The EDM in the g-2 experiment

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Introduction

The techniques for measuring the EDM at the new g-2 experiment at Fermilab and the expected sensitivity

- Physics motivation
- Summary of the experiment
- The effect of an EDM
- Measuring an EDM
    - Vertical angle oscillations
    - Vertical position oscillations
    - Phase changes with vertical position
- Summary

Physics motivation

UCL

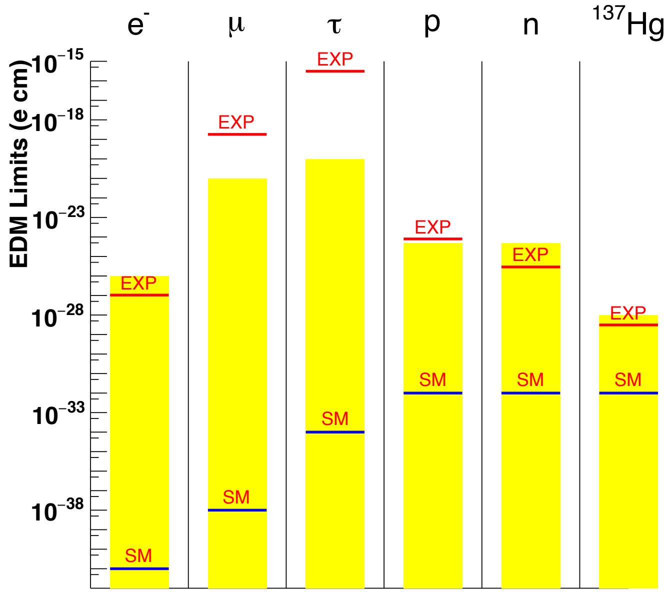
Fundamental particles can also have an EDM defined by an equation similar to the MDM:

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

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_μ scale of 10^{-25} e•cm

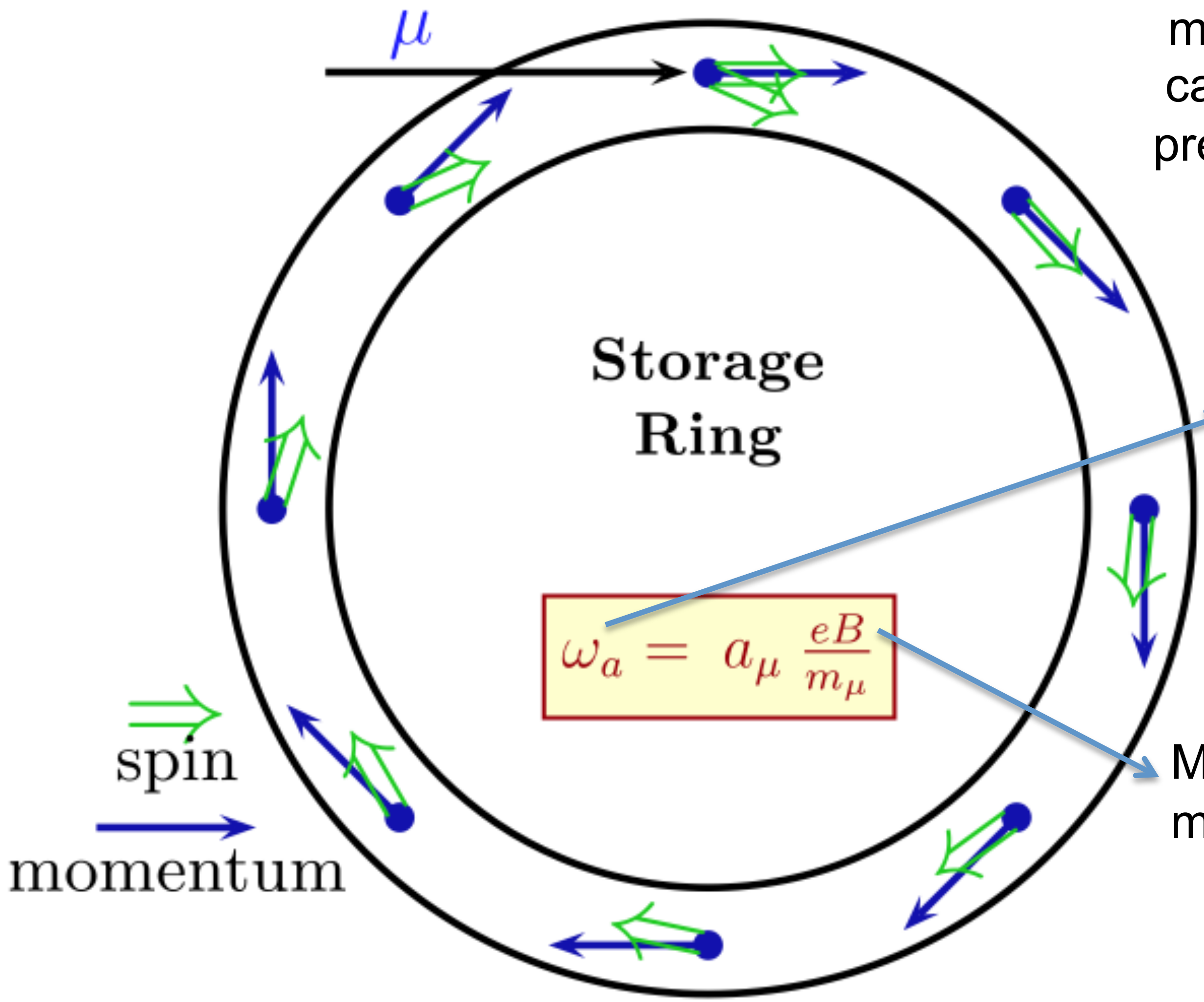
But some BSM models predict non-standard scalings
(quadratic or even cubic)

