An Improved Limit on the Muon EDM

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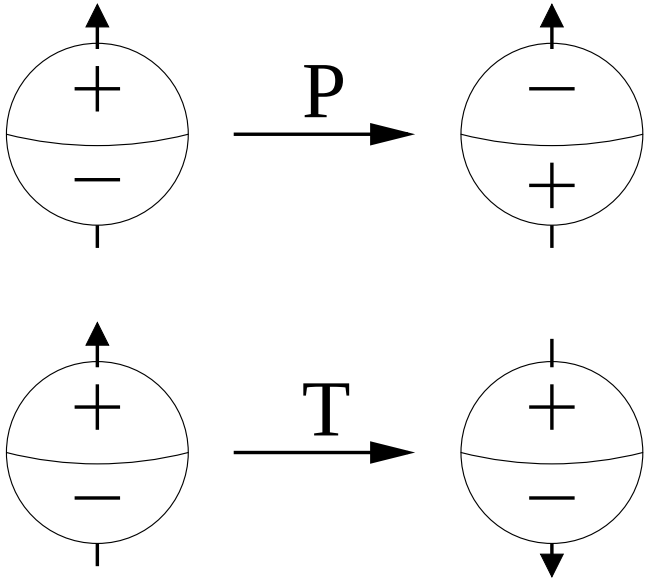
(Muon $(g-2)$ Collaboration)

An Elementary Particle EDM Violates P and T Symmetries

$$\begin{aligned} \vec{D} &\propto \vec{S} \\ \mathbf{P}\vec{D} &\propto \mathbf{P}\vec{S} \\ -\vec{D} &\propto \vec{S} \end{aligned}$$

$$\begin{aligned} \vec{D} &\propto \vec{S} \\ \mathbf{T}\vec{D} &\propto \mathbf{T}\vec{S} \\ \vec{D} &\propto -\vec{S} \end{aligned}$$

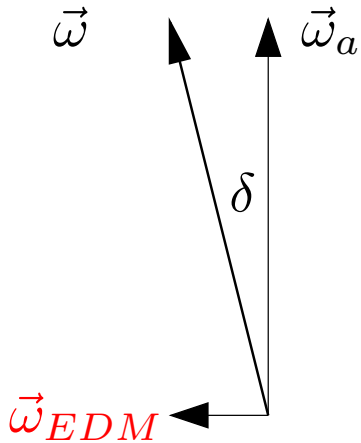


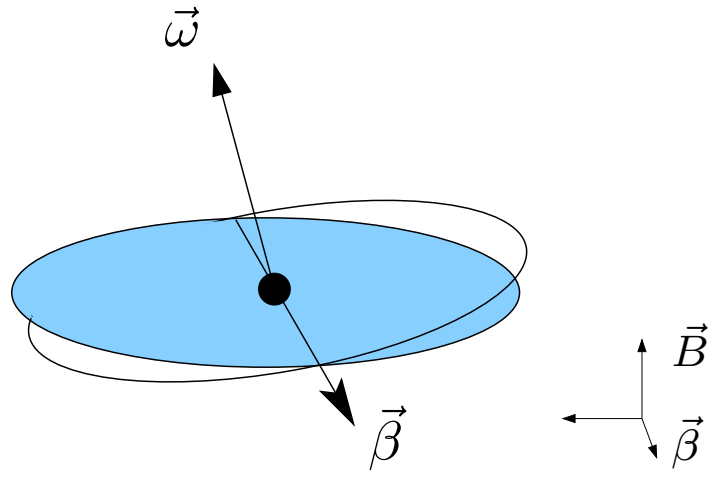
Particle	Limit/Measurement (e-cm)
e	$< 1.6 \times 10^{-27}$
μ	$< 1.05 \times 10^{-18}$
τ	$(-2.2 < d_\tau < 4.5) \times 10^{-17}$
n	$< 6.3 \times 10^{-26}$
p	$(-3.7 \pm 6.3) \times 10^{-23}$
Λ	$(-3.0 \pm 7.4) \times 10^{-17}$
$\nu_{e,\mu}$	$< 2 \times 10^{-21}$
ν_τ	$< 5.2 \times 10^{-17}$

An EDM Would Tilt the Precession Plane

- An EDM ($D_\mu = f\frac{e\hbar}{4m_\mu c}$) would modify the spin precession:

$$\vec{\omega}_a = -\frac{e}{m_\mu c}a_\mu \vec{B}$$





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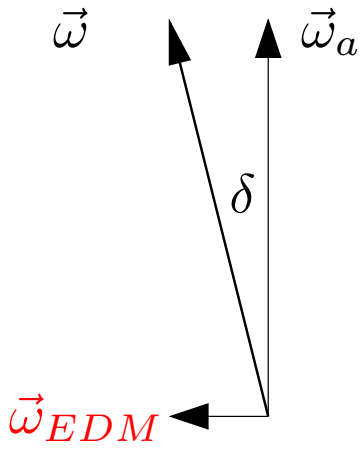
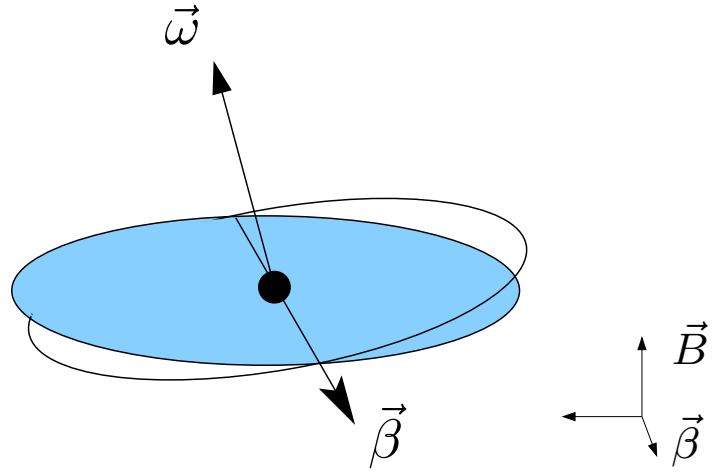
- An EDM ($D_\mu = f\frac{e\hbar}{4m_\mu c}$) would modify the spin precession:

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{EDM} = -\frac{e}{m_\mu c}\left[a_\mu \vec{B} + \tfrac{1}{2} f\left(\vec{\beta}\times\vec{B}\right)\right]$$





