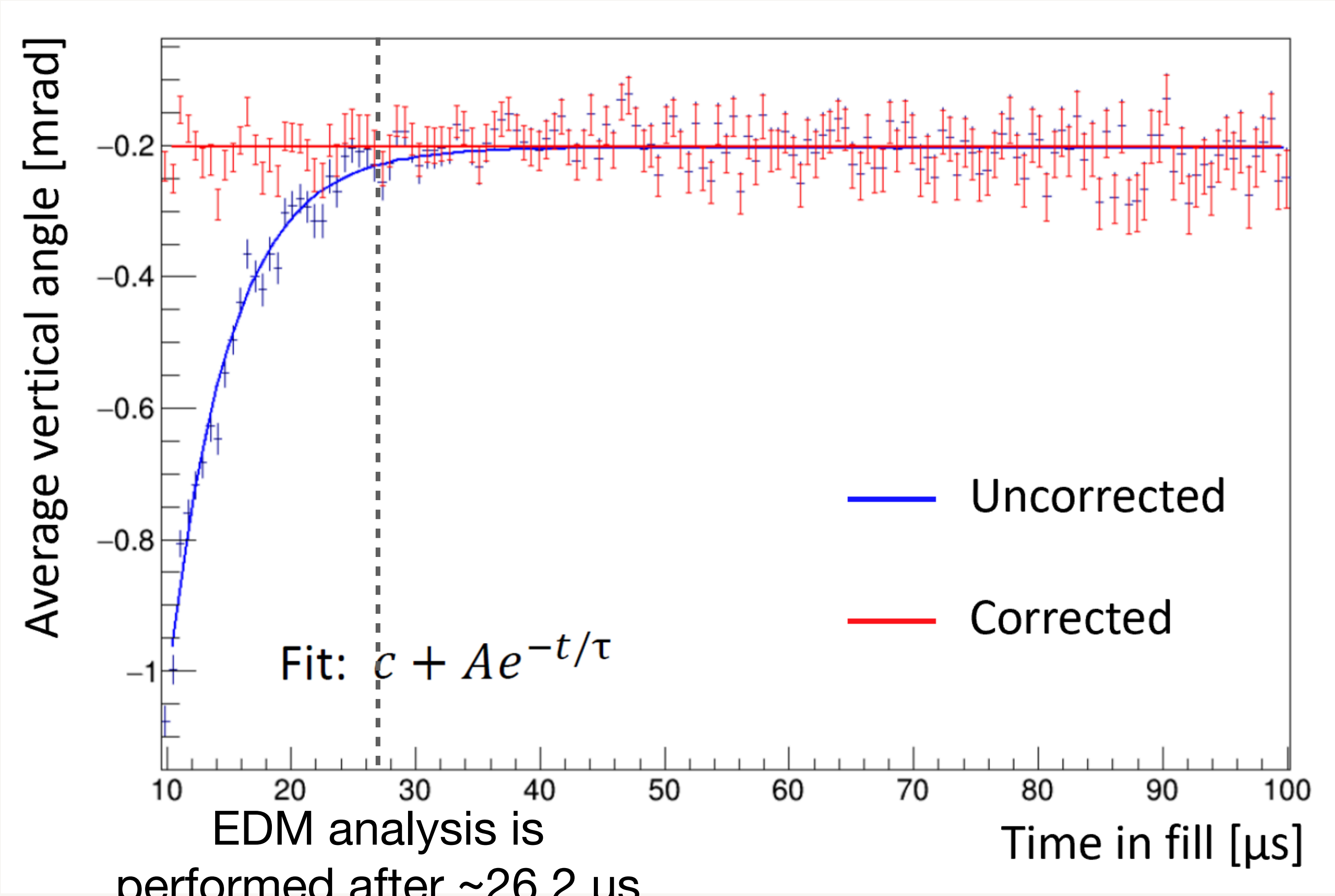
- Muon beam has a vertical betatron oscillation which appears in the FFT of the fit residuals
  - Before the analysis, apply time randomisation via a uniform smearing within the oscillation period
  - Fast rotation effect, which is relevant at early times, is similarly randomised out





