

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

NuFact 2025

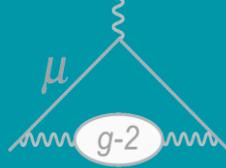
Dominika Vasilkova

On behalf of the Fermilab Muon $g-2$ collaboration



Dominika Vasilkova

Muon EDM – why do we care?



- Analogous to the magnetic dipole moment (MDM), charged particles might also have an intrinsic electric dipole moment (EDM):

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

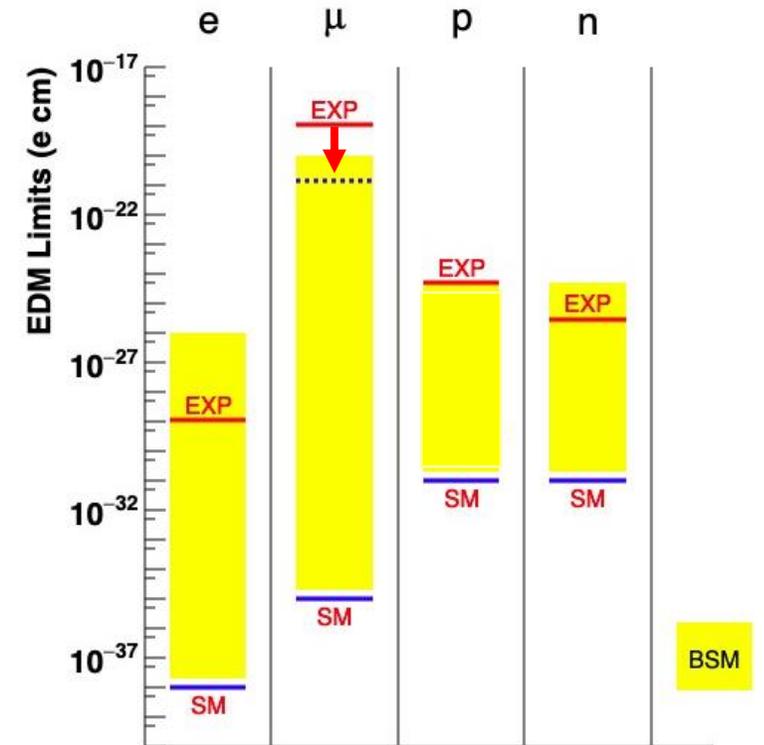
MDM:

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

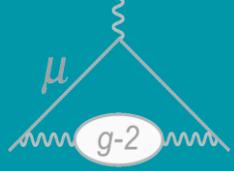
EDM:

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

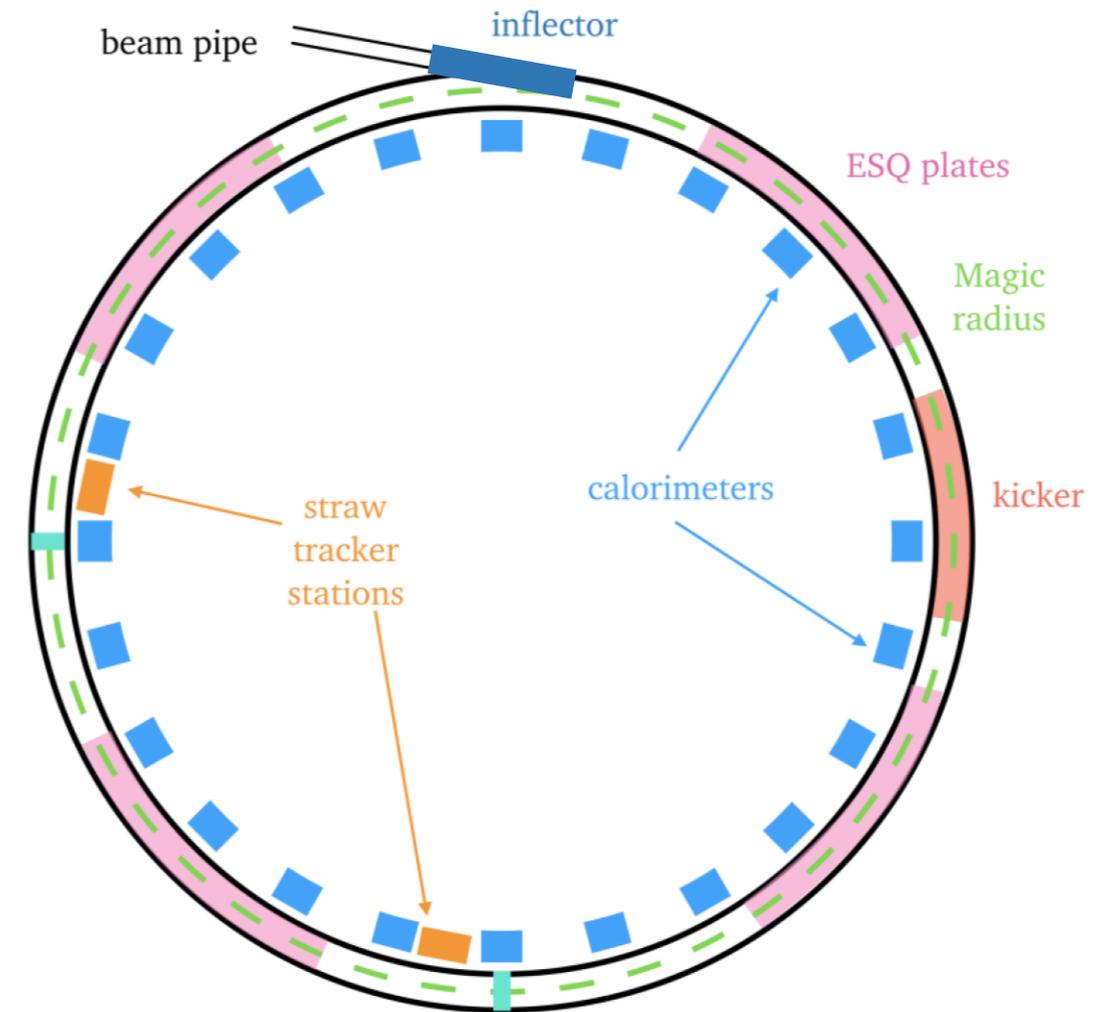
- Why muon EDM?
 - SM muon EDM well below the range of current experiments.
 - $\mathbf{d \cdot E}$ is CP-odd, so observation gives a **new source of CP violation** in the lepton sector.
- Previous best direct limit was set at Brookhaven National Laboratory (BNL): $1.9 \times 10^{-19} e \cdot cm$.



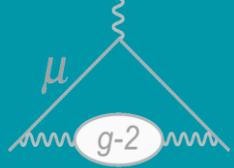
The Muon g-2 experiment at Fermilab



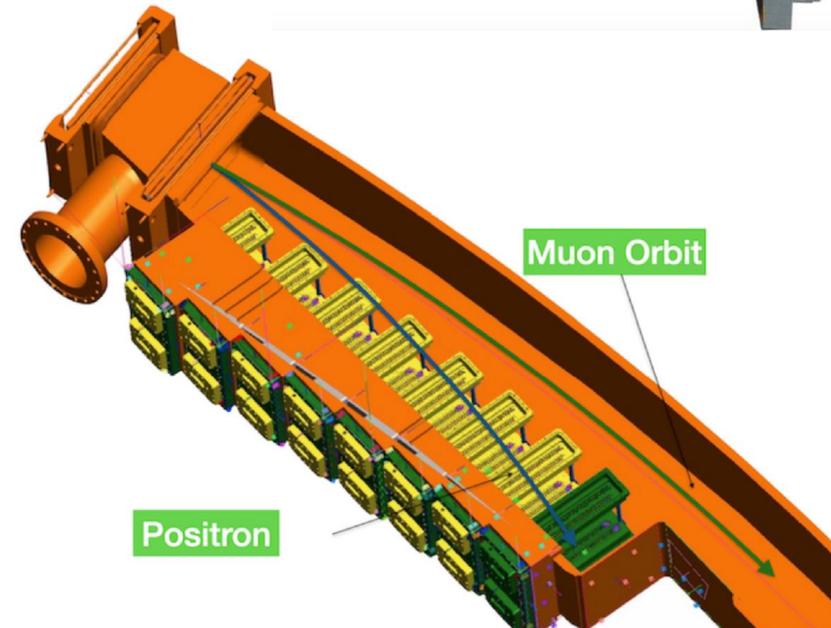
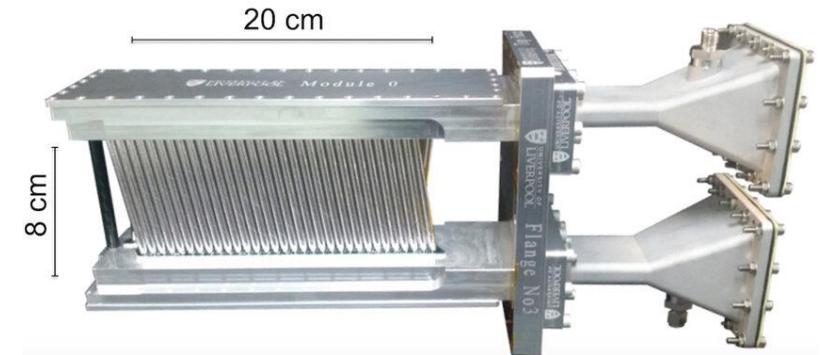
- Polarized muons injected into a storage ring, ring magnet provides a field of 1.45T.
- Magnetic field causes the direction of spin to precess in a plane.
- Positrons from decay preferentially emitted along the spin direction.
- Can then analyze the decay with 24 calorimeters + 2 straw tracker stations.



