# Searching for a Muon EDM and measuring Muon g-2 at Fermilab

International Workshop on Muon Physics at the Intensity and Precision frontiers, 2025

Dominika Vasilkova

# The magnetic moment of the muon

- Charged particle in B field interacts via intrinsic magnetic moment:

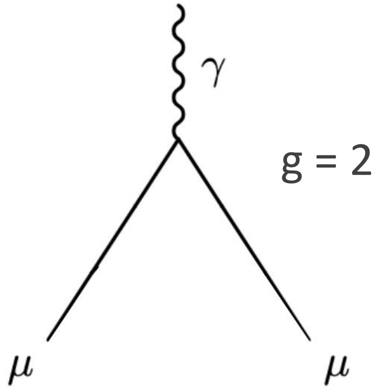
$$\vec{\mu} = g\frac{q}{2m}\vec{S}$$

- Dirac equation predicts g = 2 for spin ½ particles, but virtual particles in loops lead to corrections: **g > 2.**

- Unique indirect way to test precision of SM!

- We define the 'anomalous magnetic moment' and measure that: $a_\mu = \dfrac{g-2}{2}$

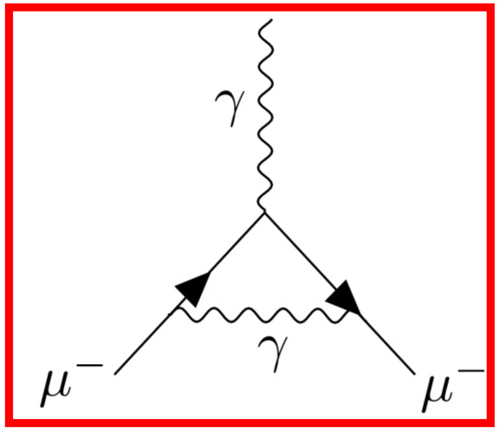
# Theoretical predictions of g-2 (2020 status)



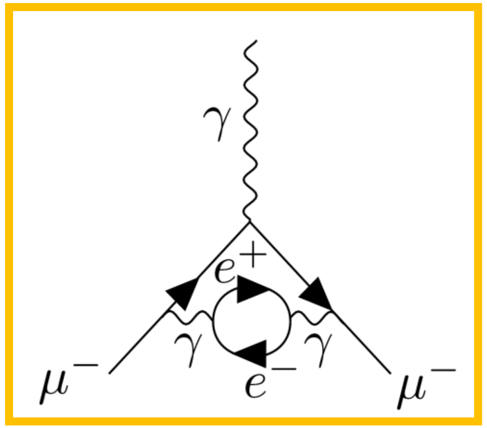

$a_\mu$ (SM) = 116591810(43) x $10^{-11}$

(Muon g-2 theory initiative: WP2020)

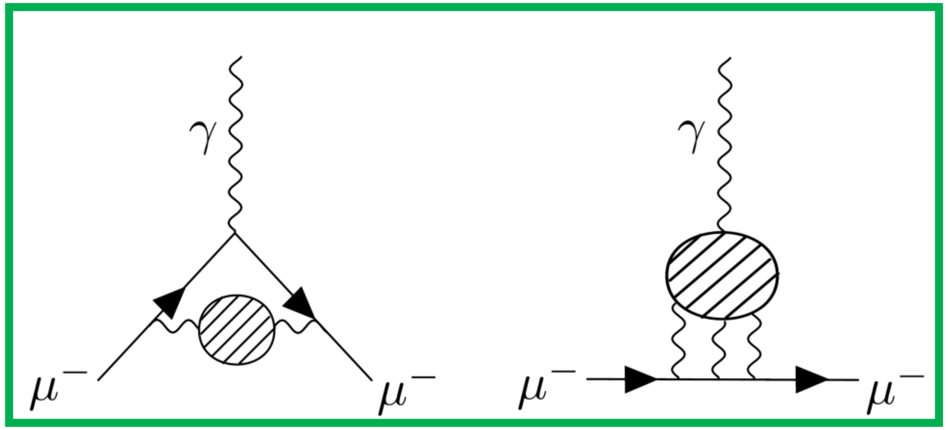
1st Order QED (Schwinger)



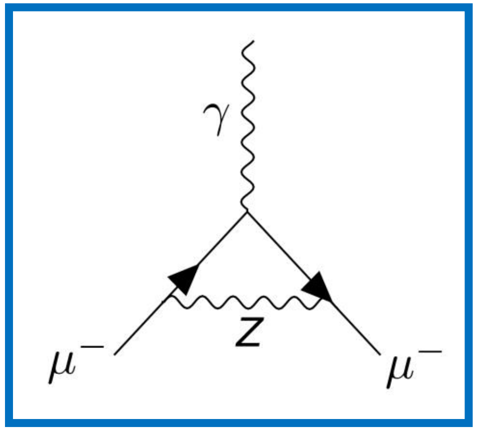

Higher order QED (Vacuum polarization)




Hadronic (HVP or HLBL)



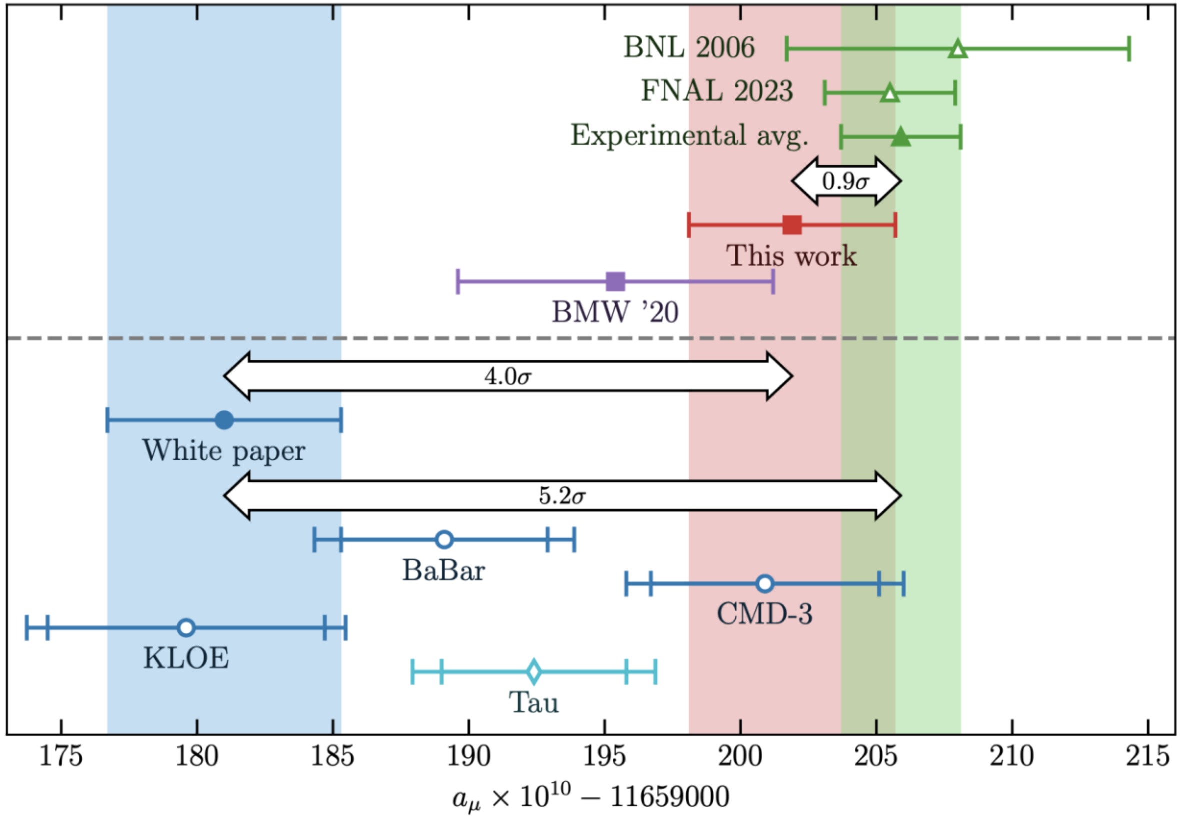

Electroweak




Uncertainties: ~ 0.1 x $10^{-11}$ HVP: ~ 40 x $10^{-11}$ HLBL: ~ 19 x $10^{-11}$ ~ 1 x $10^{-11}$

# Theoretical predictions of g-2

- Uncertainty dominated by HVP.
- Two methods to get this – dispersive methods (data-driven), and lattice QCD.
- In recent years, there has been a growing tension between these methods – allows for a 3-way comparison.
  - New CMD-3 result also in tension with data-driven methods.
  - Most recent lattice results are creeping towards the experimental prediction.




New lattice result from [Arxiv:2407.10913](https://arxiv.org/abs/2407.10913)

# Measuring $a_\mu$ in a storage ring

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

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

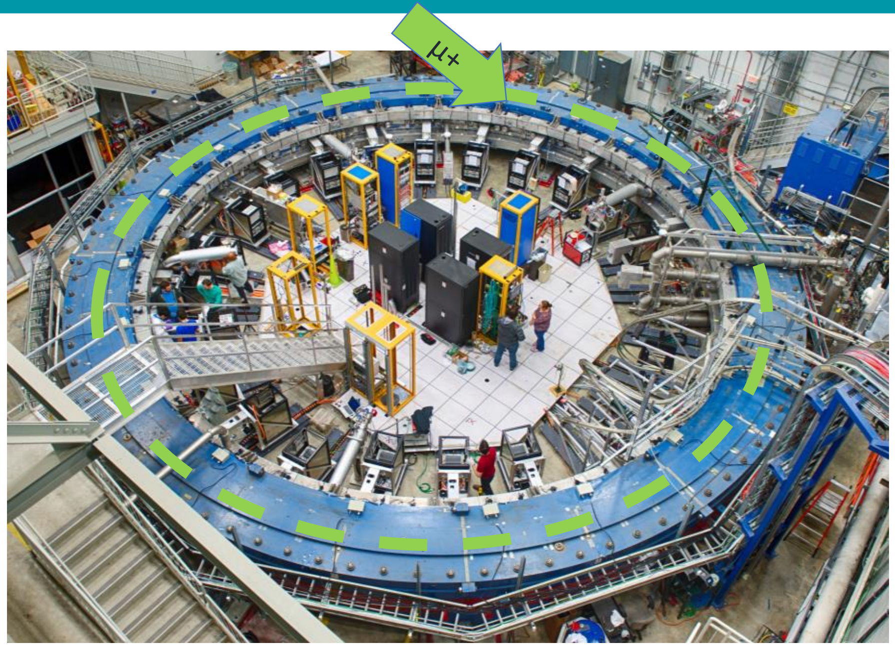
$$\omega_a = \omega_s - \omega_P \cong a_\mu \frac{eB}{m_\mu}$$

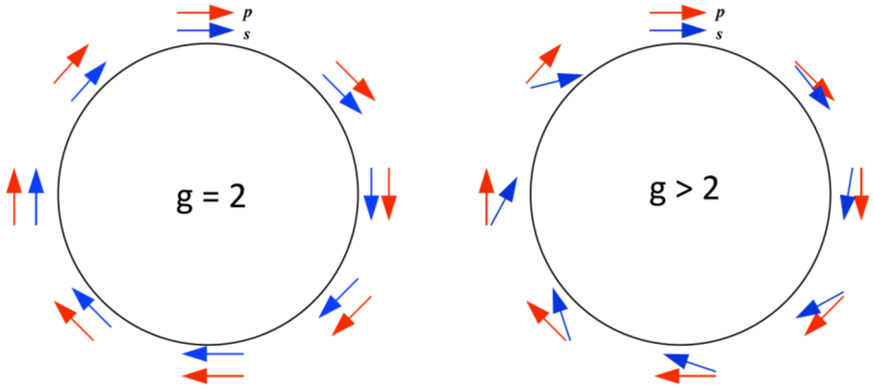
- If we also measure the field to high precision: can extract $a_\mu$.

$$a_\mu = \boxed{\frac{\omega_a}{\tilde{\omega}_p}} \boxed{\frac{g_e}{2} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e}}$$