Early time beam scraping correction

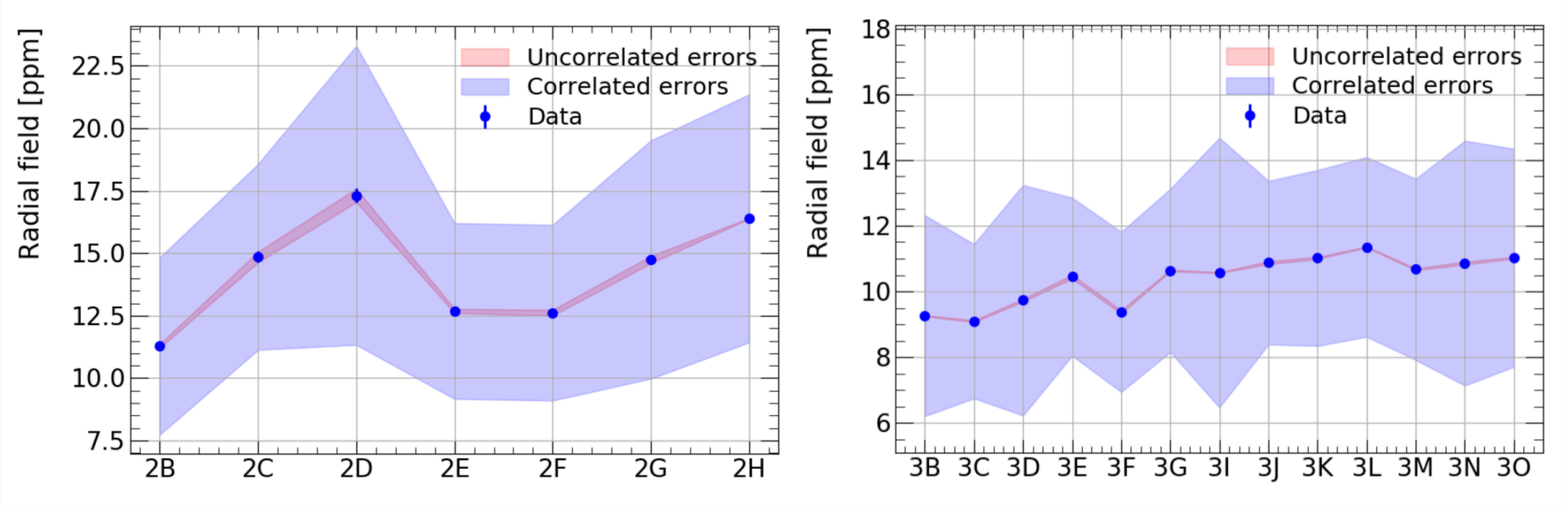
- At early times, the average vertical beam position changes rapidly over time due to beam scraping
  - This consequently changes the average vertical decay angle as well
  - Remove the quick angle change by fitting the data for each momentum bin per tracker station



