The EDM in the g-2 experiment

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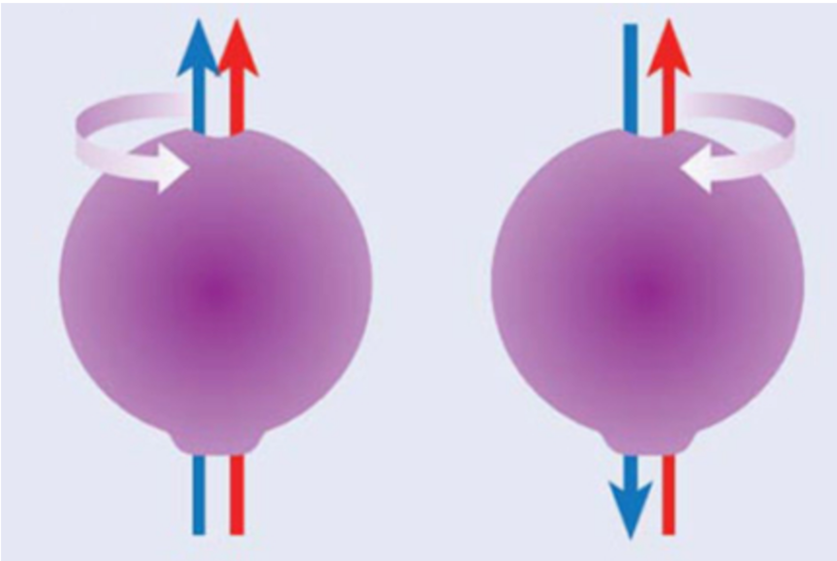
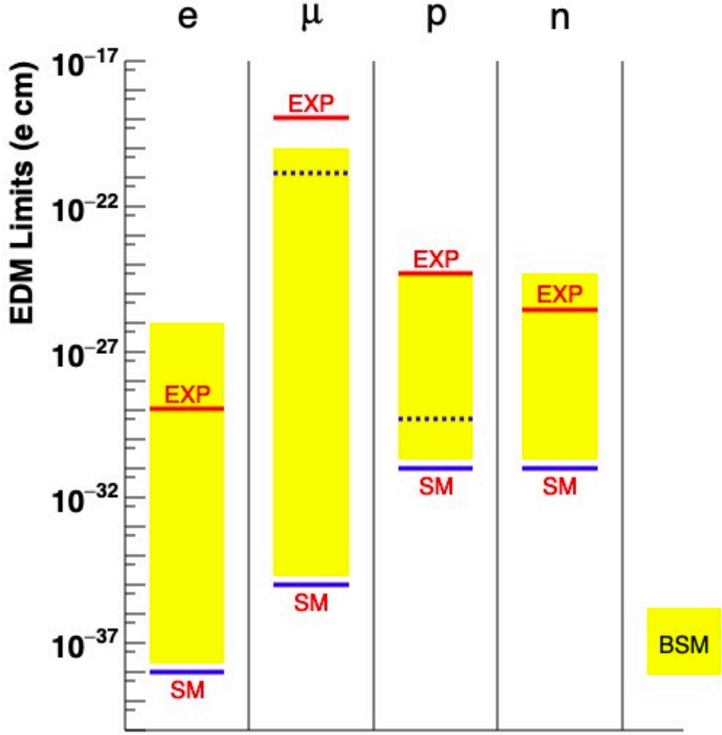
Electric Dipole Moments

Fundamental particles can have an EDM which is analogous to the MDM

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

Provides an additional source of CP violation





The power of EDM measurements has recently been demonstrated by the latest electron EDM measurement

The EDM in the g-2 experiment

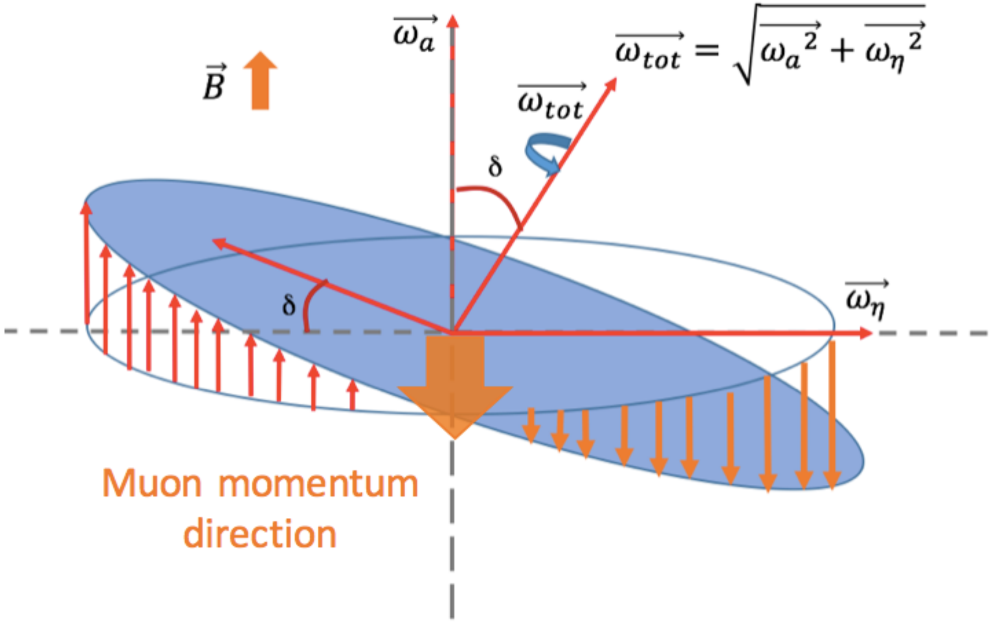
If an EDM is present the spin equation is modified to:

MDM   EDM

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

Dominant term

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



Produces a vertical oscillation 90 degrees out of phase :

$$\omega_{a\eta} = \sqrt{\omega_a^2 + \omega_\eta^2}$$

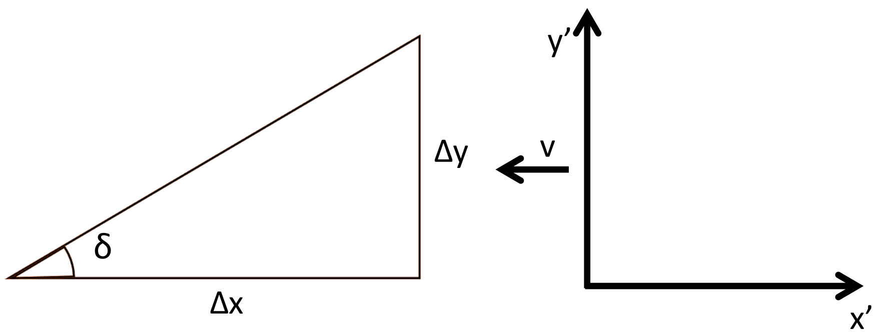
$$\delta = \tan^{-1}\left(\frac{\eta\beta}{2a}\right)$$

