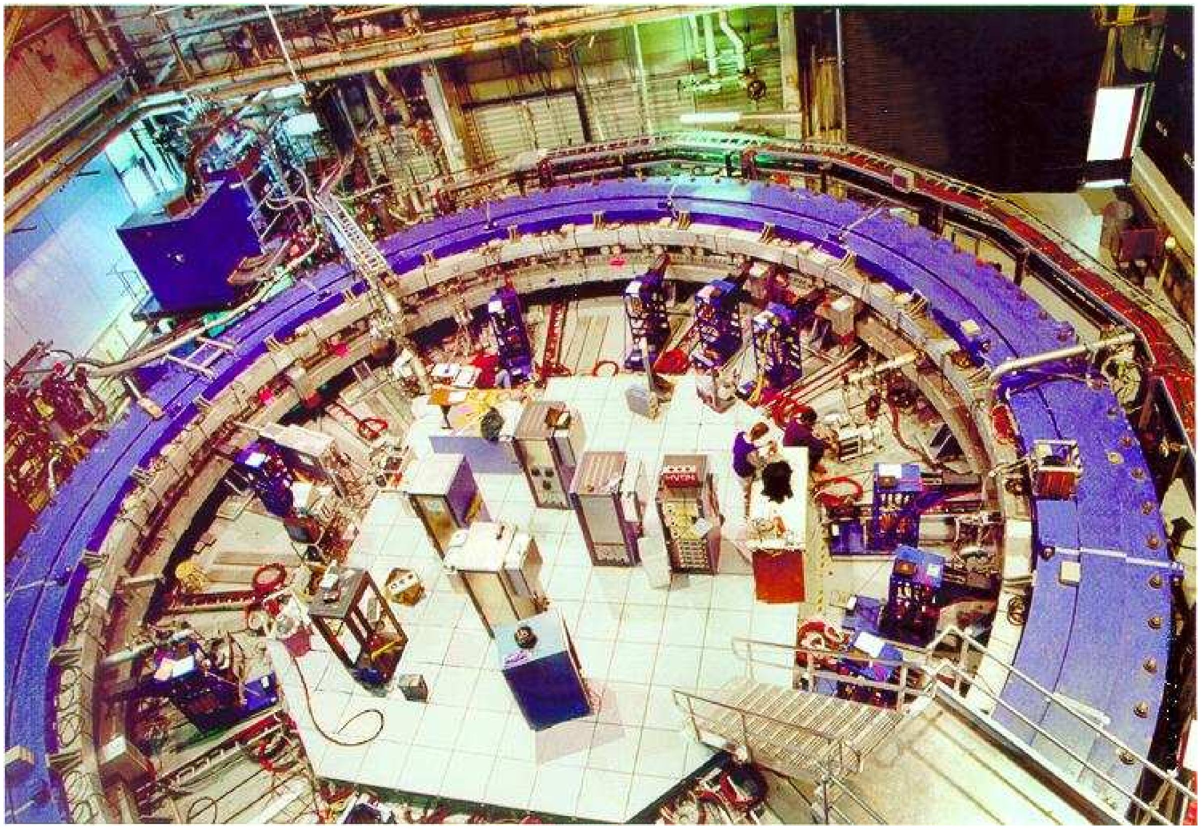
Toward an Improved Limit on the Muon Electric Dipole Moment from the g-2 Experiment



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The Muon g-2 Experiment

- Measure the anomalous magnetic moment of the muon to $\sim 0.5 ppm$

- Search for a muon EDM

- Measure the muon lifetime at $\gamma = 29.3$ (test of Special Relativity)

Electric Dipole Moments

An EDM in an elementary particle would violate CP symmetry.

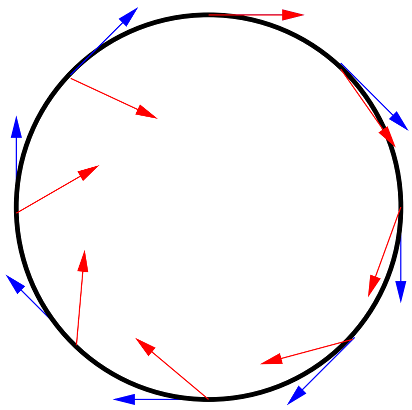
No EDM has been observed in any elementary particle. The neutron and electron have the lowest EDM limits.

The muon has the lowest limit of charged particles outside the first generation.

Particle	Limit/Measurement (e-cm)	Method
e	$< 1.6 \times 10^{-27}$	Thallium beam
μ	$< 1.05 \times 10^{-18}$	Tilt of precession plane in magnetic moment experiment
τ	$< 3.1 \times 10^{-16}$	L3 search for $e^+e^- \to \tau\tau\gamma$ excess events
n	$< 6.3 \times 10^{-26}$	Ultra-cold neutrons
p	$(-3.7 \pm 6.3) \times 10^{-23}$	120kHz thallium spin resonance
Λ	$(-3.0 \pm 7.4) \times 10^{-17}$	Tilt of precession plane in magnetic moment experiment
$\nu_{e,\mu}$	$< 2 \times 10^{-21}$	Inferred from magnetic moment limits
ν_τ	$< 5.2 \times 10^{-17}$	Z decay width

