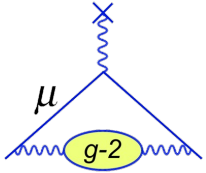
The search for a muon EDM at the Fermilab $g-2$ experiment

Samuel Grant
On behalf of the $g-2$ collaboration



NuFact 2022

Electric dipole moments (EDMs)

- Classically, an EDM, $\vec{d}$, describes the permanent polarisation of a system of electric charges

- For an elementary particle, it is defined by its interaction with an external electric field, $\boldsymbol{E}$, via the Hamiltonian

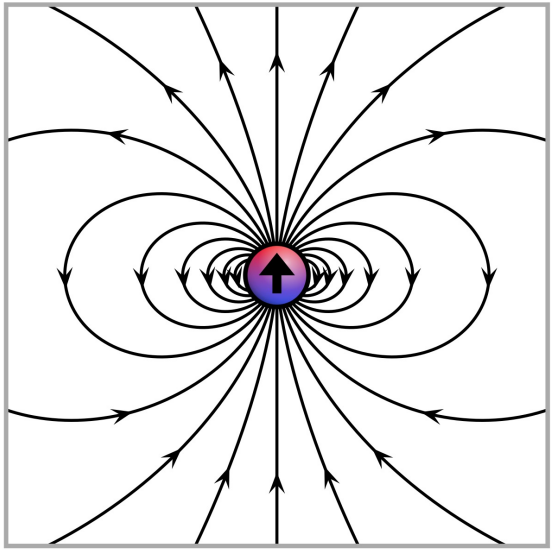
$$\mathcal{H} = -\boldsymbol{d} \cdot \boldsymbol{E}$$

- The EDM must be directed along the spin polarisation vector

$$\boldsymbol{d} = \eta \frac{e}{2mc} \boldsymbol{s}$$

- η is coupling constant analogous to the magnetic g-factor

- EDMs are CP-violating quantities!



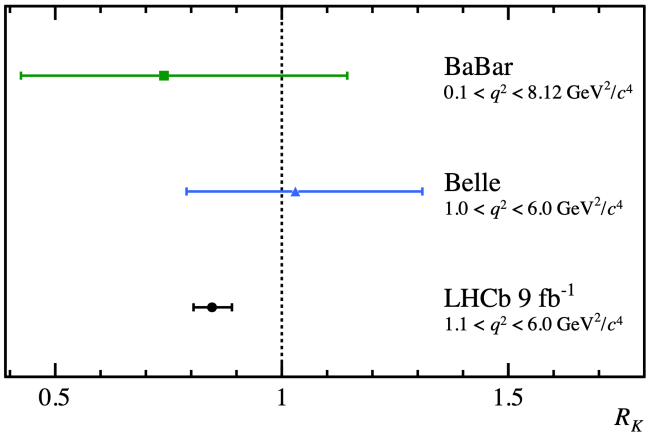
The EDM landscape

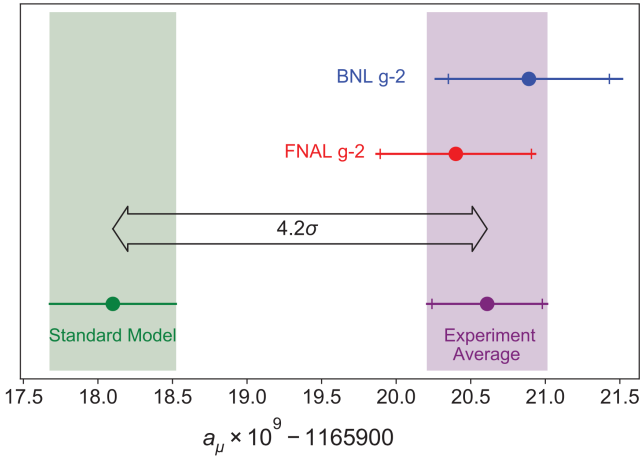
- No permanent EDM has ever been discovered for any particle or atom
- SM predicted values are well beyond the sensitivity of today's experiments
- The muon EDM upper limit was set by the BNL E821 $g-2$ experiment
- Assuming linear mass scaling, a muon EDM upper limit of $\sim 10^{-27}$ e ·cm may be inferred from the electron upper limit
- Any detection of an EDM would signal new physics!

Particle	Upper limit [e ·cm]	SM prediction [e ·cm]	Ref.
p	2.0×10^{-26} (95% C.L.)	$\sim 10^{-32}$	[1], [2]
n	1.6×10^{-26} (95% C.L.)	$\sim 10^{-32}$	[1], [2]
e	1.1×10^{-29} (90% C.L.)	$\sim 10^{-38}$	[3], [4]
μ	1.8×10^{-19} (95% C.L.)	$\sim 10^{-36}$	[5], [4]

Anomalies in the flavour sector

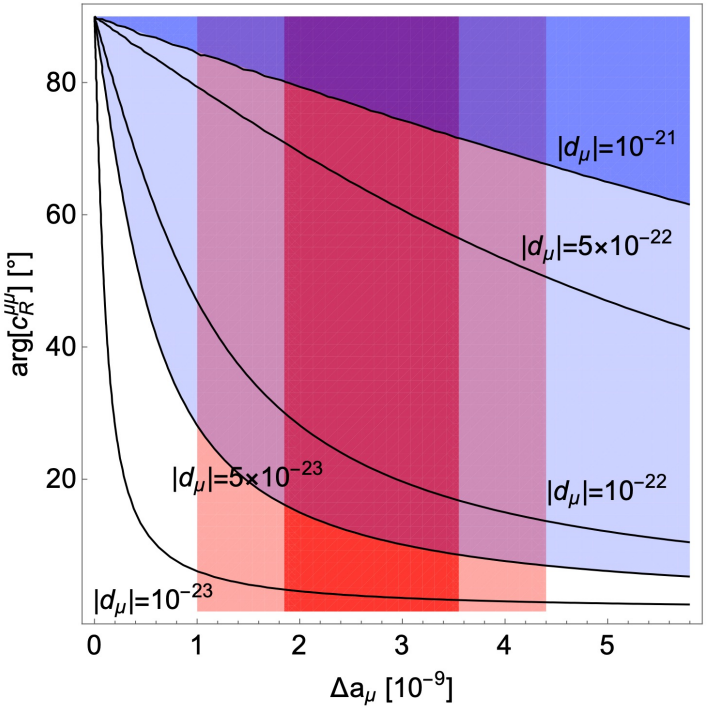
- 2021 was a year of flavour anomalies at $2\sigma+$
- The anomalous magnetic moment of the muon (Muon $g-2$ [6])
- The ratio of B-meson decays to muons vs electrons (Belle [7] and LHCb [8])
- Does new physics couple differently to muons?





A large muon EDM?

- The linear mass scaling of EDMs between lepton generations is challenged by flavour anomalies
- The muon sector could be decoupled from the electron sector
- Heavy solutions to the magnetic anomaly, such as leptoquarks, introduce an unconstrained CP violating phase which could allow for a large (measurable) muon EDM [9]
- An interesting time to conduct a muon EDM search!



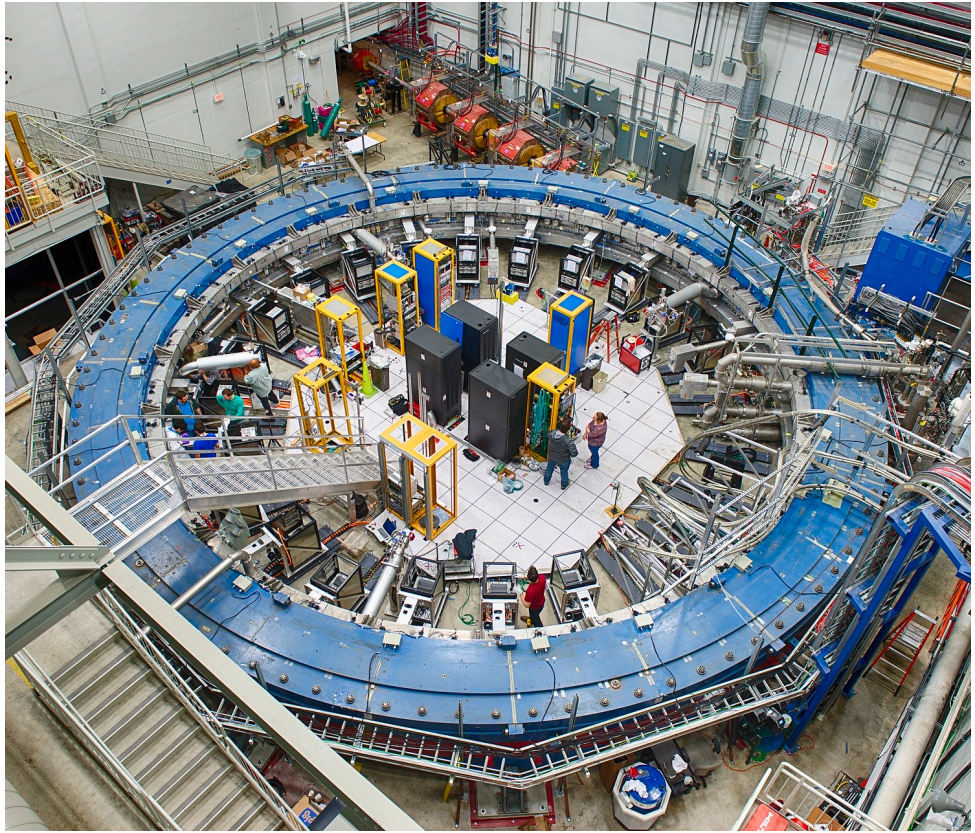
The Fermilab $g-2$ experiment

- The latest iteration in six decade-long campaign to measure muon $g-2$/EDM
- Run-5 recently completed, with an integrated dataset ~19x the BNL $g-2$ experiment

<u>Aims:</u>

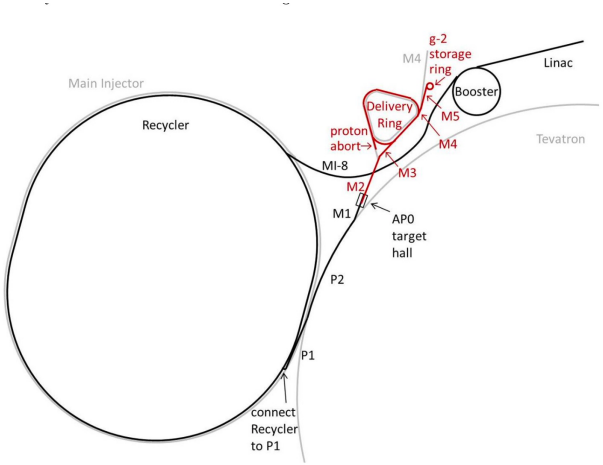
1) Measure the anomalous magnetic moment of the muon to a precision of 140 ppb

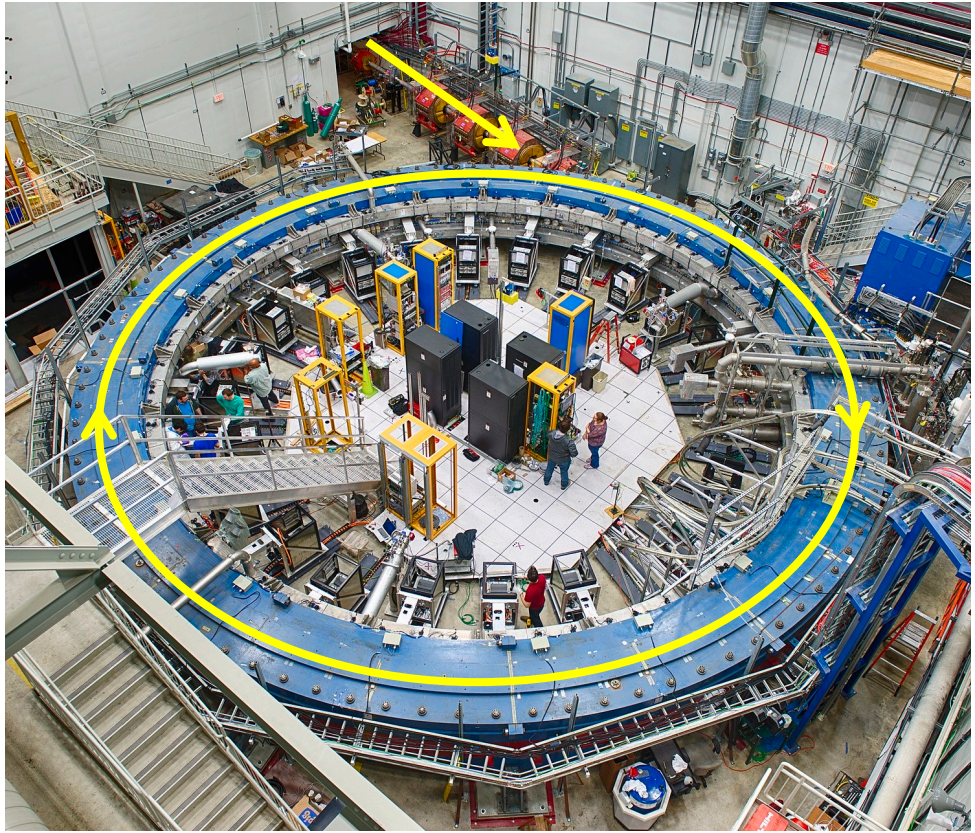
2) Conduct a world-leading search for a muon EDM