Measured by us

Measured by other experiments



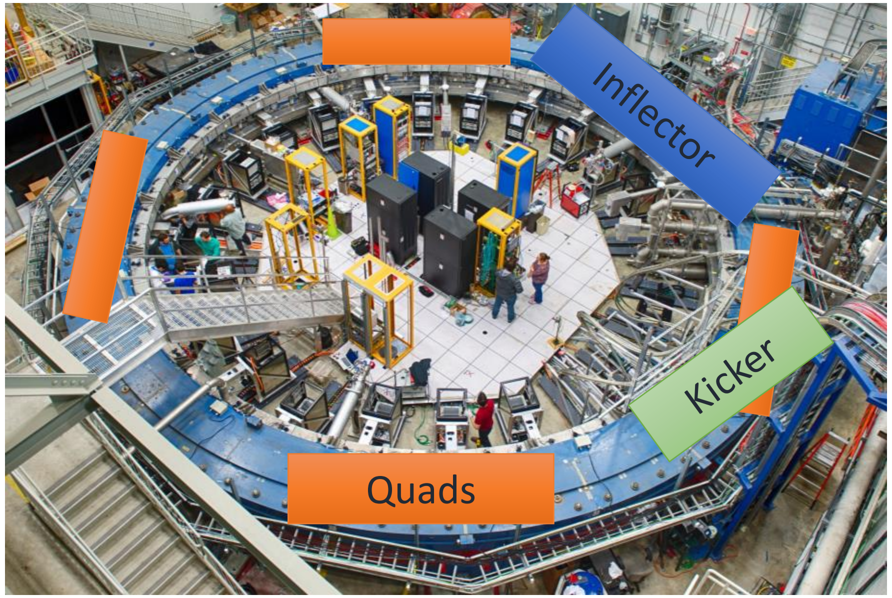
# Muon storage

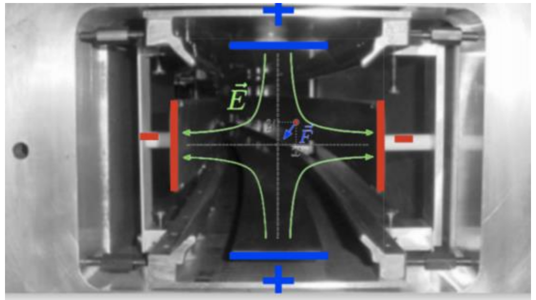
- Magnet: provides radial focusing + field for g-2.
- Inflector: Prevents large beam deflections.
  - Located at entrance to ring, cancels local B field.
- Kicker: Pushes incoming beam onto equilibrium orbit.
- Electrostatic quadrupoles: vertical focusing.

0 when in a flat plane

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

0 at the ‘magic momentum’ = 3.094 GeV

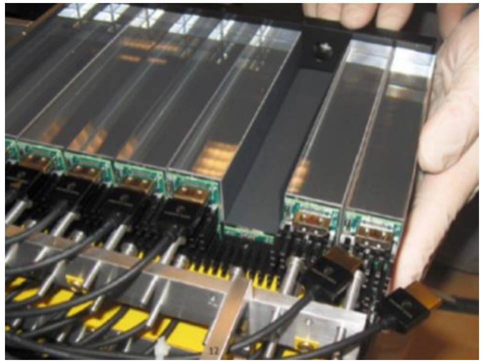


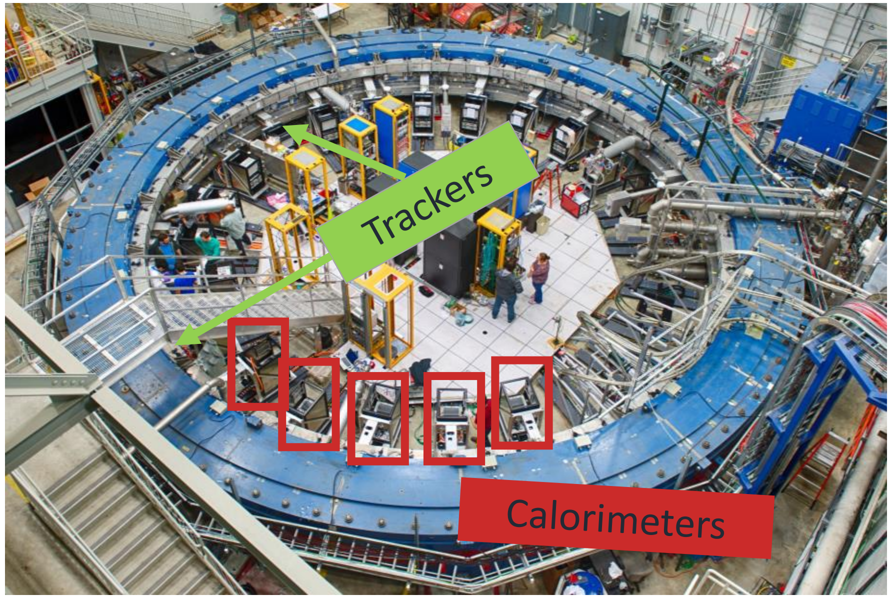



# Making measurements

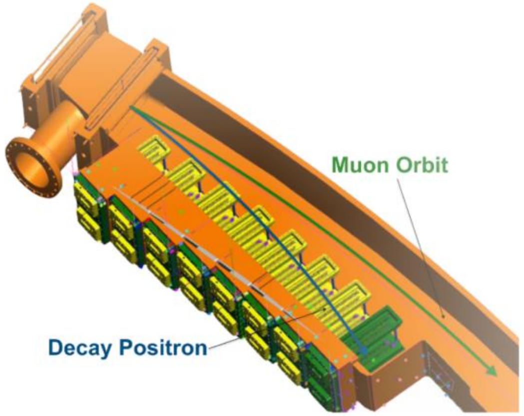
- Two main detector systems: calorimeters and trackers.

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






- 2 straw tracker stations:
  - 8 modules per station, 4 x 32 straws Ar:$C_2H_6$.
  - Beam dynamics and muon distribution.
  - Bonus analyses: e.g. muon EDM (more on this later!).



# Extracting $a_\mu$ from data

- All effects accounted for in the 'master formula' for $\omega_a / \tilde{\omega}_p{}'$ :

**blinding factor** **precession** **beam dynamics corrections**

$$\frac{\omega_a}{\tilde{\omega}_p{}'} = \frac{f_{clock}\, \omega_a^{meas} \left(1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd}\right)}{f_{calib} \left\langle \omega_p'(x,y,\phi) \times M(x,y,\phi) \right\rangle \left(1 + B_k + B_Q\right)}$$

**absolute field calibration** **magnetic field sampled by the muon distribution** **magnetic transient corrections**

# Blinding + fitting $\omega_a$

$$\frac{\omega_a}{\tilde{\omega}_p'} = \frac{\boxed{f_{clock}\,\omega_a^{meas}}\,(1+C_e+C_p+C_{ml}+C_{pa}+C_{dd})}{f_{calib}\,\langle\omega_p'(x,y,\phi)\times M(x,y,\phi)\rangle\,(1+B_k+B_Q)}$$

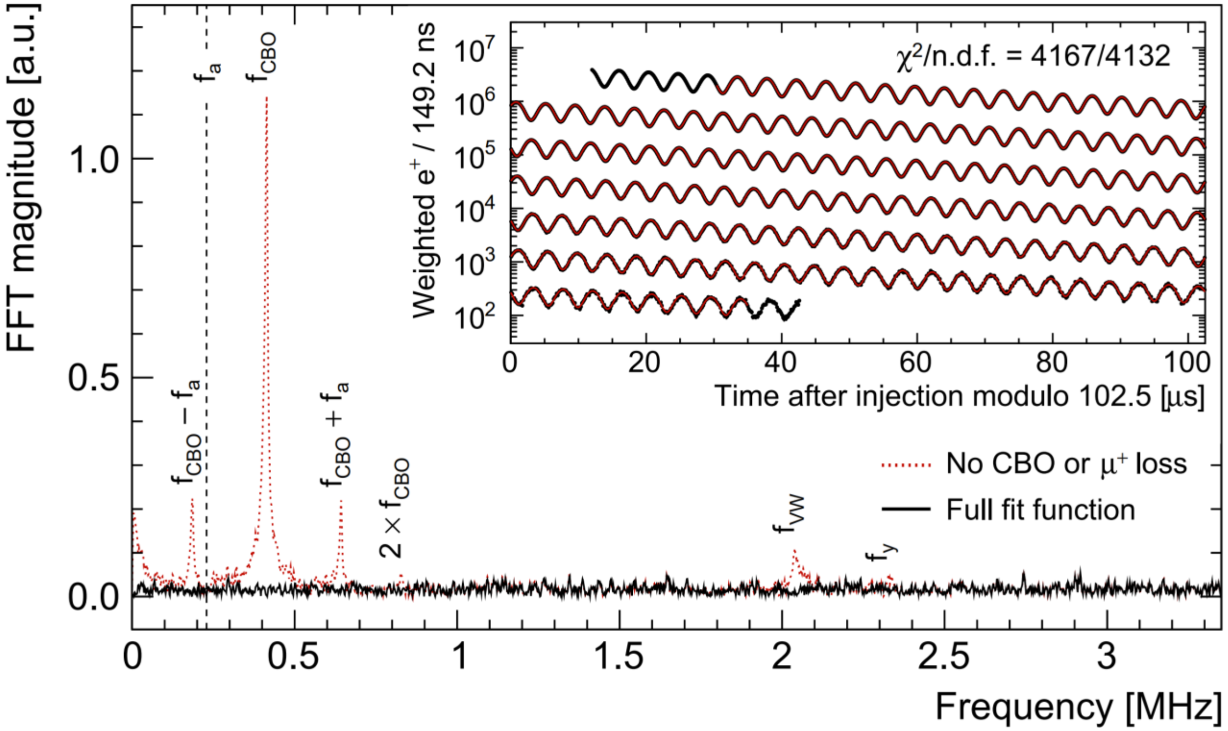
- To avoid bias, we blind the frequency at a hardware and software level.
  - Relative unblinding at software level used to check consistency.

- Parity violating decay – high energy positrons emitted preferentially along spin direction.

- $\omega_a$ extracted from the wiggle plot using ~ 30 fit parameters.
  - Basic 5-parameter fit:

    $$N(t) = N_0 e^{-t/\tau}[1 + A\cos(\omega_a t + \phi)]$$

  - Extra parameters for beam motions, lost muon effects, slow-varying effects etc.



# Beam dynamics corrections

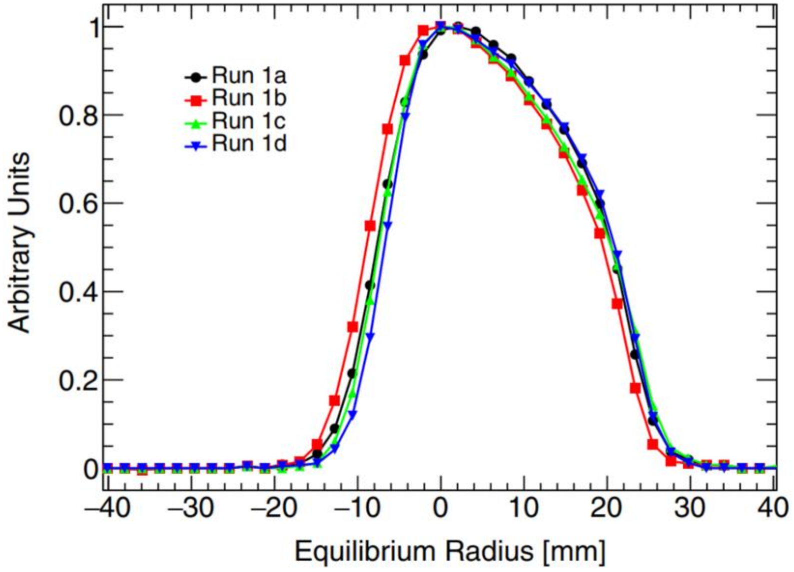
$$\frac{\omega_a}{\tilde{\omega}_p'} = \frac{f_{clock}\,\omega_a^{meas}\boxed{\left(1+\ C_e + C_p + C_{ml} + C_{pa} + C_{dd}\right)}}{f_{calib}\,\langle \omega_p'(x,y,\phi) \times M(x,y,\phi)\rangle \left(1+\ B_k +\ B_Q\right)}$$

- E-field correction ($C_e$) and pitch correction ($C_p$):
  - Spread in muon momentum values/ vertical betatron oscillations make these not exactly 0.

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

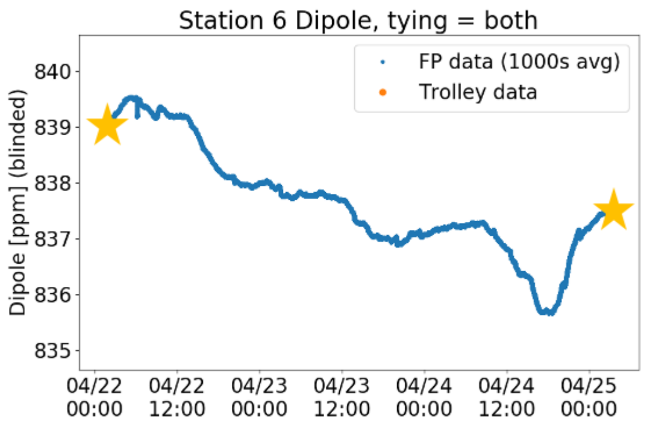



- Muon loss ($C_{ml}$) , Phase acceptance ($C_{pa}$), Differential decay ($C_{dd}$).
  - Lost muons have a different phase, which can bias the overall fits.
  - Phase varies across beam, and boosted muon lifetime depends on the momentum.
  - These lead to time-varying phase.
- Quantify these using tracker data/MC simulation.