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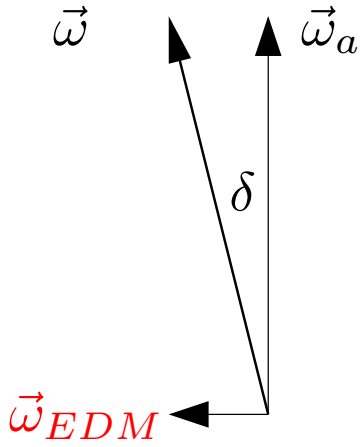
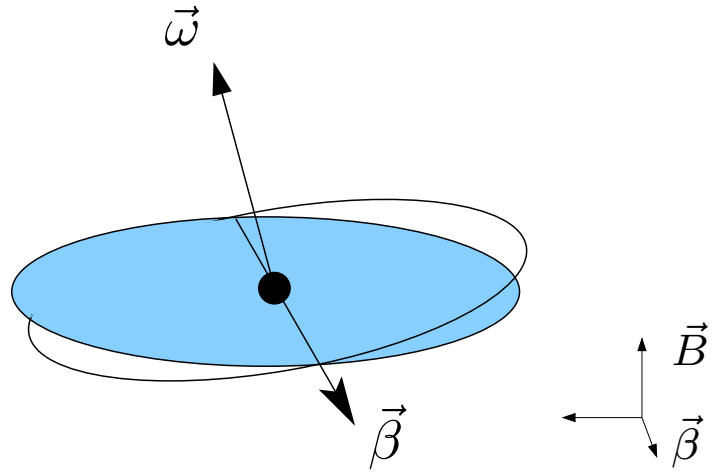
- The precession plane would tilt by: $\delta \approx \frac{f}{2a_\mu}$
- The frequency would increase: $\frac{\Delta\omega}{\omega_a} = \frac{1}{2}\delta^2$





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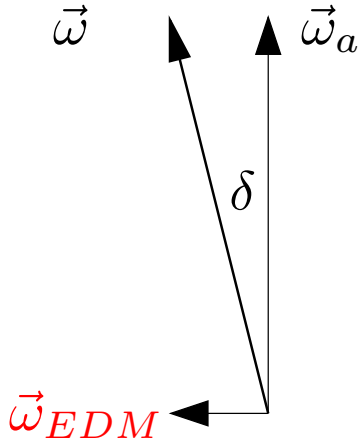
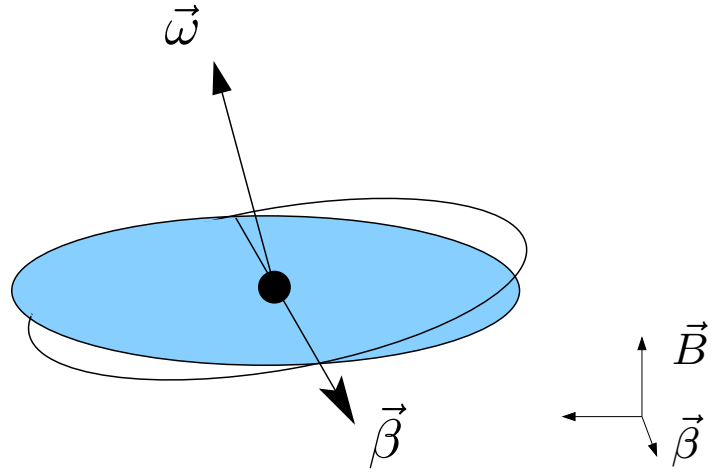
- The precession plane would tilt by: $\delta \approx \frac{f}{2a_\mu}$
- The frequency would increase: $\frac{\Delta\omega}{\omega_a} = \frac{1}{2}\delta^2$
- Current muon EDM limit $1.05\times10^{-18} e-cm$:

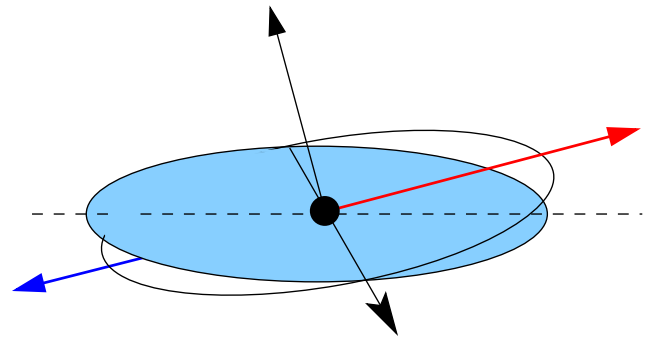
$$\delta = 9.3 mrad \qquad \frac{\Delta\omega}{\omega_a} = 46 ppm$$