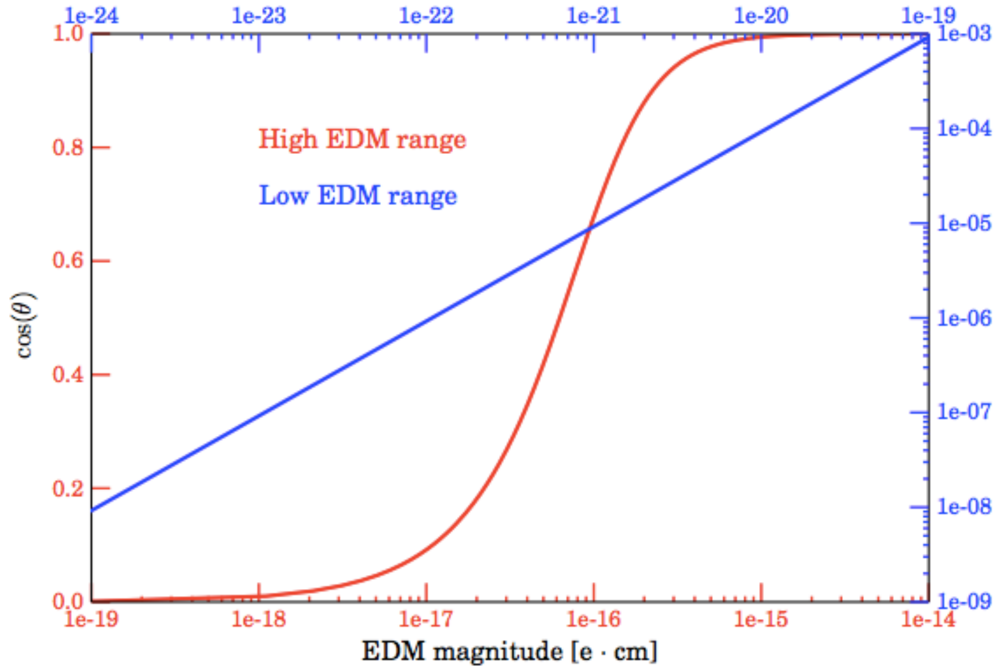
The vertical angle

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

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

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





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

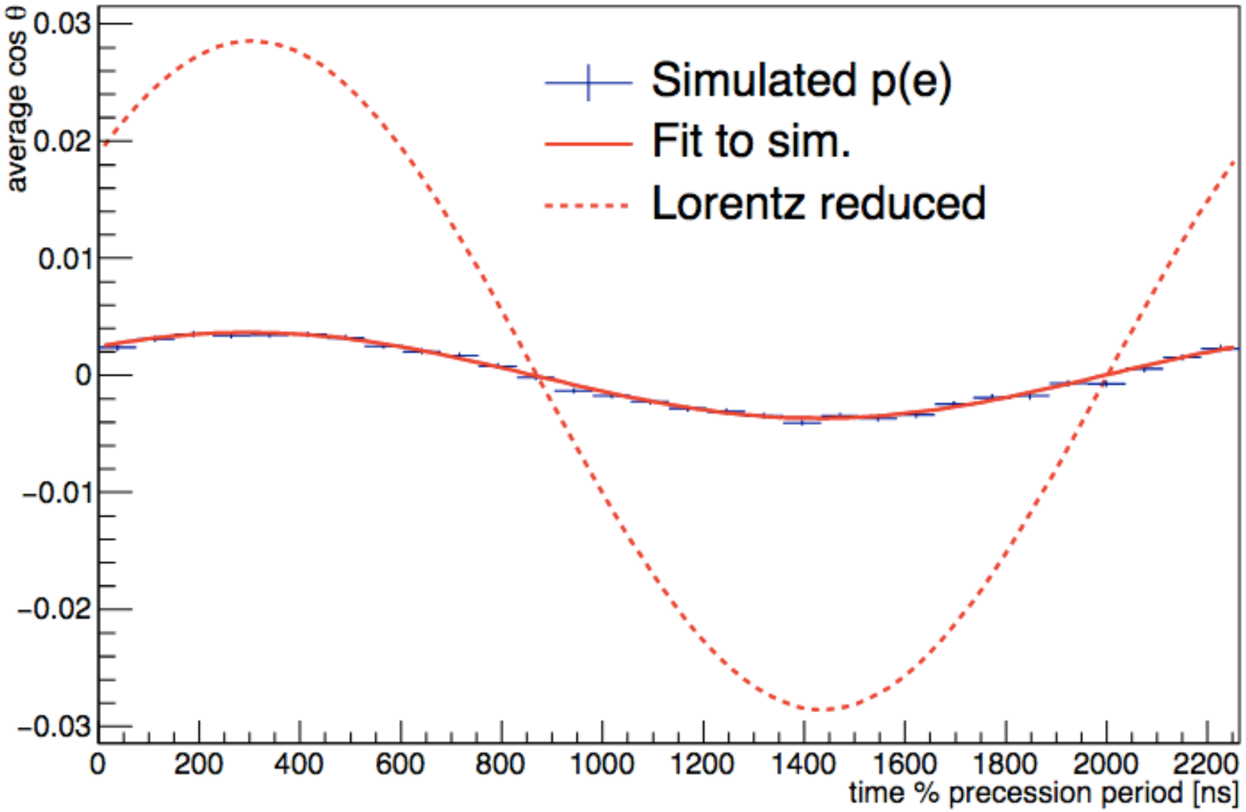
(neglecting the vertical momentum component)

The measured angle

The measured decay asymmetry is further reduced because :

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

Simulation suggests that this reduces the amplitude to 10%



The decay asymmetry

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

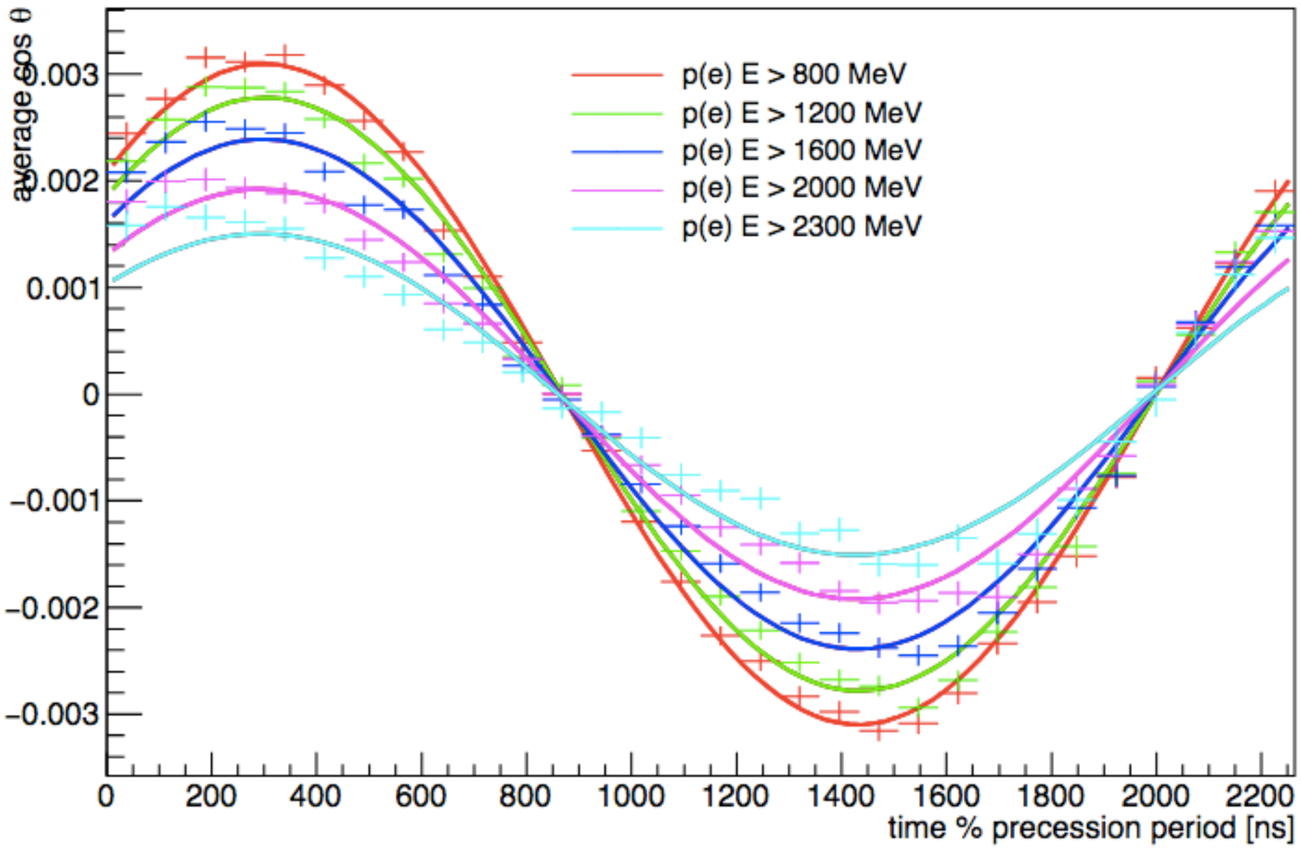
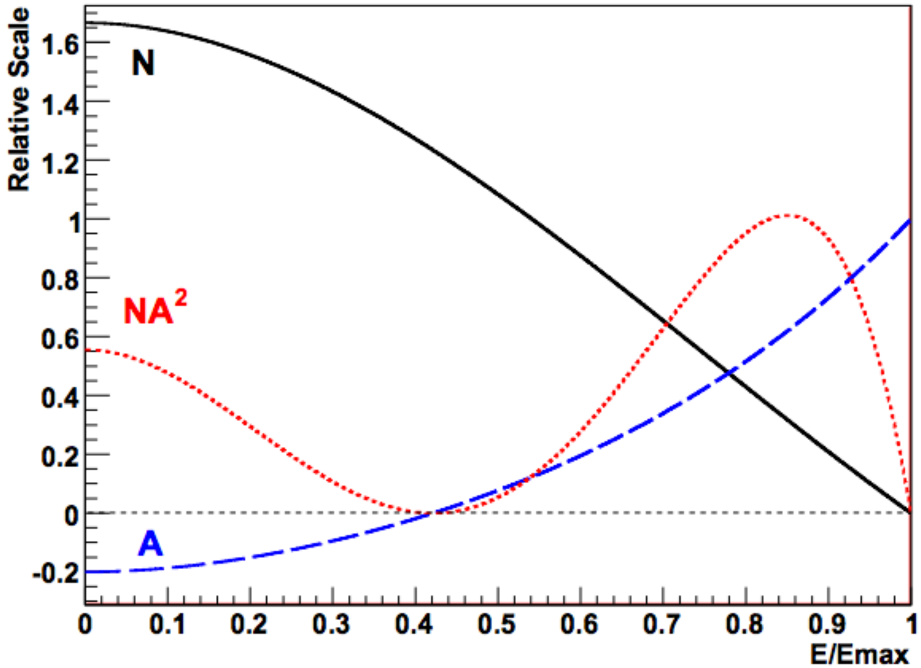


Figure of Merit

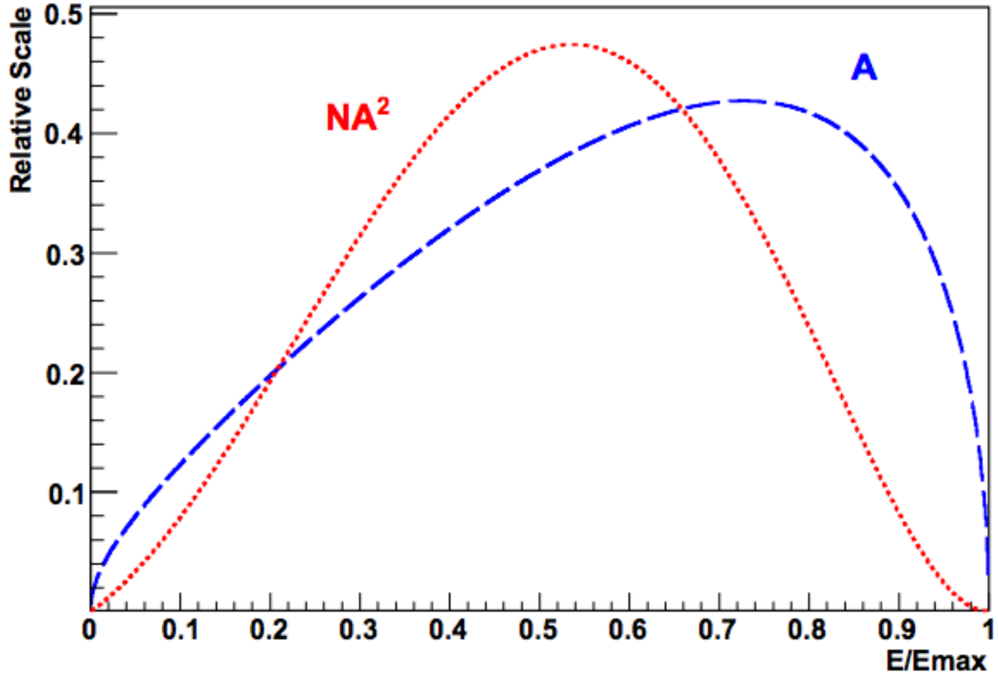
The statistical uncertainty is inversely proportional to NA²