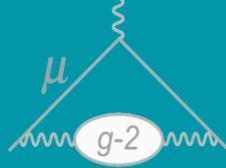
The straw trackers at FNAL g-2



- Argon-Ethane straw trackers, straw hit resolution of $\sim 100 \mu\text{m}$.
- Two 'stations' (12 and 18) of 8 straw modules each, designed to operate inside the vacuum chambers.
- Hits are fitted into tracks, which are then extrapolated back to the vertex of decay (used for the EDM analysis) and forward into the calorimeters.



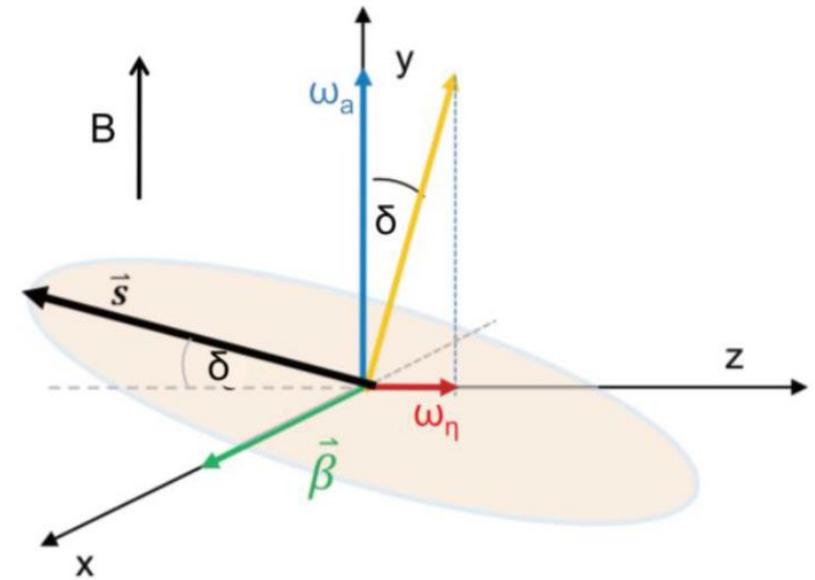
Measuring the muon EDM



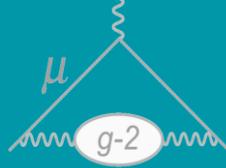
- A non-zero EDM introduces an extra term into the oscillation of the muons:

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

- **Two key effects:**
- A (very) small increase in the precession frequency.
- A second ‘tilt’ precession, $\pi/2$ out of phase with g-2 and perpendicular to it.



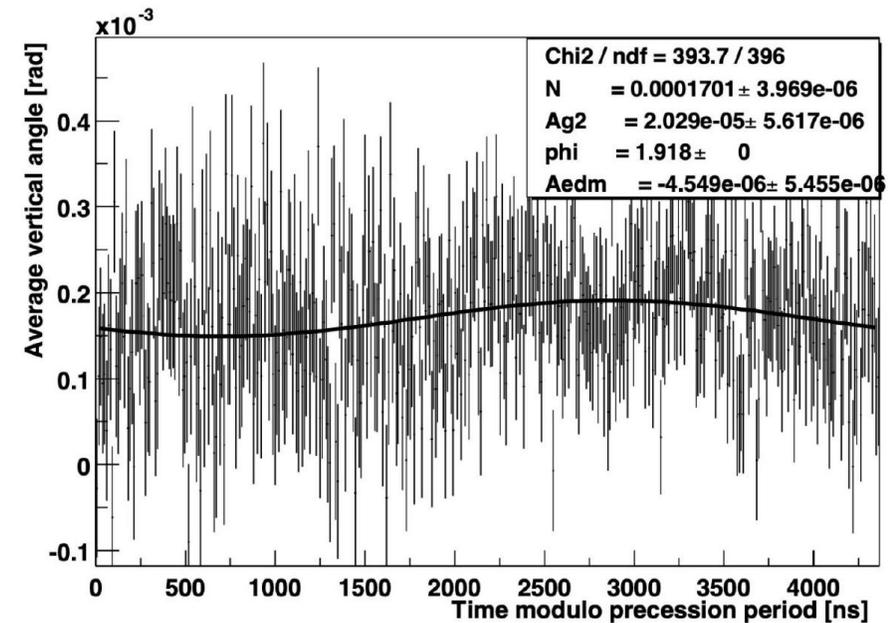
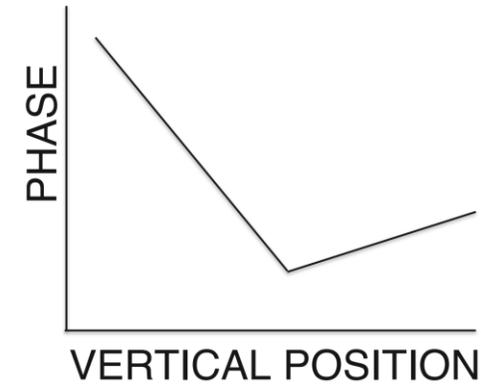
EDM signals at Fermilab g-2



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

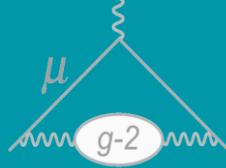
- **Direct vertical angle oscillation measurement:**
 - Calorimeter measurement still systematically limited.
 - Trackers better for this as statistically limited.

 - Best method for the FNAL setup!

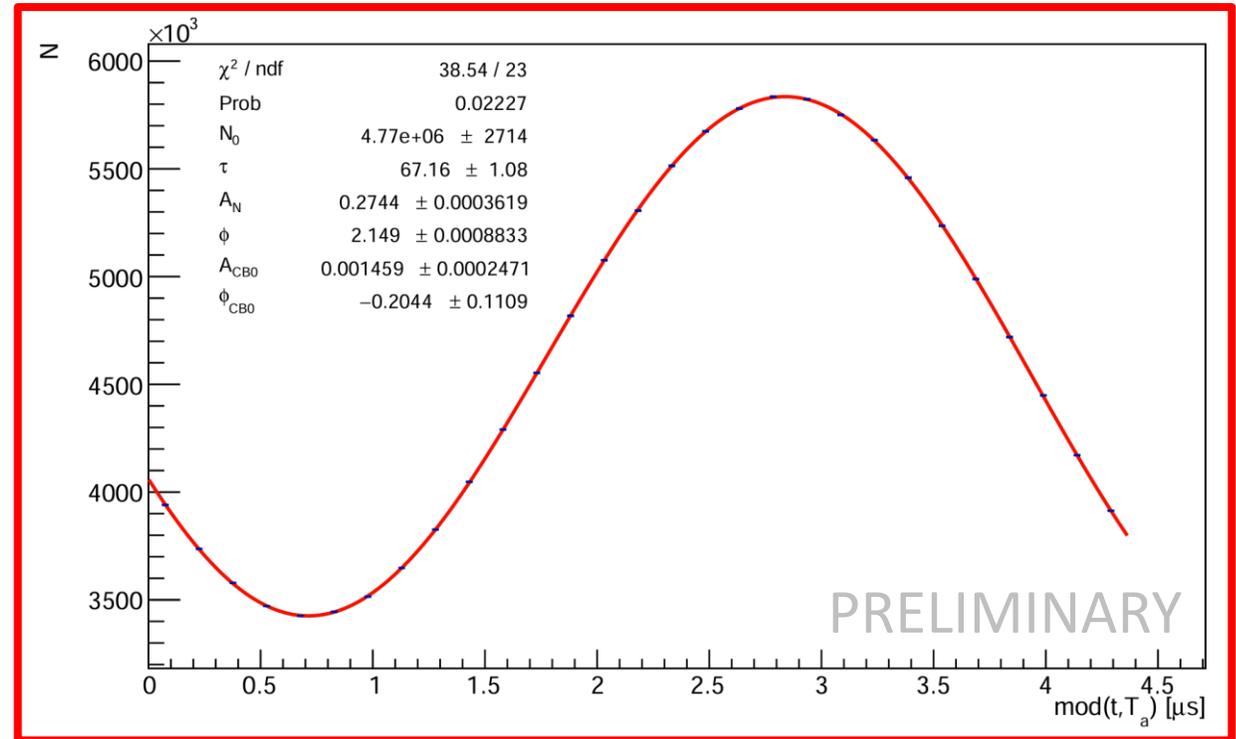


BNL
2000
data

Extracting the EDM signal

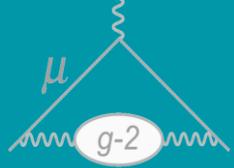


- First fit the g-2 oscillation: 9-parameter fit, includes ω_a and CBO.
 - Extract the phase of the g-2 oscillation.
 - Momentum cut > 1700 MeV.