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

The g-2 experiment

The new g-2 experiment aims to measure the muon anomalous magnetic moment to 140 ppb precision

Inject muons into the ring



The anomalous magnetic moment causes the spin to precess around the momentum

Measure the spin precession from the muon decays

Measure the magnetic field

The effect of an EDM

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

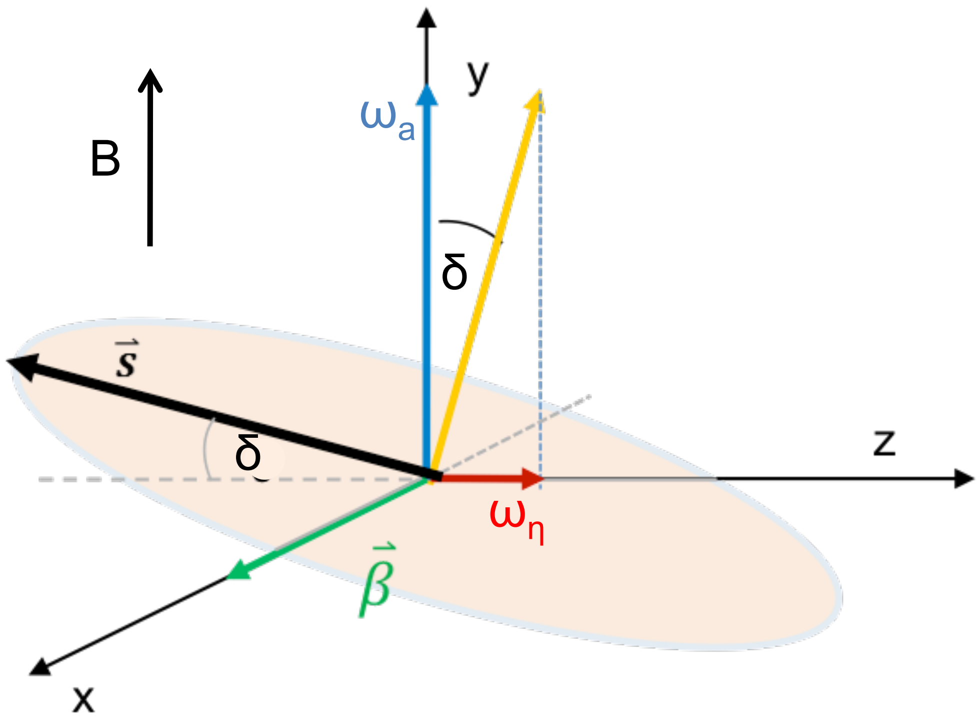
MDM — EDM

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

Dominant term

Run at the "magic momentum"

γ_{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 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:

- **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

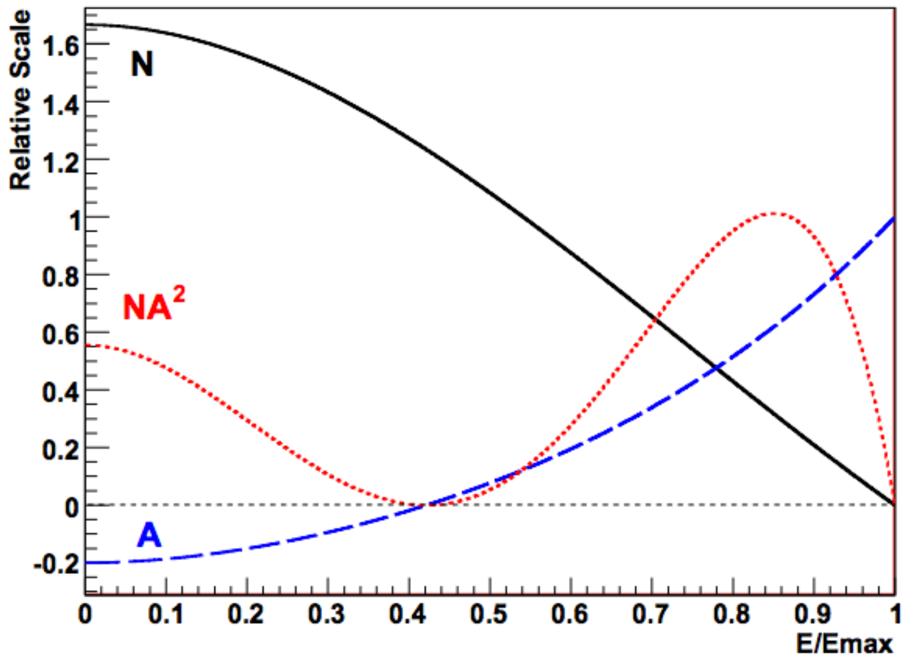
The following slides will discuss each of the methods, their uncertainties and possible improvements

Measuring the EDM - Direct

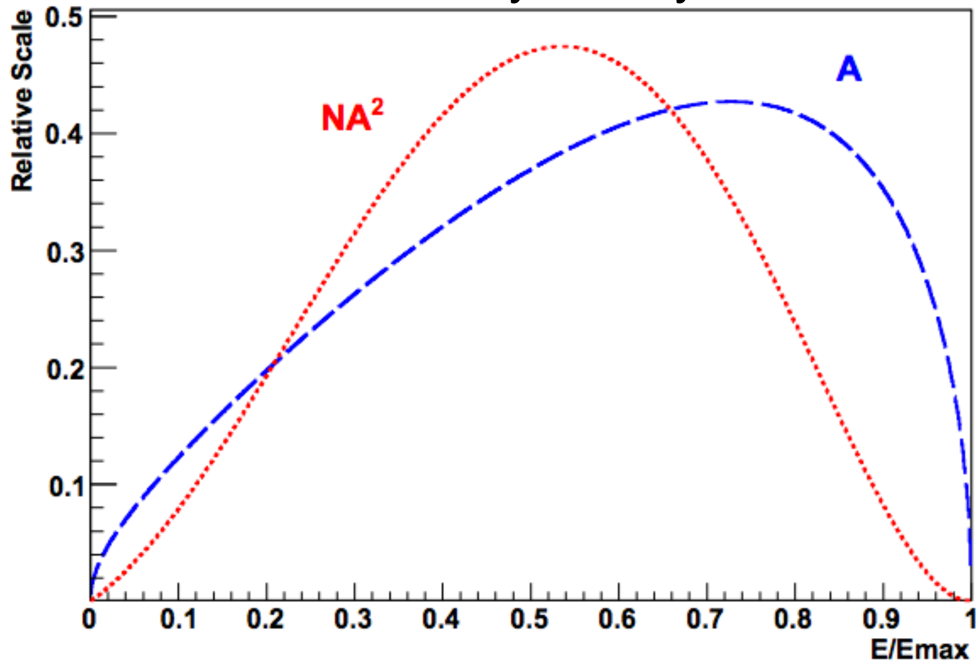
The statistical uncertainty is inversely proportional to NA^2

Number of muons — Asymmetry

G-2 asymmetry



EDM asymmetry



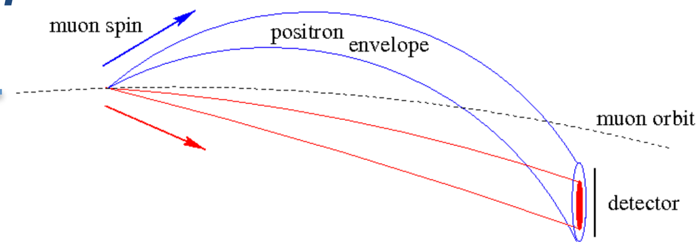
Get the highest values of NA^2 towards the higher end of the energy spectrum