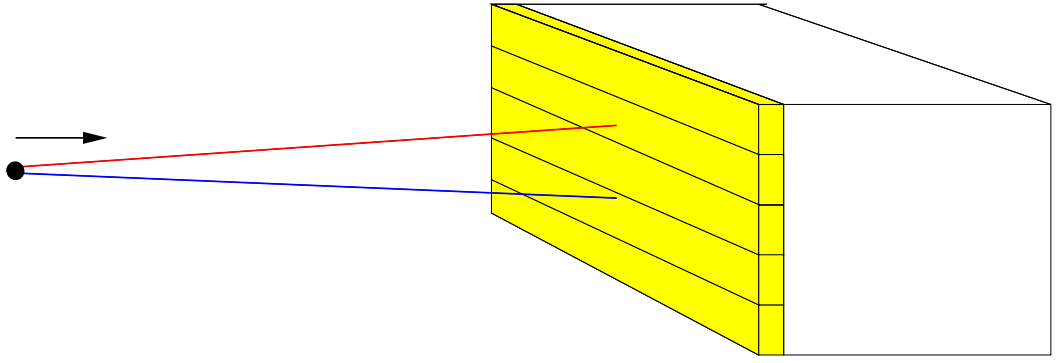




Signal for an EDM:
Vertical Oscillation at the g-2 Frequency

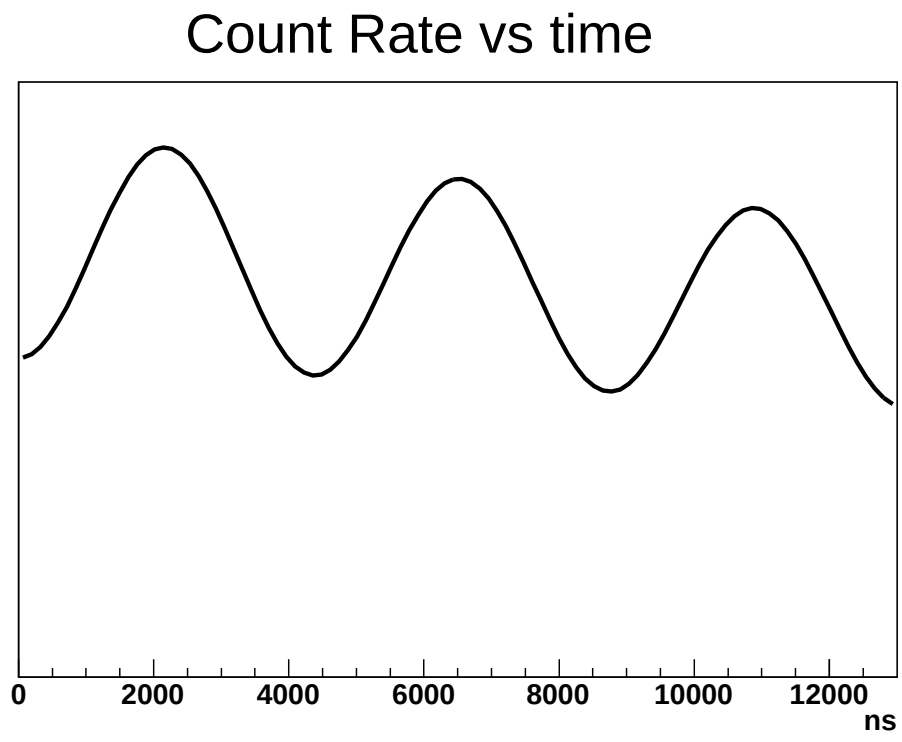
- Spin direction oscillates vertically
- Positrons emitted in spin direction
- Vertical oscillation in final position
- $90°$ out of phase with the oscillation in count rate





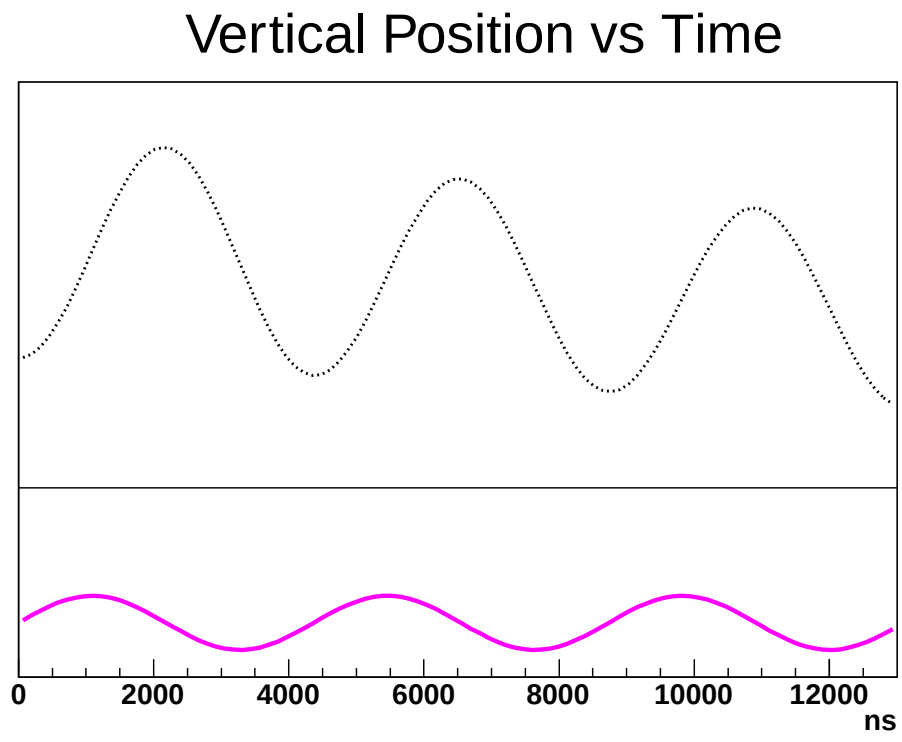
- Front Scintillator Detector(FSD)
- 5 tiles on the front of the calorimeter
- 9 FSDs used for the 2000 analysis

Fits to Position vs Time:
Search for a Vertical Oscillation at ω_a



Fits to Position vs Time: Search for a Vertical Oscillation at ω_a

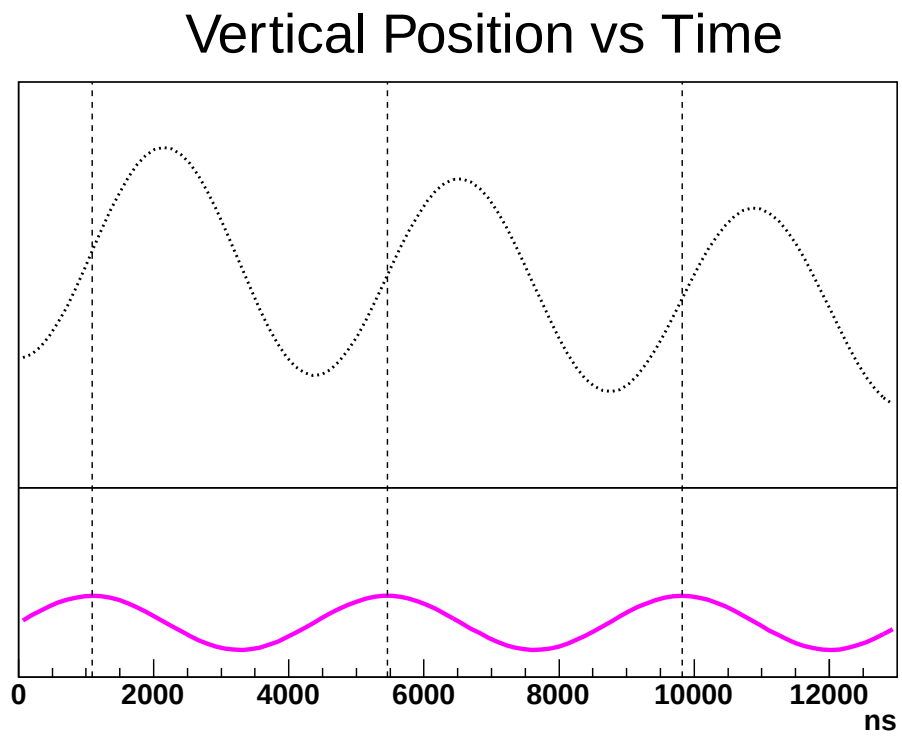
- Plot mean position vs time



$$y(t) \quad = \quad Y_0 + [S_{g2} sin\,(\omega_a t) + C_{g2}\, cos\,(\omega_a t)]$$