EDM analysis is performed after ~26.2 μs

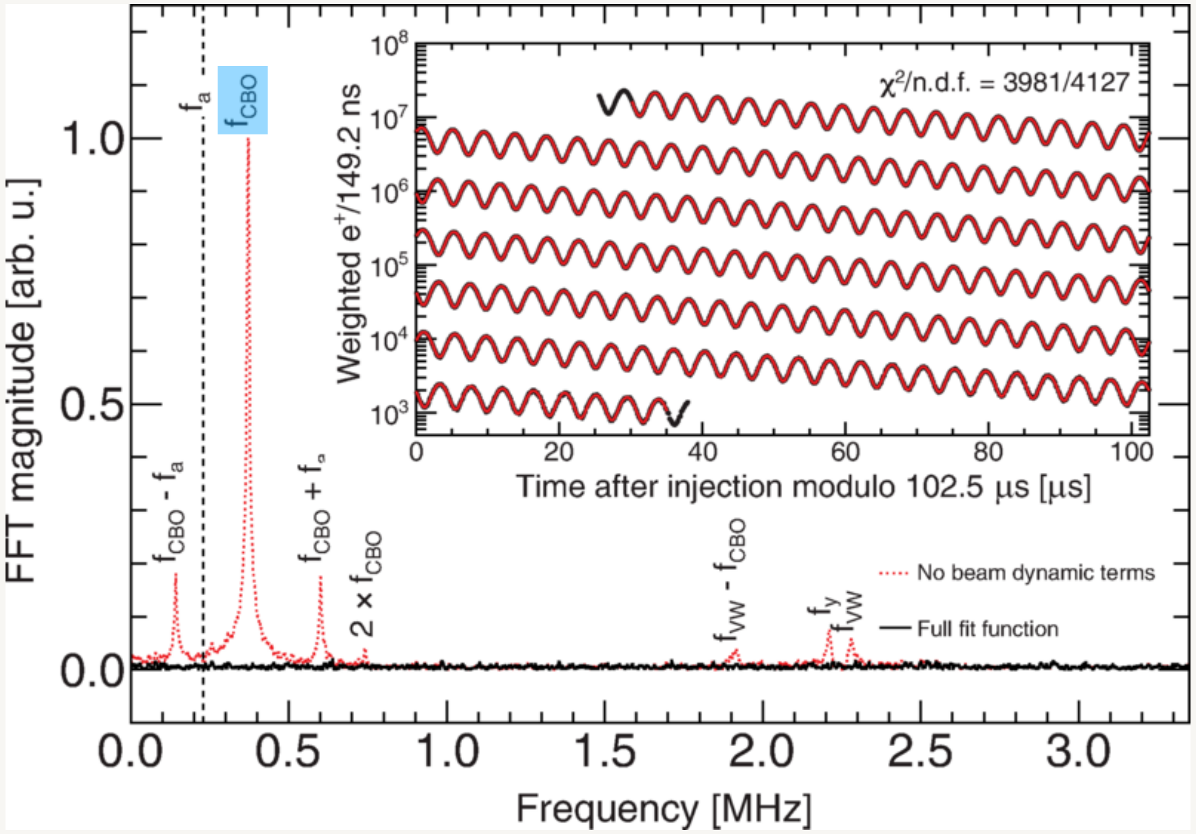
Radial magnetic field

- MDM coupling to the radial magnetic field B_r mimics an EDM signal
- Dedicated 'radial field scans' campaign were performed in Run-4/5/6 and extrapolate the measurements to Run-2/3 using the vertical beam position
- Sufficient precision was achieved ensuring that the radial field does not limit the EDM measurement

