Muon EDM simulation in the Fermilab g-2 experiment

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Muon EDM Workshop — University of Liverpool

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Introduction

- Recap of muon EDM signal in g-2 experiment
- Overview of ‘gas gun’ simulation
- How the EDM was added into the gas gun
- Sanity tests — EDM out == EDM in?
- Results

Reminder of EDM in the g-2 experiment

- EDM is analogous to MDM:

$$\boldsymbol{\mu} = g\frac{q}{2m}\boldsymbol{s} \qquad \boldsymbol{d} = \eta\frac{e\hbar}{4mc}\boldsymbol{s} \qquad \eta = \frac{4d_{\mu^+}m_\mu c}{\hbar}$$

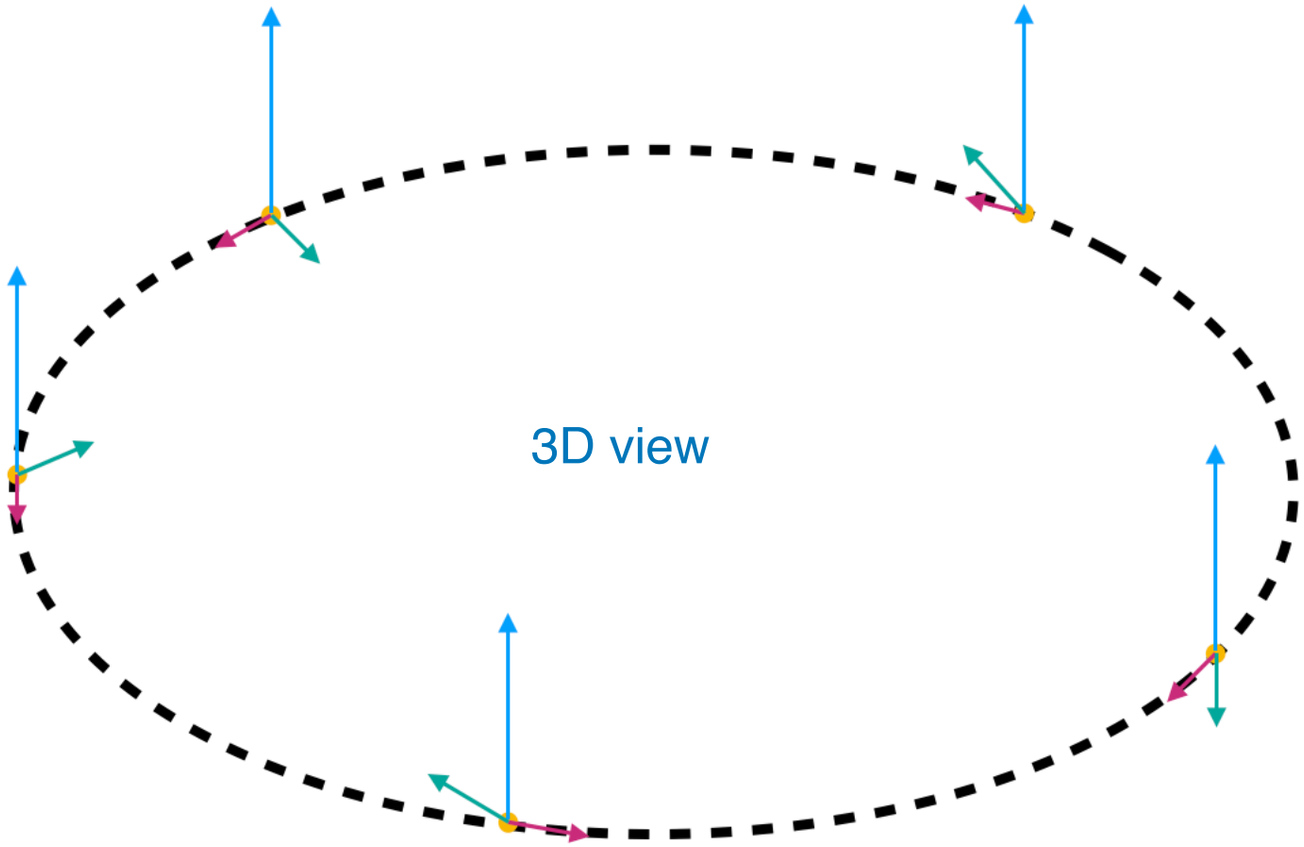
- Three main signals in g-2 experiment:
  - Increase in muon precession frequency
  - Oscillation in average vertical angle of decay e+
  - Vertical asymmetry in the average arrival position of decay e+ at detectors

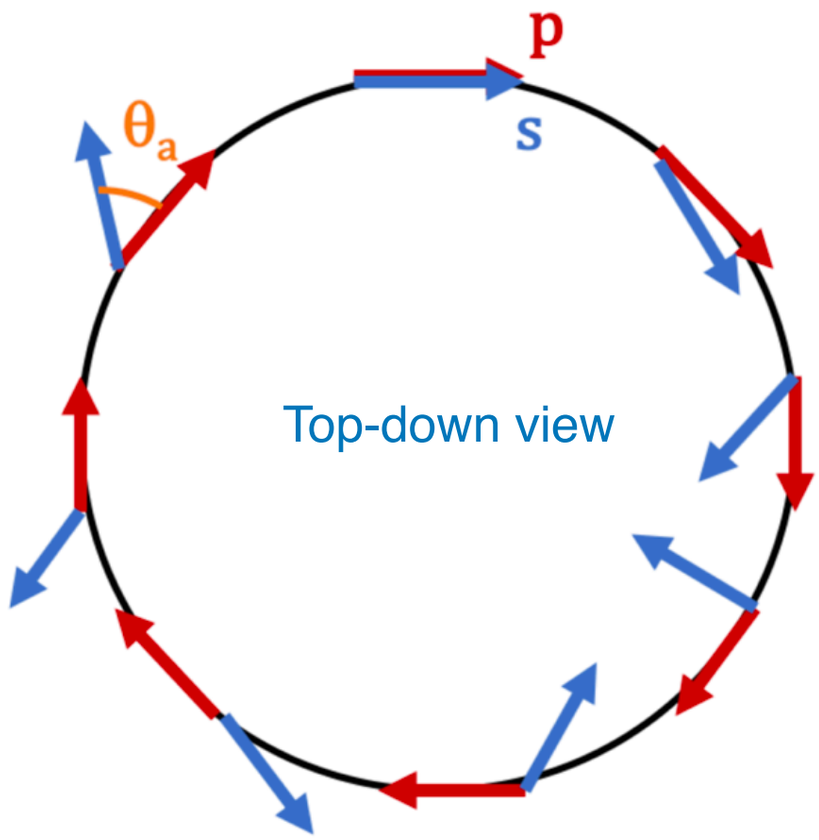
- This arises because the EDM introduces a small oscillation perpendicular to ω_a

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

Spin precession with no EDM

With no EDM, the muon spin precesses about the vertically aligned magnetic field vector in the horizontal plane





Assuming there is no radial B-field component, there is no vertical component to the spin precession