Fits to Position vs Time: Search for a Vertical Oscillation at ω_a

- Plot mean position vs time
- 90° out of phase



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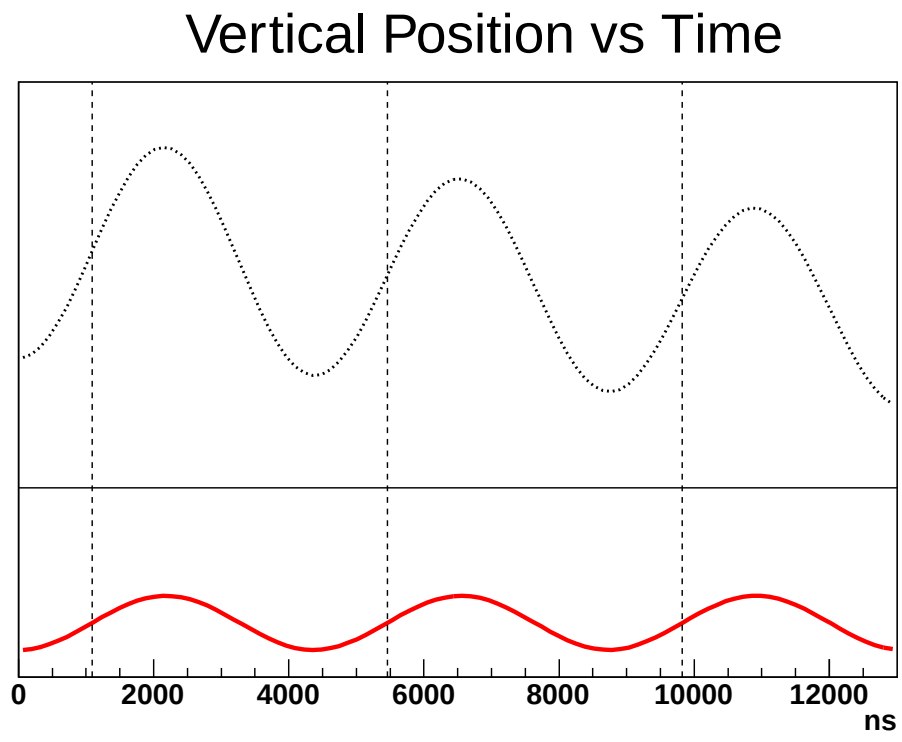
- Oscillations in phase:
  Not an EDM



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Fits to Position vs Time: Search for a Vertical Oscillation at ω_a

- Plot mean position vs time
- $90°$ out of phase
- Oscillations in phase:
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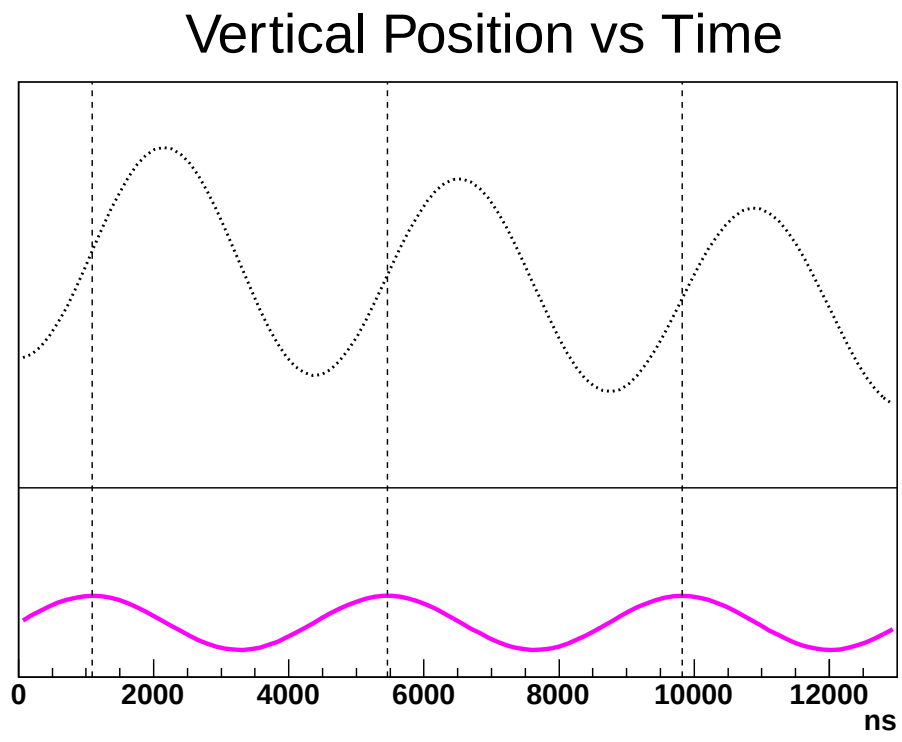
- Second component:
  CBO



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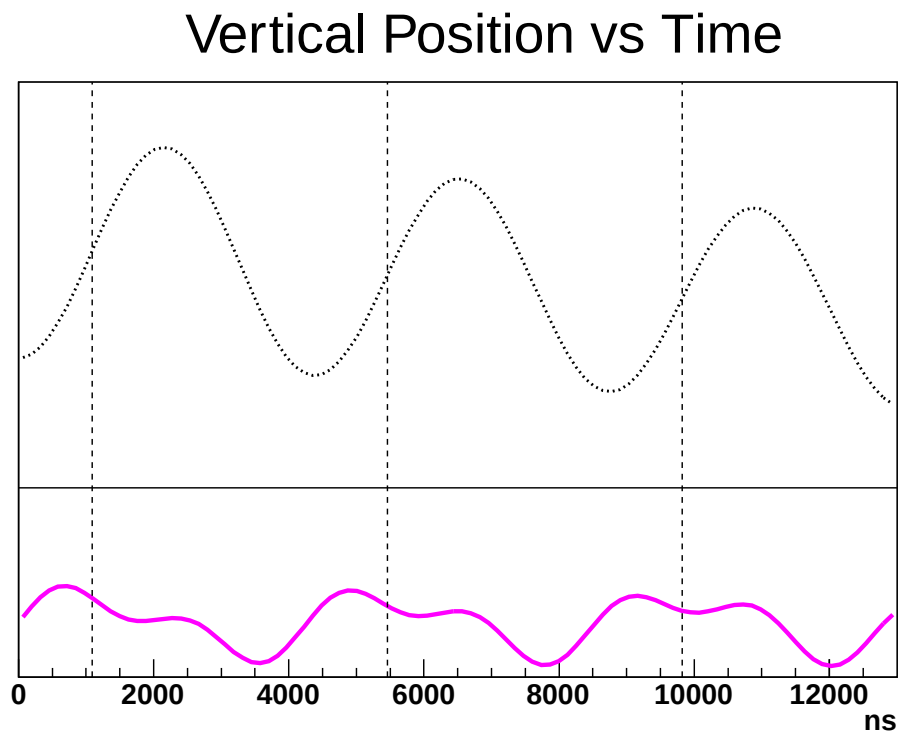