Number of muons — Asymmetry

G-2 asymmetry



EDM asymmetry



E_{max} ~ 3.1 GeV

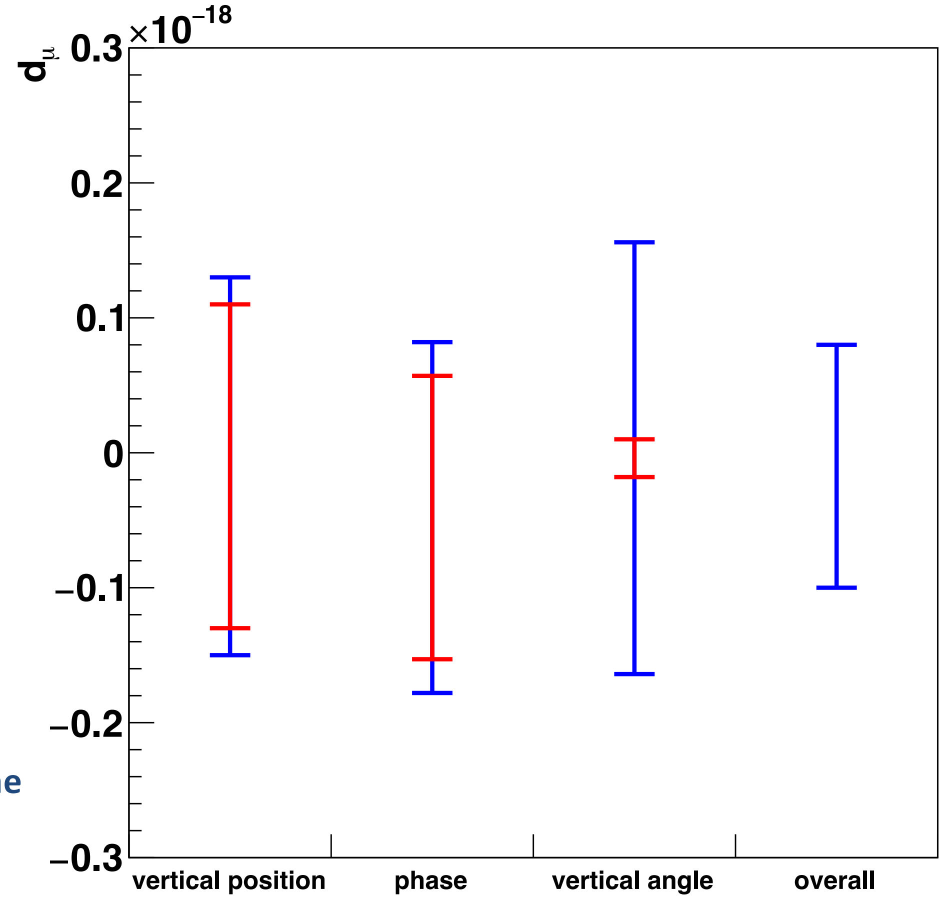
The BNL measurement

The EDM can be measured

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

For the direct method 3 techniques were used at BNL:

- **Phase as a function of vertical position**
- **Vertical position oscillation as a function of time**
- **Vertical decay angle oscillation as a function of time**

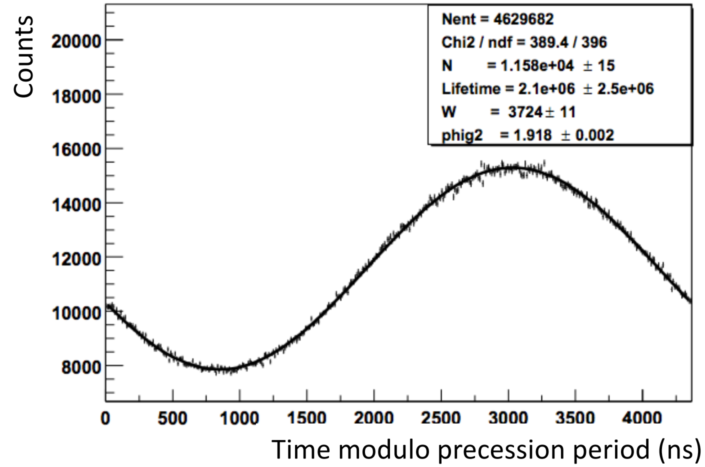


Vertical decay angle uncertainties

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

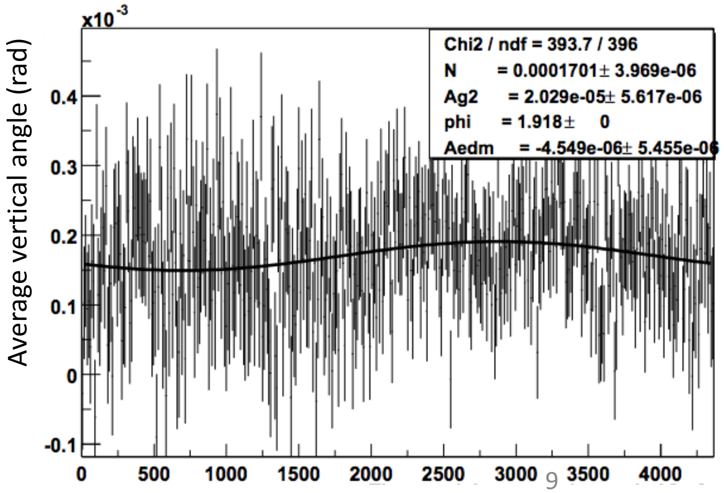
Plot the number oscillation as a function of time modulo the precession period

Minimises period disturbances at other frequencies



Use the period calculated from the ω_a fit
Fit to calculate the phase :

$$N(t) = e^{-t/\tau_e}\left(N_0 + W\cos(\omega t + \Phi)\right)$$



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

Vertical decay angle uncertainties

Main systematic uncertainties to be considered for this method:

Radial Magnetic field:

Would cause a tilt in the precession plane

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

E821:

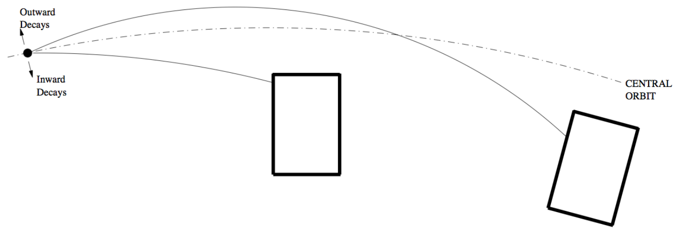
Oscillation amplitude : $(-0.1 \pm 4.4) \times 10^{-6}$ rad

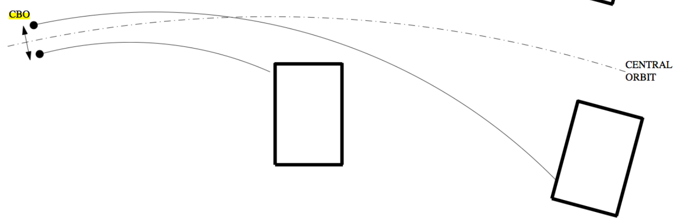
→ $d_\mu = (-0.04 \pm 1.6) \times 10^{-19}$ e•cm

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

Dominated by the statistical error

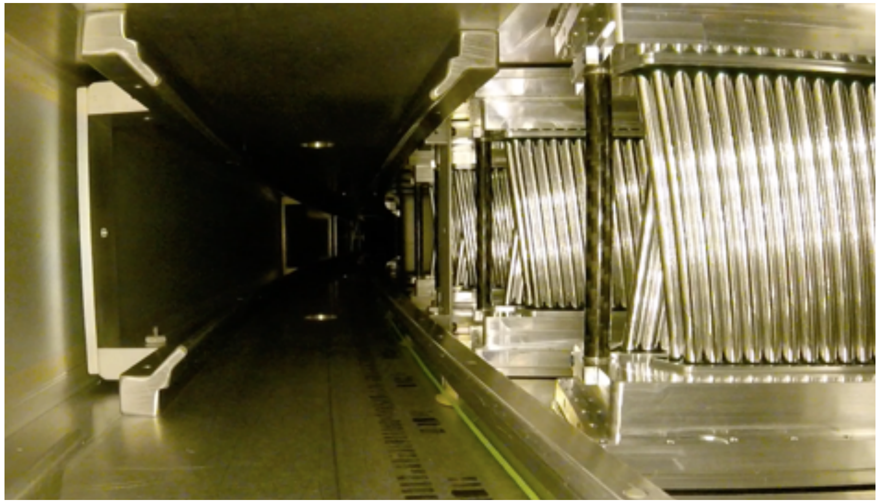
Systematic error	Vertical oscillation amplitude (μrad lab)	Precession plane tilt (mrad)	False EDM generated 10^{-19} ($e \cdot$ cm)
Radial field	0.13	0.04	0.045
Acceptance coupling	0.3	0.09	0.1
Horizontal CBO	0.3	0.09	0.1
Number oscillation phase fit	0.01	0.003	0.0034
Precession period	0.01	0.003	0.0034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

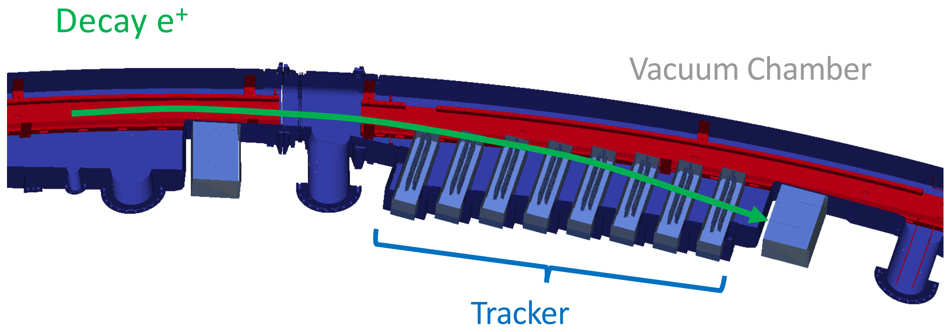


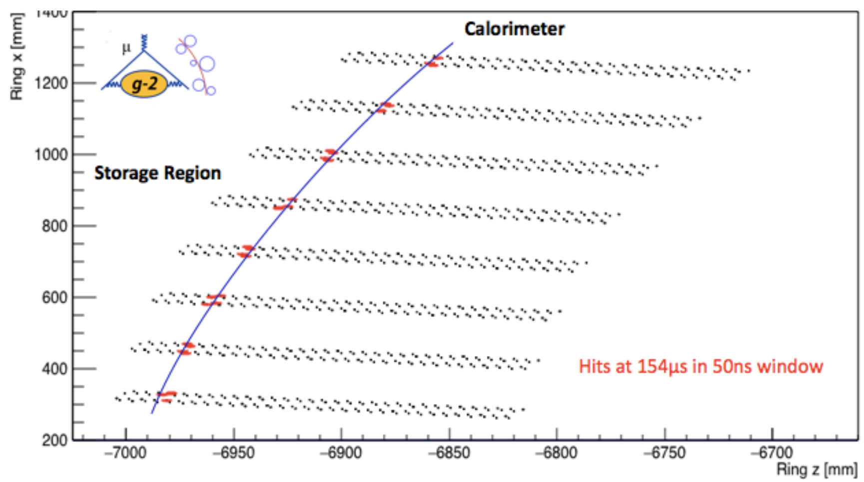


The measurement at FNAL

The tracking detectors in the experiment at FNAL should allow for a large improvement in the limit from the vertical angle EDM analysis at BNL