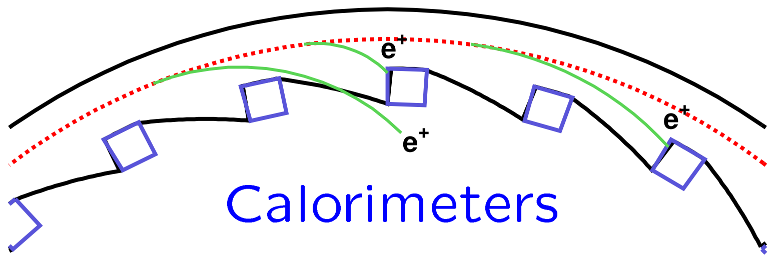
The Muon g-2 Experiment

3.1GeV polarized muons are injected into a storage ring with R=7m and B=1.4T



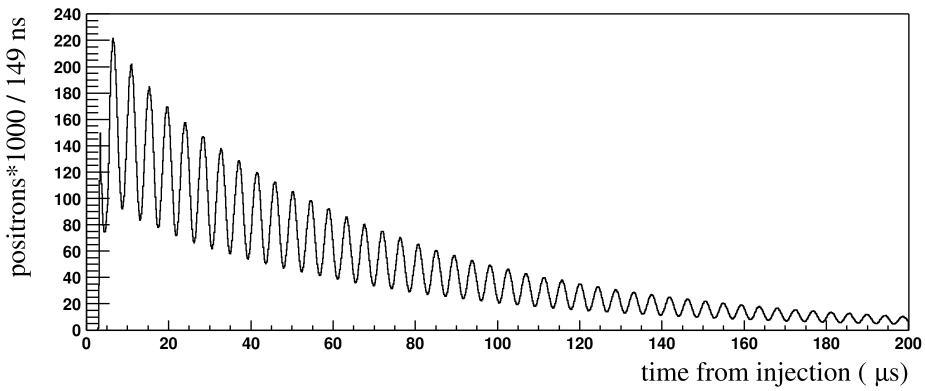
The spin vector precesses faster than the momentum vector.
The difference in frequencies ($\omega_a = \omega_p - \omega_c$) is used to measure the anomalous magnetic moment. ($\vec{\omega}_a = a_\mu \frac{e}{mc}\vec{B}$)

Positrons from muon decay are detected by Pb/SciFi calorimeters.

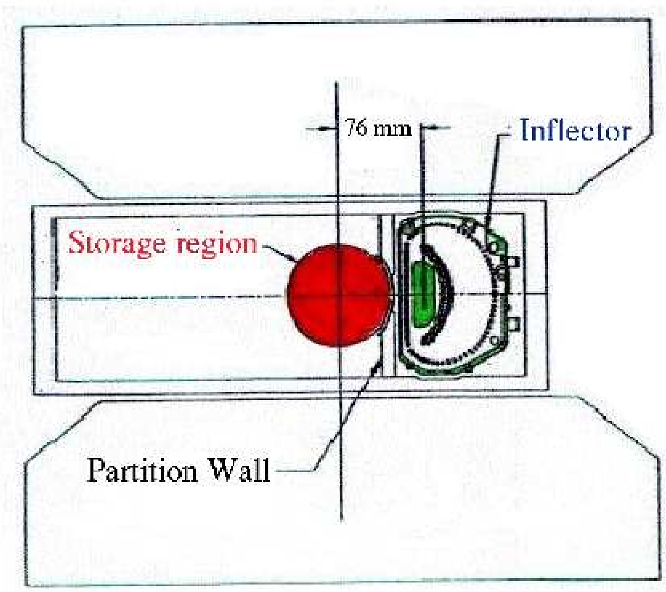


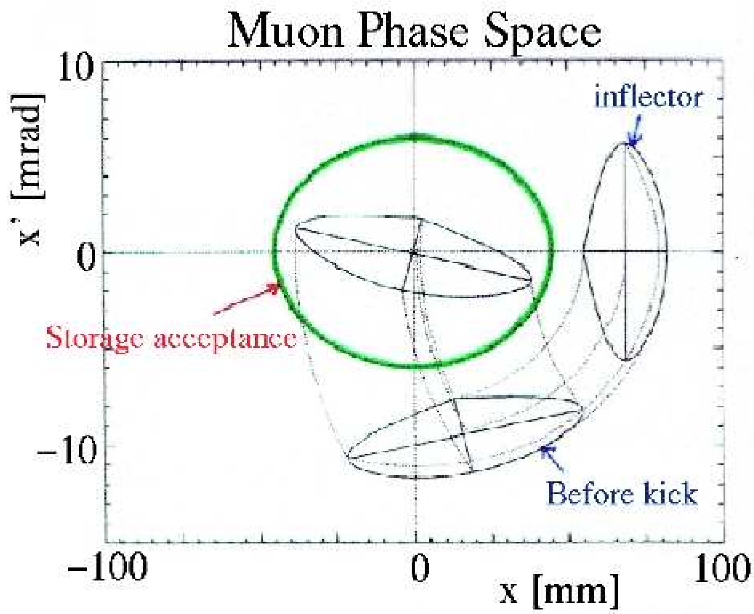
Since positrons are emitted along the muon spin direction there is an oscillation in the number of positrons detected

Time Spectrum of Positons $> 2GeV$



Coherent Betatron Oscillations





Effect	Period
g-2 Oscillation	4365ns
Cyclotron	149ns
Vertical Betatron	408ns
Horizontal Betatron	160ns
Hor. Beta. Observed	2150ns