Muon production

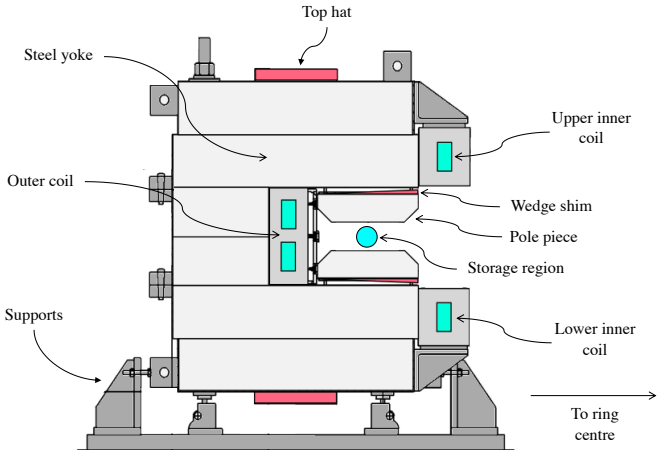
- A beam of longitudinally polarised μ^+ are delivered from Fermilab's accelerator complex
- μ^+ are produced via π^+ decay

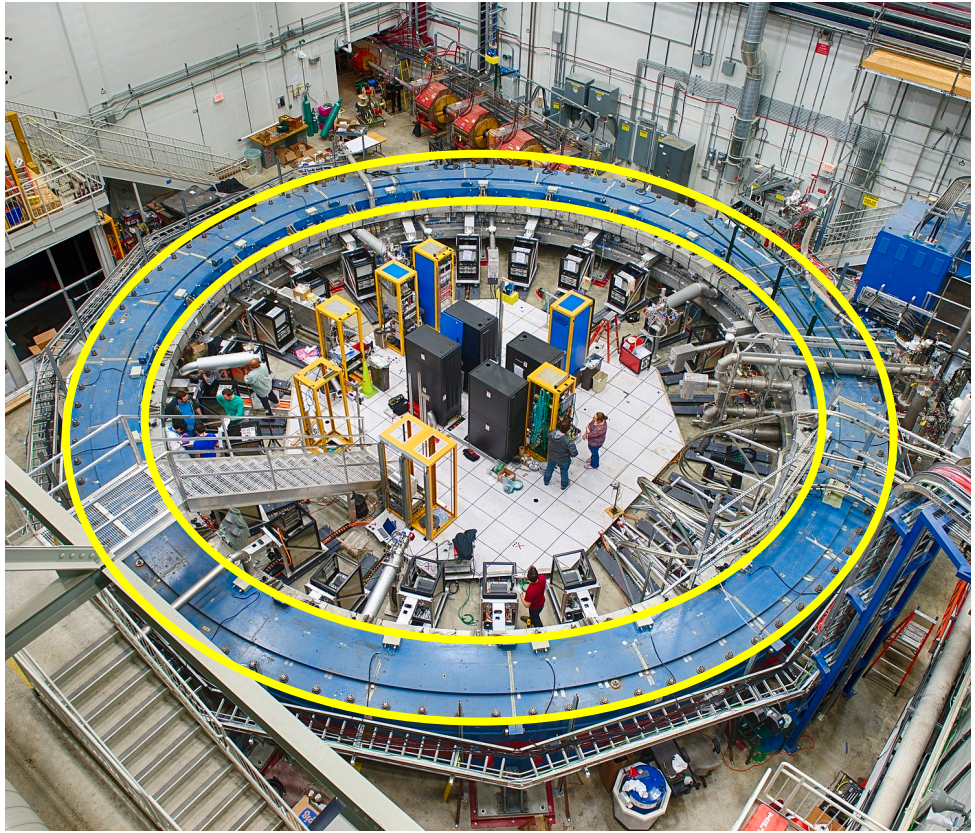




The magnet

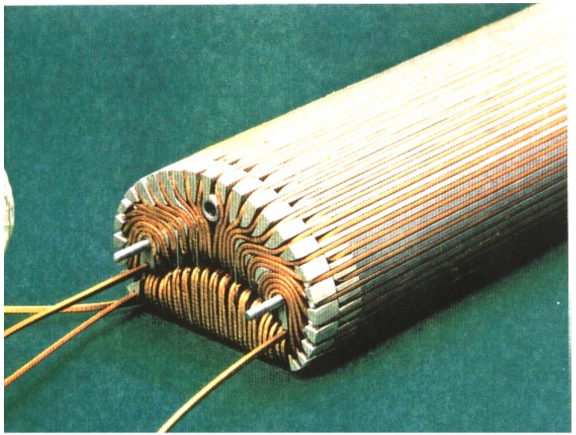
- C-shaped, ~680 metric superferric electromagnet, originally from the BNL $g-2$ experiment
- 1.45 T vertical field with a uniformity of ±1 ppm
- Field is mapped by a suite of NMR probes

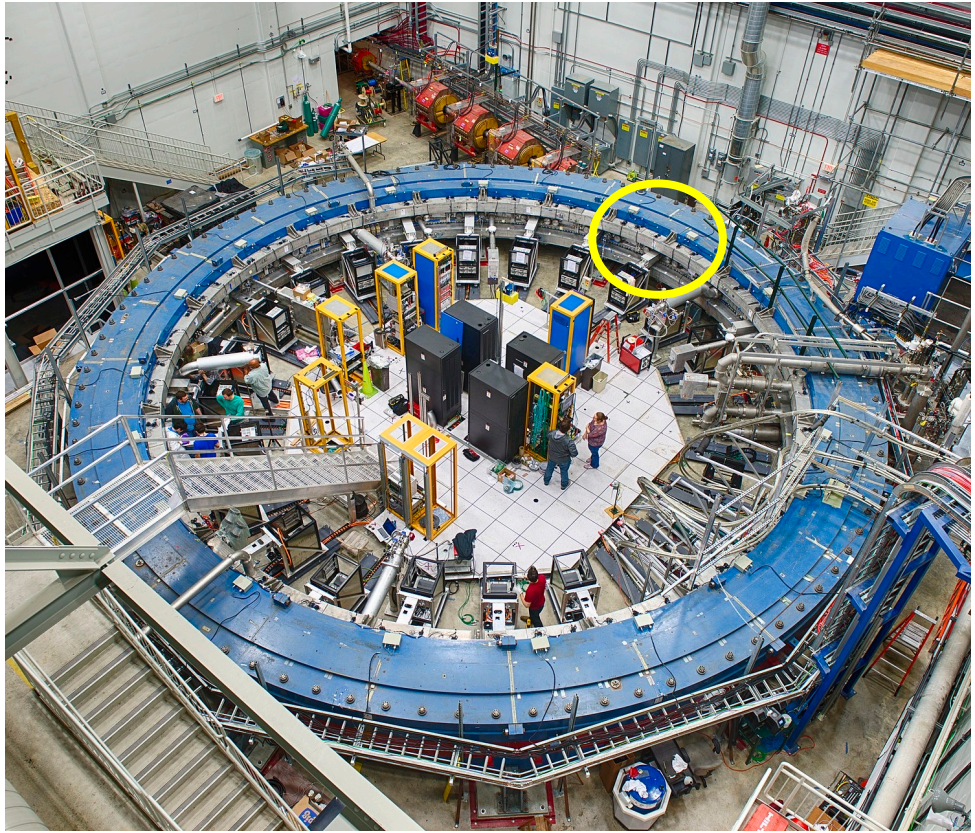




Injection / the inflector

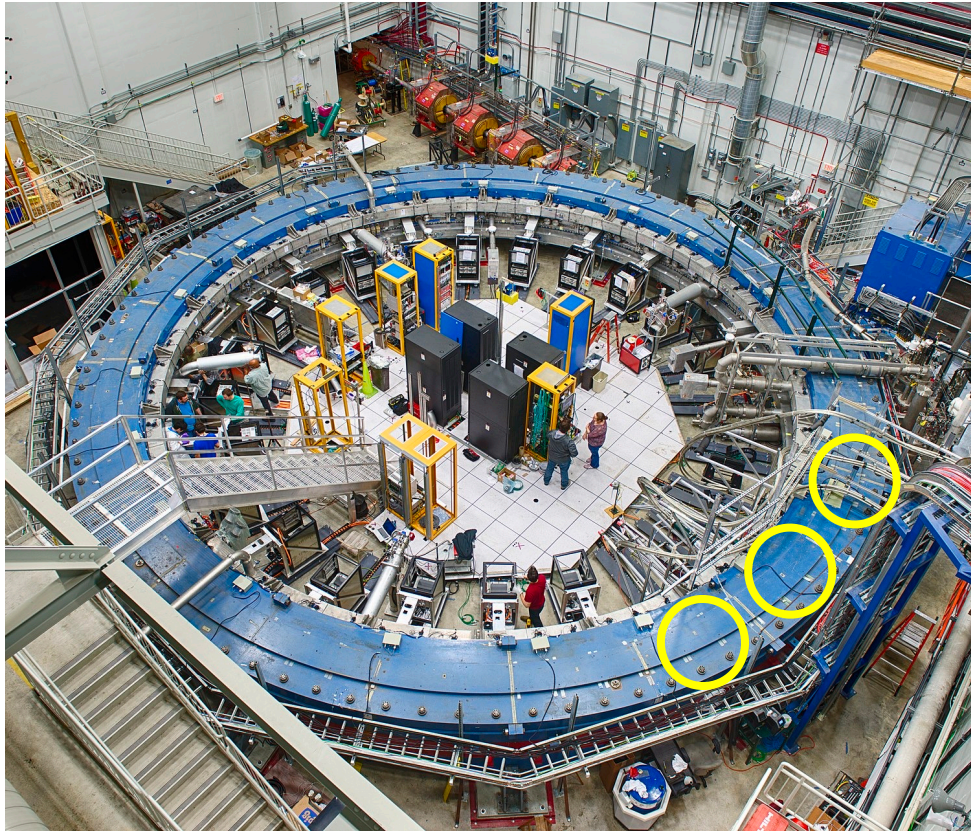
- μ^+ are injected directly through the magnet
- A field-cancelling superconducting inflector magnet is used to prevent deflection





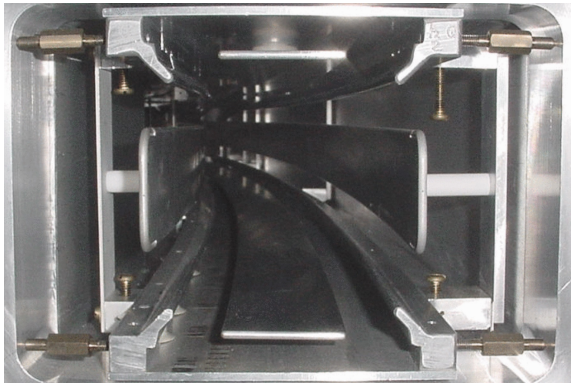
The kickers

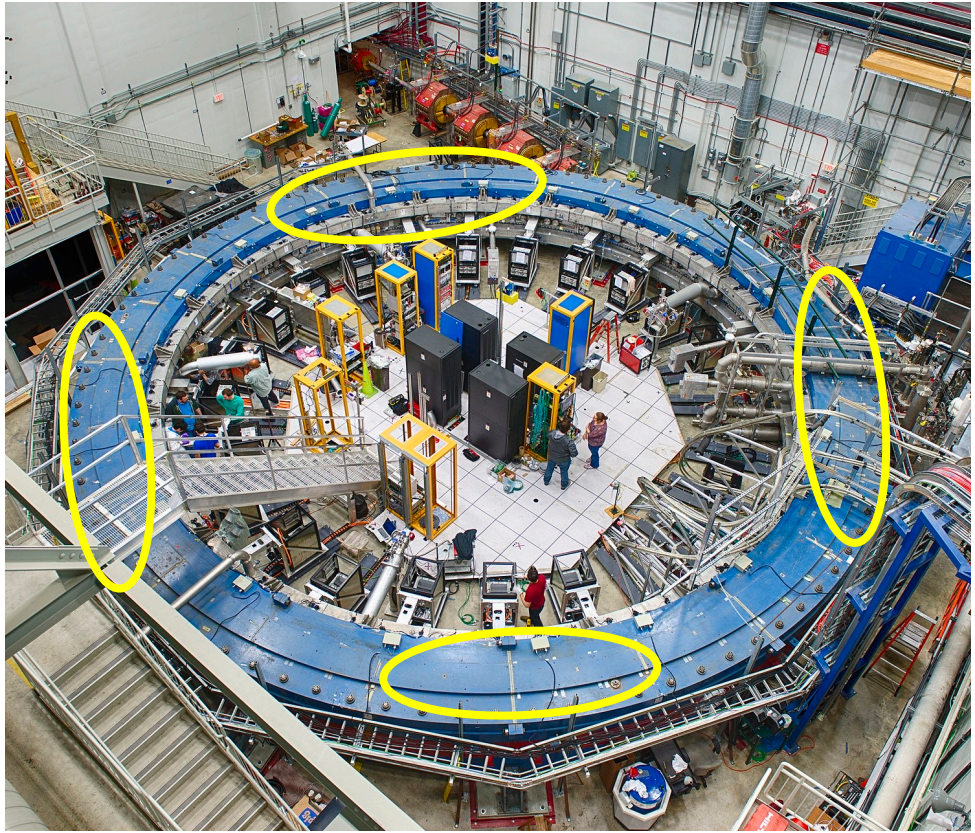
- Three electromagnetic kickers set the beam on a stable orbit
- They produce a 120 ns pulsed vertical magnetic field, which dies away before the μ^+ circulate back around