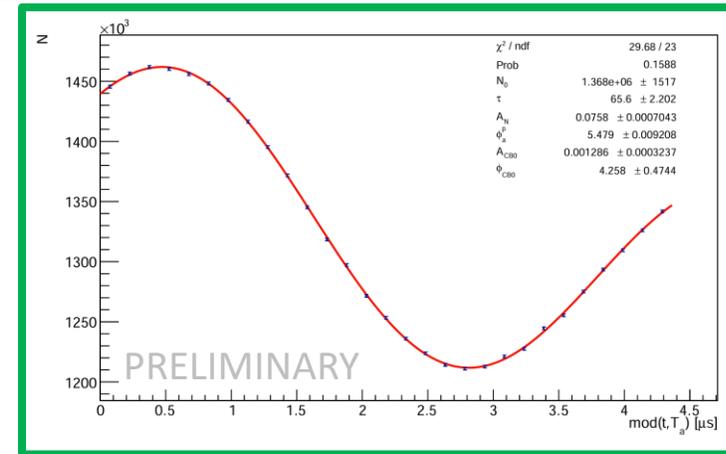


$$N(t) = N_0 e^{-t/\gamma\tau} (1 + A_N \cos(\omega_a t + \phi_a)) (1 + A_{\text{CBO}} \cos(\omega_{\text{CBO}} t + \phi_{\text{CBO}}))$$

Extracting the EDM signal



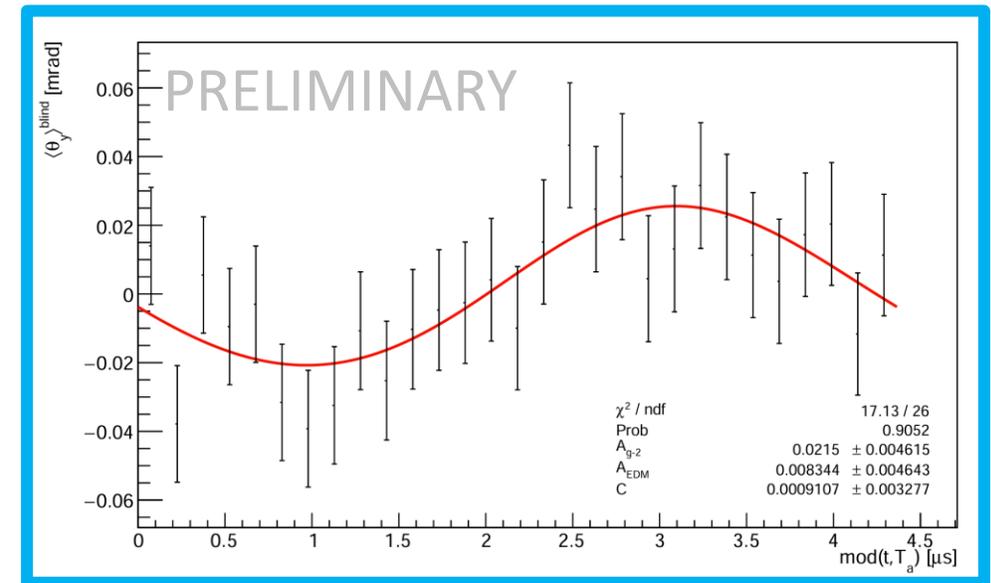
- Then, fit the average vertical angle oscillation using the g-2 phase.
 - Blind analysis – inject large fake signal.
 - Fit in momentum bins, per station, to maximize sensitivity to an EDM.
 - Denominator from momentum binned N(t) fit.
 - EDM is the out-of-phase amplitude.



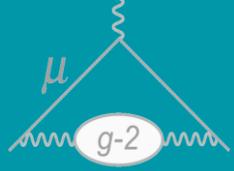
750-1000 MeV,
Run 3b, s18

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

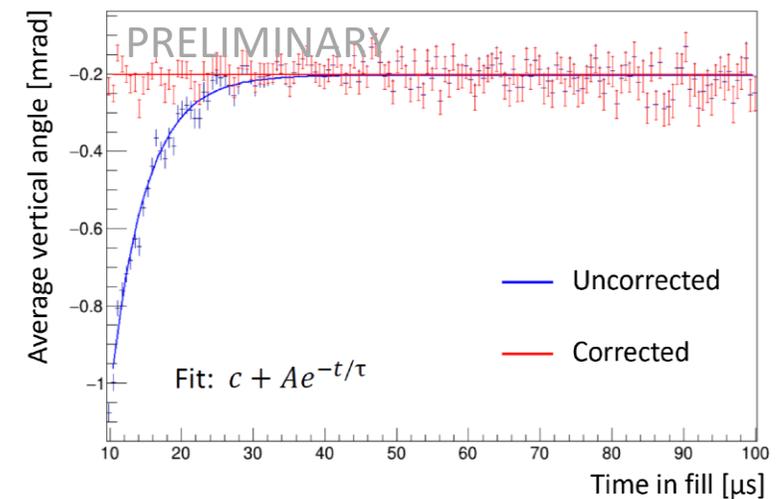
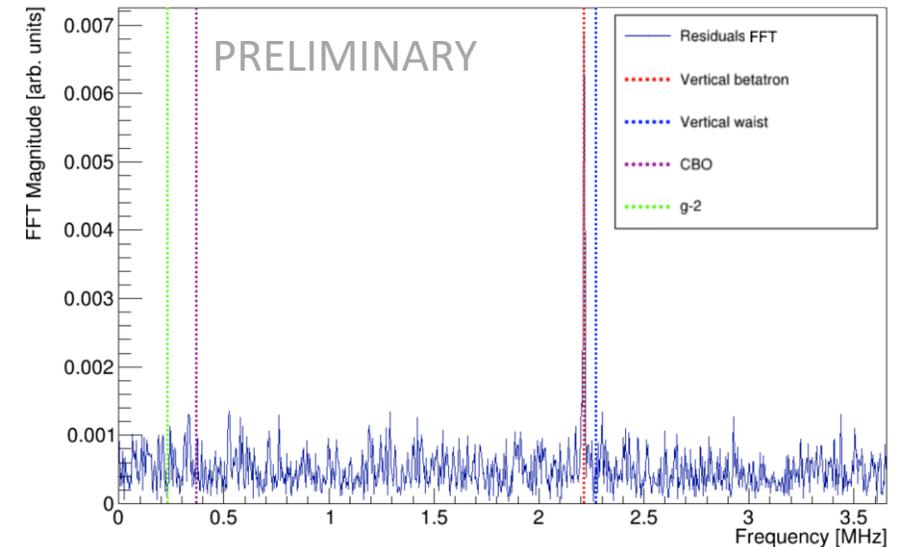
Phase from > 1700 MeV N(t) fit EDM amplitude
Momentum-binned N(t) fit parameters



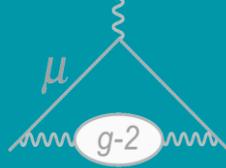
Accounting for beam oscillations



- Various muon beam motions that require special attention:
- Largest effect comes from **vertical betatron** motions – data is time-randomized to remove this.
 - FFTs used to confirm removal/lack of other oscillations.
- **Early-time rise** seen in the average vertical angle – this is fitted and removed from the data.
- **Coherent betatron oscillation (CBO)** – potential fake EDM, max uncertainty quantified.



