Searching for a muon EDM at the Fermilab Muon g-2 experiment

Liverpool HEP seminars, 21/10/25

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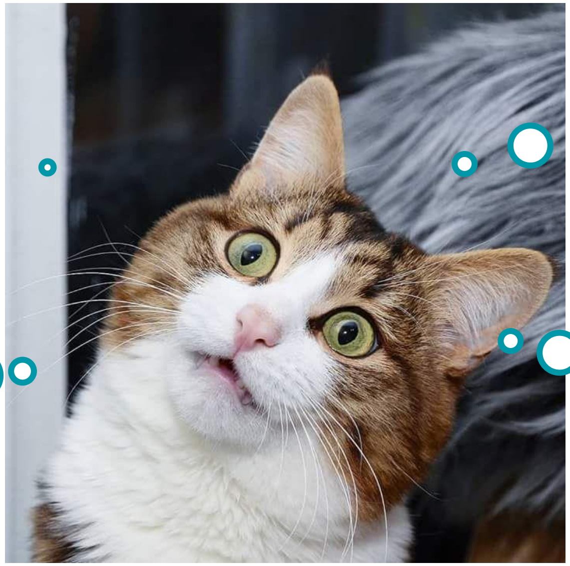
BSM physics: a lot of things we don't know…

- Despite the great success of the Standard Model (SM), many ongoing mysteries for Particle Physics!

What's going on with dark matter?

Why wasn't there more antimatter in the early universe? Where's the CP violation needed to cause that?



Why do we have three generations in the SM, and why do they have the structure they do?

Is there any physics beyond the Standard Model (besides what we've already found) ?

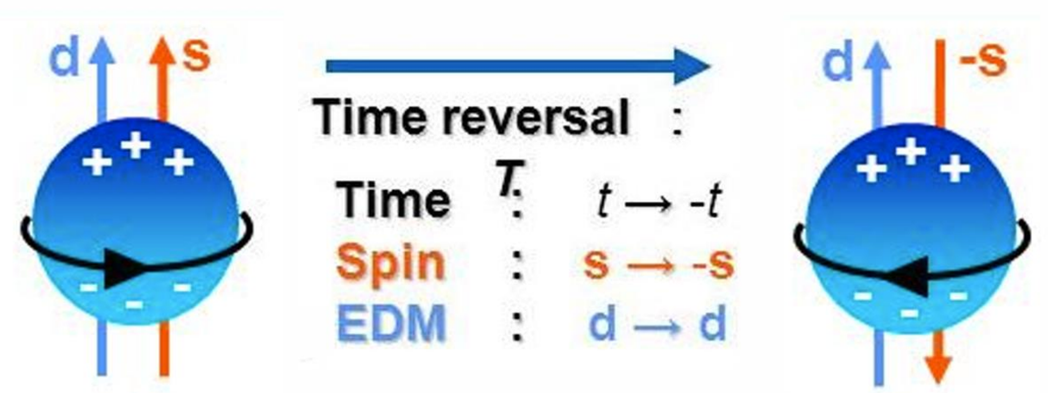
+ much more!

Enter the noble electric dipole moment!

- Test the SM via precision measurements of the fundamental electric dipole moment (EDM) of particles.

- EDM is a measure of the overall polarity of the system – charge asymmetry along the spin axis.
  - "How spherical are fundamental particles?"

- Analogously to magnetic dipole moment (MDM): permanent non-zero EDM + an external E field = torque force on particle.
  - Leads to EDM-induced motion, which is generally how you look for it!



$$H = -\underline{\vec{\mu} \cdot \vec{B}} + \underline{\vec{d} \cdot \vec{E}}$$

MDM:

$$\boxed{\vec{\mu} = g\frac{e}{2m}\vec{S}}$$

EDM:

$$\boxed{\vec{d} = \eta\frac{Qe}{2mc}\vec{S}}$$

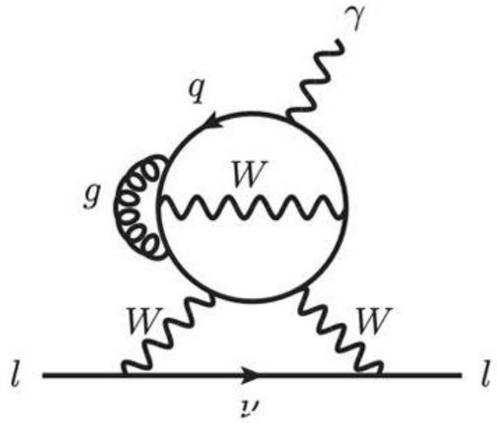
- **d·E** changes under T as E is polar – so the **EDM interaction is CP-violating!**

EDMs in the SM

- EDMs do arise in the Standard Model, for both fundamental and composite particles:

- Fundamental: leptons get nonzero terms from quark EDMs (complex phase in CKM matrix) , but first contributions come at the four loop level, so very tiny!!

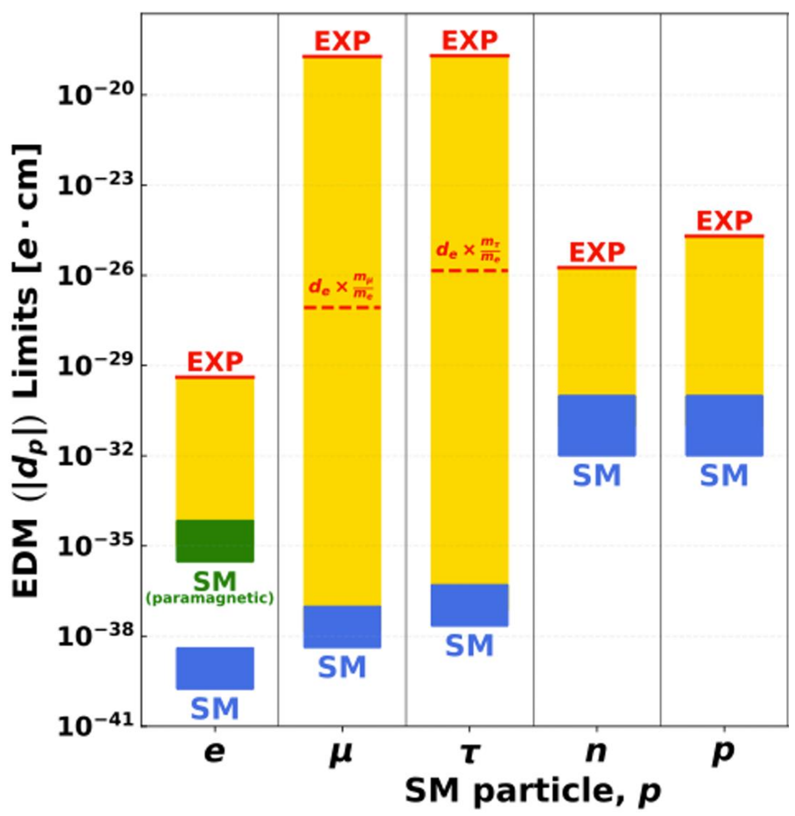
$$d_e^{(\mathrm{SM})} = 5.8 \times 10^{-40} e\,\mathrm{cm},$$
$$d_\mu^{(\mathrm{SM})} = 1.4 \times 10^{-38} e\,\mathrm{cm},$$
$$d_\tau^{(\mathrm{SM})} = -7.3 \times 10^{-38} e\,\mathrm{cm}.$$



- Composite (neutron and proton) EDM arises from CKM CP phase via hadronic loops, also predicted to be very small, O(~ $10^{-31}\ e\ \cdot cm$).

BSM searches for the muon EDM

- SM EDMs below current experimental sensitivity – so any observation would be new physics!
  - Loop structure: sensitive to a wide variety of things.
- Electron EDM very well measured – sets tight limits on muon/tau EDMs, assuming MFV…
- To get a large muon EDM, need large CP violating phase, something to decouple it from the mass ratio, or chiral enhancement (stronger lepton-Higgs coupling).
  - Eg, theories like two Higgs doublet, MSSM, scalar leptoquarks, and some dark matter predict large EDMs.
- So far, no permanent nonzero EDM found: for muon, previous best direct limit set at BNL, **1.9 × 10^{-19}** $\boldsymbol{e \cdot cm}$**.**
  - Indirect limit from ThO: ~ 2 × 10^{-20} $e \cdot cm$.



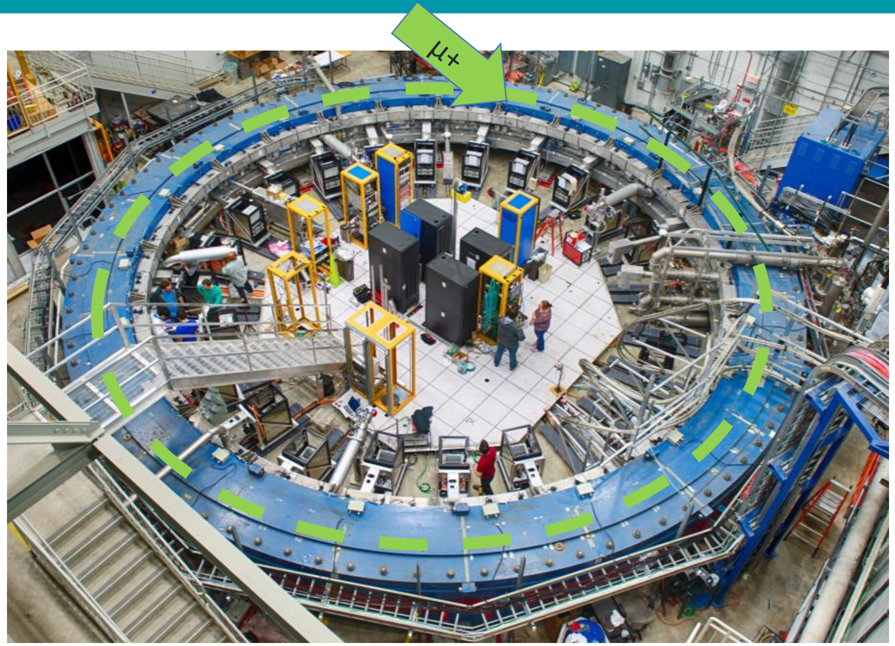
BNL’s successor – Muon g-2 at Fermilab!

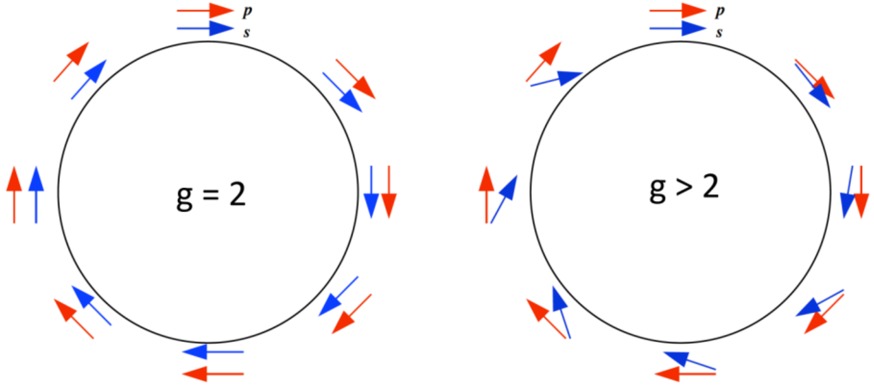
- Main goal was to measure the muon **magnetic** dipole moment (MDM) to 140 ppb (target surpassed with final result this summer!).
  - But, can also use this setup to measure the muon EDM…

- Beam of polarized muons in a storage ring, 1.45 T vertical B field.

- Two oscillations: cyclotron frequency and spin precession from MDM . Measure the difference:

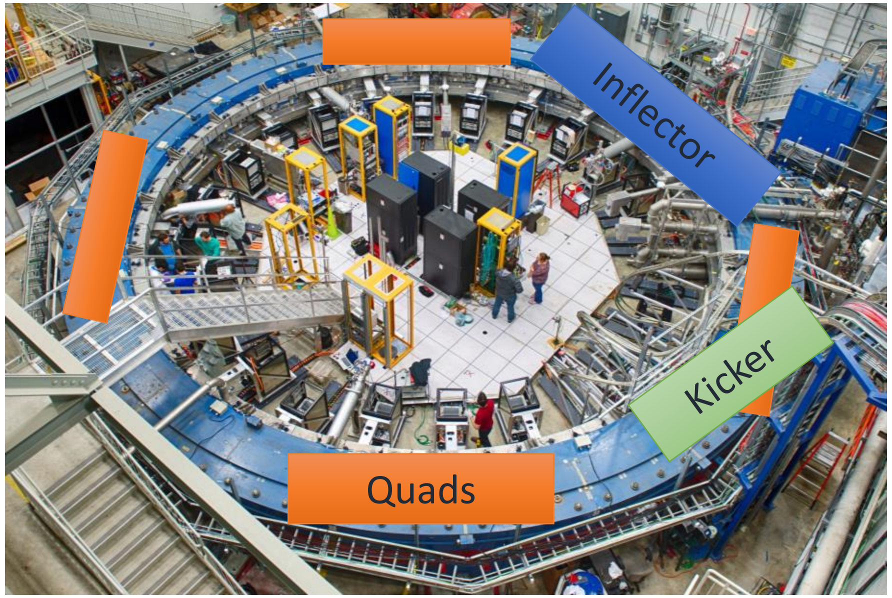
$$\omega_a = \omega_s - \omega_P \cong a_\mu \frac{eB}{m_\mu}$$

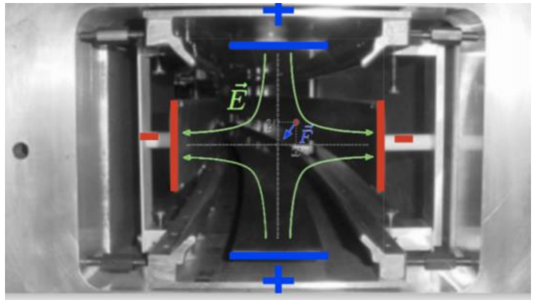




Muon storage

- Magnet: provides radial focusing + field for g-2.
- Inflector: Prevents large beam deflections on entry.
  - Located at entrance to ring, cancels local B field.
- Kicker: Pushes incoming beam onto equilibrium orbit.
- Electrostatic quadrupoles: vertical focusing.





