Projected muon EDM sensitivity at FNAL

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Outline

- FNAL experimental technique
- How an EDM affects the g-2 experiment
- How we measure the EDM
- Early look at systematic uncertainties

Introduction

- The FNAL experiment measures the precession of the muon spin vector relative to its momentum
- Primary goal is to measure the magnetic dipole moment (MDM)
- Detectors are optimised for MDM measurement, but are sensitive to a permanent EDM
- Targeting ~10^{12} detected positrons (10^{11} tracks)
- 20 times more decays than at BNL
- BNL set the current limit on a muon EDM

$$|d_\mu| < 1.9 \times 10^{-19} \ e{\cdot}\mathrm{cm} \ (95\% \ \mathrm{C.L.})$$

arXiv: 0811.1207

The g-2 experimental technique

g-2 experiment

- Store longitudinally polarised muons in a dipole field (~1.45T)
- Measure 2 quantities:
  - ω_a - the precession frequency
  - <B>, the average magnetic field sampled by the muon distribution

$$\boxed{\omega_a} = \omega_s - \omega_c = a_\mu \frac{e \boxed{< B >}}{m_\mu c}$$

Larmor Precession   Thomas Precession

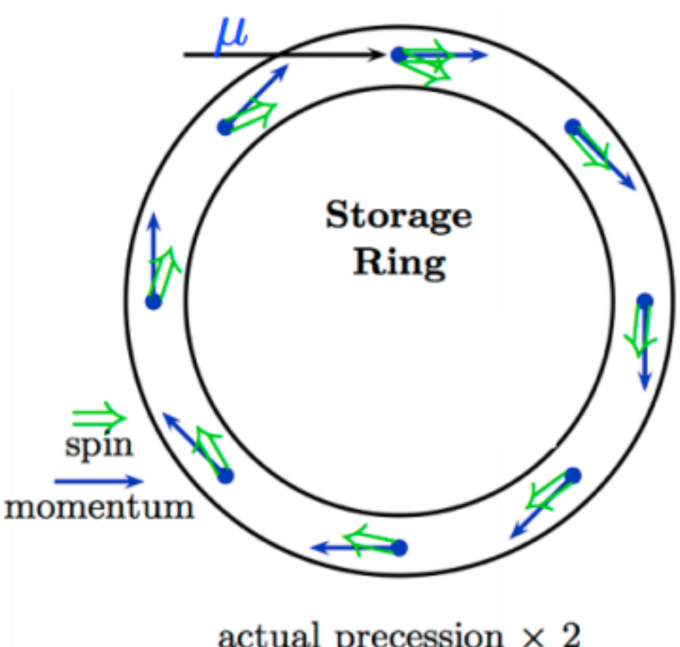
$$\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