The quadrupoles

- Four sets of electrostatic quadrupole plates provide vertical focusing
- The magnetic field provides radial focusing

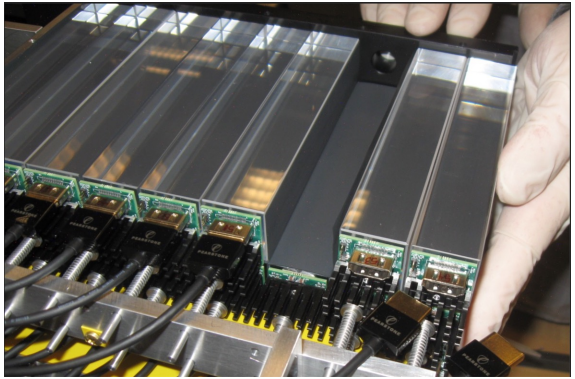


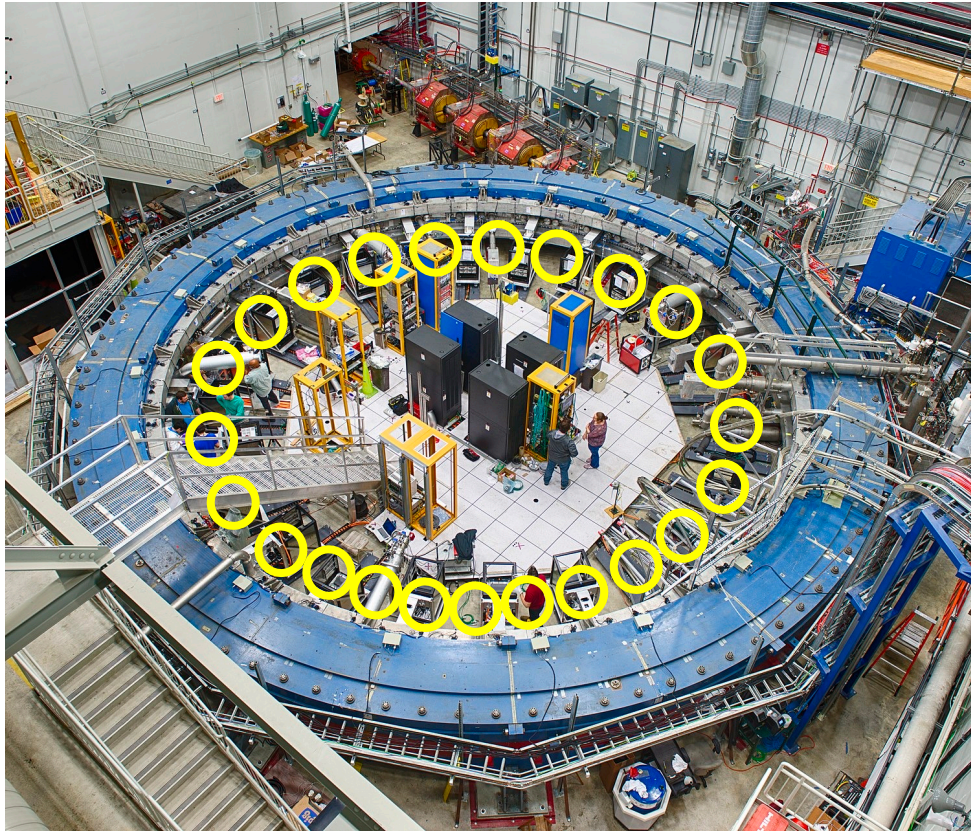


The calorimeters

- Twenty-four calorimeters measure the time and energy spectrum of decay e^+ falling out of the magnetic field; they can also measure hit position

- e^+ produce Cherenkov light in a 9-wide x 6-high array of lead-fluoride crystals, sensed by silicon photomultipliers

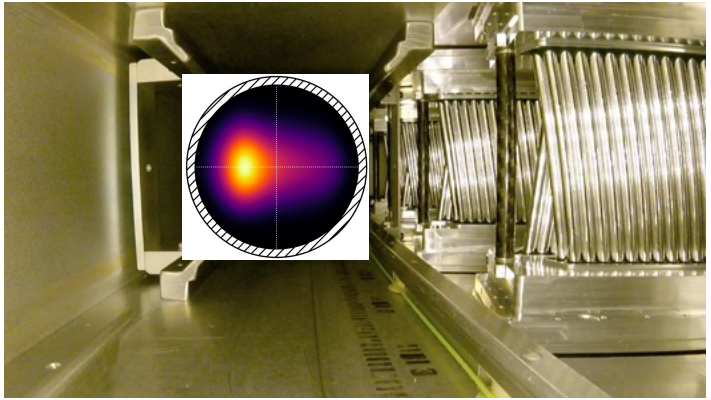


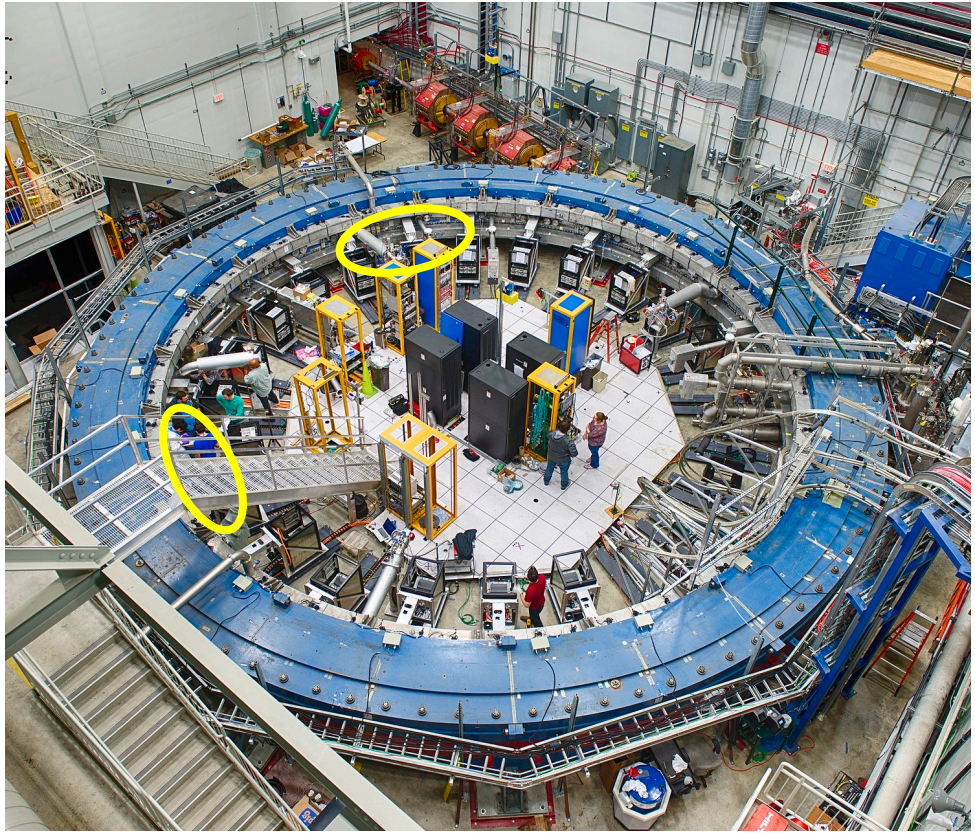


The trackers

- Two in-vacuum straw tracker detectors measure decay e^+ position and momentum

- 2048 Mylar straws in total, each enclosing an argon-ethane atmosphere. A sense wire, surrounded by a radial electric field, records hits which are reconstructed into tracks

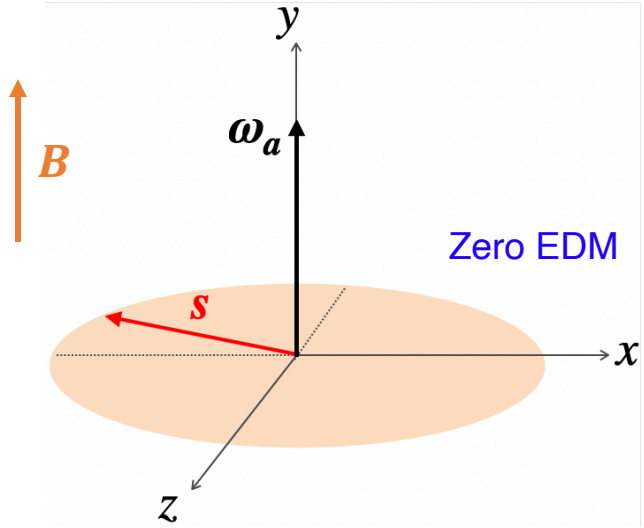


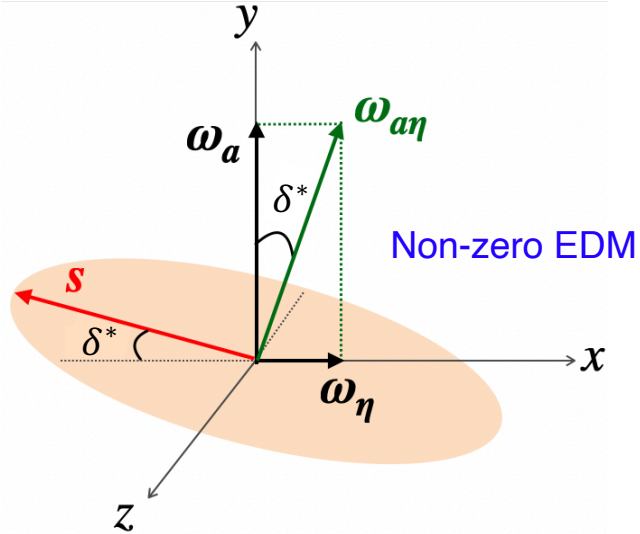


A muon EDM in the $g-2$ storage ring

$$\boldsymbol{\omega}_{a\eta} = \boldsymbol{\omega}_a + \boldsymbol{\omega}_\eta = a_\mu \frac{e}{m}\boldsymbol{B} + \eta\frac{e}{2m}\left(\boldsymbol{\beta}\times\boldsymbol{B} + \frac{\boldsymbol{E}}{c}\right)$$

$$\boldsymbol{d} = \eta\frac{e}{2mc}\boldsymbol{s}$$





- High energy e^+ are preferentially emitted along the μ^+ spin
- The μ^+ polarisation vector precesses at the anomaly frequency, $\boldsymbol{\omega}_a$
- An EDM would interact with the electric fields in the ring
- The resulting torque tips the precession plane and introduces an orthogonal frequency, $\boldsymbol{\omega}_\eta$

Measurement techniques

Calorimeter method

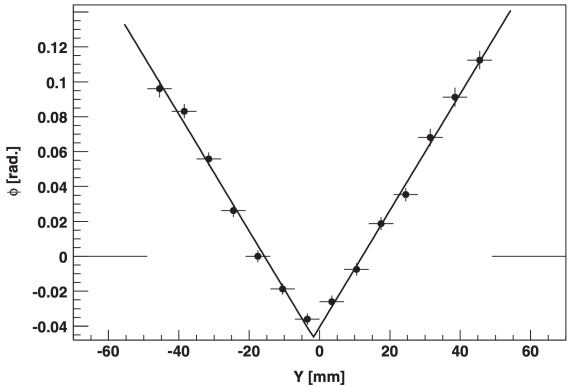
- Measure the $g-2$ phase as function of vertical position. With an EDM, we would observe an asymmetric distribution (a tilted V-shape)
- Systematically limited by detector alignment