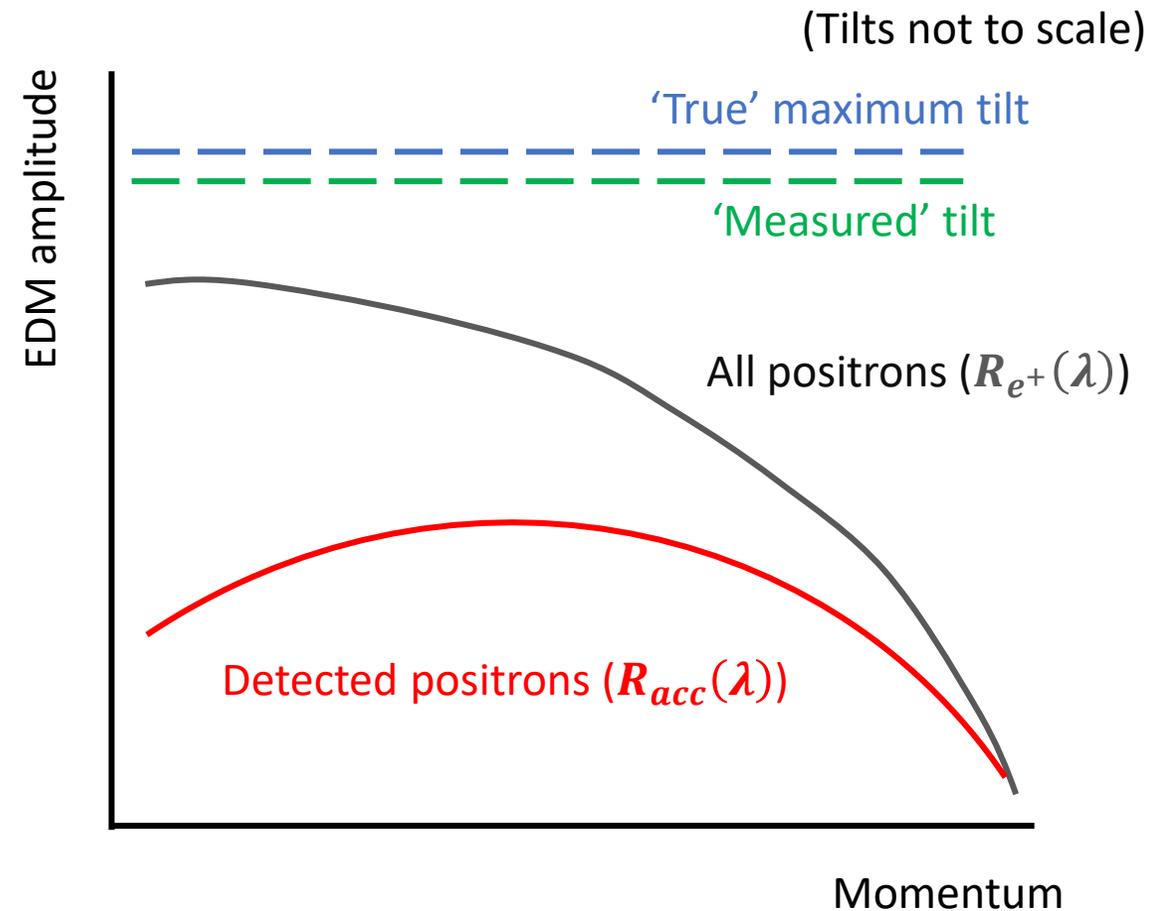
Reductions to the measured vertical angle



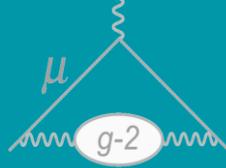
- The vertical angle measurable in the trackers is reduced by four effects:

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

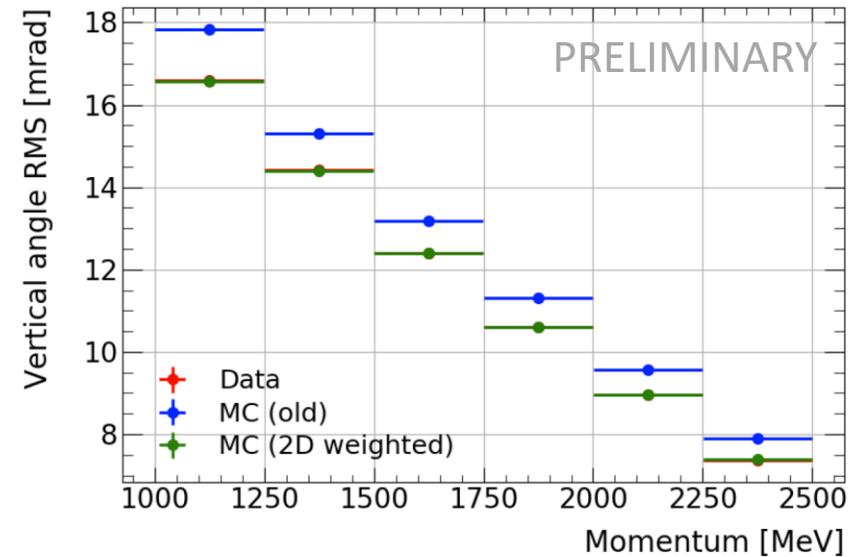
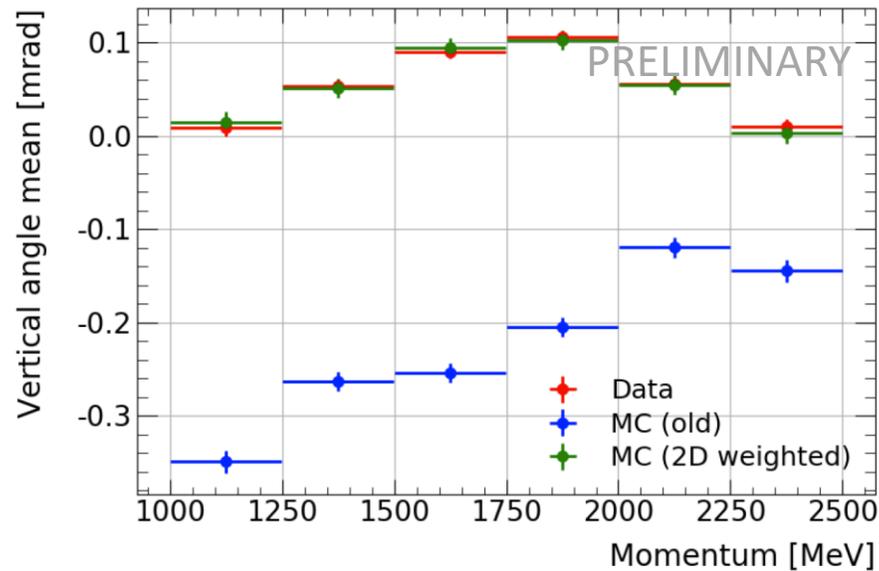
- R_γ : boost factor from muon rest frame to lab frame.
 - Factor is $1/\gamma$, so $\sim 1/29$.
- R_p : beam polarization reduction (as is $< 100\%$).
- $R_{e^+}(\lambda)$: muon decay asymmetry shape.
 - Has an analytical form, $f(\lambda)$, where λ is fractional momentum, calculated up to first order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



Data/MC matching

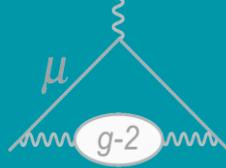


- Distributions in data and MC do not match perfectly, so a weighting is applied based on individual run period datasets to ensure the acceptance corrections are accurate.
 - Is a 2D weighting of vertical angle and detected beam vertical position, applied in the analysis momentum bins and interpolated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

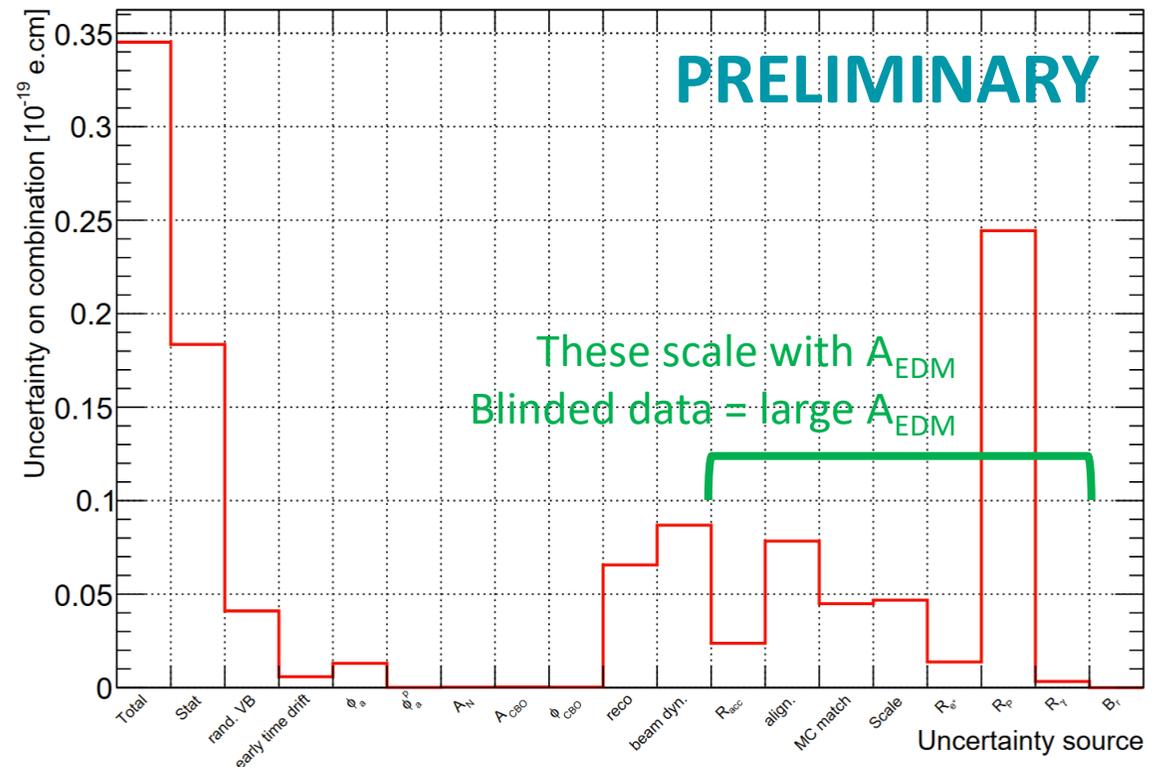


- All residual difference treated as a systematic uncertainty: small compared to the statistical uncertainty (<1%).