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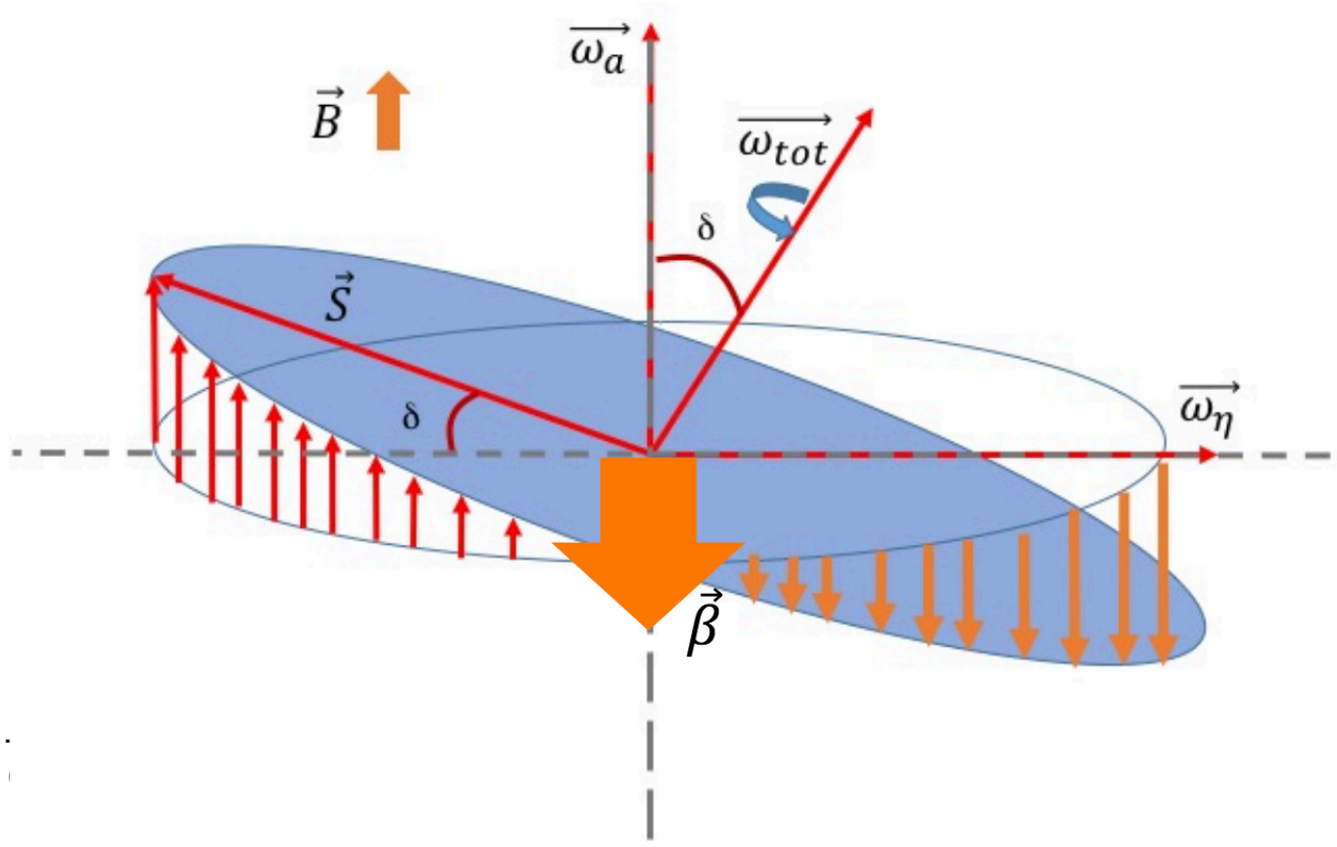
Muon spin precession with $|d_\mu| > 0$

- EDM introduces an oscillation in the radial direction (perpendicular to ω_a)
- Net effect is a tilt away from the vertical — analogous to non-zero radial field component
- Spin precesses about the tilted vector ω_{tot}, rather than ω_a



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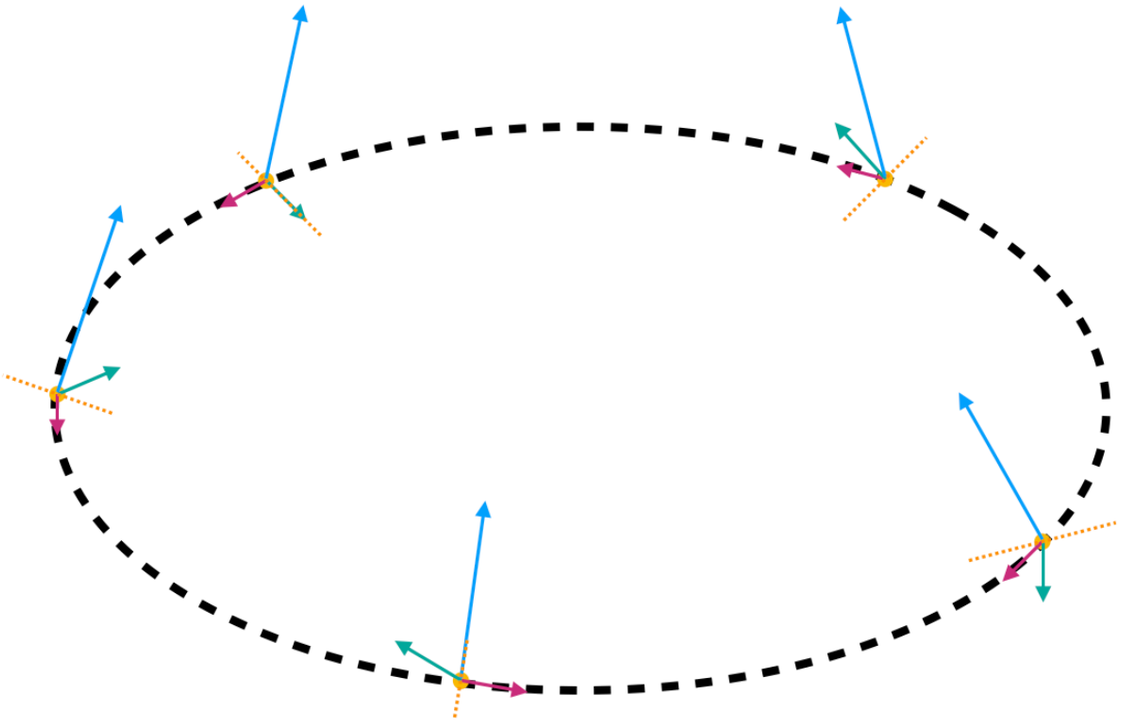
Muon spin precession with $|d_\mu| > 0$



Schematic diagram

Architectural version

Putting this in the simulation

- The muon gas gun instantaneously creates and decays muons and a random location around the ring based on an initial distribution at the inflector exit

- The initial polarization vector (at t=0) for each plane is calculated:

Putting this in the simulation

- The polarization vector is then rotated by an amount ωt about the vector ω_{tot} in each plane:

Putting this in the simulation

- The polarization vector is then rotated by an amount ω_t about the vector ω_{tot} in each plane:

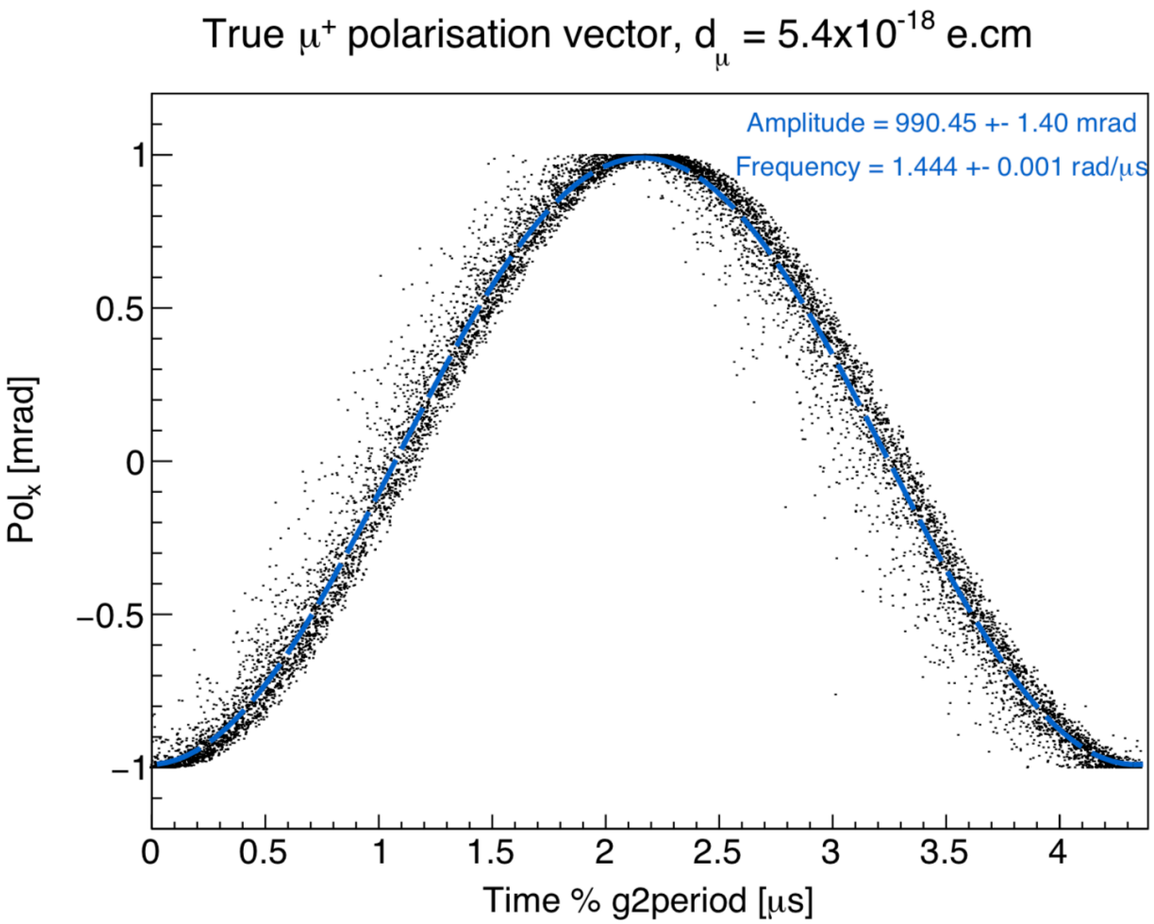
Sanity checks — does the polarization vector rotate as it should?

