The EDM measured at BNL

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Workshop on future muon EDM searches at Fermilab and worldwide

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 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 E821:

- **Vertical position oscillation as a function of time**
  - Systematics dominated
- **Phase as a function of vertical position**
  - Again systematics dominated
  - Provides a useful cross check
- **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

Physics motivation

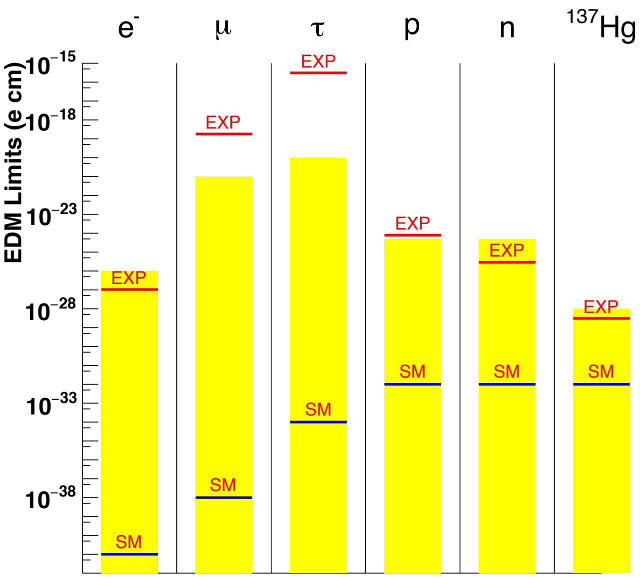
Fundamental particles can also have an EDM defined by an equation similar to the MDM:

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

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 : $\dfrac{d_\mu}{d_e} \sim \dfrac{m_\mu}{m_e}$

d_e limits imply d_μ 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

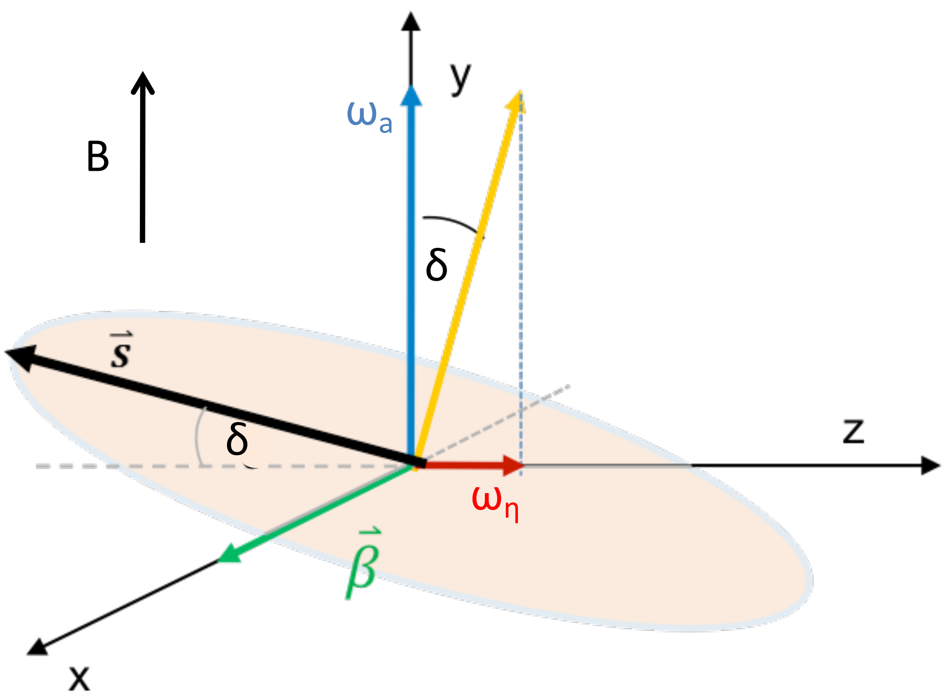
If an EDM is present the spin equation is modified to:

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

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

(π/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

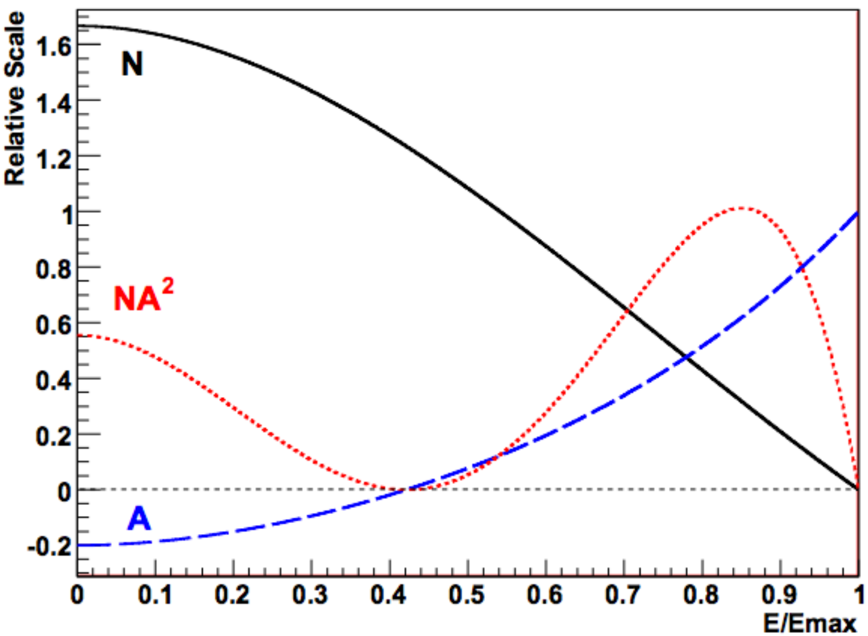
Measuring the EDM

The statistical uncertainty is inversely proportional to NA²

Number of muons

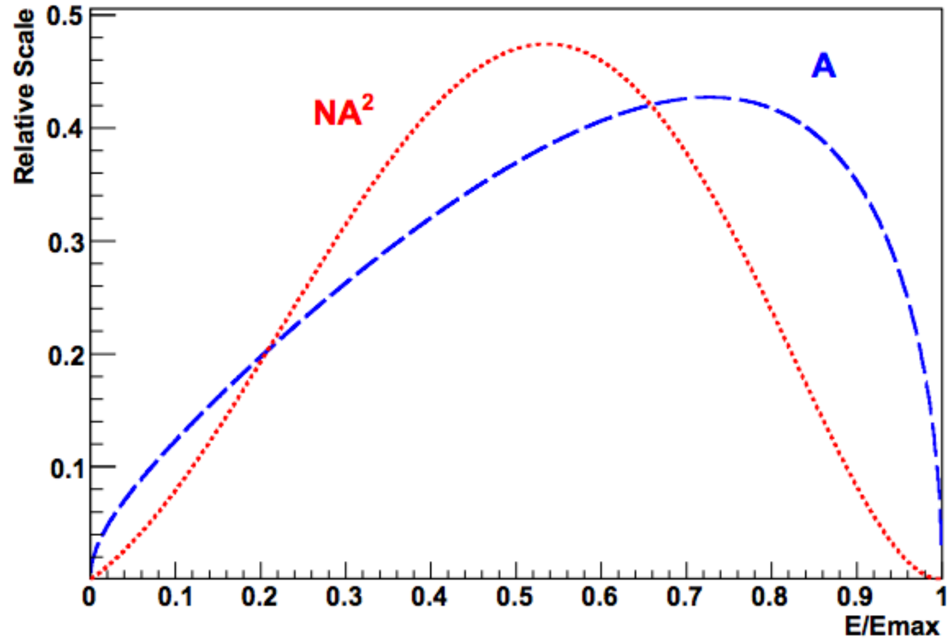
Asymmetry

G-2 asymmetry



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

EDM asymmetry



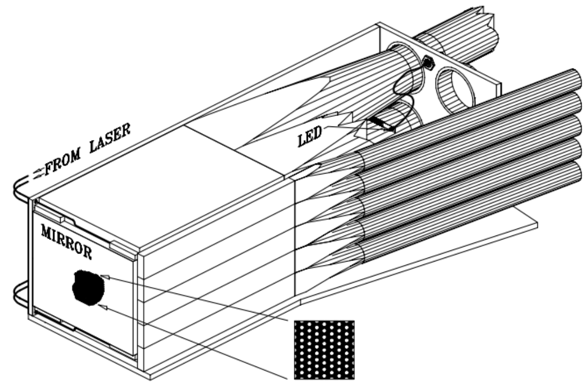
Sensitive over a broad range of energies around ~1.5 GeV

E_{max} ~ 3.1 GeV

Measuring the EDM – vertical position

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

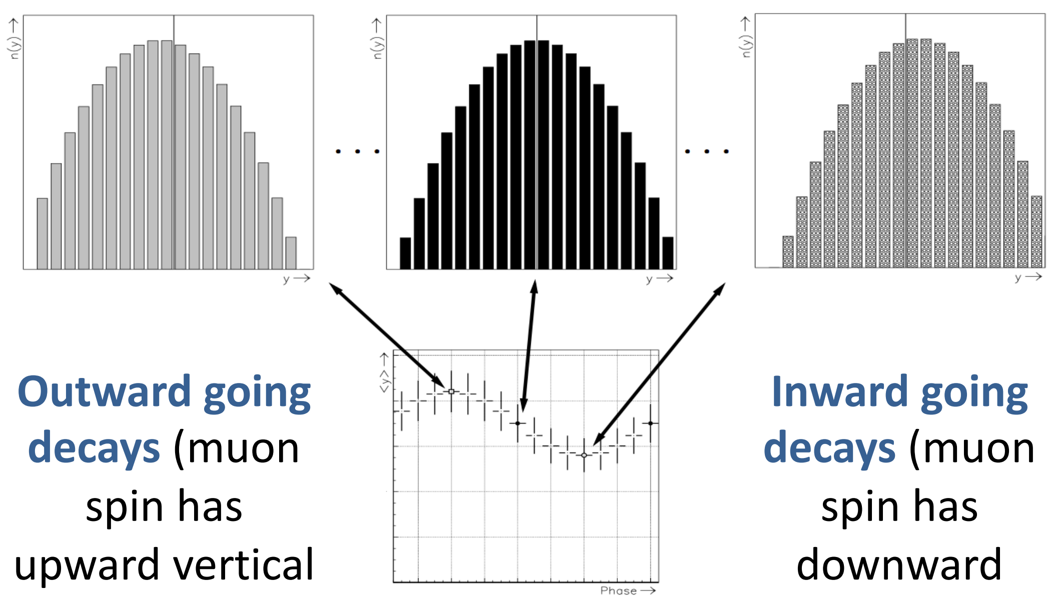
Measured using the front scintillator detectors (FSDs) and position sensitive detectors (PSDs)



Energy taken from matching to calorimeter hits

In simple terms :

VERTICAL DISTRIBUTION SEEN BY POSITION SENSITIVE DETECTORS



MEAN VERTICAL POSITION VERSUS (g−2) PHASE

Outward going decays (muon spin has upward vertical component)

Inward going decays (muon spin has downward vertical component)

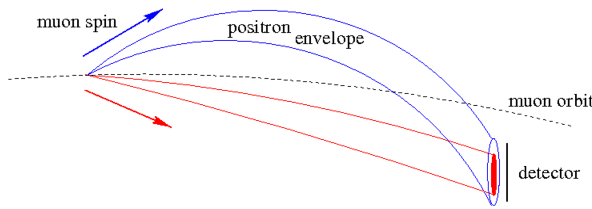
However there are other effects that cause an oscillation in the average vertical position even without an EDM…

Vertical Beam Distribution

The vertical distribution of the positrons hitting the calorimeters changes as the muon spin precesses (without an EDM)

Effects at the g-2 frequency :

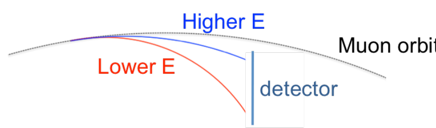
Differences in path length:



Positrons emitted outwards travel further to reach the calorimeter

→ Wider beam spread

Differences in average energy:



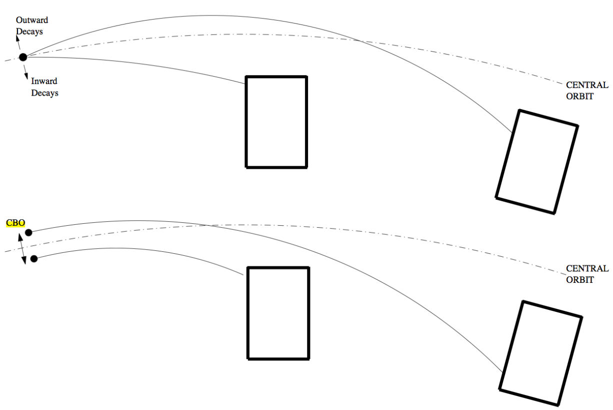
Higher energy positrons curve less so hit the calorimeter closer to the beam

→ Smaller path length

→ Narrower beam spread

Effects not at the g-2 frequency :

CBO :



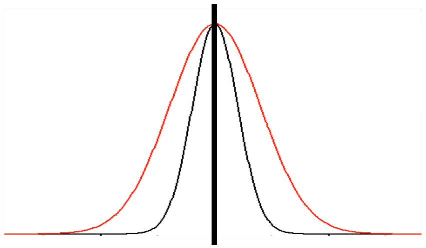
Positrons released at a larger radius have a longer path length to the calorimeter

→ Wider beam spread

Fitting the width

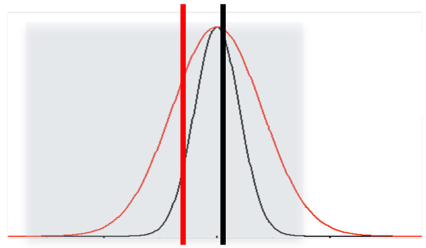
The changes in the width of the distribution can lead to changes in the average vertical position

Perfectly aligned detector :



mean

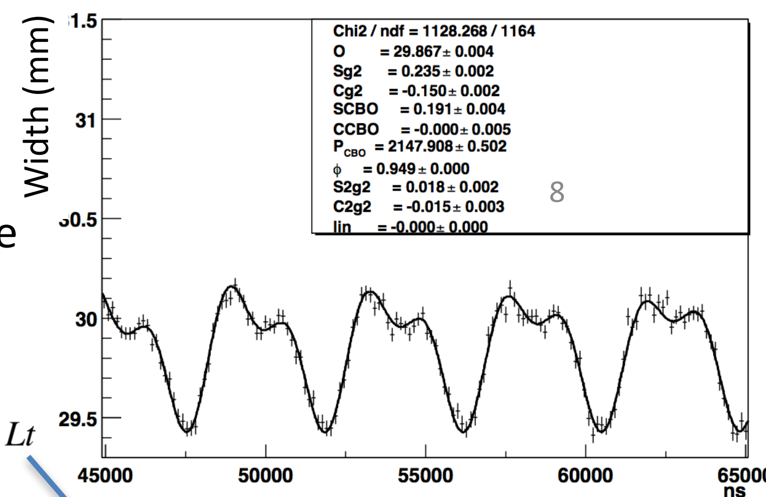
Misaligned detector :



Mean (wide)

Mean (narrow)