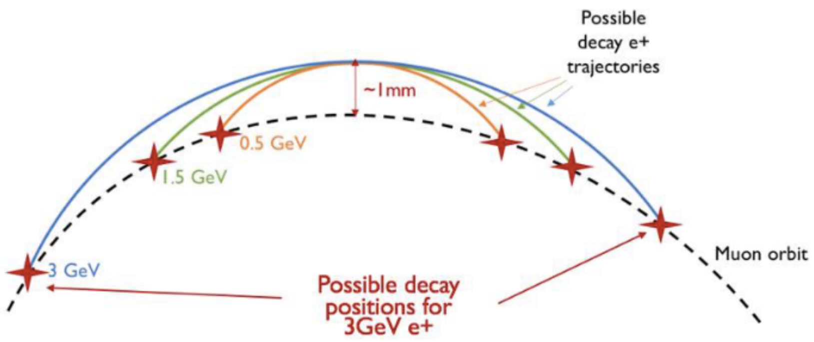
Expect O(1000) times better statistics than at BNL

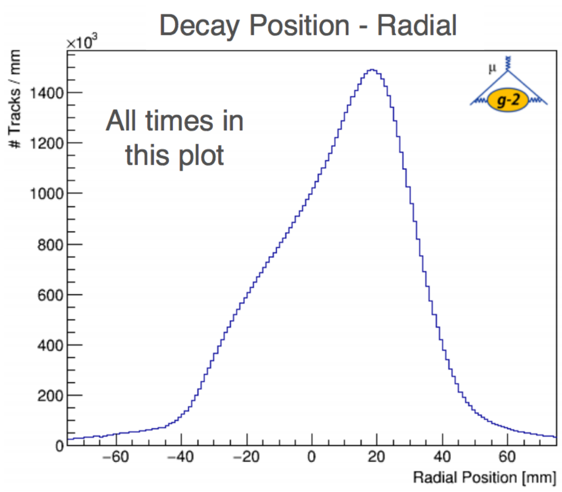
Reduce error by 1 order of magnitude quickly, approaching 2 orders of magnitude by the end

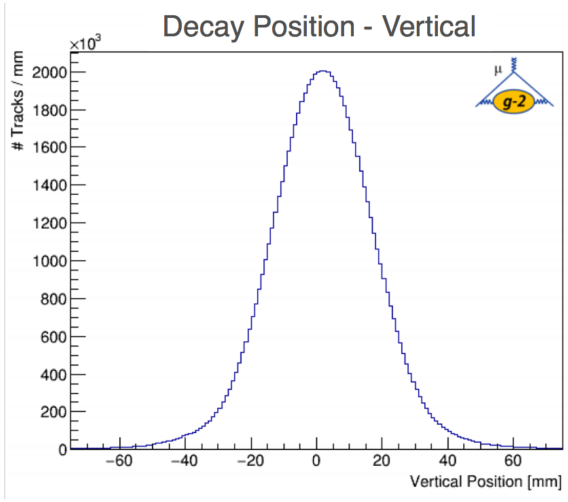
But need careful control of the systematic errors

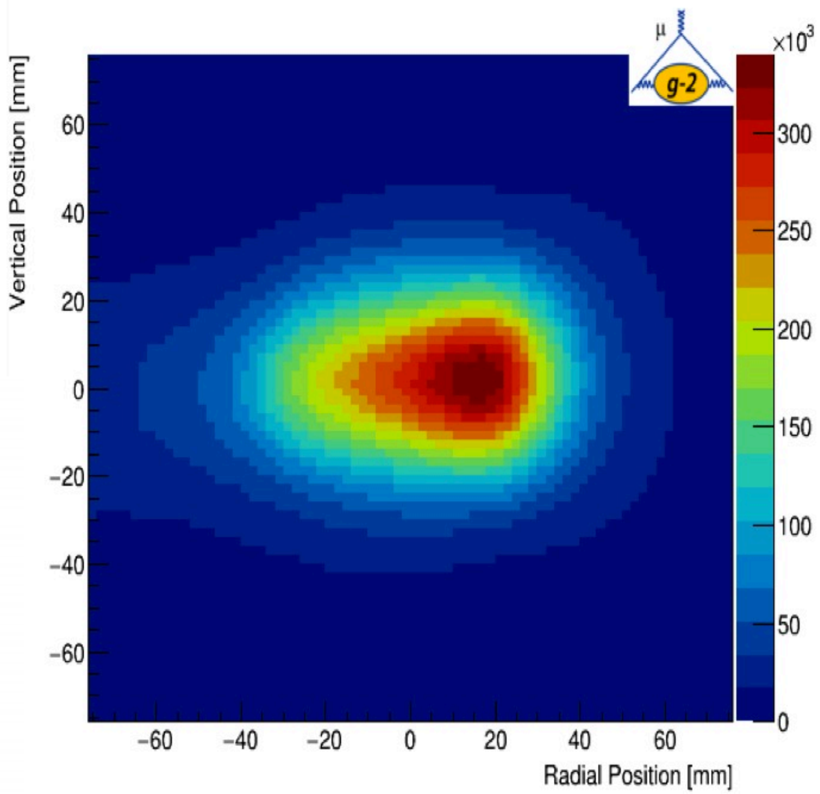
Beam reconstruction

The tracks are extrapolated back to the point of radial tangency as an approximation of the decay position