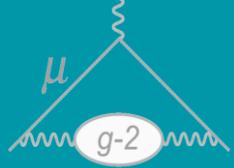
Systematic uncertainties



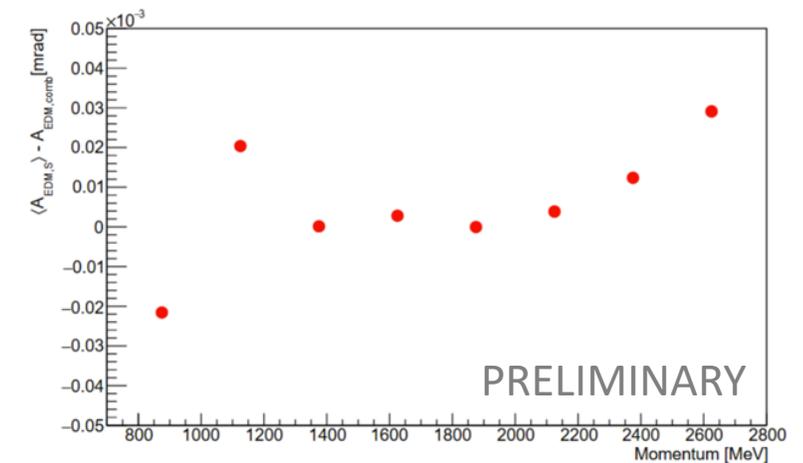
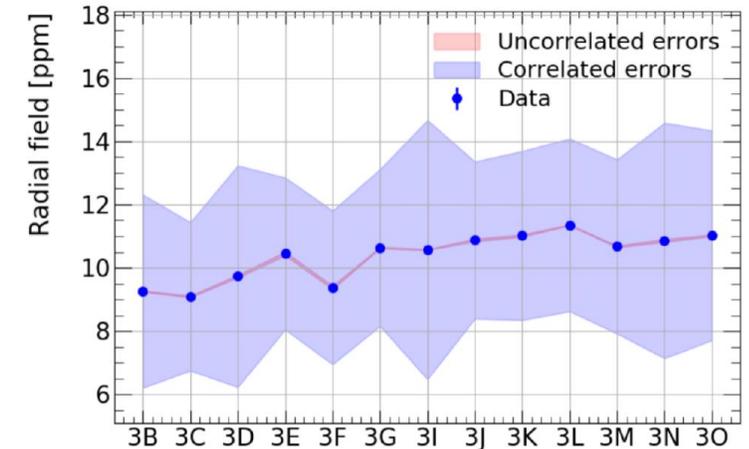
- Analysis is statistically limited – stat. unc is $\sim 2x$ larger than any of the systematics.
- Largest systematics all roughly comparable:
 - Uncertainty in track reconstruction (reco).
 - Impact of CBO beam oscillation (beam dyn).
- Align and R_p scale with measured A_{EDM} – currently, large blinding EDM, so will reduce.
 - Both also currently undergoing extra studies which may improve our understanding.
- Expect beam dynamics uncertainty to be our largest after unblinding.



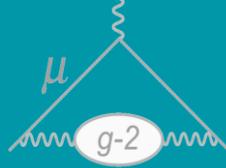
Controlling 'fake EDM' signals



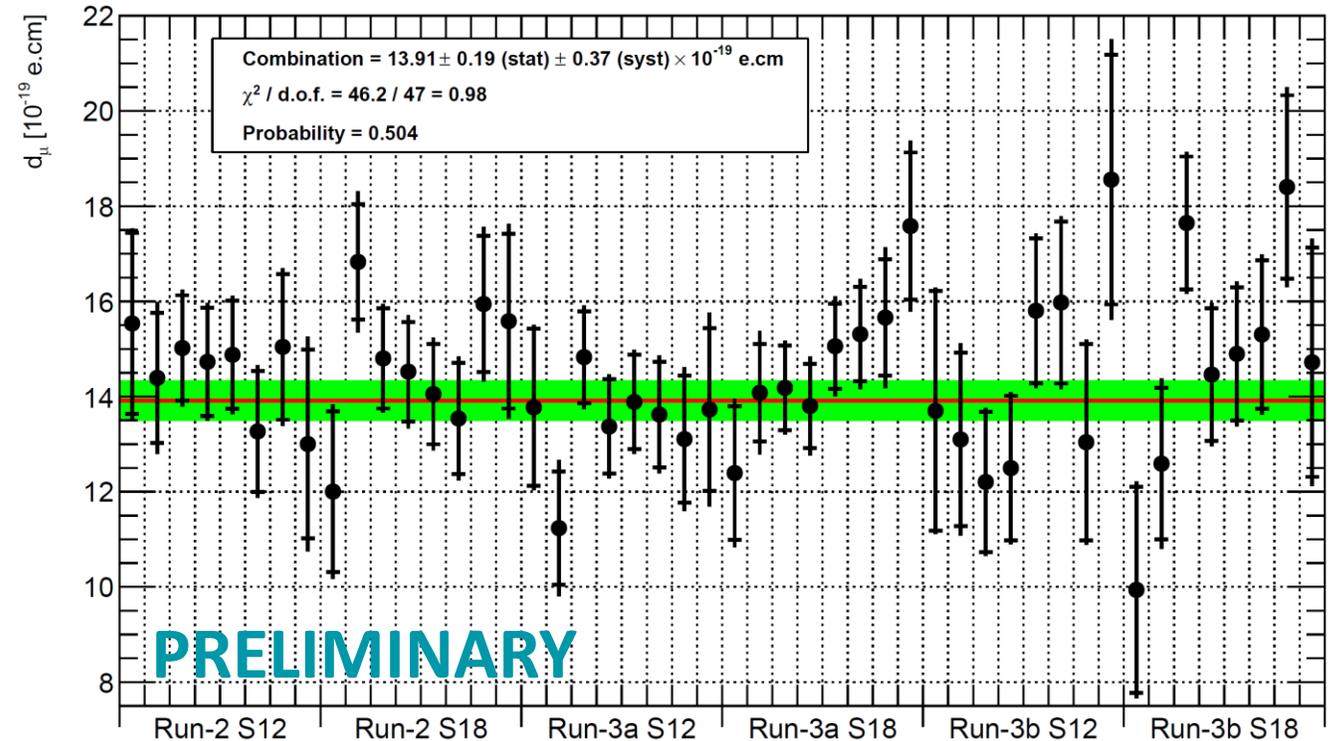
- Radial field
 - Non-zero radial field tilts precession plane – fake EDM!
 - Radial field scans, to measure to within 1ppm uncertainty – successful!
 - Small effect, at $\sim 10^{-22}$ e.cm level
- CBO
 - Acceptance couples radial/vertical beam motion, so the CBO could also introduce a fake EDM.
 - Difference across stations used to quantify maximum possible impact + cross-checked in MC.
 - Potentially large effect, accounted for as uncertainty.