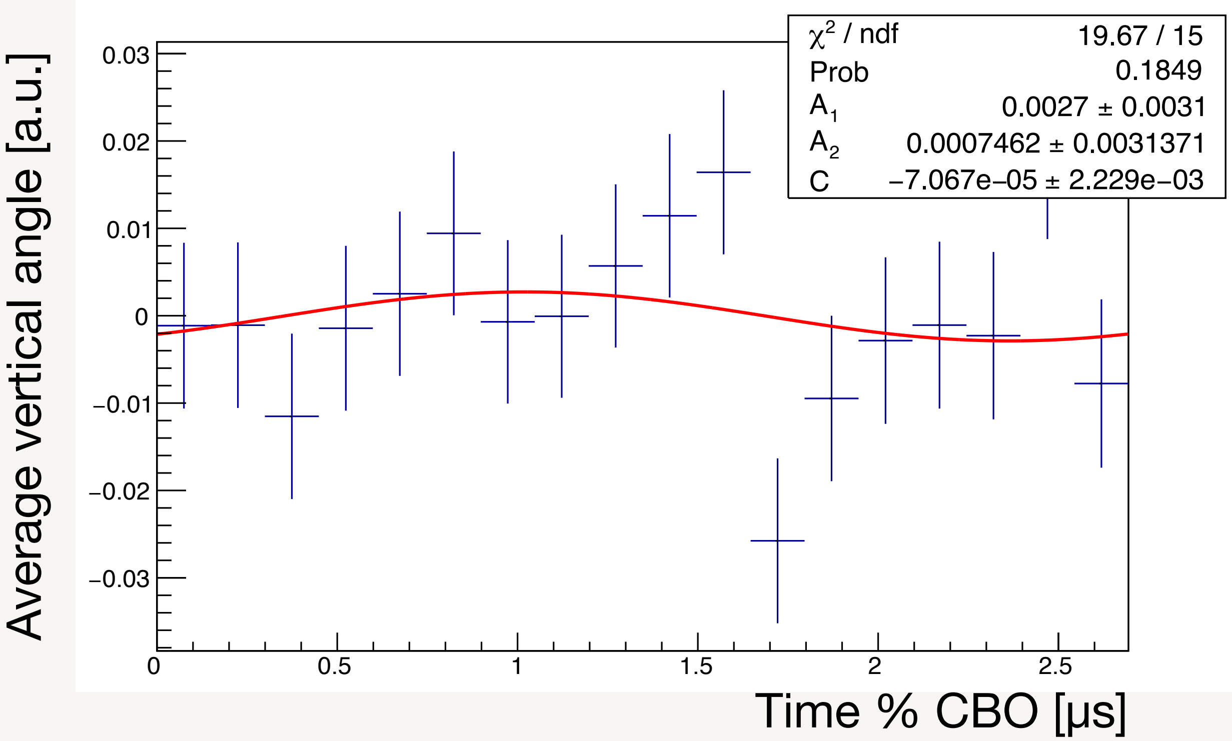


Cross-check at other oscillation frequencies

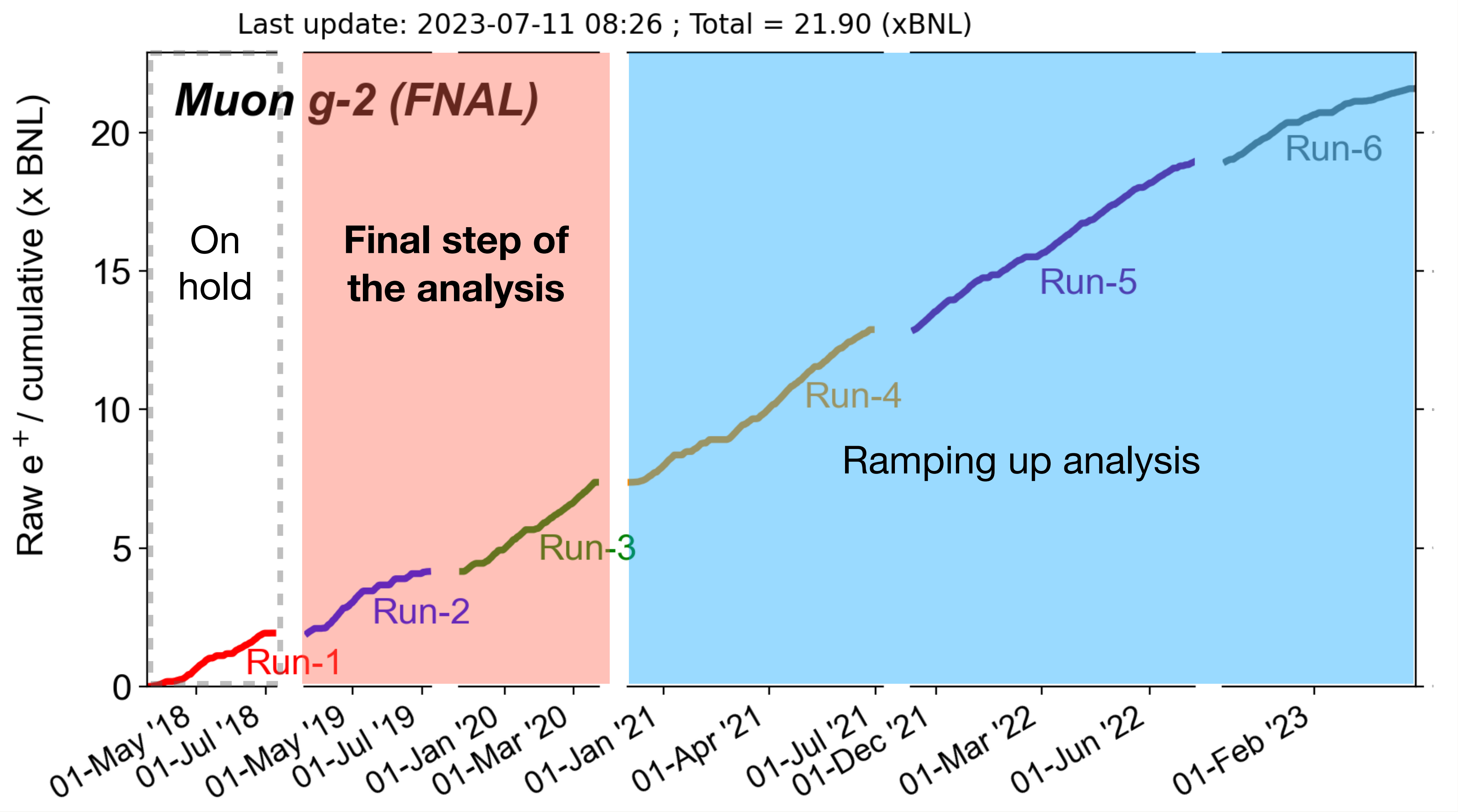
- EDM signal: average vertical angle oscillation π/2 out of phase with g-2 oscillation
- Cross-check to confirm no average vertical angle oscillation at
  - coherent betatron oscillation (CBO) frequency – the most in-and-out effect
  - random frequency
- The same approach as the main analysis: Plot vertical angle modulo another frequency and fit for oscillation at that frequency
- Unblinded fits confirm no vertical angle oscillation at those frequencies



D.P. Aguillard *et al.*, PRL 131, 161802 (2023)



Timelines for FNAL EDM analysis



- Run-1: 'complete' but still blinded
  established analysis approach through collaboration review for Run-2 onwards analyses
- **Run-2/3**: nearly completing the analysis, new results expected next year!
  collaboration review has started
- Run-4/5/6 + full dataset: analysis just started
  The FNAL muon EDM search aims to improve the current best limit by an order of magnitude

Conclusions

- The search for the muon EDM is a unique opportunity to explore CP violation in BSM physics and has the potential to probe the role of LFU
- The FNAL muon EDM search focuses on the tracker-based approach
- Run-2/3 analysis is nearly finalised
  – new results are expected next year and will improve the BNL limit
- With the full dataset, the FNAL muon EDM search amis to improve the BNL limit by an order of magnitude