$$y(t) = Y_0 + [S_{g2} sin(\omega_a t) + C_{g2} cos(\omega_a t)]$$

$$+ e^{-\frac{t}{\tau_c}} \times [S_c sin(\omega_c t) + C_c cos(\omega_c t)]$$

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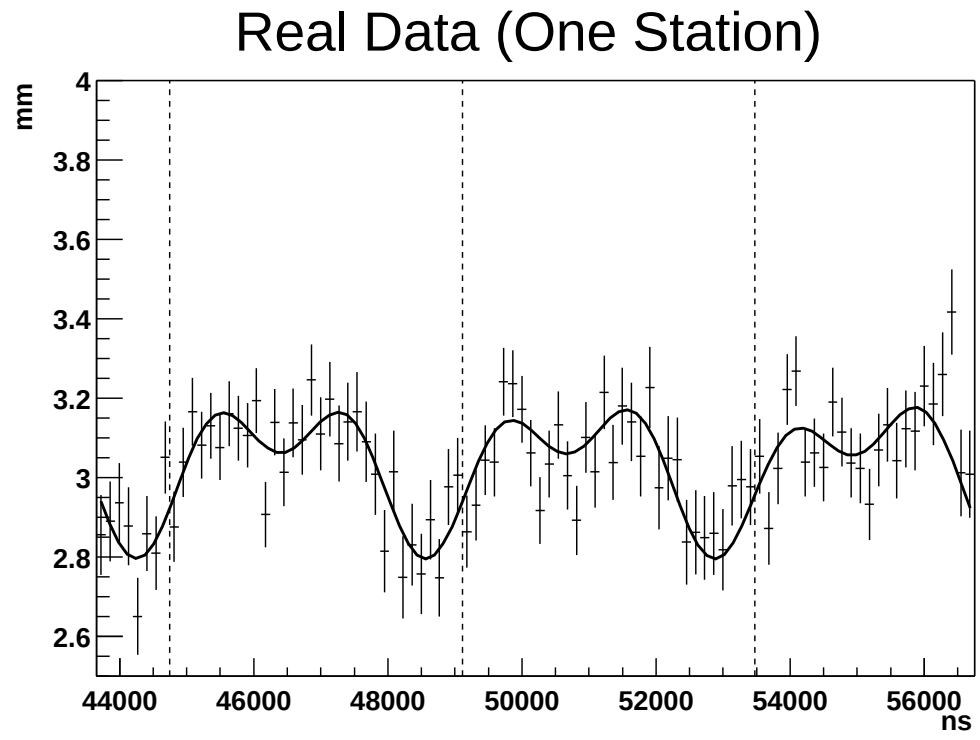

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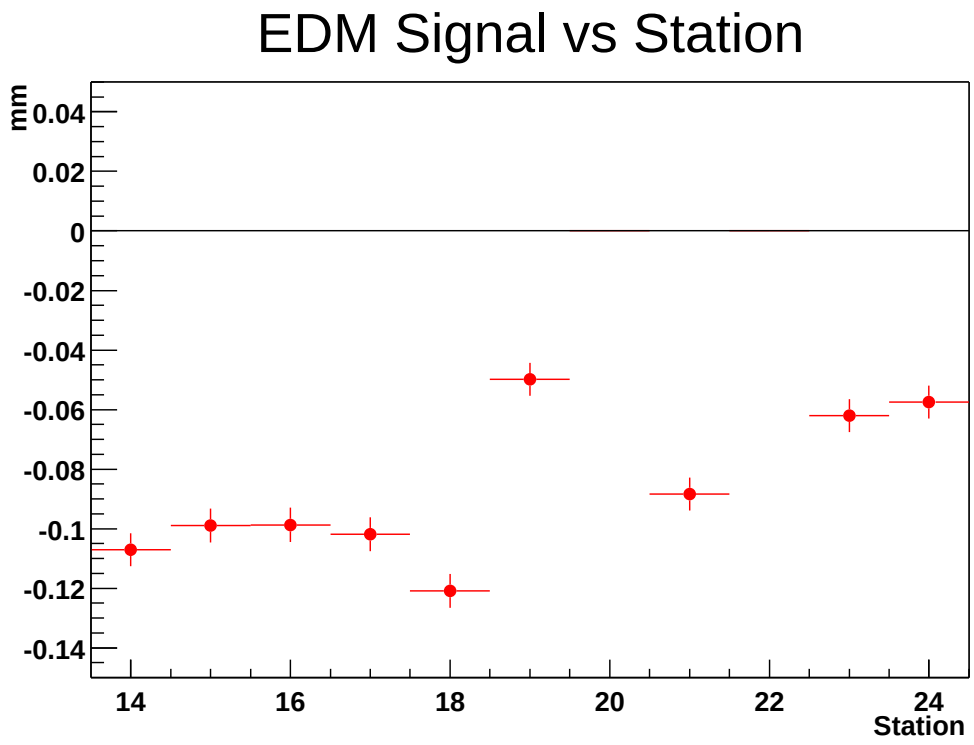
"EDM" Signals are Inconsistent