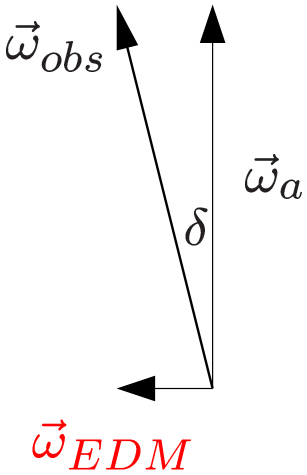
Quadrupole focusing causes vertical and horizontal betatron oscillations

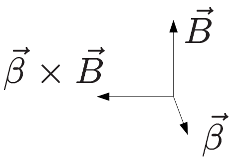
The observed horizontal betatron frequency is the difference between the actual betatron frequency and the cyclotron frequency

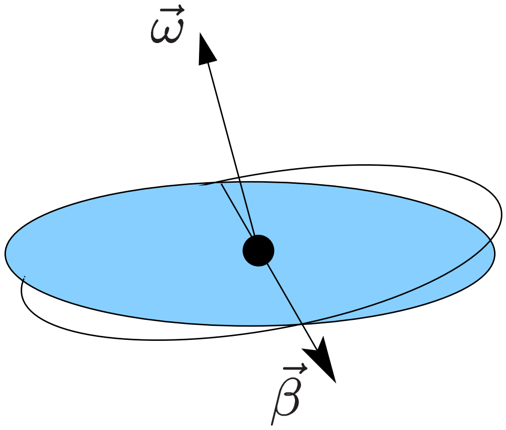
Effect of an EDM

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

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







The precession plane would tilt by: $\delta \approx \frac{f}{2a_\mu}$

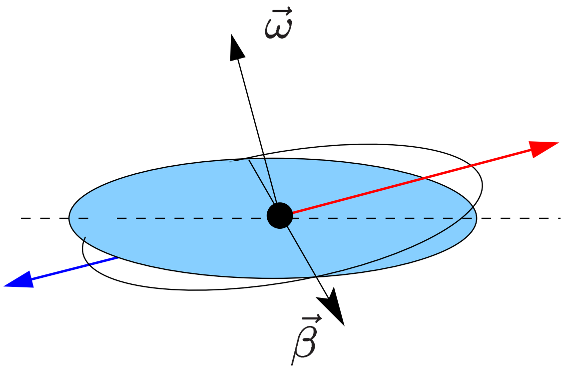
The frequency would increase: $\frac{\Delta\omega}{\omega_a} = \frac{1}{2}\delta^2$

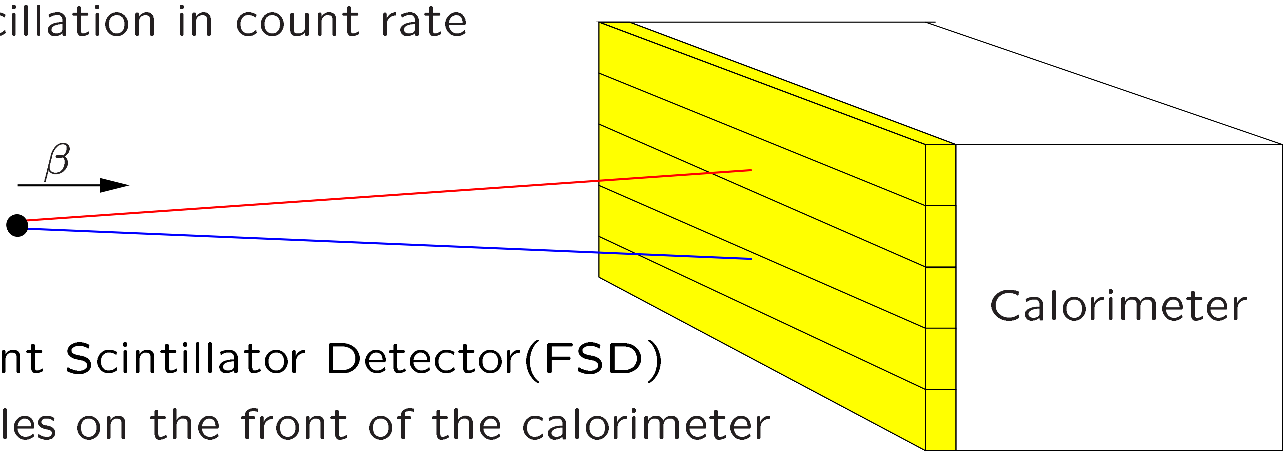
The muon EDM limit from the CERN g-2 experiment: $1.05\times 10^{-18} e - cm$

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

Detecting an EDM

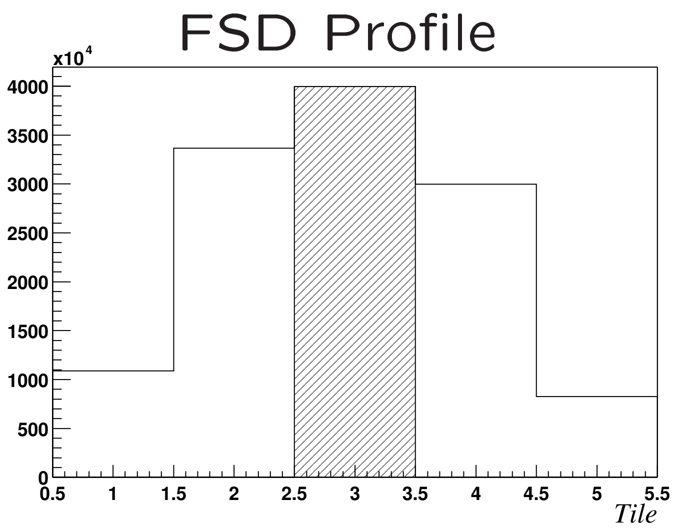
- Spin direction oscillates vertically as the muon precesses due to tilt.
- Causes an oscillation in the position of hits on the calorimeter
- 90° out of phase with the oscillation in count rate