So first fit the oscillations in the width to extract the CBO parameters



Fixed from ω_a analysis

Average width

g-2 terms, number count oscillation aligned to cosine phase

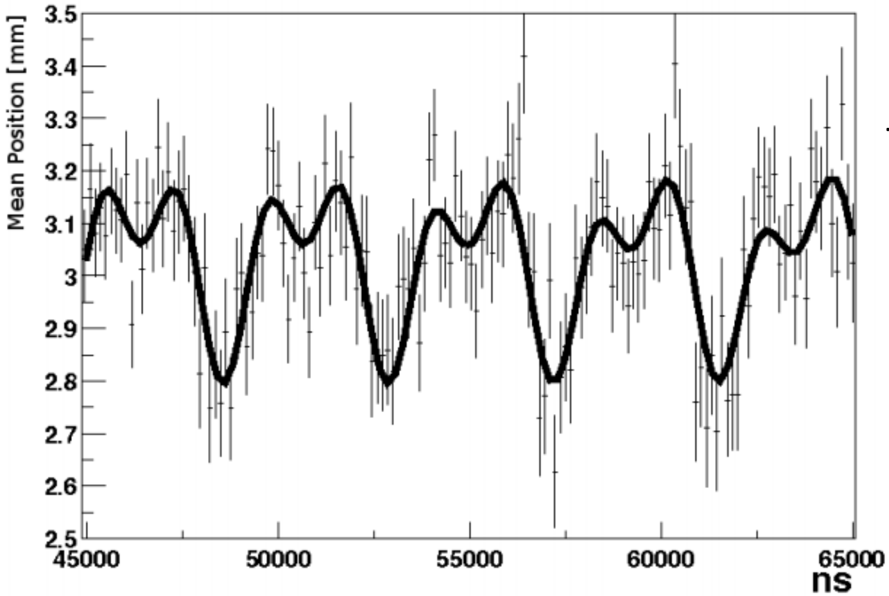
$$f(t) = W + S_{g2}\sin(\omega t) + C_{g2}\cos(\omega t) + S_{2g2}\sin(2\omega t) + C_{2g2}(2\omega t)$$
$$+e^{-t/\tau_{CBO}}\left[S_{CBO}\sin\left(\omega_{CBO}\left(t-t_0\right)+\Phi_{CBO}\right)+C_{CBO}\cos\left(\omega_{CBO}\left(t-t_0\right)+\Phi_{CBO}\right)\right]+Lt$$

CBO terms : chosen such that oscillation is in the sine term

Deadtime (more hits in the centre tiles are eliminated at early times)

Fitting the Average Vertical Position

Now plot the mean vertical position as a function of time



Use the parameters determined from the fit to the width in the fit to the average vertical position

Plotted for each detector separately

Energy range : 1.4 – 3.2 GeV

Detector misalignment

g-2 terms : ω fixed

EDM

CBO terms : τ_{CBO}, ω_{CBO}, Φ_{CBO} fixed from width fit

$$f(t) = K + \boxed{S_{g2}\sin(\omega t)} + C_{g2}\cos(\omega t)$$

$$+e^{-t/\tau_{CBO}}\left[S_{CBO}\sin\left(\omega_{CBO}\left(t-t_0\right)+\Phi_{CBO}\right)+C_{CBO}\cos\left(\omega_{CBO}\left(t-t_0\right)+\Phi_{CBO}\right)\right]$$

$$+Me^{-t/\tau_M}$$

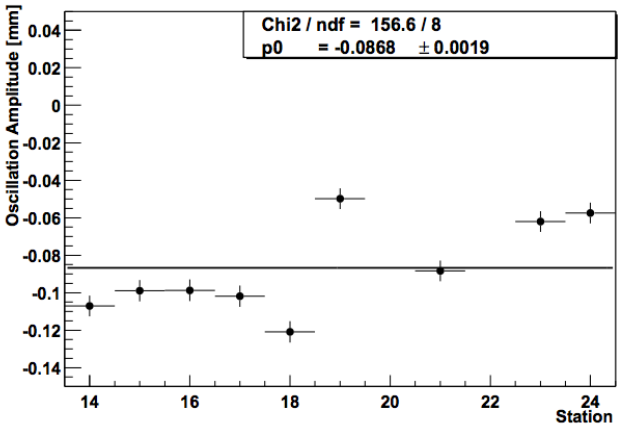
Slow changes in detector response, pileup

The average vertical position is centred on ~3mm (detector misalignment)

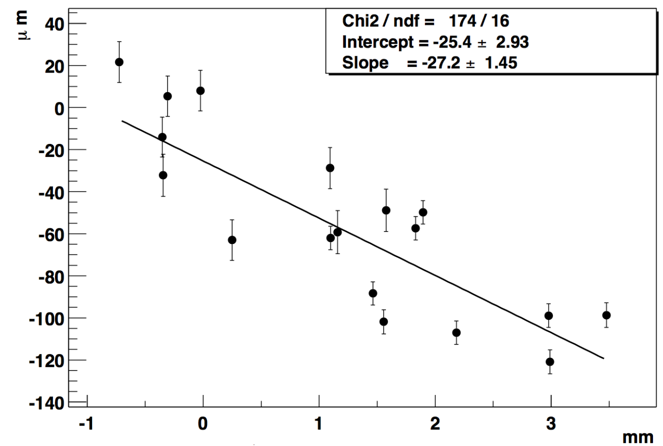
Correct for detector misalignment

A misalignment of the detectors with the beam can show up in the EDM amplitude

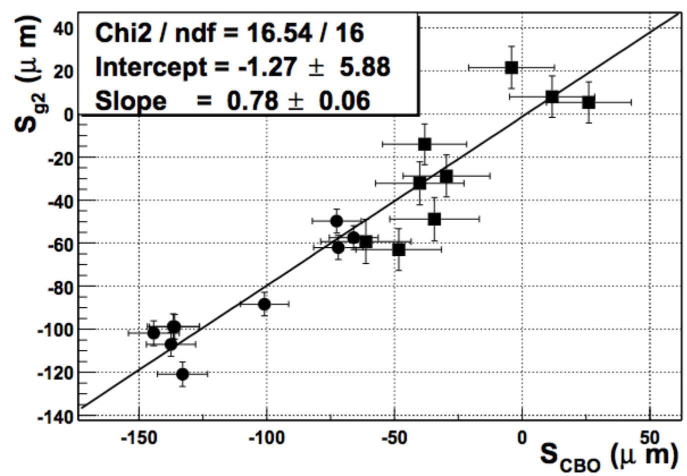
Seen in the difference in the sine amplitude between stations



And the correlation between the offset and the amplitude



Expected the oscillations at the CBO and g-2 frequencies both to be due to the width oscillations combined with the detector misalignment



Plot the CBO amplitude against the g-2 sine amplitude

→ Intercept corresponds to the EDM

→ $S_{g2}(0) = (-1.27 \pm 5.88)\ \mu m$

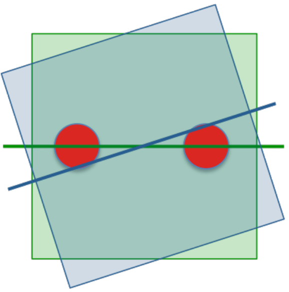
Simulation : $(8.8 \pm 0.5)\ \mu m$ per 10^{-19} e cm → $d_{\mu} = (-0.14 \pm 0.67) \times 10^{-19}$ e cm

Vertical position uncertainties

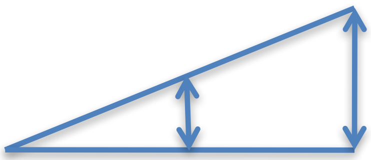
Statistical error
5.88 μm

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

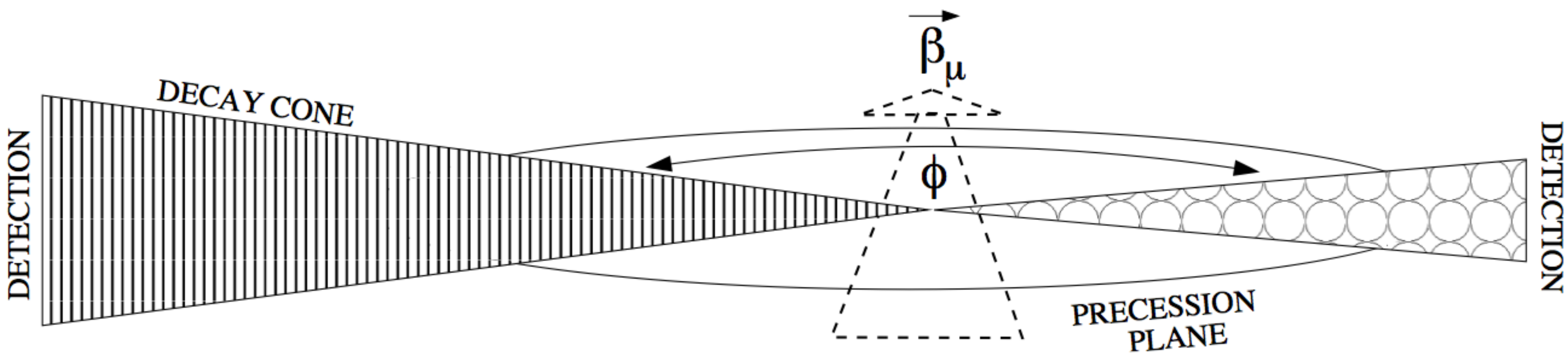
Back scattering from the calorimeter

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

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

Measuring the EDM – phase

We expect the fitted phase to change as a function of vertical position even in the absence of an EDM



Outward decays have a longer path length before reaching the calorimeter

→ Tend to hit further away from the centre of the detector

→ There are more outward going decays hitting the top and bottom

Also the decays that hit the top and bottom have to travel further

→ Slight difference in the time they were created

There is a different mix of phases at different parts of the calorimeter

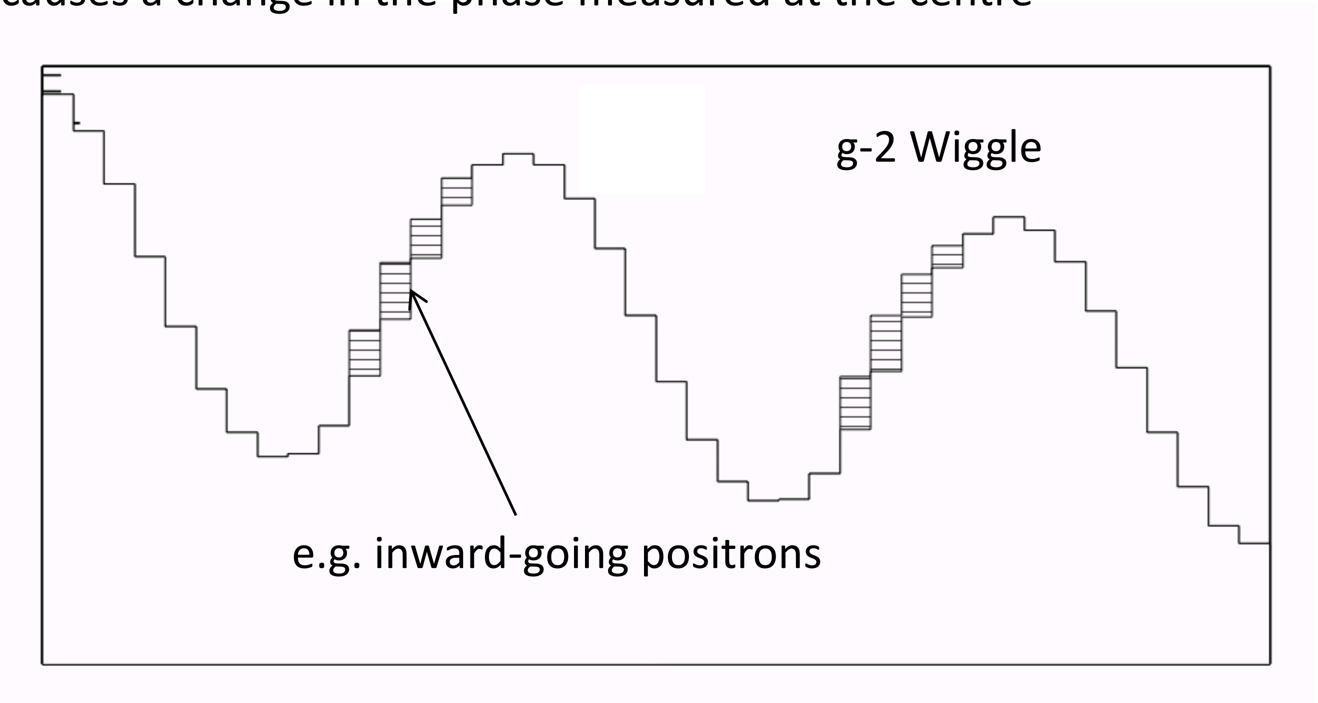
Measuring the EDM – phase

We expect the fitted phase to change as a function of vertical position even in the absence of an EDM

The inward going and outward going positrons are 180 degrees out of phase with each other

→ In the centre of the calorimeter there are more inward going decays detected

→ This causes a change in the phase measured at the centre

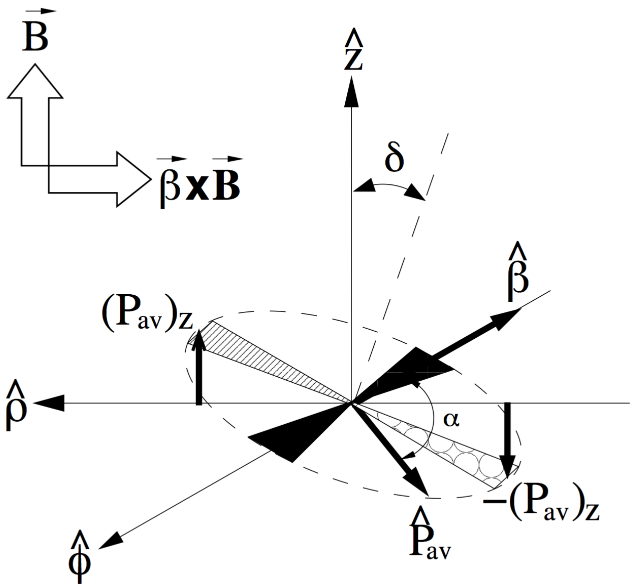


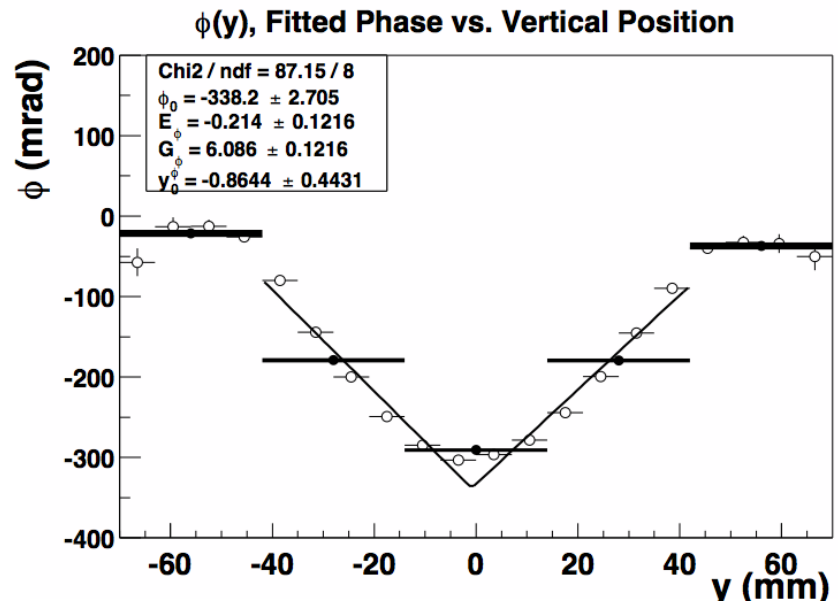
The opposite effect happens at the top and bottom of the calorimeter where there are more outward going decays detected

