# The EDM at the g-2 experiment

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# Physics motivation

Fundamental particles can also have an EDM defined by an equation similar to the MDM:

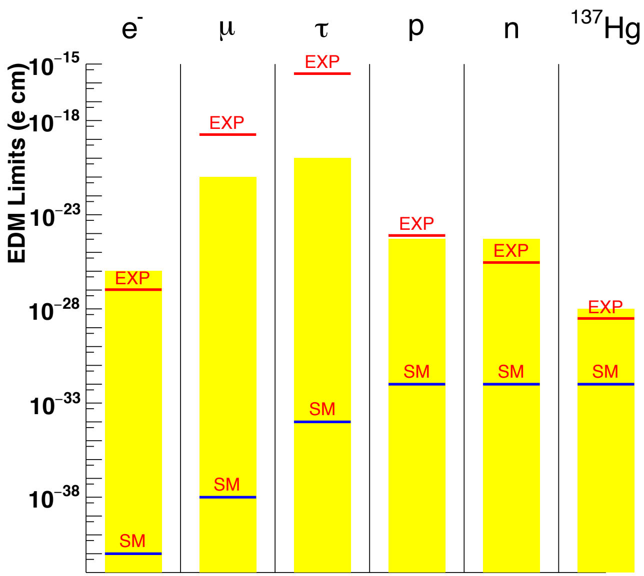
$$\vec{d} = \eta \frac{Qe}{2mc} \vec{s} \qquad \vec{\mu} = g \frac{e}{2mc} \vec{s}$$

Defined by the Hamiltonian:

$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

→ **Provides an additional source of CP violation**

| | E | B | μ or d |
|---|---|---|---|
| P | - | + | + |
| C | - | - | - |
| T | + | - | - |




Standard scaling : $\frac{d_\mu}{d_e} \sim \frac{m_\mu}{m_e}$

$d_e$ limits imply $d_\mu$ scale of $10^{-25}$ e•cm

**But some BSM models predict non-standard scalings**

(quadratic or even cubic)

***The muon is a unique opportunity to search for an EDM in the 2nd generation***

# The effect of an EDM

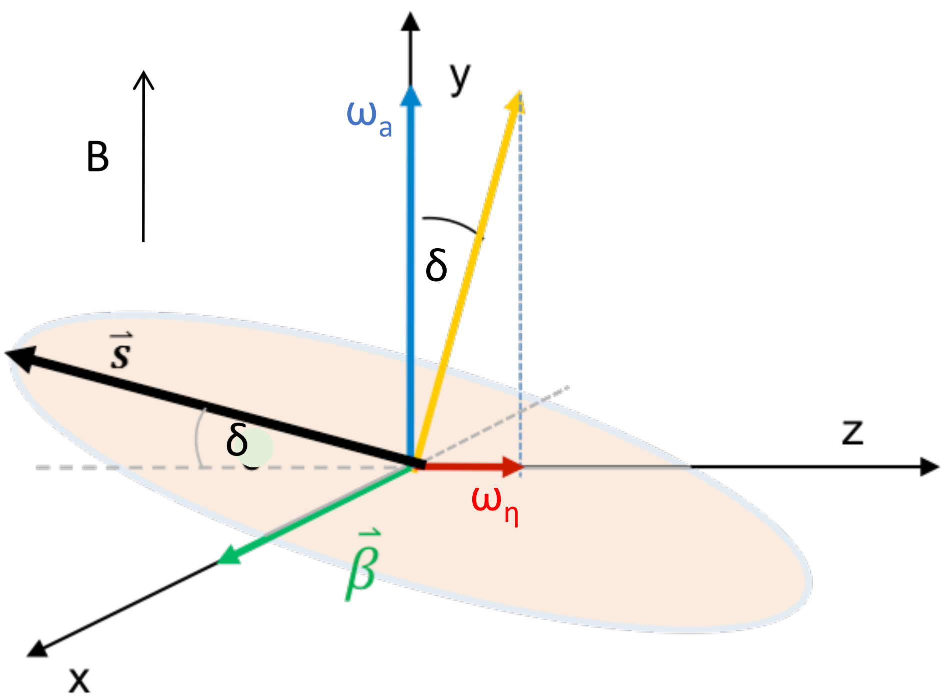
**If an EDM is present the spin equation is modified to:**

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

Dominant term

Run at the "magic momentum"

$\gamma_{magic} = 29.3$, $p_{magic} = 3.094$ GeV




**An EDM tilts the precession plane towards the centre of the ring**

→ Vertical oscillation ($\pi/2$ out of phase)

$$\omega_{a\eta} = \sqrt{\omega_a^2 + \omega_\eta^2} \qquad \delta = \tan^{-1}\left(\frac{\eta\beta}{2a}\right)$$

Assuming the motional field dominates

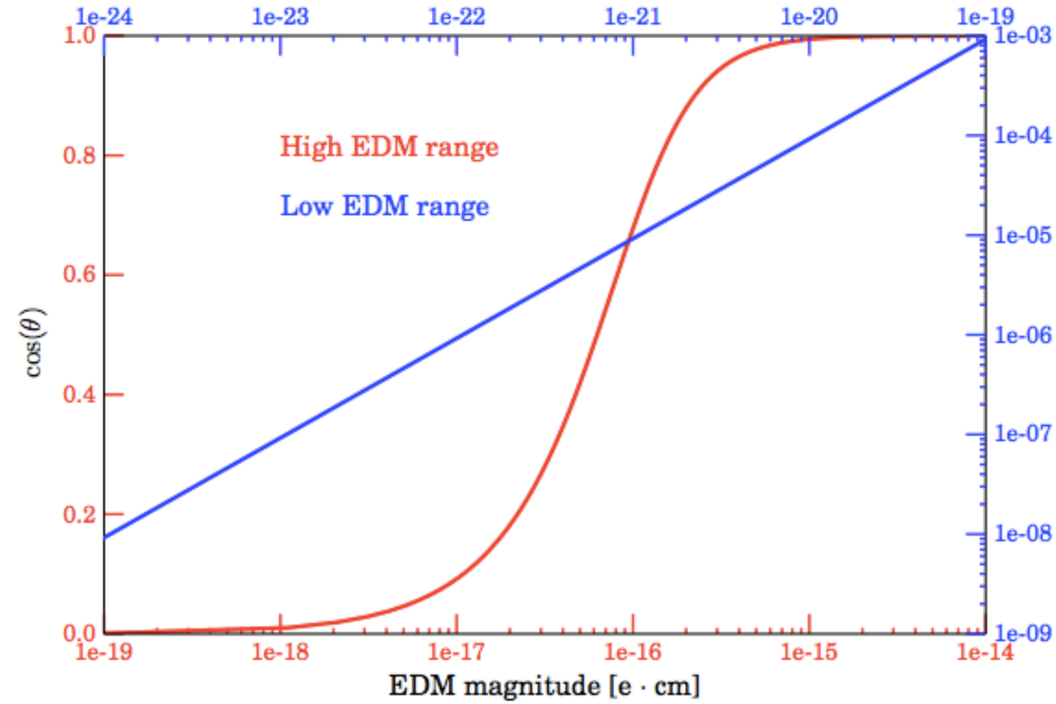
Expect tilt of ~mrad for $d_\mu \sim 10^{-19}$