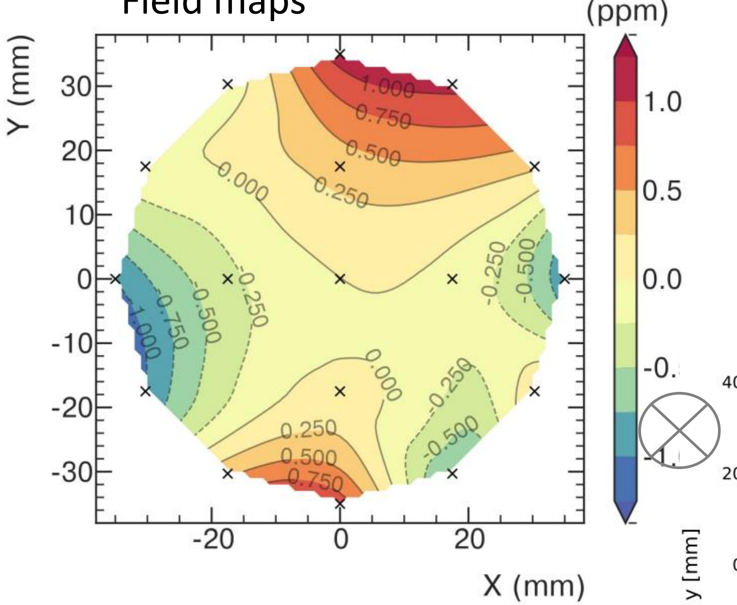
# Magnetic field measurements

$$\frac{\omega_a}{\tilde{\omega}_p{}'} = \frac{f_{clock}\,\omega_a^{meas}\,(1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd})}{\boxed{f_{calib}\,\langle \omega'_p(x,y,\phi) \times M(x,y,\phi)\rangle}\,(1 + B_k + B_Q)}$$

- Field is measured with a series of probes (on trolley and around ring) which need to be calibrated.
  - External $H_2$0 probe used with $He^3$ as a cross-check.
- Trolley measures field maps, then fixed probes monitor in between trolley runs.

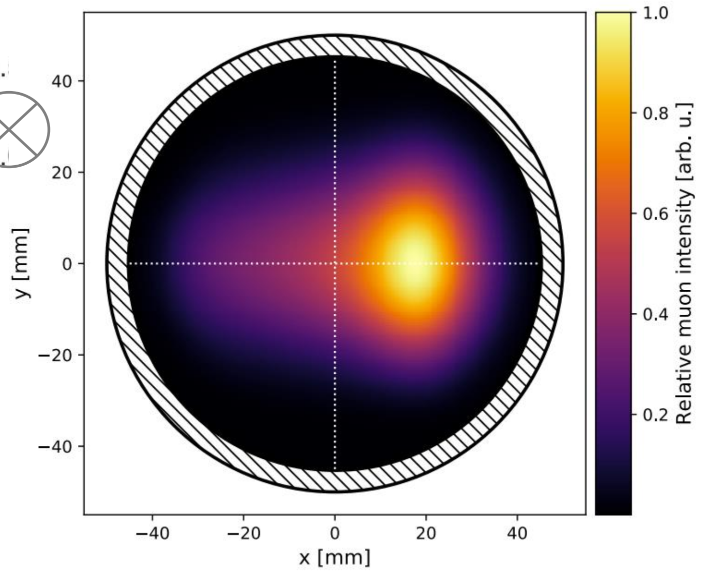



Field maps




- Need to know what field the muons 'see': so convolute with the beam measured by the trackers.

Muon distribution

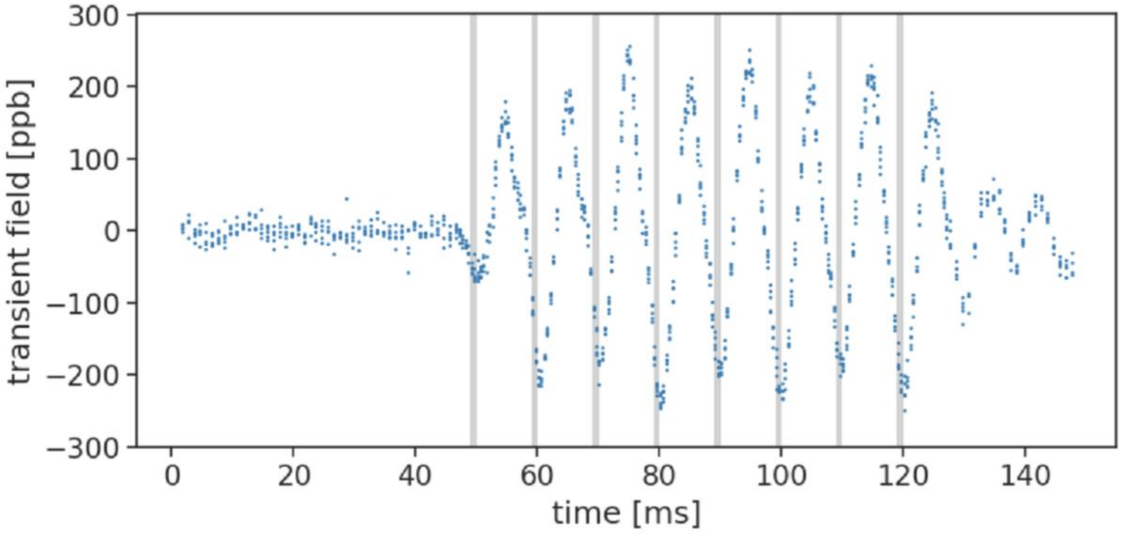


# Field transients

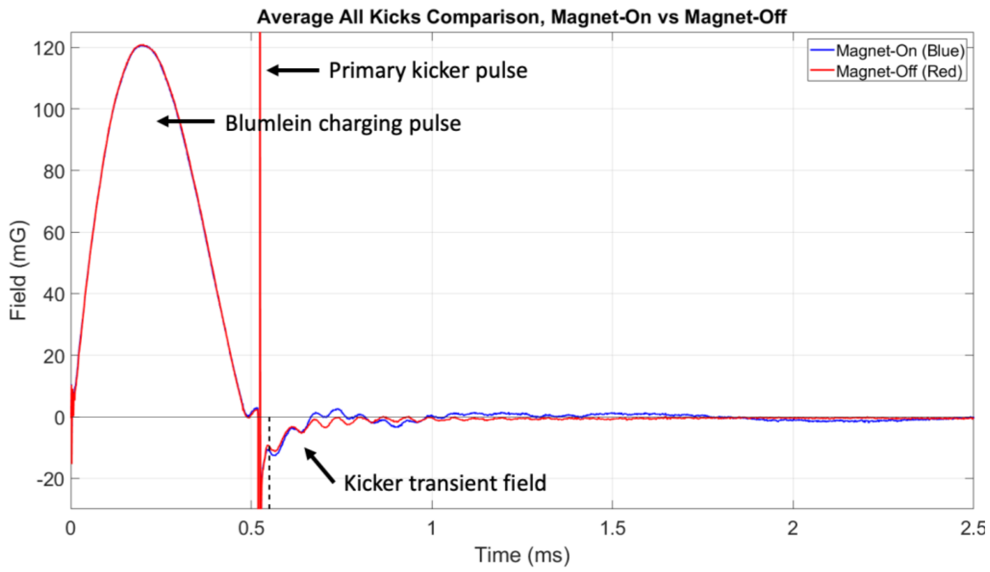
- Both kickers and the quadrupoles perturb the field:

$$\frac{\omega_a}{\tilde{\omega}_p{}'} = \frac{f_{clock}\,\omega_a^{meas}\left(1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd}\right)}{f_{calib}\,\langle \omega_p'(x,y,\phi) \times M(x,y,\phi)\rangle \boxed{\left(1 + B_k + B_Q\right)}}$$

**Quadrupoles introduce a mechanical vibration when charging/discharging:**




**Kickers cause eddy currents:**




- Both effects need to be accounted for to accurately get the field seen by the muons.
  - Run 1 had very large quad transients due to damaged resistors.

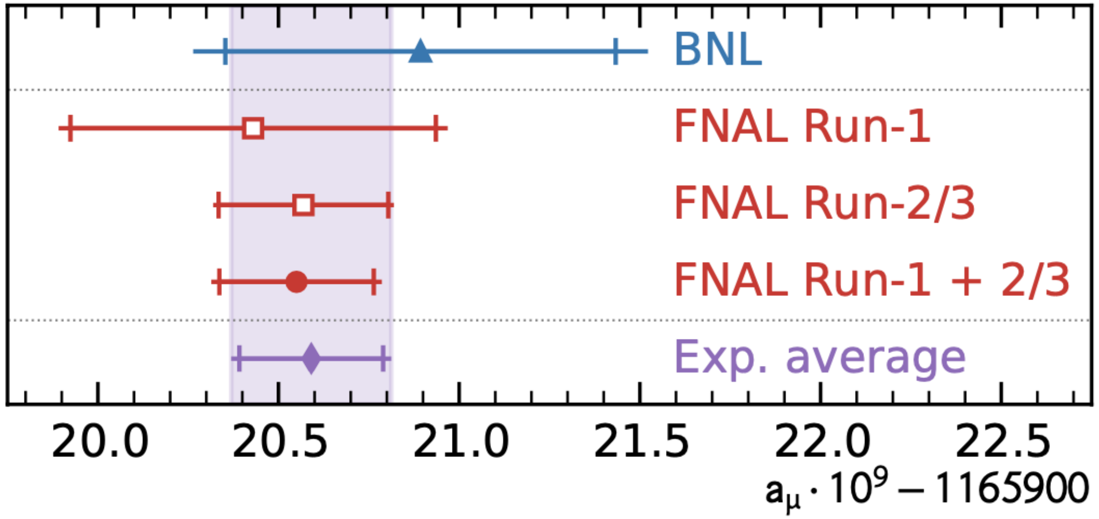
# Run 1/2/3 results + what's next?

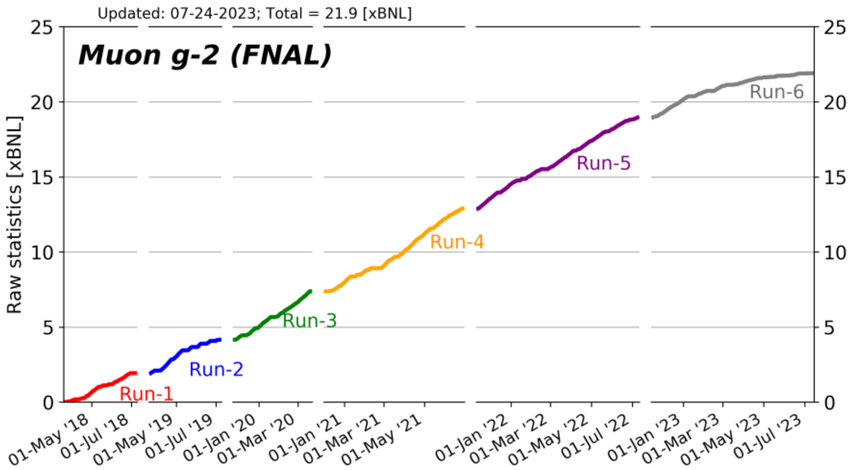
- Data collection ended in summer 2023, having successfully exceeded the statistical TDR goal (21xBNL).

- **Run 1:** 0.46 ppm precision, ~ 4.2σ away from the 2020 WP prediction.

- **Run 2/3:** 0.20 ppm precision, but… theory much less clear!
  - Many improvements both in data collection + analysis to reach this.

- **Run 4/5/6:** final result, coming soon (2025!), target 140 ppb uncertainty
  - Expecting a new theory WP to compare with.