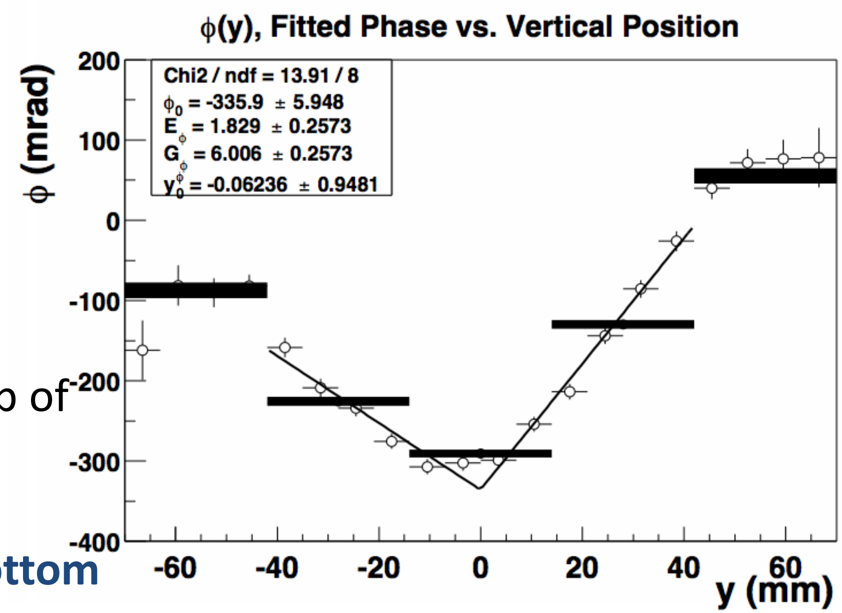
Measuring the EDM – phase

Without an EDM we therefore expect the phase to change symmetrically across the calorimeter face :

In the case there is an EDM the precession plane is tilted :







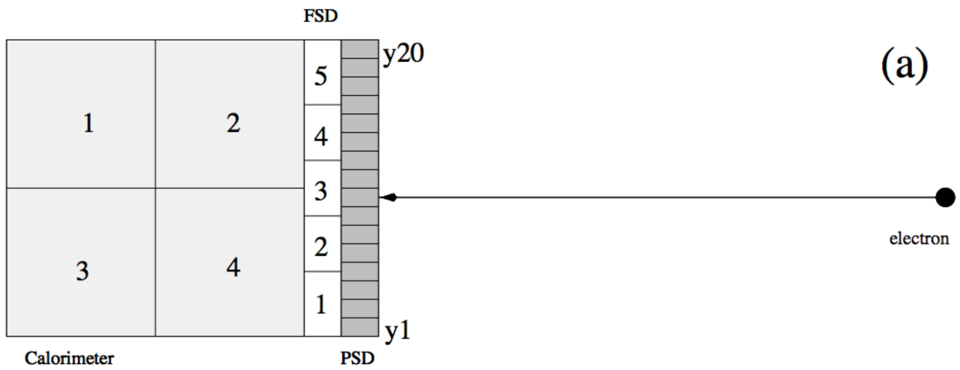
This biases the outward going decays to be at the top of the calorimeter

- → **Causes a skew in the distribution**
- → **Suppresses the phase difference at the bottom**

Measuring the EDM – phase

Consider the phase variation as a function of vertical position

This was measured using the PSDs and FSDs



The energy measurement isn't reliable at the edges of the calorimeter

→ Only use 3 central FSDs, 12 central PSDs

The distribution is fit to extract the asymmetry :

Arbitrary phase

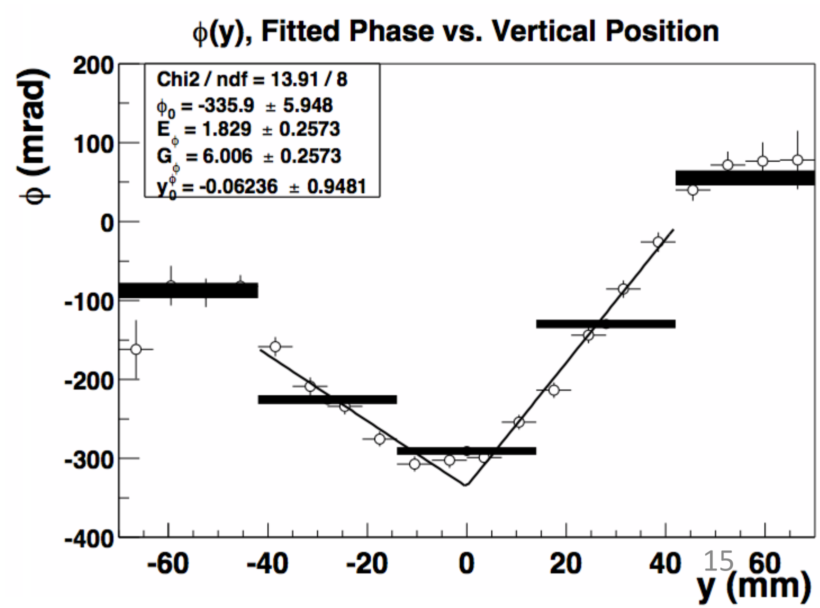
Muon mid plane

$$\phi(y) = \phi_0 + \boxed{E_\phi}(y - y_0^\phi) + |G_\phi(y - y_0^\phi)|$$

Up-down asymmetry

EDM

Phase changes not related to EDM

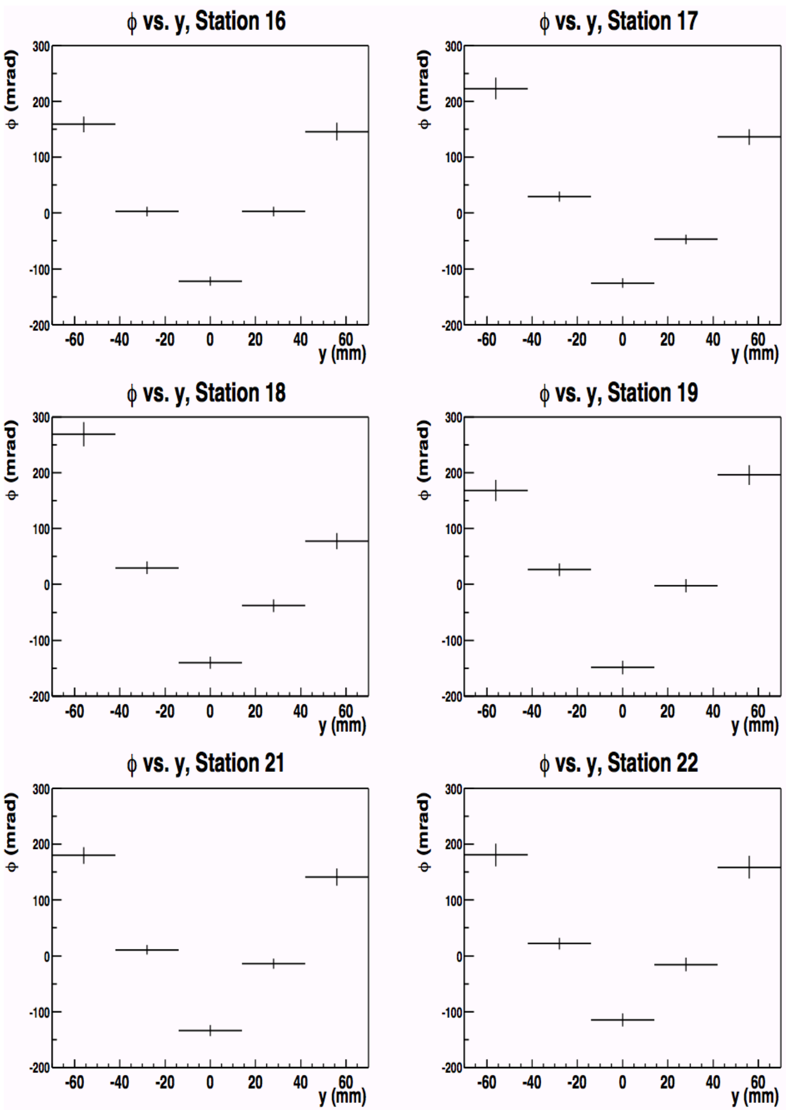


For FSDs, just use : $\Delta\phi = \phi_4 - \phi_2$

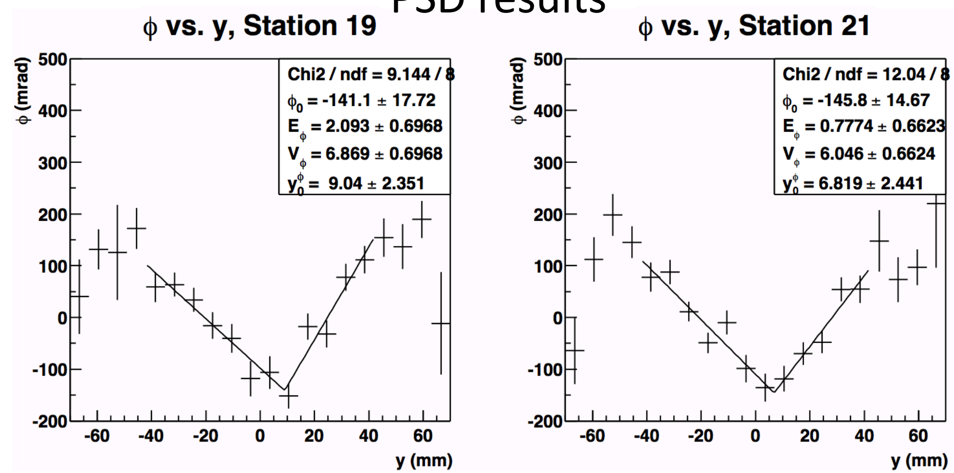
Measuring the EDM – phase

The results show some variability between stations

FSD results



PSD results



Can see that the distributions are not exactly symmetric

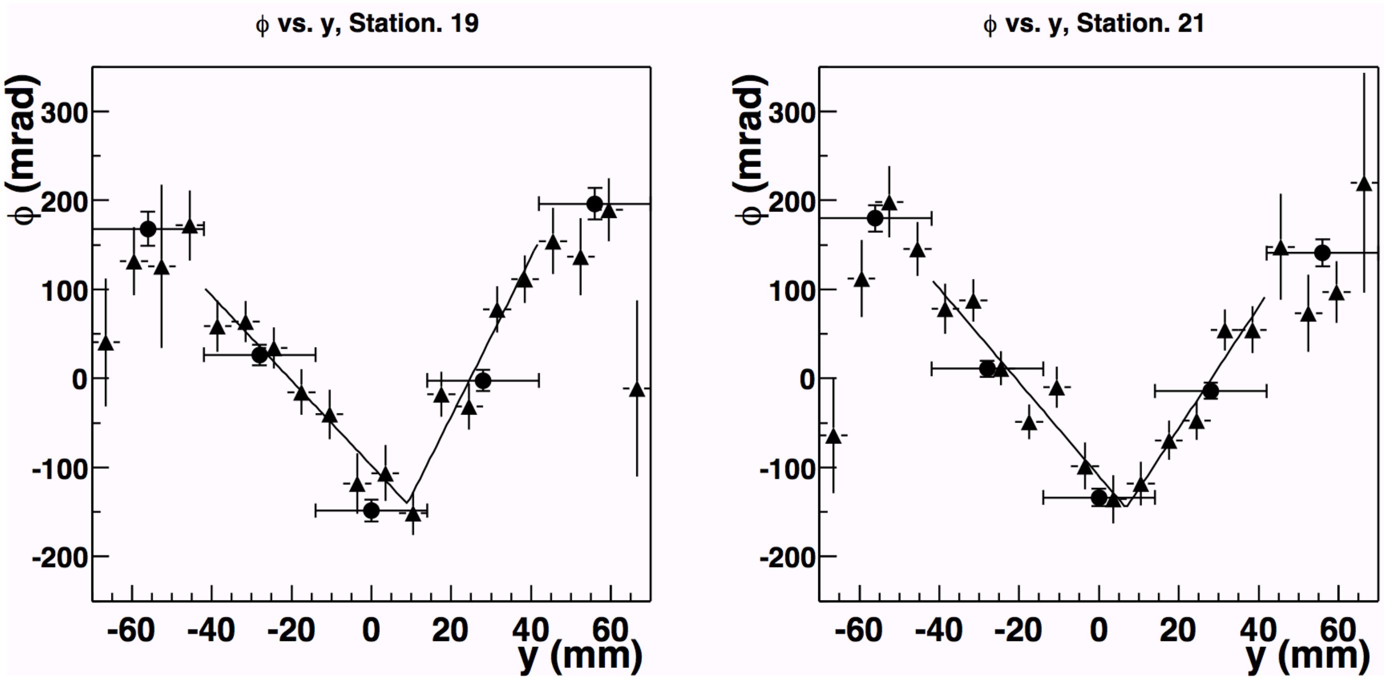
→ But we haven't included systematics

There is a large variability between stations

→ Indicates its likely to be due to misalignment

Measuring the EDM – phase

The FSD and PSD results agree when overlaid



Station	y_0^ϕ(mm)	E_ϕ (mrad/mm)	G_ϕ (mrad/mm)	$\phi_0(mrad)$	χ^2_ϕ
19	9.040 ± 2.351	2.093 ± 0.6968	6.869 ± 0.6968	-141.1 ± 17.72	1.14
21	6.819 ± 2.441	0.7774 ± 0.6623	6.046 ± 0.6924	-145.8 ± 14.57	1.51

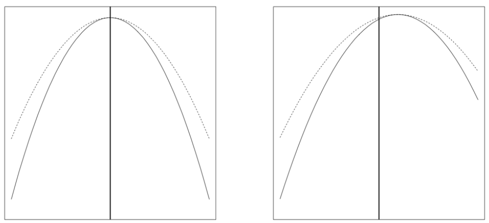
Station 19 would indicate an EDM but station 21 is consistent with 0

The two detectors agree – indicates this is most likely an alignment effect

Phase uncertainties

The systematic uncertainities are similar to the vertical position measurement

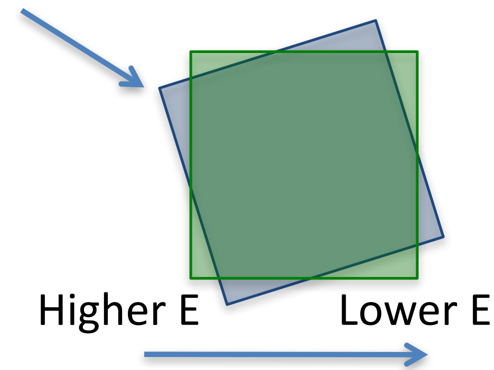
Detector misalignment is more important



induces an up down asymmetry
→ fake EDM signal

Detector Tilt

causes asymmetric vertical loses



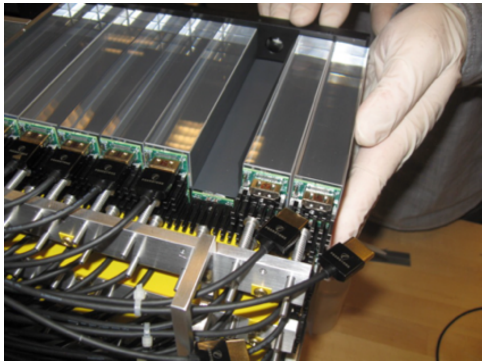
Source	Sensitivity	Result
Detector Tilt	26 μrad/mm/mrad$\times$ 0.75 mrad	20 μ rad/mm
Detector Misalignment	138 μrad/mm/ mm $\times$ 0.2 mm	28 μ rad/mm
Energy Calibration	43 μrad/mm/ % $\times$ 0.1%	4.3 μ rad/mm
Muon Vertical Spin	1.0 μrad/mm $\times$ 8%	8.0 μ rad/mm
Radial B field	0.72 μrad/mm/ppm $\times$ 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

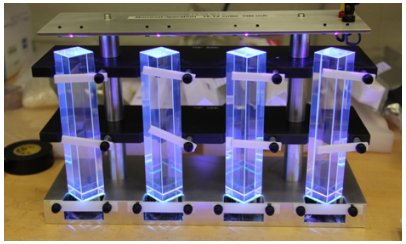
Calorimeter analyses E989

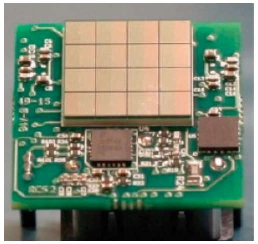
The calorimeter based analyses are mostly systematics dominated



Have a segmented calorimeter (6x9 cells)

→ E821 used scintillator panels on the the front of about half calorimeters





Planned improvements:

- **Calorimeter segmentation**

  Improves ability to control pileup, beam position, detector tilt
- **Laser calibration system and lower energy acceptance**

  Improves the timing information and energy/gain calibration
- **Reduced CBO oscillations**
- **Introduction of 3 straw tracking stations**

  Improves the knowledge and monitoring of the beam distribution
- **Increased statistics**
- **BMAD / G4Beamline simulations** all the way from the production target

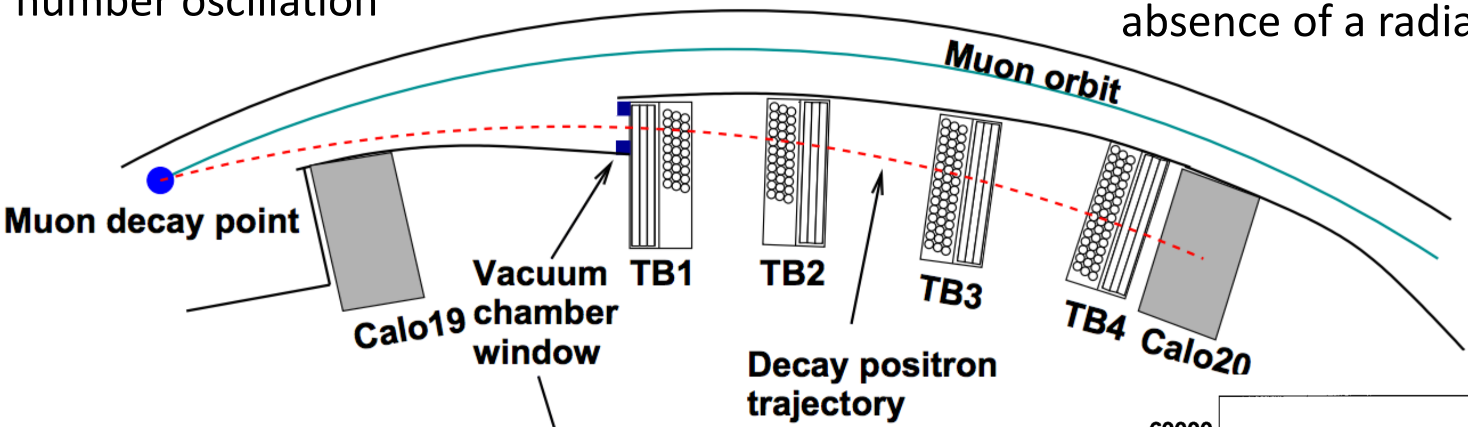
Vertical decay angle oscillations

Look for an oscillation in the vertical decay angle of the positrons measured by the tracker

An EDM would produce a vertical oscillation 90° out of phase from the number oscillation

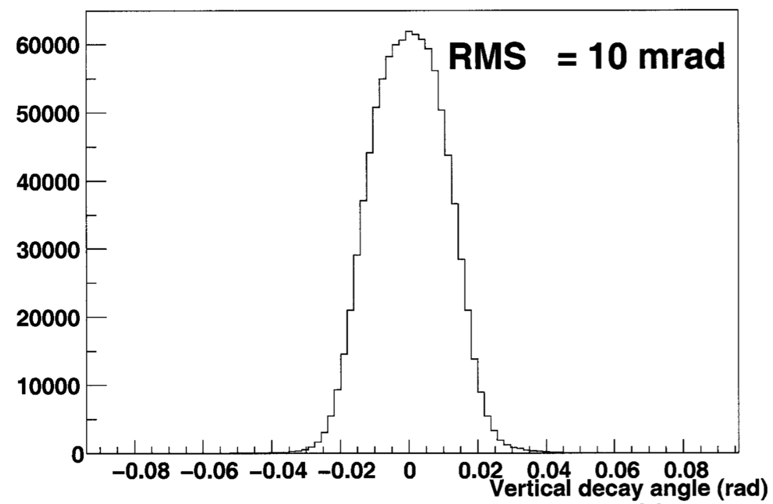
Use the tracker to reconstruct the vertical angle of the positron at decay

(same in the tracker as at decay in the absence of a radial magnetic field)



The positron decay distribution has a 10 mrad RMS width around the muon spin direction

Sets the intrinsic resolution to an EDM signal

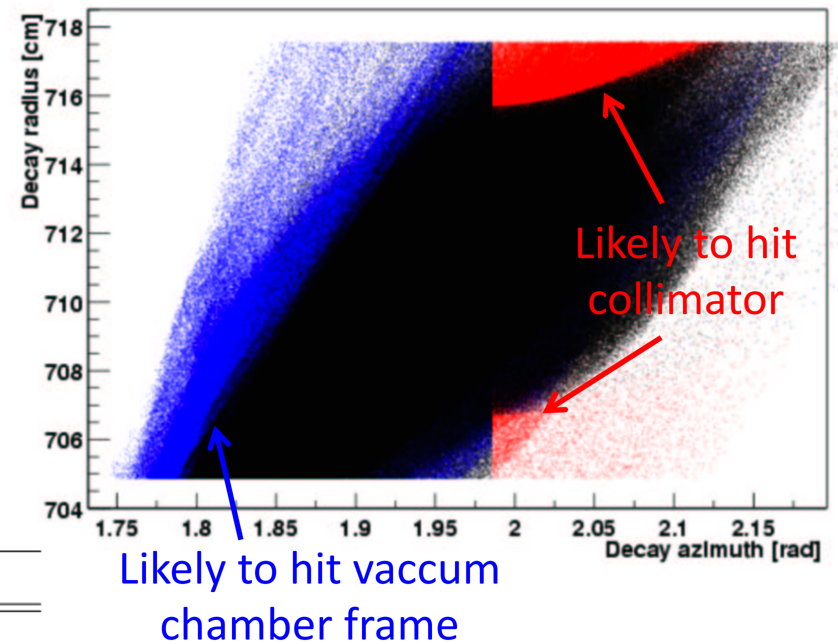


Much less dependent on detector alignment, statistics dominated measurement

Selection of events

The tracks used in the analysis should not pass through massive objects which could cause deflections in the track

Tracks from the red and blue regions are removed



Cuts are also made to select regions which have the highest, flattest acceptance (to prevent the need for corrections):

Parameter	Cuts
Momentum	1.5 GeV/c to 2.6 GeV/c
Azimuth	1.8 rad to 2.2 rad from inflector
Transverse position	$\sqrt{r^2 + z^2} < 4.5$ cm (circular aperture)
Time	130 μs to 600 μs after injection

Greater than 2.6 GeV the large radius of curvature produces large errors the decay point

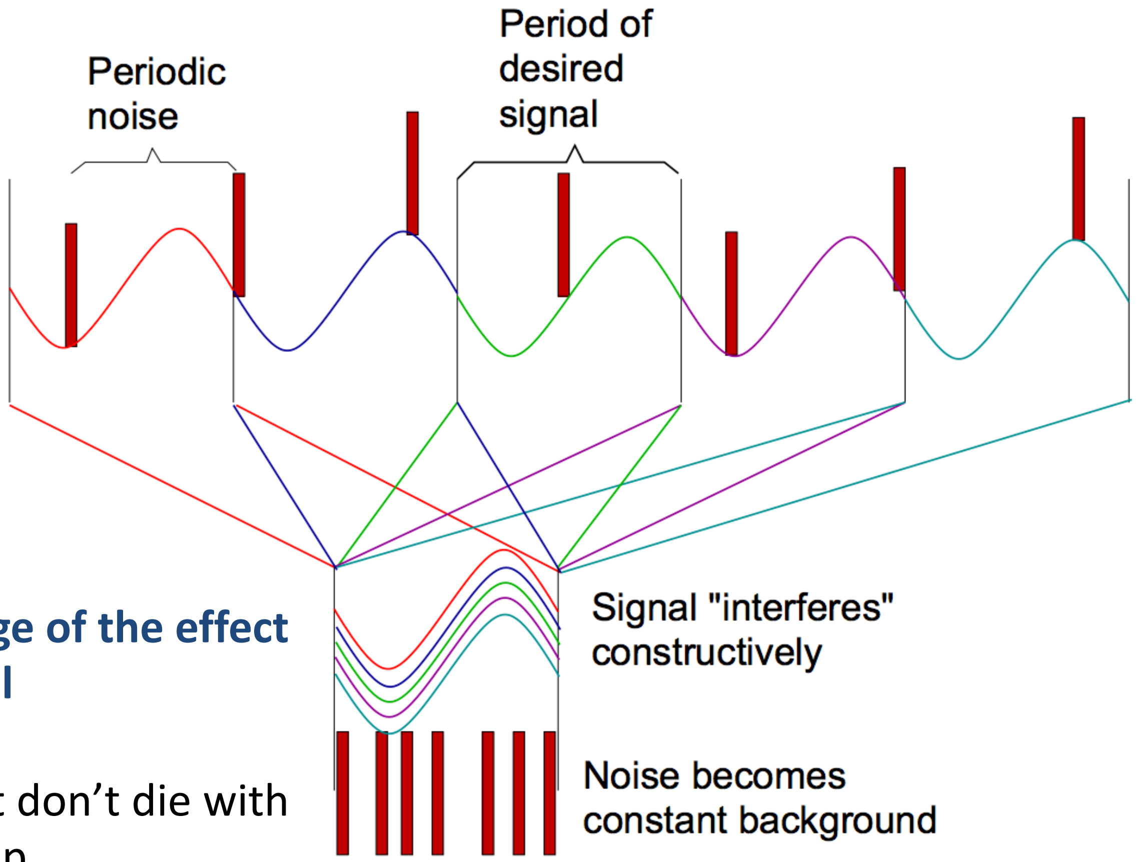
Such that they come from the 9cm diameter storage region

To cut out high rates at early times after injection

Period Binned Analysis

Plotting the data modulo the precession period minimizes period disturbances at other frequencies and non periodic effects

The period of the vertical oscillations that would indictate an EDM are known from the ω_a analysis



The resulting plot shows the average of the effect over the time interval

→ Only effects that don't die with time will show up

→ Suitable for looking at the EDM, not for looking at CBO

Fitting the number oscillation

Step 1 : Fit the number oscillation modulo the precession period to extract the phase

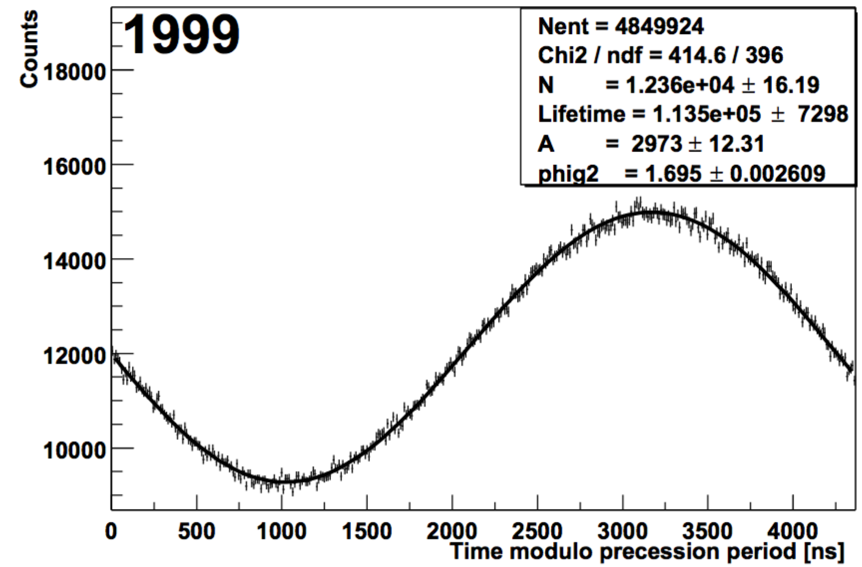
The precession period is taken from the g-2 analysis :

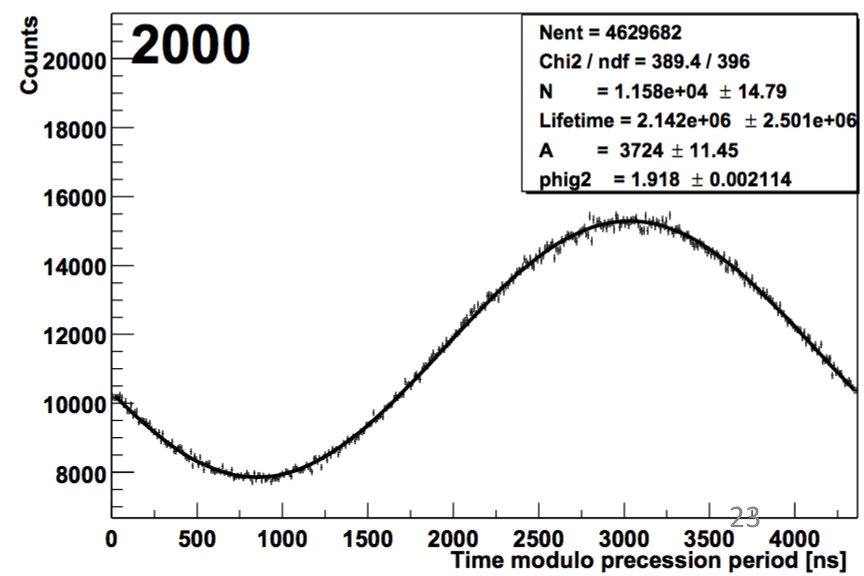
$$T = \frac{2\pi}{\omega} = 4365.4\,ns$$

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

The lifetime characterises the muon decay and the detector rate acceptance

Fit to find φ, such that the number oscillation is in the cosine term





Fitting the vertical angle oscillation

Step 2 : Fit the vertical angle oscillation modulo the precession period

$$T = \frac{2\pi}{\omega} = 4365.4\,ns$$

from g-2 analysis

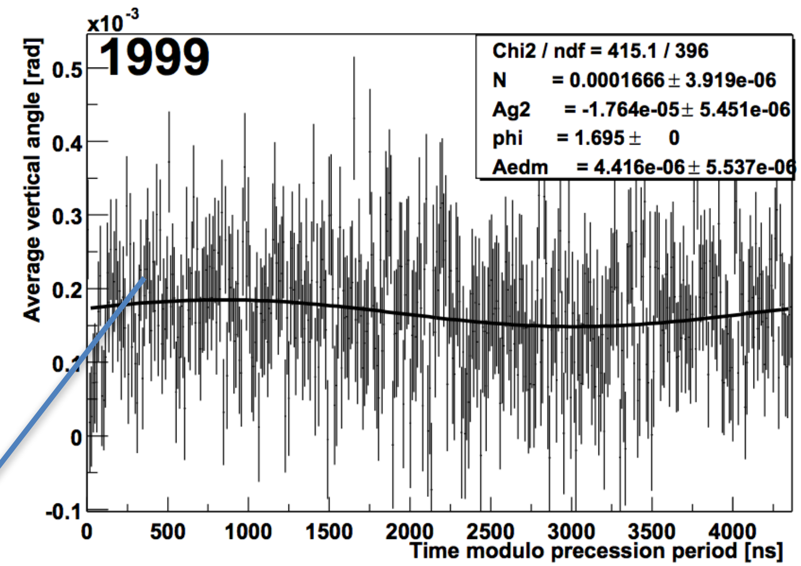
Fixed from number oscillation fit

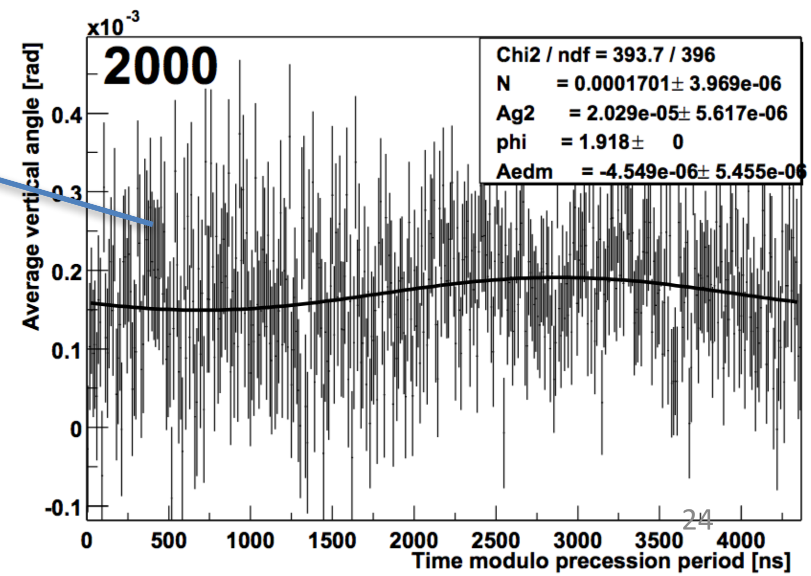
$$\theta(t) = M + A_\mu \cos(\omega t + \Phi) + \boxed{A_{EDM}} \sin(\omega t + \Phi)$$