**An EDM also increases the precession frequency**

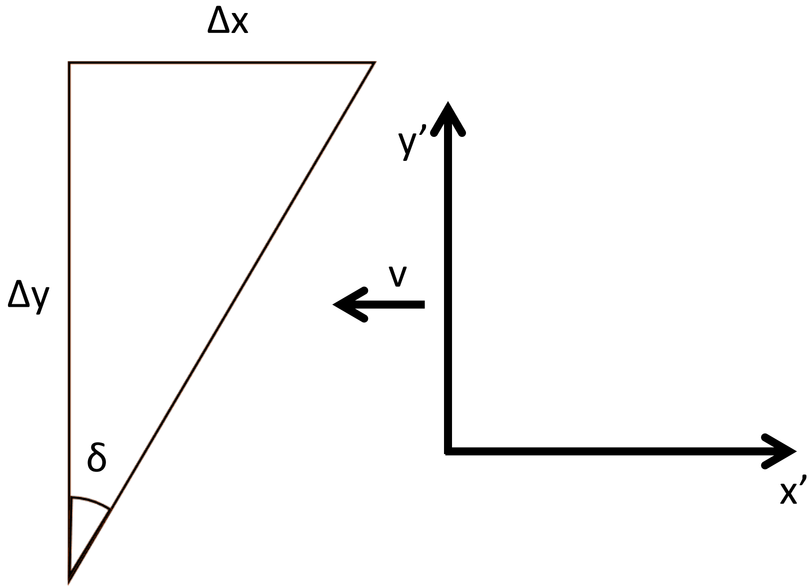
# The decay angle

***The tilt of the precession plane is determined by the size of the EDM***

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



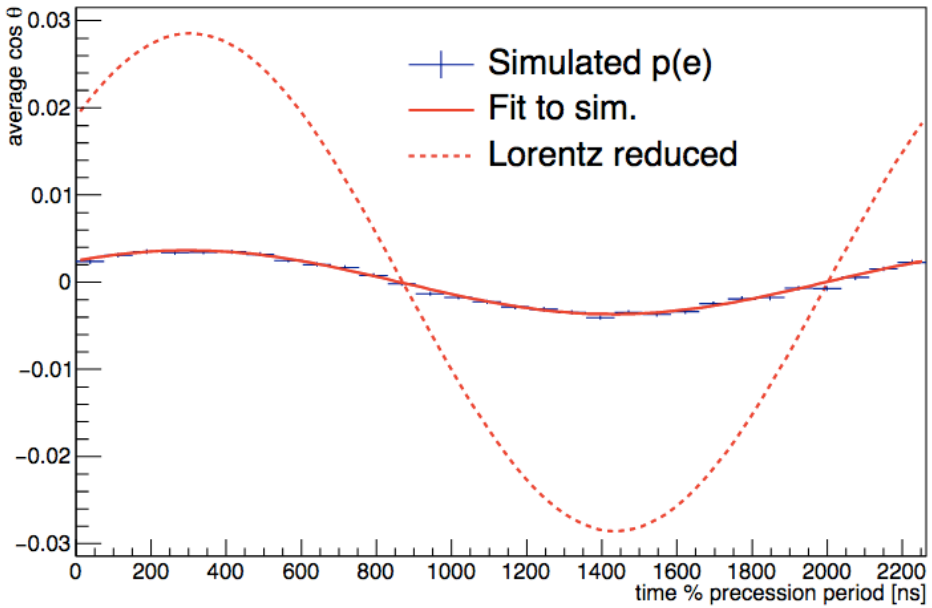

However, the precession angle is reduced due to the Lorentz boost :




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

(neglecting the vertical momentum component)