Spin Precession frequency

$$\omega_c = \frac{eB}{\gamma mc}$$

Cyclotron frequency

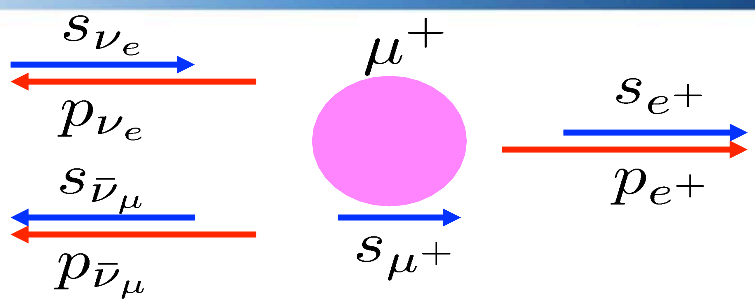
~140ns @ FNAL   ~149ns @ FNAL

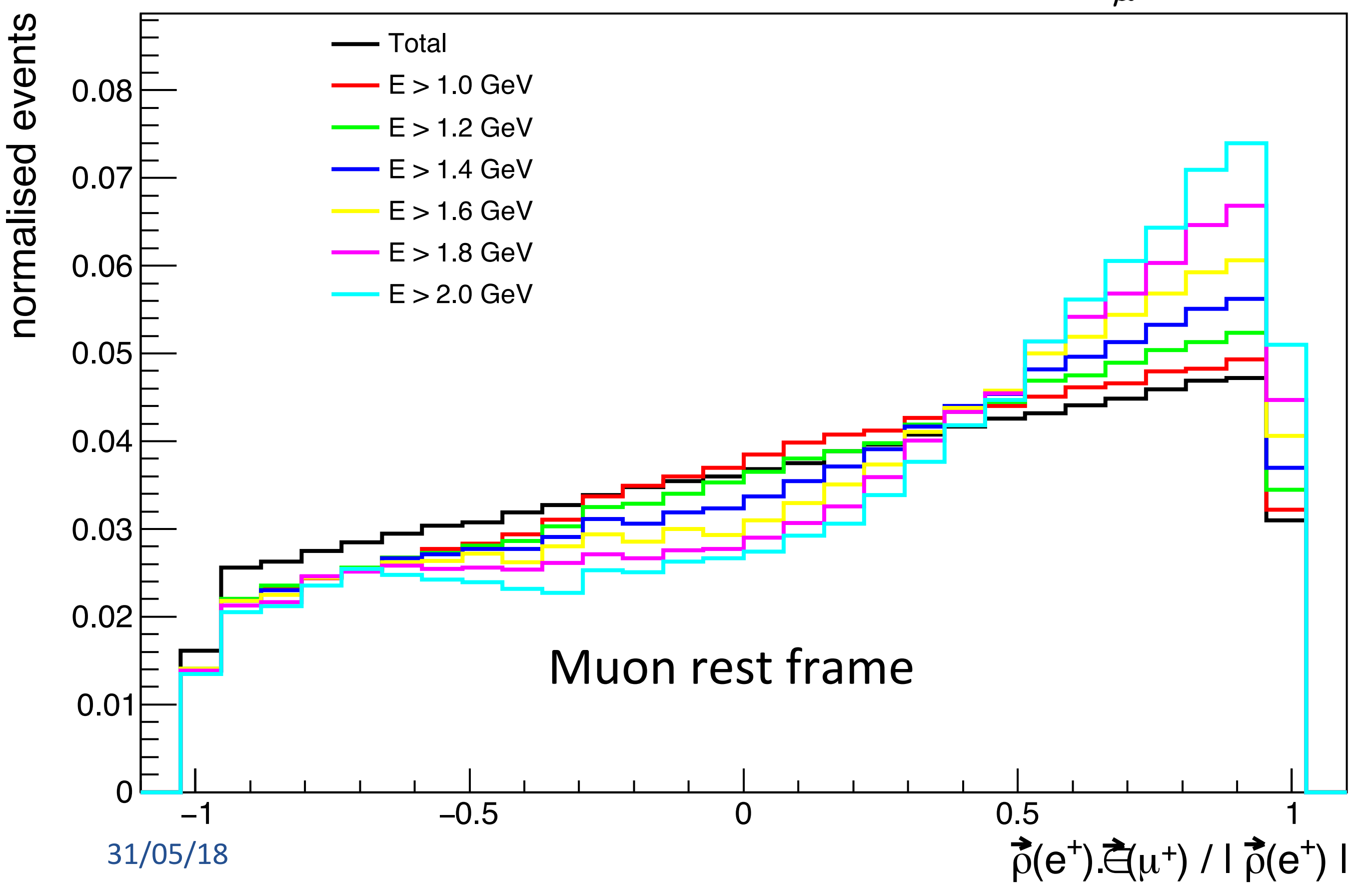


- Spin precession > 2π per cyclotron turn

μ^+ decay

- e^+ preferentially emitted in direction of the μ^+ spin



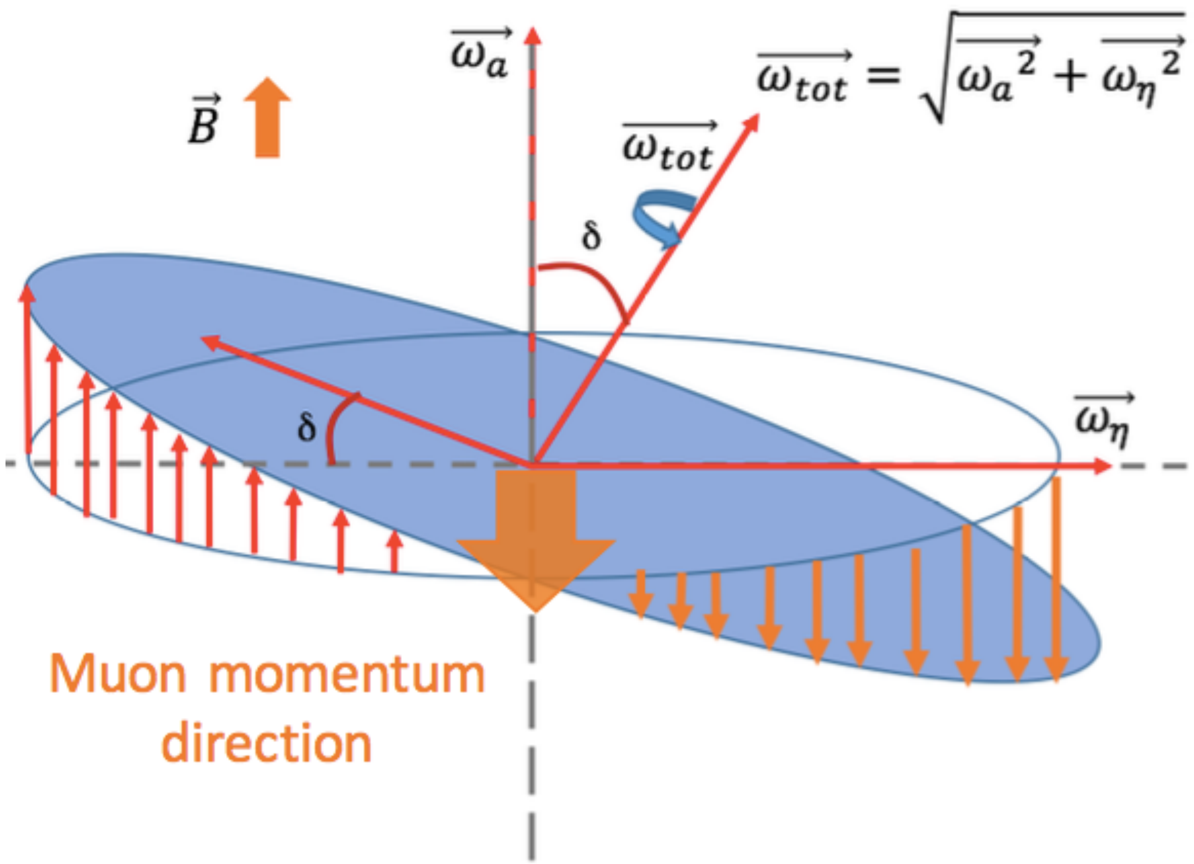


- Asymmetry is larger for higher energy positrons
- Optimal cut at ~E > 1.8 GeV