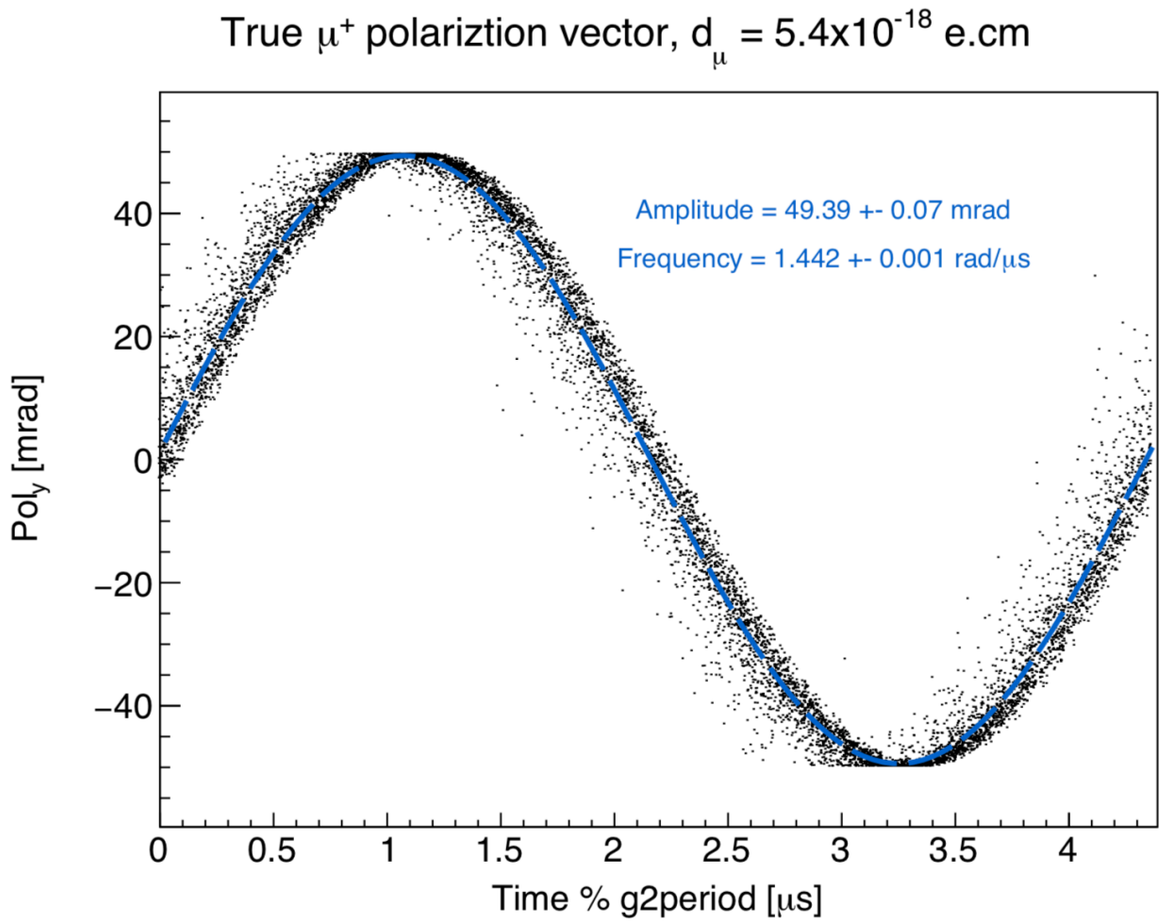
- To simulate a dataset with an EDM, the user passes in an EDM magnitude from which the precession plane tilt angle δ is calculated

- To check that this introduces an oscillation of the correct magnitude, plot the vertical component of the true polarization vector at the time of decay as a function of time for a sample of simulated muons

- Oscillation of the vertical component should be 90° out of phase with that of the radial component (ω_a)

Sanity checks — does the polarization vector rotate as it should?





- Analytical tilt for $d_\mu = 5.4 \times 10^{-18}$ e.cm: $\delta = 49.75$ mrad
- Simulated: $\delta = 49.39 \pm 0.07$ mrad
- Checked with other EDM values to verify

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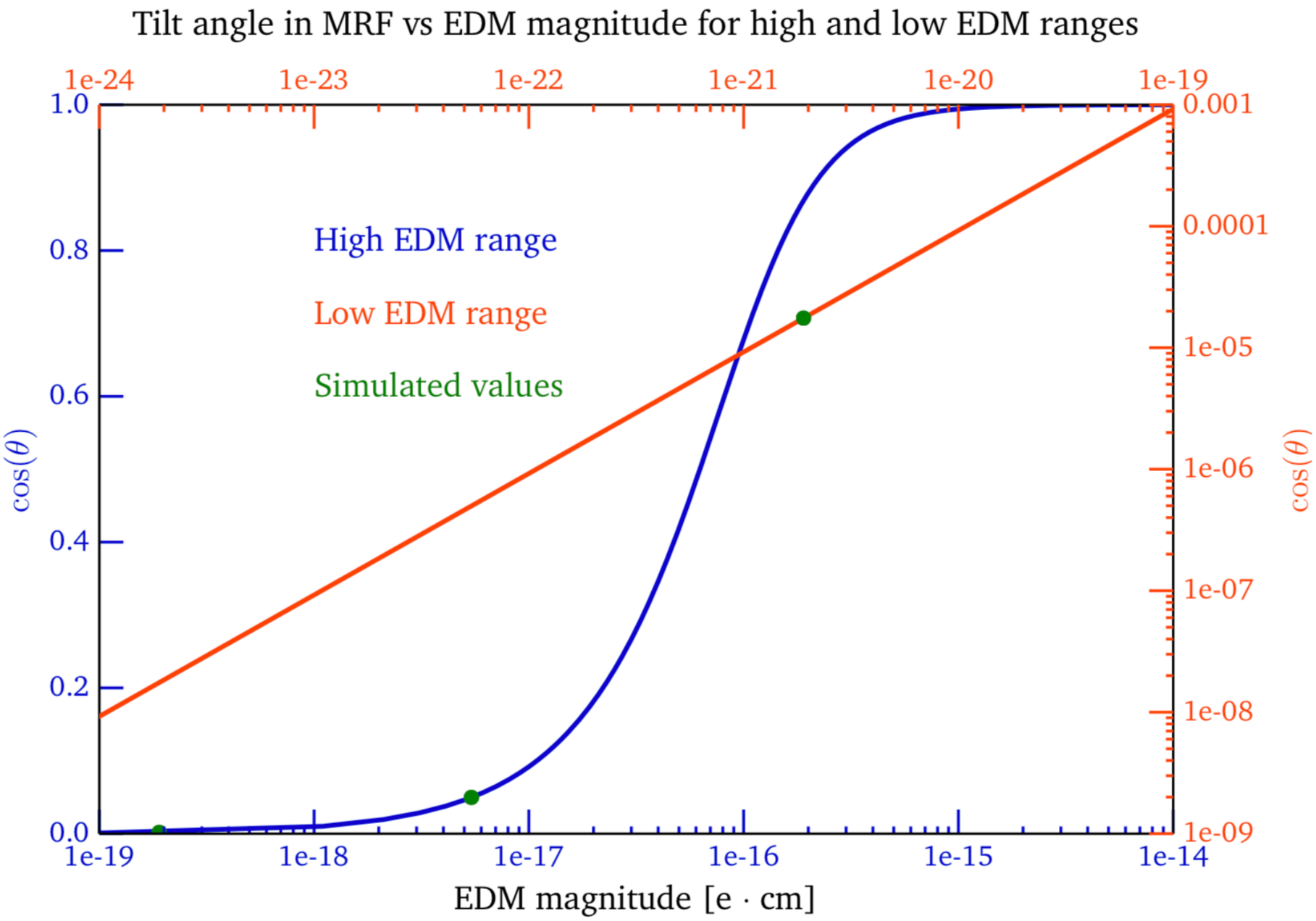
Sanity checks — does the polarization vector rotate as it should?