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

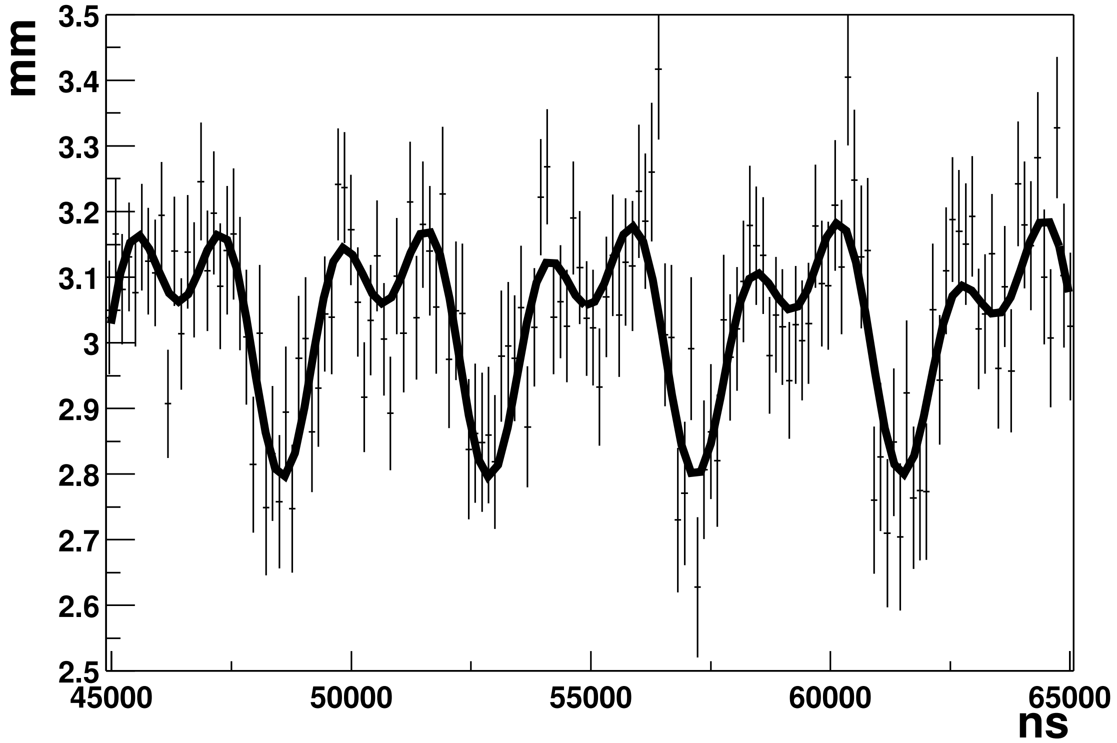
- Mean of 4 tiles vs. time
- $1.4GeV < E < 3.2GeV$
- Fit to find oscillation amplitude
- Simulation: $\dfrac{8.8\mu m}{10^{-19}e{-}cm}$



Fits to Vertical Position vs Time

$$
\begin{aligned}
f(t) &= Offset + \left[S_{g2}\, sin\left(\frac{2\pi t}{P_a}\right) + C_{g2}\, cos\left(\frac{2\pi t}{P_a}\right)\right] \\
&+ e^{-\frac{t}{\tau_{CBO}}} \times \left[S_{CBO} sin\left(\frac{2\pi t}{P_{CBO}} + \phi_{CBO}\right) + C_{CBO} cos\left(\frac{2\pi t}{P_{CBO}} + \phi_{CBO}\right) \right] \\
&+ M e^{-\frac{t}{\tau_M}}
\end{aligned}
$$

Vertical Position vs Time After Injection (Station 15)



Free parameters are in red.

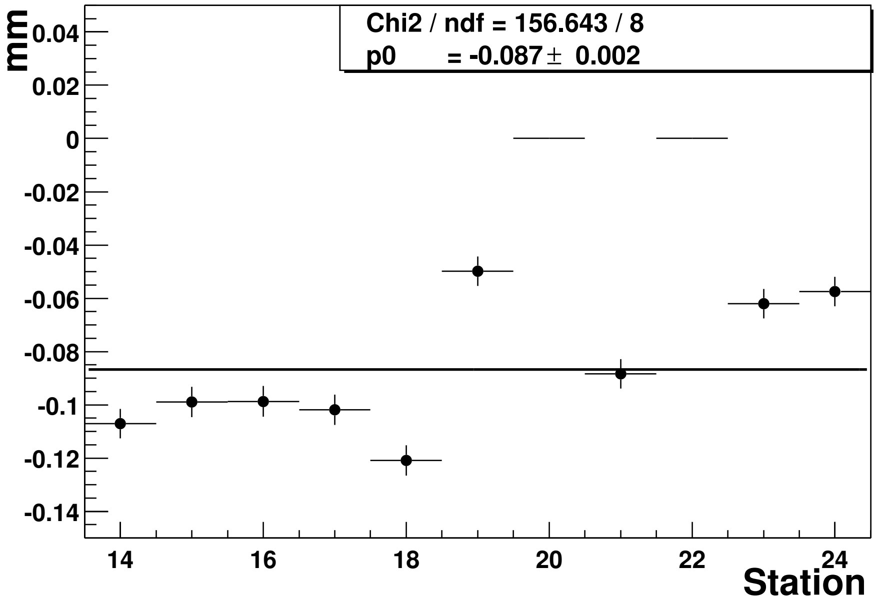
The g-2 phase is aligned so that the EDM signal should be in the g-2 sine amplitude.