# The decay asymmetry



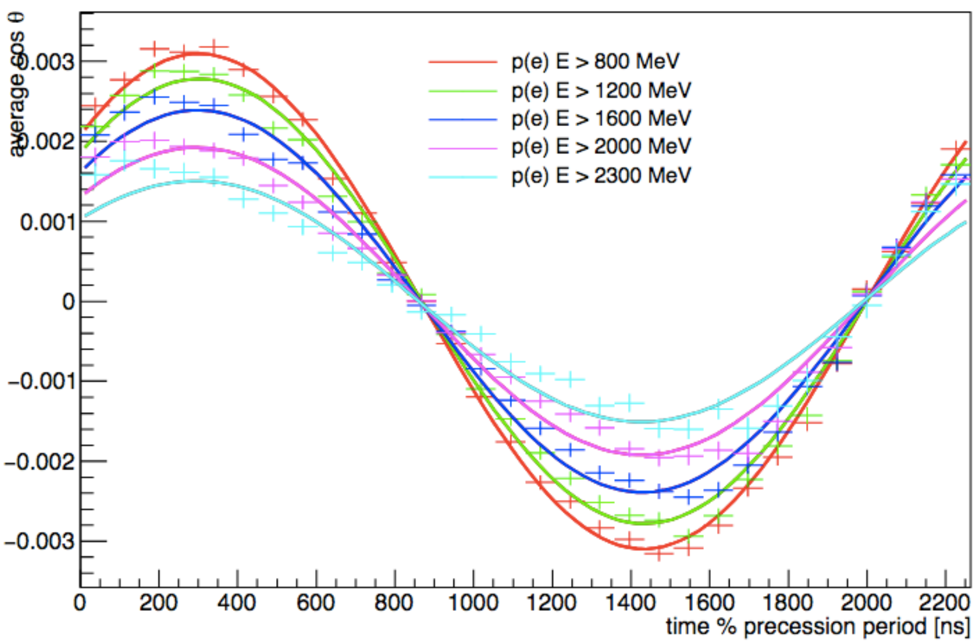

**The measured decay asymmetry is further reduced because :**

- The positrons are not always emitted along the spin direction
- Detector acceptance

**The lower momentum positrons have a larger decay angle asymmetry**

However :

- Lower energy positrons contain less information about the muon spin direction
- The statistics drop off at lower energies



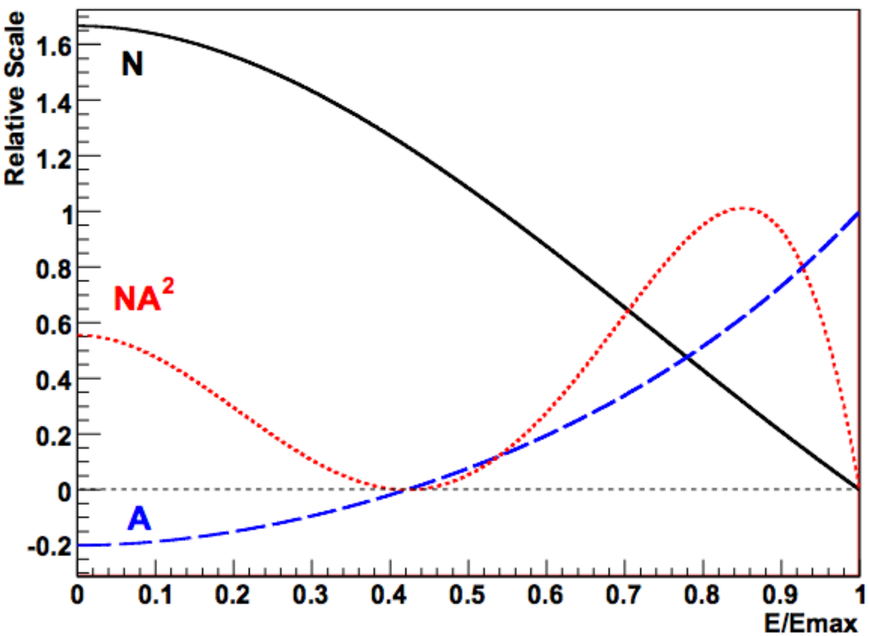
# Measuring the EDM

***The statistical uncertainty is inversely proportional to $NA^2$***

Number of muons

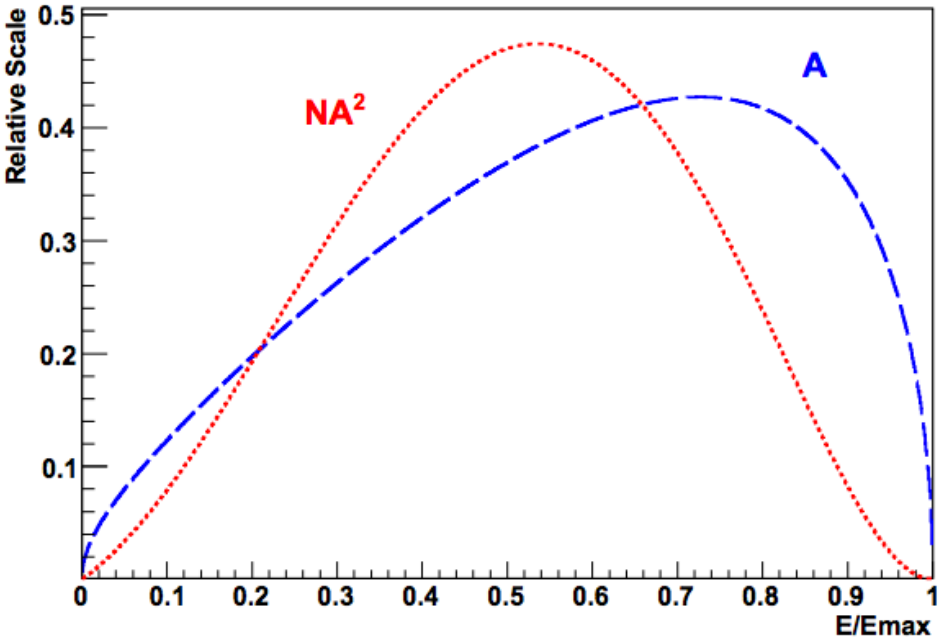
Asymmetry

G-2 asymmetry




Get the highest values of $NA^2$ towards the higher end of the energy spectrum

EDM asymmetry




Sensitive over a broad range of energies around ~1.5 GeV

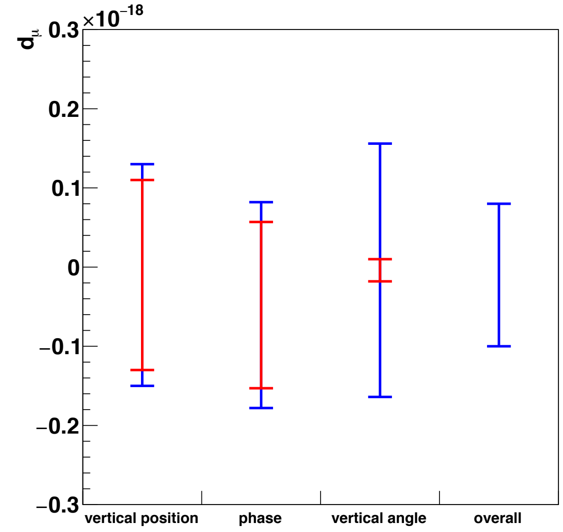
$E_{max}$ ~ 3.1 GeV

# Measuring the muon EDM

***Several methods were used to measure the EDM at the g-2 experiment at BNL (E821)***

The EDM can be measured

- **Indirectly** by comparing the measured value of $\omega_a$ to the SM prediction
- **Directly** by looking for a tilt in the precession plane