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



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

Average width

fixed

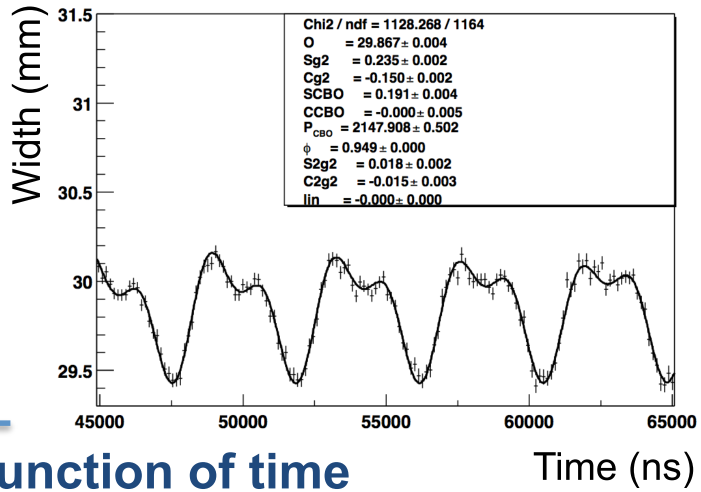
g-2 terms: changes in average energy and time of flight

$$f(t) = W + S_{g2}\sin(\omega t) + C_{g2}\cos(\omega t) + S_{2g2}\sin(2\omega t) + C_{2g2}(2\omega t)$$

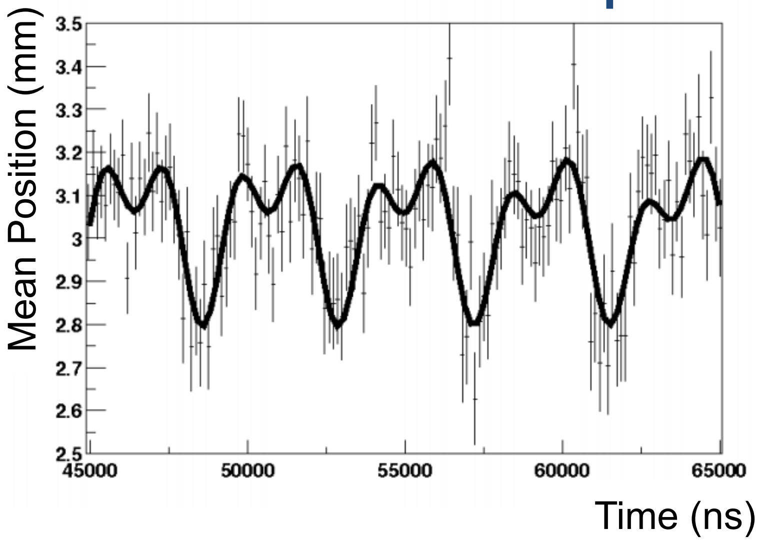
$$+e^{-t/\tau_{CBO}}\left[S_{CBO}\sin\left(\omega_{CBO}(t-t_0)+\Phi_{CBO}\right) + C_{CBO}\cos\left(\omega_{CBO}(t-t_0)+\Phi_{CBO}\right)\right] + Lt$$

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

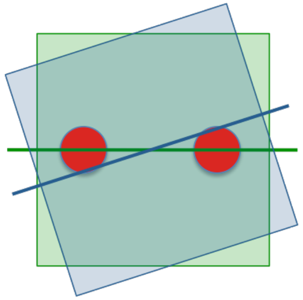
Slow changes in detector response/pileup

Vertical position uncertainties

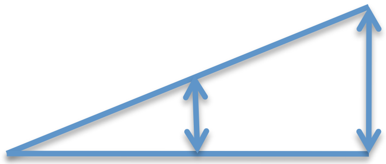
Statistical error
5.88 μm

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

Timing Offset, Energy Calibration → Differences between the top and bottom halves of the calorimeter