EDM oscillation comes in 90° out of phase from the number oscillation

RMS ~10mrad for each bin, as expected

1999 : 4.4 ± 5.5 μrad
2000 : -4.5 ± 5.4 μrad



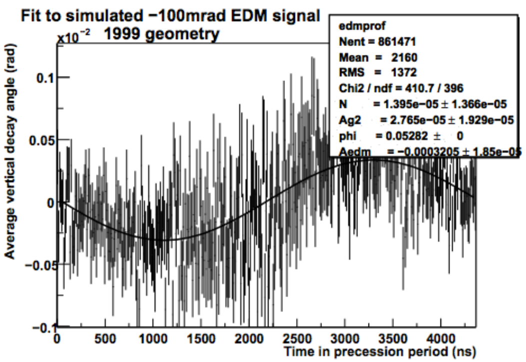


Conversion to precession plane tilt

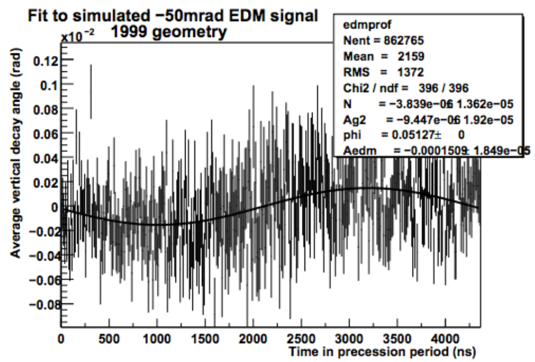
The amplitude of the oscillations in vertical angle are converted into a precession plane tilt using simulation

The boost to the momentum between the MRF and the lab frame means the measured vertical angle oscillations don't directly correspond to the precession plane tilt

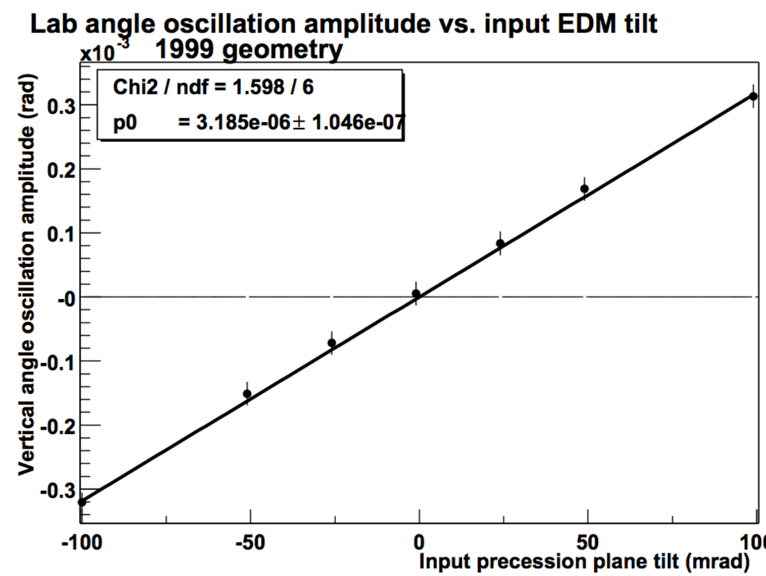
Simulate different tilts to work out the corresponding oscillation

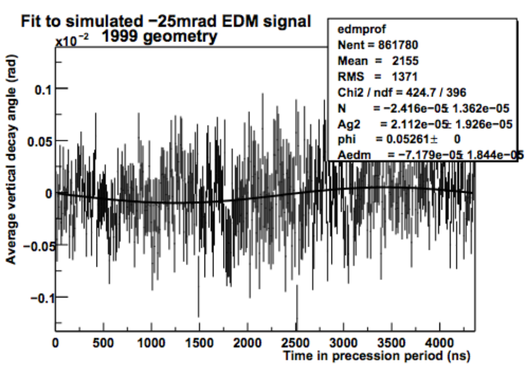


(a) -100 mrad simulated signal

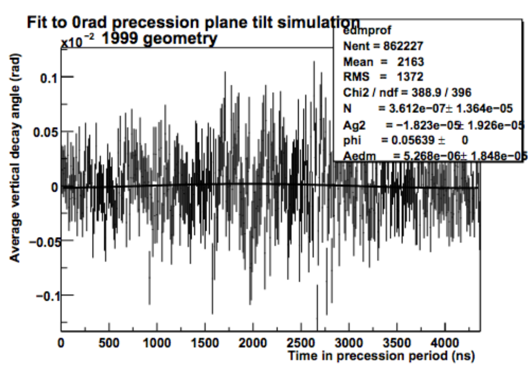


(b) -50 mrad simulated signal





(c) -25 mrad simulated signal



(d) 0 mrad simulated signal

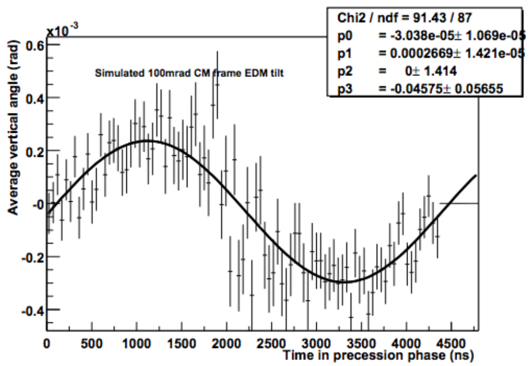
1 mrad precession plane tilt = 3μrad oscillation amplitude

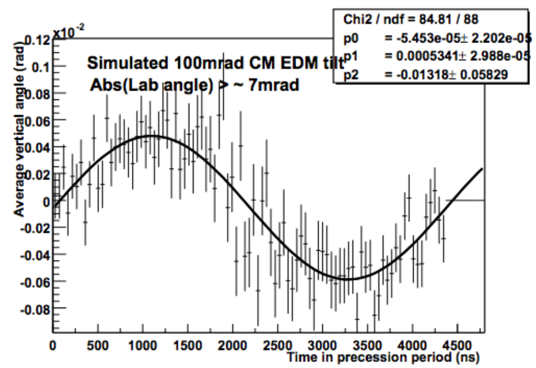
Maximising Signal to Noise

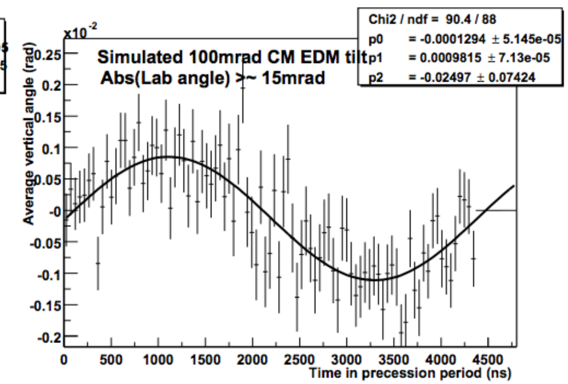
As particles with small angles are though to carry little of the signal the significance of the measurement could be improved by cutting them out

To test this hypothesis use simulation with a tilt angle of 100mrad:

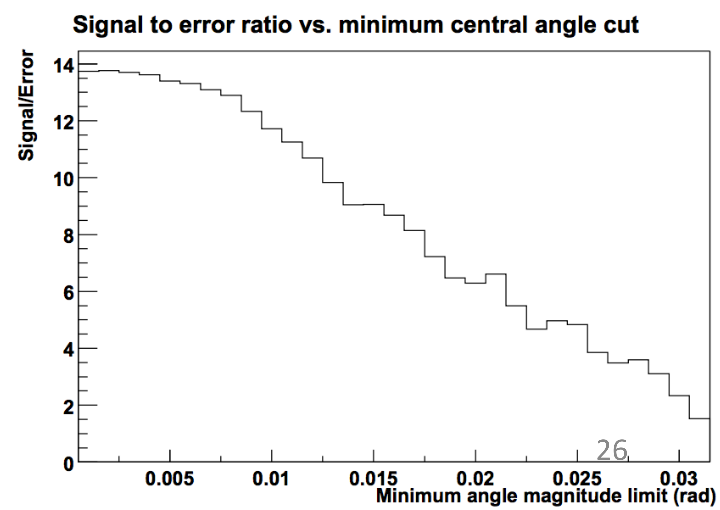
- Plot average vertical decay angle vs time for different cuts on the decay angle
- Calculate the ratio of the signal to the error for each value







The amplitude of the signal increases with increasing minimum angle cuts but the errors also increase



Placing any cut reduces the signal/noise

→ The changes at the centre of the distribution provide valuable information

Maximising Signal to Noise

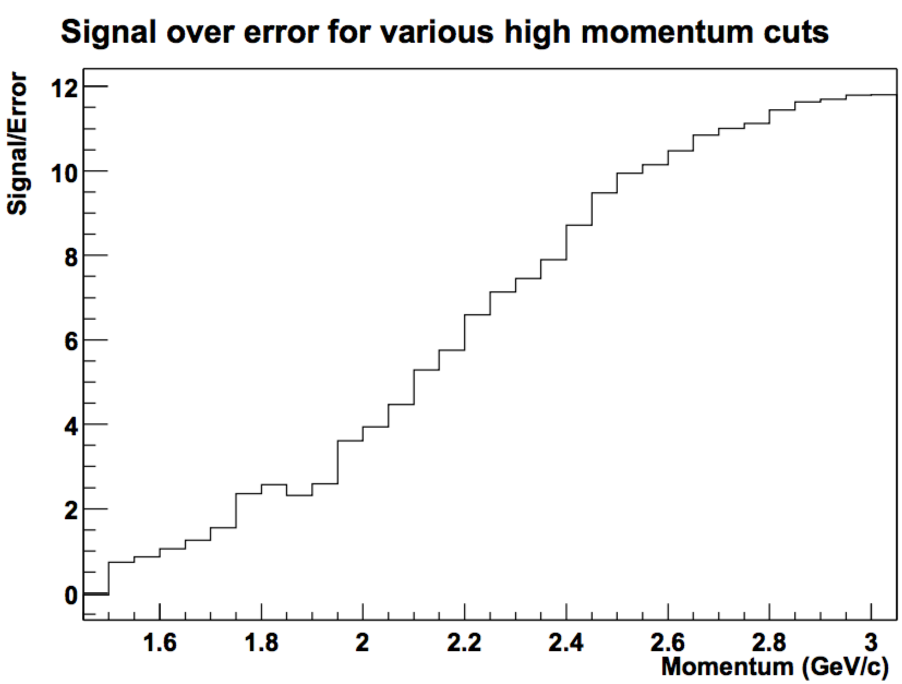
Consider whether cuts on the momentum can improve the signal to noise

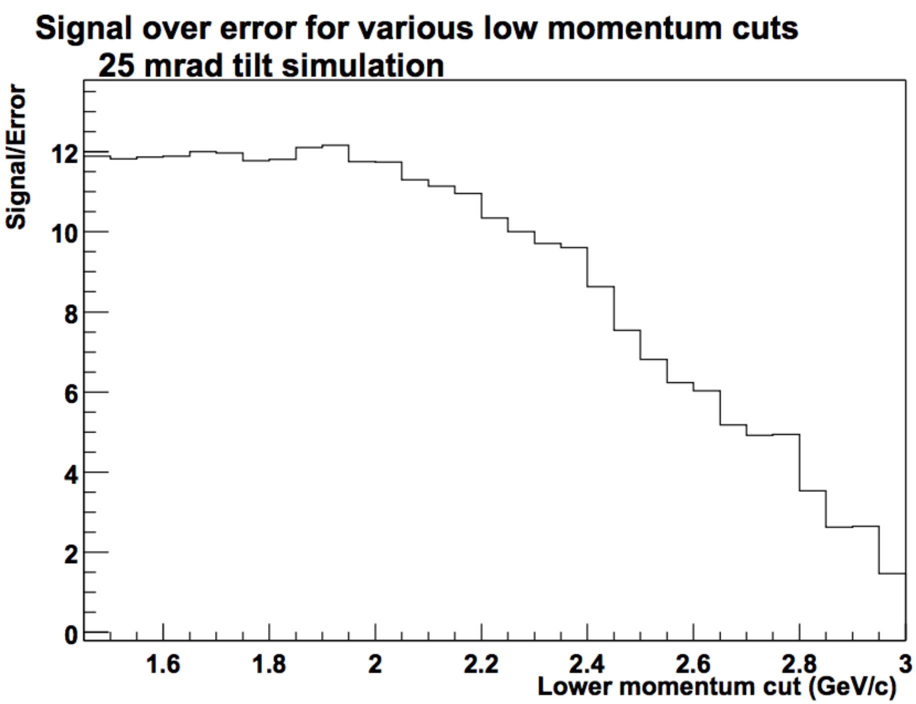
The highest momentum positrons tend to come when the spin is aligned with the muon momentum

→ **where the EDM signal is minimal**

The lowest momentum positrons are less aligned with the spin

→ **could dilute the asymmetry**





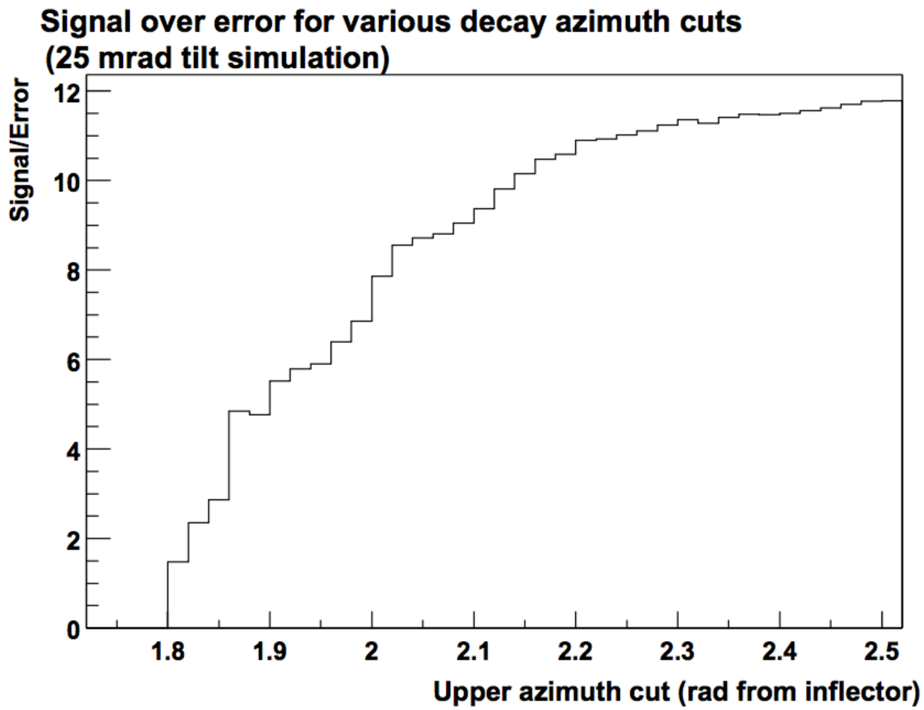
In both cases the signal to noise is reduced by applying a cut, valuable information comes from all particles included