# Muon EDM – why do we care?

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

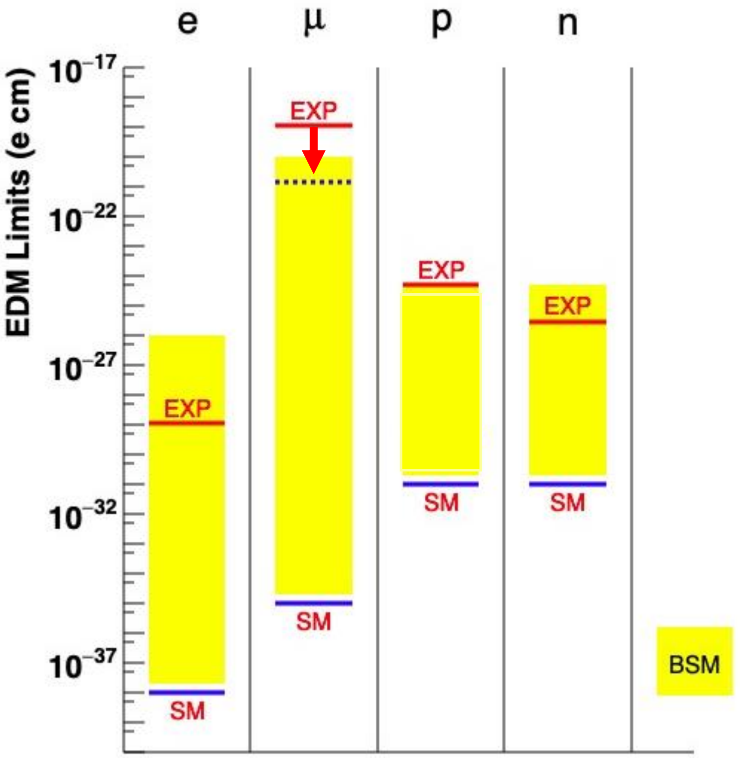
$$H = -\underbrace{\vec{\mu}\cdot\vec{B}}_{} + \underbrace{\vec{d}\cdot\vec{E}}_{}$$

**MDM:**

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

**EDM:**

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




- Why muon EDM?
  - SM muon EDM well below the range of current experiments.
  - **d.E** is CP-odd, so observation gives a **new source of CP violation** in the lepton sector.

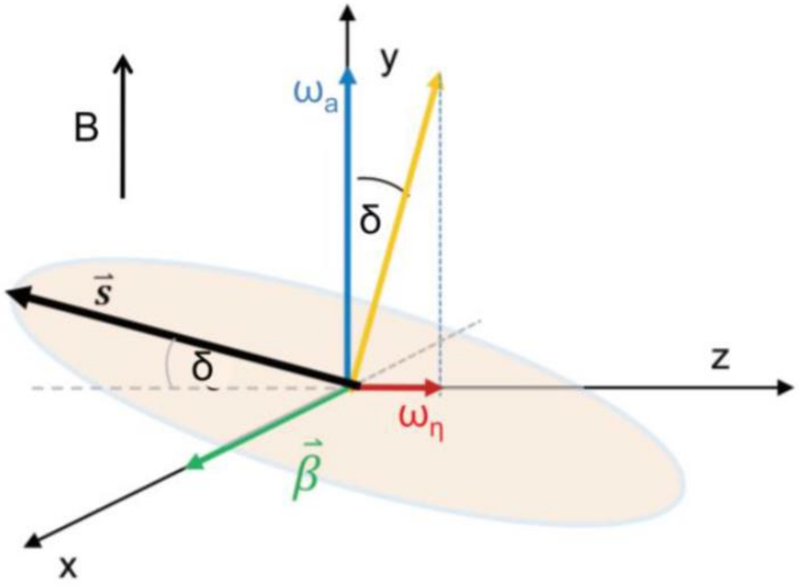
- Previous best direct limit was set at Brookhaven National Laboratory (BNL): **1.9** $\times$ **10**$^{-19}$ $\boldsymbol{e \cdot cm}$**.**

UNIVERSITY OF LIVERPOOL LEVERHULME TRUST

# Measuring a muon EDM in a storage ring

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

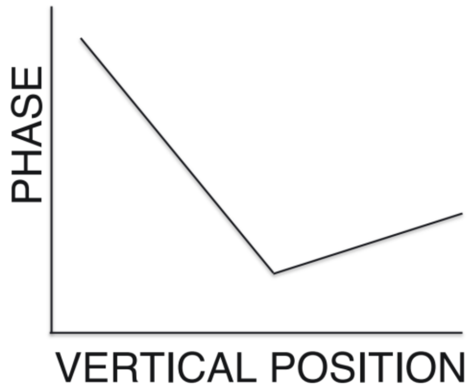
$$\vec{\omega} = -\frac{q}{m}\left[\underbrace{a_\mu \vec{B} + \left(\frac{1}{1-\gamma^2} - a_\mu\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{\text{g-2 precession } \vec{\omega}_a} + \underbrace{\frac{2d_\mu mc}{q\hbar}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)}_{\text{EDM precession }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




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

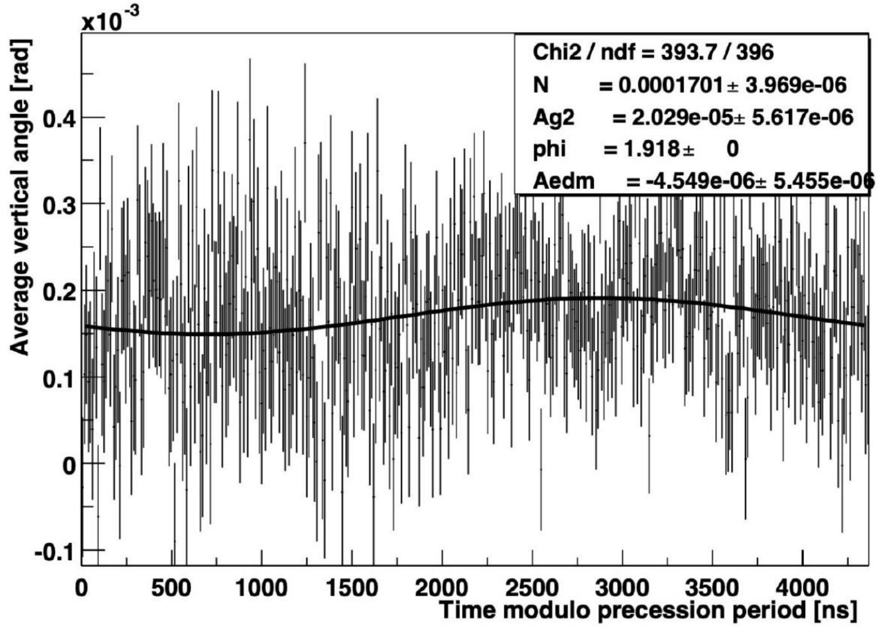
# EDM signals at Fermilab g-2

- **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.

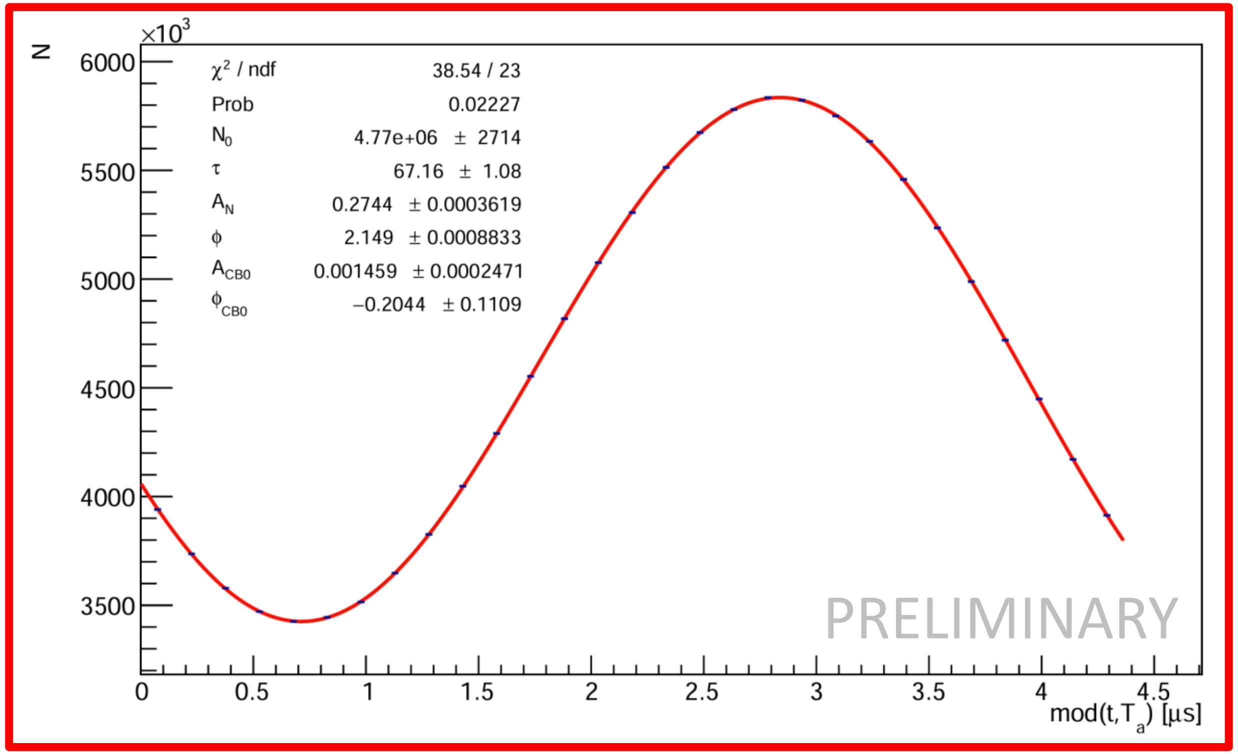
  - Best method for the FNAL setup!




BNL 2000 data

# Extracting the EDM signal

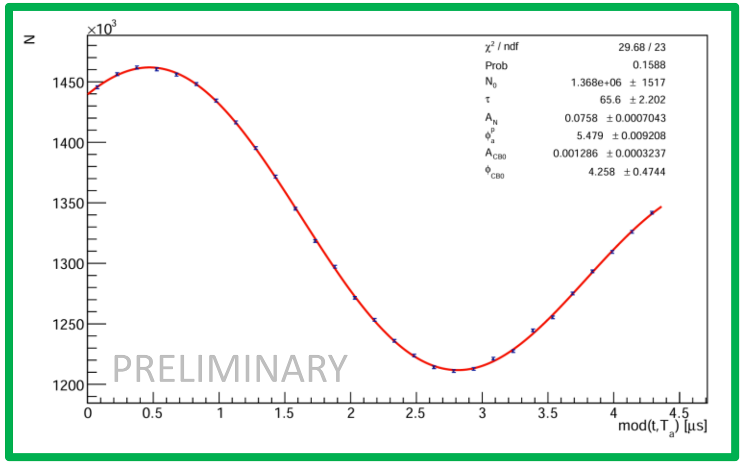
- First fit the g-2 oscillation: 9-parameter fit, includes $\omega_a$ and CBO.
  - Extract the phase of the g-2 oscillation.
  - Momentum cut > 1700 MeV.