Radial Magnetic Field → Would cause a tilt in the precession plane

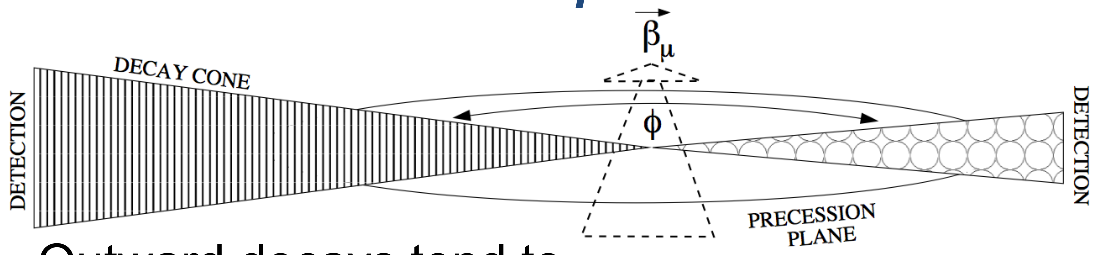
Albedo and Doubles → Back scattering from the calorimeter

E821 : $S_{g2} = (1.27 \pm 11.9)$ 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

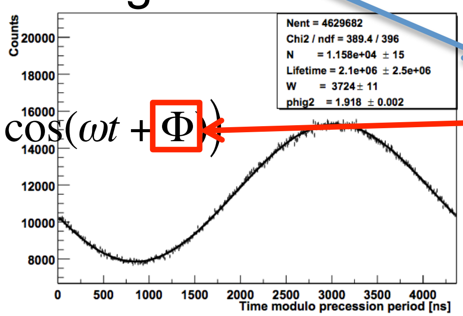
Consider the phase variation as a function of vertical position



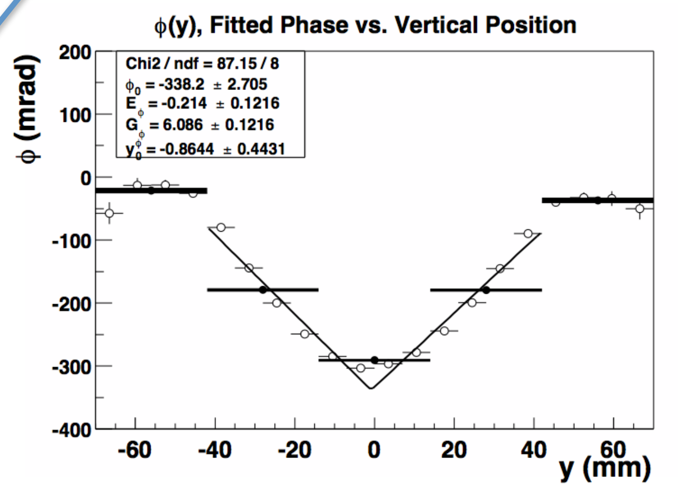
Decays that strike higher in the detector have to travel further

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

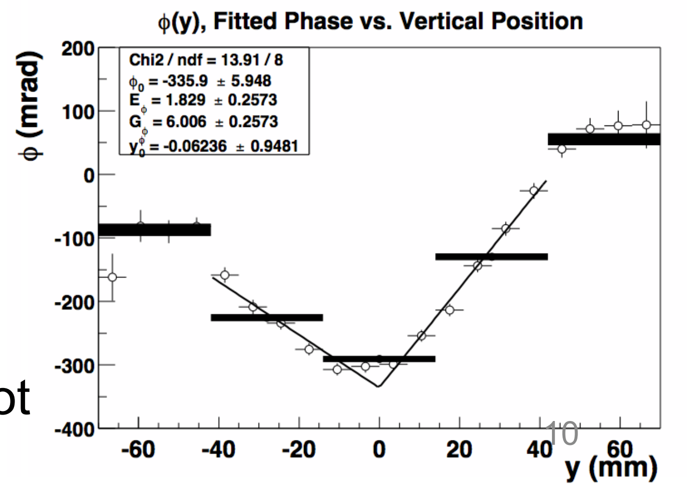
- More outward decays at the top
- More inward decays at the bottom