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What do the detectors see?

- The oscillating vertical decay angle of the positrons leads to an asymmetry in the number of positrons arriving in the top and bottom halves of the calorimeters that will vary with time:

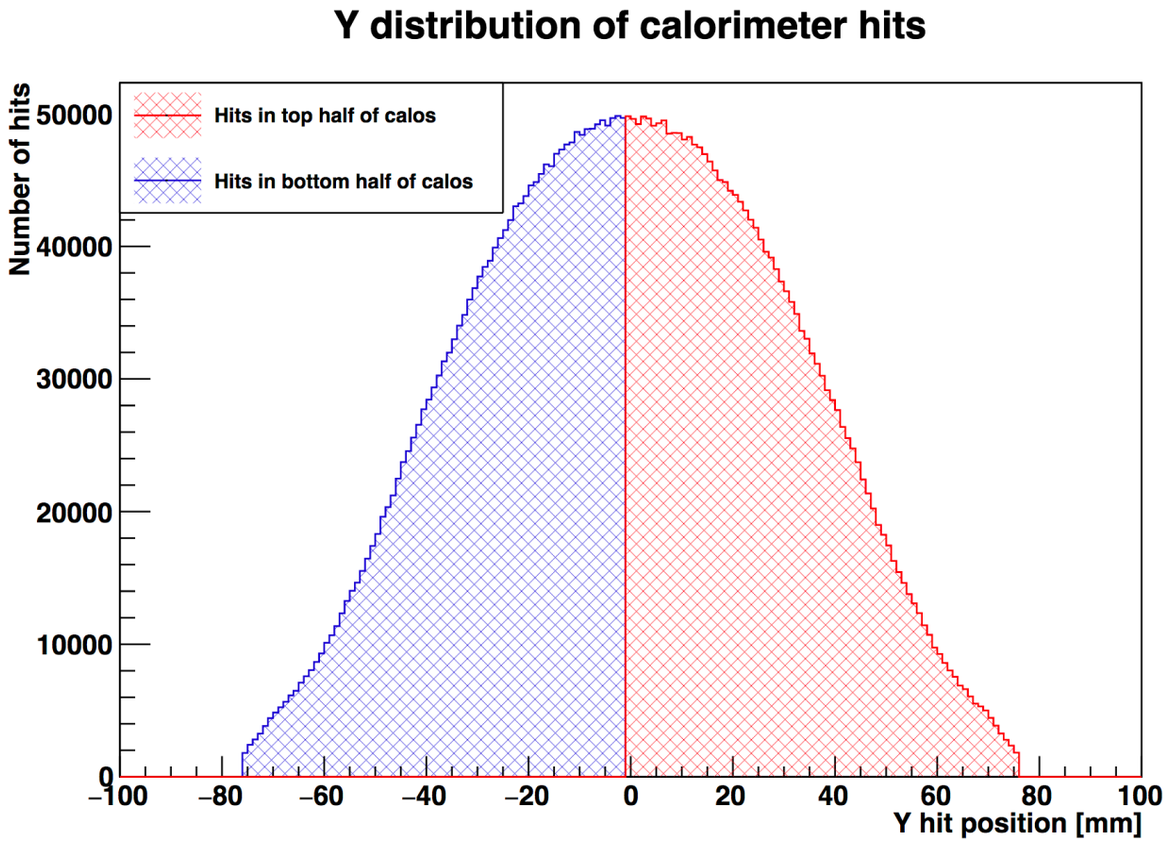
$$\frac{N(up) - N(down)}{N(up) + N(down)}$$

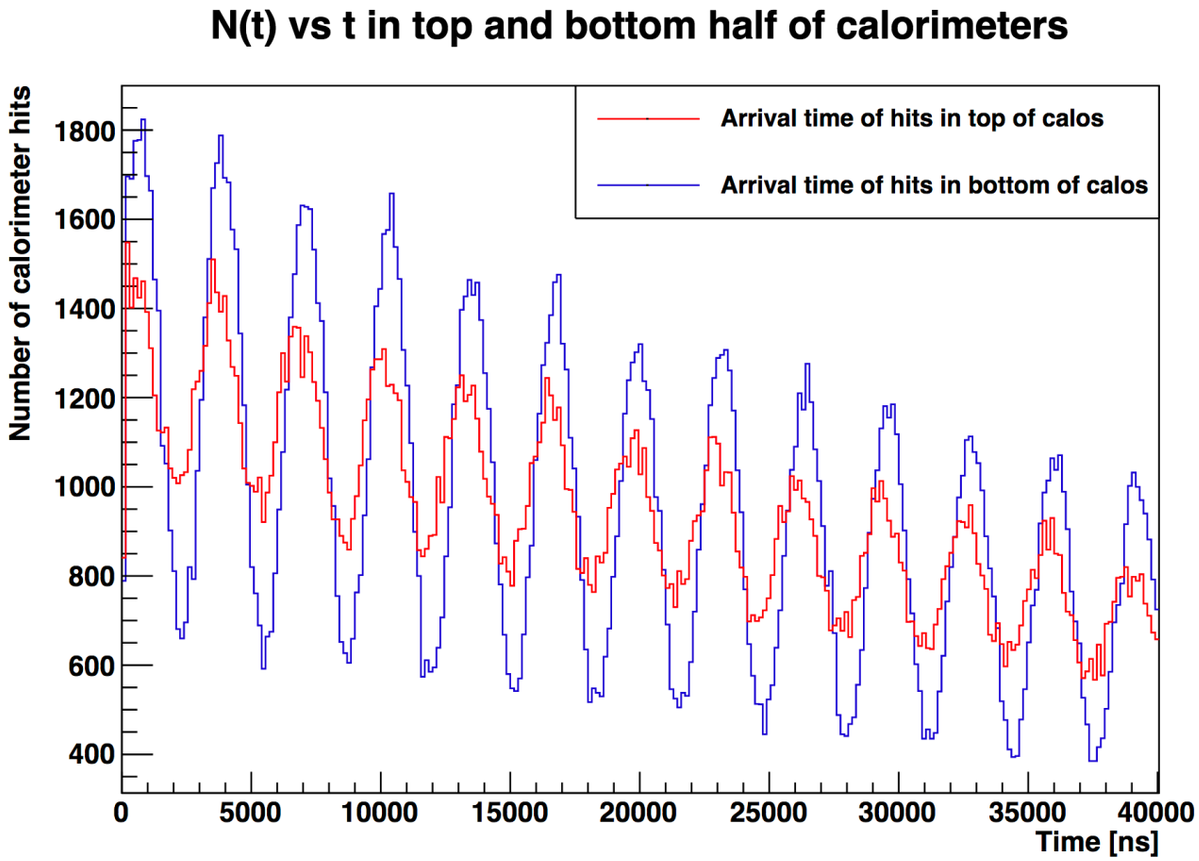
- Oscillation of this term proportional to the EDM magnitude — indirect method (not a direct measurement of the tilt angle)

- As a first test, use GEANT truth information (not reconstruction) to verify that the up-down asymmetry is observed

- Use unphysically large EDM values to test performance of simulation

What do the detectors see?