0 when in a flat plane

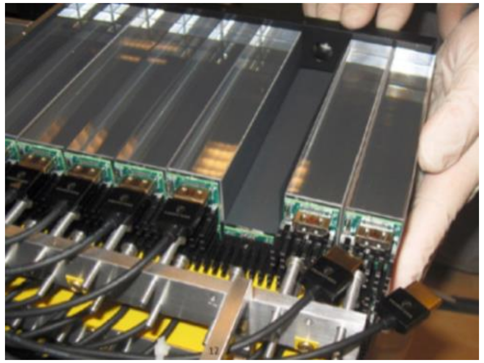
$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - \cancel{a_\mu \frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta}} - \cancel{\left(a_\mu - \frac{1}{\gamma^2-1}\right)}\vec{\beta}\times\vec{E}\right]$$

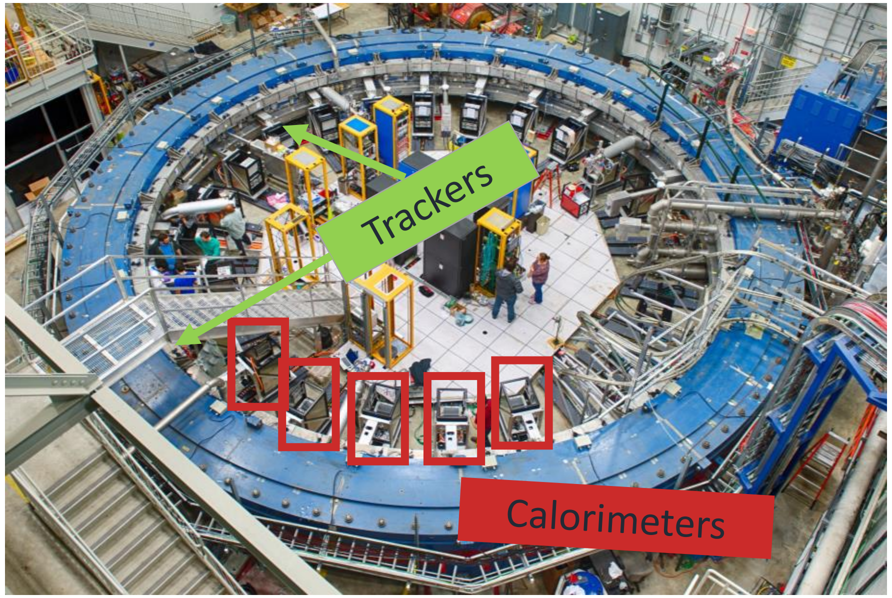
0 at the ‘magic momentum’ = 3.094 GeV

Main detector systems

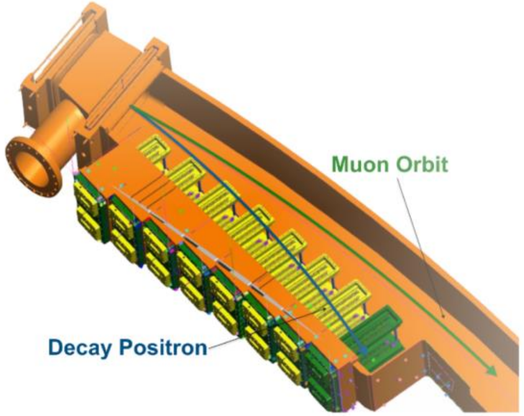
- Two main detector systems: calorimeters and trackers.

- 24 PbF_2 calorimeters around inside of ring:
  - 54 crystals read by SiPMs.
  - Calibrated using laser system.





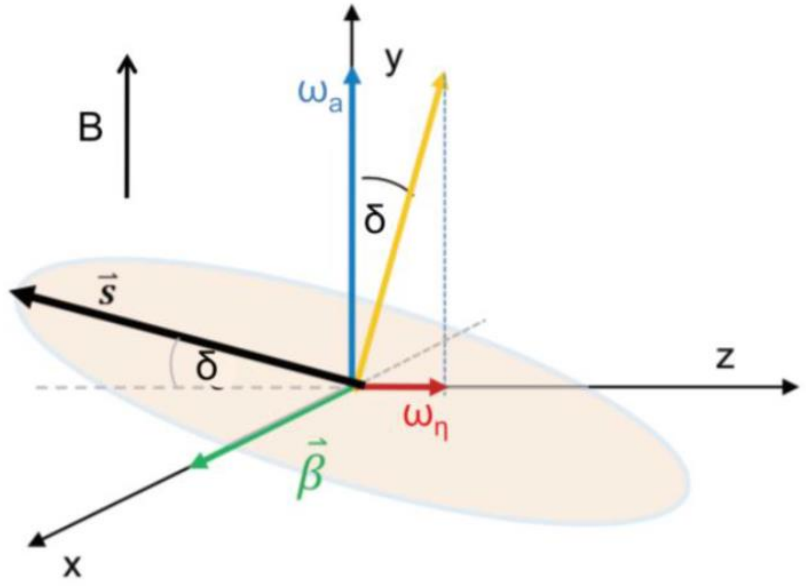
- 2 straw tracker stations ("12" and "18"):
  - 8 modules per station, 4 x 32 straws $Ar:C_2H_6$.
  - Hits grouped and fitted into tracks, which are extrapolated to decay.
  - Crucial for beam dynamics + muon distribution understanding.



Measuring the muon EDM

- A non-zero EDM introduces an extra term into the oscillation of the muons:
  - (due to Lorentz transformation of B field)

$$\vec{\omega} = -\frac{q}{m}\left[\underbrace{a_\mu \vec{B} + \left(\frac{1}{1-\gamma^2} - a_\mu\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{\text{g-2 precession } \vec{\omega}_a} + \underbrace{\frac{2d_\mu mc}{q\hbar}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)}_{\text{EDM precession } \vec{\omega}_\eta}\right]$$

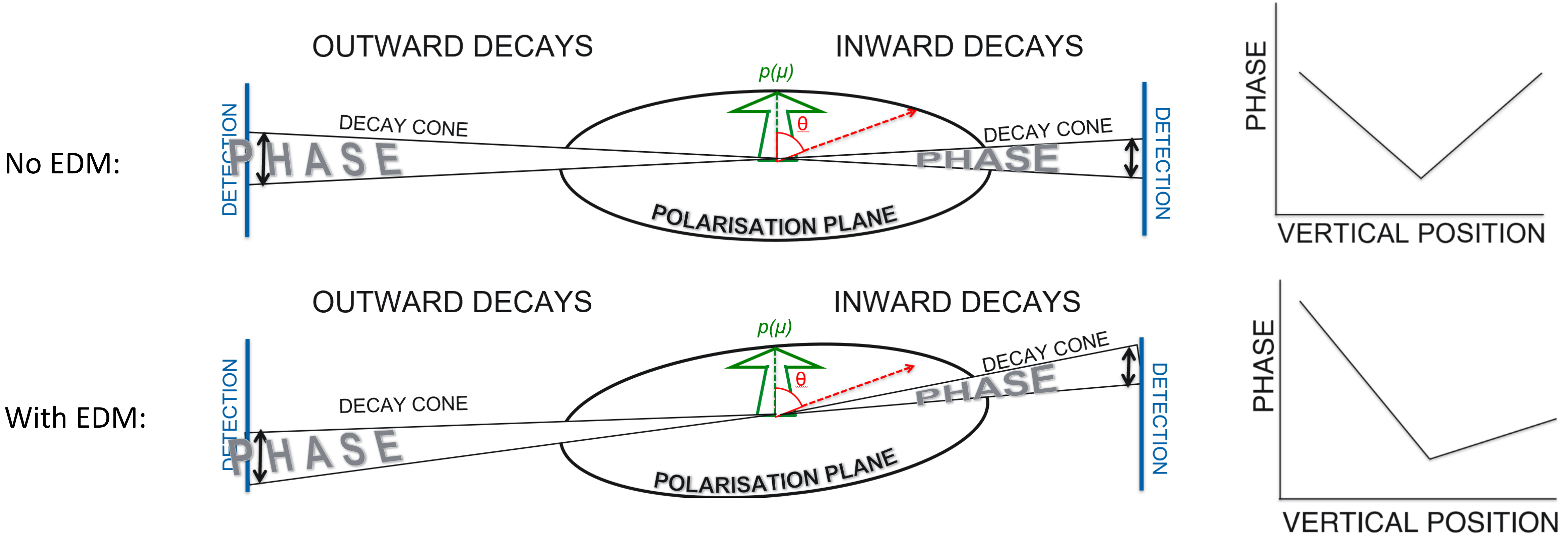


- **Two key effects:**
- A (very) small increase in the precession frequency.
- A second ‘tilt’ precession, π/2 out of phase with g-2 and perpendicular to it.
  - Vertical angle max when spin/momentum are perpendicular.

$$\delta = \tan^{-1}\frac{\omega_\eta}{\omega_a} \approx \frac{\omega_\eta}{\omega_a} = \frac{\beta\eta}{2a_\mu}$$

EDM signals at Fermilab g-2

- **Phase difference:** using calorimeters to look for a vertical asymmetry between ingoing and outgoing positrons.
  - Systematically limited at BNL/FNAL: mainly by calorimeter alignment.



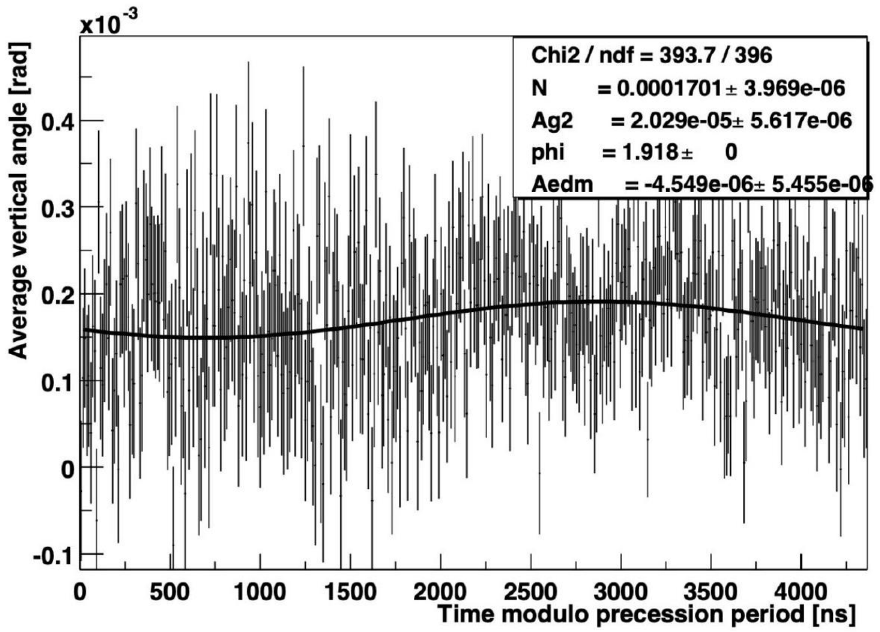
EDM signals at Fermilab g-2

- **Direct vertical angle oscillation measurement:**

- Plot average vertical angle as a function of time, look for an oscillation at the g-2 frequency but out of phase with it.

- Can hypothetically do this with both calorimeters and trackers:
  - Calorimeters have much higher statistics, but despite vertical segmentation, not good position measurement.
  - Trackers have lower stats (due to there only being two) but a hit resolution of ~ 100µm – so with enough muons, this becomes the better method!

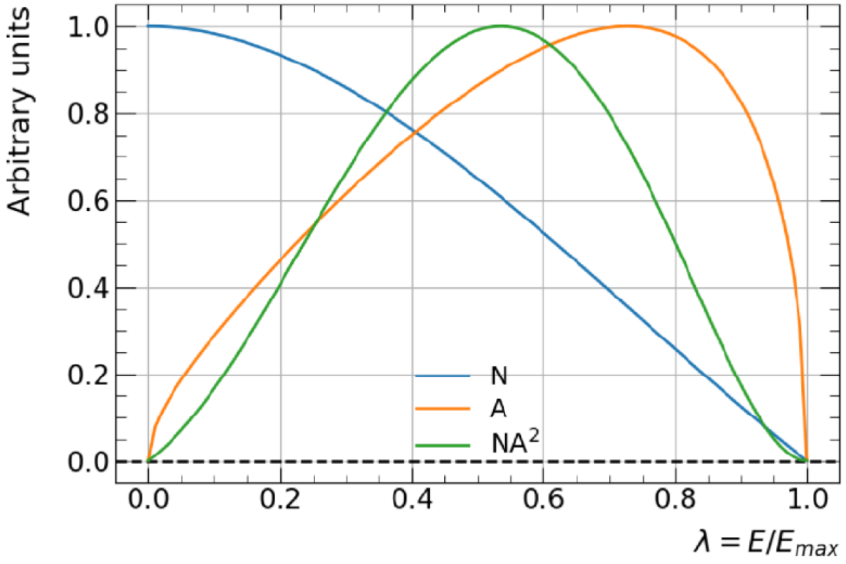
- FNAL collected > 21x BNL – so tracker method wins!