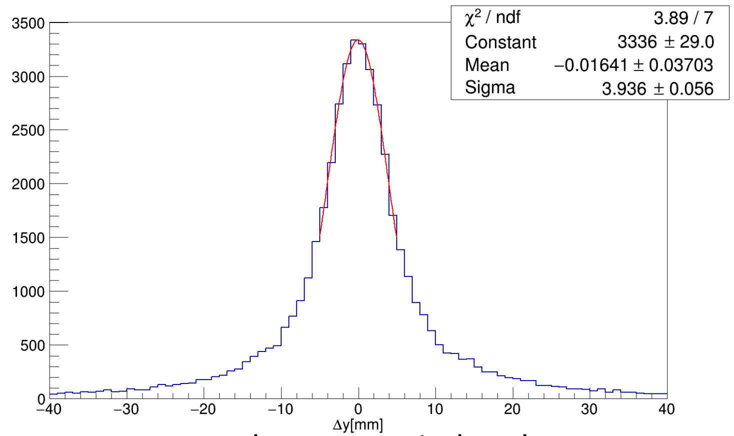




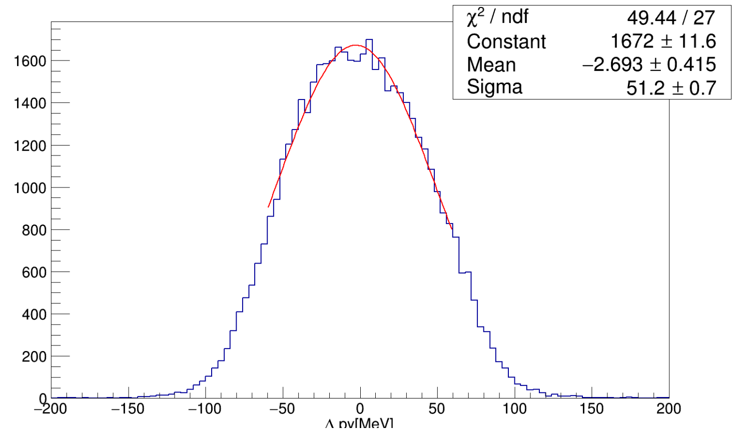


Vertical angle measurements

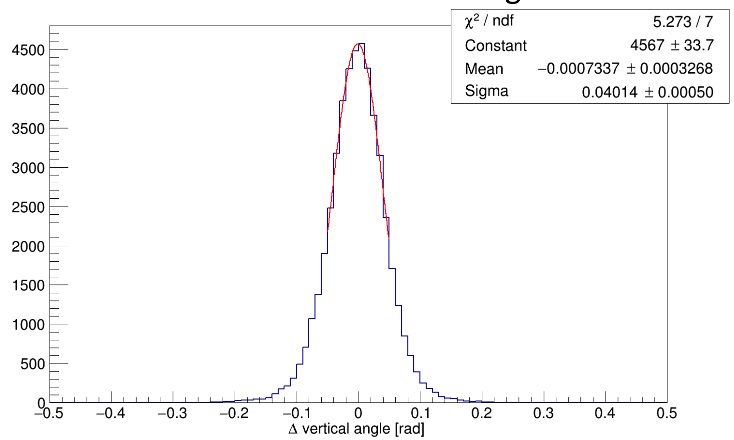
truth - reco vertical position



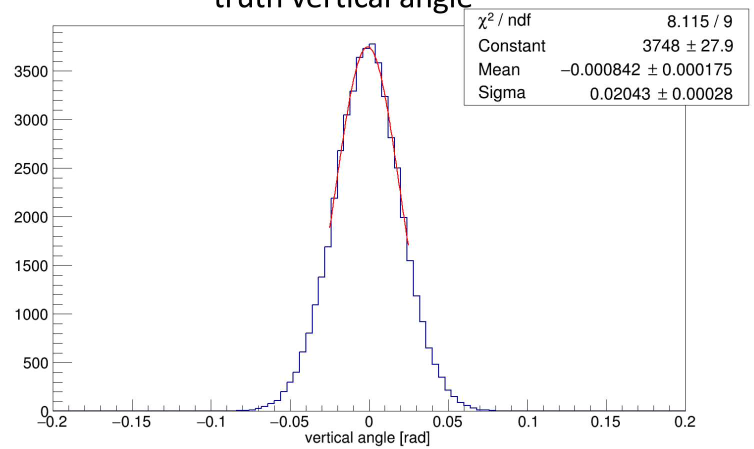
truth - reco vertical momentum



truth - reco vertical angle

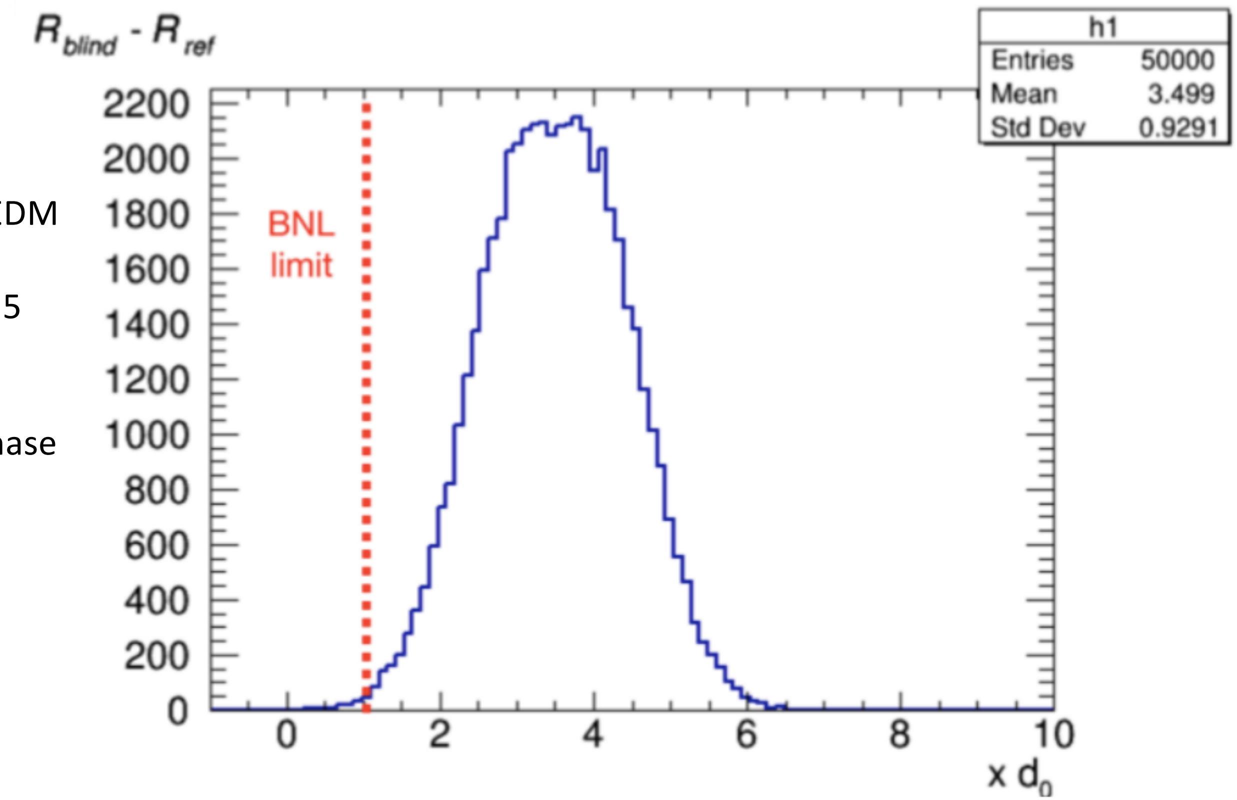


truth vertical angle



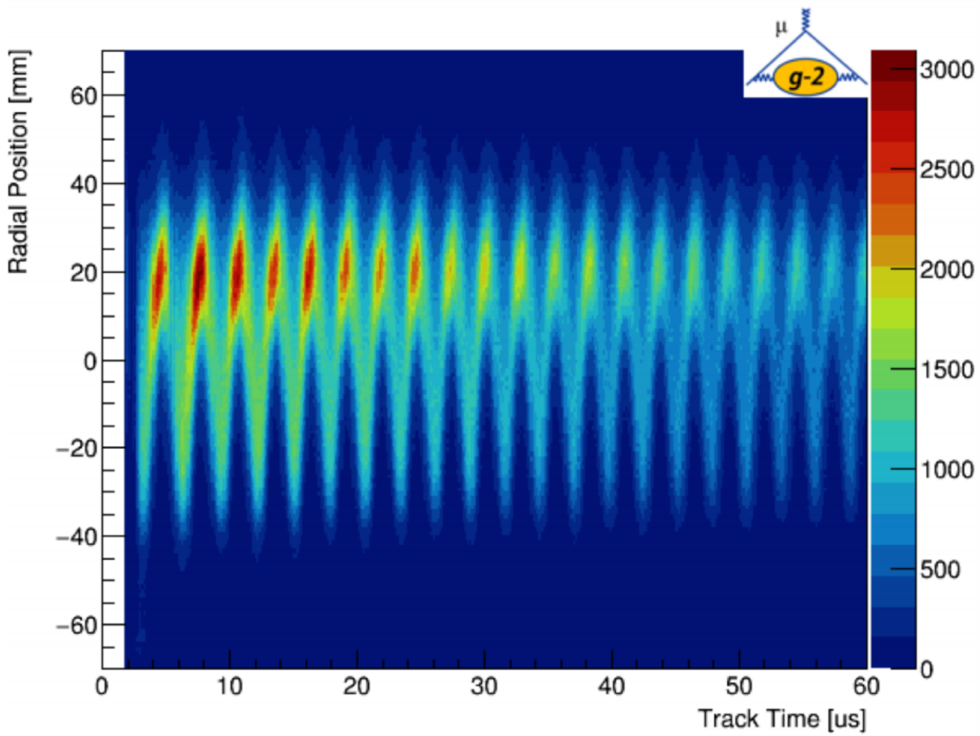
EDM blinding

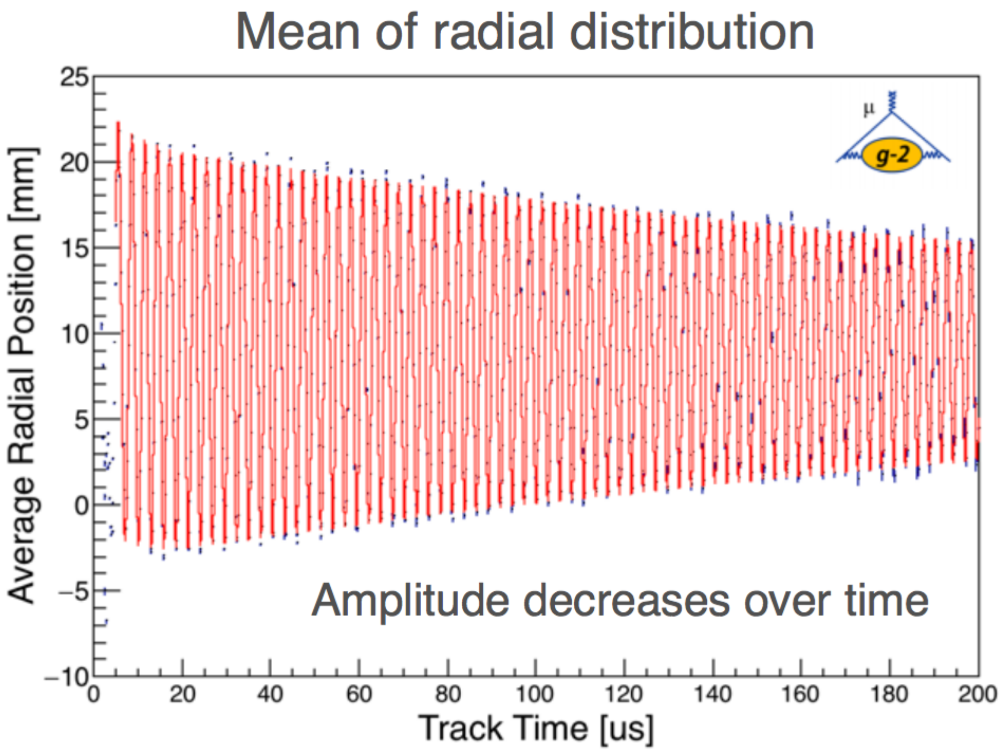
- The clock blinding used for the g-2 measurement is not sufficient to blind the EDM
- Instead generate an EDM centred around 3.5 times the BNL limit
- This produces a vertical oscillation out of phase with g-2, much larger than a potential EDM signal
- Once the analysis is complete unblind