For the direct method 3 techniques were used at E821:

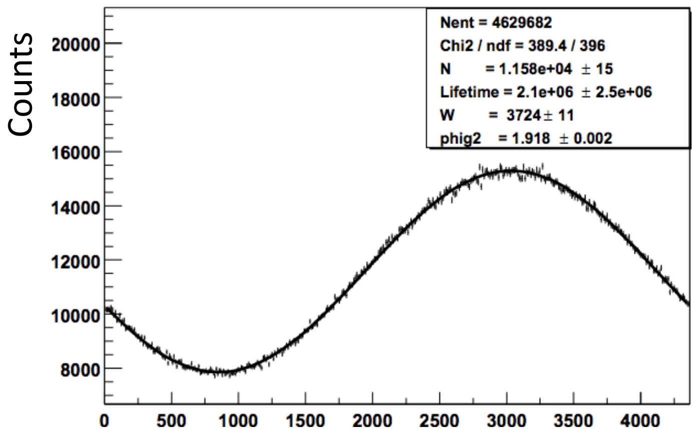
- **Phase as a function of vertical position**
  - Systematics dominated
  - Provides a useful cross check
- **Vertical position oscillation as a function of time**
  - Again systematics dominated
- **Vertical decay angle oscillation as a function of time**
  - Statistics dominated
  - Easiest improvement at E989

***The following slides will discuss each of the methods, their uncertainties and possible improvements***

# The EDM at BNL – vertical decay angle

*Look for an oscillation in the vertical decay angle of the positrons*

## Plot the number oscillation as a function of time modulo the precession period



Time modulo precession period (ns)

Minimises period disturbances at other frequencies

Use the period calculated from the $\omega_a$ fit

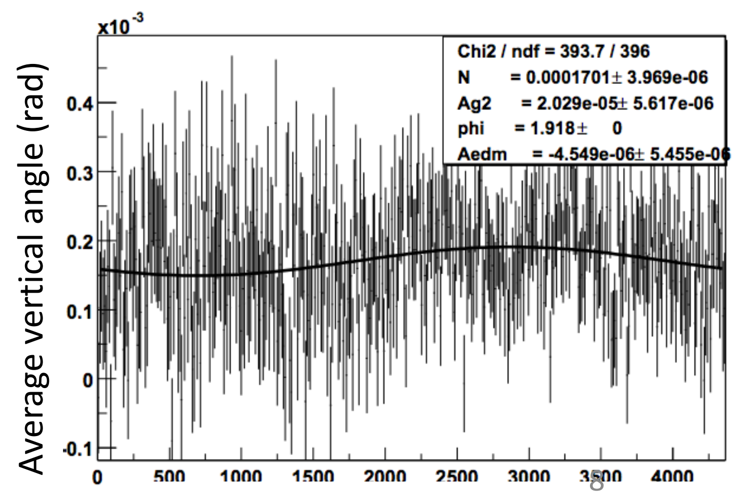
Fit to calculate the phase : $N(t) = e^{-t/\tau_e}\left(N_0 + W\cos(\omega t + \boxed{\Phi})\right)$

## Plot the average vertical decay angle as a function of time modulo the precession period

Fit (fix phase from above):

$$\theta(t) = M + A_\mu \cos(\omega t + \Phi) + A_{EDM} \sin(\omega t + \Phi)$$

EDM oscillation comes in π/2 out of phase from the MDM



Time modulo precession period (ns)

# Decay angle uncertainties

Main systematic uncertainties to be considered for this method:

## Radial Magnetic field:

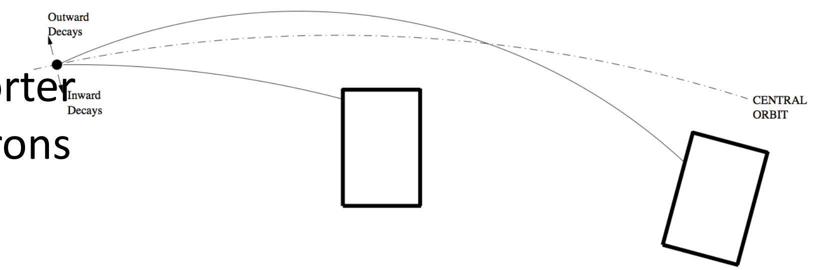
Would cause a tilt in the precession plane

$$\vec{\omega}_a = -\frac{Qe}{m} a\vec{B}$$

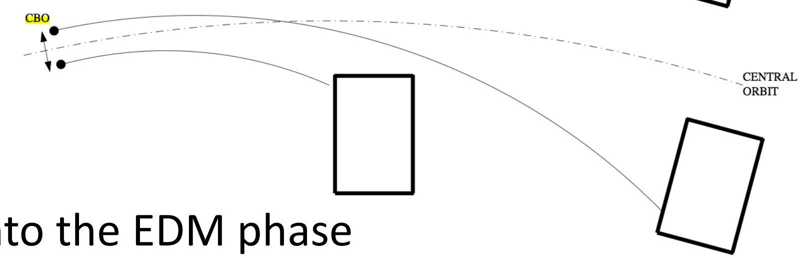
## Detector acceptance:

Inward going positrons travel a shorter distance than outward going positrons

→ narrower beam spread




## Horizontal CBO oscillations




## Phase or period errors:

Could mix the number oscillation into the EDM phase

| Systematic error | Vertical oscillation amplitude ($\mu$rad lab) | Precession plane tilt (mrad) | False EDM generated $10^{-19}$ ($e\cdot$ cm) |
|---|---|---|---|
| Radial field | 0.13 | 0.04 | 0.045 |
| Acceptance coupling | 0.3 | 0.09 | 0.1 |
| Horizontal CBO | 0.3 | 0.09 | 0.1 |
| Number oscillation phase fit | 0.01 | 0.003 | 0.0034 |
| Precession period | 0.01 | 0.003 | 0.0034 |
| Totals | 0.44 | 0.13 | 0.14 |

E821:

Oscillation amplitude : $(-0.1 \pm 4.4) \times 10^{-6}$ rad

→ $d_\mu = (-0.04 \pm 1.6) \times 10^{-19}$

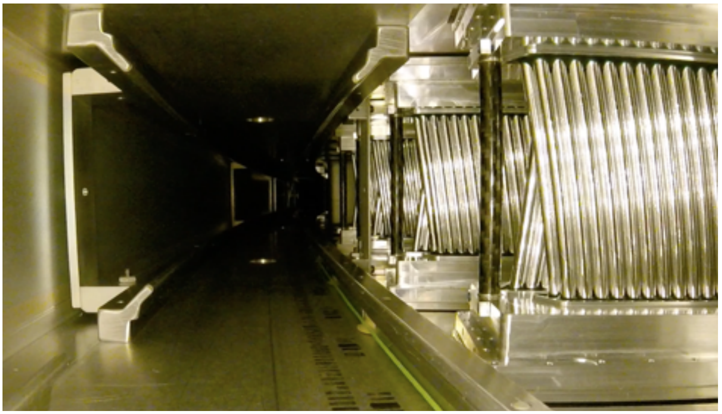
e•cm

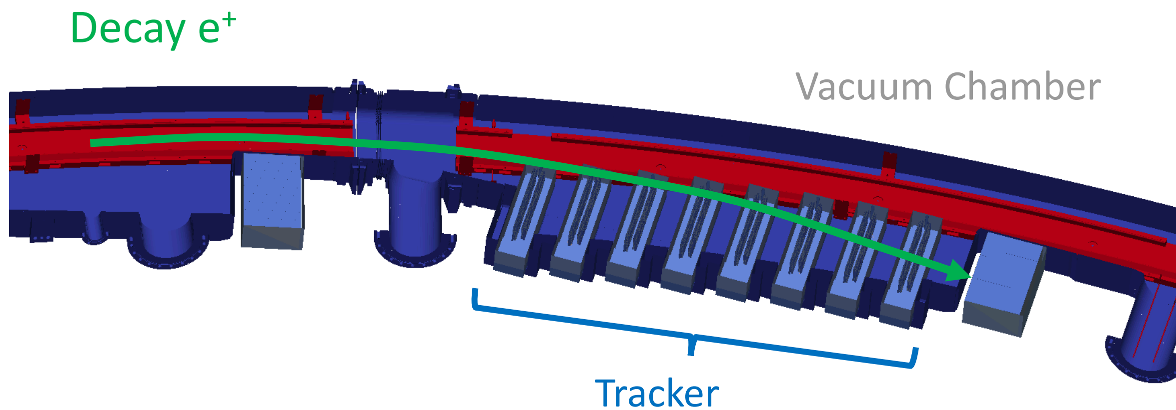
→ $|d_\mu| < 3.2 \times 10^{-19}$ e•cm (95% C.L)

***Dominated by the statistical error***

# The measurement at FNAL

***The new experiment has tracking detectors at 2 locations around the ring with greater acceptance than at BNL***

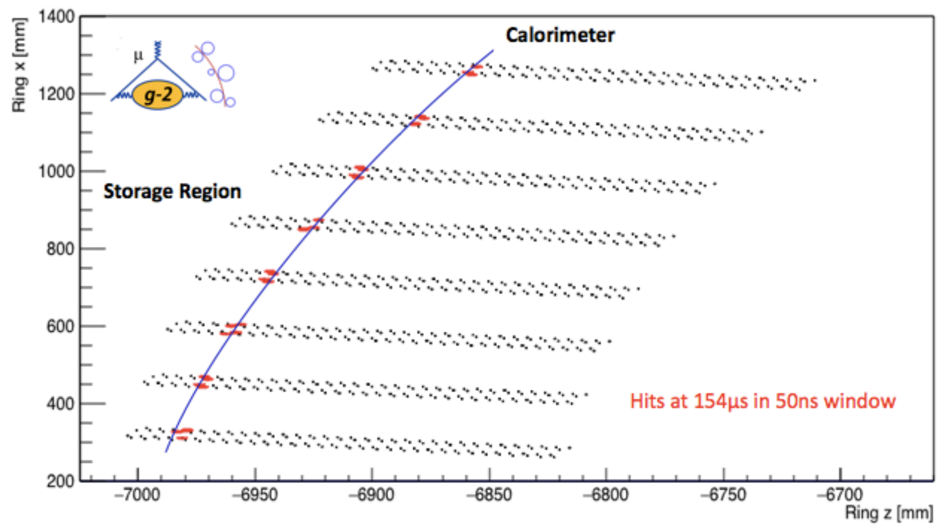





Expect O(1000) times better statistics than at BNL

**Reduce error by 1 order of magnitude quickly, approaching 2 orders of magnitude by the end**

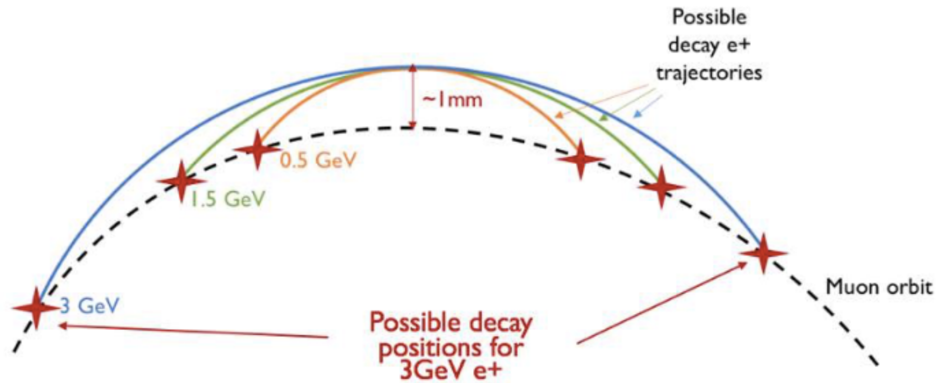
But need careful control of the systematic errors