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

# 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.



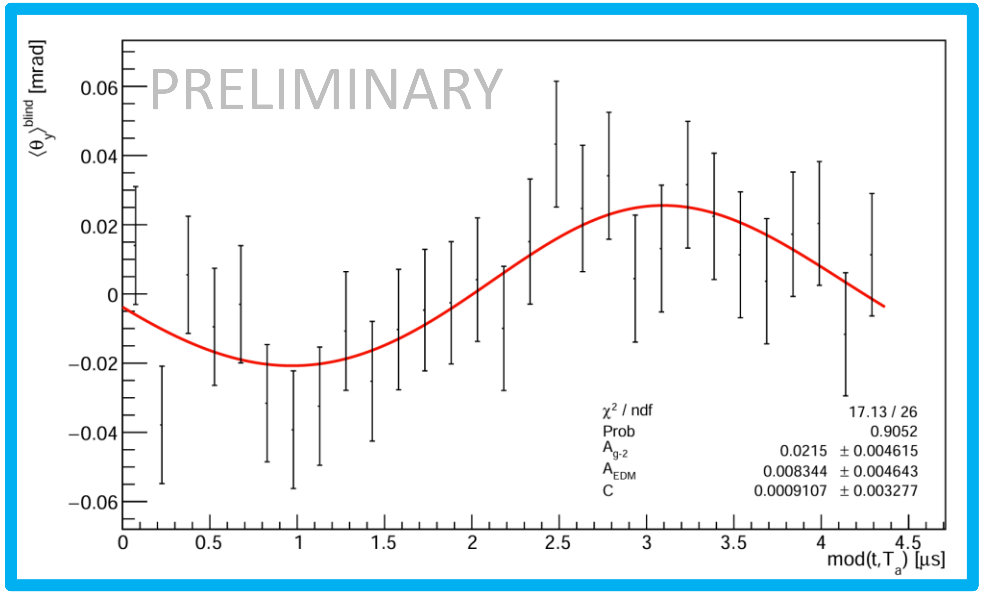

750-1000 MeV, Run 3b, s18

Phase from > 1700 MeV N(t) fit

EDM amplitude

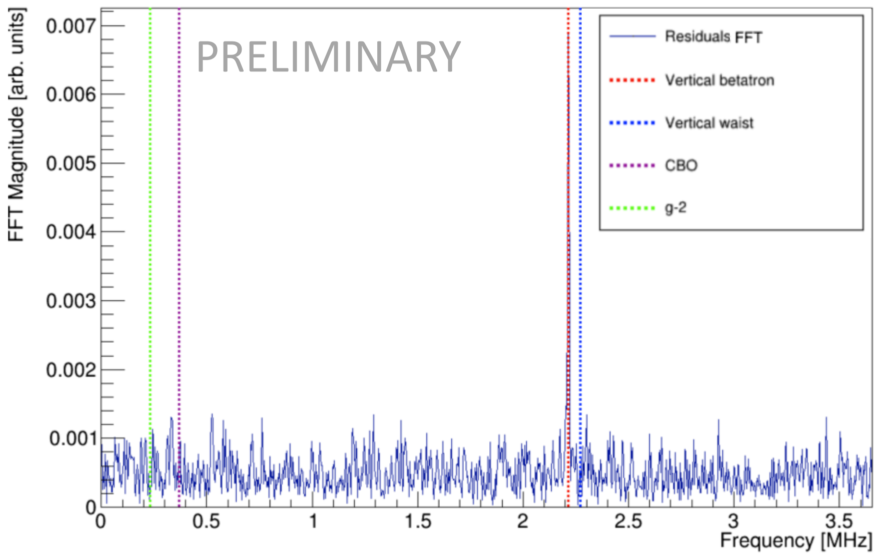
$$\langle\theta_y\rangle(t) = \frac{\boxed{A_{g-2}}\cos(\omega_a t + \boxed{\phi_a}) + \boxed{A_{\mathrm{EDM}}}\sin(\omega_a t + \boxed{\phi_a})}{\boxed{(1 + A_N\cos(\omega_a t + \phi_a^p))\,(1 + A_{\mathrm{CBO}}\cos(\omega_{\mathrm{CBO}} t + \phi_{\mathrm{CBO}}))}} \boxed{+\,C}$$

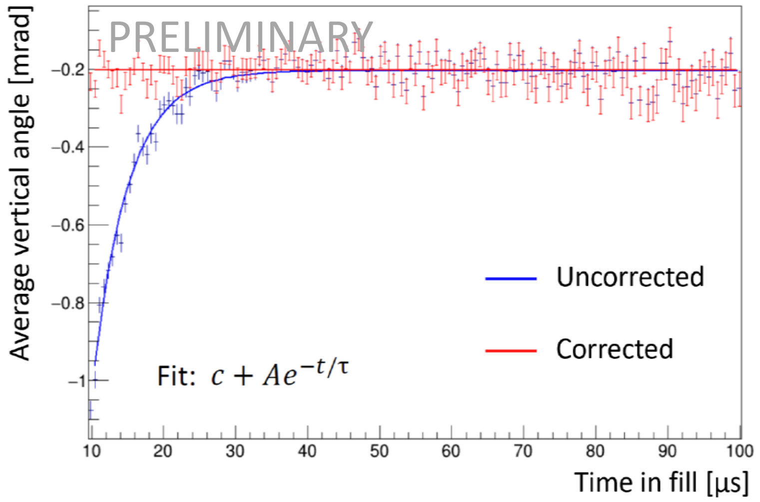
Momentum-binned N(t) fit parameters



# 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.
- Plots binned at the **cyclotron frequency** to remove any impact from that.



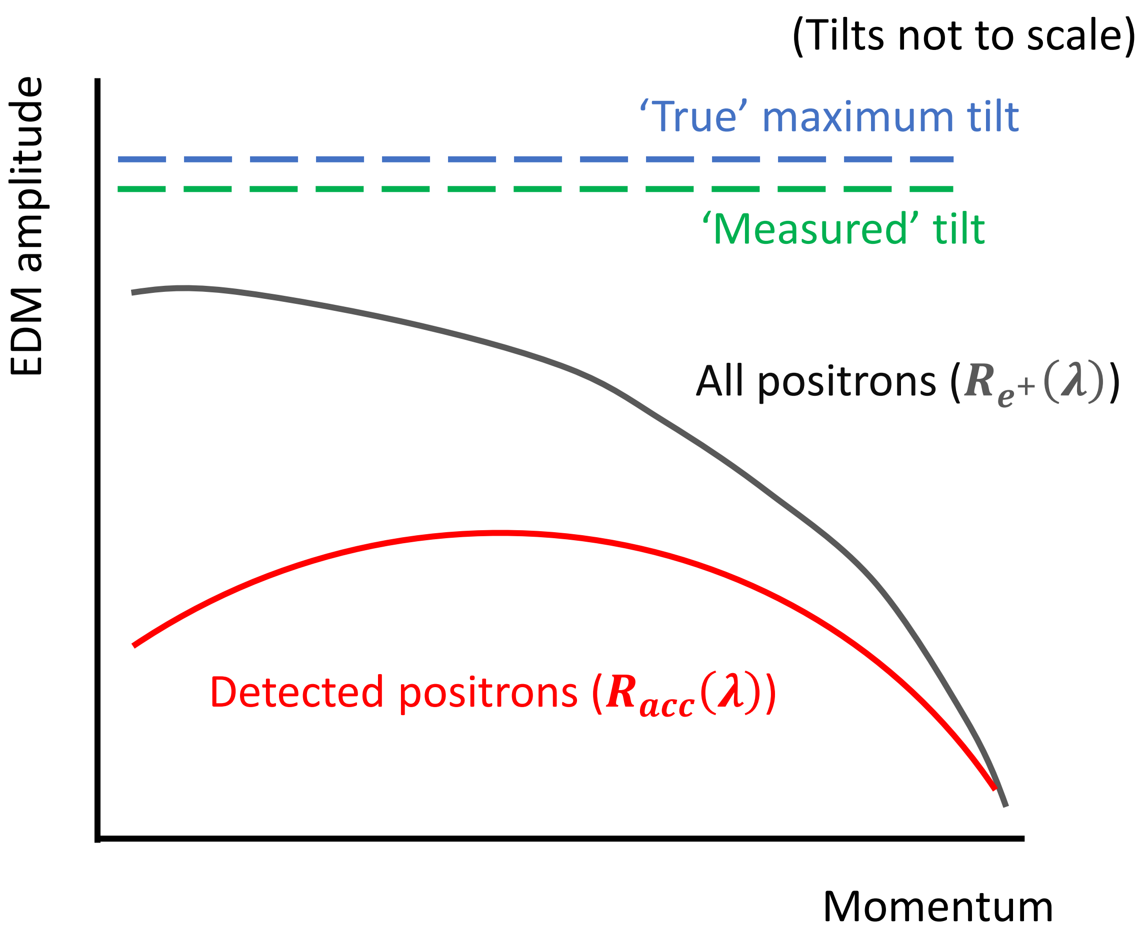



# Reductions to the measured vertical angle

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

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

- $R_\gamma$ : 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.



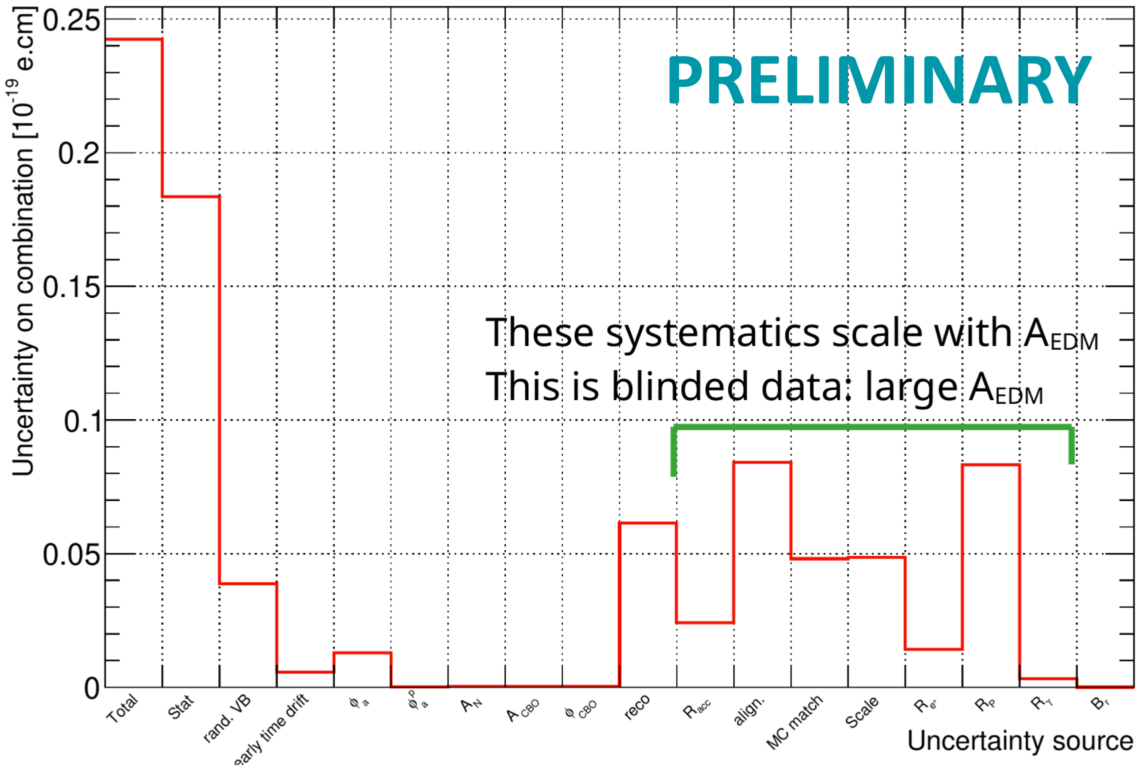
# Systematic uncertainties

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

- Largest systematics all roughly comparable:
  - Uncertainty in track reconstruction (reco).
  - Tracker alignment (align).
  - Beam polarization uncertainty ($R_p$).

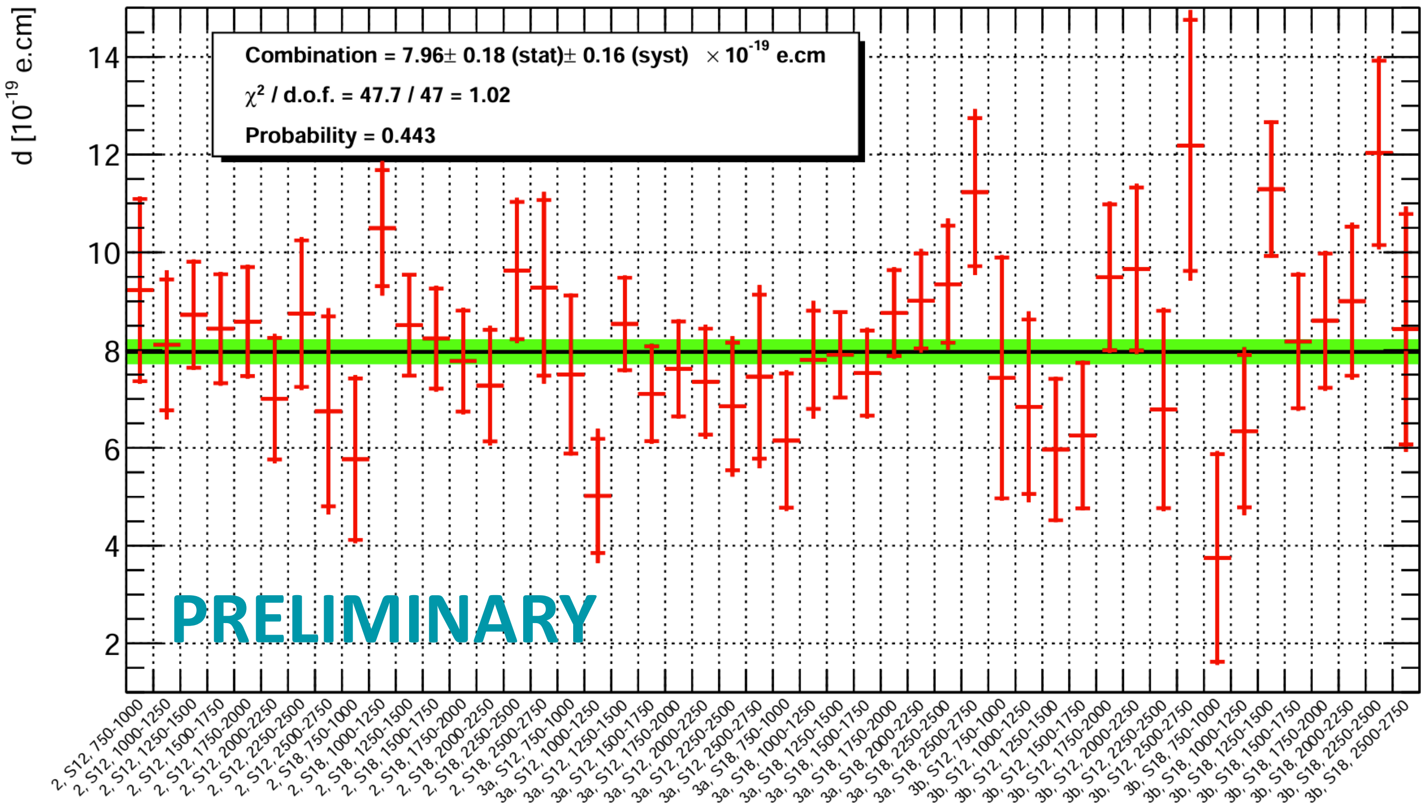
- Align and $R_p$ scale with measured $A_{EDM}$ – currently, large blinding EDM, so will reduce.
  - Both also currently undergoing extra studies which may improve our understanding.