Tracker method (this talk)

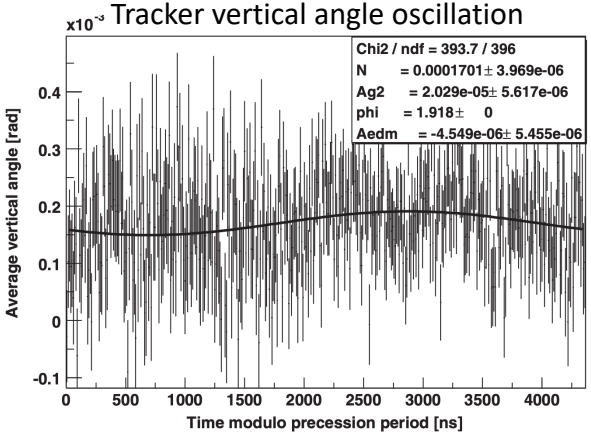
- Measure the EDM oscillation by fitting the vertical $\boldsymbol{e}^+$ decay angle, θ_y, for an oscillation $\pi/2$ out-of-phase with $\boldsymbol{\omega}_a$
- Statistically limited

$$\theta_y = \sin\left(\frac{p_y}{p}\right)$$

Calo phase asymmetry



Tracker vertical angle oscillation

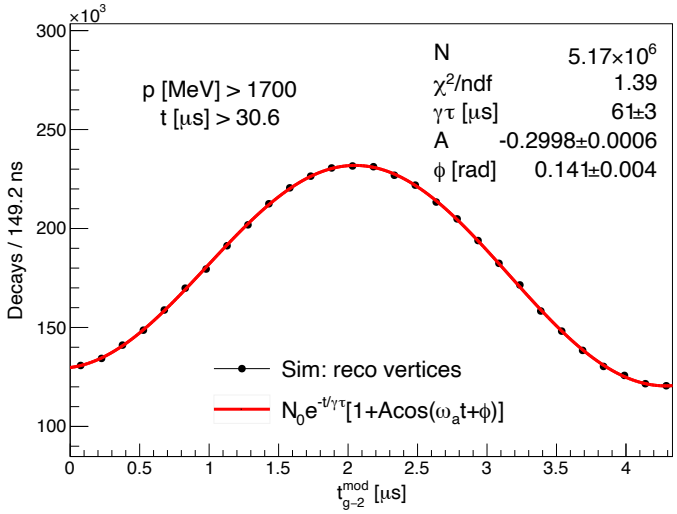


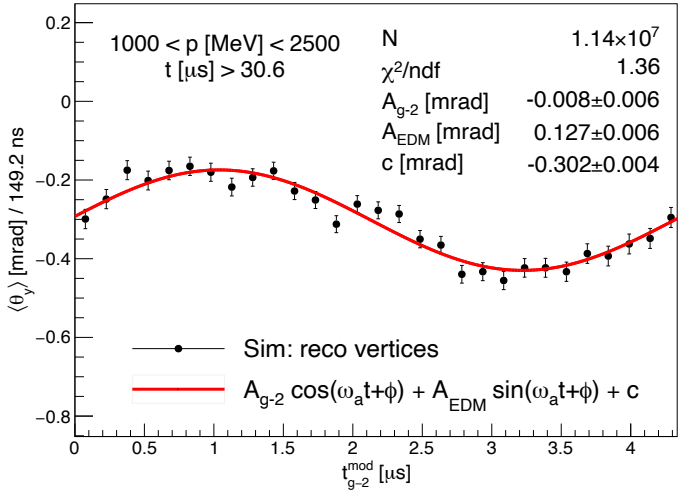
*Plots from the BNL $g-2$ experiment [10]

Demonstration fits (simulation)

- Using a large-scale Monte Carlo sample with a known injected EDM
- Fit first for the phase, then for the amplitude of the oscillation in-phase with ω_η, with a function of two orthogonal terms

$$\langle\theta_y\rangle(t) = A_{g-2}\cos(\omega_a t + \phi) + A_{EDM}\sin(\omega_a t + \phi)$$

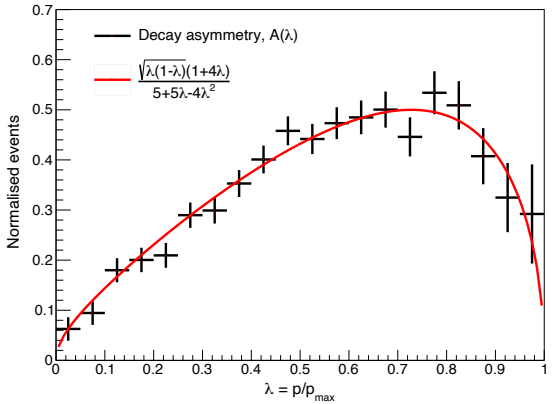




Sensitivity to an EDM

- The fitted angle, A_{EDM}, is diluted compared to the true tilt angle, δ
- This is track momentum dependent, dictated by the V-A structure of weak decays, kinematics, and geometry
- Simulation with an known injected EDM, and 100% acceptance, show the variation in the EDM signal from the first two of these effects

Decay asymmetry



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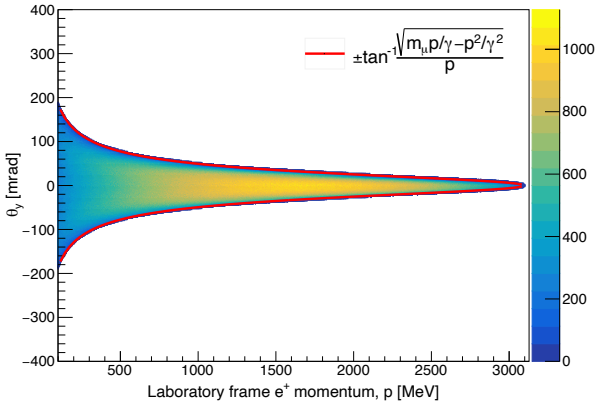
Lorentz boost



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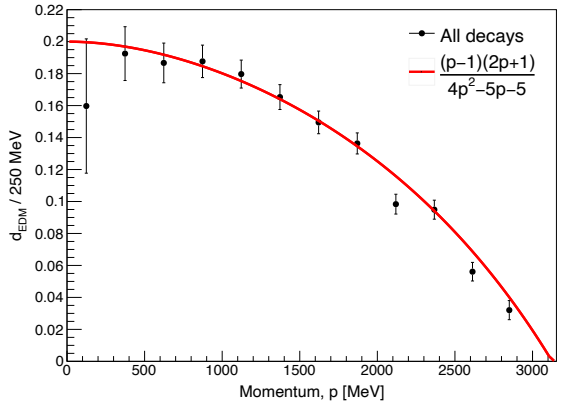
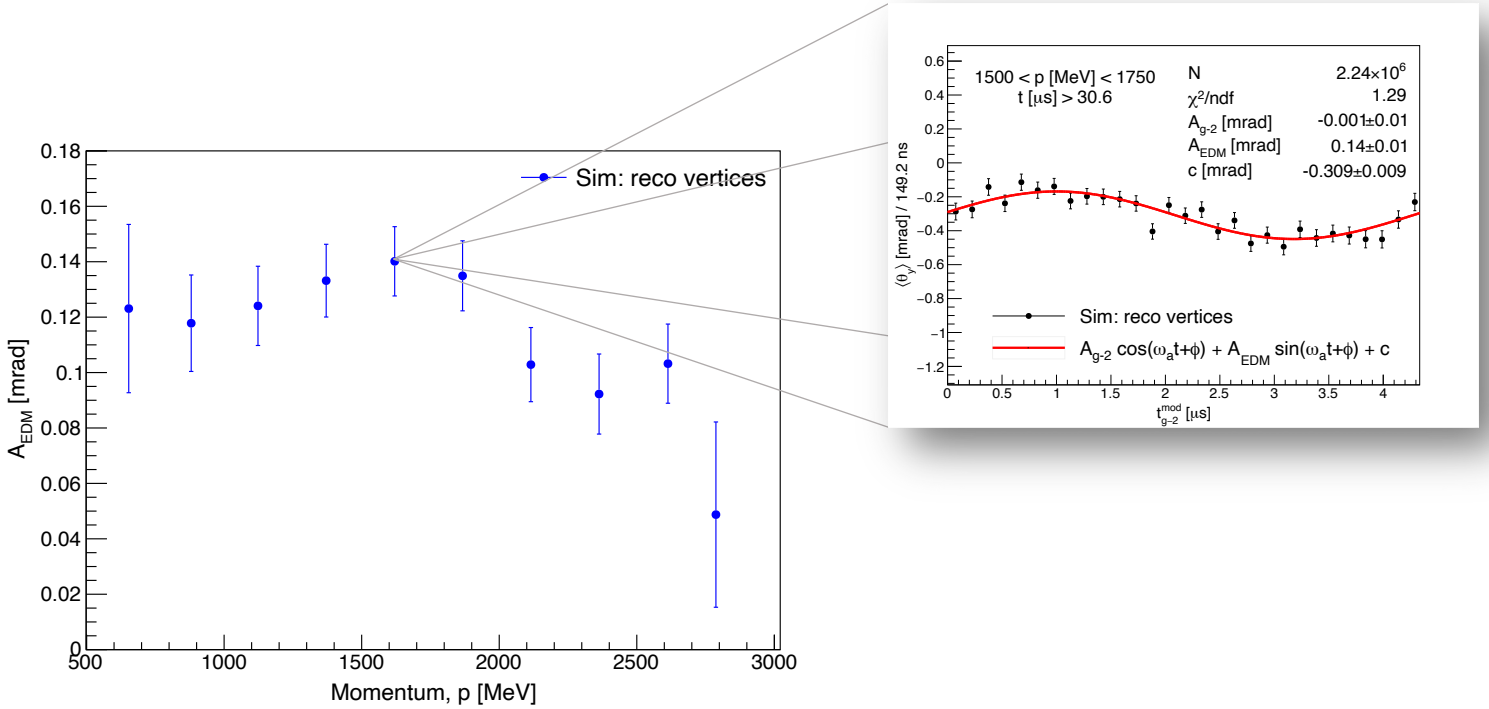
EDM signal (100% acceptance)



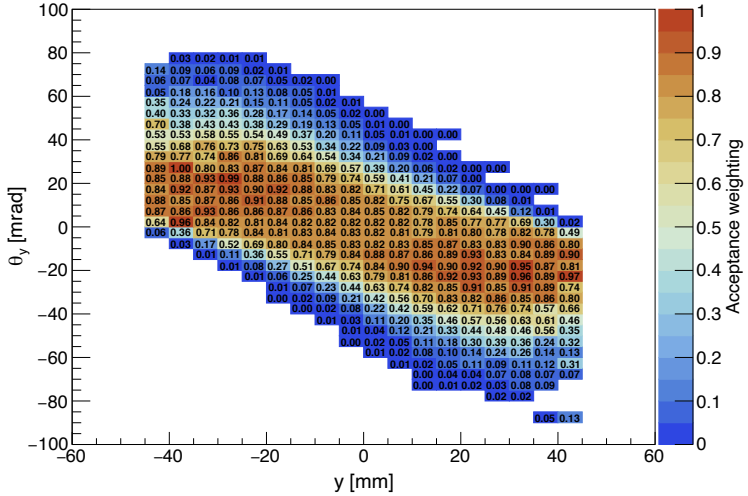
Momentum-binned analysis

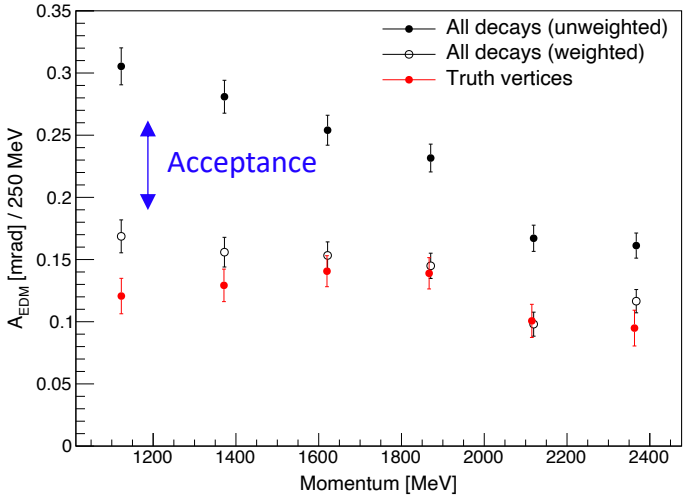
- Our signal is momentum dependant, so we perform fits for A_{EDM} in momentum bins in order to try and maximise our sensitivity