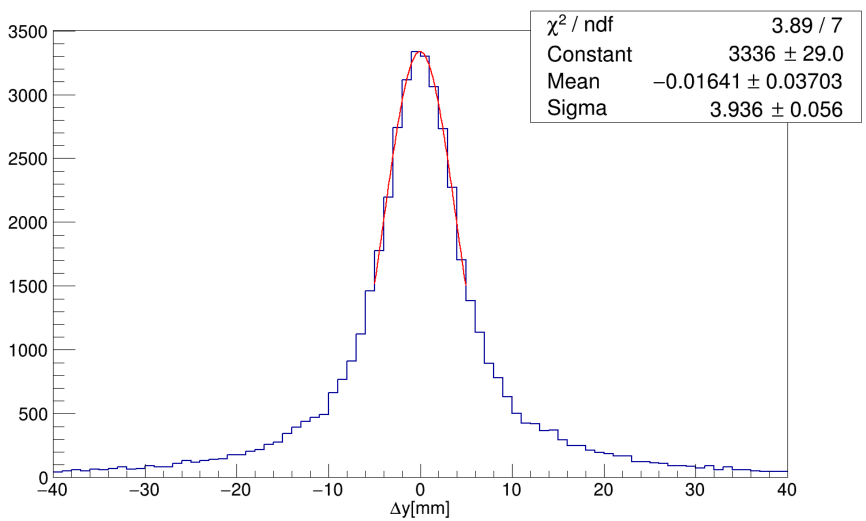
# The measurement at FNAL

***The tracks are expolated back to the point of tangency as an approximation of the decay position***

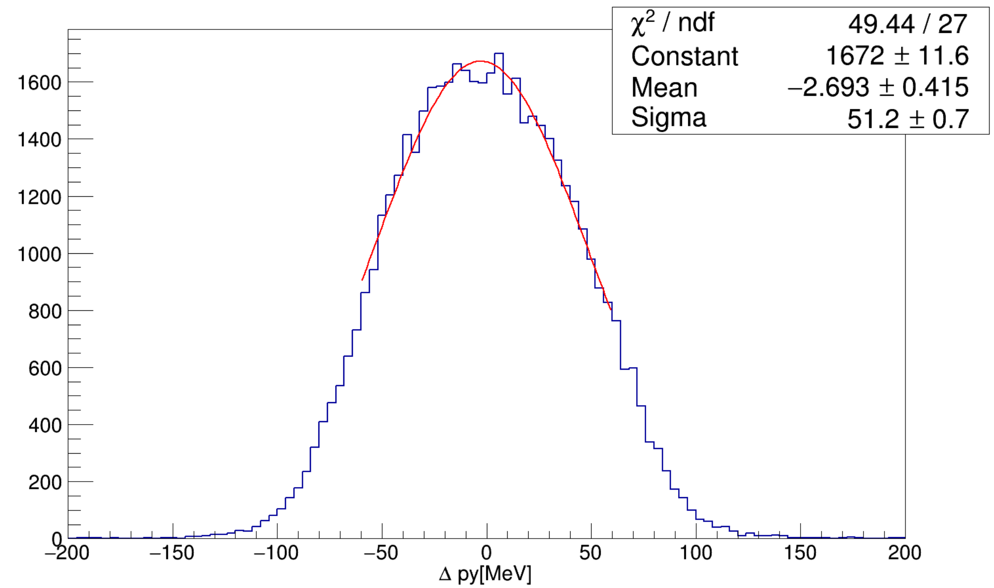
This introduces ~1mm offset in the radial position but has a much smaller impact on the vertical position and momentum