→ **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

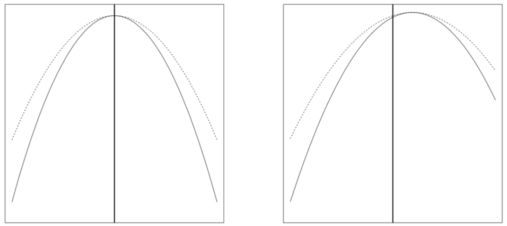
Phase changes not related to EDM



Phase uncertainties

The systematic uncertainities are similar to the vertical position measurement

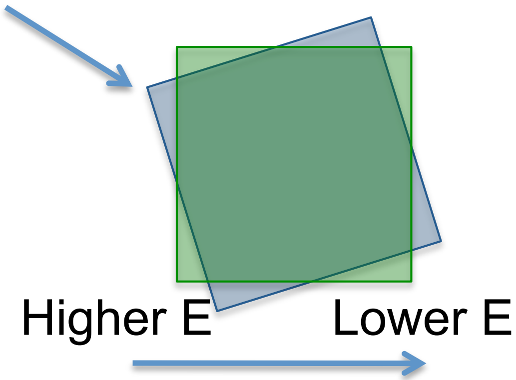
Detector misalignment is more important



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

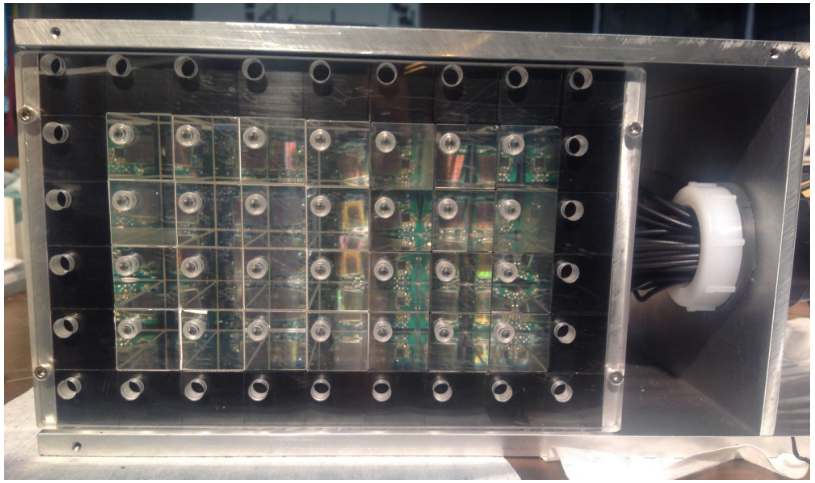
Again systematics dominated, although statistics play a larger role

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



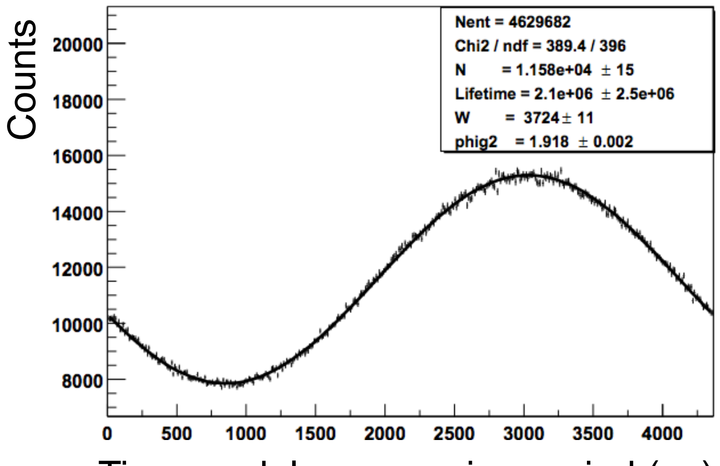
Planned improvements:

- **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

Measuring the EDM – 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



Minimises period disturbances at other frequencies

Use the period calculated from the ω_a fit

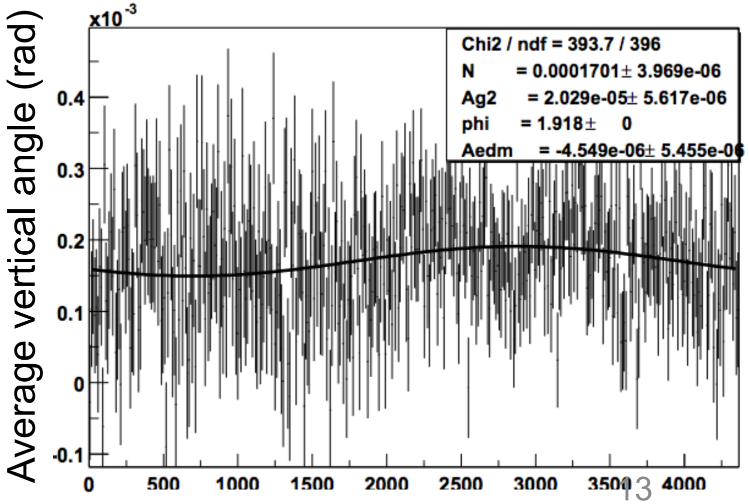
Fit to calculate the phase : $N(t) = e^{-t/\tau_e}\left(N_0 + W\cos(\omega t + \Phi)\right)$