Detector acceptance

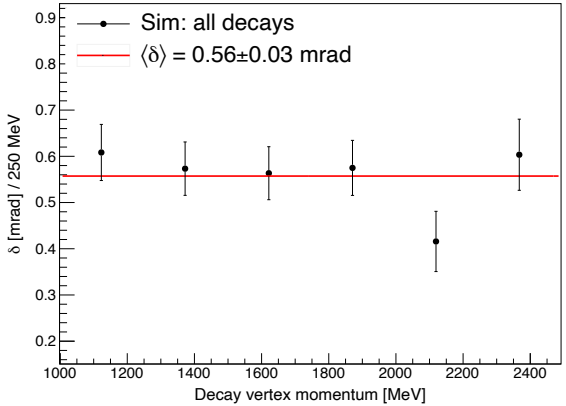
- The trackers sample a vertically asymmetrical subset of the true θ_y distribution, which must be characterised in simulation
- Produce acceptance maps in θ_y over y, weight the vertical angles in an MC sample with 100% acceptance, and compare to the results using reconstructed track decay vertices
- Calculate a correction factor per momentum bin to correct for acceptance

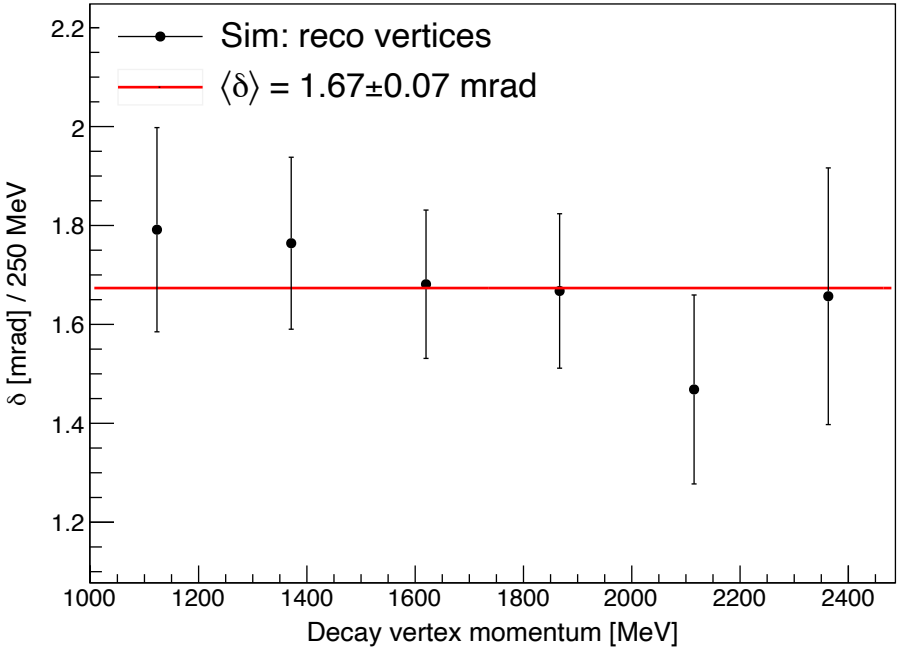




Verification

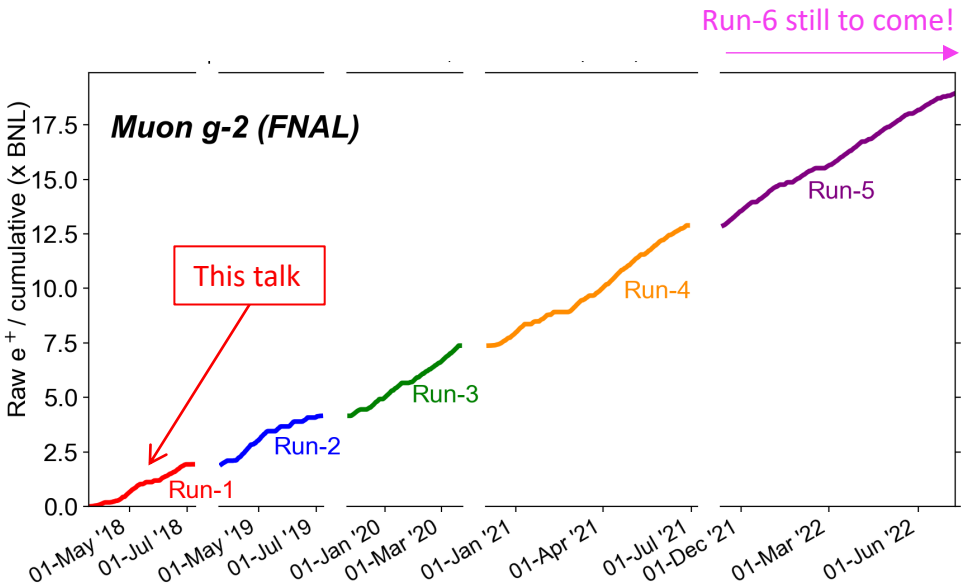
- Can we extract the injected signal? Yes!
- The injected tilt is 1.69 mrad
- This was also done for a smaller injected signal, with an injected angle of 0.564 mrad





The Run-1 muon EDM search

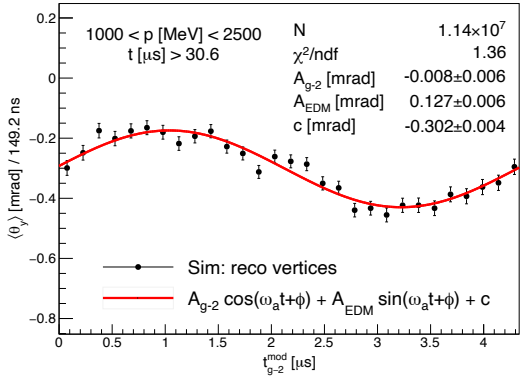
- Our smallest dataset, but still larger than the combined BNL dataset
- Also, a challenging dataset due to two damaged ESQ resistors causing non-typical beam conditions
- Only a tracker-based analysis was attempted for this dataset, with an order of magnitude more tracks than BNL
- Run-1 is split into four datasets: 1a, 1b, 1c, and 1d



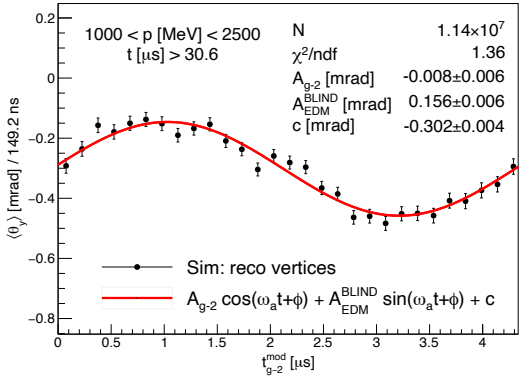
Blinding

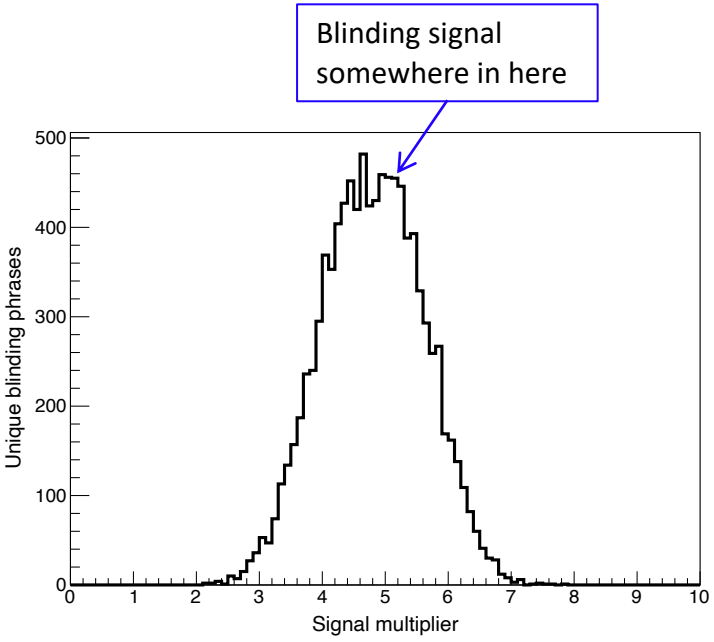
- Avoid bias!
- Superimpose a blind EDM signal from a flattened Gaussian distribution, drawn based on a unique, and secret, phrase
- Blinding only modifies A_{EDM}

Unblinded sim

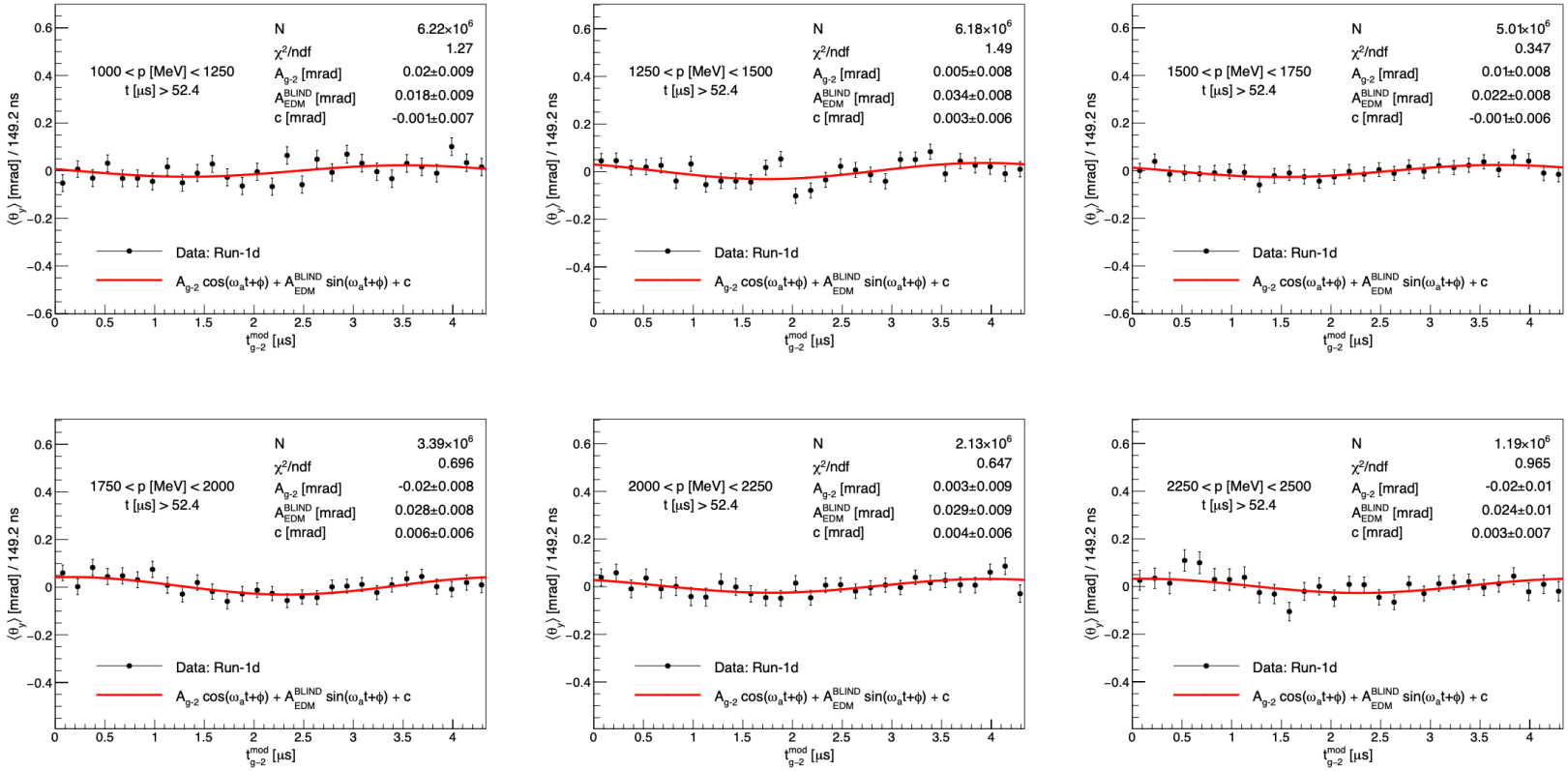


Blinded sim



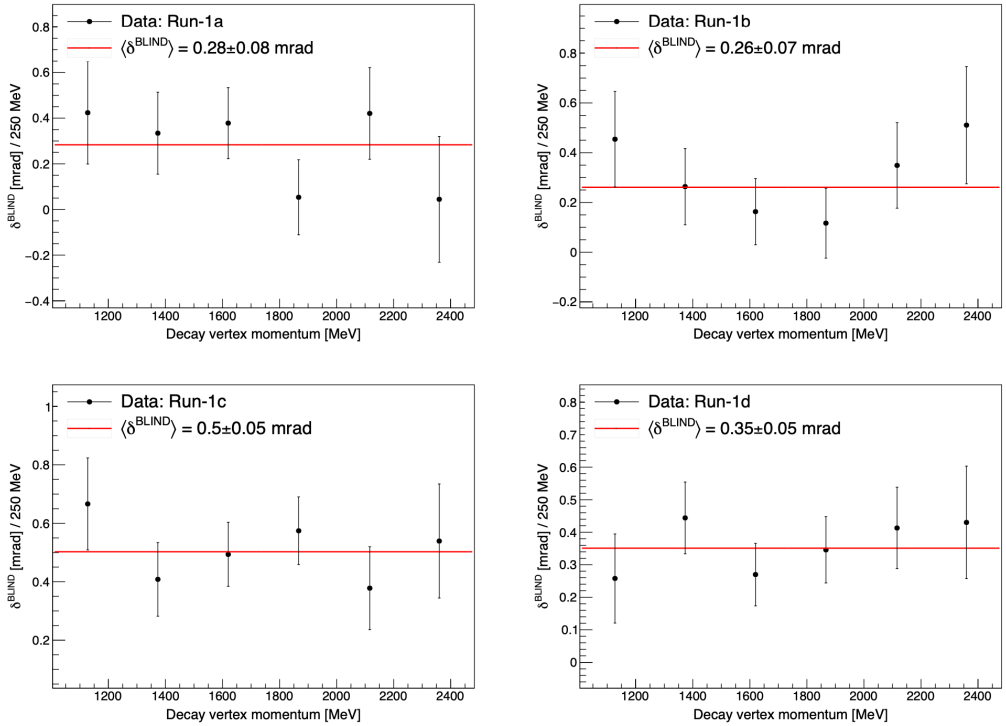


Blinded fits (Run-1d)