The EDM Signal:
g-2 Sine Amplitudes

About $\frac{2}{3}$ of the way though data taking the stored beam alignment was improved.

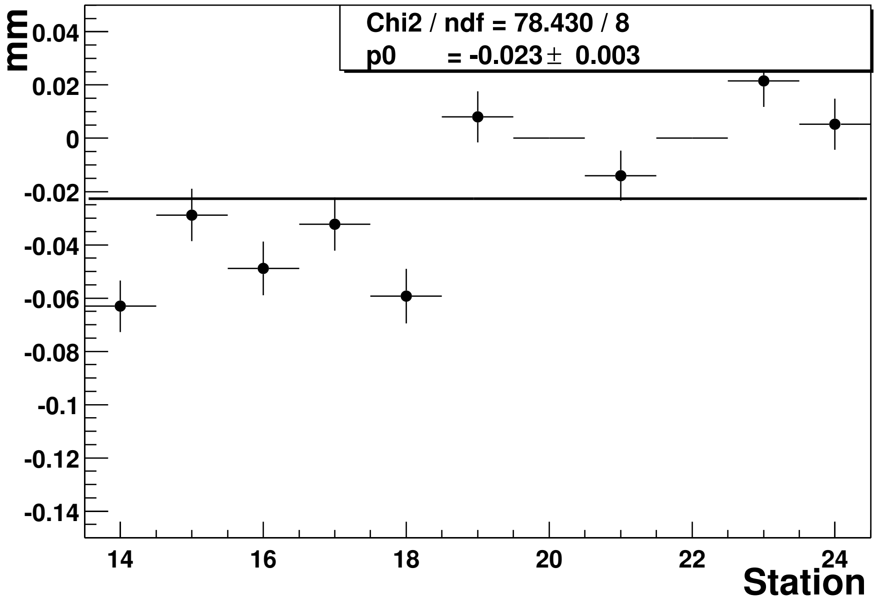
S_{g2} vs. Station

Before Alignment



S_{g2} vs. Station

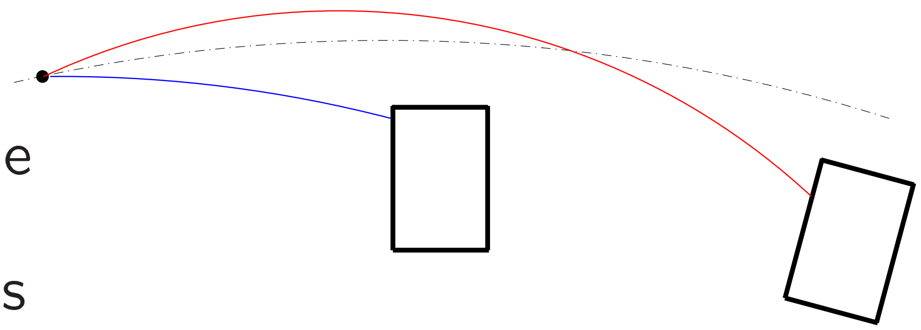
After Alignment



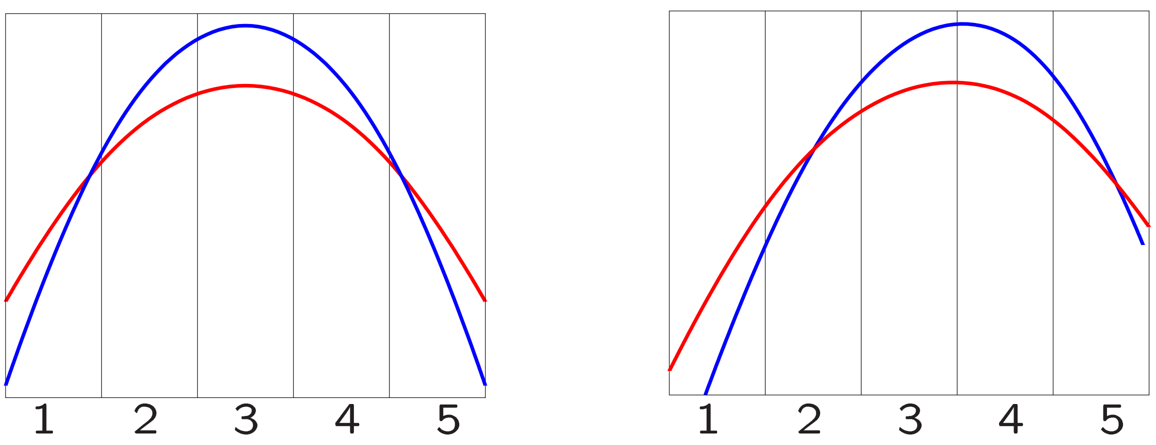
Detector-Beam Alignment

The systematic error on the CERN EDM measurement was due to the alignment between the beam and detectors.