Beam oscillations - radial

The beam oscillates in the storage ring both radially and vertically

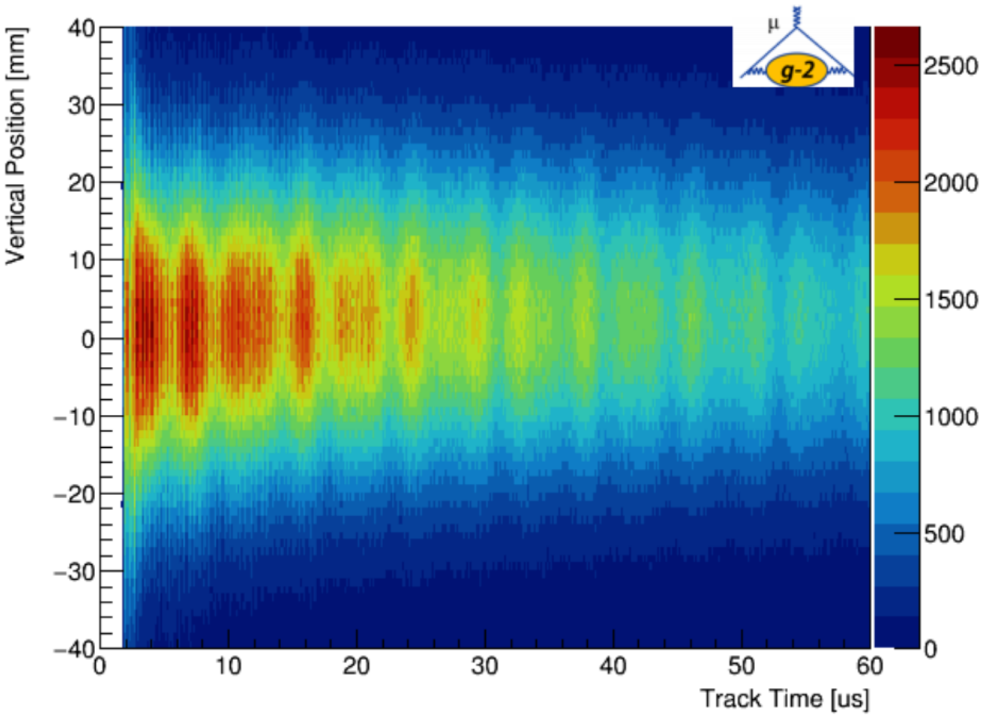


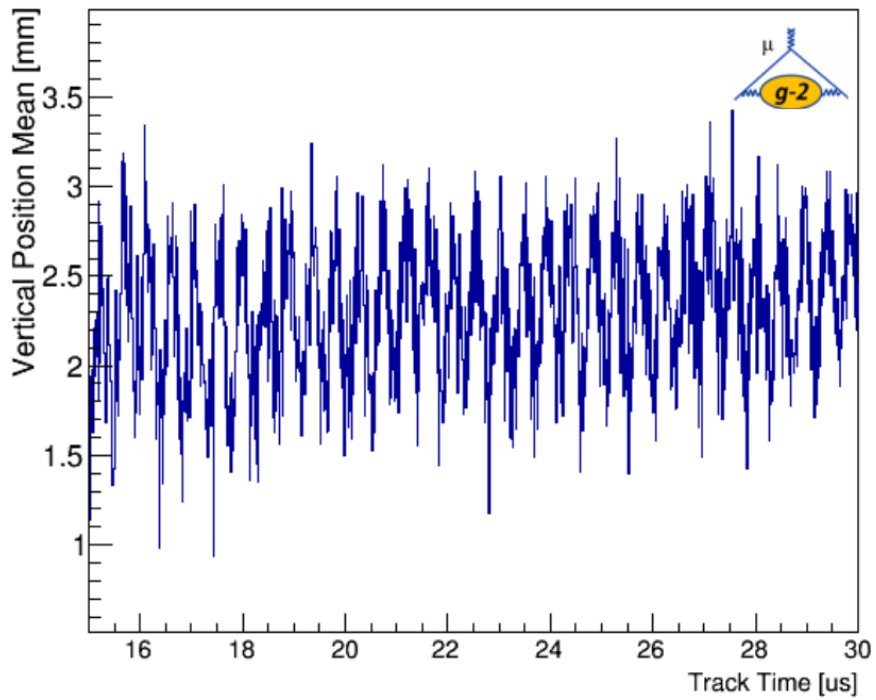


These beam oscillations affect the acceptance over time which can look like a vertical oscillation
The trackers allow for a full understanding of the beam motion which helps to improve the systematics

Beam oscillations - vertical

The beam oscillates in the storage ring both radially and vertically

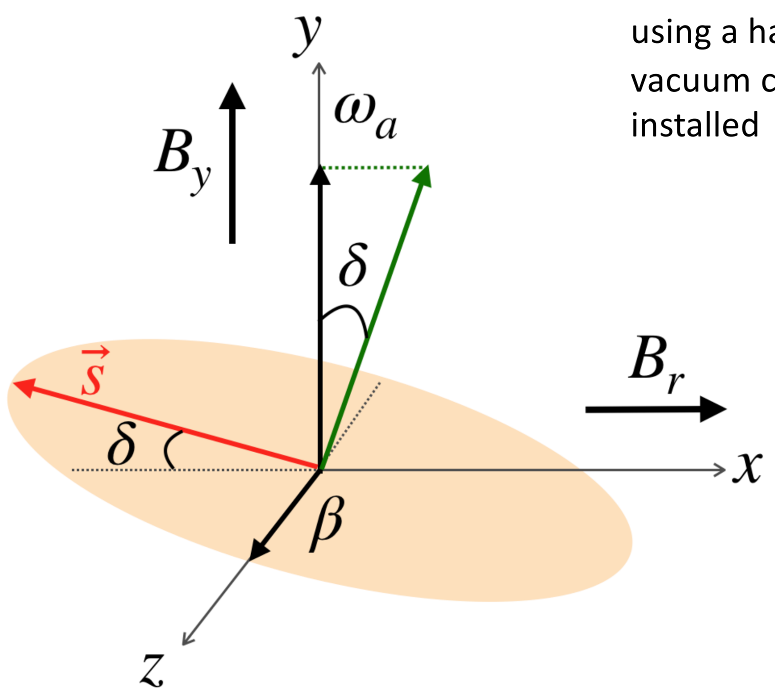




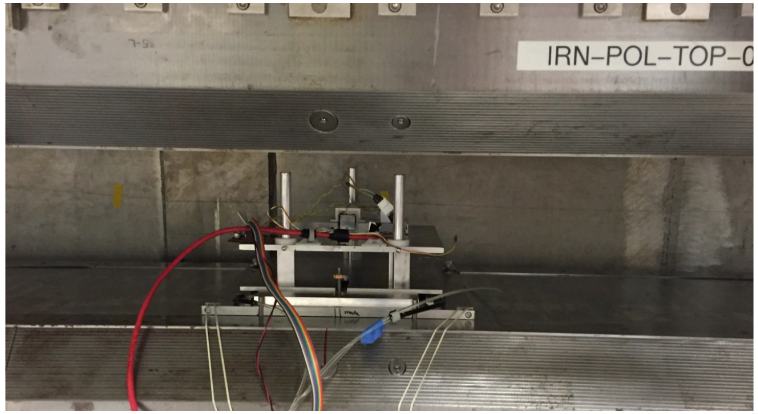
The vertical oscillations are smaller and at a higher frequency but can still feed into the measurement

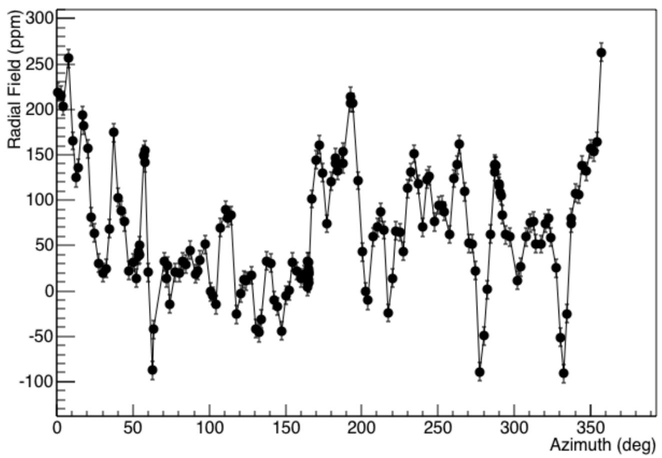
Radial field

A radial field also tilts the precession plane, just like the EDM signal



The radial field was measured using a hall probe before the vacuum chambers were installed





Average Radial Field: 68.5ppm

The surface coils are used to null the radial field

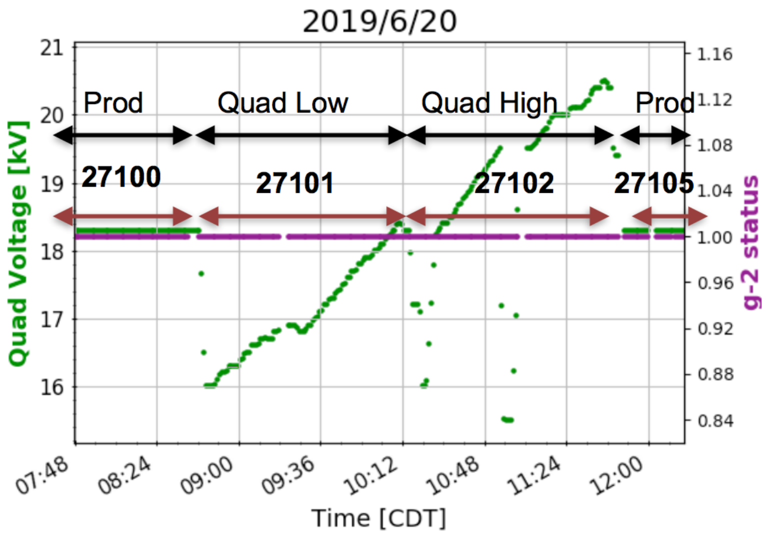
Measuring the radial field

The vertical position of the beam is affected by both the quads and the radial field

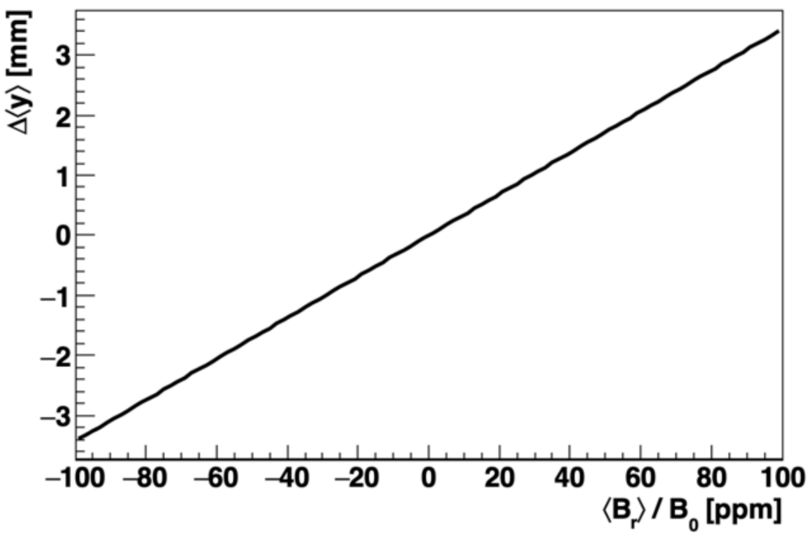
- A radial field causes the muons to experience a vertical force
- The quads focus vertically providing a restoring force

$$\langle y \rangle \sim \left(\frac{R_0}{n}\right)\left(\frac{\langle B_r \rangle}{B_0}\right)$$

→ The vertical position of the beam depends on both of these
Vary the quad settings and look at how the vertical position changes