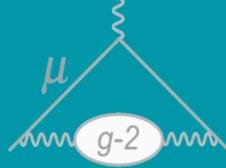
Preliminary blinded Run 2/3 results



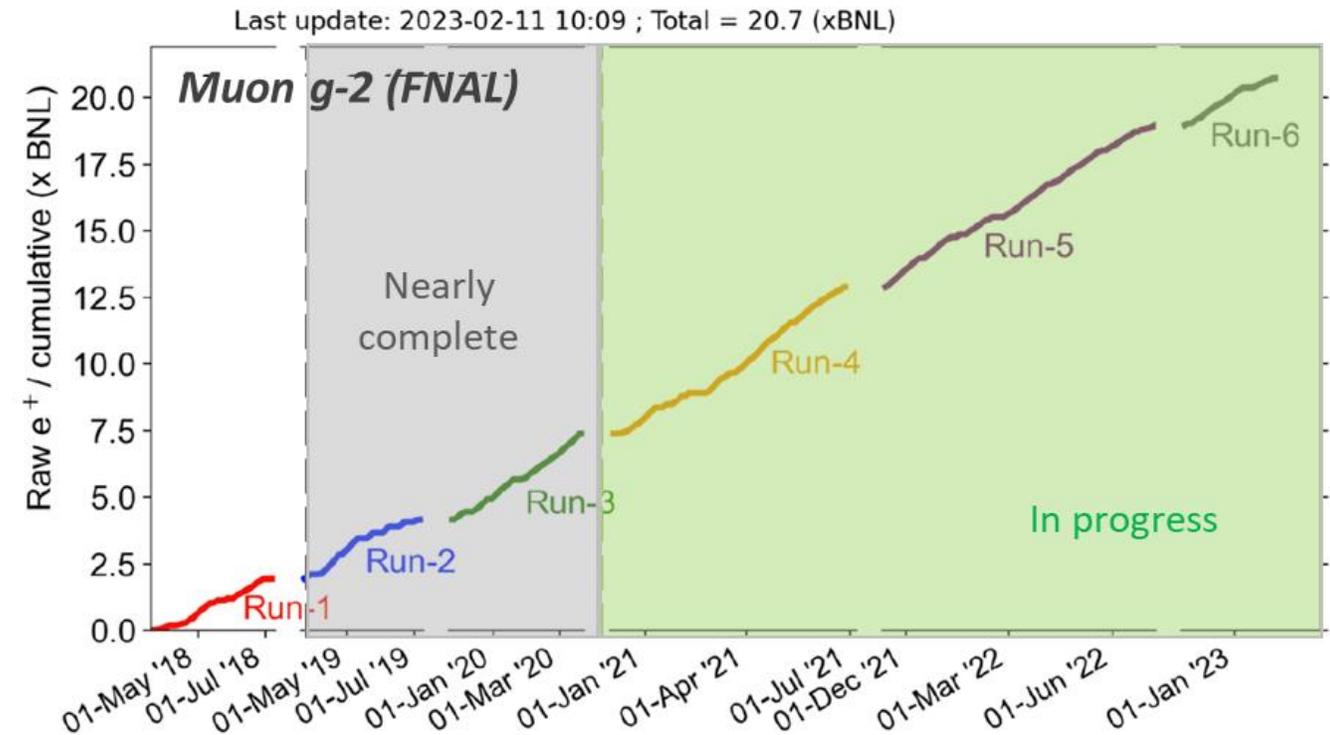
- All results still globally blinded – during analysis, each run period blinded separately.
- Relative unblinding of Run 2/3 performed recently: results show good agreement.
- Assuming central value = 0 after unblinding, gives a limit of $3.3 \times 10^{-20} e \cdot cm$ – **5.5x improvement vs BNL.**
 - Is the ‘best case scenario’, in practice a nonzero d_μ will increase this.

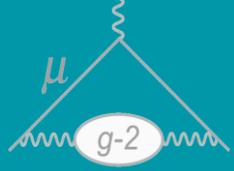


Timelines for FNAL analysis



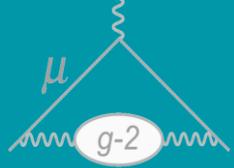
- Run 2/3: analysis mostly complete, in collaboration review
 - Expect results this year!
 - Best possible limit is $\sim 5.5x$ better than BNL limit in the absence of observed signal.
- Run 4/5/6 + full dataset:
 - Analysis started, $\sim 4x$ as much data as Run 2/3.
 - Final result will be a combination of runs 2-6.
 - Expected to improve on BNL limit by \sim an order of magnitude.



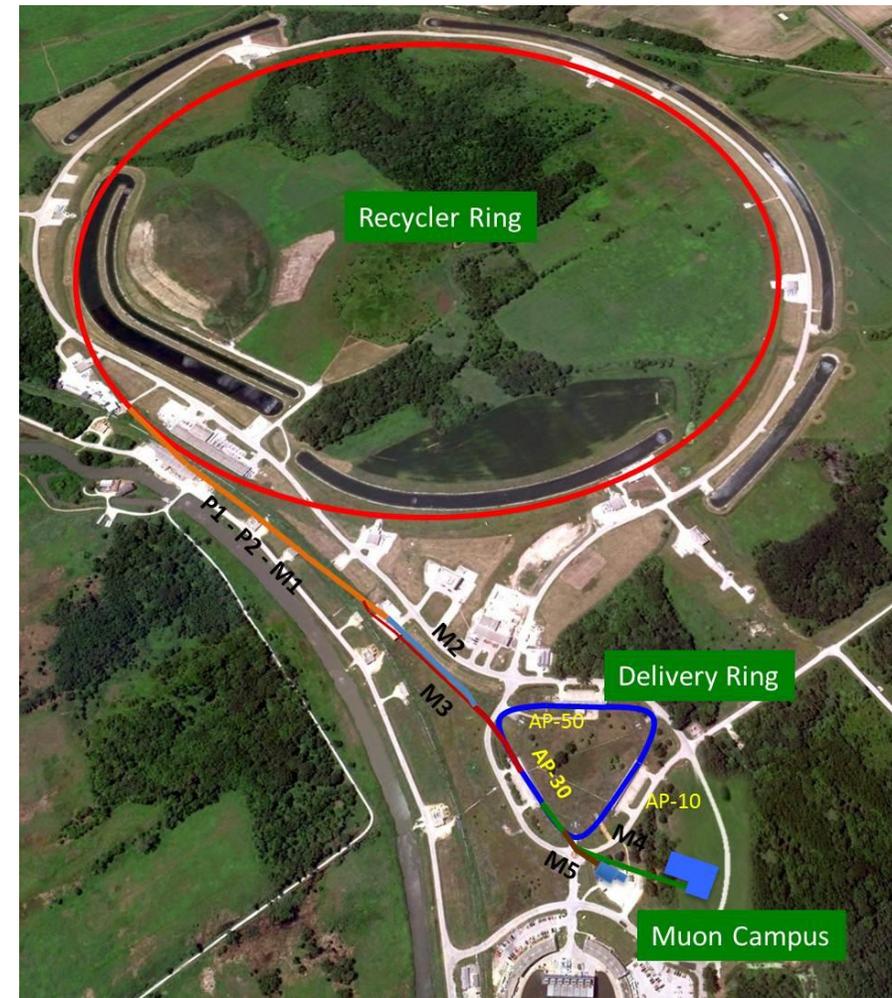


Bonus slides

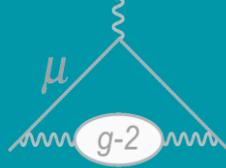
Fermilab muon beamline



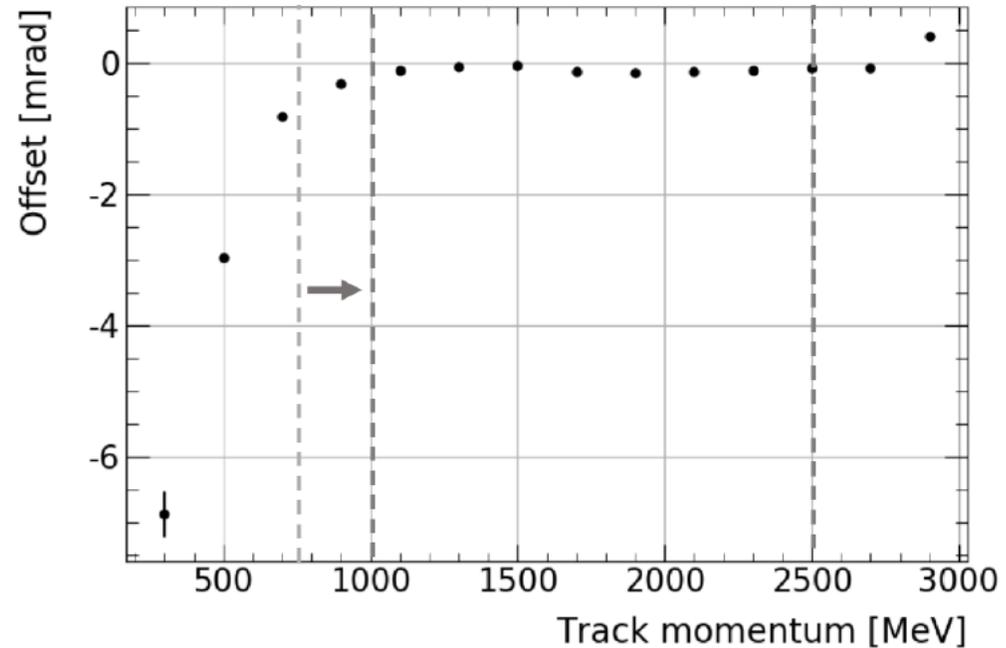
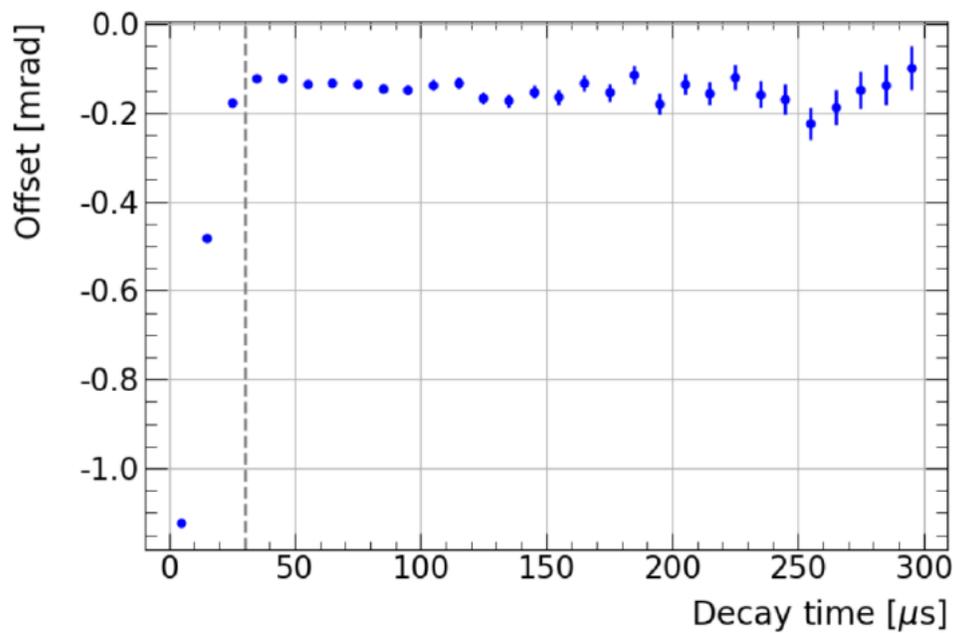
- Protons incident on a target make pions.
- Pions are stored in the delivery ring until they decay into muons.
- Muons injected into our ring.