Due to different path lengths the width of the FSD profile for inward and outward decays is different.

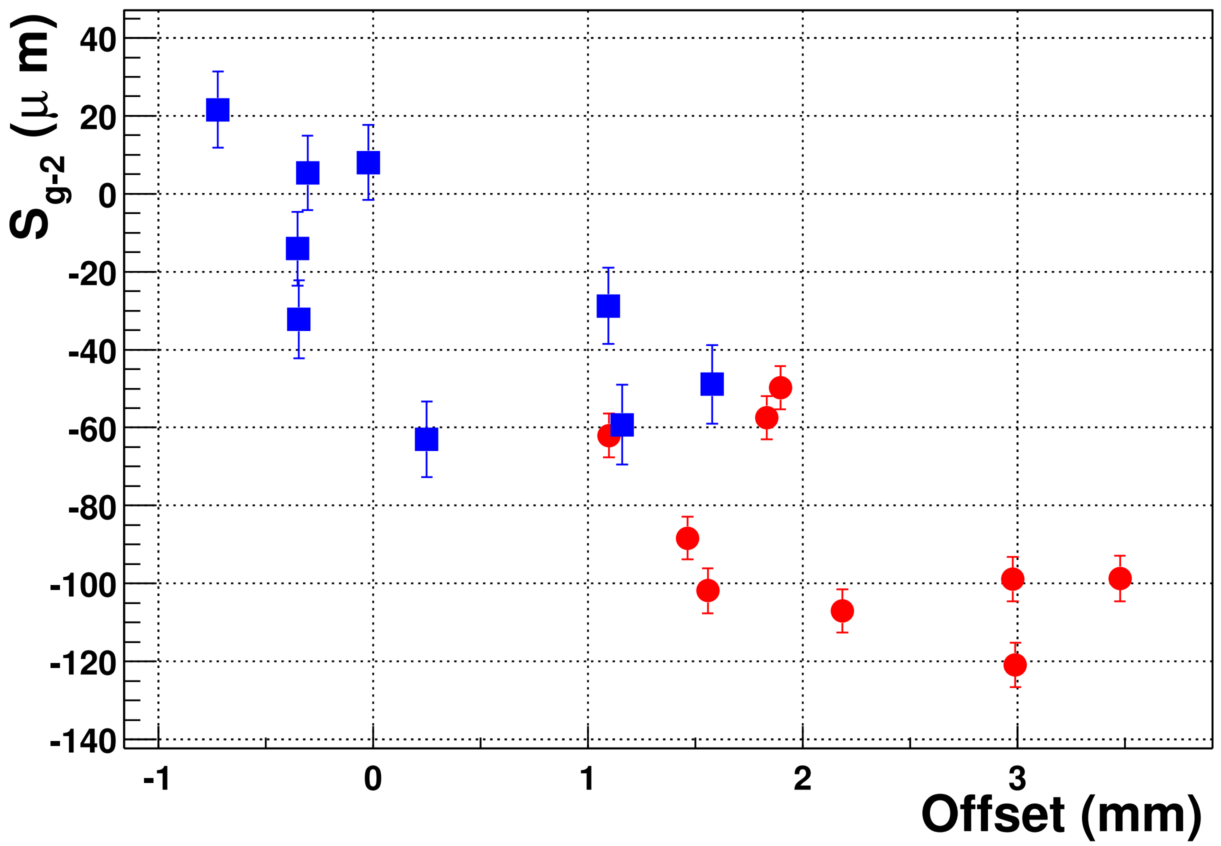


If the beam and detectors are not aligned this "breathing" results in an oscillation in the mean.



Oscillation Amplitude vs Detector Offset

- S_{g2} vs Offset for each detector
- Data from before and after the alignment.
- Obvious correlation between Offset and S_{g2}