- Variations between detectors



"EDM" Signals are Inconsistent

- Variations between detectors
- Data sets before and after
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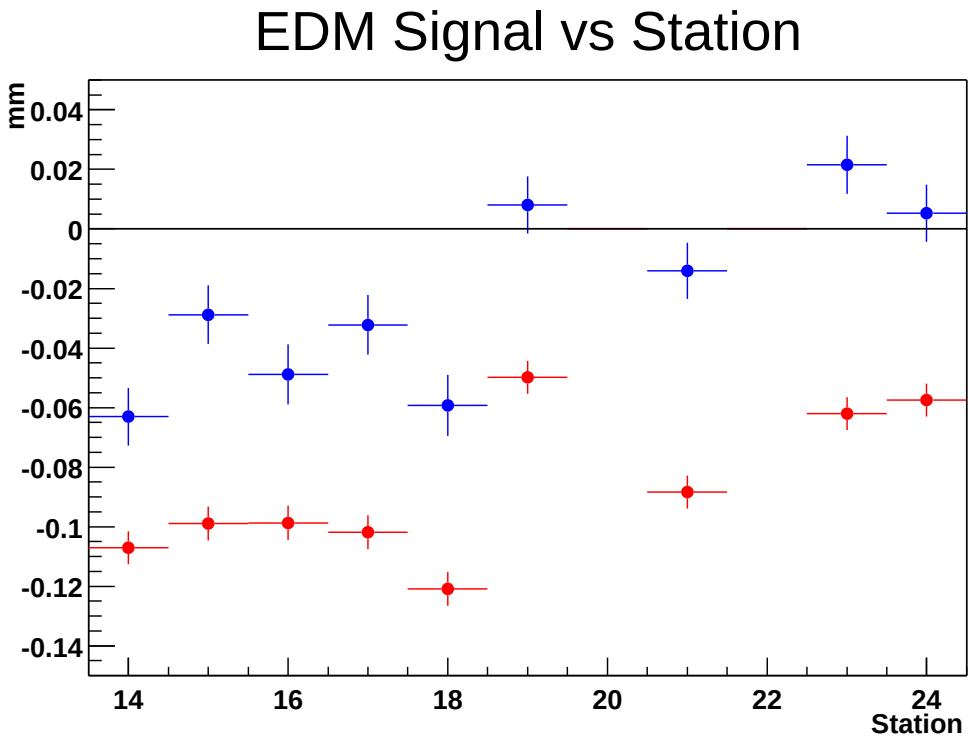

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- Variations between detectors
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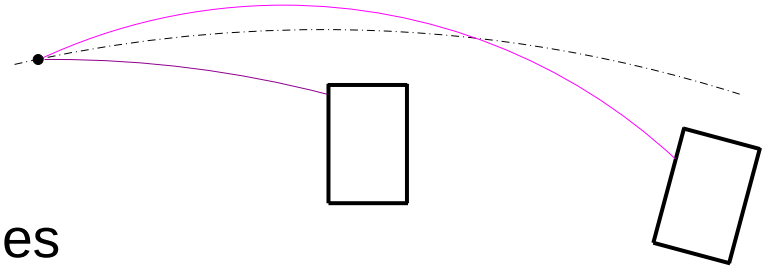
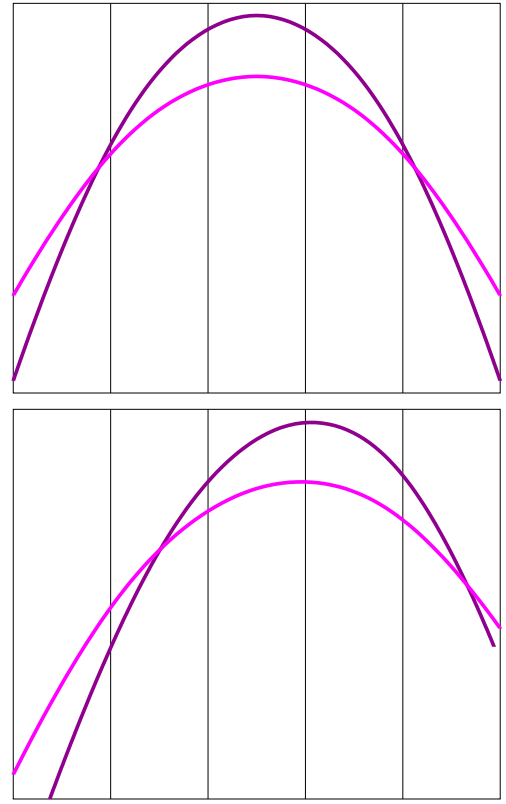
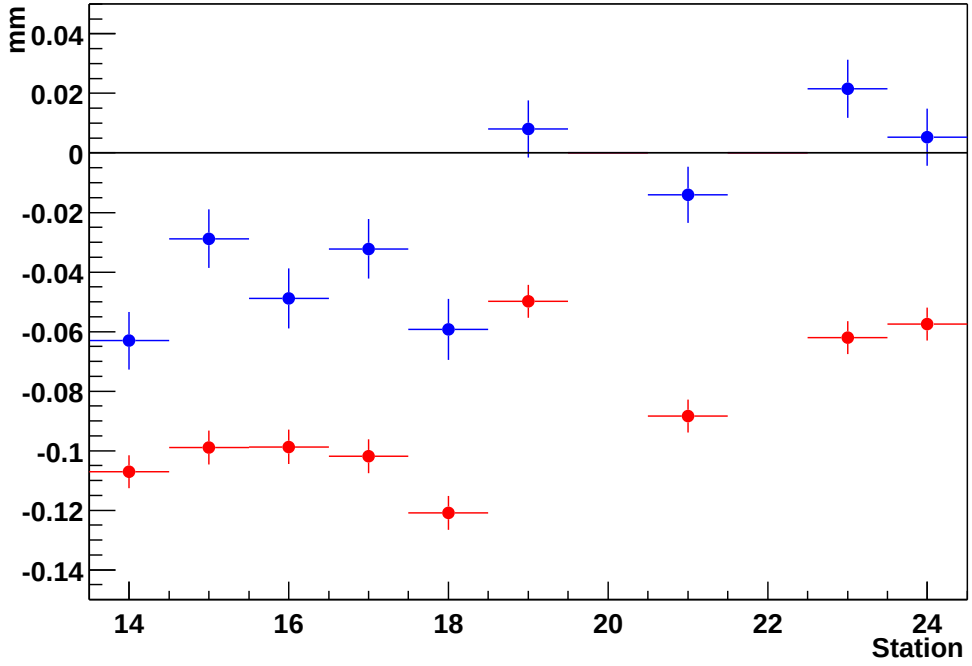
- Due to oscillation in vertical width