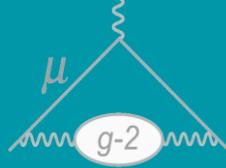
Analysis cuts



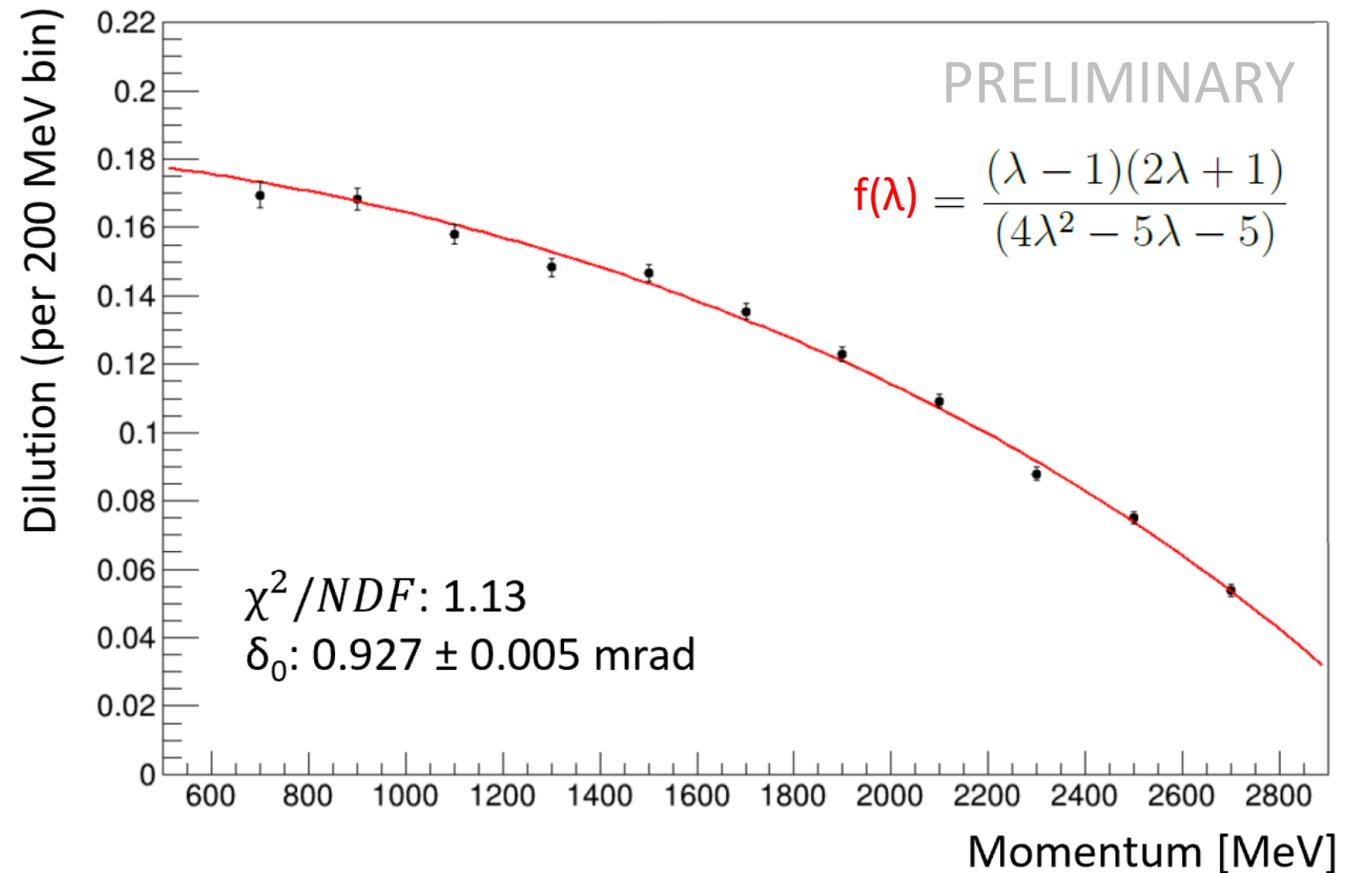
- Most sensitive to an EDM in the mid-momentum ranges, so cut to maximise that sensitivity.
- Cut on time to minimise beam dynamics effects at early times, and statistical fluctuations at late times.



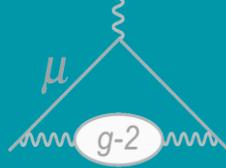
Momentum dependence ($R_{e^+}(\lambda)$) factor



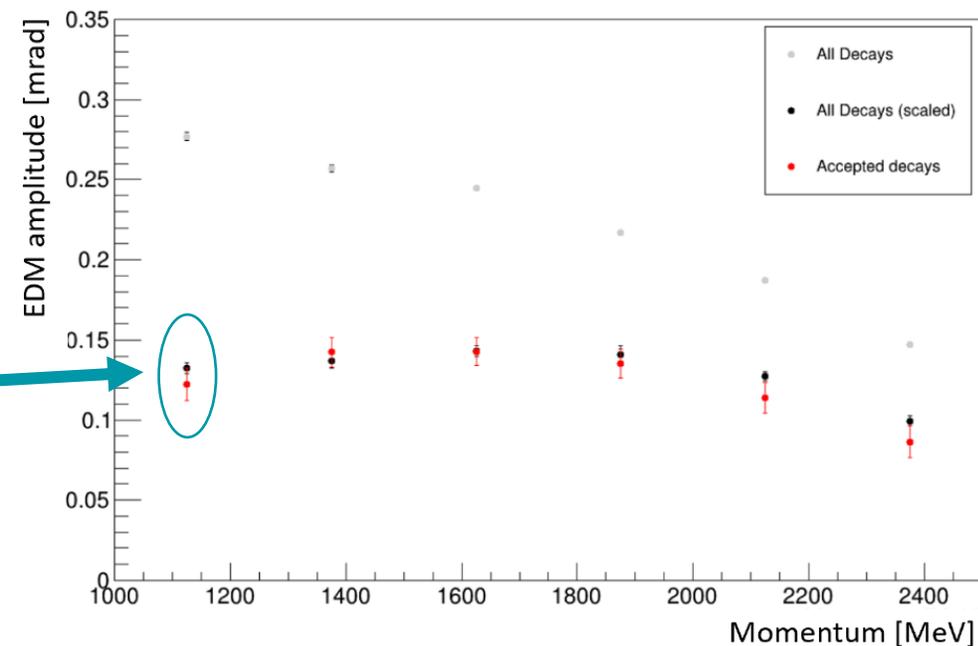
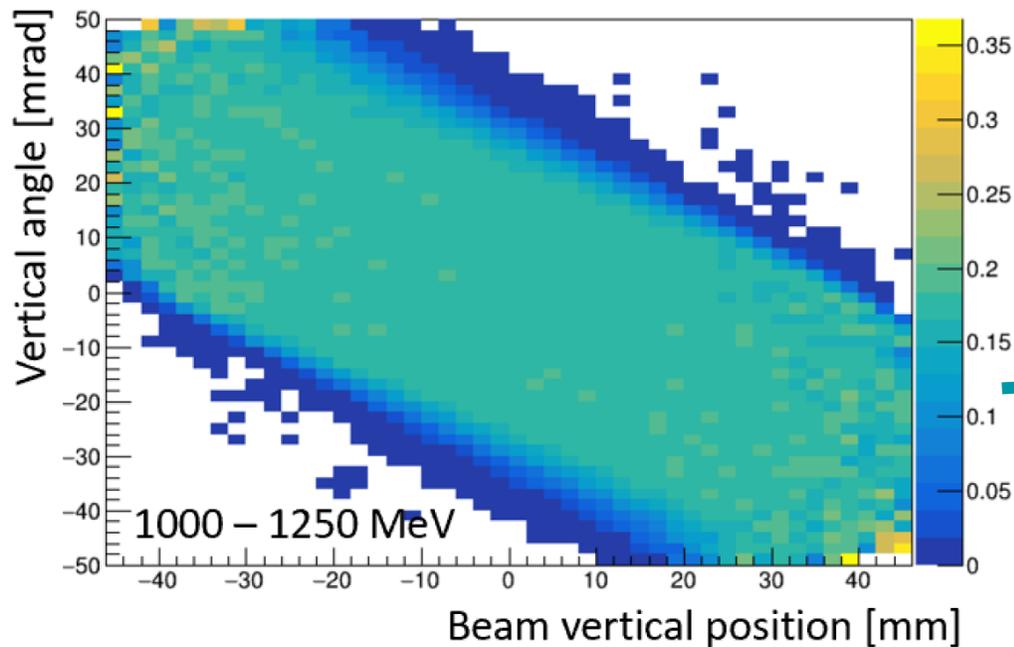
- Analytical form is only first-order: radiative corrections lead to a small reduction in the tilt seen.
- Currently, extract this from MC by plotting and fitting the 'all decays' sample:
- Now moving to an updated function that includes the radiative corrections – but still fit to account for higher-order terms.