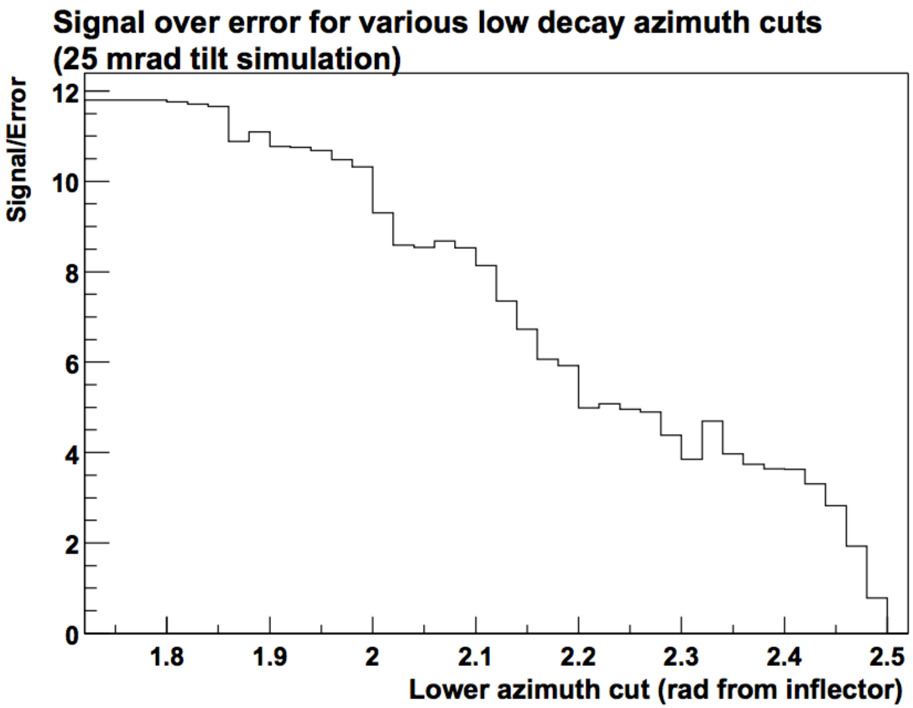
Maximising Signal to Noise

Lastly a cut in azimuth was considered to improve the signal to noise

The range of accepted angles varies as a function of azimuth

→ There could be a region in azimuth where the signal is reduced





Again, any cut decreases the signal to noise

Although applying some cuts improves the size of the signal the increase is not statistically advantageous to the measurement

Decay angle uncertainties

Main systematic uncertainties to be considered for this method:

Radial Magnetic field:

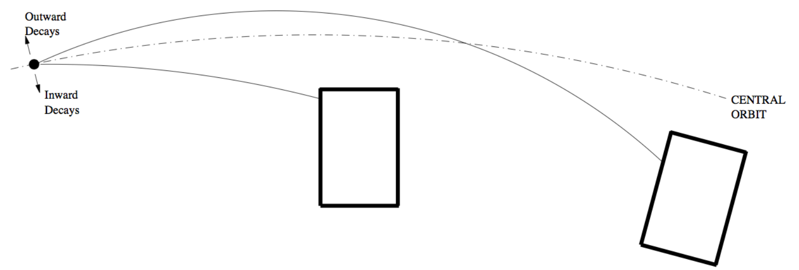
Would cause a tilt in the precession plane

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

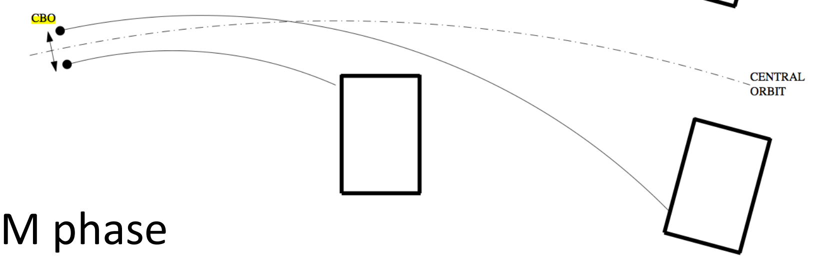
Detector acceptance:

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 (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

E821:

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

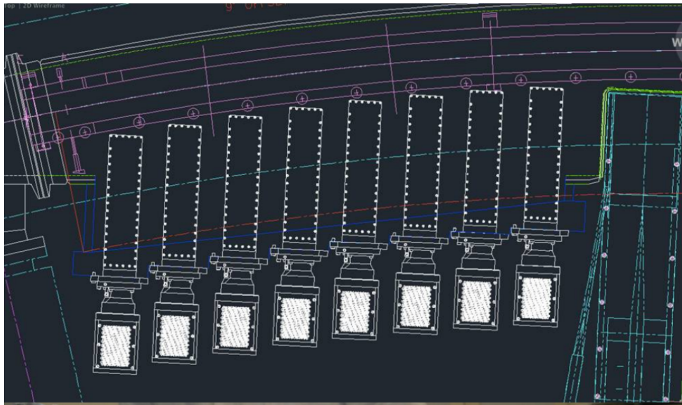
→ $d_\mu = (-0.04 \pm 1.6) \times 10^{-19}$ e•cm

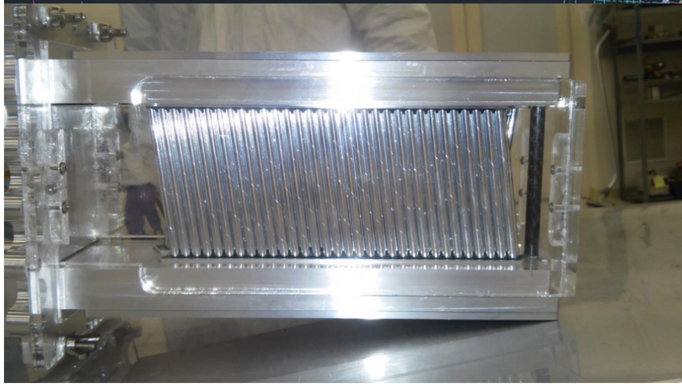
→ $|d_\mu| < 3.2 \times 10^{-19}$ e•cm (95% C.L)

Dominated by the statistical error

Decay angle E989

The vertical angle measurement was mostly statistics dominated in E821





E989 will be fitted with three straw tracking stations around the ring

Each station has 8 modules each with 2 layers of 2 straws tilted at 7.5°

Expect O(1000) times the E821 statistics

(more muons, better acceptance)

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

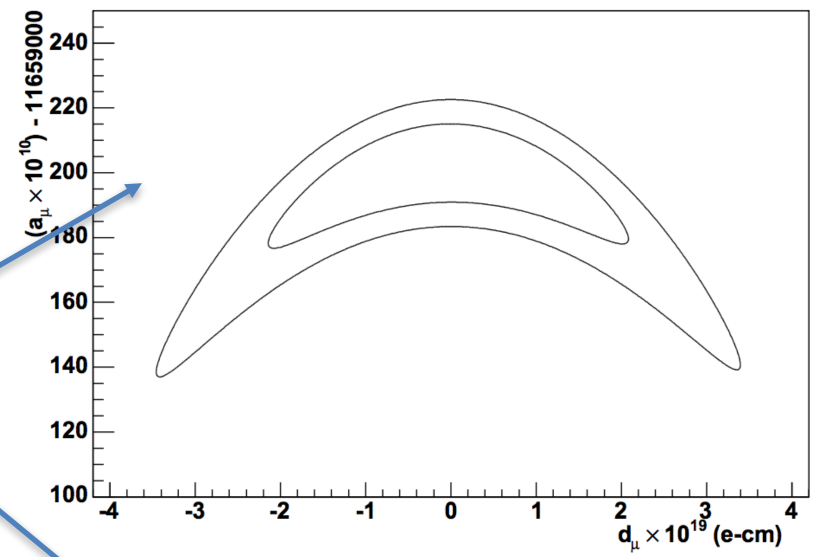
Need to control the systematic errors:

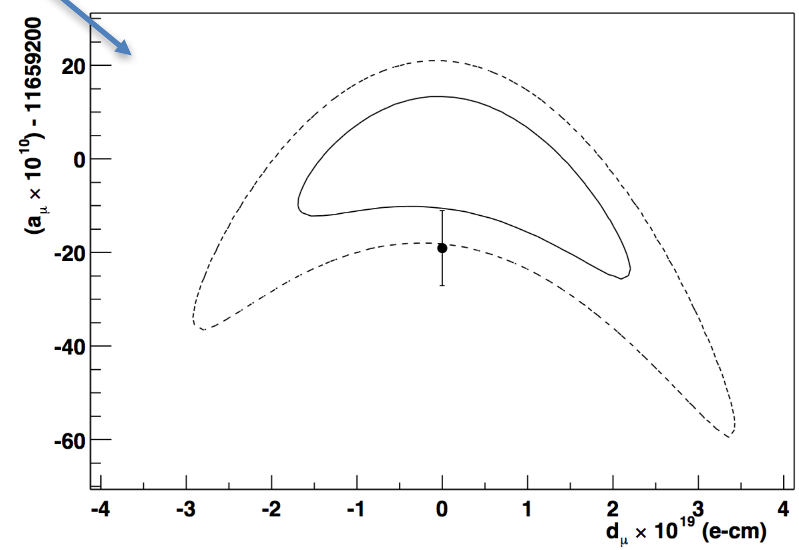
- Amplitude of CBO reduced by factor 4
- Geometrical acceptance increased
- Tracker in vacuum chamber
- Understanding the beam and aligning the detectors well is key

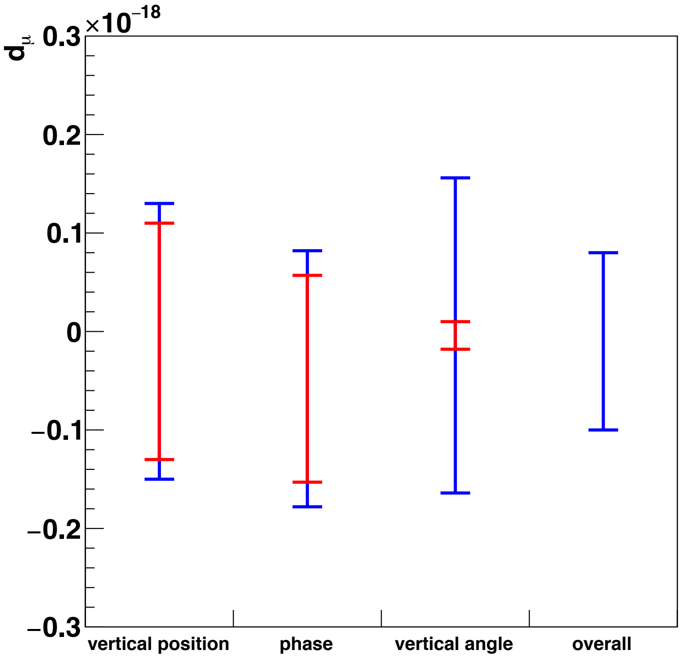
Conclusions

There are several analysis techniques for measuring an EDM at g-2

- Indirectly from the difference of the g-2 phase
- Directly by measuring the vertical decay angle or vertical position oscillation
- Directly by looking at the phase variation as a function of vertical position



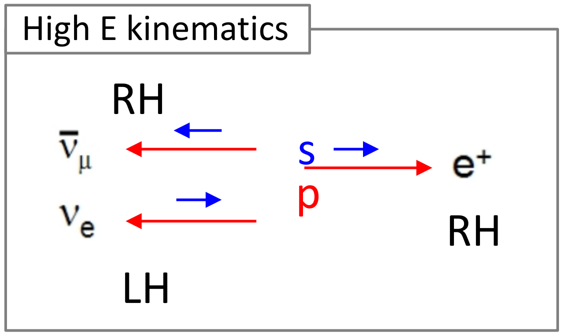




Backup

Measuring the EDM - Indirect

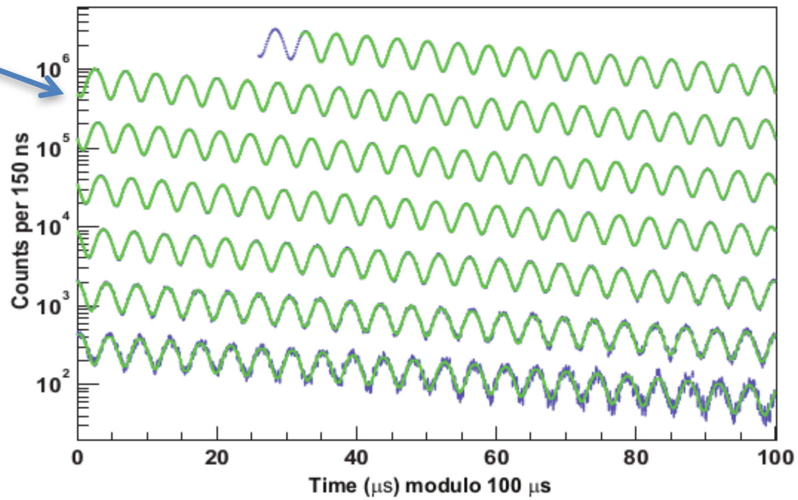
Look for an increase in the precession frequency (compared to SM prediction)



Measure the spin precession via the anti-muon decays:

→ Positrons are preferentially emitted parallel to the muon spin

Count the number of positrons with E > 1.2 GeV hitting the calorimeters

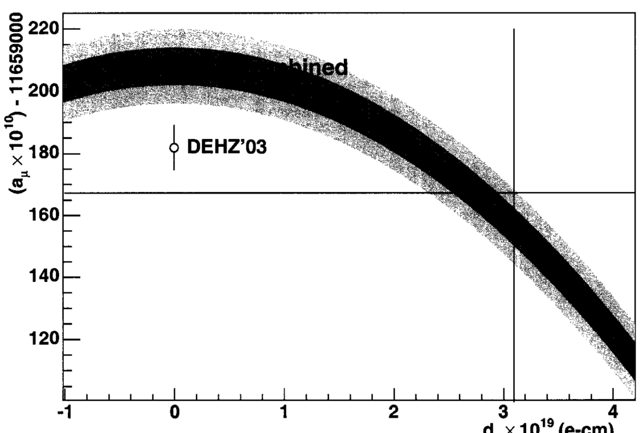


Fit to extract the spin precession:

$$N(t,E_{th}) = N_0(E_{th})e^{-t/\gamma\tau}\left[1 + A(E_{th})\cos(\omega_a t + \phi(E_{th}))\right]$$

Agrees with SM : use error to set limit

Larger than SM : use difference to set limit



E821:

Δa_μ (E821 – SM) = (26.1 ± 9.4) x 10^{-10}

→ $|d_\mu| < 3.1 \times 10^{-19}$ e•cm (95% C.L.)