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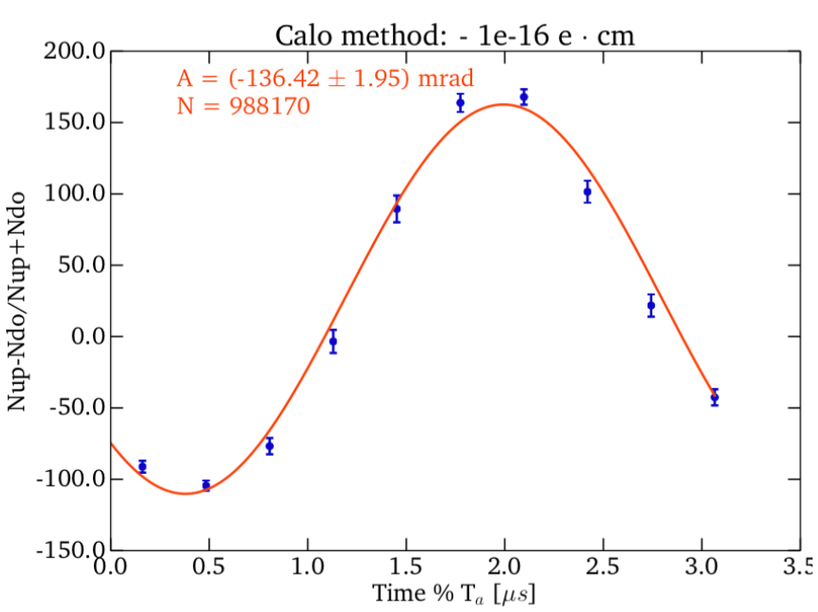
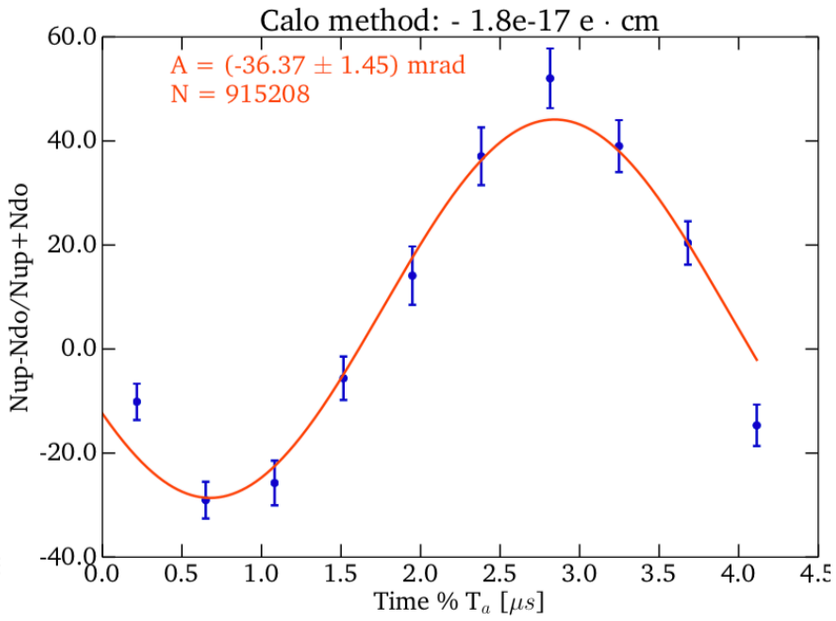
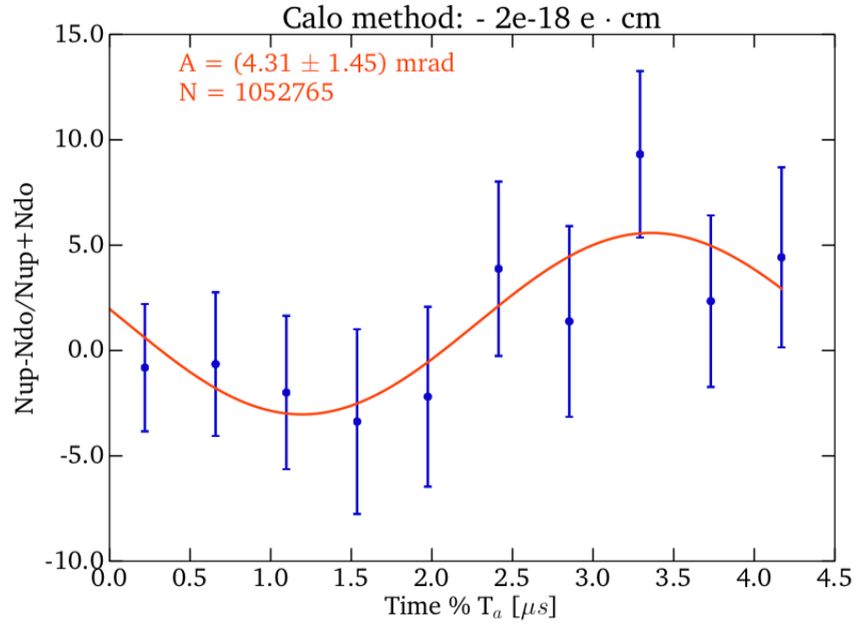
Calorimeter EDM analysis using GEANT truth

- Plot the oscillation in the asymmetry term modulo the precession period for different EDM datasets and compare with analytical values

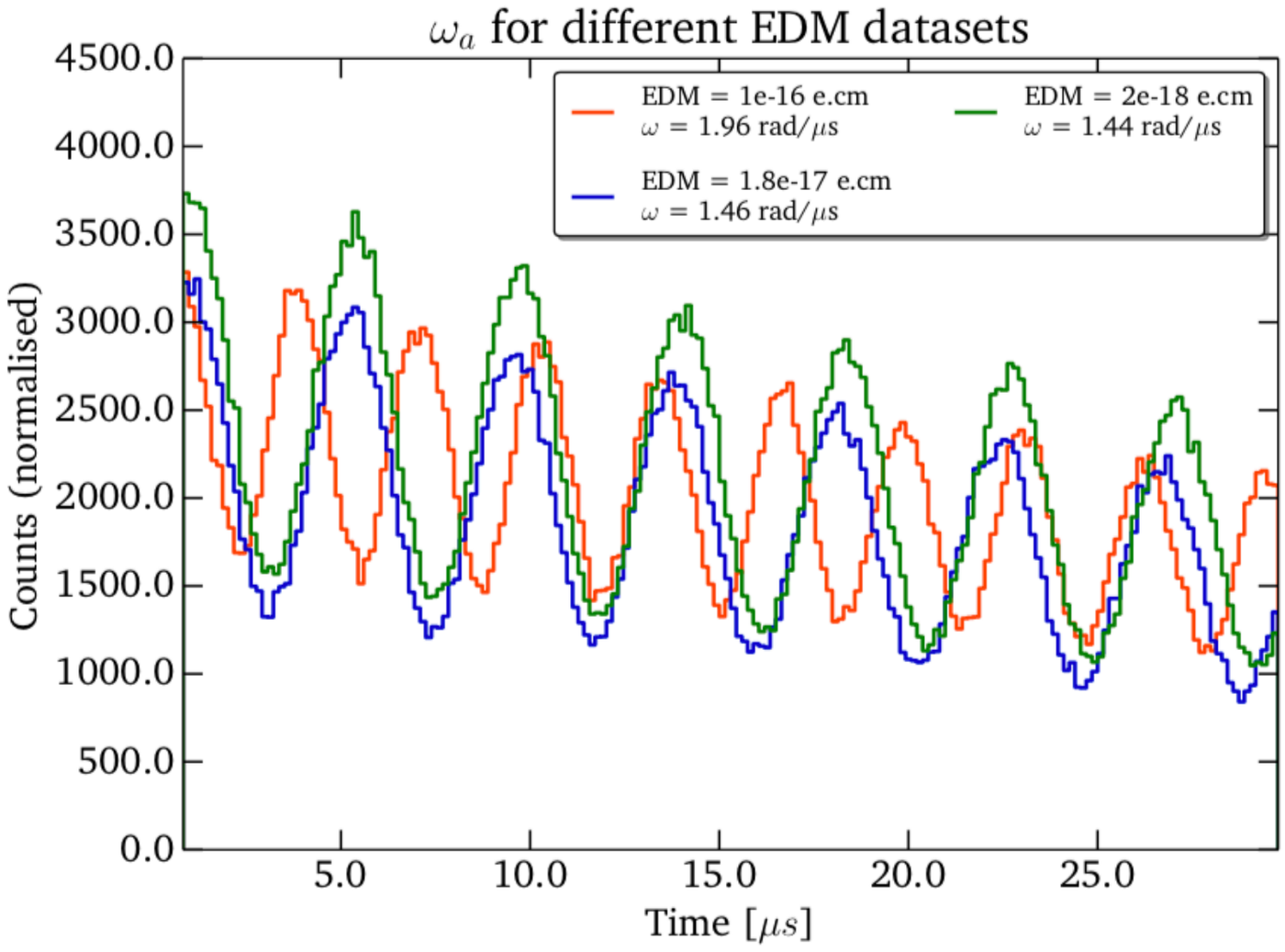






Calorimeter EDM analysis using GEANT truth

- Plot the N(t) oscillation for the different datasets —> observe expected increase in precession frequency with very large EDMs



Calorimeter EDM analysis using GEANT truth

- δ_{sim} is calculated from the measured amplitude and compared to analytical values