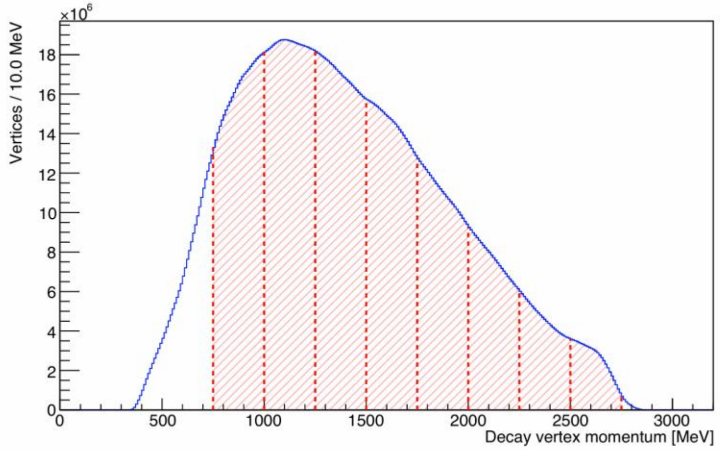
BNL 2000 data

Analysis cuts and setup

- The EDM signal depends on momentum, combined with the number distributions, have greatest sensitivity in the mid-momentum ranges.
  - So perform a momentum-binned analysis!
  - Momentum range chosen is 750-2750 MeV, 8 bins of width 250 MeV.



- Unstable beam at very early times, so analysis start is 6 g-2 periods after the start of a 'fill' (when muons are injected into the ring).



Analysis cuts and setup

- Vertex/tracker quality cuts: to ensure high accuracy in extrapolation, remove a subset of tracks and vertices:

Track variable	Quality track requirements
Number of straws hit	$>\cancel{12}$ 11
Fit p-value	> 5 %
Drift time	$0\ \mathrm{s} < t < 70\ \ \mathrm{s}$
Track x entrance point	$60\ \mathrm{mm} < x < 150\ \mathrm{mm}$
Track y entrance point	$-40\ \mathrm{mm} < y < 40\ \mathrm{mm}$
Track residuals	$< 500\ \mu\mathrm{m}$
Fraction of missed layers	$< \cancel{30\ \%}$ 40%
|U-V| layers	≤ 4

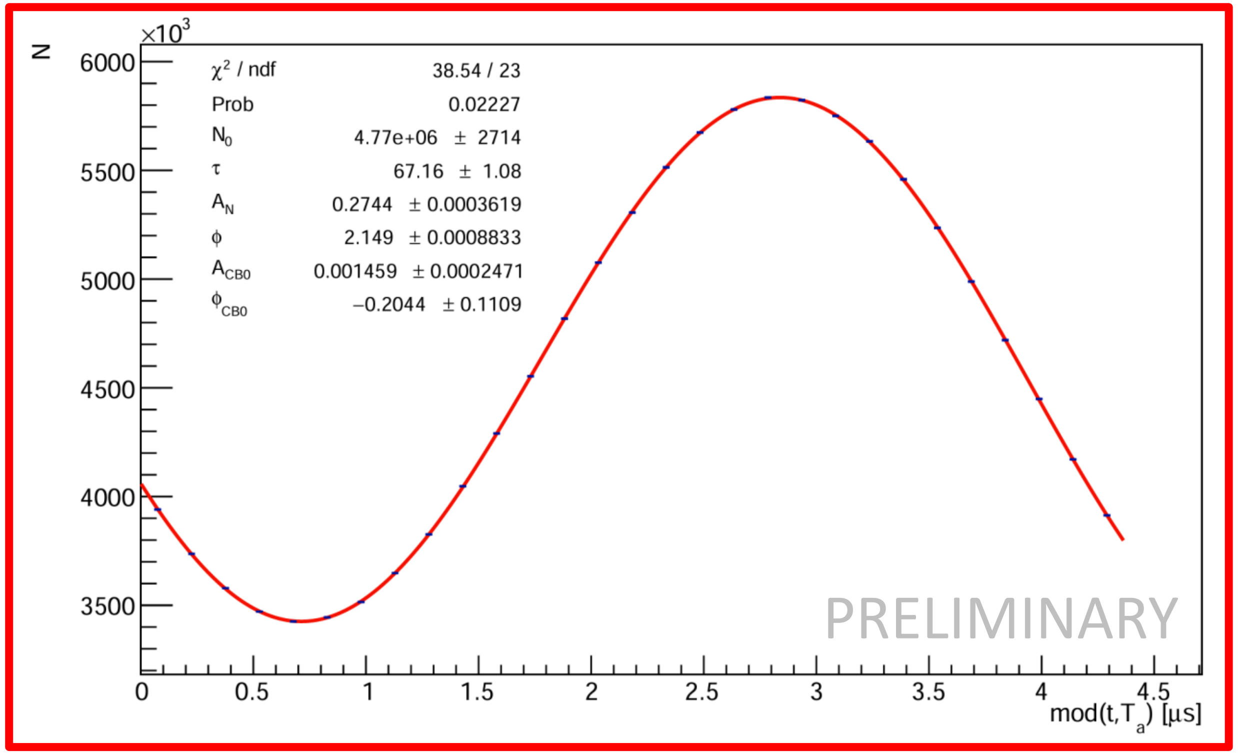
Vertex variable	Quality vertex requirements
Volume hit	No volumes hit
Extrapolation distance	> 40 cm
Vertex uncertainty in R	$0.5\ \mathrm{mm} < \sigma_Y < 5.0\ \mathrm{mm}$
Vertex uncertainty in Y	$0.5\ \mathrm{mm} < \sigma_R < 3.5\ \mathrm{mm}$

Values changed slightly for the EDM analysis to maximise stats!

- Analysis split per station, and per dataset: Run 2, Run 3a and Run 3b (for Run 2/3 analysis).
  - Run 1 data found to have large variations due to damaged quad resistors, so not used for the analysis.
  - Later data (Run 4/5/6) will also eventually be analysed for the final result.

Extracting the EDM signal

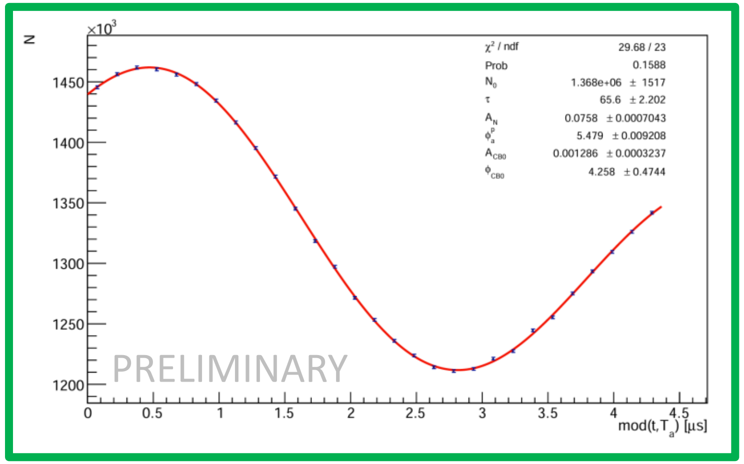
- Step 1: Need to know the g-2 phase
  - EDM signal is π/2 out of phase with it.
- So, fit the g-2 oscillation: 9-parameter fit, includes ω_a and CBO.
  - Momentum cut > 1700 MeV.
- Other parameters used in main g-2 analysis not needed.
  - Uncertainty propagated through to the impact on EDM as a systematic.



$$N(t) = \underbrace{N_0 e^{-t/\gamma\tau}(1+A_N\cos(\omega_a t+\phi_a))}_{\text{g-2 wiggle}}\underbrace{(1+A_{\mathrm{CBO}}\cos(\omega_{\mathrm{CBO}}t+\phi_{\mathrm{CBO}})}_{\text{CBO terms}}$$

Extracting the EDM signal

- Then, fit the average vertical angle oscillation using the g-2 phase.
  - Denominator from momentum binned N(t) fit.
  - EDM is the out-of-phase amplitude.



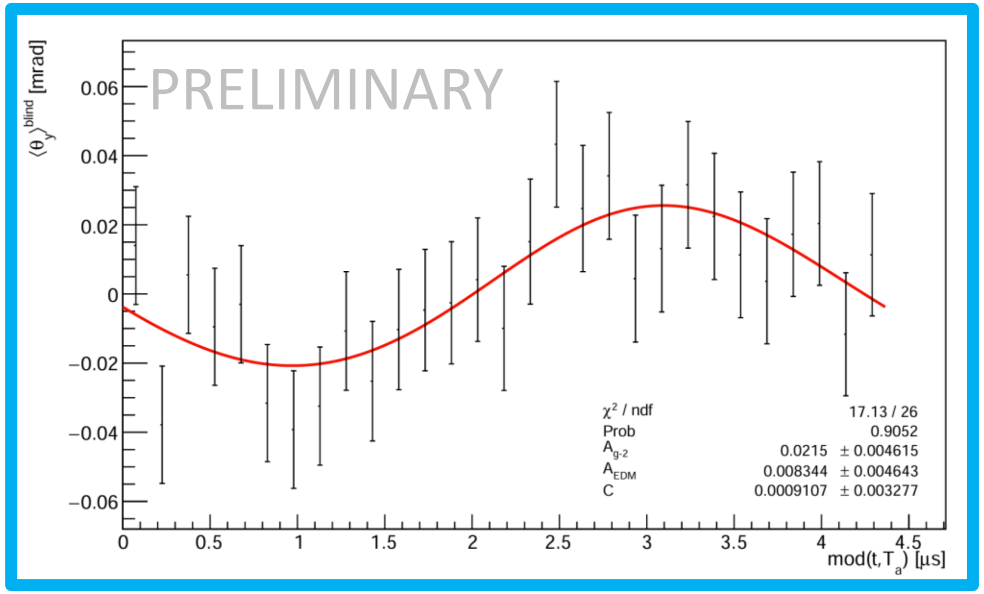
750-1000 MeV,
Run 3b, s18

Phase from > 1700 MeV N(t) fit

EDM amplitude

$$\langle\theta_y\rangle(t) = \frac{\boxed{A_{g-2}}\cos(\omega_a t + \boxed{\phi_a}) + \boxed{A_{\mathrm{EDM}}}\sin(\omega_a t + \boxed{\phi_a})}{\boxed{(1 + A_N\cos(\omega_a t + \phi_a^p))\,(1 + A_{\mathrm{CBO}}\cos(\omega_{\mathrm{CBO}} t + \phi_{\mathrm{CBO}}))}} \boxed{+\,C.}$$

Momentum-binned N(t) fit parameters

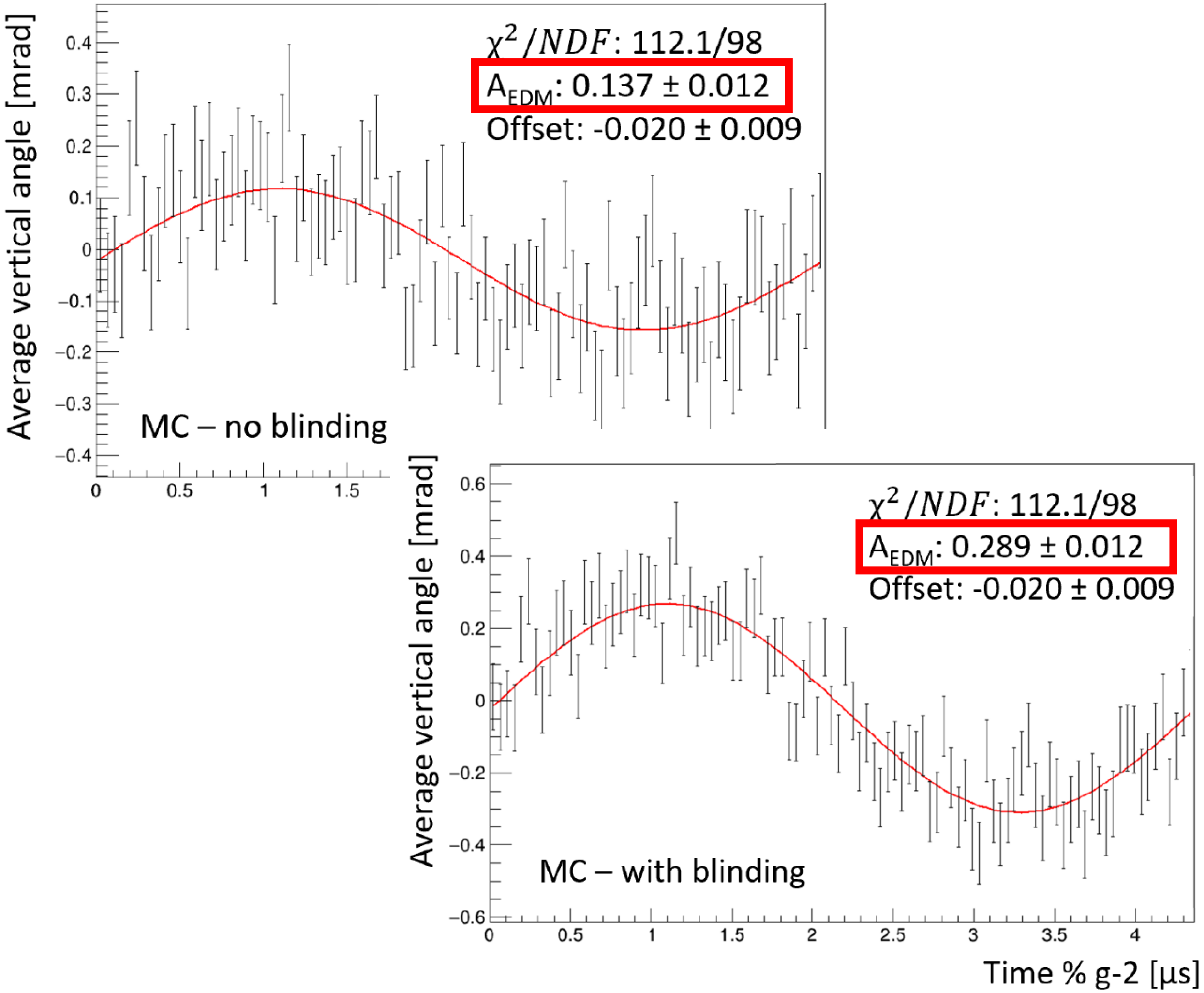


Blinding the EDM

- Need to blind the vertical angle oscillation to prevent bias in the analysis.