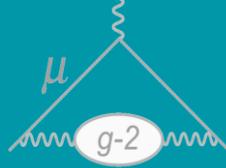
Acceptance ($R_{acc}(\lambda)$) factor



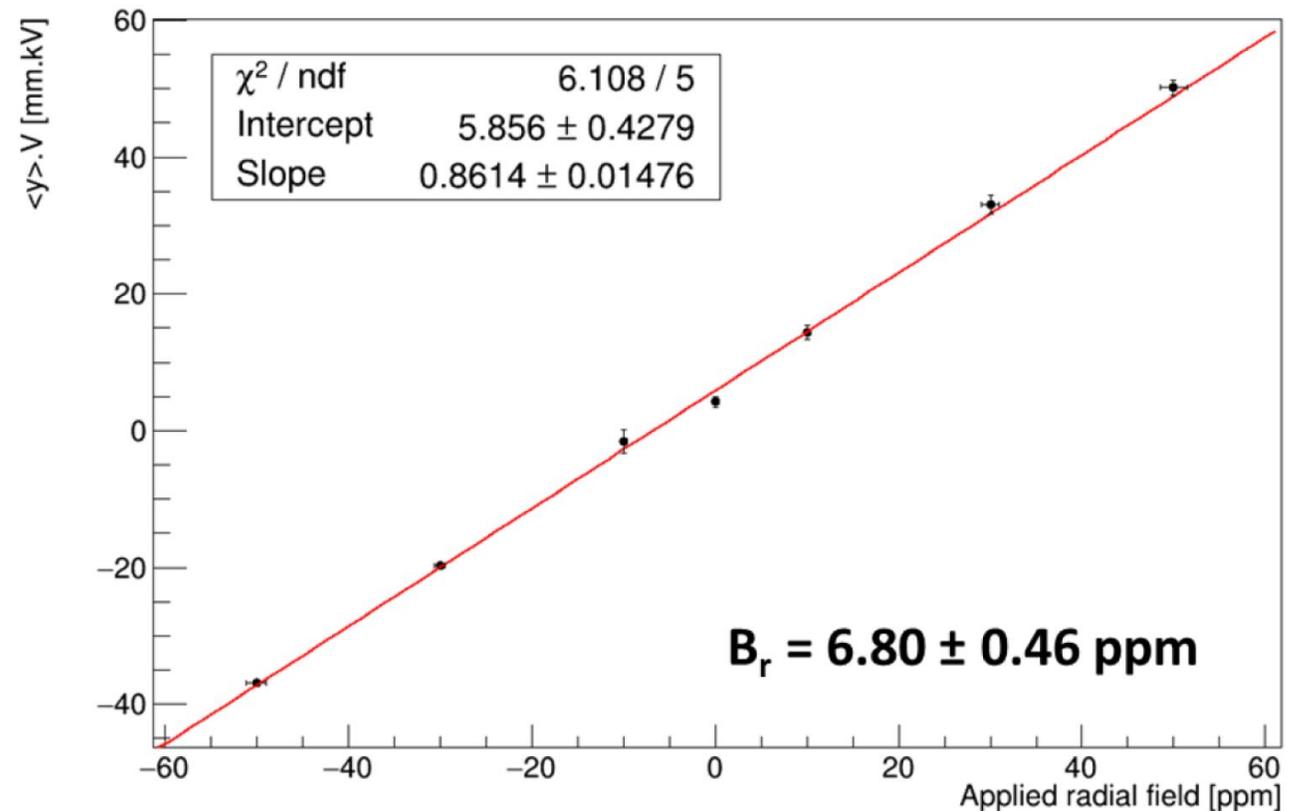
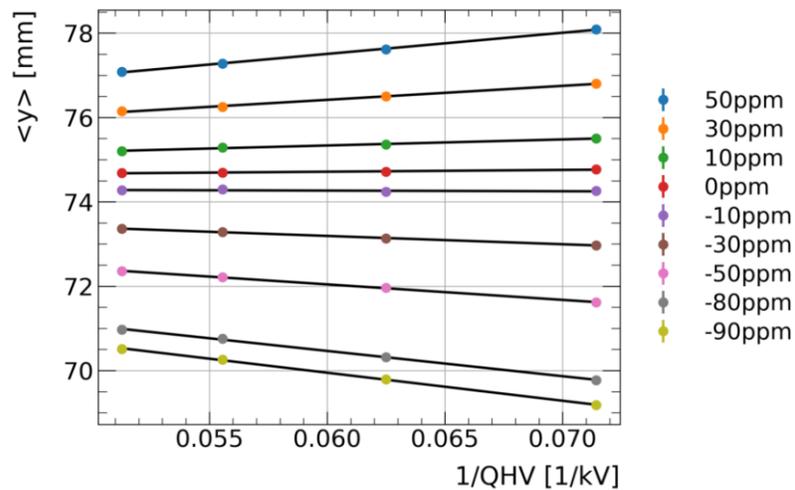
- The ratio of tracker-detected decays to all decays gives $R_{acc}(\lambda)$: used for Run 1.
 - Low stats due to low numbers of decays hitting the tracker, but is \ll the statistical uncertainty for Run 1.
- For Run 2/3, 2D maps in momentum bins to apply the shape without the overall reduction in stats- \sim 3x smaller uncertainties.



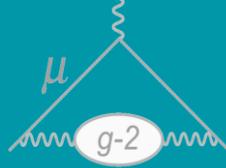
The radial field - measurement



- 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.
 - ~ 1 ppm is achievable by performing a radial field scan:



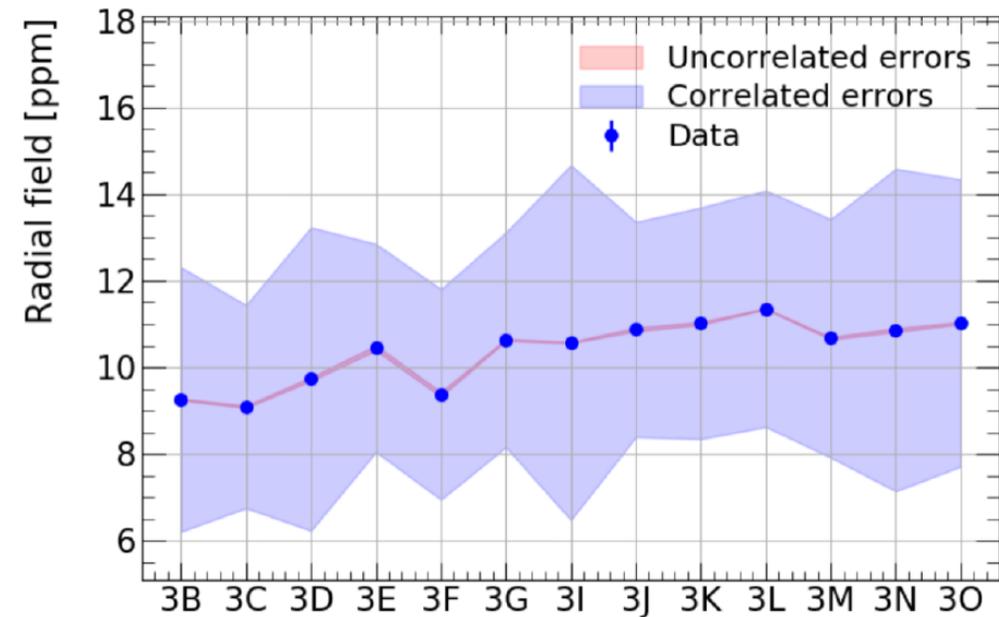
Radial field - results



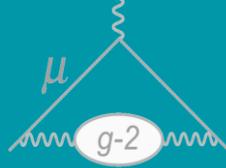
- Scans are performed in Run 4/5/6 – so need to extrapolate the measurements to Runs 1/2/3 using the vertical beam position.
- Sufficient precision for this to not be the limiting systematic.

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

S. Grant



Analysis cross-checks



- CBO/other 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
- Toy MC studies on potential fake EDM signals
 - Aim is to set limits on anything that might induce a fake EDM signal, for example a combination of misalignment and tracker acceptance
 - All effects seen \ll statistical uncertainty.