truth - reco vertical position



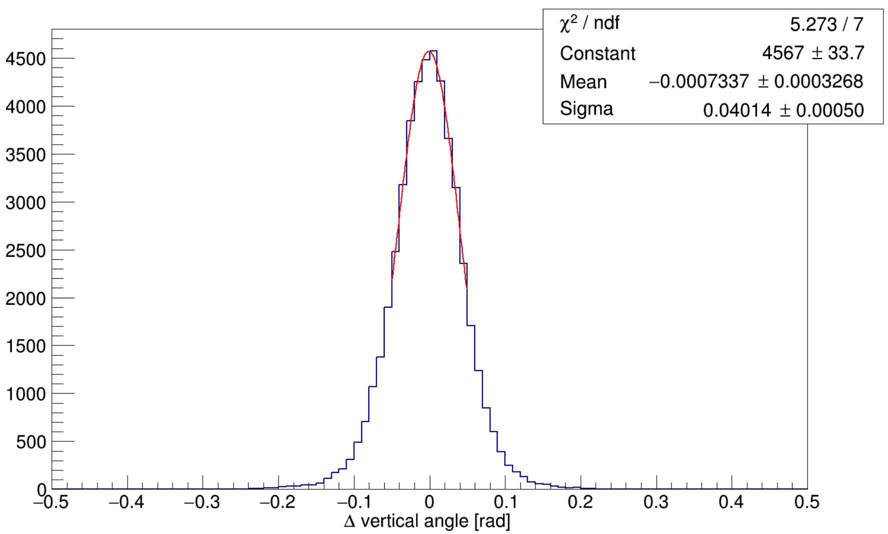

truth - reco vertical momentum



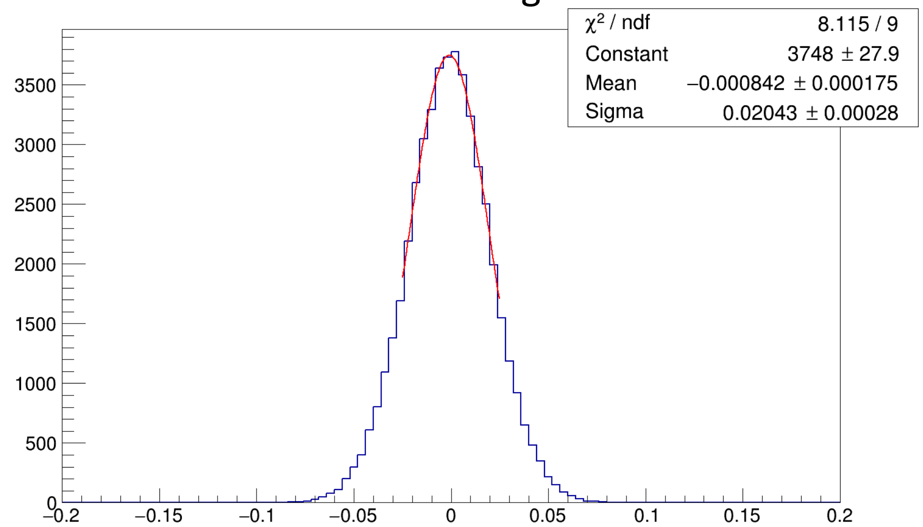
# The measurement at FNAL

***For the EDM measurement it is the vertical decay angle that is necessary***

truth - reco vertical angle



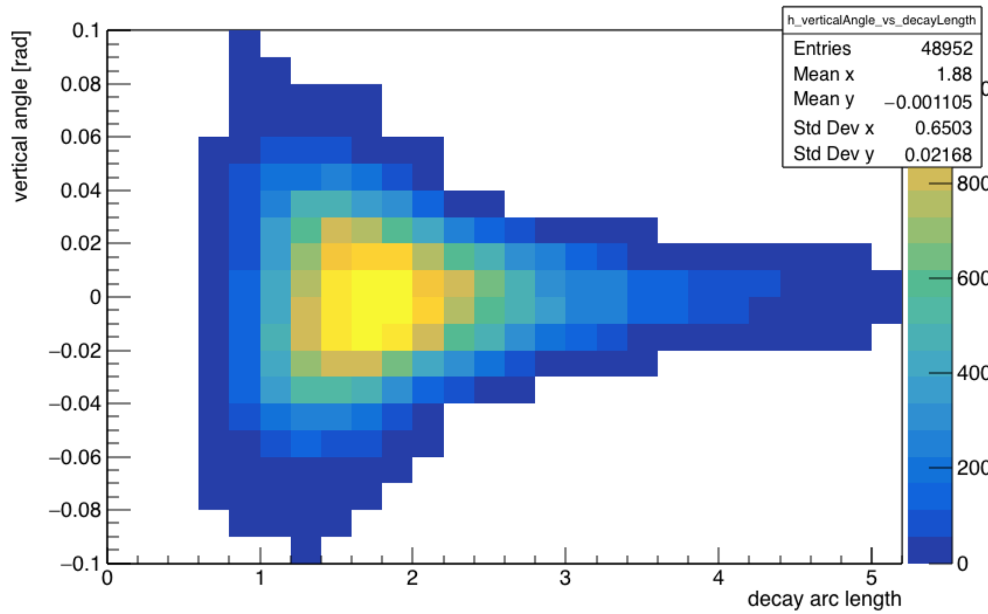

truth vertical angle




The RMS is ~0.04 mrad

The accuracy of the measurement is determined by the error on the mean (dependent on statistics)

Larger angles are measured for tracks extrapolated a shorter distance (lower momentum)