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



Decay angle uncertainties

Main systematic uncertainties to be considered for this method:

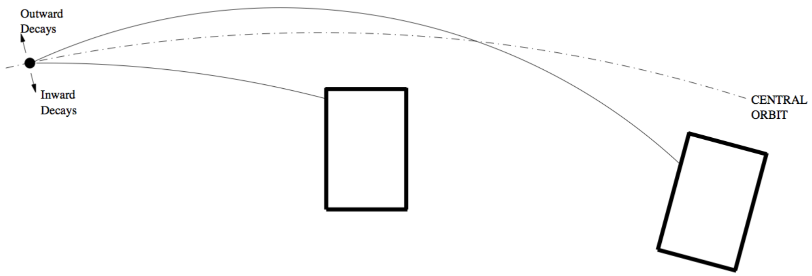
Radial Magnetic field:

Would cause a tilt in the precession plane $\vec{\omega}_a = -\frac{Qe}{m} a\vec{B}$

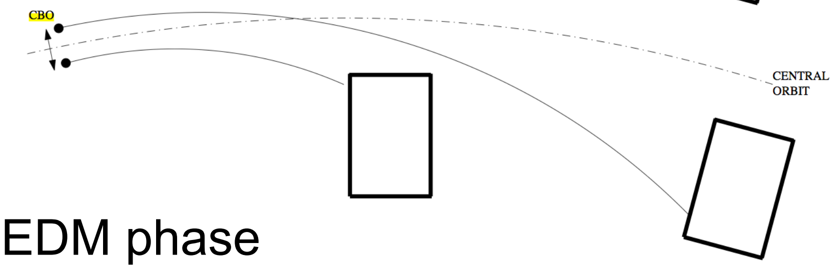
Detector acceptance:

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)

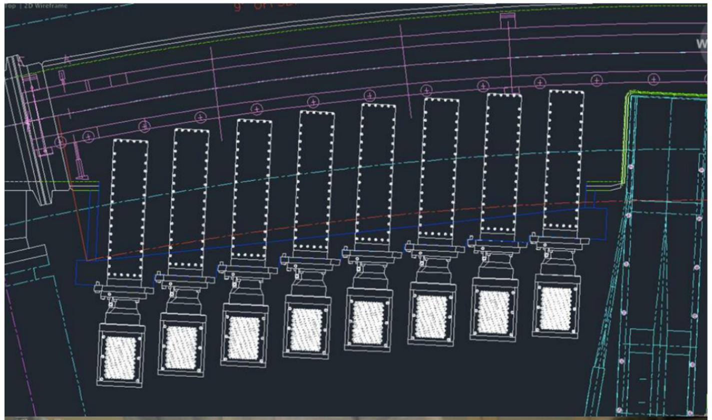
Dominated by the statistical error

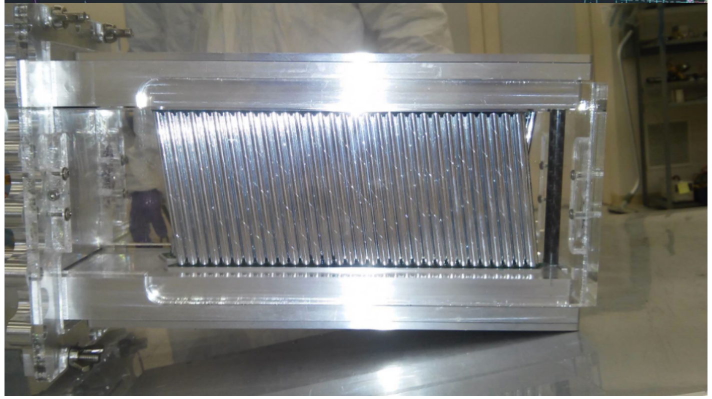
Decay angle E989

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

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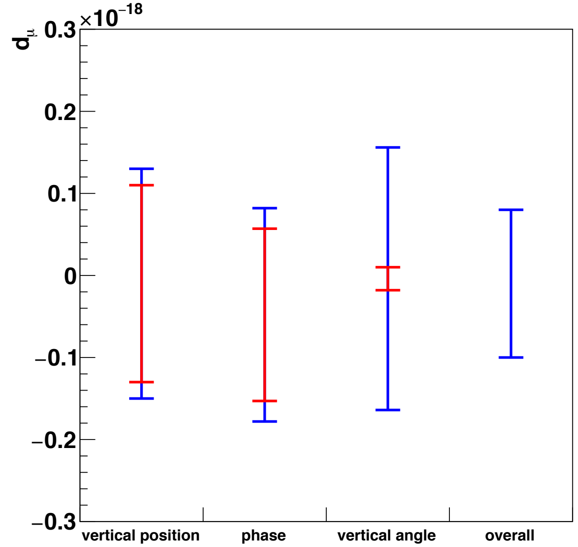
The new g-2 experiment aims to improve the limit on the EDM set at BNL by 2 orders to magnitude to 10^{-21} e•cm