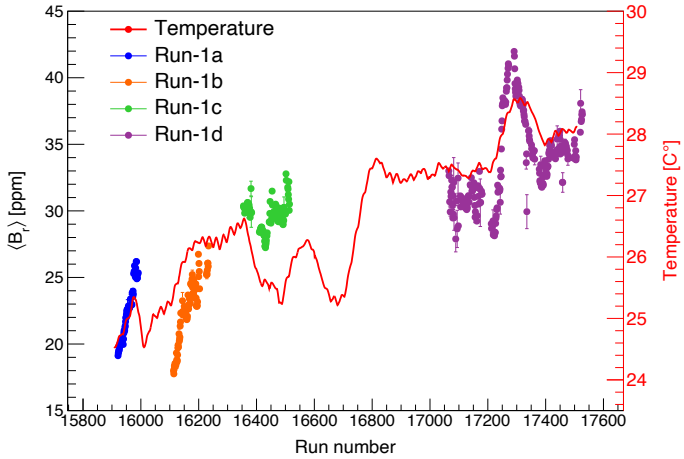
Blinded tilt angles

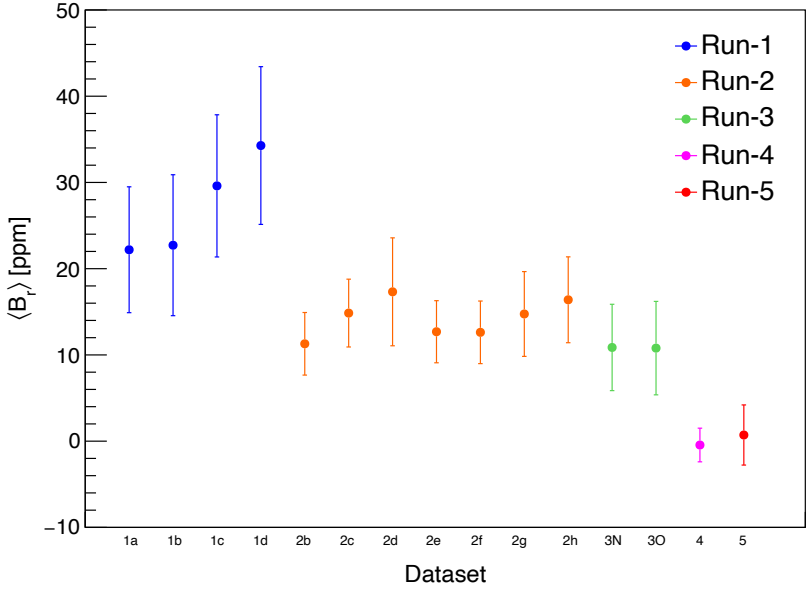
- Correct diluted A_{EDM} to δ
- Zeroth order polynomial fit gives an uncertainty weighted average
- These results are blinded and preliminary



The radial magnetic field systematic

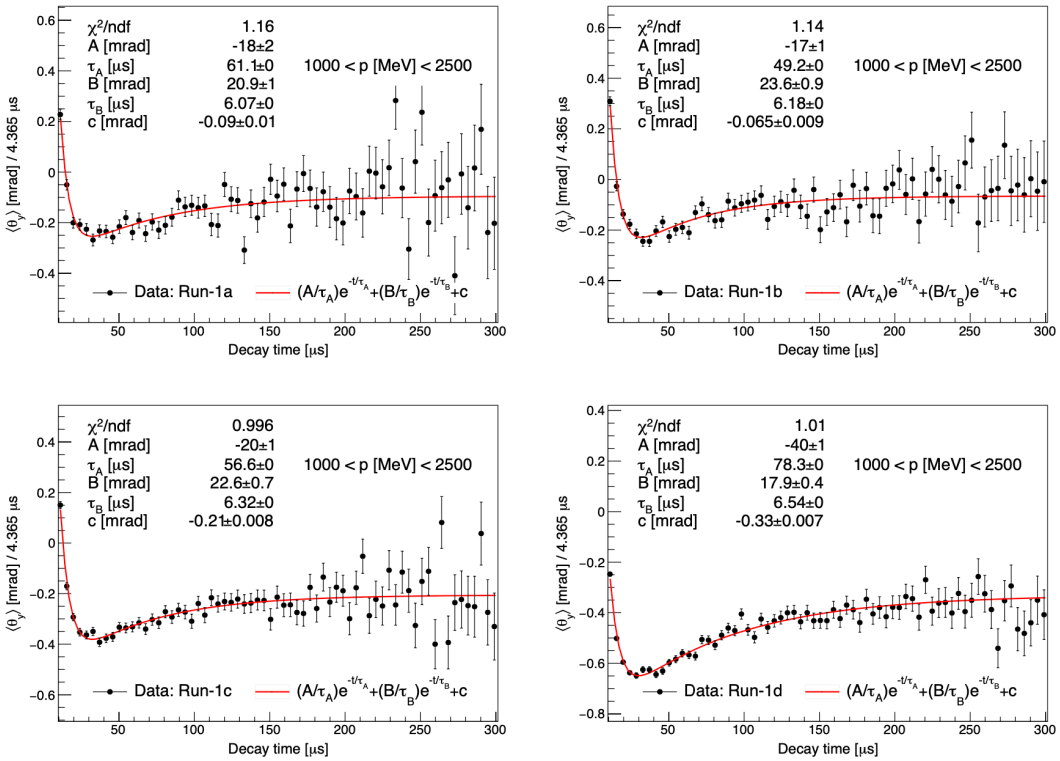
- The radial magnetic field component can tilt the precession plane: mimicking an EDM signal!
- Radial field component to within 10 ppm in Run-1, making it a non-limiting systematic
- Some correlation with temperature (additional insulation is used post Run-1)





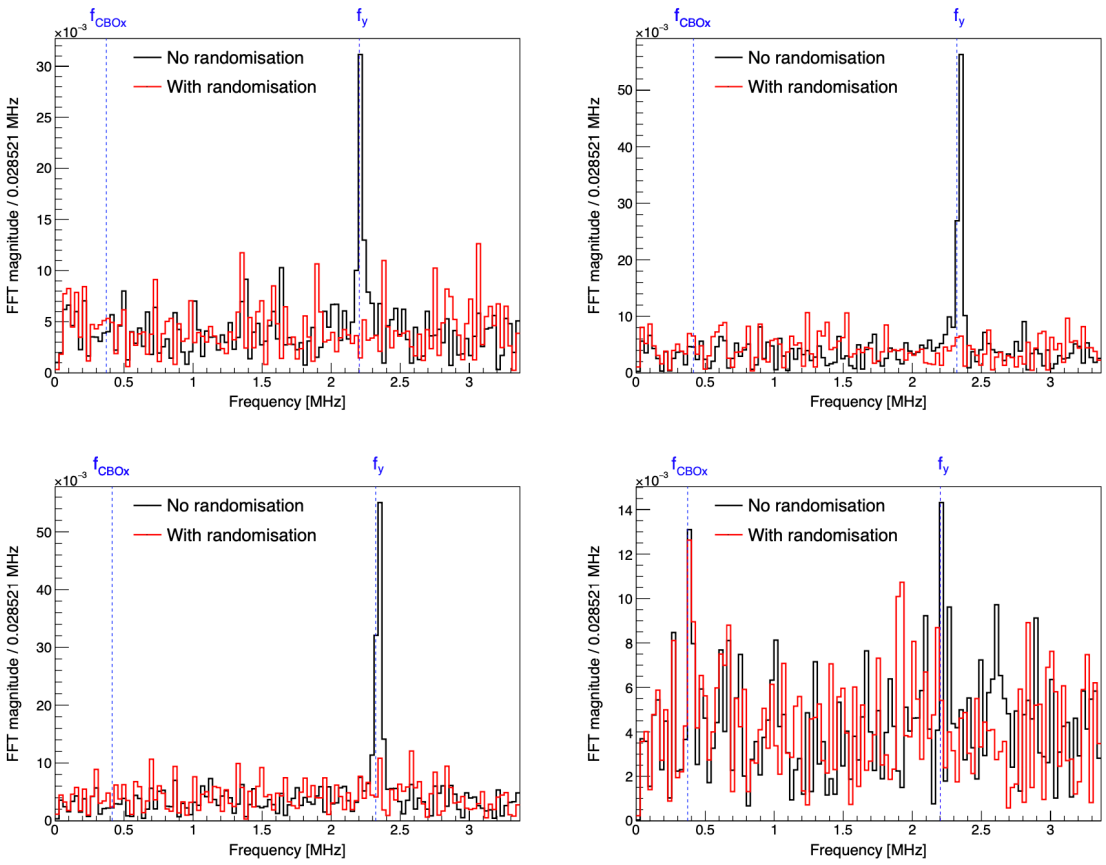
Average θ_y time dependance

- Damage to quad resistors in Run-1 causes results time dependence in the average θ_y
- We can correct this with a double exponential fit, using lifetime parameters reported in the Run-1 ω_a analysis
- Most pronounced in Run-1d, motivating a later fit start-time



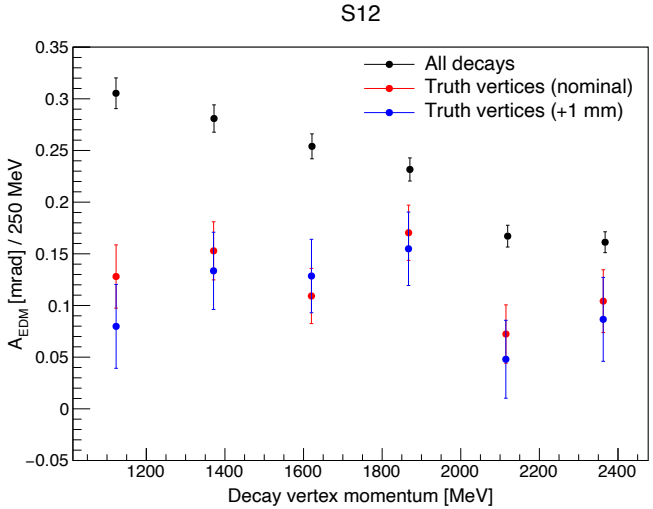
Betatron oscillations

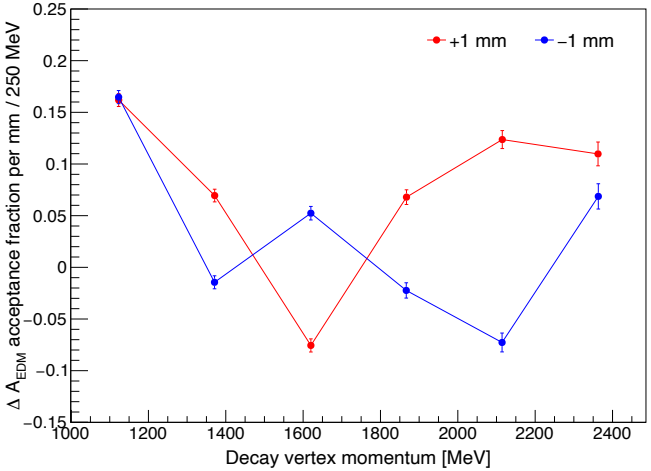
- Restoring forces from magnetic and electric fields in the ring cause the muons to undergo simple harmonic motion
- Vertical betatron frequency, f_y, is present in the fit residuals at early times after injection
- Removed by sampling randomly sampling decay times about $\pm T_{f_y}/2$
- Impact on final result is negligible, fit quality improves