- Good agreement for precession frequency increase

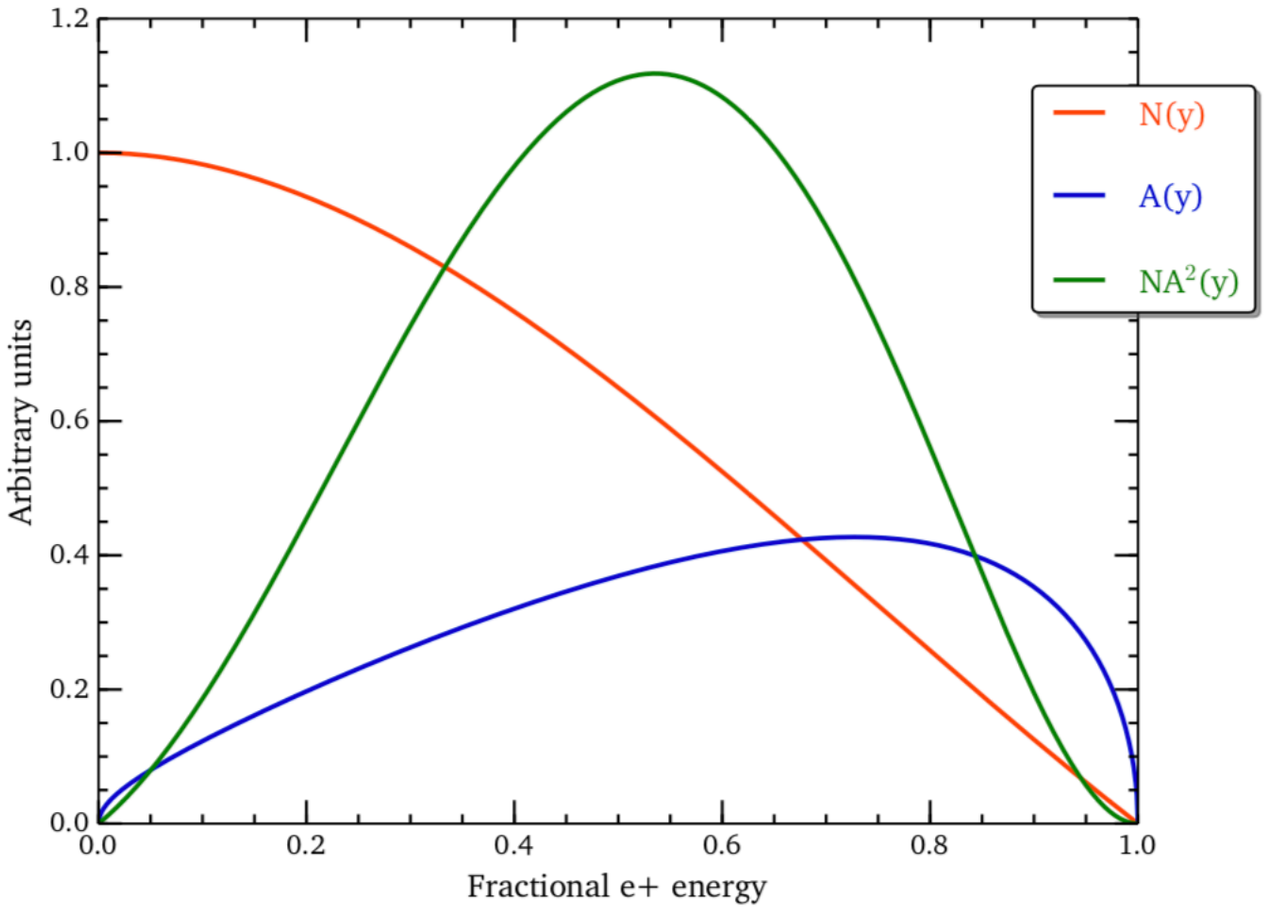
- Measured tilt angle differs from analytical angle by around 10% —> **asymmetry factor**

EDM (e.cm)	1e-36	2e-18	1.8e-17	1.0e-16
w_{theory} (rad/ns)	0.00143	0.00143	0.00145	0.00195
w_{sim} (rad/ns)	0.00145	0.00145	0.00147	0.00197
δ_{theory} (rad)	9.23e-21	0.019	0.165	0.745
δ_{sim} (rad)	-	0.002	0.018	0.075

Decay asymmetry factor

- In E821 analysis, the relationship between the tilt angle measured in the muon rest frame and that measured at the detectors was determined in simulation —> accounted for asymmetry factor

- Can we understand the asymmetry better here?



- Medium-energy positrons carry the strongest EDM signal

- The BNL analysis used only e+ in the 1.2 - 1.8 MeV range

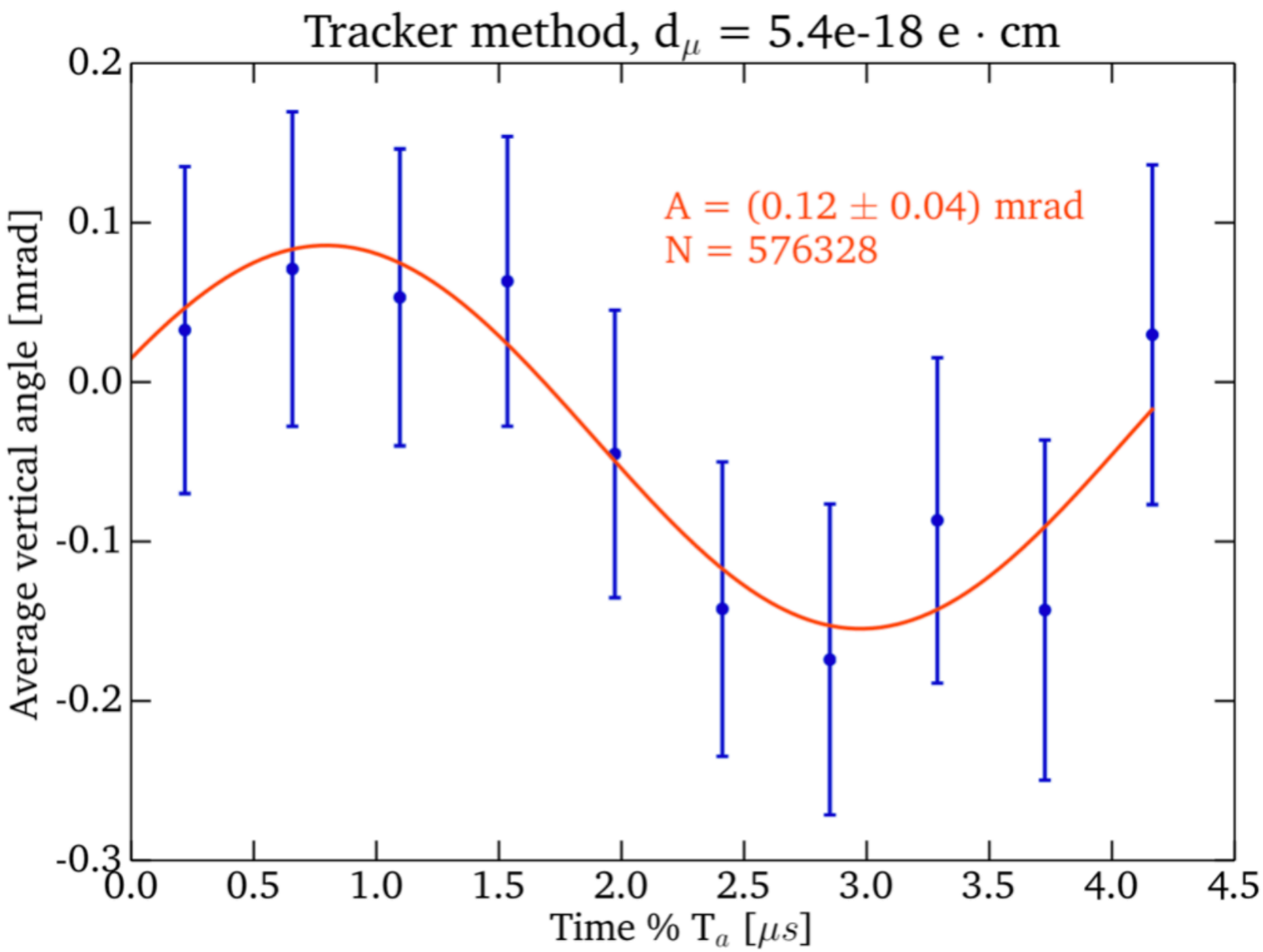
- Does the momentum cut applied affect the asymmetry factor?