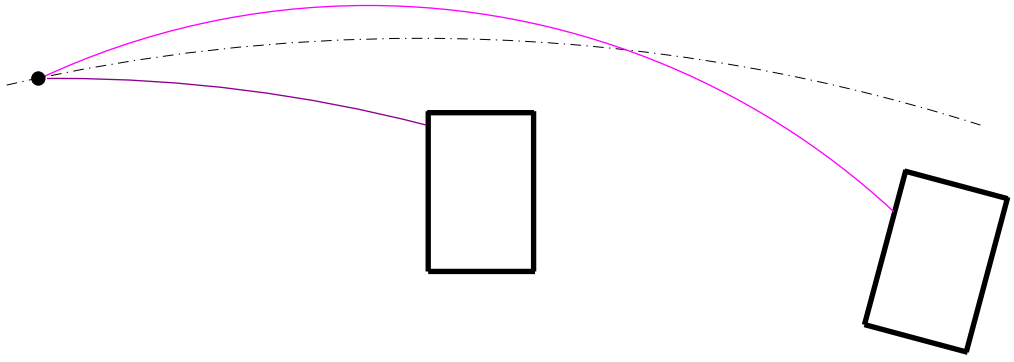
Vertical Profiles

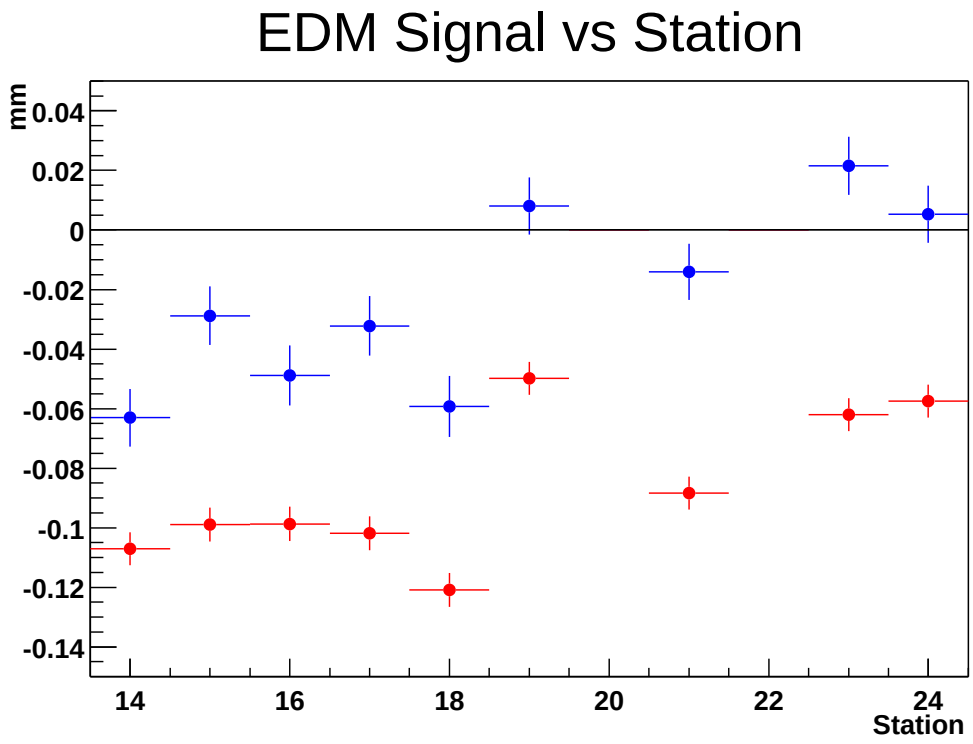


EDM Signal vs Station



Similar Effect Due to Betatron Oscillations





- Beam oscillates radially
- Changes vertical width
- Mean oscillates if beam is not aligned with detector
- This can be used to correct for misalignment

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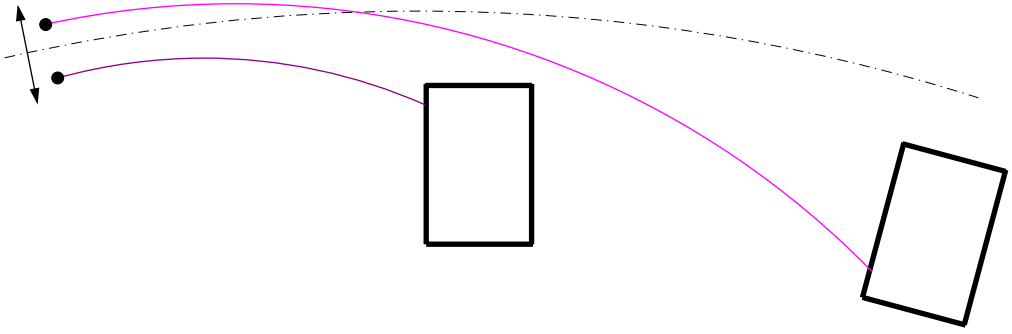