$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{2\pi f_a \tau_\mu \sqrt{N A^2}}$$

Effect of an Electric dipole moment

EDM in a storage ring

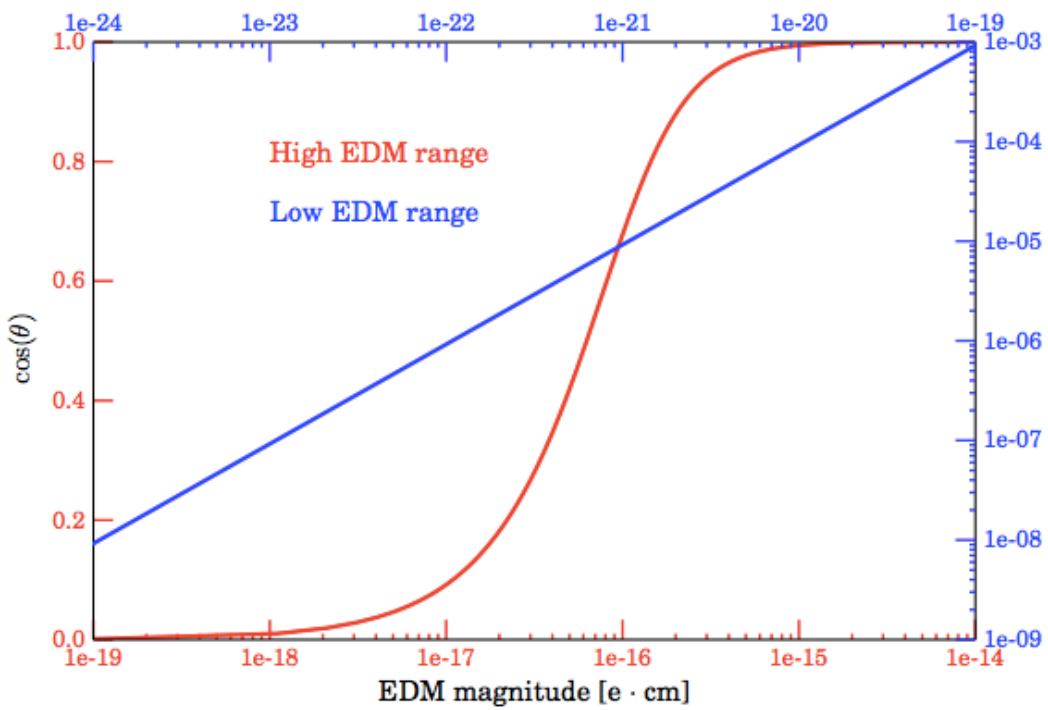


- A muon EDM tilts the precession plane of the spin vector
- Causes a vertical oscillation at same frequency as observed g-2 signal
- +/- 90° out of phase (depending on sign)
- Large EDM increases the precession frequency