Tracker-based analysis

- To investigate this, use the tracker data
- Trackers can measure the positron decay angle directly —> plot as a function of time to see EDM oscillation
- Generated a dataset with d_μ = 30 x BNL and imposed a range of symmetric momentum cuts on the data
- No systematic effects included — assumed a ‘perfect world’ with no significant radial field component and no detector misalignment
- Compare measured oscillation amplitude for the different cuts

Tracking detector studies

- No momentum cuts



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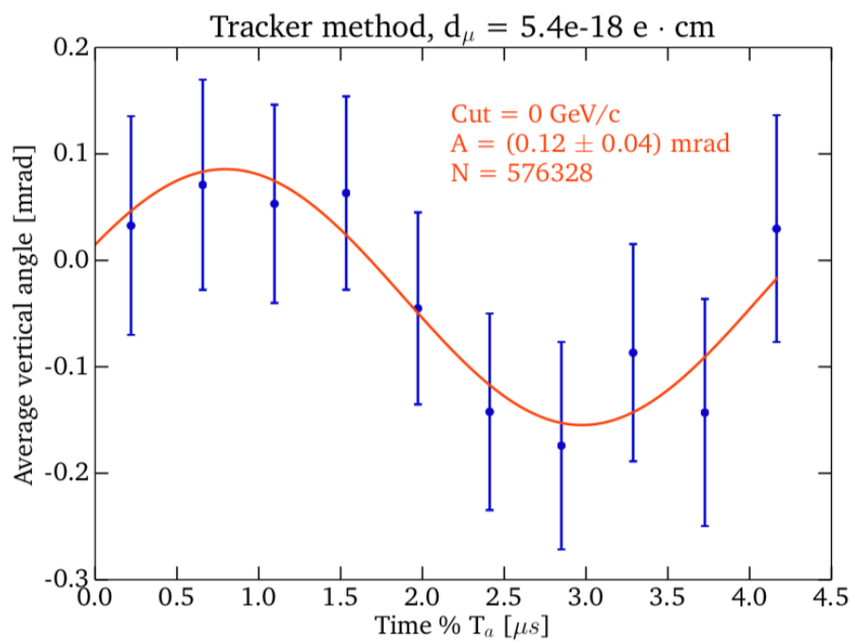
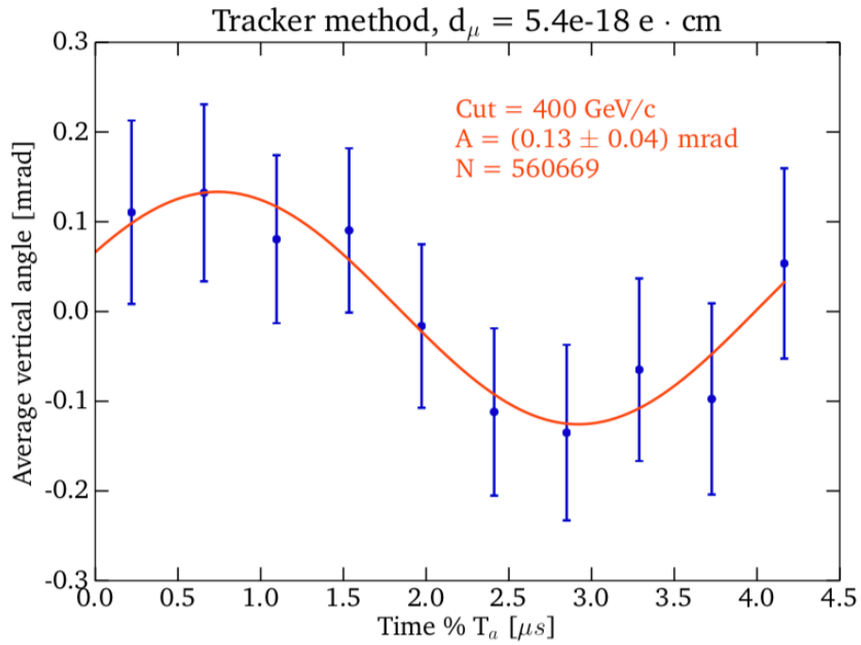
Tracking detector studies — momentum cuts

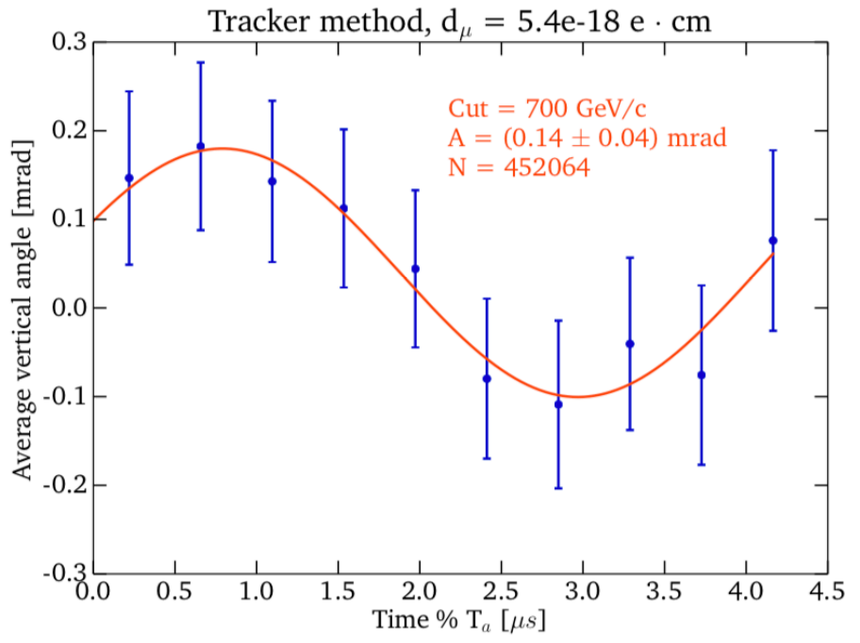
- Does the measured amplitude depend on the momentum cut applied?