- Expect track reconstruction uncertainty to be our largest after unblinding.



# Preliminary blinded Run 2/3 results

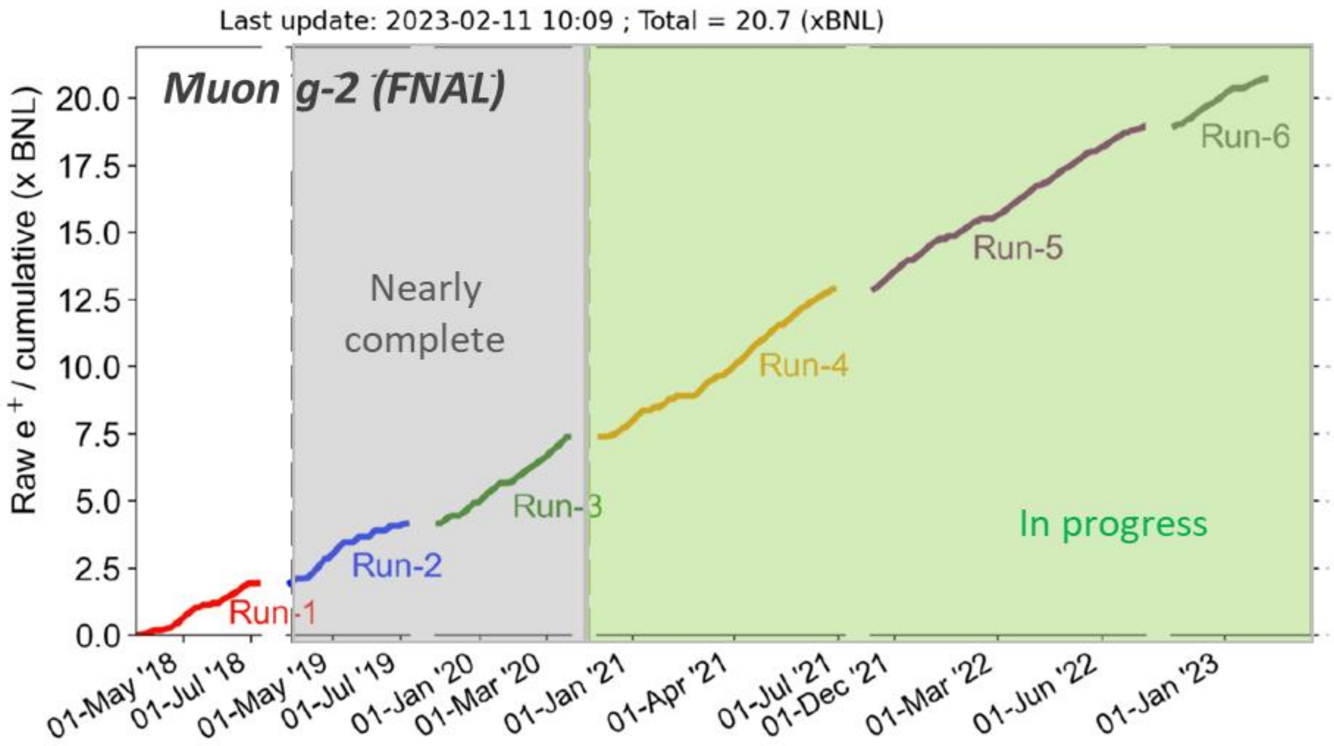
- All results still globally blinded – during analysis, each run period blinded separately.
- Relative unblinding of Run 2/3 performed recently: results show good agreement.
- Assuming central value = 0 after unblinding, gives a limit of $3.3 \times 10^{-20}\ e \cdot cm$ – **5.5x improvement vs BNL**.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



# Timelines for FNAL analysis

- Run 2/3: analysis mostly complete, in collaboration review
  - Expect results this year!
  - Best possible limit is ~ 5.5x better than BNL limit in the absence of observed signal.

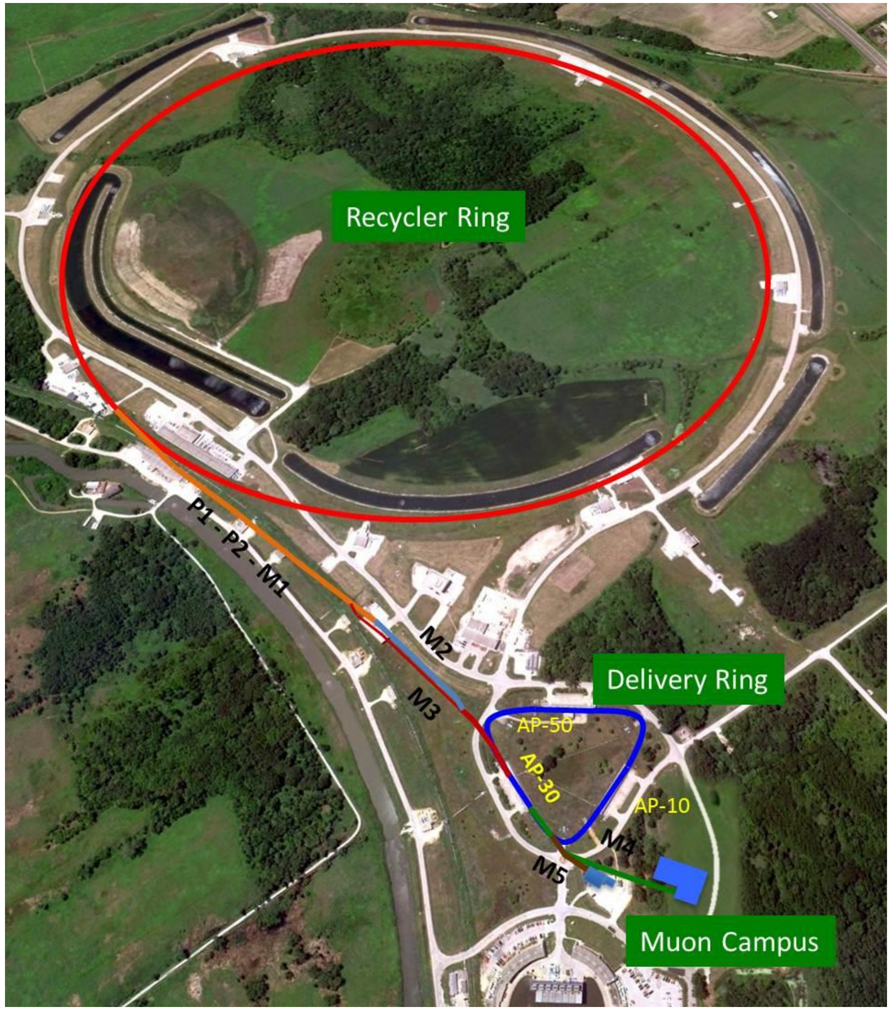
- Run 4/5/6 + full dataset:
  - Analysis started, ~ 4x as much data as Run 2/3.
  - Final result will be a combination of runs 2-6.
  - Expected to improve on BNL limit by ~ an order of magnitude.



# Bonus slides

# Fermilab muon beamline

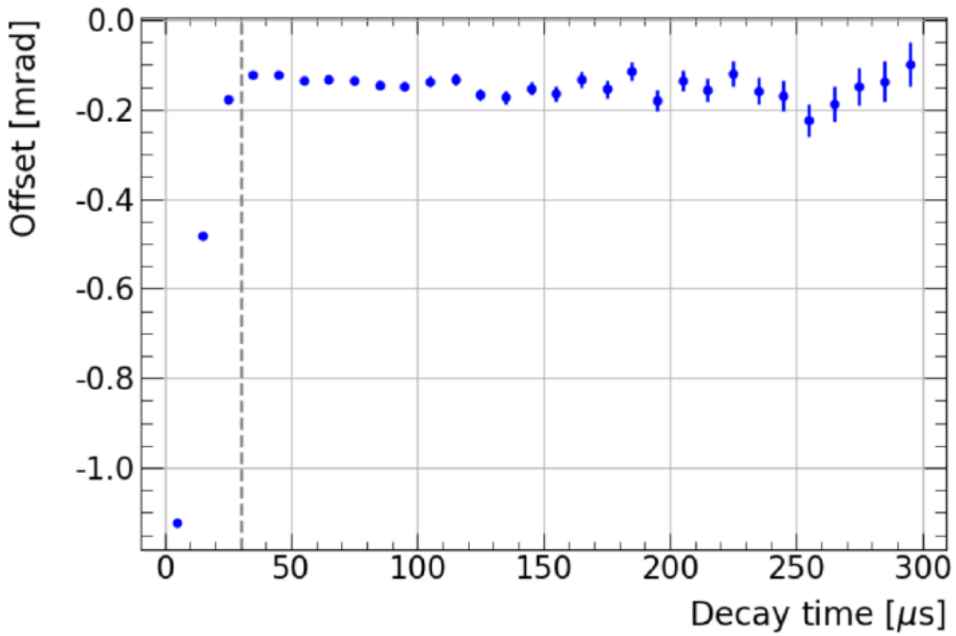
- Protons incident on a target make pions.
- Pions are stored in the delivery ring until they decay into muons.
- Muons injected into our ring.

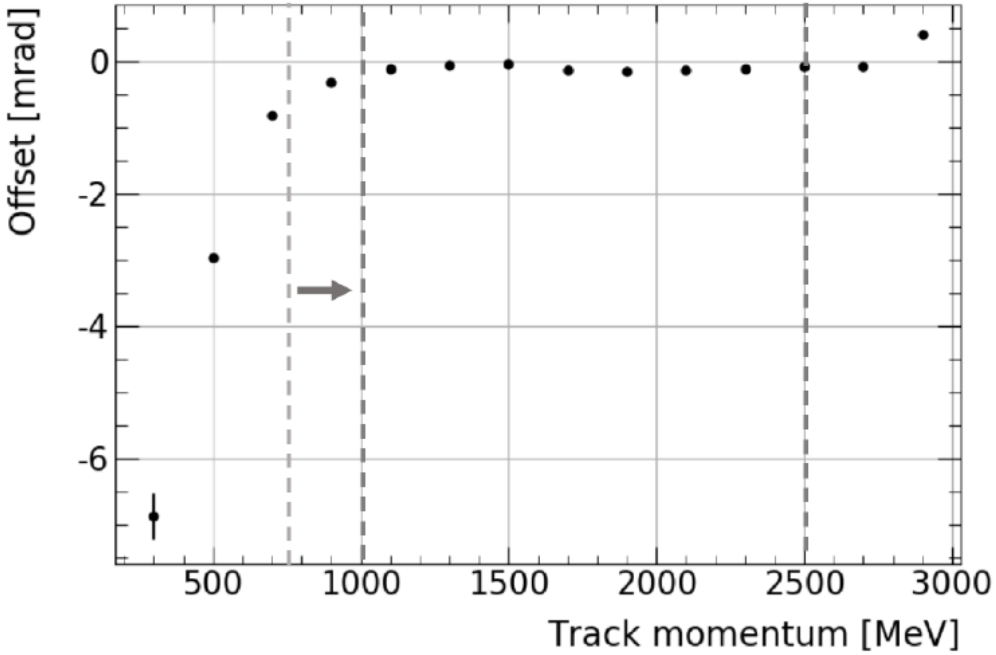


# Analysis cuts

- 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.