Tilt angle

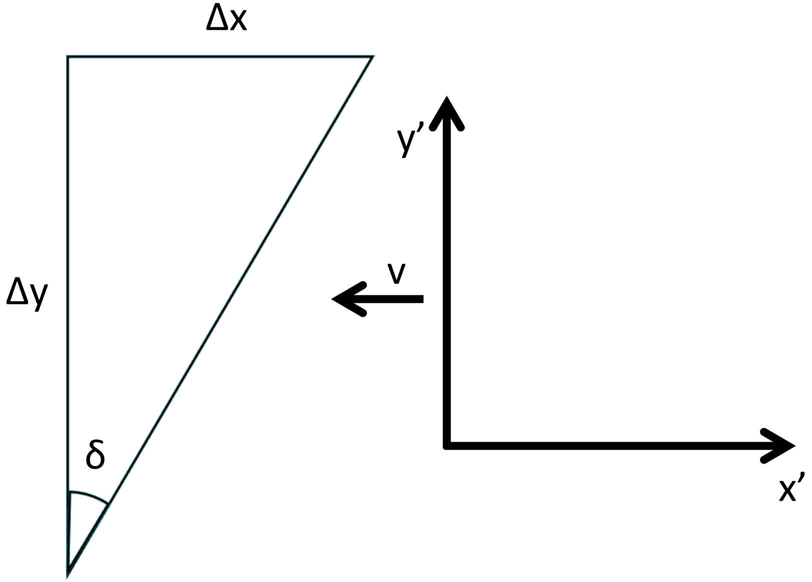
- The tilt of the precession plane is determined by the size of the EDM, and is given by:

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



Vertical angle boost

- The precession angle due to the EDM is reduced by the Lorentz boost
- Neglecting the vertical component of the muons momentum a simple formula can be derived:



$$\tan(\delta) = \frac{\Delta x}{\Delta y}$$

$$\Delta x' = \frac{\Delta x}{\gamma} \qquad \Delta y' = \Delta y$$

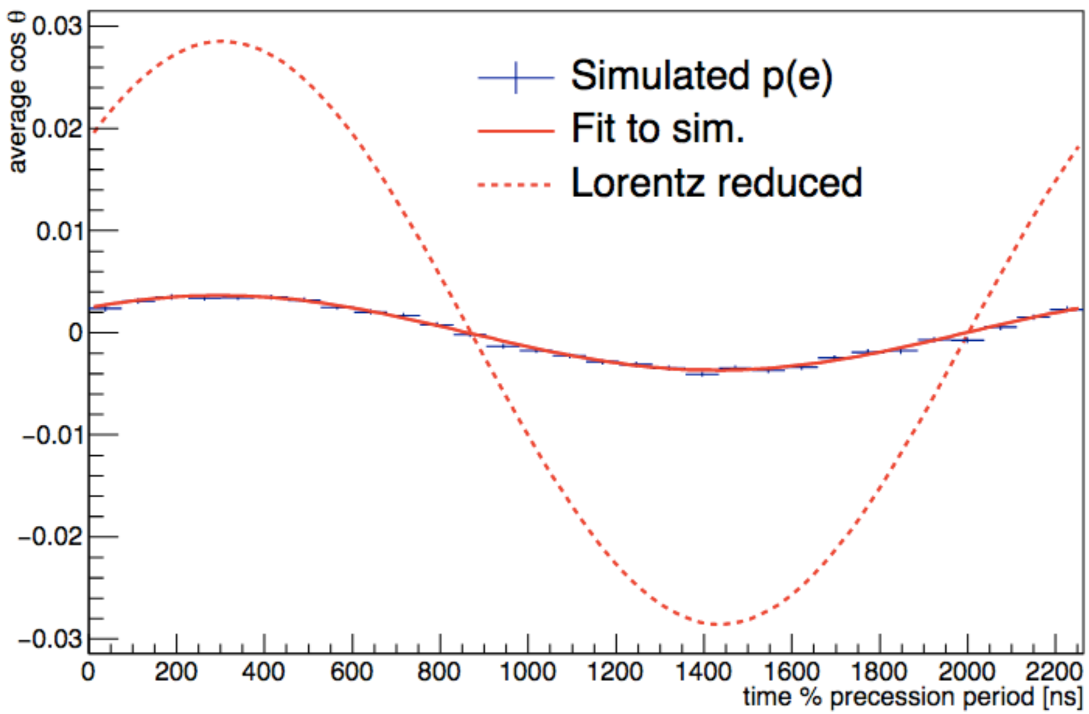
$$\tan(\delta') = \frac{\Delta x'}{\Delta y'} = \frac{\Delta x}{\gamma \Delta y}$$