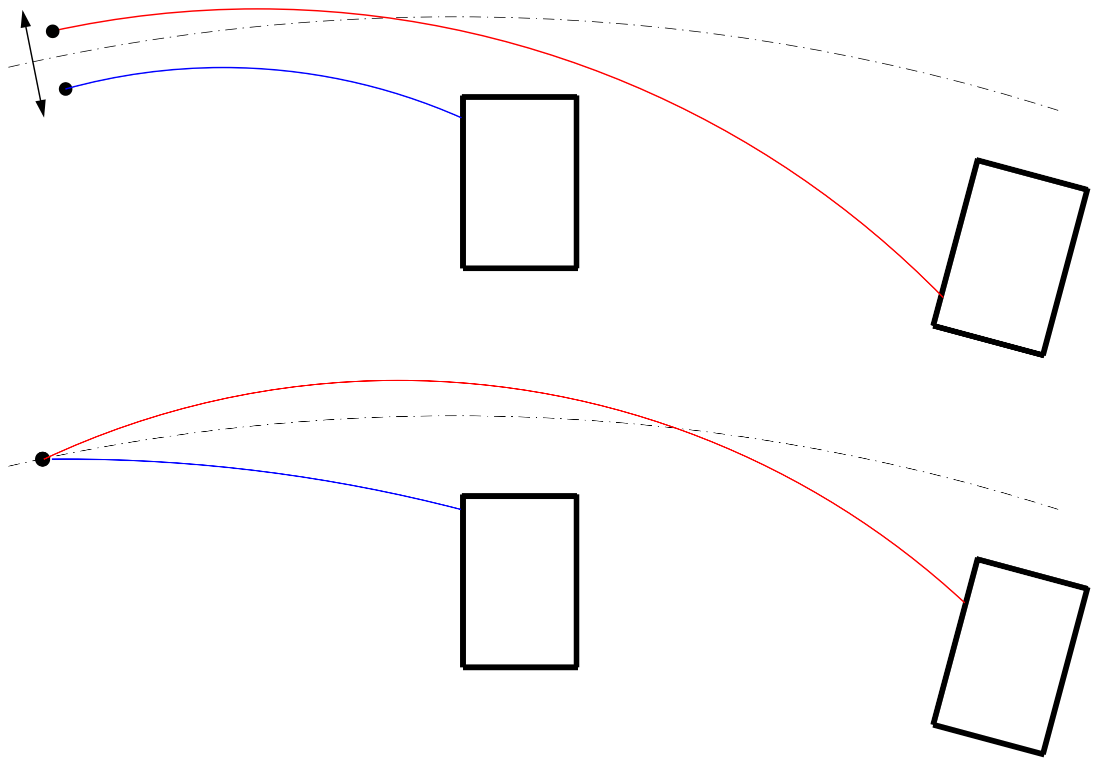
Coherent Betatron Oscillations

- Change in profile width with horizontal position

- Vertical offset between beam and detector

- Asymmetric losses

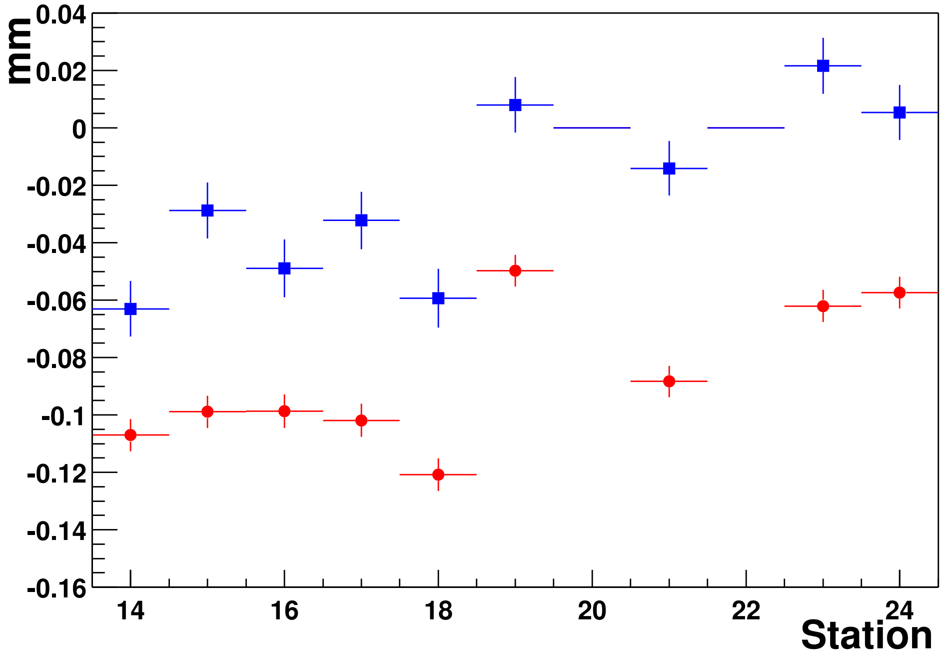
- Oscillation in mean of vertical profile



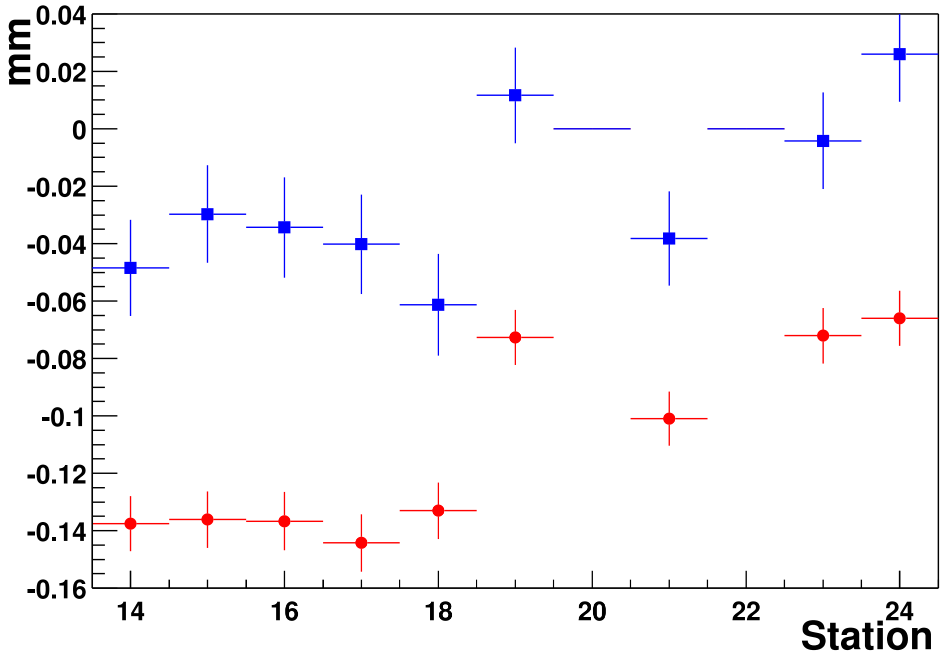
Coherent Betatron Oscillations

CBO and g-2 mean sine amplitudes have similar responses to the beam alignment.