(a) No momentum cut



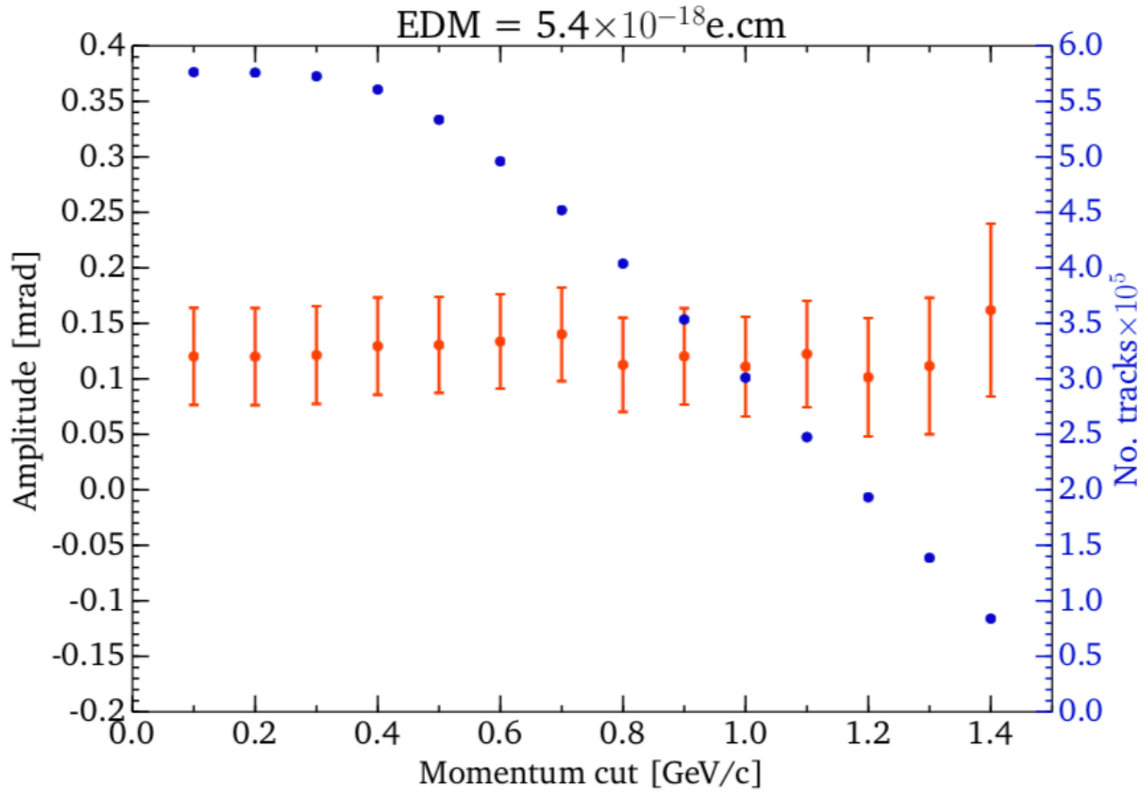
(b) 0.4 GeV/c < $|p_{e^+}|$ < 2.7 GeV/c

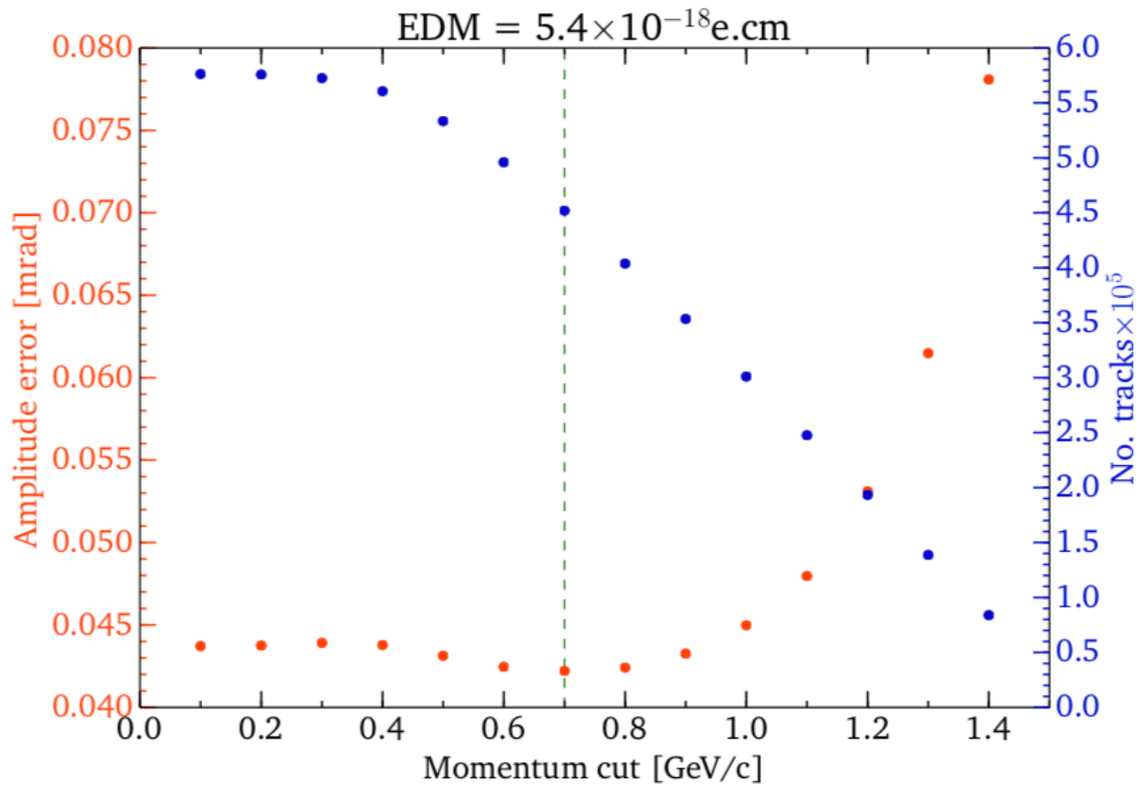


(c) 0.7 GeV/c < $|p_{e^+}|$ < 2.4 GeV/c

Tracking detector studies — momentum cuts

- Plot the measured amplitude and its measurement error vs applied momentum cut and compare to number of tracks for that sample





- Measured amplitude does not change significantly, but error on measurement doesn't start increasing as soon as N starts decreasing

- Suggestion that mid-range energy cuts are more powerful? Possibly, but a higher statistics sample required to say this with confidence

Further simulation requirements

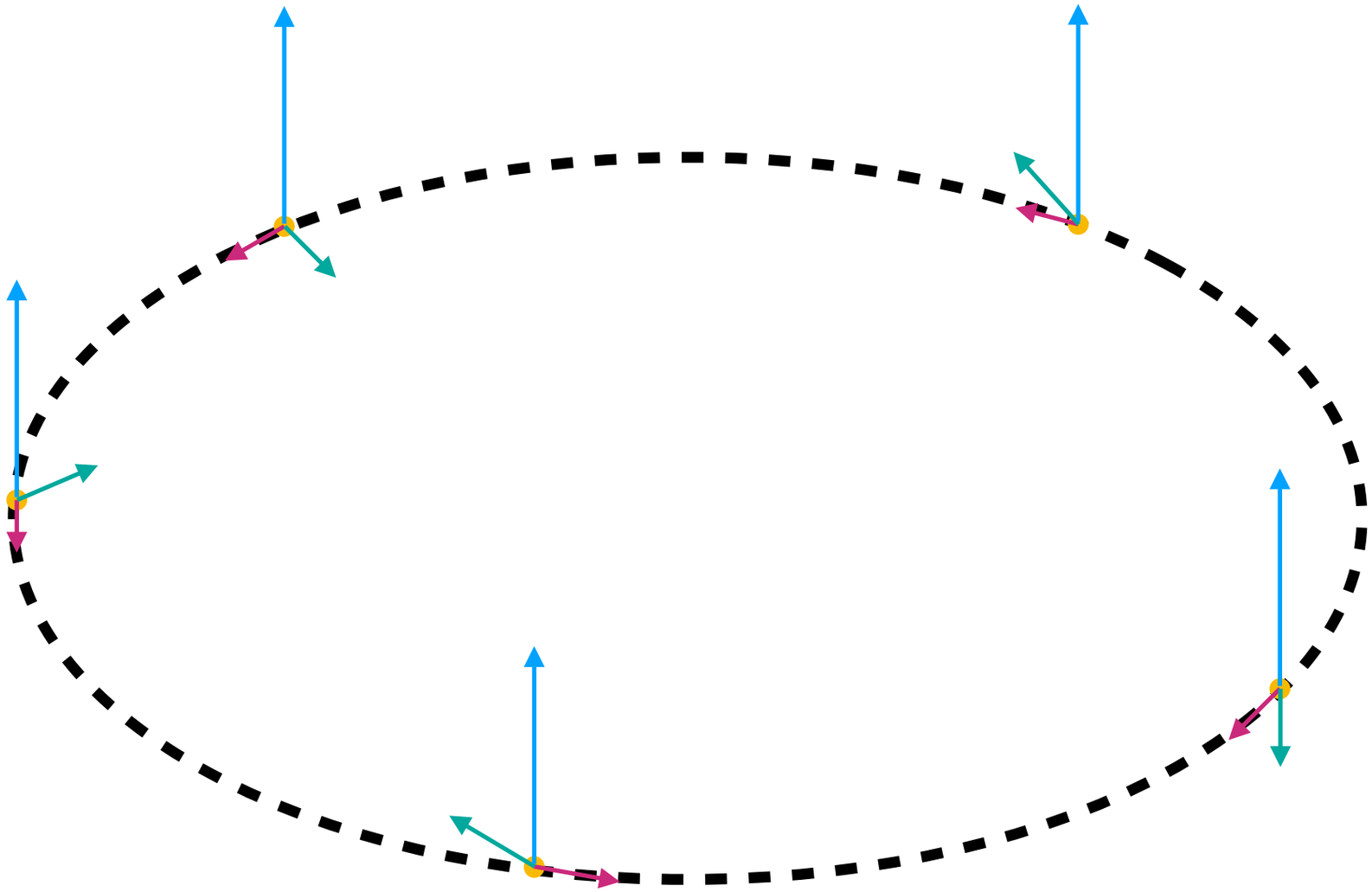
- The simulation is currently being improved to include more realistic effects
- Datasets can be generated with certain features e.g. radial magnetic field, misaligned detectors, to study effect of these sources of uncertainty
- Example study: impose some detector misalignment by moving the tracker modules slightly and see how this effects measured EDM
- Studies are ongoing

Conclusions

- EDM is simulated using a ‘gas gun’ for quick generation of large datasets
- Verified that the simulation produces the expected oscillations when truth data considered
- Tracking detector based sensitivity study underway —> more advanced simulation required to study effect of detector misalignment
- Different momentum cuts have been considered to try to maximize statistical sensitivity and parameterize asymmetry factor

Muon precession

With no EDM, the muon spin precesses about the vertically aligned magnetic field vector



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