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

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

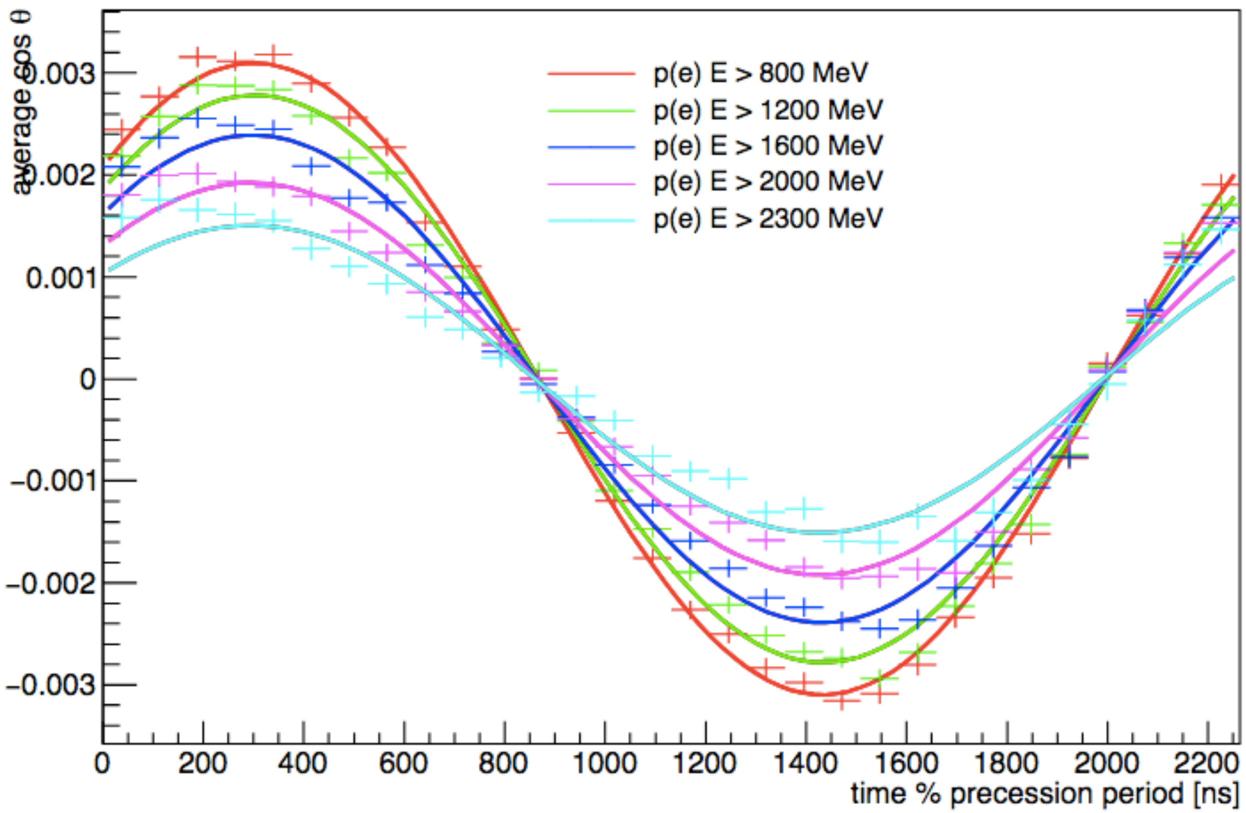
Decay asymmetry

- There is a further reduction due to fact that not all positrons are emitted in the muons momentum direction, and due also to detector acceptance
- Using simulation, this is estimated to be ~10%, as was the case for the Brookhaven experiment



Decay asymmetry vs momentum

- Unlike the MDM it is the low energy positrons carry the EDM signal



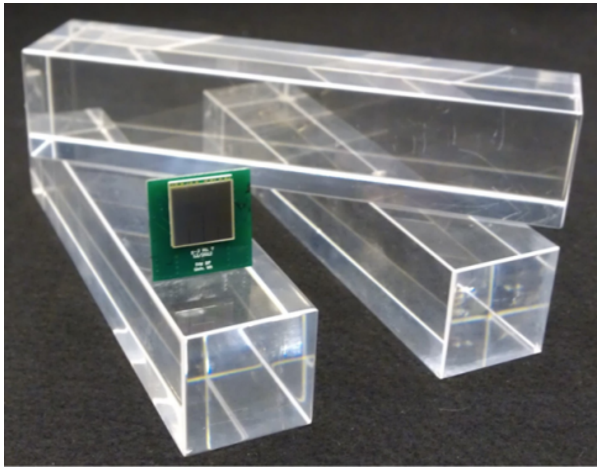
for EDM of
$d_\eta = 1.8\times10^{-16}$ e.cm

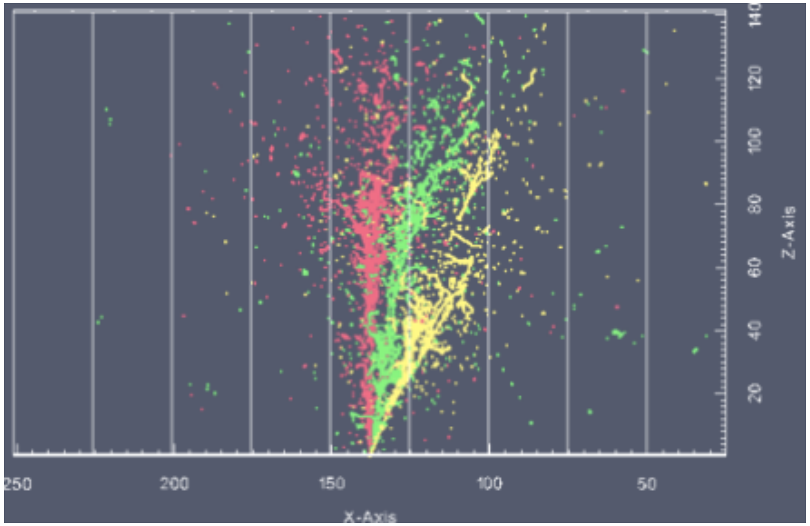
- However very low energies contain less information about the muon polarisation direction, so a lower and upper bound on the positron energy is used