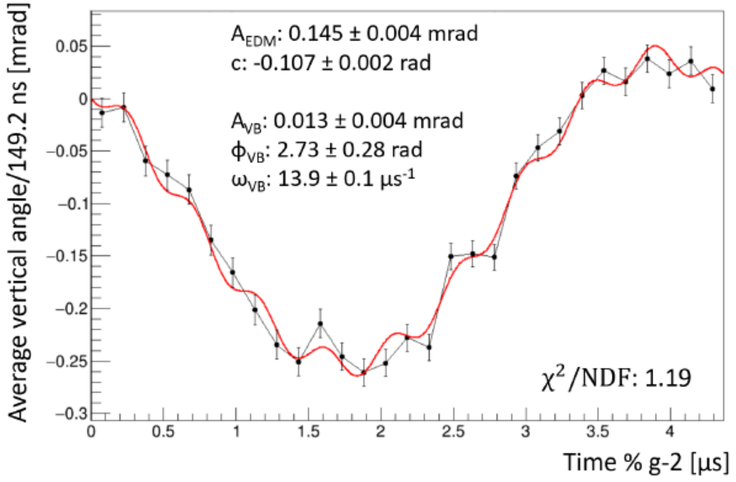
- Achieve this by injecting a very large fake signal in each momentum bin.
  - Amplitude sampled randomly from a gaussian distribution, chosen to be >> BNL limit.
  - Includes momentum dependence of A_{EDM} + reductions in measurable tilt (more on this later).

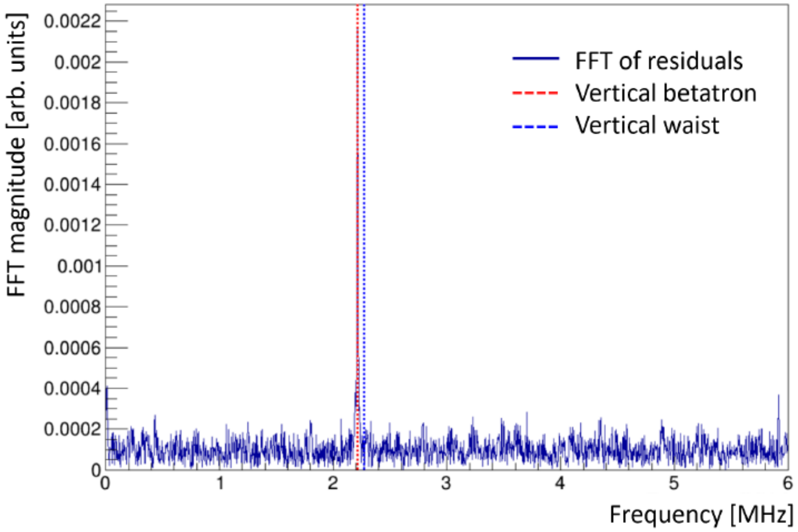
- Unblinding happens in stages: e.g. relative unblinding of datasets to check consistency before final unblinding.

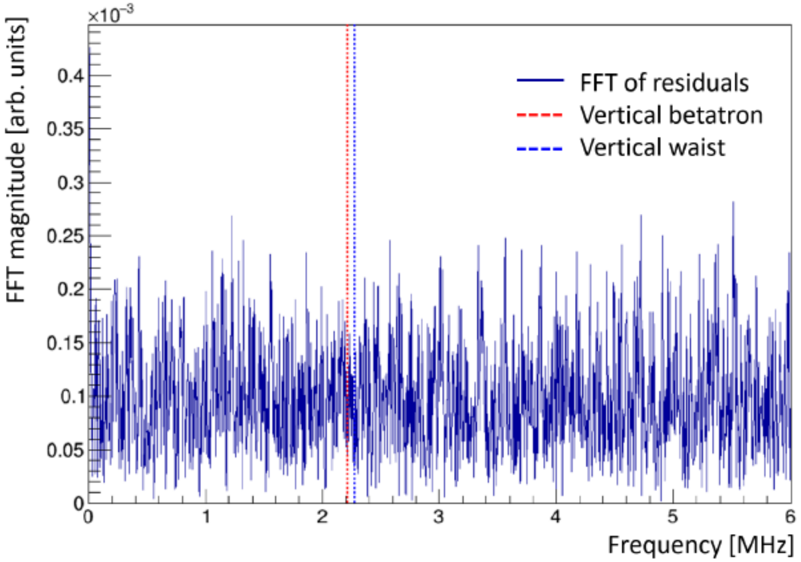


Accounting for beam oscillations

- Largest effect comes from **vertical betatron** motions – data is time-randomized to remove this.
  - FFTs used to confirm removal/lack of other oscillations.



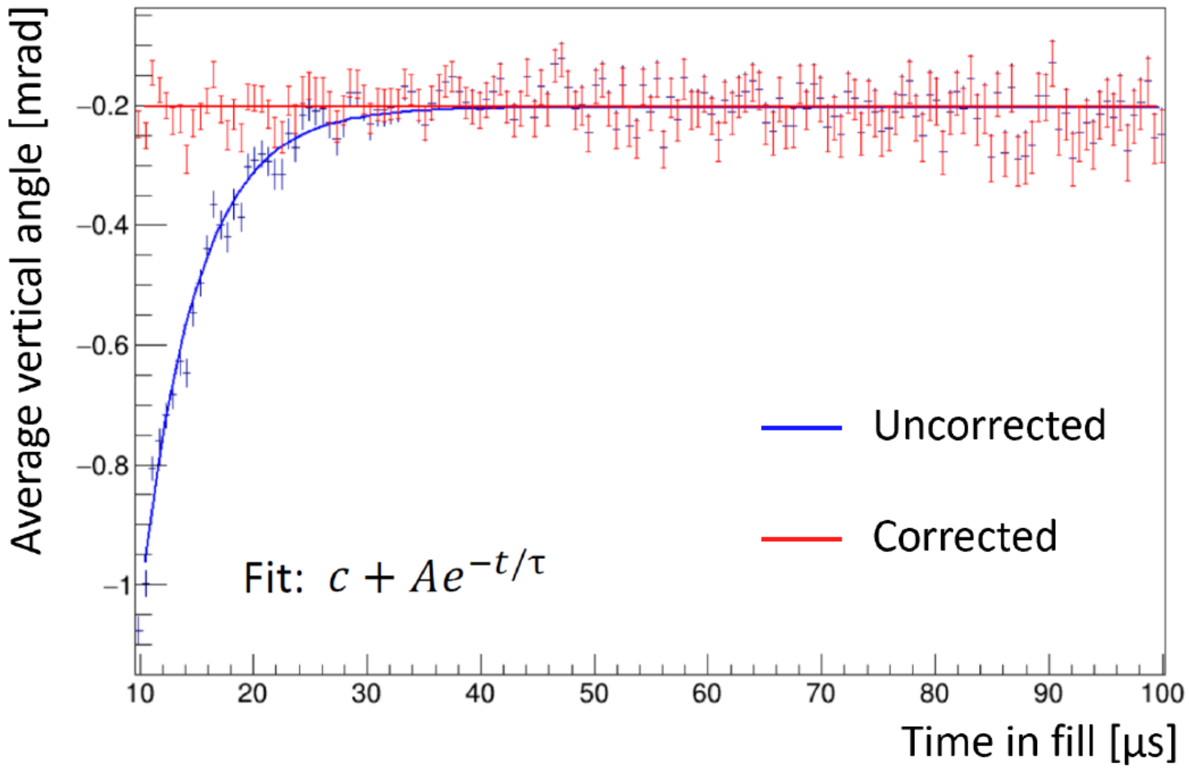




Accounting for beam oscillations

- **Early-time rise** seen in the average vertical angle – from a combination of ‘tracker pileup’ (space-charge effect) and quadrupole charging time.

- Previously limited the start time cut of the analysis – fitting and correcting allows a shift to 6 g-2 periods for more stats.

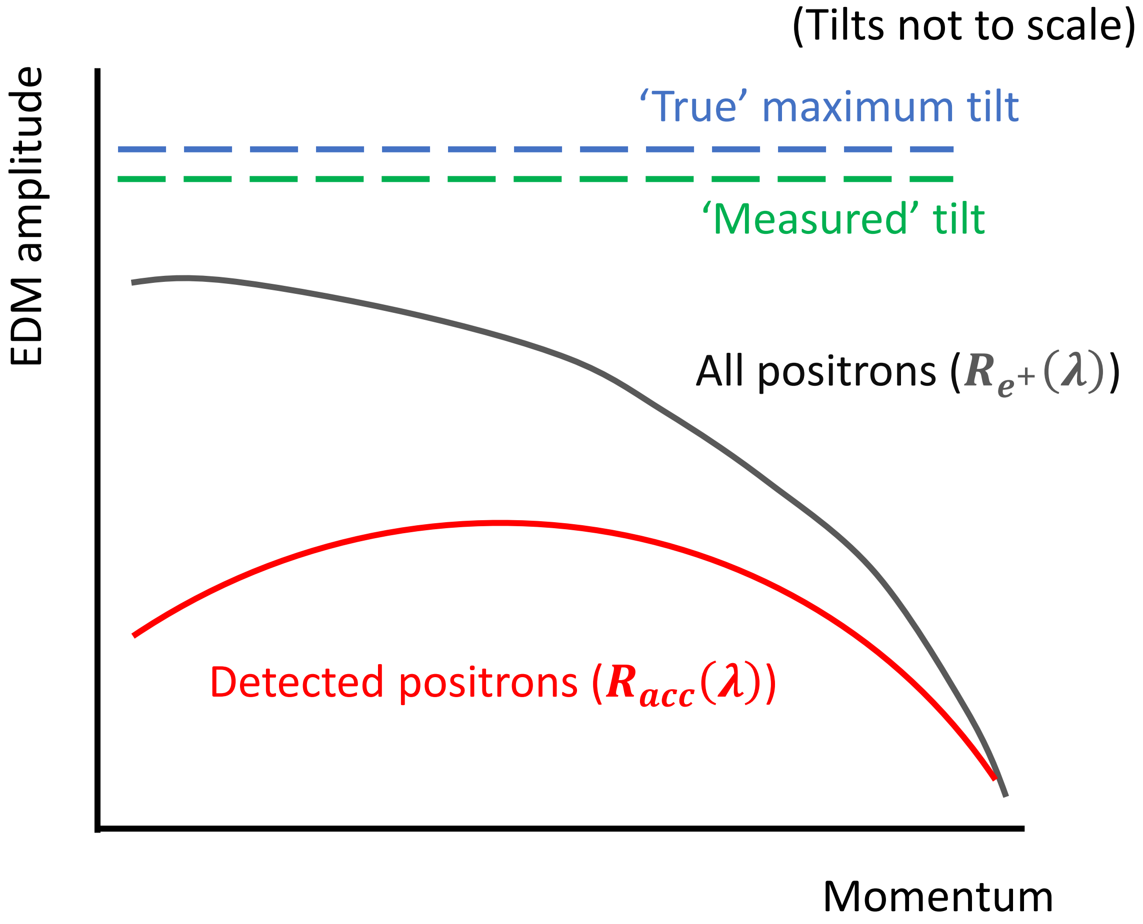


Reductions to the measured vertical angle

- The vertical angle measurable in the trackers is reduced by four effects:

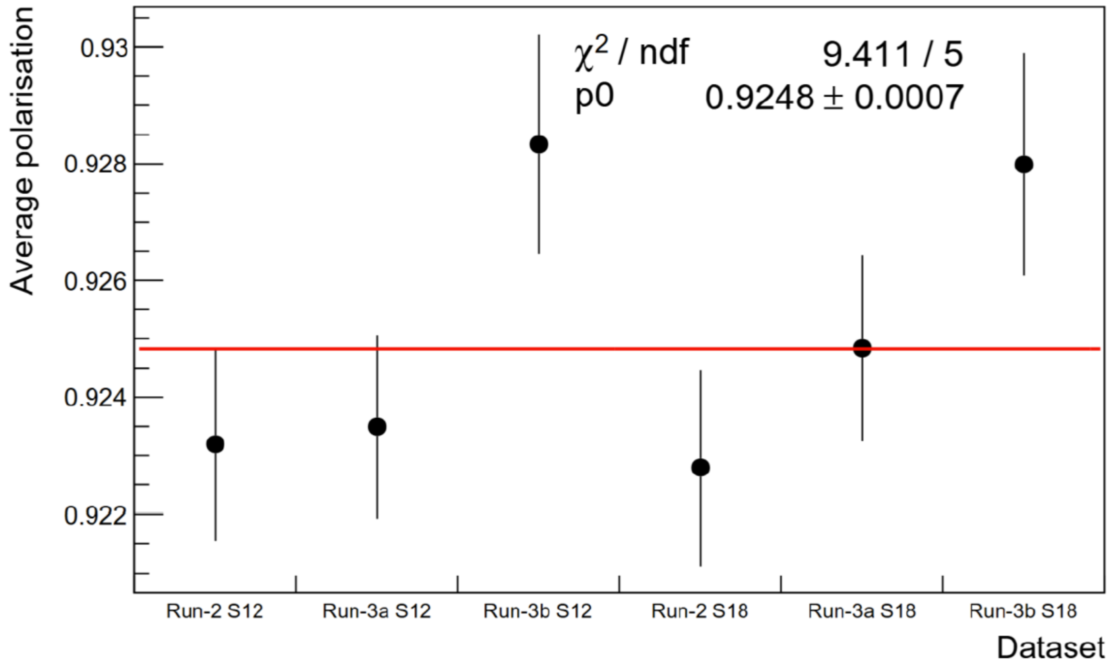
$$\text{Measured tilt} = R_\gamma\, R_p\, R_{e^+}(\lambda)\, R_{acc}(\lambda)\ \text{True tilt}$$

- R_γ : boost factor from muon rest frame to lab frame.
  - Factor is 1/γ, so ~ 1/29.
- R_p : beam polarization reduction (as is < 100%).
- $R_{e^+}(\lambda)$: muon decay asymmetry shape.
  - Has an analytical form, f(λ), where λ is fractional momentum, calculated up to first order radiative corrections.
- $R_{acc}(\lambda)$: acceptance effects, from the finite size of the tracker + reconstruction capabilities.
  - No analytical form, determined from MC ratios.



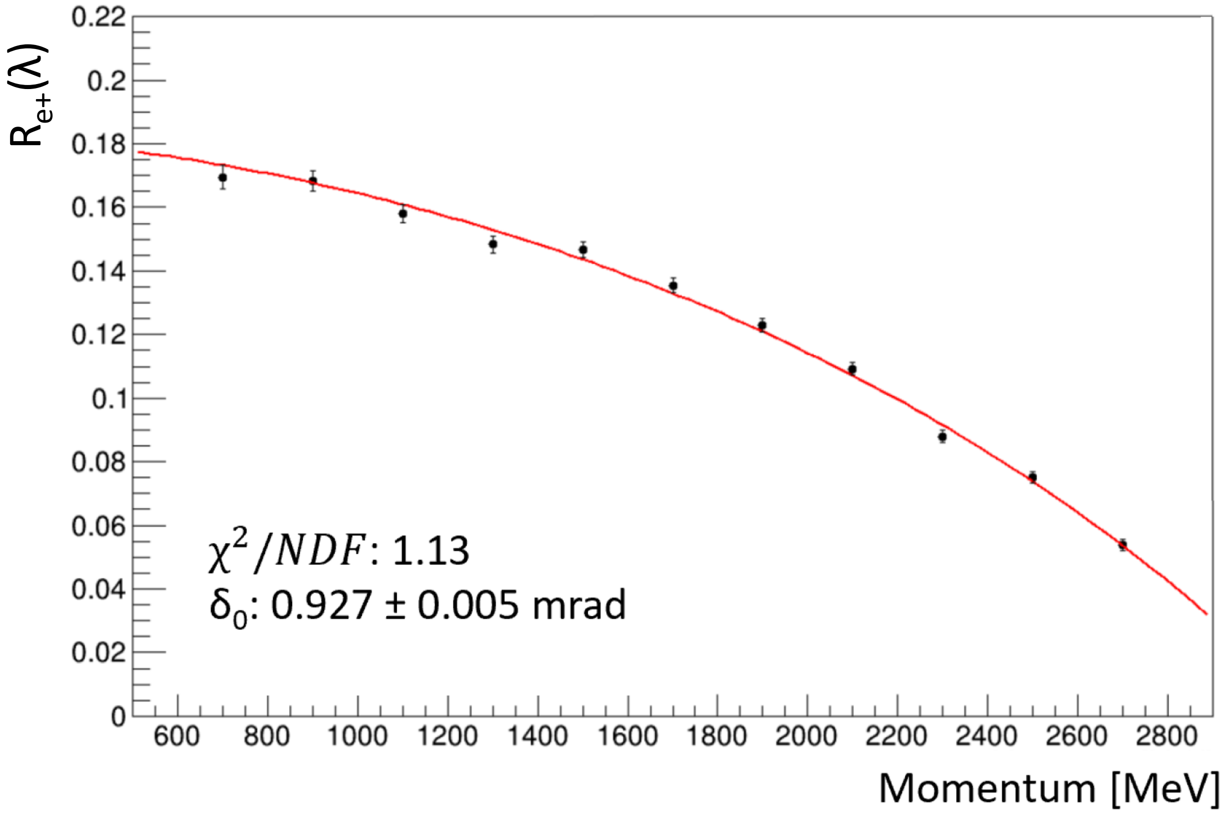
Beam polarization R_p

- In ideal case, beam would be 100% polarized - in practice is a bit less.
  - Reduces spin alignment, so impacts EDM sensitivity.
  - Need to quantify the percentage – then correction becomes %/100 + uncertainty.
- g-2 decay asymmetry also depends on the polarization – sets the amplitude of the wiggle.
- So, we can use this to determine the reduction from this effect + compare to previous measurements.
- Gives a correction factor of 0.94 ± 0.03.



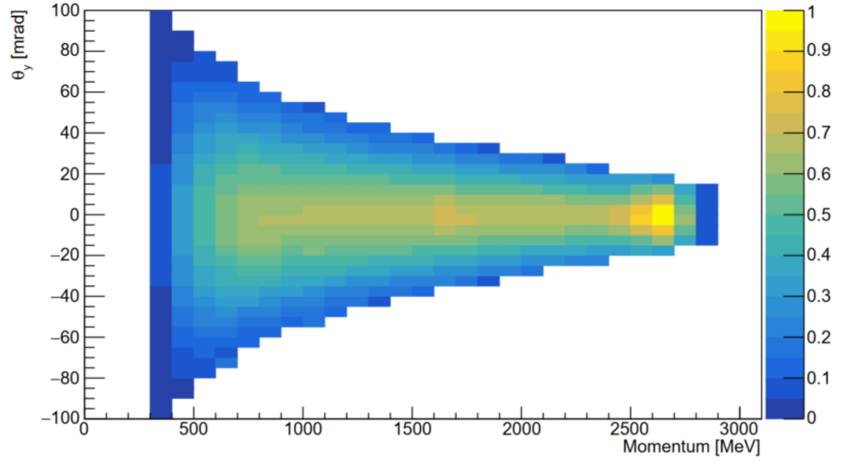
Decay asymmetry $R_{e+}(\lambda)$

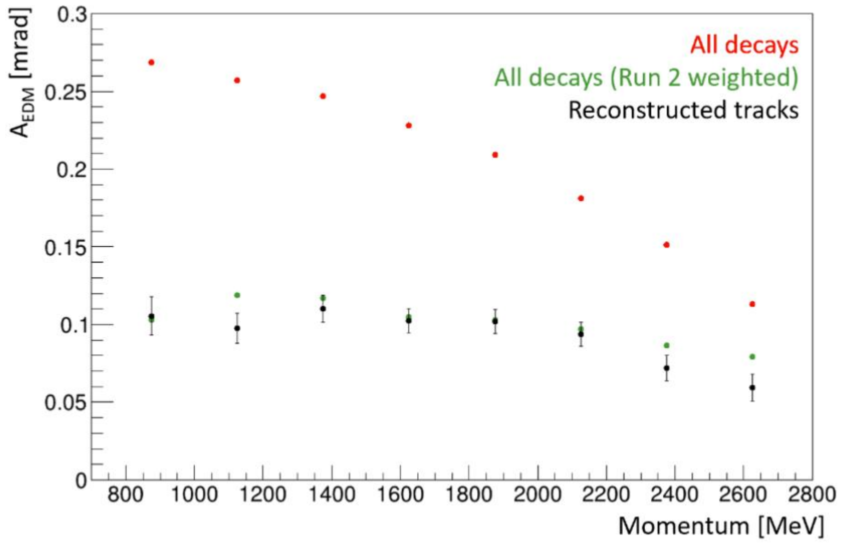
- Not all positrons are emitted exactly along the spin: Michel decay distribution.
- Can calculate the shape of this analytically to first order, but need higher order effects for accuracy.
  - So use MC to get the shape – generate decays to check final distribution.
- Is momentum dependent – so each bin of the analysis needs its own correction.



Tracker acceptance $R_{acc}(\lambda)$

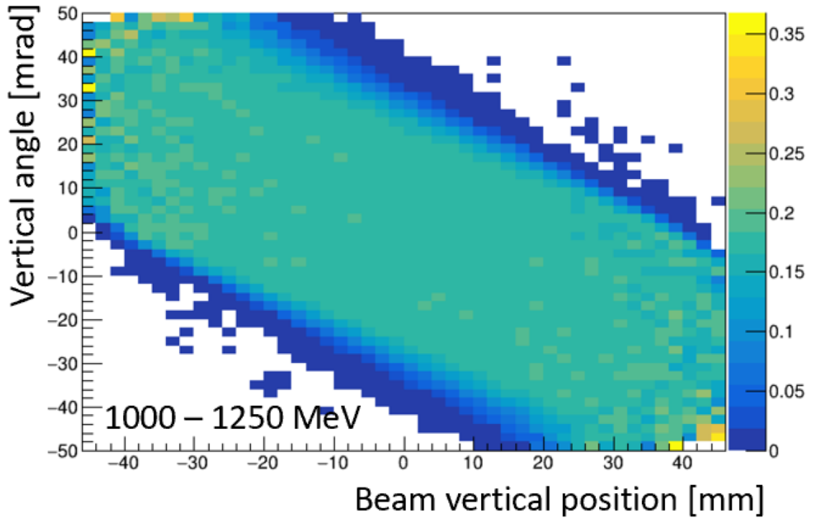
- Not every decay hits the trackers + not all hits can be reconstructed.
- Momentum-dependent – no analytical way to do this, so get this from MC with geometry.
- Run two MC samples with a large injected EDM (30x the BNL limit):
  - 'All decays': this keeps every single decay, irrespective of tracker reconstruction.
  - 'Track reco': this only keeps the things that the tracker actually extrapolates to the vertex.
- Calculate the fitted EDM amplitudes of both: the ratio of the two gives the correction.

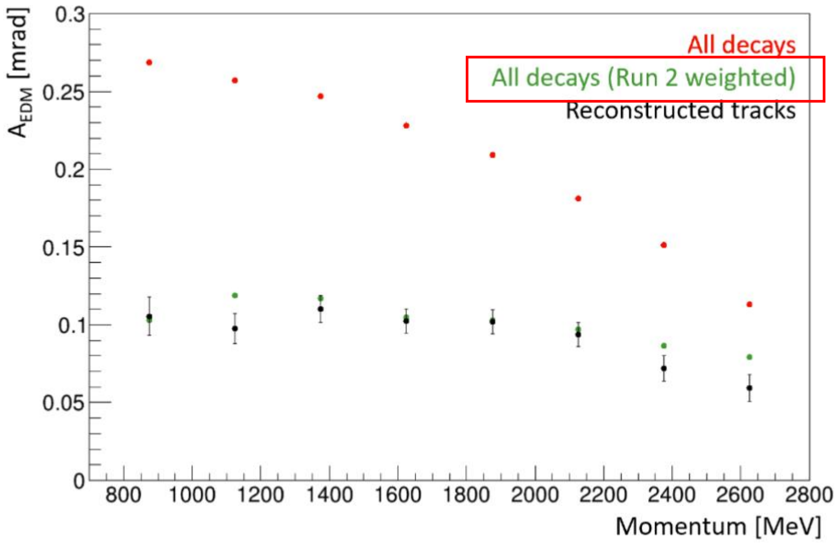




Tracker acceptance $R_{acc}(\lambda)$

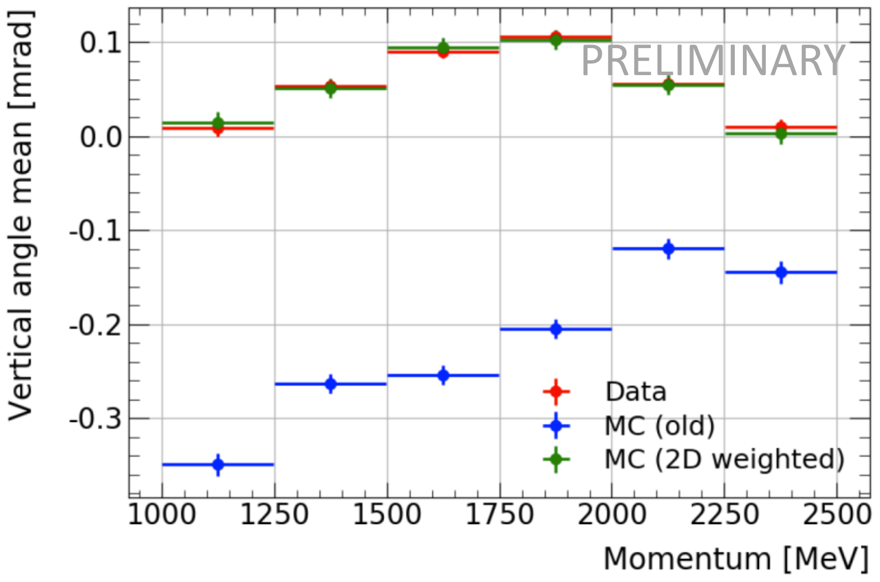
- But.. raw ratio limited by stats of tracker MC – which loses a lot of decays!
  - Leads to very large (dominant) uncertainties from this correction.
- Solution: what would it look like if we had trackers all the way around the ring?
- Use acceptance maps – 2D ratio of vertical decay angle/vertical decay position for the two MCs
  - One map per momentum bin, station, dataset
  - Apply map to the higher stats all decays MC + renormalize the map to let more decays through, while maintaining shape.
  - Improves the uncertainties by a factor of 3.
  - Extra correction 'scaling' needed to account for beam MC/data MC differences.