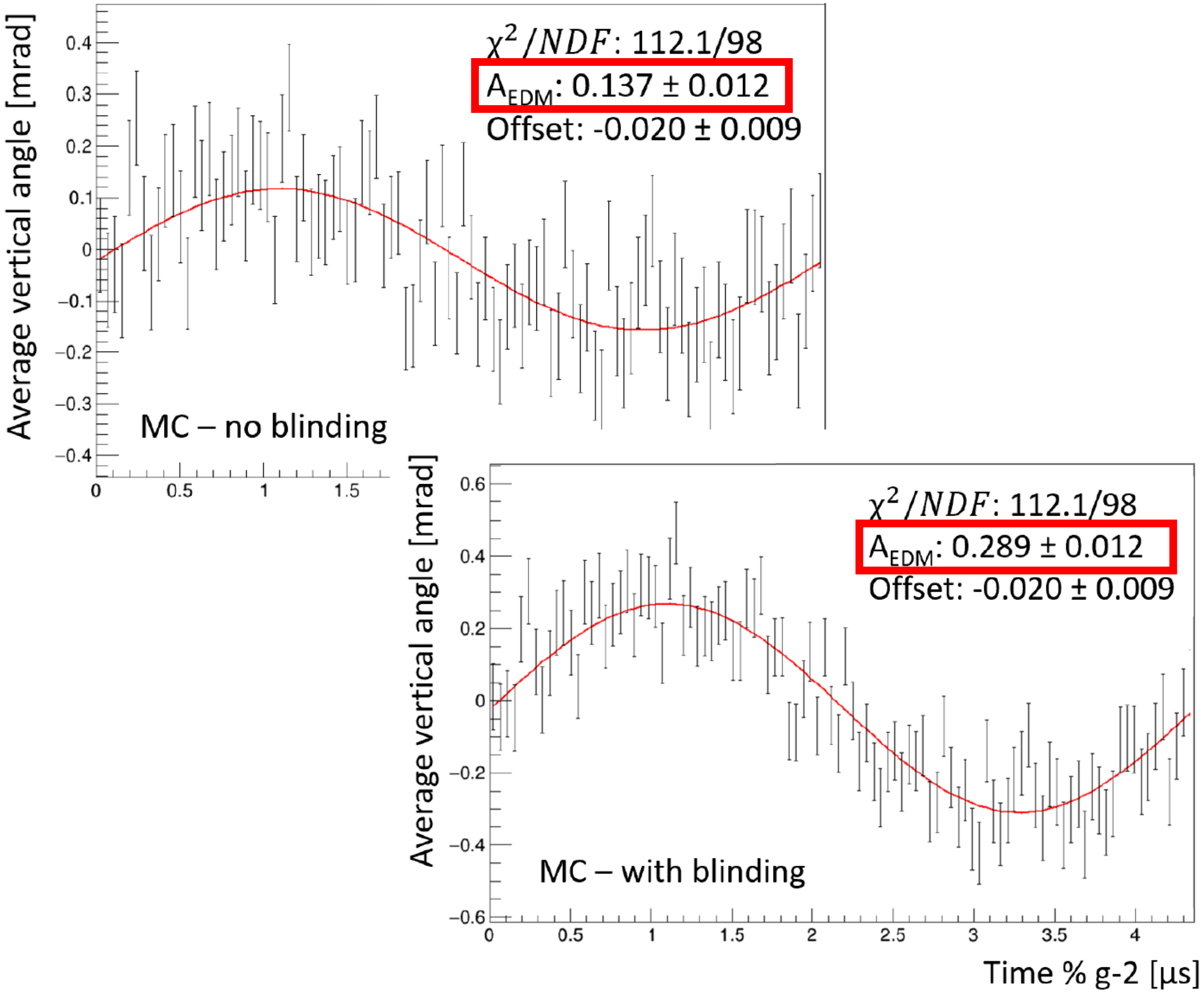


# Blinding

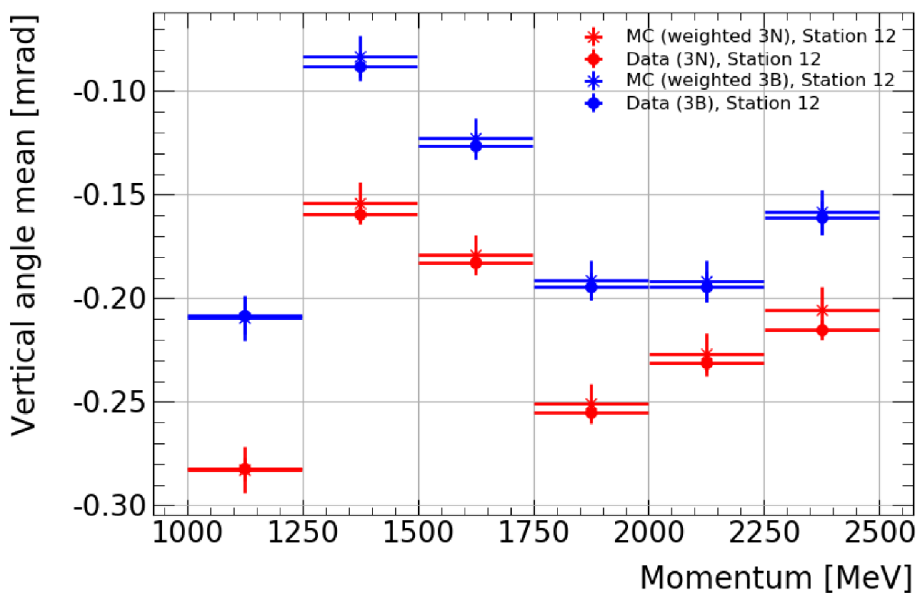
- Need to blind the vertical angle oscillation to prevent bias in the analysis.

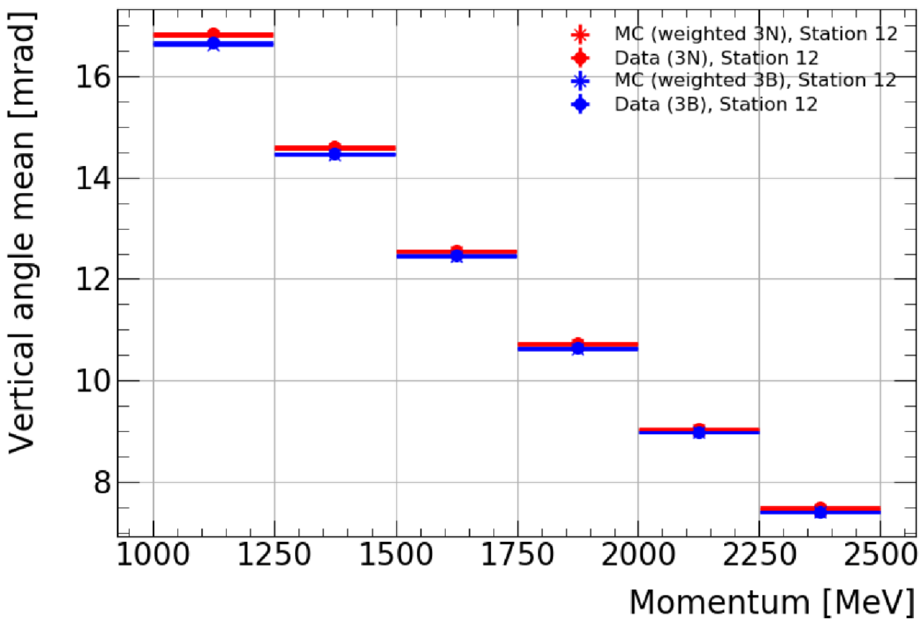
- Achieve this by injecting a very large fake signal in each momentum bin.
  - Amplitude is sampled randomly from a gaussian distribution, chosen to be >> BNL limit.
  - Includes the momentum-dependence.



# Data/MC differences

- Known differences in data and MC – e.g. vertical decay width is different.
  - Fix by weighting events in the maps based on the vertical angle distributions to make them match better:

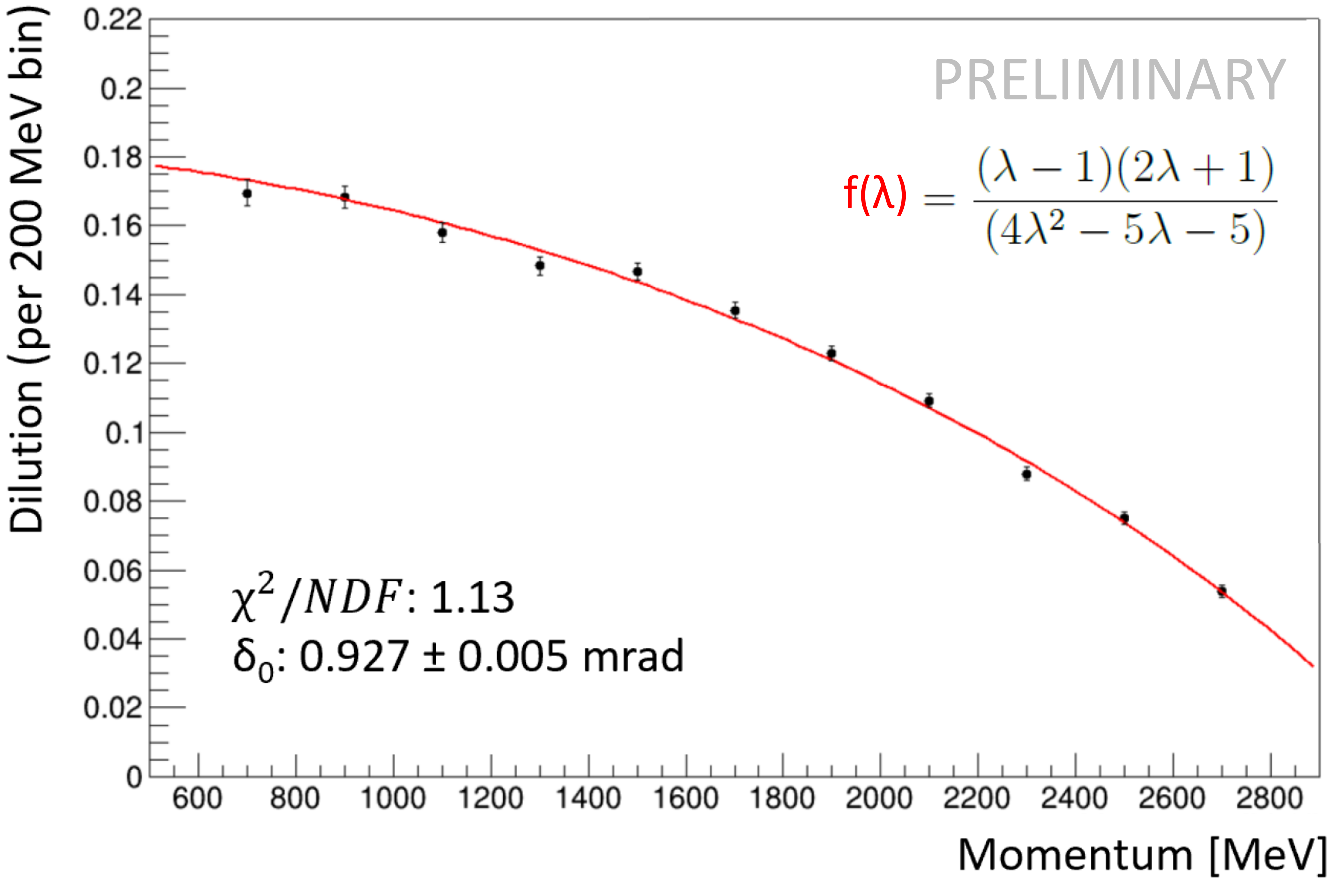



- Residual differences treated as a systematic uncertainty: propagated through to the impact on the final tilt.