Detectors in the FNAL E989 experiment

Detectors: Calorimeters

- 24 calorimeters placed on the inside of the ring
- Each with and array of 6 × 9 lead flouride crystals

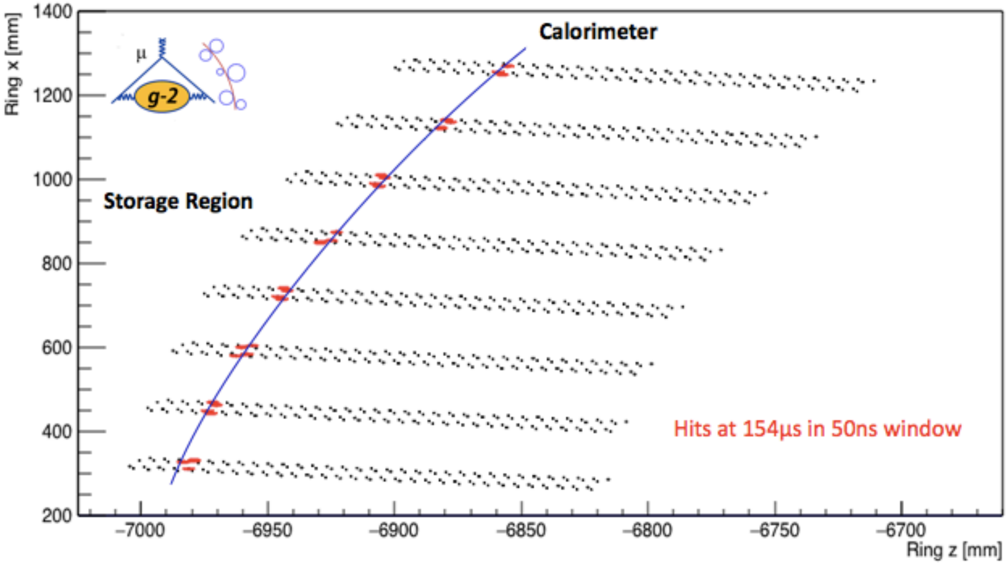


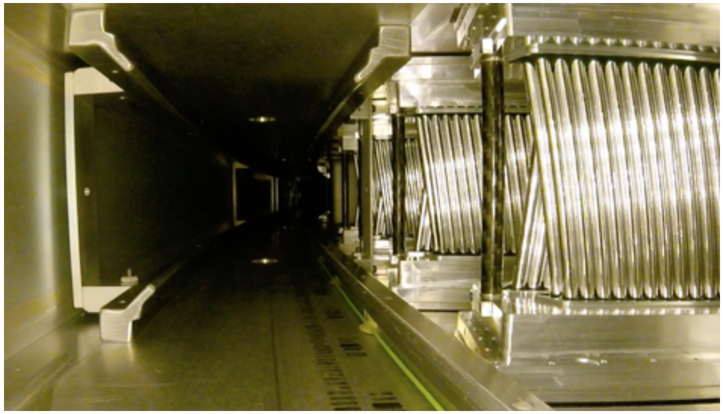


- Detect the incident decay positrons and measure arrival time and energy
- Can measure the radial and vertical position of incident decay positron with an accuracy < 3mm

Detectors: Trackers

- 2 tracking detectors placed around the inside of the ring, 90° apart
- In front of 2 of the 24 calorimeters

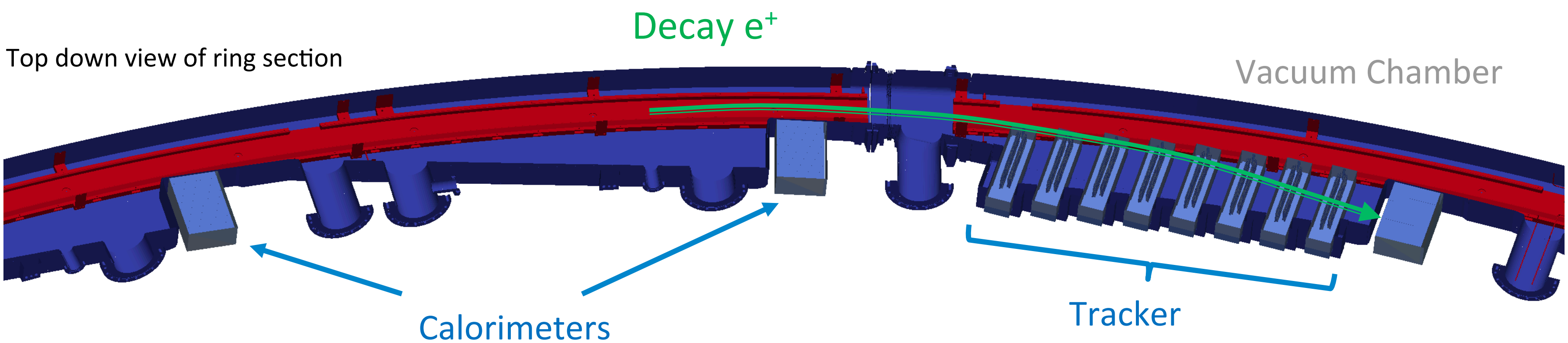




- Measure the decay positron tracks and give radial and vertical positional and angular information, and a track that points back to the decay point…