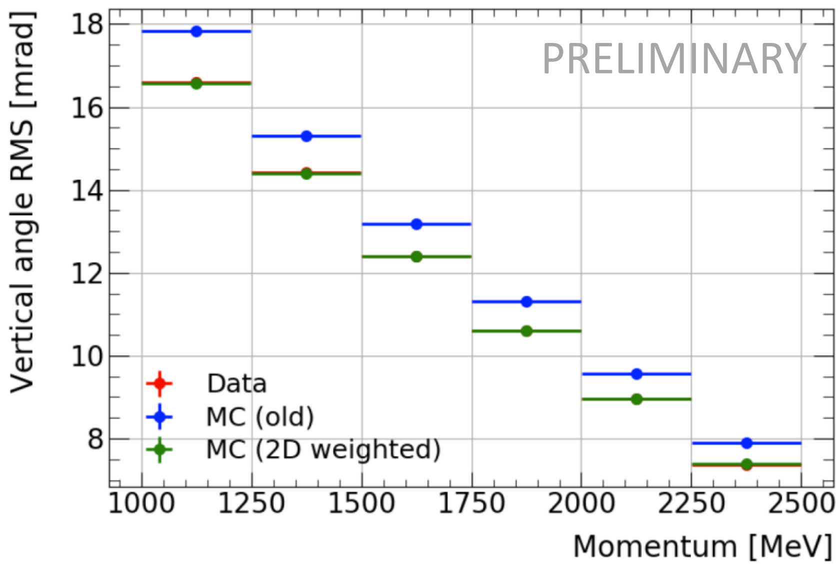




Data/MC matching

- Distributions in data and MC do not match perfectly, so a weighting is applied based on individual run period datasets to ensure the acceptance corrections are accurate.
  - Is a 2D weighting of vertical angle and detected beam vertical position, applied in the analysis momentum bins and interpolated for each decay's exact momentum.



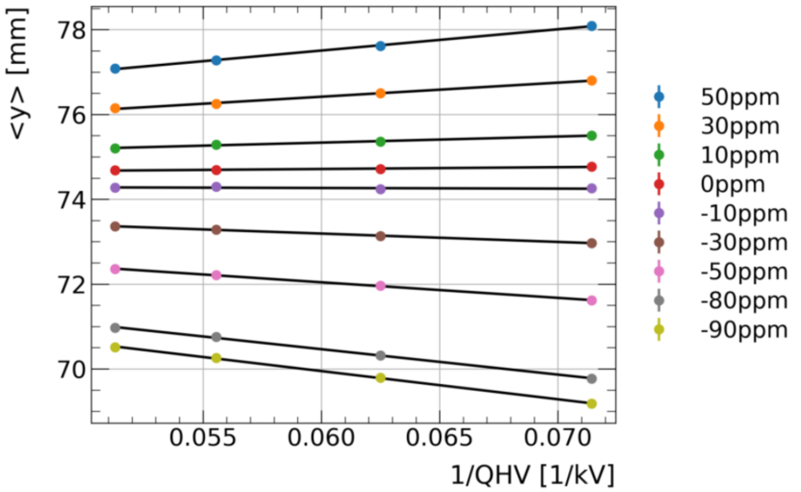


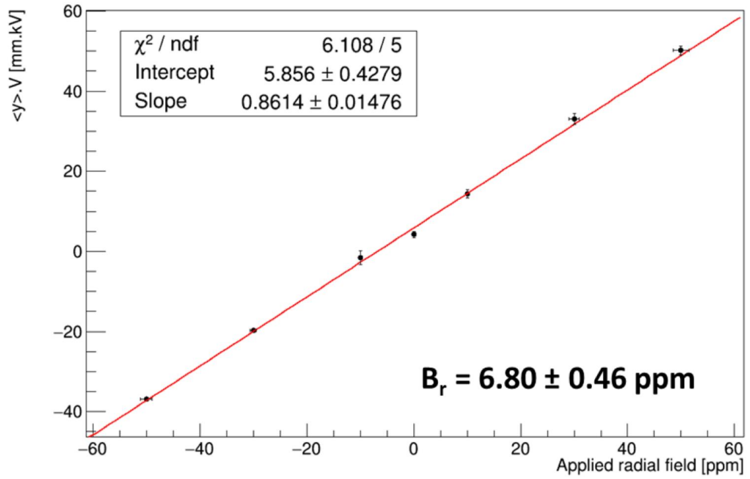
- All residual difference treated as a systematic uncertainty: small compared to the statistical uncertainty (<1%).

Potential sources of fake EDM – Radial field

- Given the EDM signal is a tilted precession plane/vertical asymmetry, important to properly understand how large any ‘fake EDM’s could be.
- A radial B field component in the ring would also cause a tilt of the precession plane.
    - Suppressed by a factor of γ in the muon rest frame.
- Perform radial field scans to measure, extrapolate to all data using the beam Y position.
    - Means we can use the average for each dataset, and subtract the tilt off like a background.

Dataset	$\langle B_r \rangle$ (ppm)	δ^* (μrad)
Run-2	14.9 ± 4.5	14.9 ± 4.5
Run-3a	11.2 ± 2.2	11.2 ± 2.2
Run-3b	12.0 ± 2.5	12.0 ± 2.5

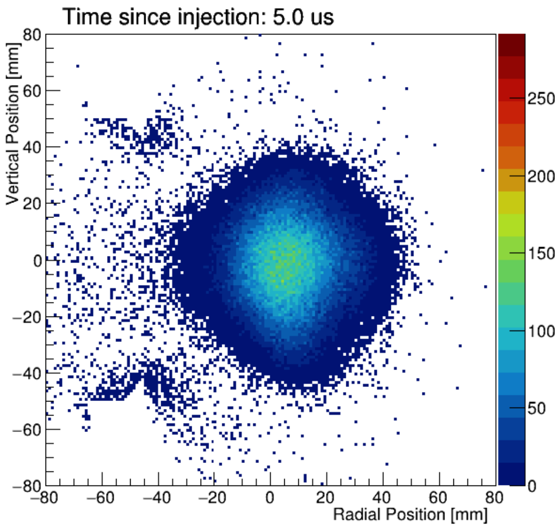


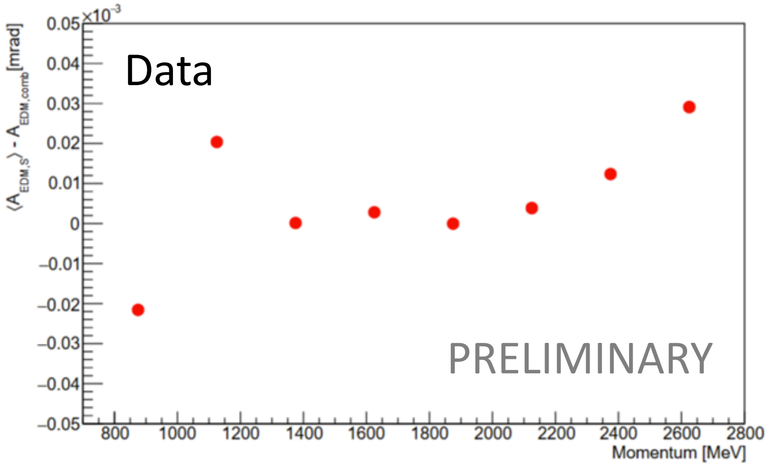


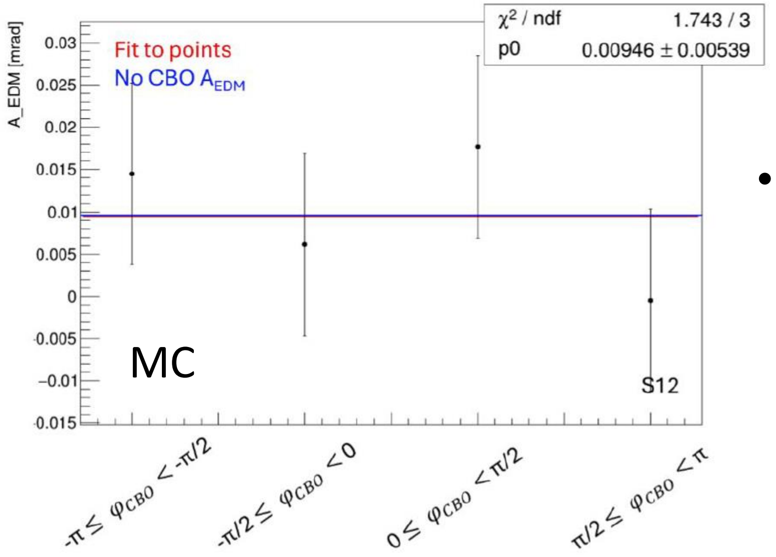
Potential sources of fake EDM – CBO

- The coherent betatron oscillation (CBO) is a radial beam oscillation in the data – shows up in the g-2 fits.

- Tracker acceptance couples the radial and vertical motion, so could end up with a time-varying vertical asymmetry.



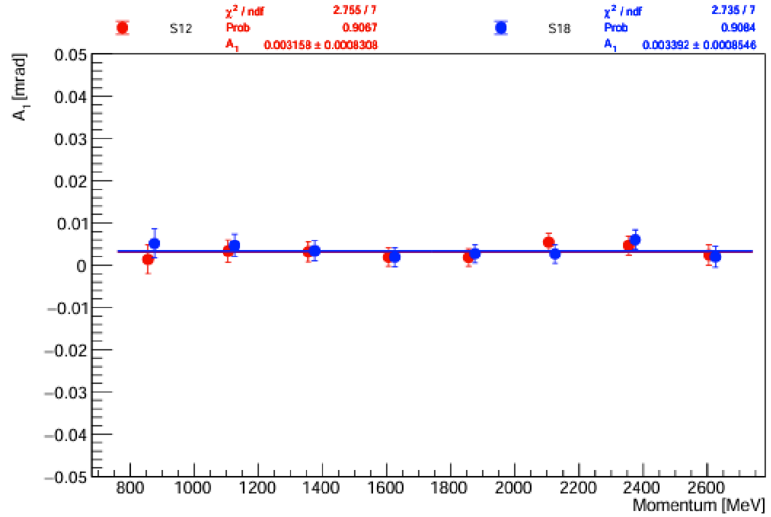




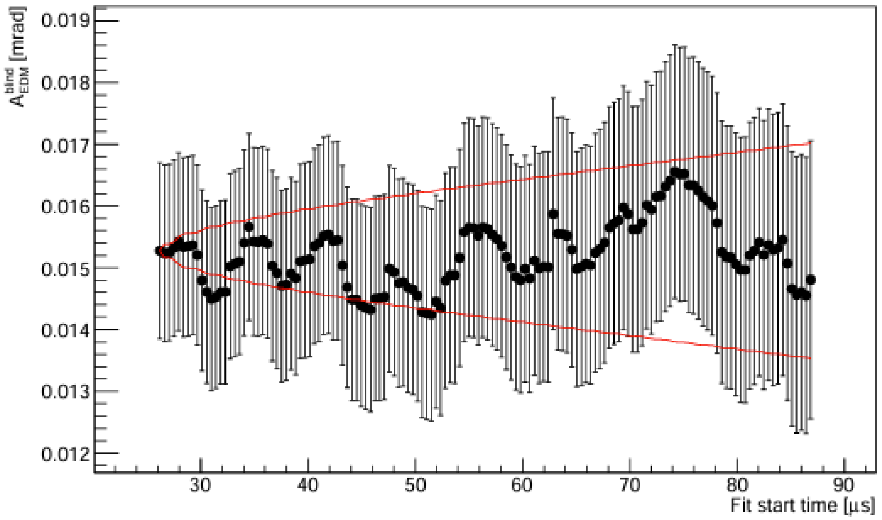
- Quantify size of effect in both data and MC as cross-checks:
  - Data: use station differences, as CBO phase is π/2 out of phase.
  - MC: Look at A_{EDM} with/without CBO.
  - **Upper bound sets uncertainty.**

Analysis cross-checks

- ‘Sideband’ frequency searches
  - Change frequency of modulation/fit, look for in-phase and out-of-phase terms, should be zero if there’s nothing there!
  - ‘Random’ frequency is zero out-of-phase in fits.
  - CBO seems to be slightly nonzero – investigating this further.