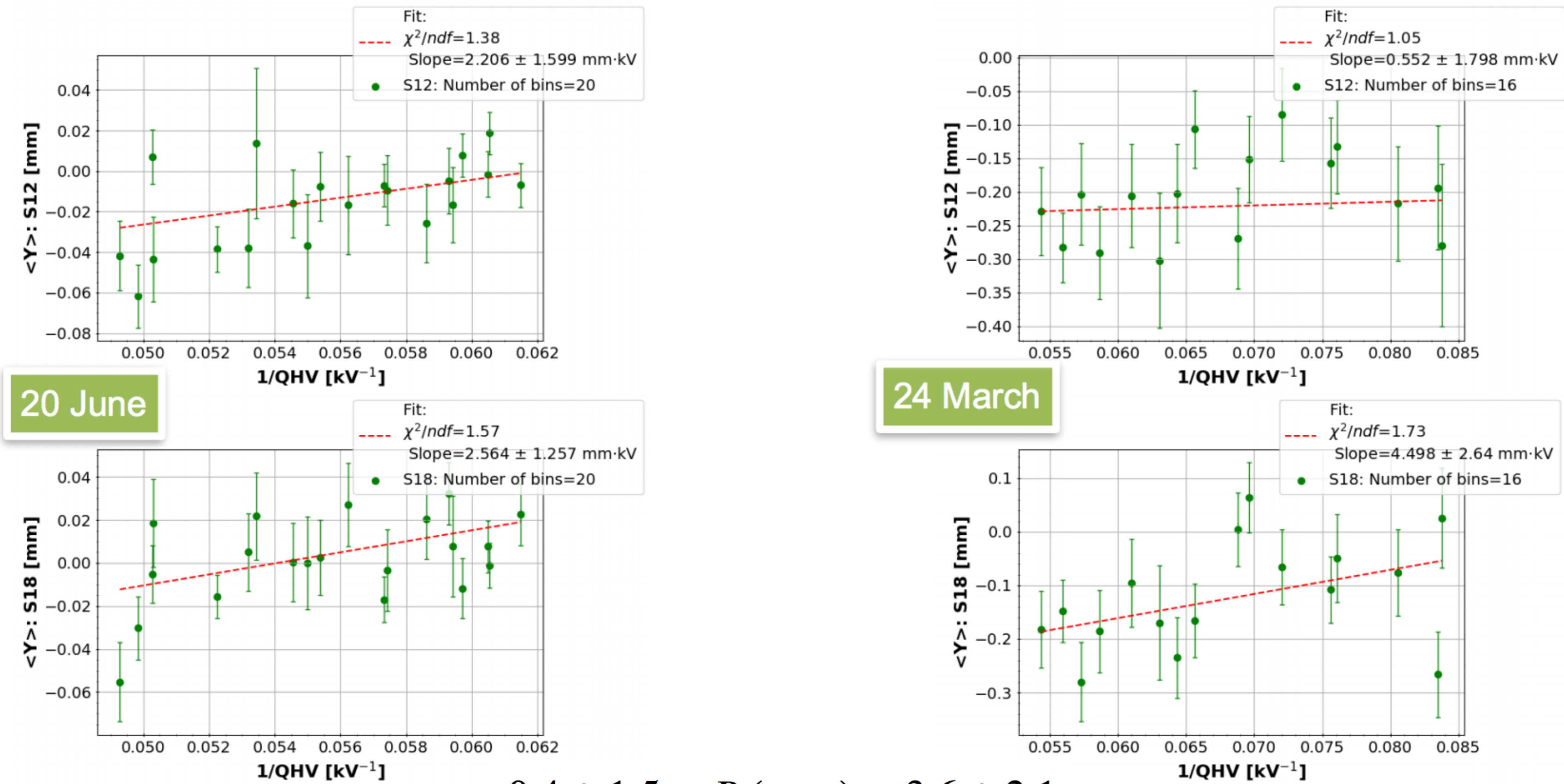


For 13 and 20.4 kV quad settings



Measuring the radial field

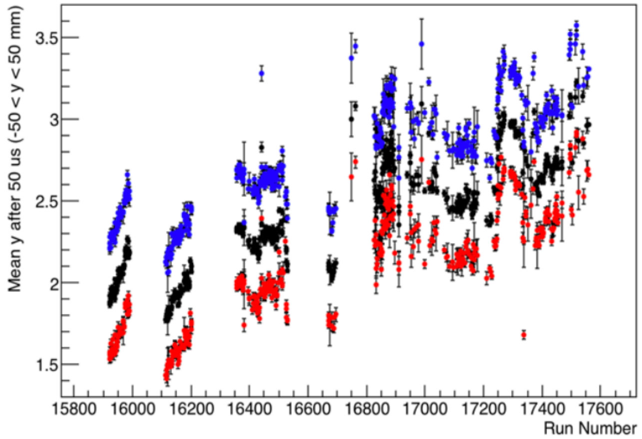
The feasibility can be assessed using the quad scan data taken during run 2

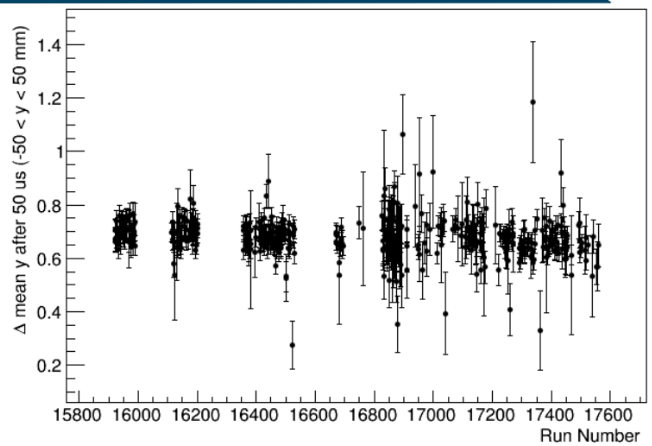


$$0.4 \pm 1.5 < B_r(ppm) < 3.6 \pm 2.1$$

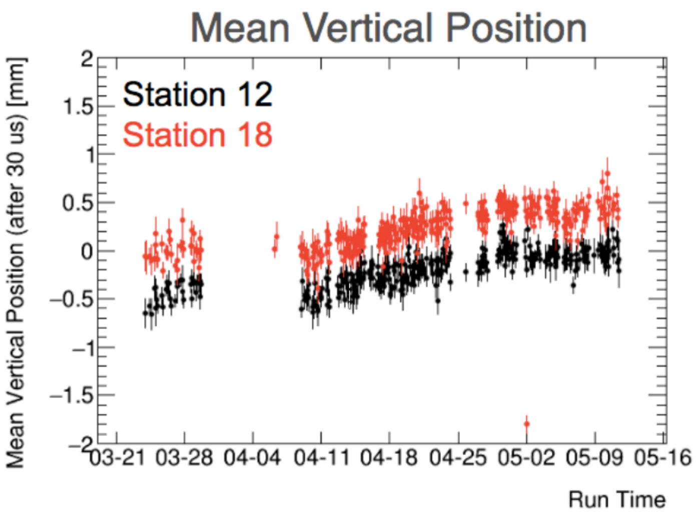
Changing vertical position

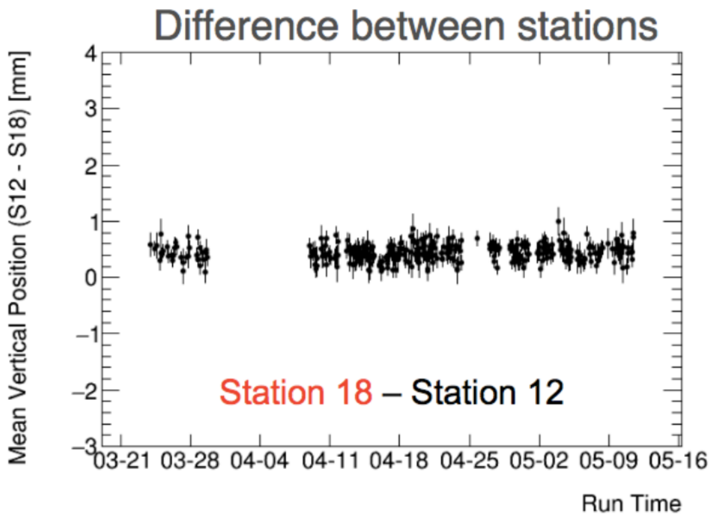
Run 1:





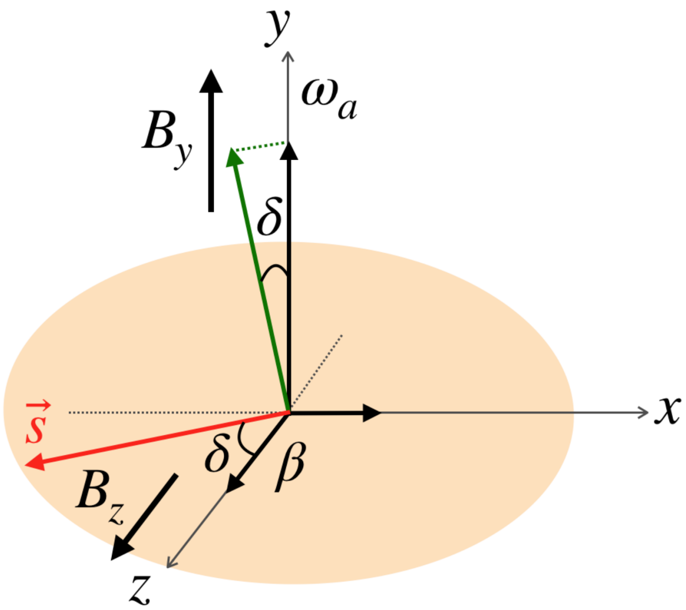
Run 2:





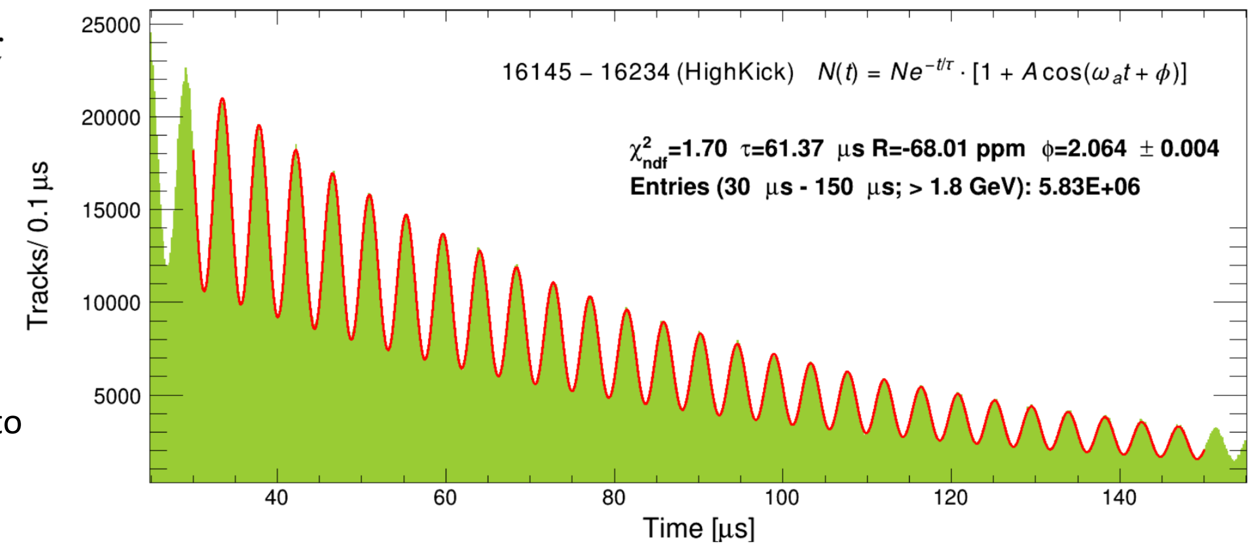
Longitudinal field

A longitudinal field induces a vertical oscillation in phase with the g-2 oscillation