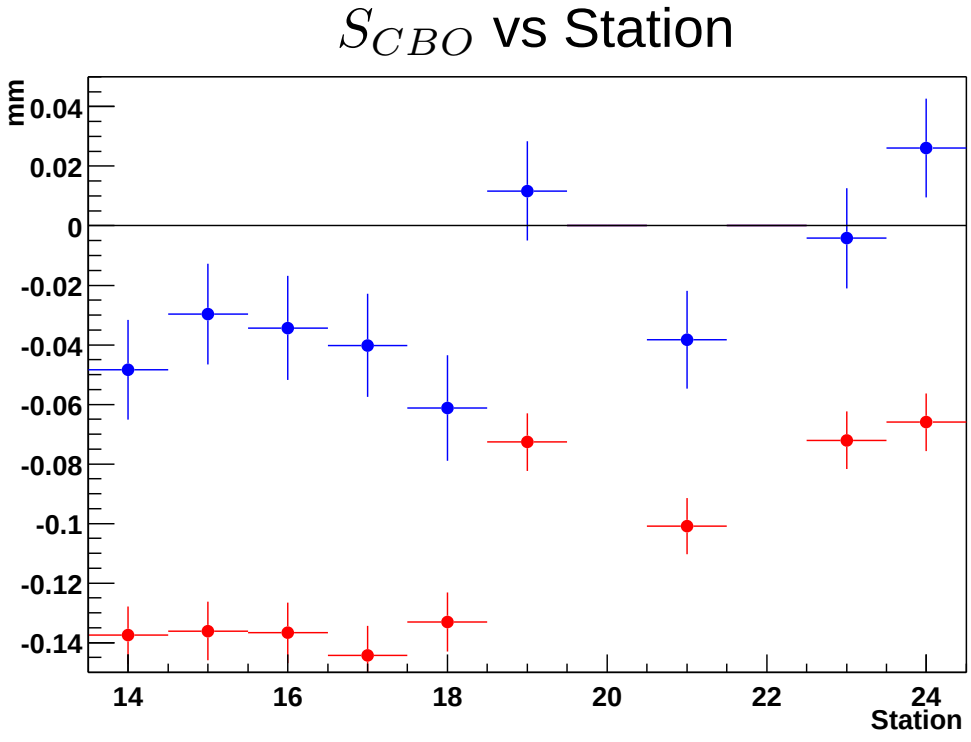

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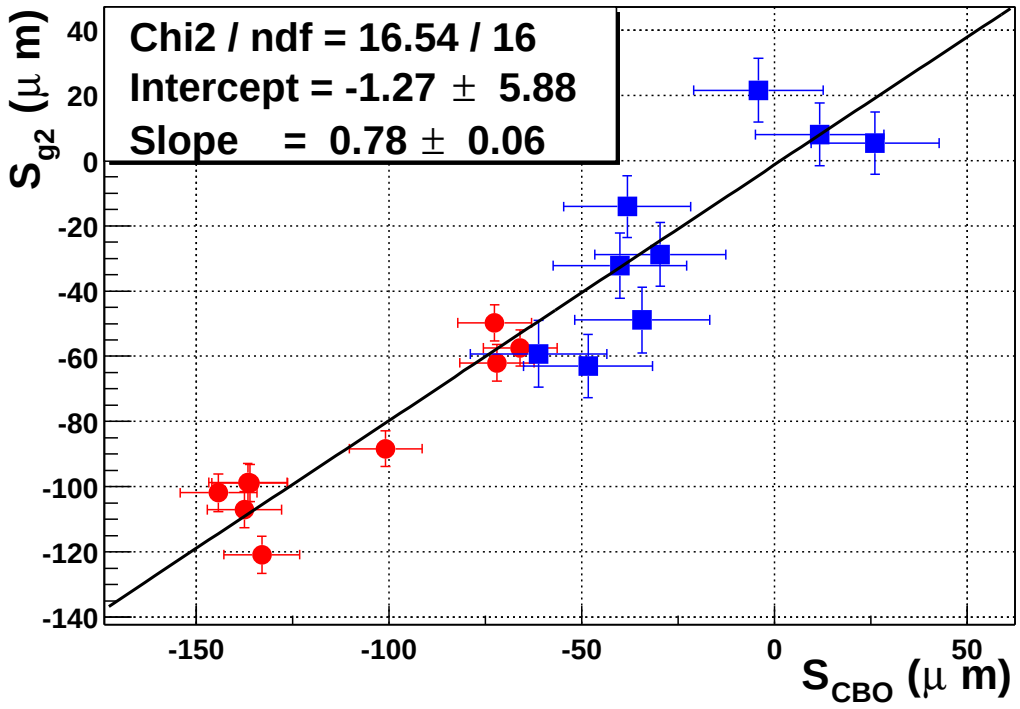
Using the CBO to Correct for Alignment



- Plot the g-2 vs CBO vertical oscillation amplitudes for each detector.
- Data points from all 9 detectors before and after the beam alignment.
- Fit to a line: good χ^2
- Where $S_{CBO} = 0$ there is no effect due to detector alignment

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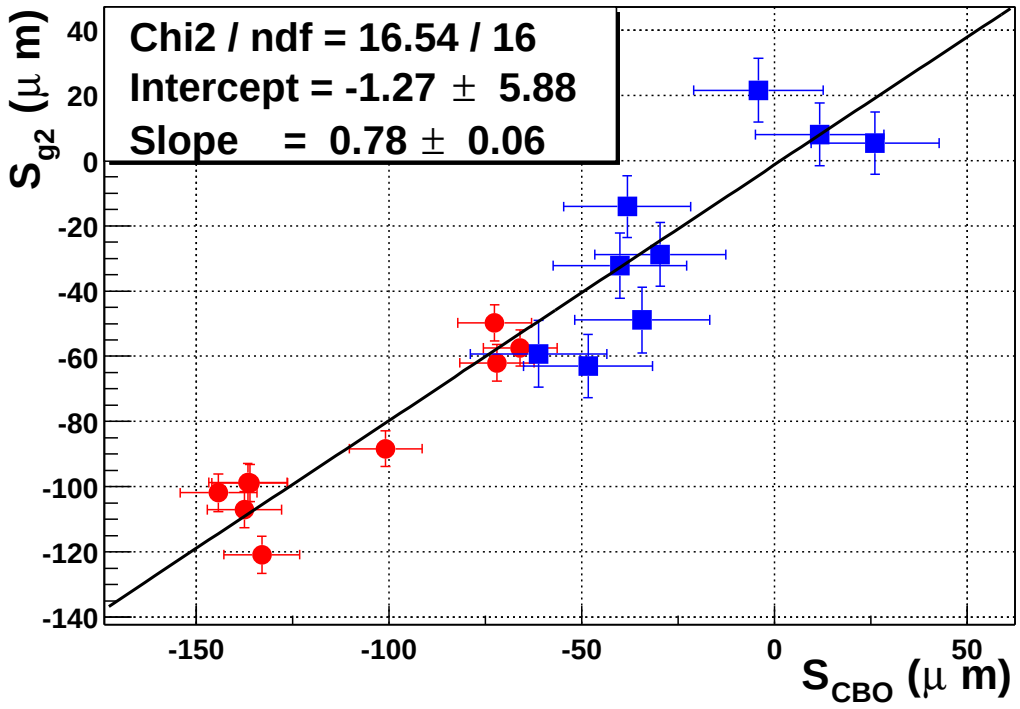

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Intercept: $-1.27 \pm 5.88 \mu m$ $\Rightarrow$ EDM: $(-0.14 \pm 0.67) \times 10^{-19} e - cm$

Results and Outlook

Error Table

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 Error	11.9
$10^{-19} e - cm$	8.8

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$10^{-19} e - cm$	8.8

- Limit(95% CL):
  $|D_\mu| \leq 2.8 \times 10^{-19} e - cm$
- A factor of 4 improvement
- $\frac{\Delta \omega_a}{\omega_a} \leq 3.1 ppm$
- Traceback:
  Parallel Analysis
- 2001 Data Set:
  Similar Statistics