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

In the new experiment many improvements to the systematics are expected

Reduction in the CBO oscillations, segmented calorimeters, tracking stations, increased statistics, improved knowledge of the energy distribution

→ Expect to improve on all the analysis methods
It is useful to have all methods for cross checks

The vertical decay angle oscillation measurement was largely statistics dominated

The introduction of 3 tracking stations produces O(1000) x more statistics

→ 1-2 orders of magnitude improvement
(provided the systematics are controlled)

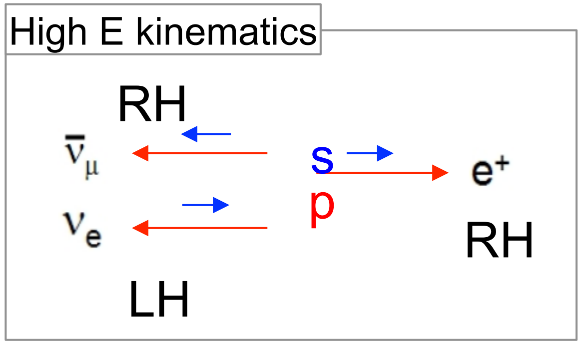
Backup

Measuring the EDM - Indirect

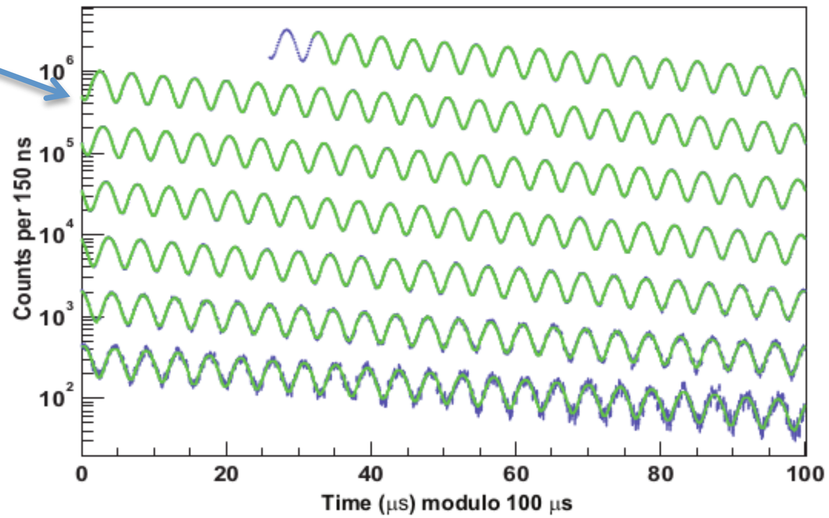
Look for an increase in the precession frequency (compared to SM prediction)

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

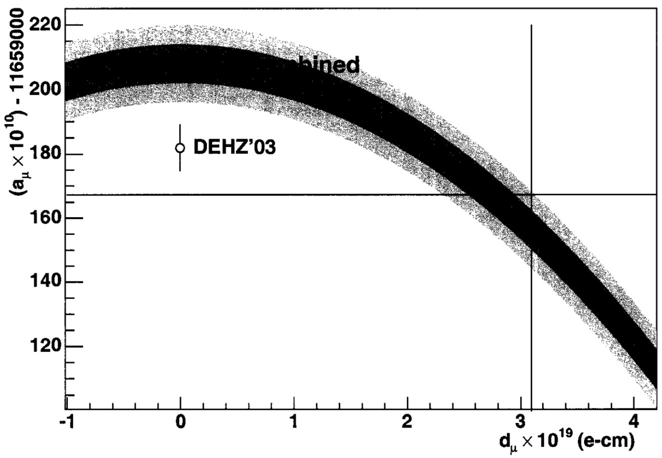


Fit to extract the spin precession:

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

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.)