Measuring the longitudinal field is the same as the EDM analysis but in phase with g-2 :

- Allows the analysis tools to be developed
- The measurement is needed for the spin precession analysis



Can also look out of phase with the CBO to assess the sensitivity

Conclusions

- The g-2 experiment at Fermilab is expected to improve upon the current limit on the muon EDM by at least one, approaching two orders of magnitude

- Enough data has already been collected to improve upon the BNL limit
    - We collect about the same number of tracks in every run!
    - Blinding is crucial before looking at any data

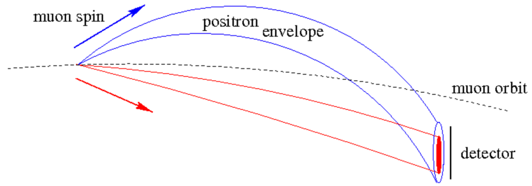
- The systematic errors will become more important for the Fermilab analysis
    - A method for constraining the radial field using the quads looks promising
    - The movements of the beam can be reconstructed using the trackers

- The analysis of the data is currently underway

Backup

Measuring the EDM – vertical position

Look for an oscillation in the average vertical position out of phase with the number oscillation

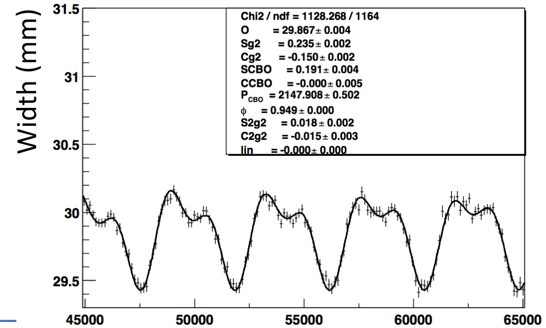


1. Plot the vertical RMS width as a function of time

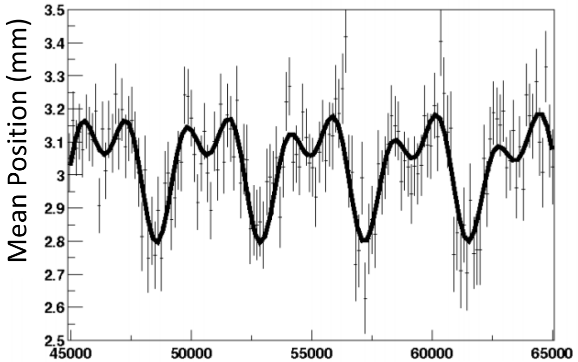
Average width — fixed — g-2 terms: changes in average energy and time of flight

$$f(t) = W + S_{g2}\sin(\omega t) + C_{g2}\cos(\omega t) + S_{2g2}\sin(2\omega t) + C_{2g2}(2\omega t)$$
$$+e^{-t/\tau_{CBO}}\left[S_{CBO}\sin\left(\omega_{CBO}(t-t_0)+\Phi_{CBO}\right)+C_{CBO}\cos\left(\omega_{CBO}(t-t_0)+\Phi_{CBO}\right)\right]+Lt$$

CBO (coherent betatron oscillation) terms : different radii lead to different times of flight — deadtime



2. Plot the mean vertical position of hits of hits as a function of time



Detector misalignment — **EDM**

$$f(t) = K + \boxed{S_{g2}\sin(\omega t)} + C_{g2}\cos(\omega t)$$
$$+e^{-t/\tau_{CBO}}\left[S_{CBO}\sin\left(\omega_{CBO}(t-t_0)+\Phi_{CBO}\right)+C_{CBO}\cos\left(\omega_{CBO}(t-t_0)+\Phi_{CBO}\right)\right]$$
$$+Me^{-t/\tau_M}$$

fixed

Slow changes in detector response/pileup

Vertical position uncertainties

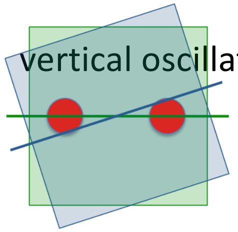
Statistical error
5.88 µm

Systematics dominated measurement

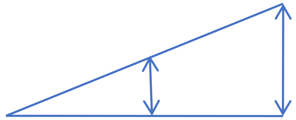
Horizontal oscillation + tilted detector

=

vertical oscillation



Vertical spin
+ longer path length
for outward positrons
= vertical oscillation



Effect	Error (μm)
Detector Tilt	6.1
Vertical Spin	5.1
Quadrupole Tilt	3.9
Timing Offset	3.2
Energy Calibration	2.8
Radial Magnetic Field	2.5
Albedo and Doubles	2.0
Fitting Method	1.0
Total Systematic	10.4
Statistical	5.9
Total Uncertainty	11.9

Differences between the top and bottom halves of the calorimeter

Would cause a tilt in the precession plane

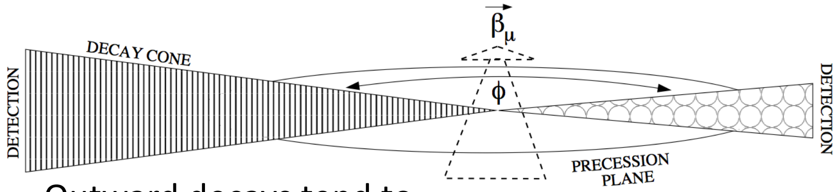
Back scattering from the calorimeter

E821 : S_{g2} = (1.27 ± 11.9) µm → $d_\mu = (-0.1 \pm 1.4) \times 10^{-19}$ e•cm

→ $|d_\mu| < 2.9 \times 10^{-19}$ e•cm (95% C.L.)

Measuring the EDM – phase

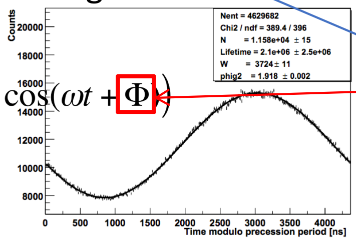
Consider the phase variation as a function of vertical position



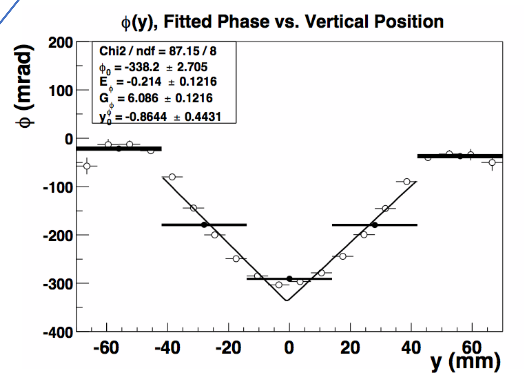
Decays that strike higher in the detector have to travel further

Outward decays tend to travel further up or down due to longer path length

$$N(t) = e^{-t/\tau_e}\left(N_0 + W\cos(\omega t + \Phi)\right)$$



The fitted phase depends on the vertical position



A non zero EDM tips the precession plane

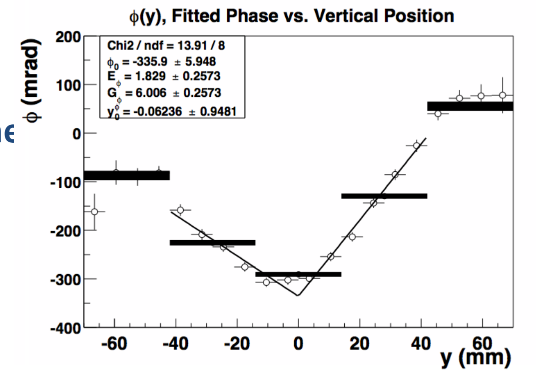
- More outward decays at the top
- More inward decays at the bottom

→ **suppresses the phase difference at the bottom of the calorimeter**

$$\Phi(y) = p_0 + p_1(y - p_2) + \left|p_3(y - p_2)\right|$$

Up-down asymmetry
EDM

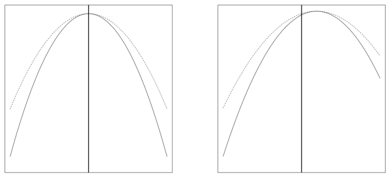
Phase changes not related to EDM



Phase uncertainties

The systematic uncertainities are similar to the vertical position measurement

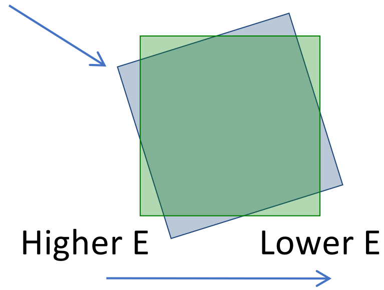
Detector misalignment is more important



induces an up down asymmetry → fake EDM signal

Detector Tilt

causes asymmetric vertical loses



Source	Sensitivity	Result
Detector Tilt	26 μrad/mm/mrad$\times$ 0.75 mrad	20 μ rad/mm
Detector Misalignment	138 μrad/mm/ mm $\times$ 0.2 mm	28 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		38 μrad/mm (0.93×10^{-19} e·cm)
Total statistical		28 μrad/mm (0.73×10^{-19} e·cm)
Total		47 μrad/mm (1.2×10^{-19} e·cm)

E821: $d_\mu = (-0.48 \pm 1.3) \times 10^{-19}$ e•cm

Again systematics dominated, although statistics play a larger role