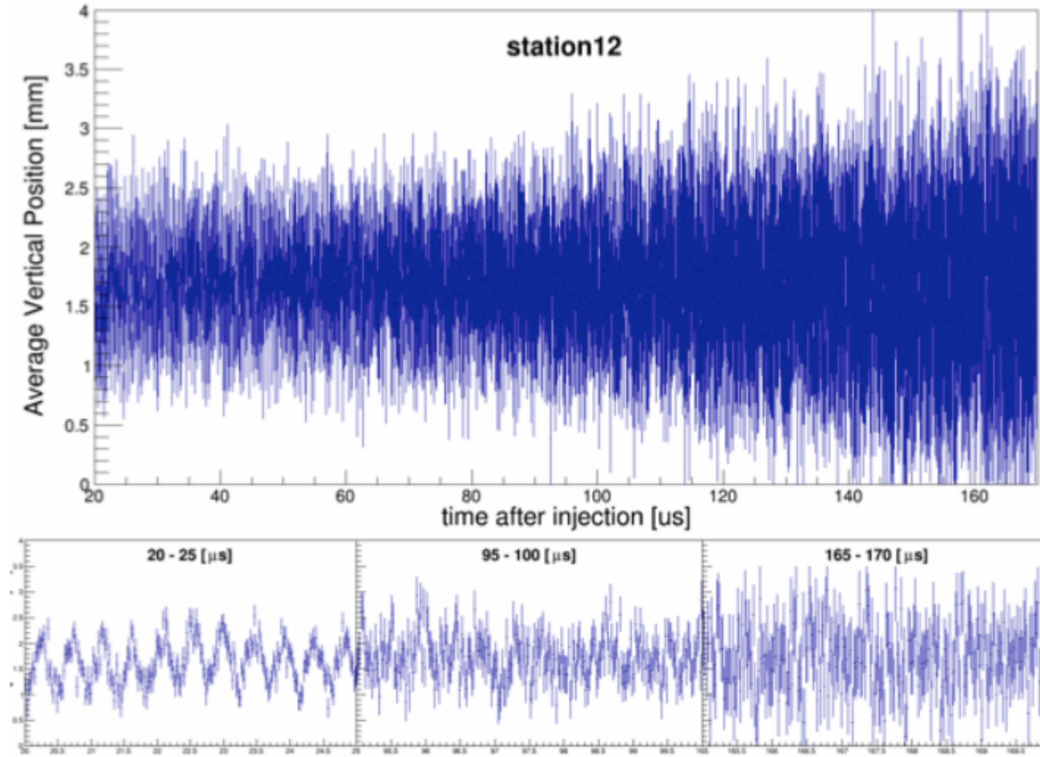


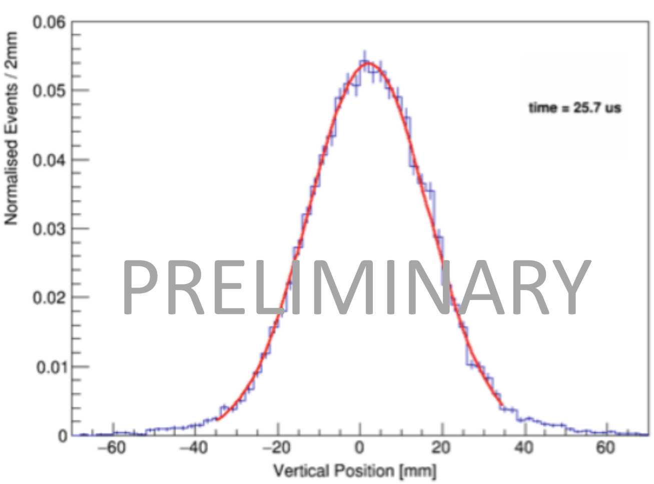
# Vertical Beam Oscillations

***There are vertical oscillations in the beam which can be used to exercise the framework for fitting vertical oscillations***

The average vertical position changes as a function of time with a lifetime of ~100μs

A gaussian is fit to each time bin to extract the mean position and the width

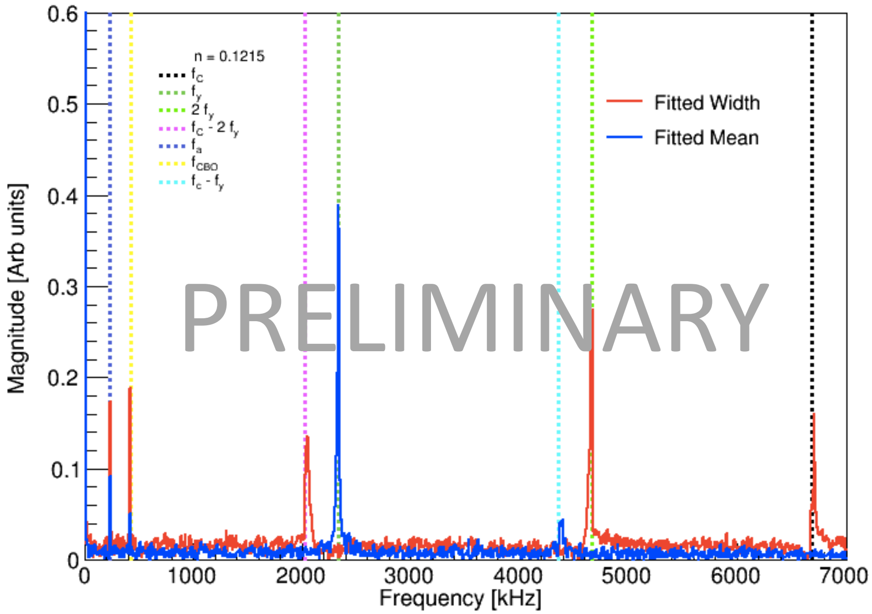



It is important to understand these oscillations for the EDM analysis as they may feed in to the fit

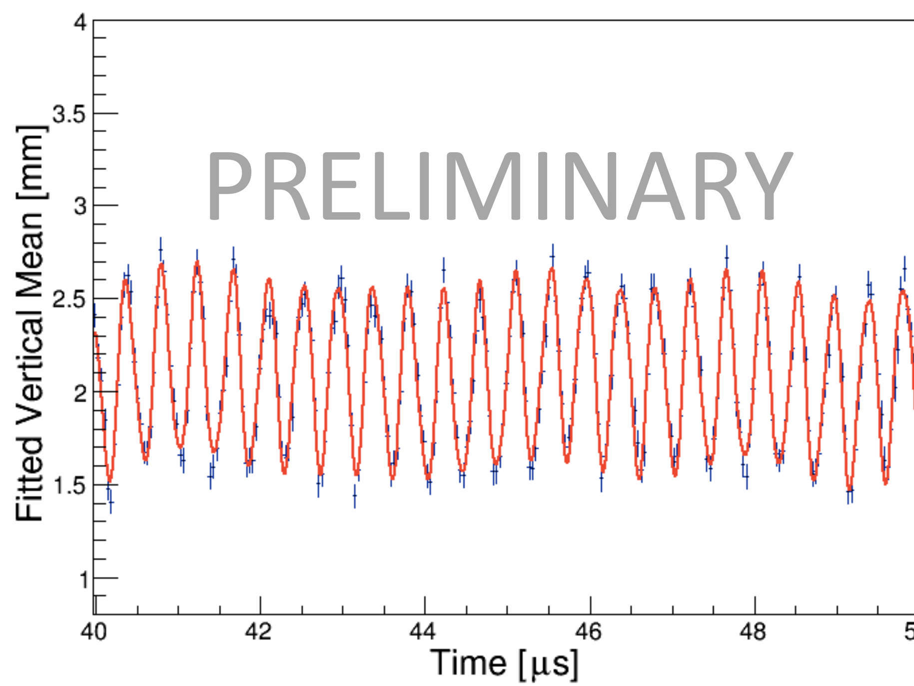
# Vertical Beam Oscillations

***A fourier transform of the mean and width shows the frequencies present in the distribution***




The frequencies match up to the known beam frequencies from acceptance effects and betatron oscillations

Based on the extracted frequencies a fit to the distribution is performed to examine the amplitude, liftetime and phase of each



# Conclusions

- The FNAL g-2 experiment is expected to improve upon the current limit by at least one, approaching two orders of magnitude
- There are already sufficient statistics to improve upon the BNL limit
- This improvement comes from the new tracking detectors with much greater acceptance
- The vertical fitting software is being exercised for fitting the betatron oscillations in the beam
- The EDM analysis of the current data is underway