- Start time scans
  - Fit parameters, look to see if the start time impacts the parameter meaningfully.
  - Could indicate an unaccounted-for beam effect.
  - All scans within expected variation.



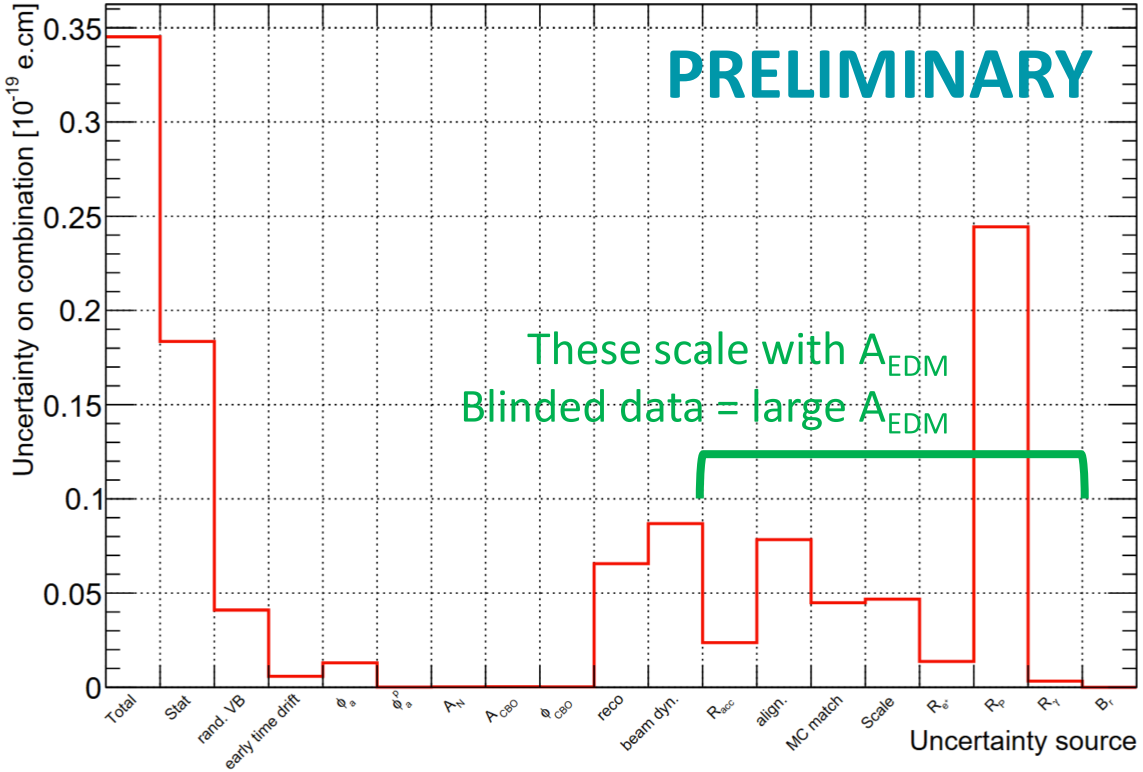
Systematic uncertainties

- Analysis is statistically limited – stat. unc is ~ 2x larger than any of the systematics.

- Largest systematics all roughly comparable:
  - Uncertainty in track reconstruction (reco).
  - Impact of CBO beam oscillation (beam dyn).

- Align and R_p scale with measured A_{EDM} – currently, large blinding EDM, so will reduce.
  - Active work ongoing to better understand impact of tracker alignment, both in reconstruction and with the beam.

- Expect beam dynamics uncertainty to be our largest after unblinding.

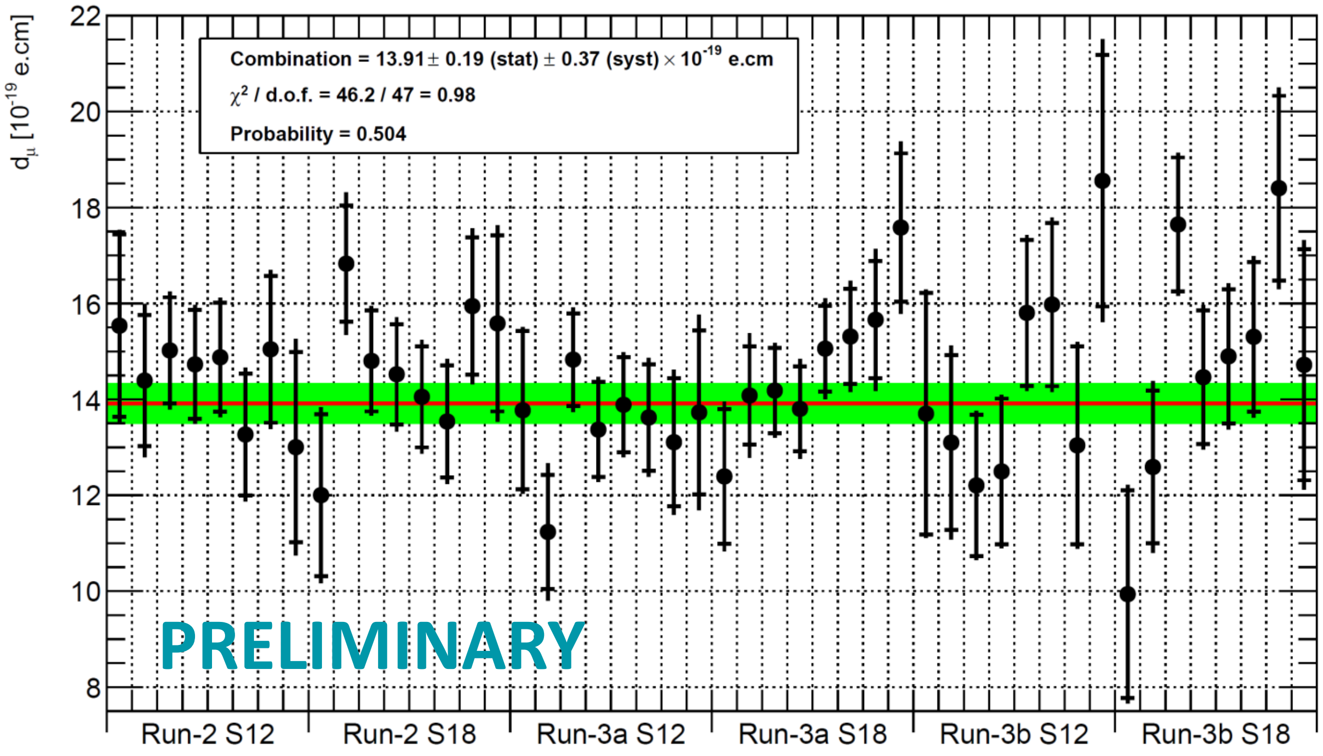


Preliminary blinded Run 2/3 results

- Relative unblinding of Run 2/3 performed.
  - Results show good agreement.

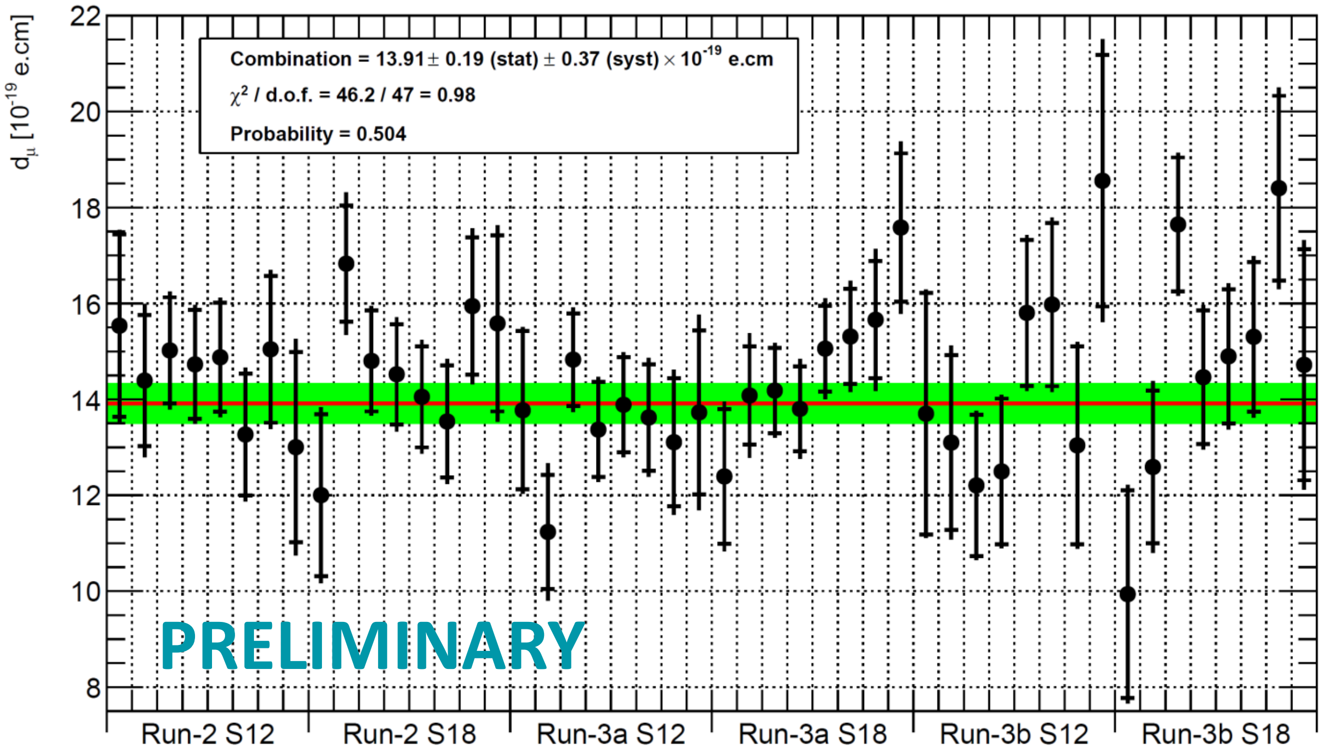
- Points combined + fitted using the Best Unbiased Linear Estimator (BLUE) method to account for correlations:

Source	Scales with A_{EDM}	Correlation Momentum	Station	Dataset
Statistics				
VBO rand.				
Beam scraping				
g-2 phase ϕ_a		Y		Y
g-2 phase ϕ_a^p				
g-2 amplitude A_N				
CBO amplitude A_{CBO}				
CBO phase ϕ_{CBO}				
Track reconstruction			Y	
Beam Dynamics		Y	Y	Y
R_{acc}	Y			Y
R_{acc}: flat MC weight	Y	Y	Y	Y
R_{acc}: alignment	Y	Y		Y
R_{acc}: data-MC match	Y	Y	Y	Y
R_{e^+}	Y		Y	Y
R_{pol}	Y	Y	Y	Y
R_γ	Y	Y	Y	Y
Radial field		Y	Y	



Preliminary blinded Run 2/3 results

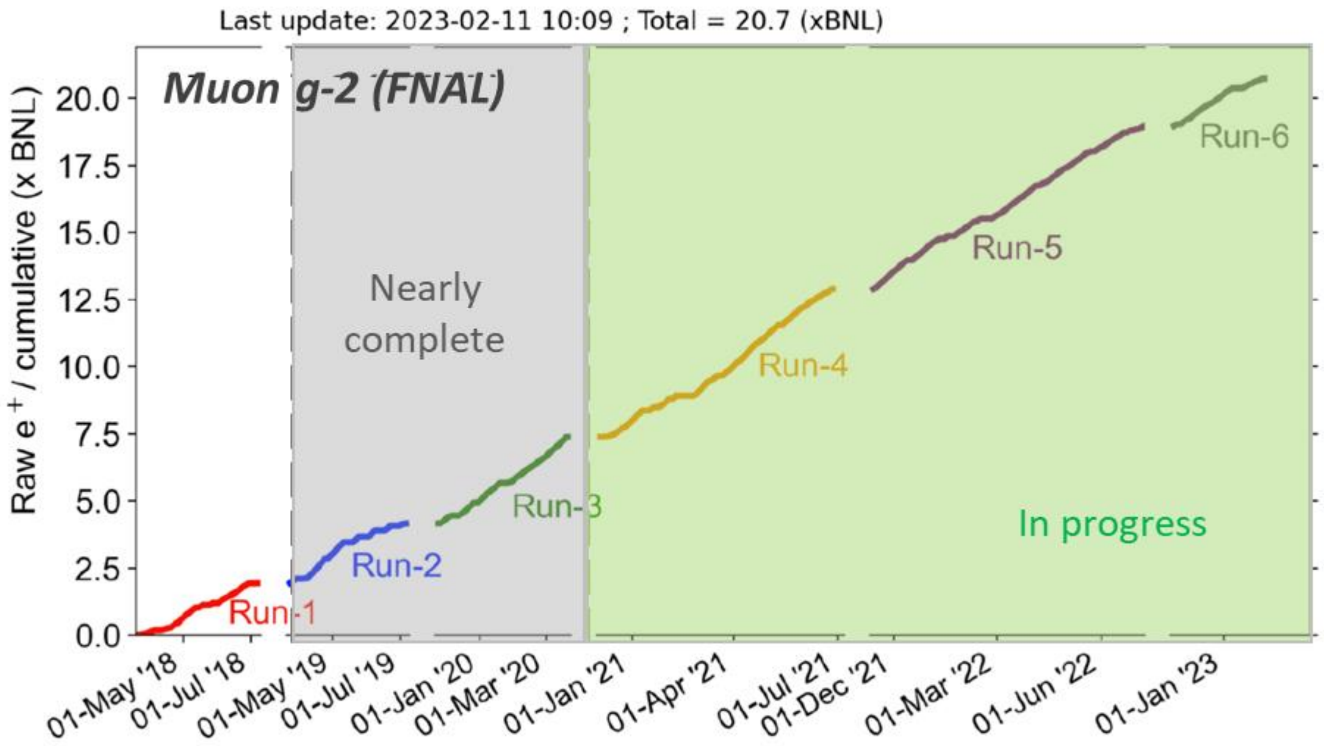
- Assuming zero signal is observed, plan to set limit using the Feldman-Cousins method.
  - Matches most recent electron EDM results so easier to compare!
- Assuming central value = 0 after unblinding, gives a limit of $3.3 \times 10^{-20}\ e \cdot cm$ – **5.5x improvement vs BNL**.
  - Is the ‘best case scenario’, in practice a nonzero d_μ will increase this.