Track extrapolation

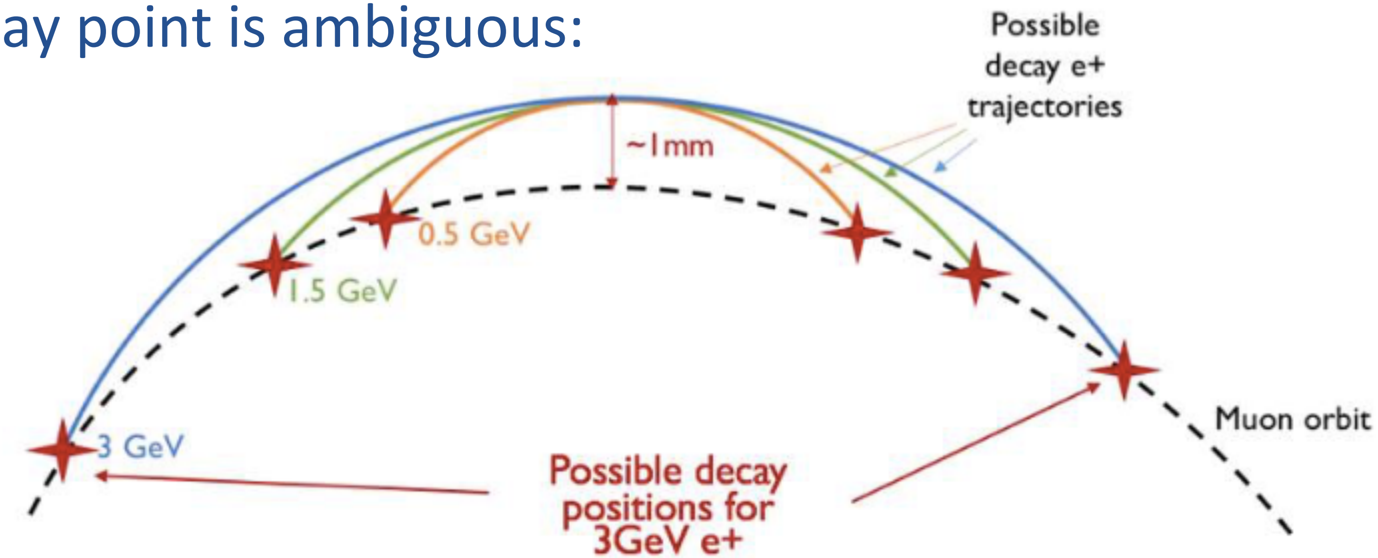
- The measured tracks are extrapolated back through the magnetic field to the storage ring using a Runge-Kutta algorithm



- This gives us an approximate radial and vertical decay position, and also the vertical decay angle