Tracker alignment (work in progress)

- The trackers have four global external alignment parameters: the Y position, the X position, the XZ angle, and the YZ angle. Each parameter has an uncertainty.
- Initial estimates made by vertically shifting the trackers ±1 mm, reconstructing the Monte Carlo, and comparing the change in the acceptance correction factors
- Estimate the shift in EDM angle per mm misalignment (only look at the vertical shift at present)



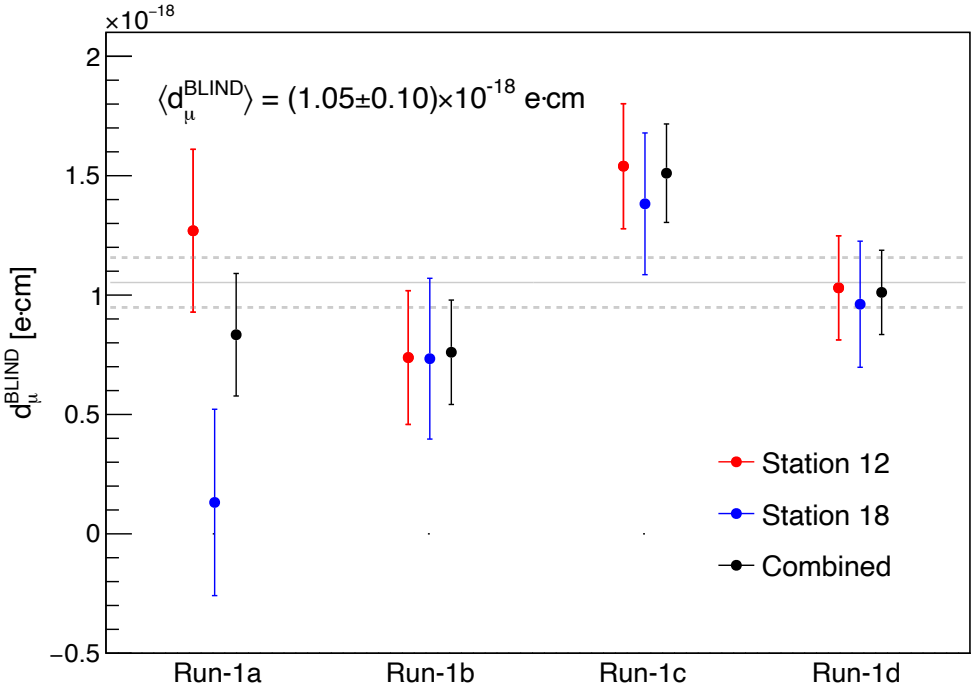


Blinded preliminary results

- Radial magnetic field contribution subtracted, error bars include all non-negligible systematic contributions
- Common blinding phrase between all datasets
- If the blinding were removed and the EDM was found to be zero, the Gaussian upper limit would be

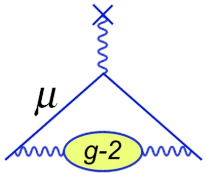
$$|d_\mu| < 2.0\times10^{-19}\ e\cdot\mathrm{cm}\ (95\%\ \mathrm{C.L.})$$

- This is an improvement on the limit from the equivalent BNL analysis!



Summary

- EDMs provide a unique window into fundamental particles and their interactions
- Flavour anomalies could point to new physics which relax the constraints on the size of the muon EDM
- The Run-1 muon EDM search at Fermilab is nearing completion, the Run-2/3 analysis is well underway
- Future muon EDM searches: the muEDM experiment at PSI and the J-PARC $g-2$/EDM experiment
- Expect to see a lot of progress in this area over the next few years!



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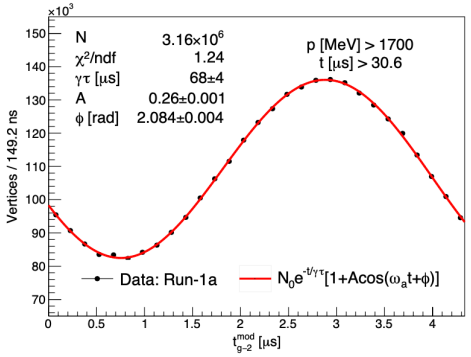
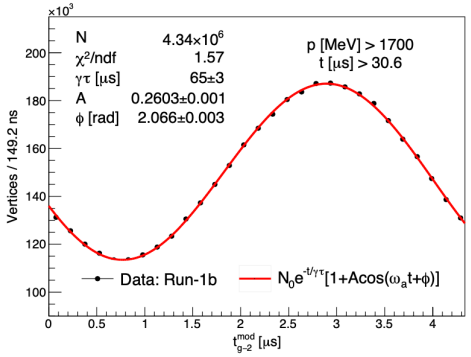
Extra slides

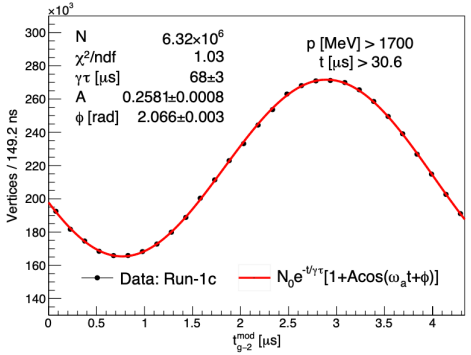
$g-2$ phases

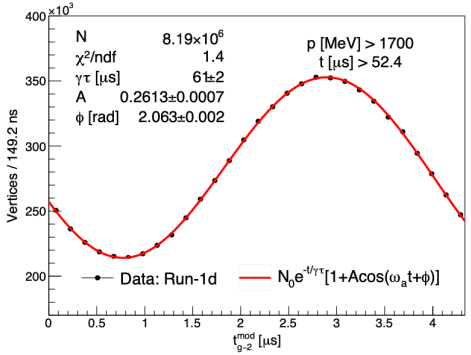
- Low momentum cut at 1.7 GeV designed to maximise statistical sensitivity
- Phase uncertainty is a negligible in terms of impact on the final result

Dataset	ϕ [rad]
Run-1a	2.084 ± 0.004
Run-1b	2.066 ± 0.003
Run-1c	2.066 ± 0.003
Run-1d	2.063 ± 0.002

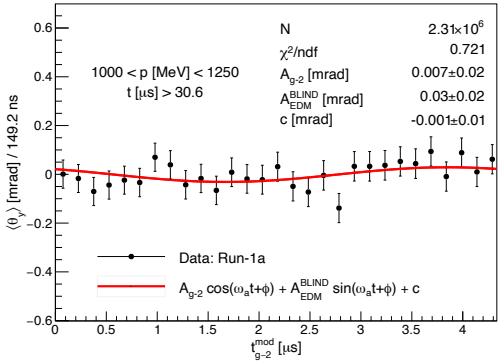


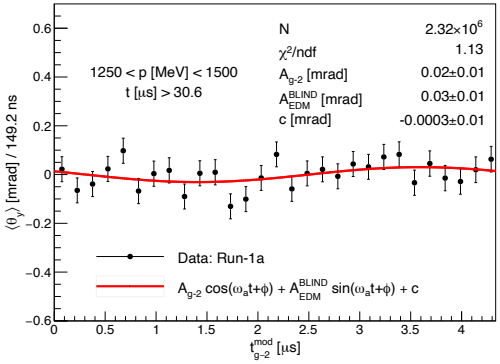


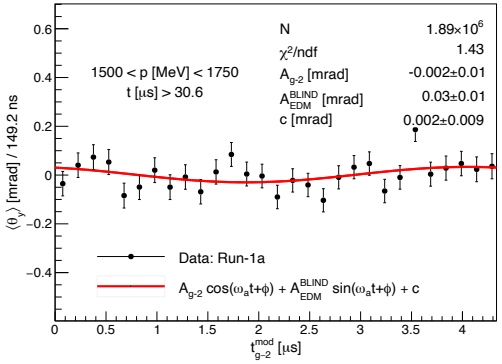


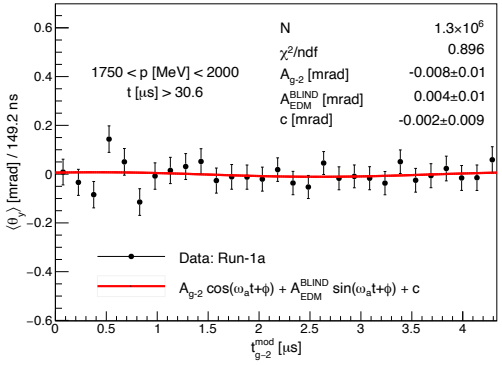


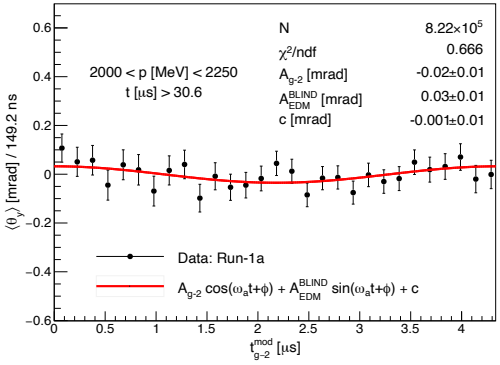
Blinded fits (Run-1a)

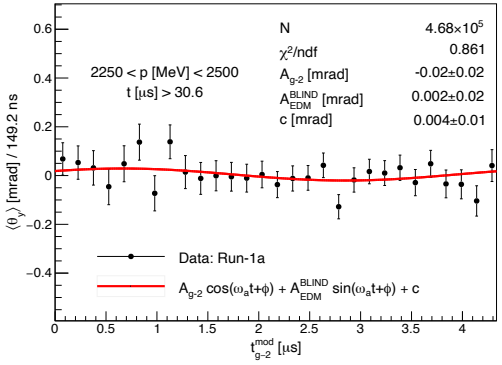




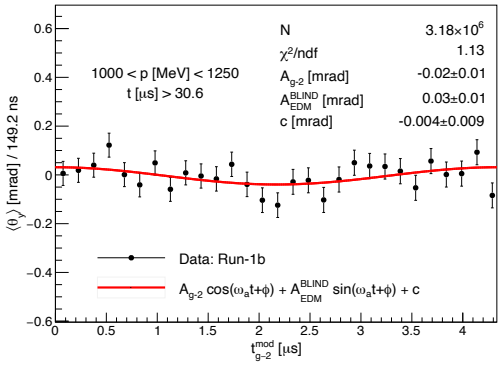


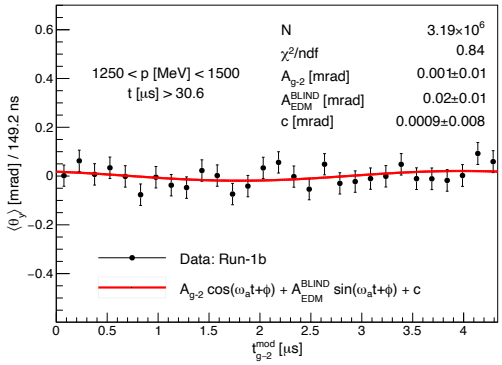


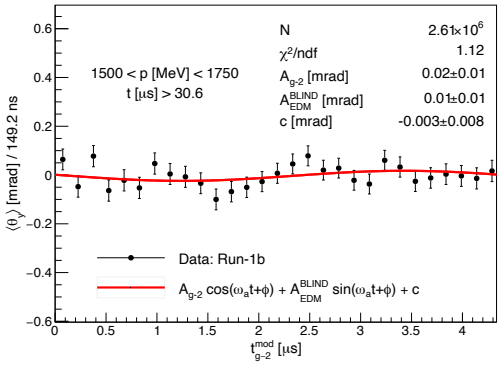


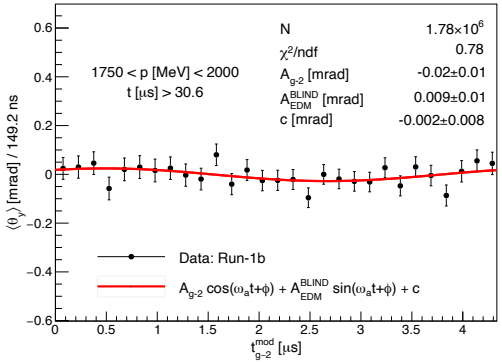


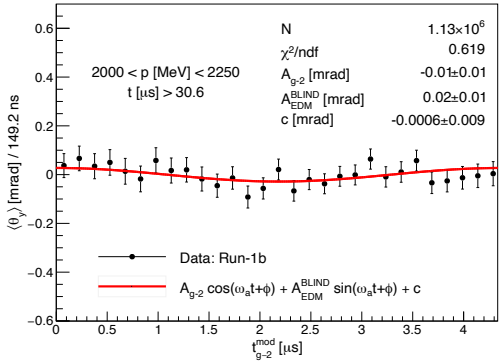
Blinded fits (Run-1b)