Timelines for FNAL analysis

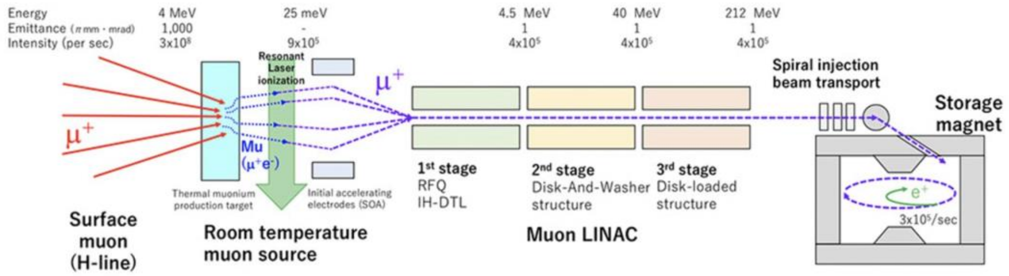
- Run 2/3: analysis mostly complete, in collaboration review.
  - Expect results this year… (hopefully!)

- Run 4/5/6 + full dataset:
  - Analysis started, ~ 4x as much data as Run 2/3.
  - Final result will be a combination of runs 2-6.
  - Expected to improve on BNL limit by ~ an order of magnitude.



What's next for the muon EDM?

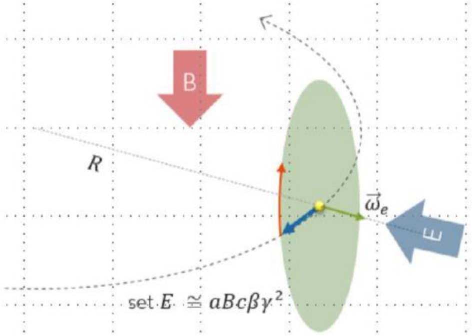
- J-PARC g-2: also planning on making an EDM measurement, targeting 1 order of magnitude further (~ 10^{-21} $\mathrm{e \cdot cm}$).

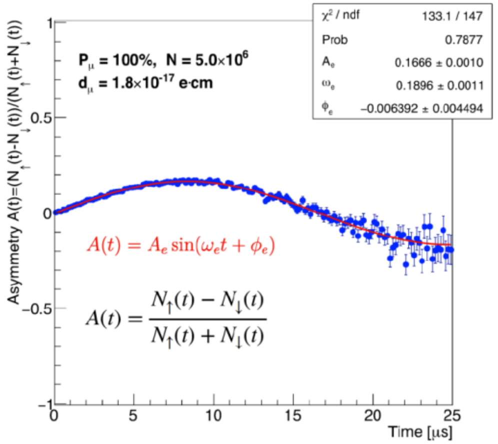


- Neither FNAL or J-PARC are dedicated muon EDM: limits sensitivity. Enter muEDM at PSI!
  - Designed to maximise EDM sensitivity using frozen spin technique: 'freeze' g-2 precession to allow EDM signal to build up over time – every positron is useful!

$$\vec{\omega} = -\frac{q}{m}\left[\underbrace{a_\mu \vec{B} + \cancel{\left(\frac{1}{1-\gamma^2} - a_\mu\right)\frac{\vec{\beta}\times\vec{E}}{c}}}_{\text{g-2 precession } \vec{\omega}_a} + \underbrace{\frac{2d_\mu mc}{q\hbar}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)}_{\text{EDM precession } \vec{\omega}_\eta}\right]$$

- Planning 'Phase 1' measurement before PSI shutdown in 2027 (~ 3-4x better than BNL limit)
  - 'Phase 2' afterwards, final target ~ 10^{-23} $\mathrm{e \cdot cm}$.





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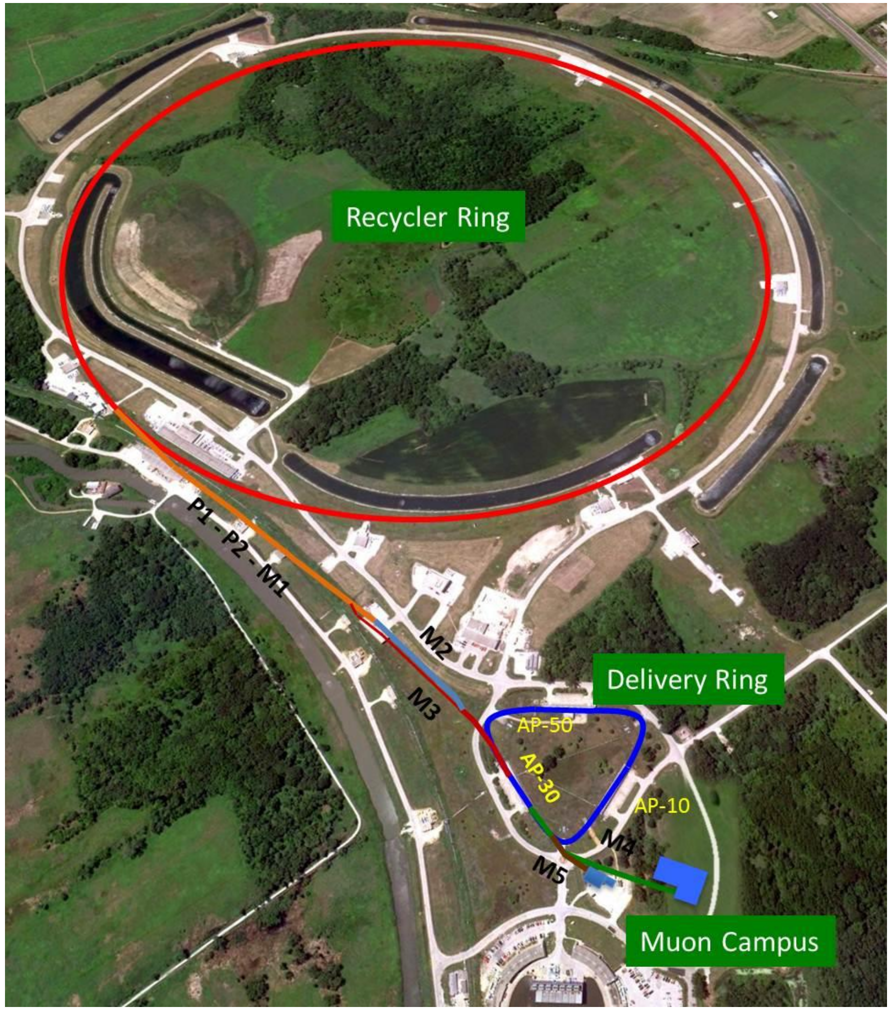
Bonus slides

Fermilab muon beamline

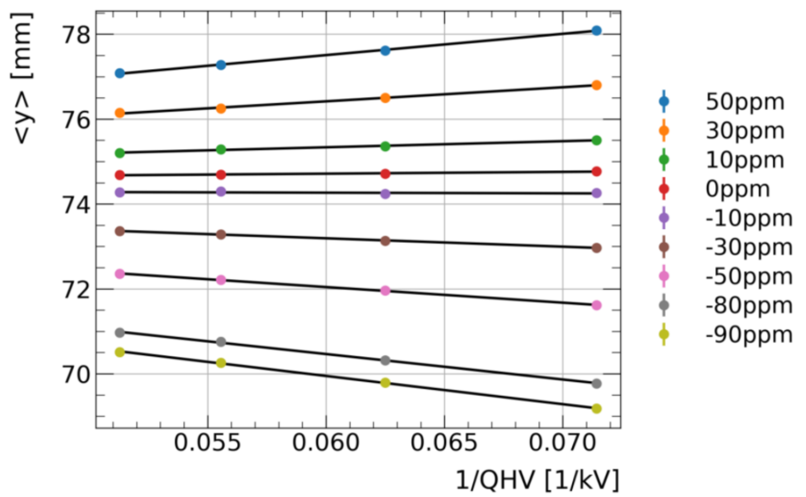
- Protons incident on a target make pions.
- Pions are stored in the delivery ring until they decay into muons.
- Muons injected into our ring.

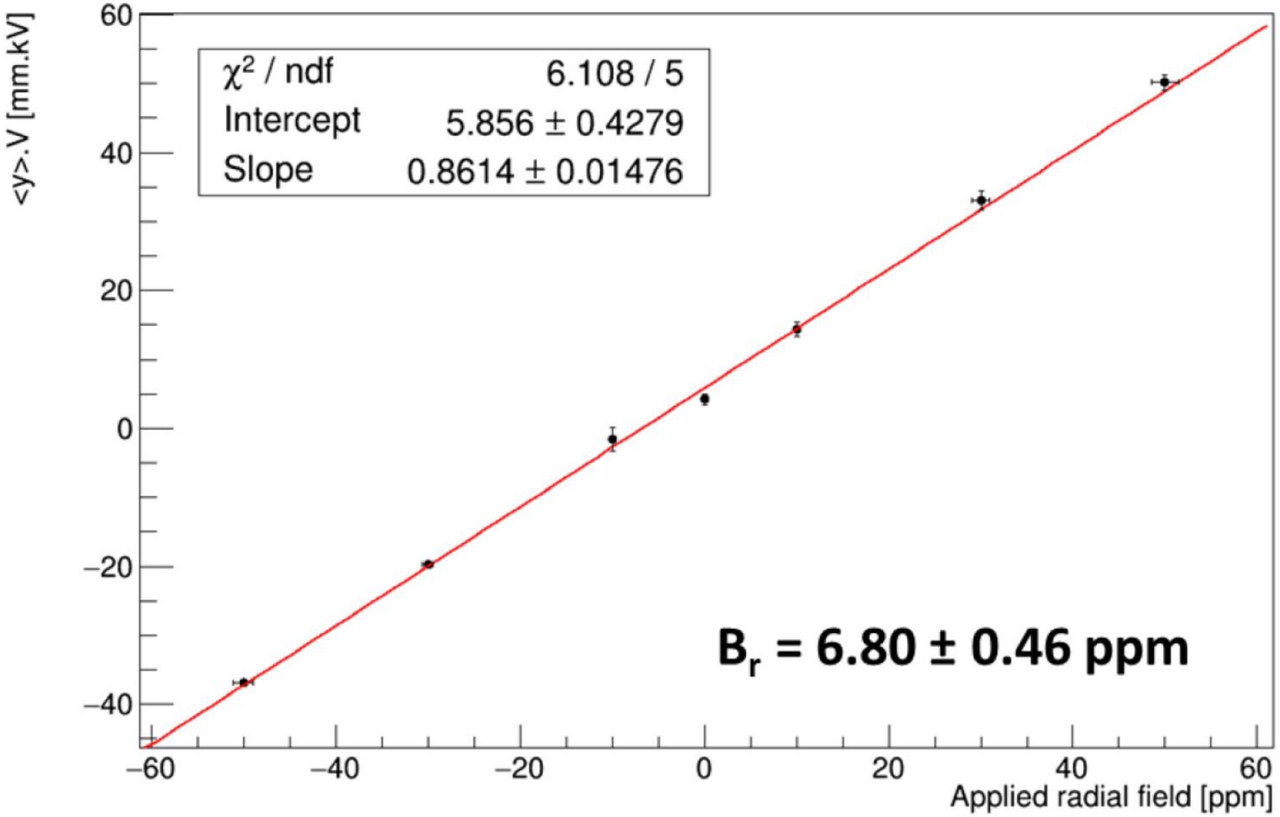


The radial field - measurement

- A non-zero radial field introduces a fake EDM signal due to also tilting the precession plane.

- Need to measure this very precisely to not be limited by the uncertainty.
  - ~ 1ppm is achievable by performing a radial field scan:





Radial field - results

- Scans are performed in Run 4/5/6 – so need to extrapolate the measurements to Runs 1/2/3 using the vertical beam position.
- Sufficient precision for this to not be the limiting systematic.

Dataset	$\langle B_r \rangle$ [ppm]	Equivalent d_μ [$\times 10^{-20}$ $e\cdot$cm]
1a	22 ± 7	7 ± 2
1b	23 ± 8	7 ± 3
1c	30 ± 8	9 ± 3
1d	34 ± 9	10 ± 3

S. Grant