Estimating decay position

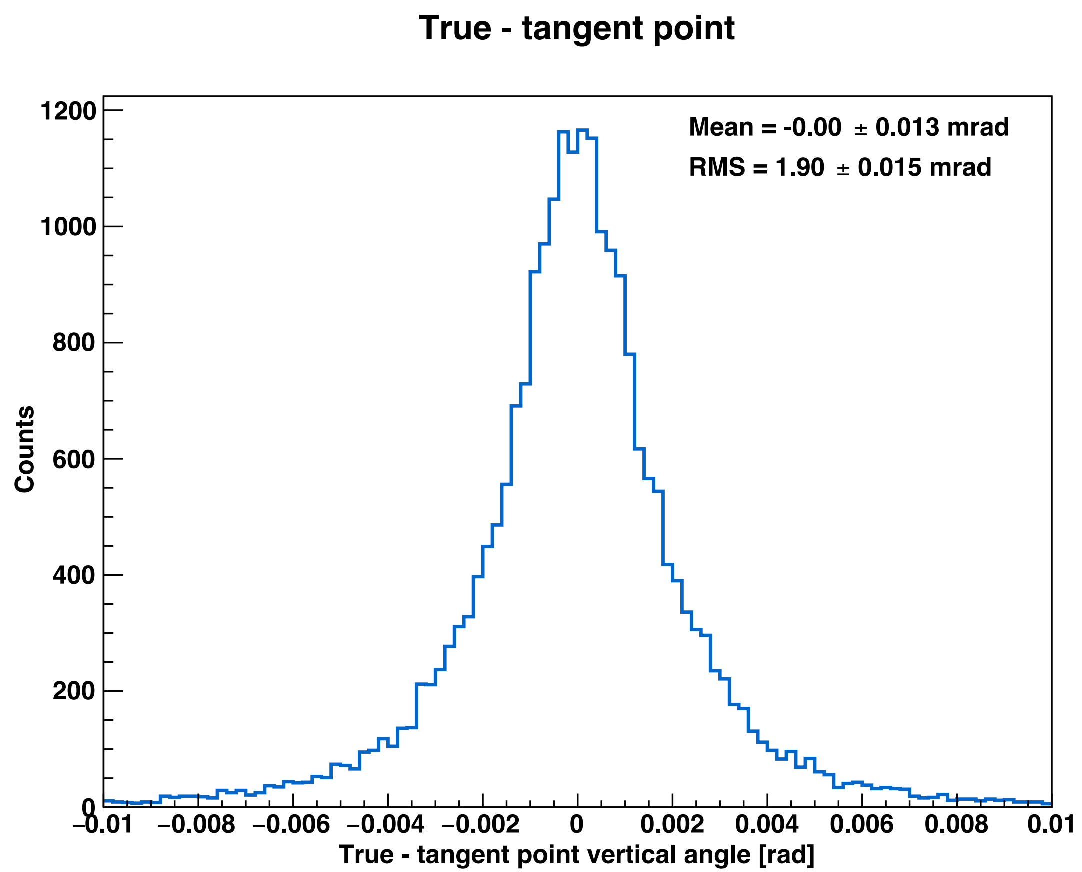
- It is only an approximation of the decay position, as the exact decay point is ambiguous:



- This introduces a bias in the radial position measurement of approximately 1mm, but has a smaller effect on the vertical decay angle measurement

Vertical angle measurement

- The error in the angle from using the approximate decay position is about 2mrad
- This corresponds to an EDM of 5×10^{-16}e.cm!
- However it is the average measured vertical angle that counts
- Therefore it is the error on the mean that determines our ultimate sensitivity



When full tracking is taken into account, the overall uncertainty on the angle is ~5 mrad

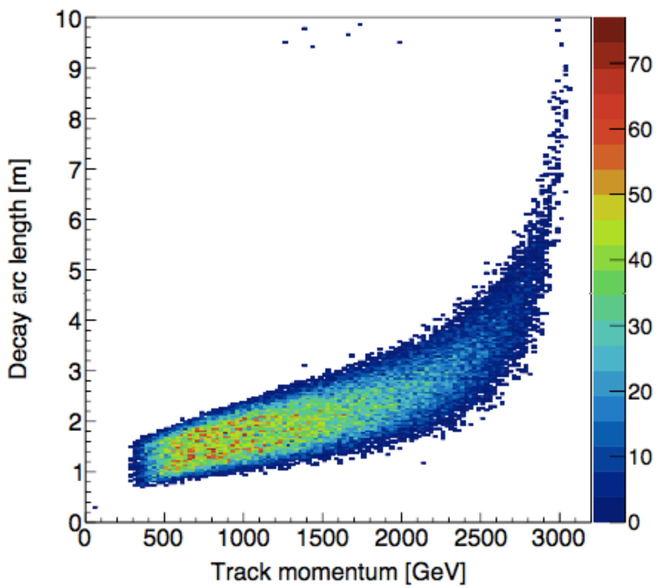
Systematics

What else causes a vertical oscillation?

- Radial field
  - Together with acceptance effects the radial field can cause a vertical oscillation at the g-2 frequency
  - Measured as a function of azimuth, but is effected by temperature fluctuations in the hall
  - $B_R < 3 \times 10^{-4}$T, slightly larger than BNL
- Beam oscillations
  - The beam oscillates (due to betatron oscillations) vertically
  - The beam is tuned such that these oscillations do not occur at the g-2 frequency
- Detector misalignments
  - Difference in inward and outward decays together with a misalignment can cause a false EDM signal

Alignment

- We expect the angle of the beam to vary as a function of azimuth due to the radial field
- Each tracker will measure a different vertical angle around the ring, however should be opposite signs
- Need to add in the measured vertical alignment and uncertainty to determine the size of the systematic uncertainty



Using plot on the left the decay angle vs extrapolated distance can be used for an alignment of each tracking station (internal g-2 plot)

Conclusions

- The FNAL E989 experiment is an improvement on the BNL experiment, which set the current best limit on the muon EDM
- A muon EDM causes a vertical oscillation at the g-2 frequency (but 90° out of phase)
- Tracking detectors can measure an approximate decay angle, and monitor any variation throughout the fill
- Using these improved traceback detectors and higher statistics the limit is expected to improve by a factor 10
- Effect of slightly increased radial field and alignment still need to be determined, early indication suggest a ~1mrad correction is needed
- Nothing yet to suggest goal will not be met!