Vertical position systematic uncertainties

Systematic Uncertainties

Any source of vertical oscillations at either the g-2 or CBO frequencies in the sine component is a source of systematic error

The effect and assessment of the various uncertainties will be discussed over the next few slides

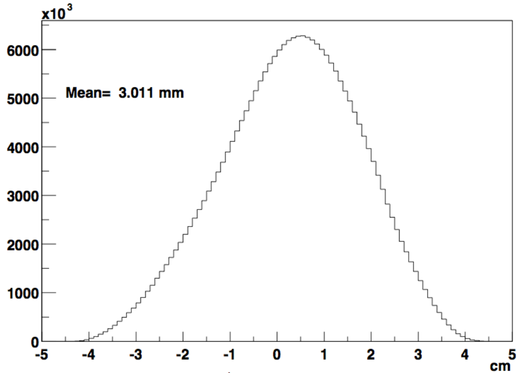
Many of the systematics require the simulation to assess the magnitude of the effect

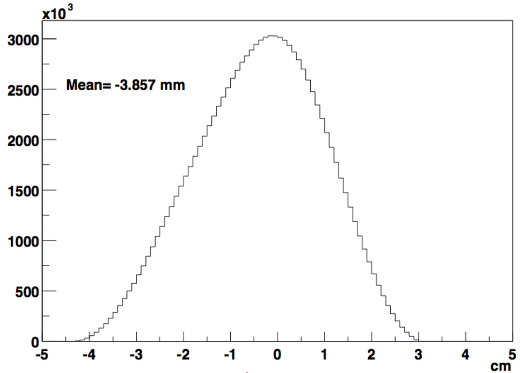
CBO oscillations systematics have reduced effect due to slope of 0.78

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

The CBO oscillations aren't well simulated

→ Produce a horizontally offset beam and use this is assess impact of a beam oscillation





6.8mm change in beam position

→ 0.25 mm change in width

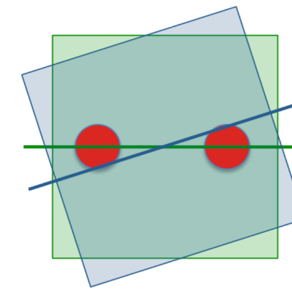
CBO width oscillations : 0.2 mm

→ **5.4mm change in beam position**

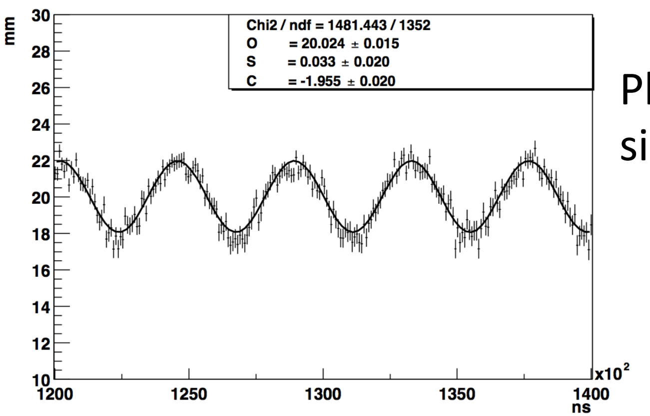
Detector Tilt

If the detector is tilted oscillations in the average horizontal position of positrons can be converted into vertical oscillations :

The tilt of the detectors was measured with a level to be < ½°



Horizontal oscillations at the g-2 frequency:



Plot the average horizontal position as a function of time (in simulation) :

33 ± 20 μm horizontal oscillation in sine term

53μm horizontal oscillation → 0.5μm vertical oscillation

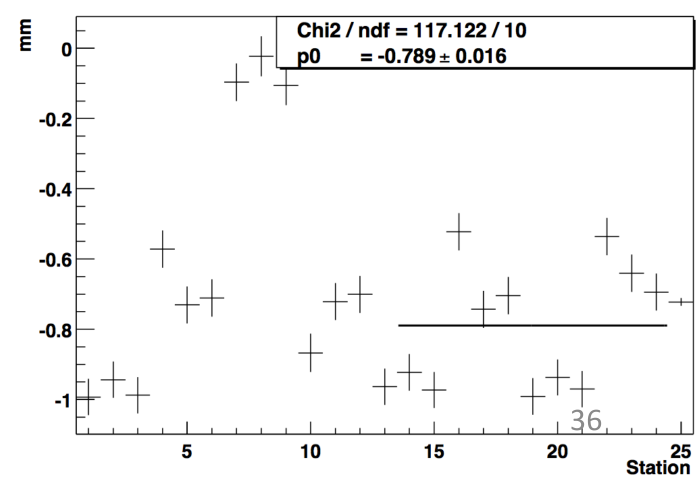
Horizontal oscillations at the CBO frequency:

Plot the horizontal shift on the calorimeters due to the horizontal beam shift :

6.8mm beam shift → 0.79mm horizontal shift

So 5.4mm beam shift → 0.6mm horizontal shift

→ **6.1μm systematic error**

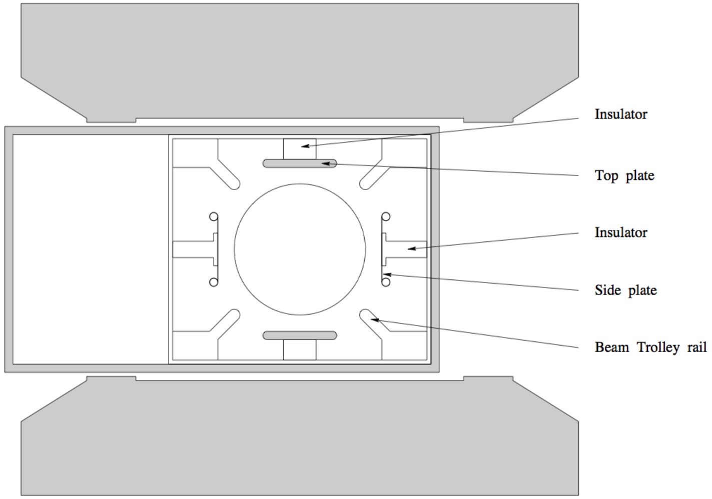


Quadrupole Tilt

A tilt in the quadrupoles would cause a tilt in the plane of the CBO oscillations, introducing a vertical component

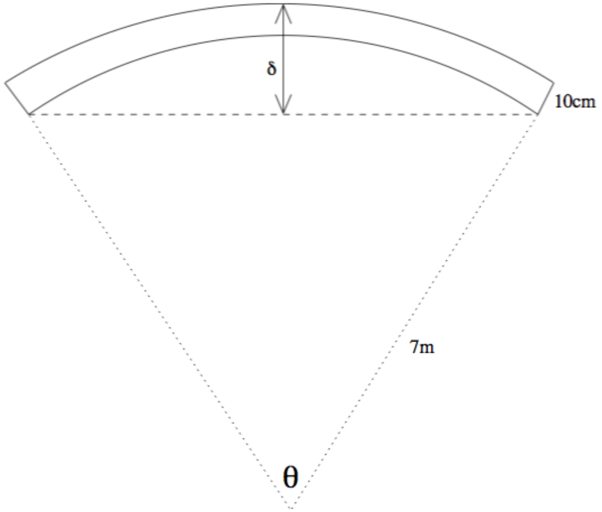
It can be shown that for a tilt in the quadrupoles, θ the **ratio of the horizontal to vertical oscillation amplitudes is** :

$$\frac{A_{vert}}{A_{hor}} = 0.38\theta$$



There are 4 quadrupoles, each consisting of a long piece (30°) and a short piece (15°), placed to better than 0.5mm

Maximum tilt angle : 3mrad long section
6mrad short section



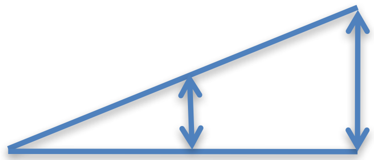
Include additional factors:

- Slope g-2 : CBO amplitudes
- Only using 4 tile mean

→ **3.9µm systematic error**

Muon Vertical Spin

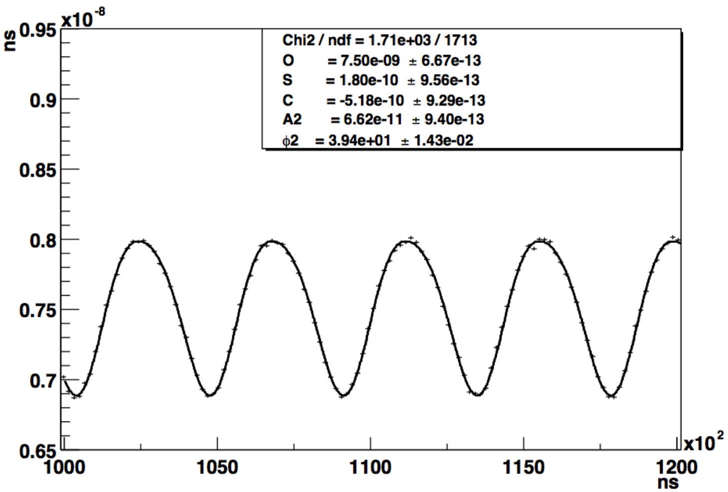
An average vertical muon spin component would result in an average vertical component in the positron momentum



Average positron vertical momentum

+ longer path length for outward going positrons

= oscillation in average vertical position



G-2 oscillation : 0.18 ns path length oscillation

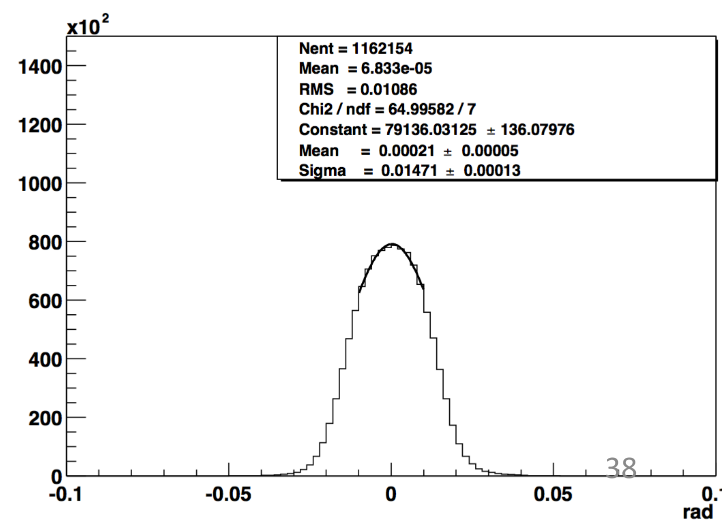
CBO oscillation : 0.16ns path length oscillation

From the tracker :

mean positron vertical angle = 0.21 mrad

→ G-2 oscillation : 11.3µm

CBO oscillation : 10.1µm



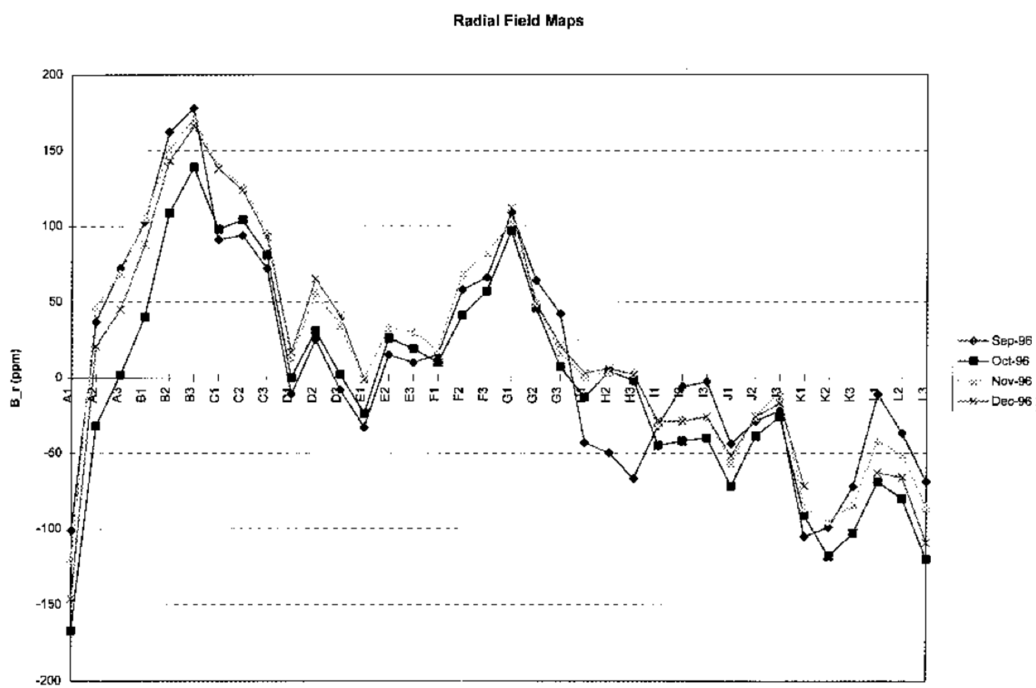
Consider effect on intercept :

→ **5.1µm systematic error**

Radial Magnetic Field

A radial magnetic field would cause the decay positrons to be deflected vertically

Radial magnetic field generally < 100 ppm



A radial magnetic field deflects the positrons vertically :

- → Similar effect to the muon vertical spin
- → Use the path lengths from before to calculate the effect

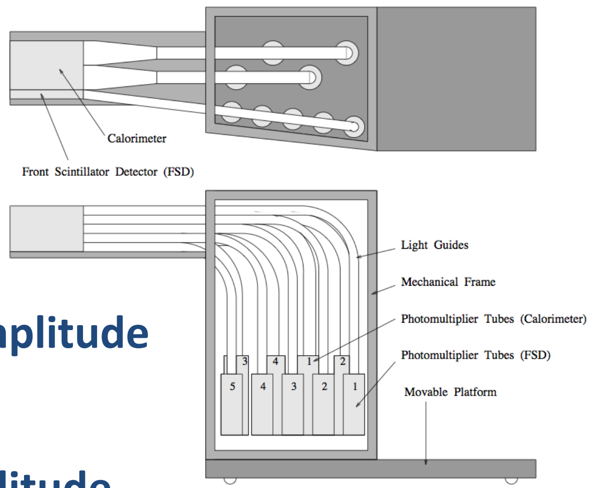
G-2 oscillation : 100ppm x 0.18ns x c = 5.4 µm
CBO oscillation : 100ppm x 0.16ns x c = 4.8 µm

Consider the effect on the intercept:

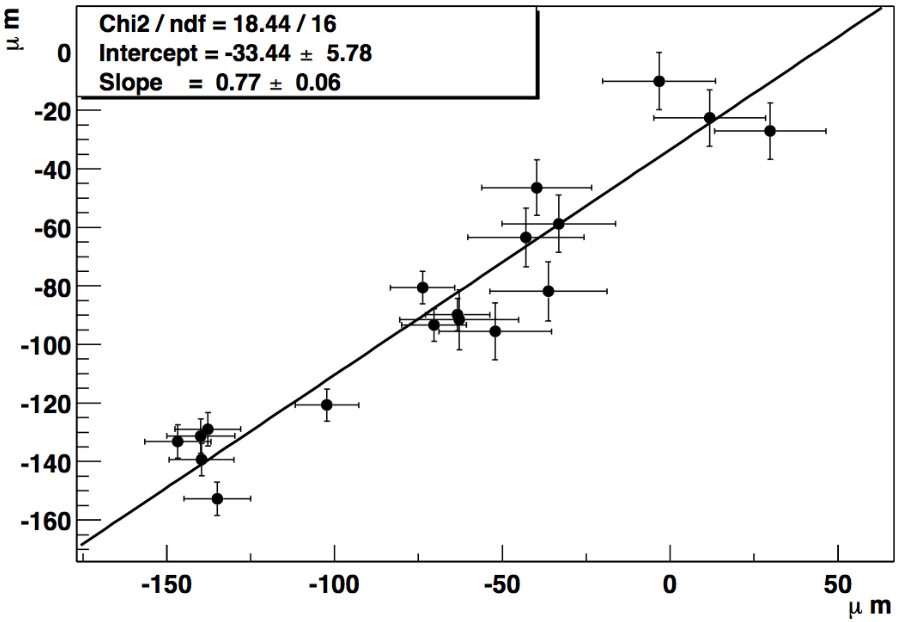
→ **1.7 µm systematic uncertainty**

Timing Offsets

The top and bottom halves of the calorimeter are read out by different PMTs which could have a timing offset



Offset the hits in the top two FSD tiles by 5ns:



CBO oscillation amplitude not affected

g-2 oscillation amplitude shifts by 25 – 30 μm

→ Due to the oscillation in number of hits at the g-2 frequency

32 μm shift in the intercept

Early data shows peaks every 149ns due to the bunched muon beam

→ Plot the positron time spectrum per FSD tile

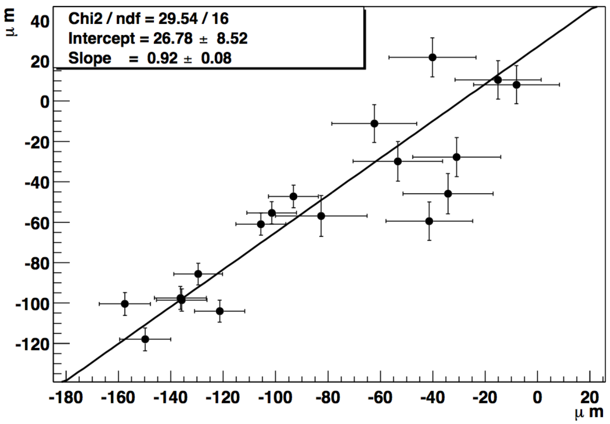
→ Compare the time of each peak

0.5 ns timing difference

→ **3.2 μm systematic error**

Energy Calibration

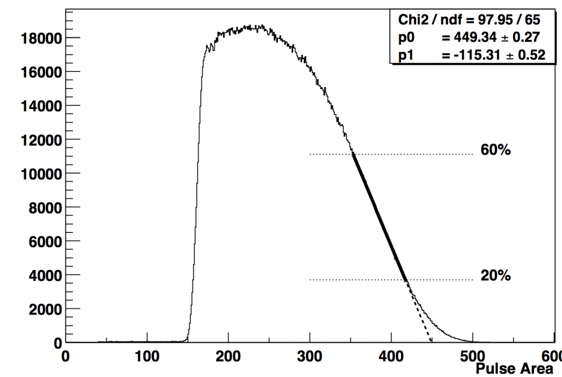
Different PMTs reading out the top and bottom of the calorimeter can also result in a difference in calibration



A tile-by-tile calibration is applied to account for the differences in gain for the different tubes but is not perfect

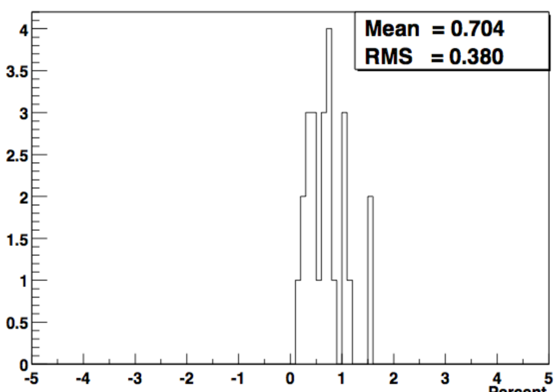
→ Apply a 5% calibration offset to the top 2 FSD tiles

5% calibration offset causes a 28μm shift in the intercept



The energy calibration is calculated by fitting the end point of the pulse area distribution

Change the fit range → 0.2% change



Use simulation to calculate change in endpoint due to a 4.5mm vertical offset in the beam

0.7% change in end point

Detectors maximally offset by 3mm → 0.5% energy calibration error

→ **2.8 μm systematic error**

Doubles

Differences in sensitivities of the FSDs to low energy positrons could cause a systematic error

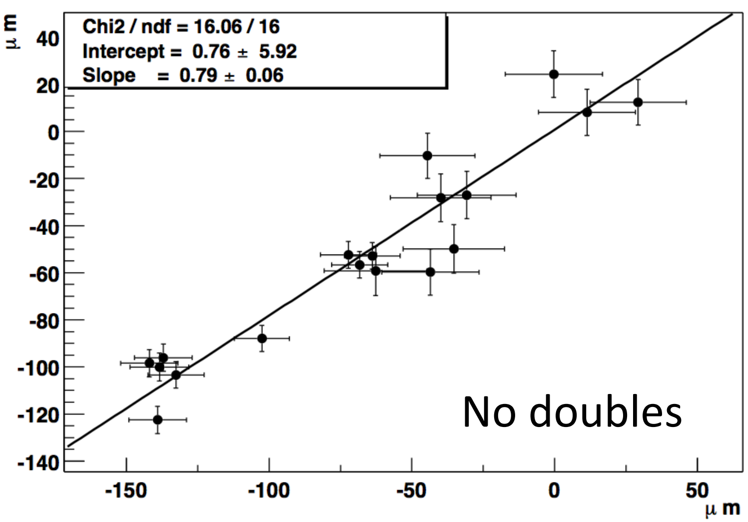
Double hits in the FSD tiles can be caused by:

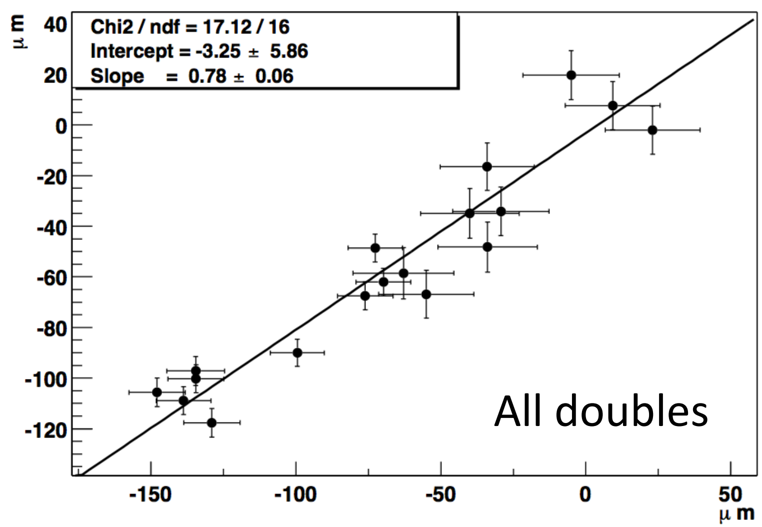
- Pre-showering
- Back scattered electrons from the calorimeter (albedo)

Double hits are thrown away unless they are in adjacent tiles in which case one tile is selected randomly as the hit tile

Consider:

- Accepting no doubles → intercept shifts by +2.0 μm
- Accepting both hits in a double → intercept shifts by -2.0 μm





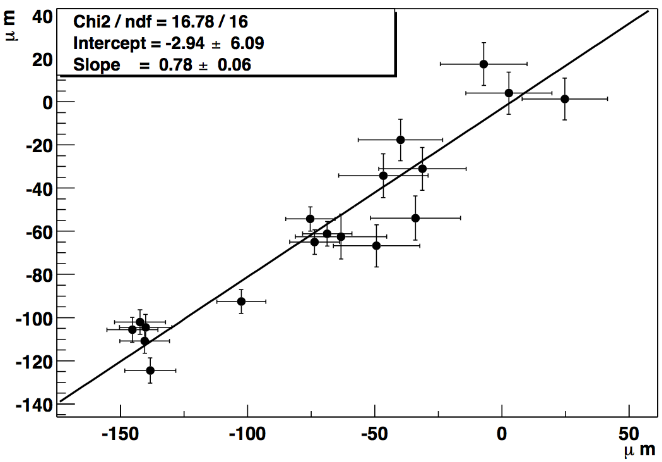
2μm systematic error

Tile Inefficiency and Dead Time

Any differences in efficiency or deadtime of the scintillator tiles could produce a systematic error

Remake the histograms with a 5% tile inefficiency in the top half of the calorimeter

(randomly throw out 5% of the events)



1.6 μm change in intercept

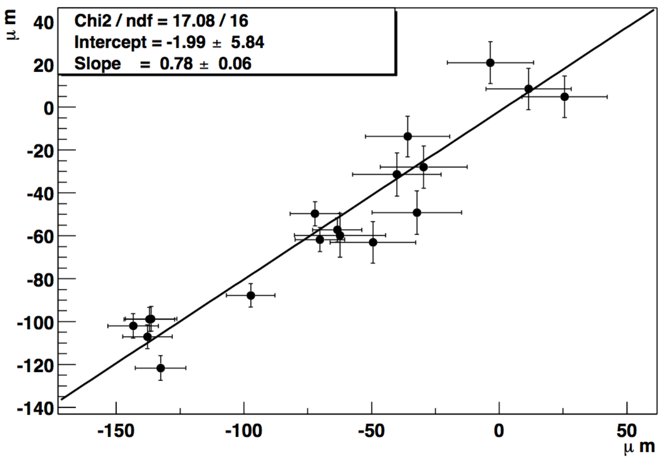
Shifts in the CBO and g-2 amplitudes tend to cancel as any oscillations will be caused by width oscillations

5% inefficiency is way too high

→ **negligible systematic**

Remake the histograms with a 50ns dead time in the top half of the calorimeter

(the tiles have a 20ns dead time)



0.6 μm change in intercept

Dead time difference will not be as high as 30ns

→ **negligible systematic**

Vertical Position Oscillation Results

The systematic uncertainties dominate the measurement

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

There are no obvious correlations between the uncertainties → add in quadrature

Oscillation amplitude = 1.3 ± 11.9 μm

From simulation expect an oscillation of (8.8 ± 0.5) μm per 10^{-19} e cm

$d_\mu = (-0.1 \pm 1.4) \times 10^{-19}$ e cm

Assume the probability for an EDM is a gaussian:

- Centre at the measured value
- Width equal to the uncertainty

Integrate outwards from the central value until 95% is included

-2.9×10^{-19} e cm $< d_\mu < 2.7 \times 10^{-19}$ e cm (95% CL)

For a limit on the absolute value, integrate outwards from 0 (rather than central value)

$|d_\mu| < 2.8 \times 10^{-19}$ e cm

Vertical Decay angle systematics

Radial Magnetic Field

Any radial magnetic field would cause a tilt in the precession plane in the same way that an EDM does

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

If the magnetic field vector is tilted, so is the precession plane vector

Asses the radial field from the vertical mean of the beam :

2mm vertical offset (1999) $\longrightarrow$ 40 ppm radial field

0.2 mm vertical offset (2000) $\longrightarrow$ 4 ppm radial field

40 ppm corresponds to **0.1 μrad vertical angle oscillation**

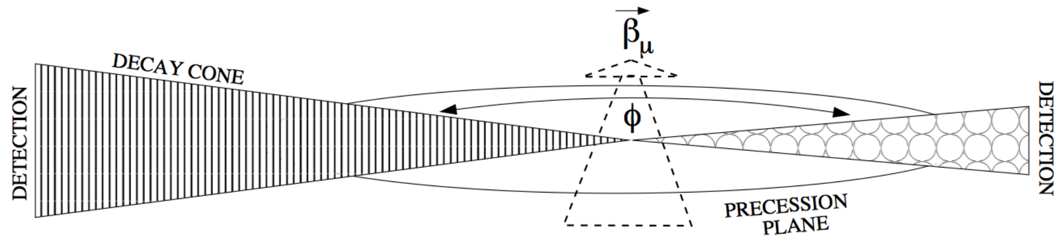
The effect a radial field has on the paths of the positrons can be neglected in this case (unlike for the vertical position oscillations)

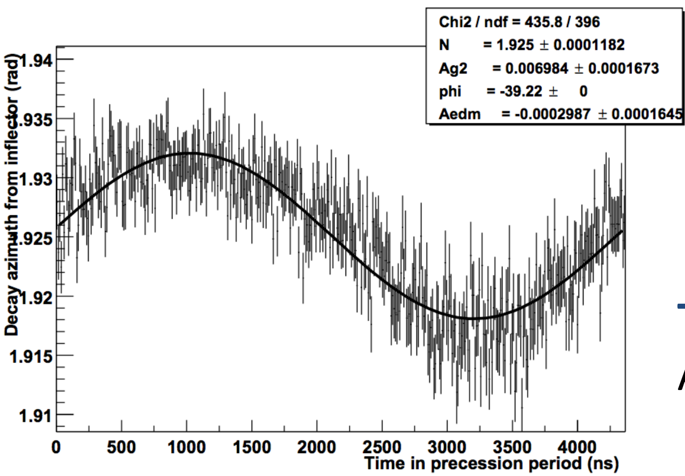
$\longrightarrow$ The tracking should track the positrons through the magnetic field

Acceptance Coupling

A variation in the acceptance of positrons at the g-2 frequency combined with an off centre beam distribution can result in a vertical oscillation

The outward going positrons have a longer path length than the inward going positrons





To hit the tracker outward going positrons come from further back

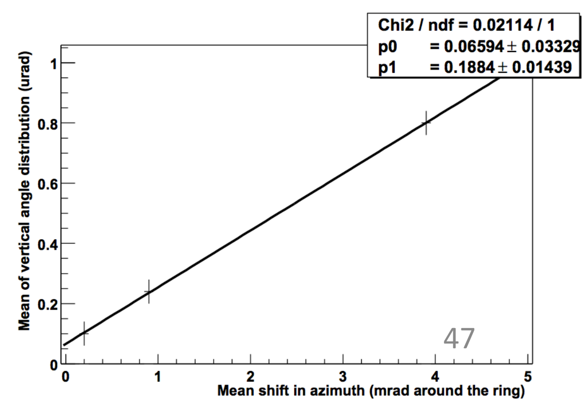
→ oscillation in average azimuth

The vertical angle acceptance varies with azimuth

Azimuthal oscillation + off centre beam

= vertical angle oscillation

Use simulation to calculate the vertical angle oscillations for different azimuthal oscillations (2mm beam offset) :



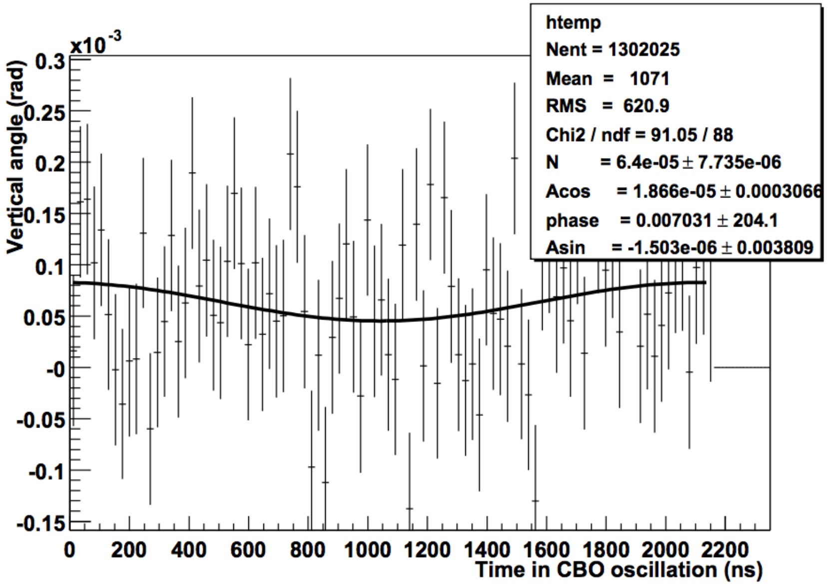
Conservative systematic error 0.3 μrad

Coherent Betatron Oscillations

Any evidence of the horizontal CBO oscillations in the vertical could cause a fake signal

Plot the vertical angle modulo the CBO period:

The amplitude of vertical angle oscillations at the CBO frequency is consistent with 0



Any vertical angle oscillations at the CBO frequency should average to 0 when plotted modulo the g-2 frequency

Cross check : Insert a vertical angle oscillation at the CBO frequency 10 times larger than the error in to simulation

→ EDM signal consistent with 0 to within 3μrad

Systematic uncertainty of 0.3μrad

Vertical Angle Oscillation Results

The results from the fit:

1999 : 4.4 ± 5.5 μrad
2000 : -4.5 ± 5.4 μrad

The statistical errors are an order of magnitude greater than the systematic errors

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

From simulation:
1 mrad precession plane tilt = 3μrad oscillation amplitude

1999 : 1.4 ± 1.8 mrad tilt **2000 : -1.5 ± 1.8 mrad tilt**

$$\vec{d} = \eta \frac{Qe}{2mc} \vec{s}$$

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

$$d_\mu = \frac{a \tan\delta}{\beta} \frac{eh}{2mc}$$

1999 : $(1.5 \pm 2.0) \times 10^{-19}$ e cm
2000 : $(-1.7 \pm 2.0) \times 10^{-19}$ e cm

Take a weighted average of the two : $d_\mu = (-0.03 \pm 1.4) \times 10^{-19}$ e cm

$|d_\mu| < 2.6 \times 10^{-19}$ e cm (95% CL)