S_{g2} vs Station before and after alignment

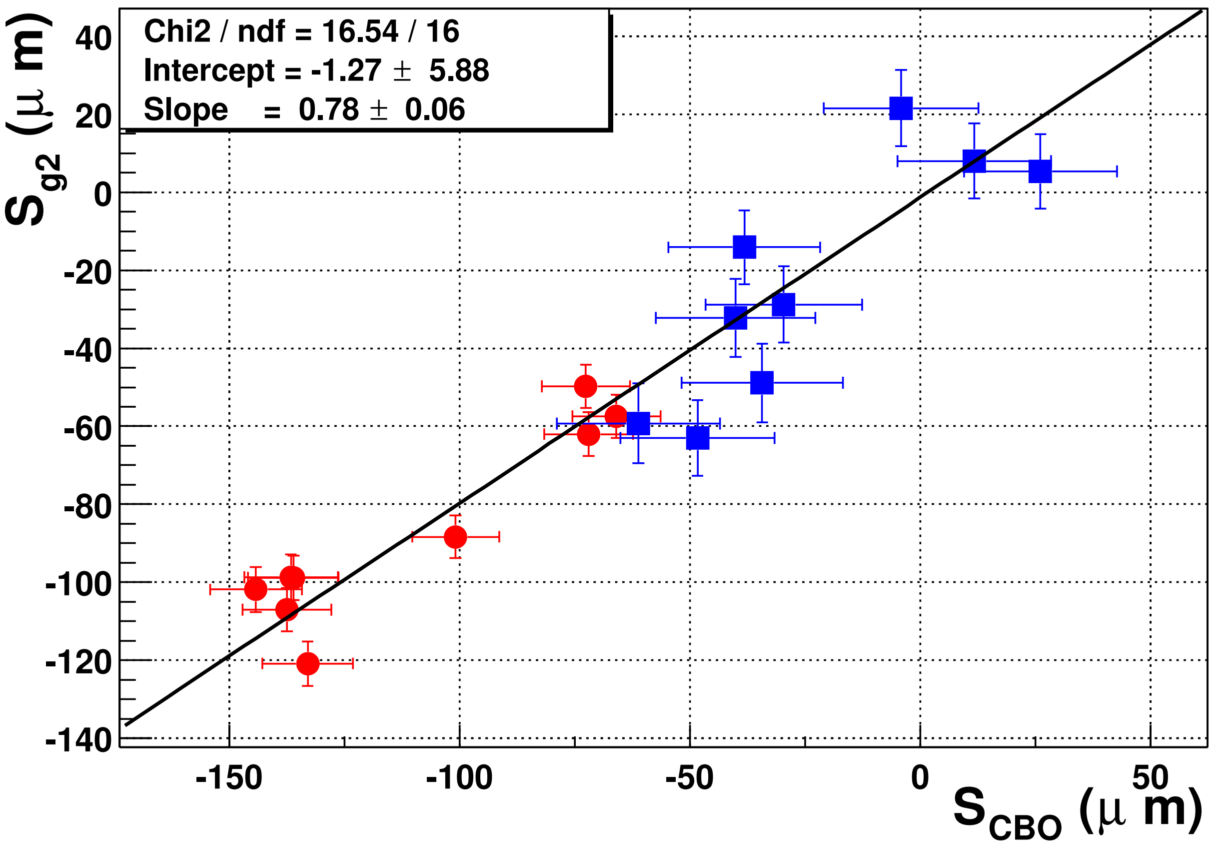


S_{CBO} vs Station before and after alignment



Using the CBO to Correct for Misalignment

- 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
- The intercept of the line is the EDM measurement



Current Error Table

Error	μm
Quadrupole Tilt	3.6
Detector Tilt	3.5
Energy Calibration	2.4
Timing Offset	3.2
Albedo and Doubles	2.0
Radial Magnetic Field and Vertical Spin	1.6
Fitting Method	1.0
Statistical	5.9
$10^{-19} e - cm$	8.8

Results and Outlook

- Eliminated the largest systematic error
- Estimated final error: $\sim 10^{-19} e - cm$
- A factor of 4-5 improvement
- Result should be approved soon
- 2001 data set contains similar statistics
- Traceback: parallel analysis
- Proposed experiment to measure the muon EDM to $10^{-24} e - cm$

FSD Profile RMS vs Time

$$
\begin{aligned}
f(t) = O \quad &+ \quad \left[S\, sin\left(\frac{2\pi t}{P_a}\right) + C\, cos\left(\frac{2\pi t}{P_a}\right)\right] \\
&+ \quad \left[S_2 sin\left(\frac{4\pi t}{P_a}\right) + C_2 cos\left(\frac{4\pi t}{P_a}\right)\right] \\
&+ \quad e^{-\frac{t}{\tau_{CBO}}} \times \left[\begin{array}{l} S_{CBO}\, sin\left(\frac{2\pi t}{P_{CBO}} + \phi_{CBO}\right) \\ \\ +\quad C_{CBO}\, cos\left(\frac{2\pi t}{P_{CBO}} + \phi_{CBO}\right) \end{array} \right] \\
&+ \quad L \times t
\end{aligned}
$$

Profile RMS vs Time After Injection (Station 15)