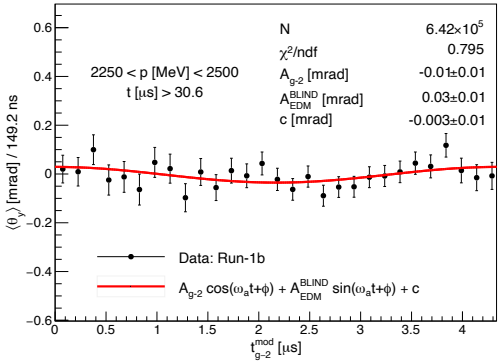




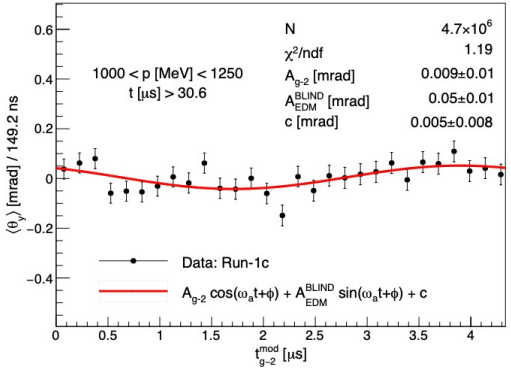


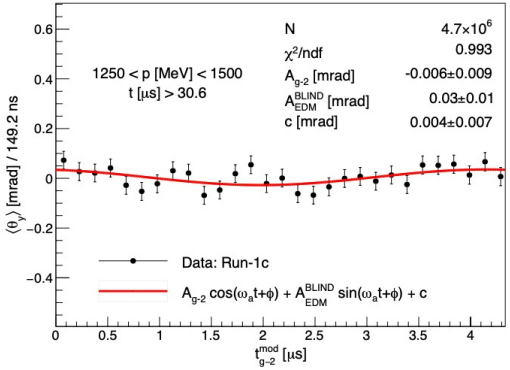


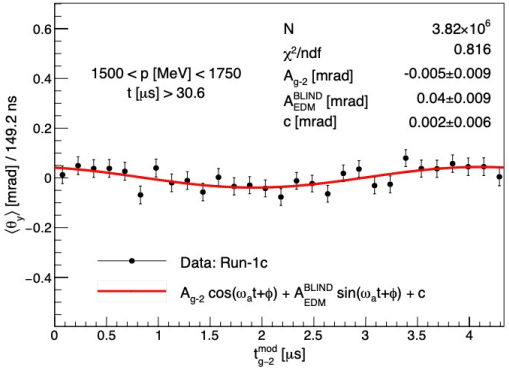


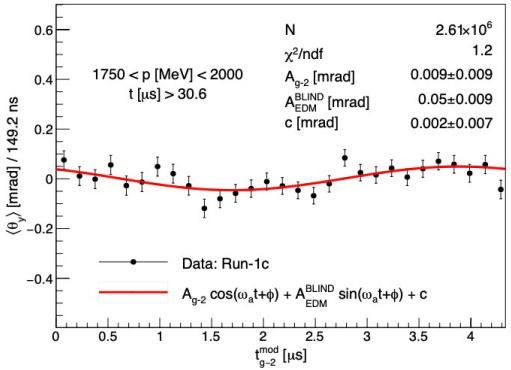


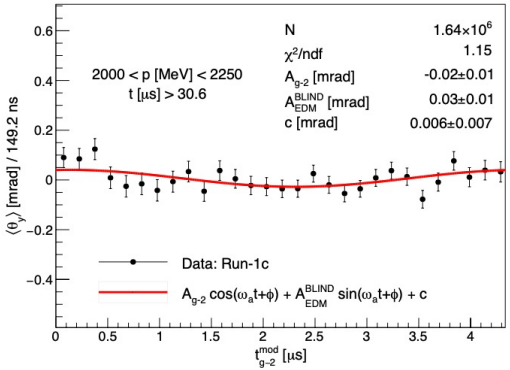
Blinded fits (Run-1c)

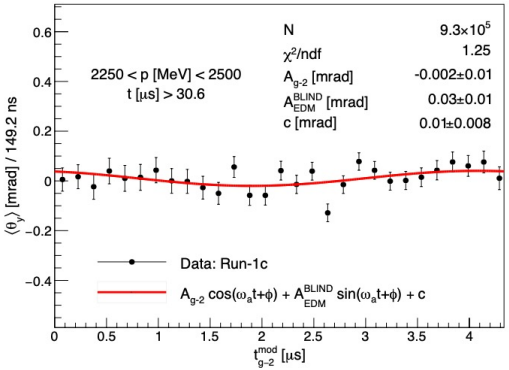






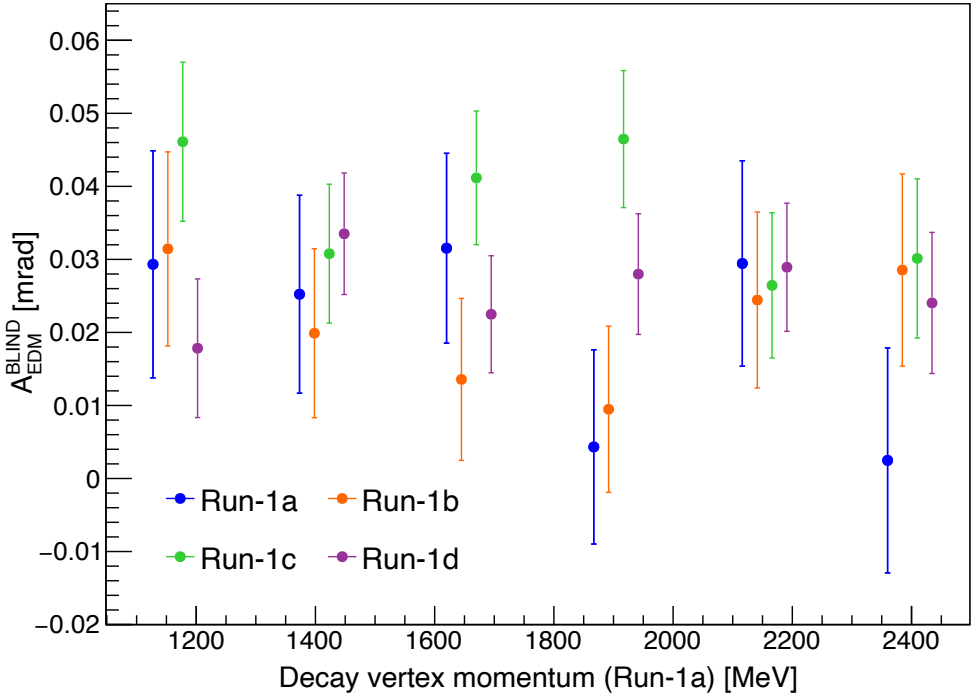






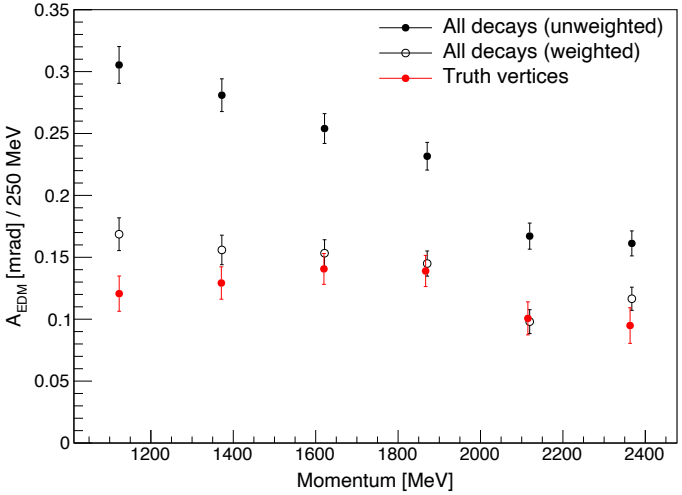
Blinded A_{EDM} results

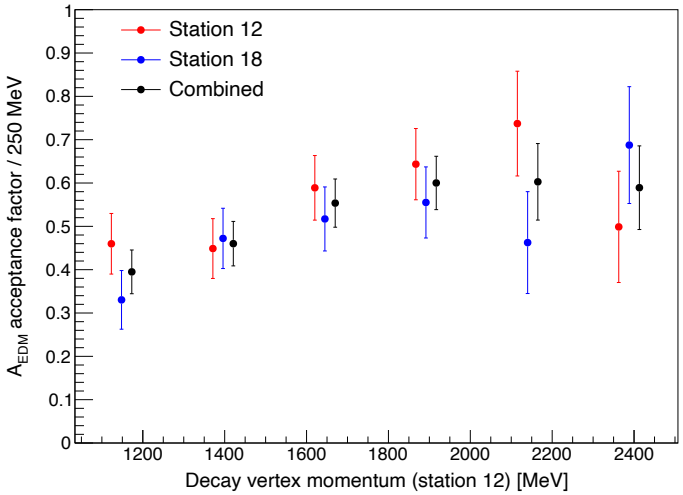
- Average χ^2/ndf is consistent with unity for all datasets
- A_{EDM} is diluted compared to the true tilt angle, δ, and must be corrected



Acceptenace correction factors

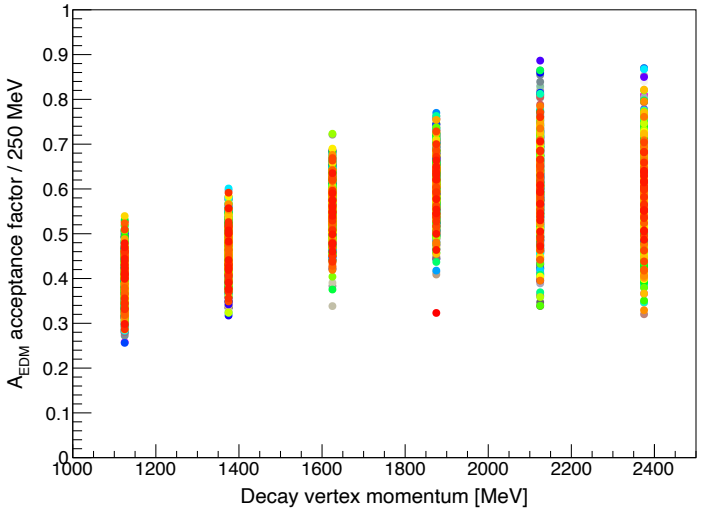
- The ratio of fit parameter A_{EDM} with/without acceptance gives a scale factor
- This approach introduces a stat uncertainty from simulation (next slide)

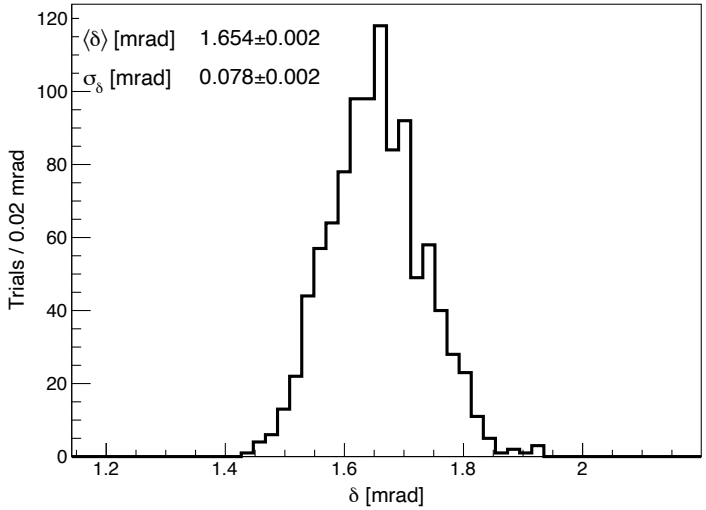




Acceptance correction uncertainty

- The uncertainty associated with this correction is estimated by randomly drawing 1000 scale factors from Gaussian distributions at each point, and using each set to populate a distribution of angles
- The width of this distribution is taken as the uncertainty





Tracker resolution

- Populate a distributions of vertical angles from truth parameters and measured parameters, then take the difference
- The average θ_y resolution is the error on the mean, which is 3 µrad
- This is negligible