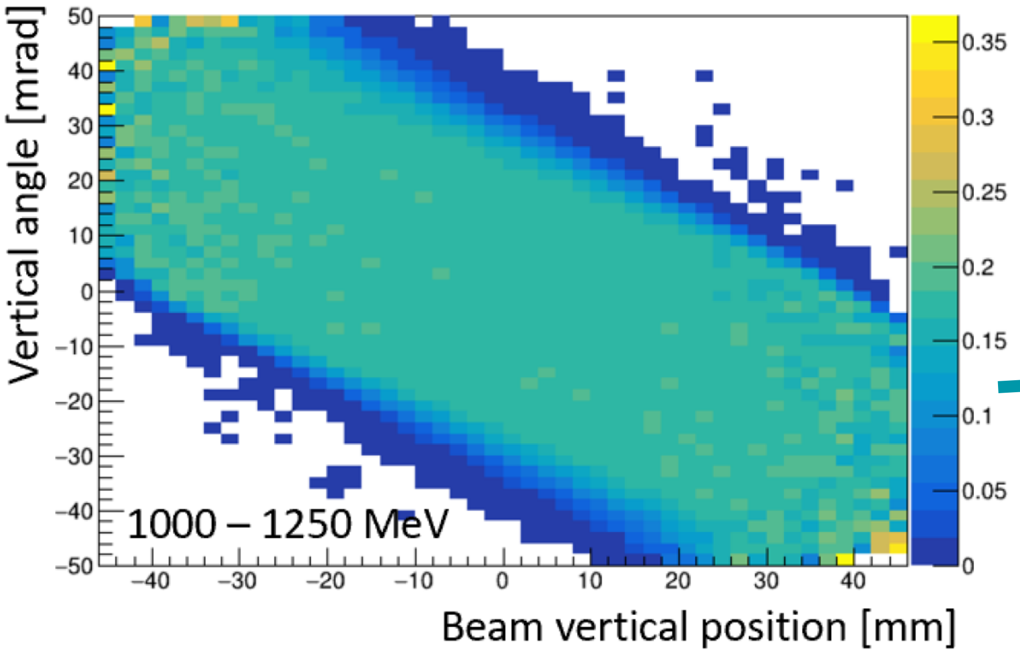
# Momentum dependence ($R_{e^+}(\lambda)$) factor

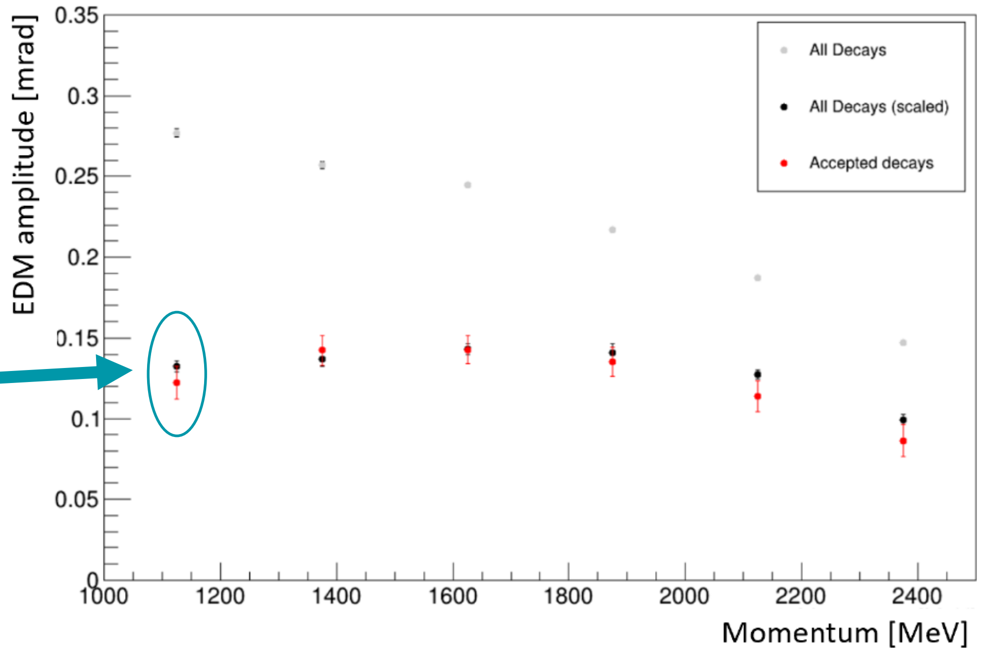
- Analytical form is only first-order: radiative corrections lead to a small reduction in the tilt seen.
- Currently, extract this from MC by plotting and fitting the 'all decays' sample:
- Now moving to an updated function that includes the radiative corrections – but still fit to account for higher-order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



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

- The ratio of tracker-detected decays to all decays gives $\boldsymbol{R_{acc}(\lambda)}$ : used for Run 1.
  - Low stats due to low numbers of decays hitting the tracker, but is << 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- ~ 3x smaller uncertainties.

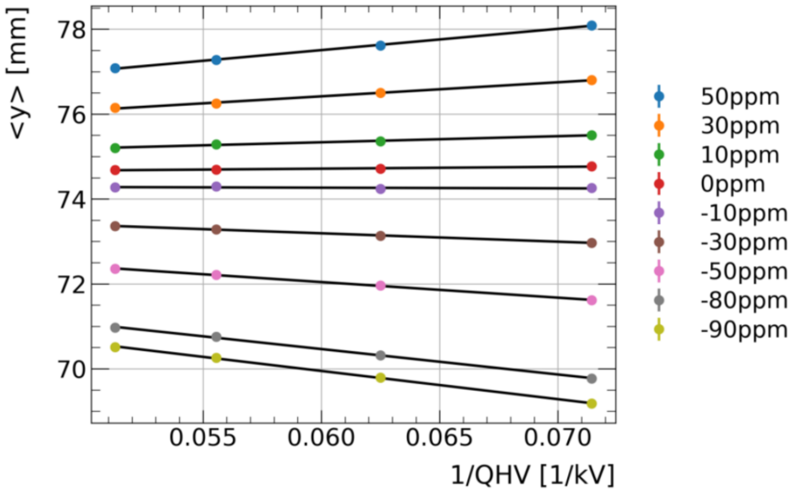


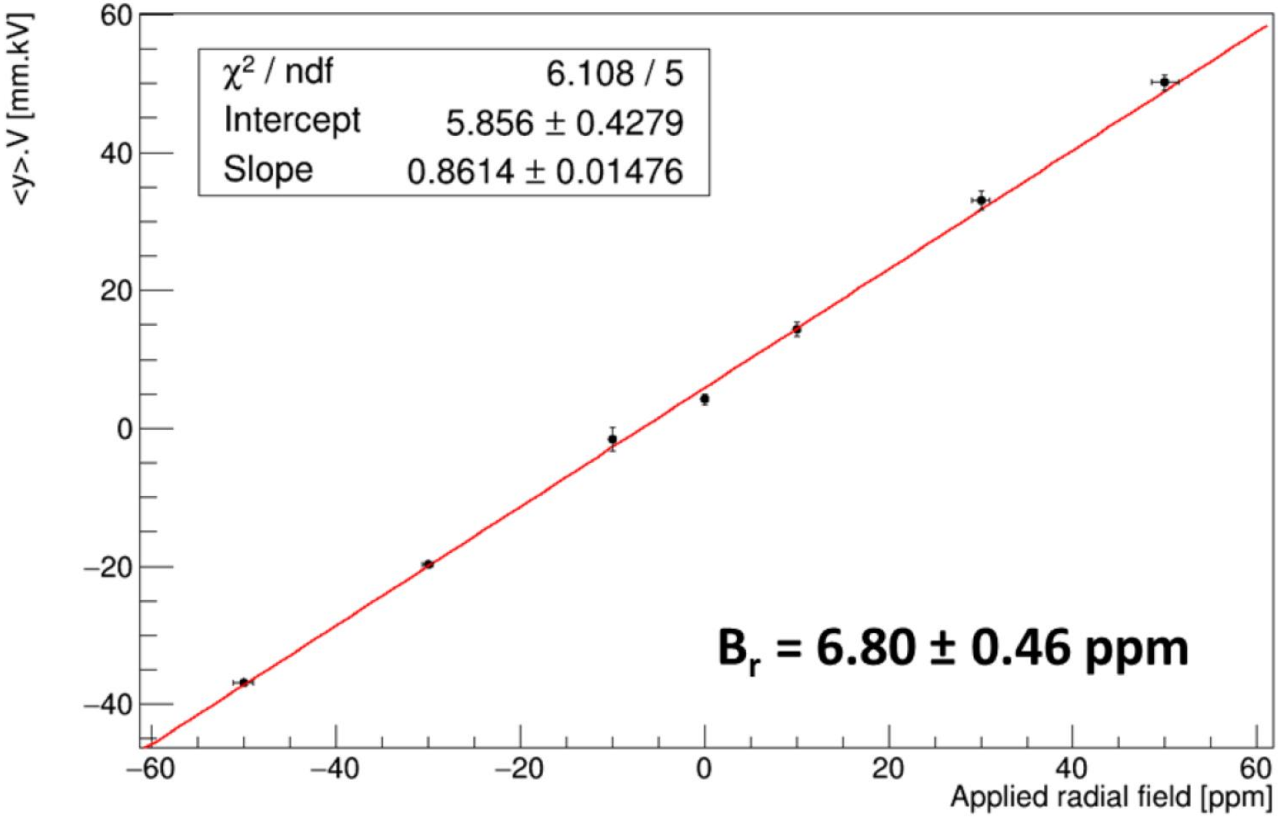



# The radial field - measurement

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




UNIVERSITY OF LIVERPOOL
LEVERHULME TRUST

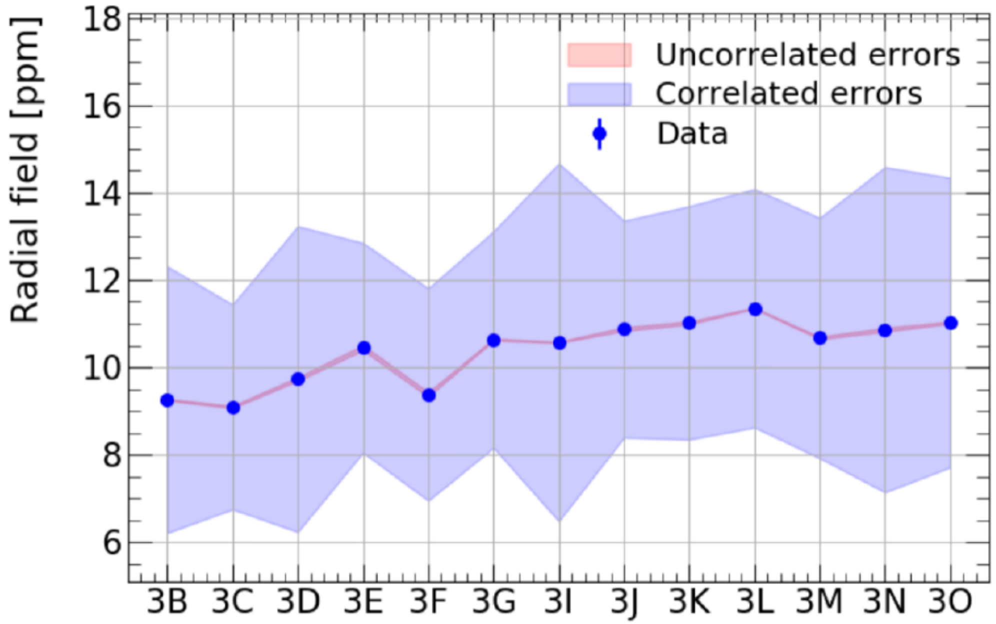
# Radial field - results

- 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.

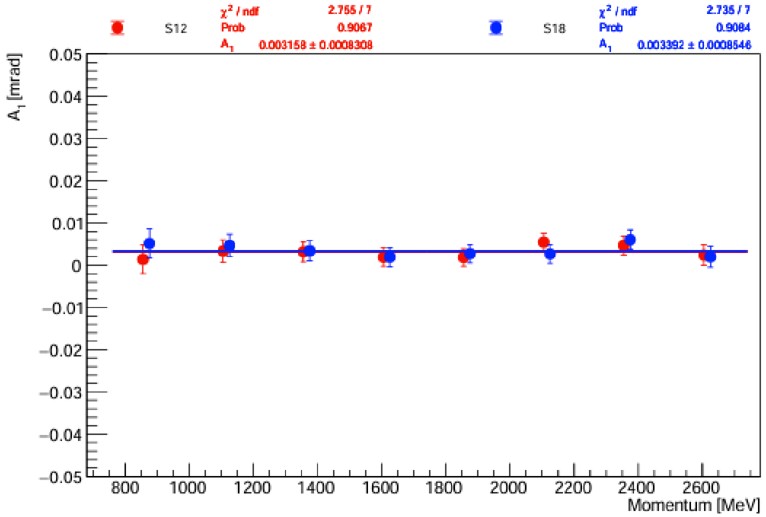
| Dataset | $\langle B_r \rangle$ [ppm] | Equivalent $d_\mu$ [$\times 10^{-20}$ $e\cdot$cm] |
|---|---|---|
| 1a | $22 \pm 7$ | $7 \pm 2$ |
| 1b | $23 \pm 8$ | $7 \pm 3$ |
| 1c | $30 \pm 8$ | $9 \pm 3$ |
| 1d | $34 \pm 9$ | $10 \pm 3$ |

S. Grant

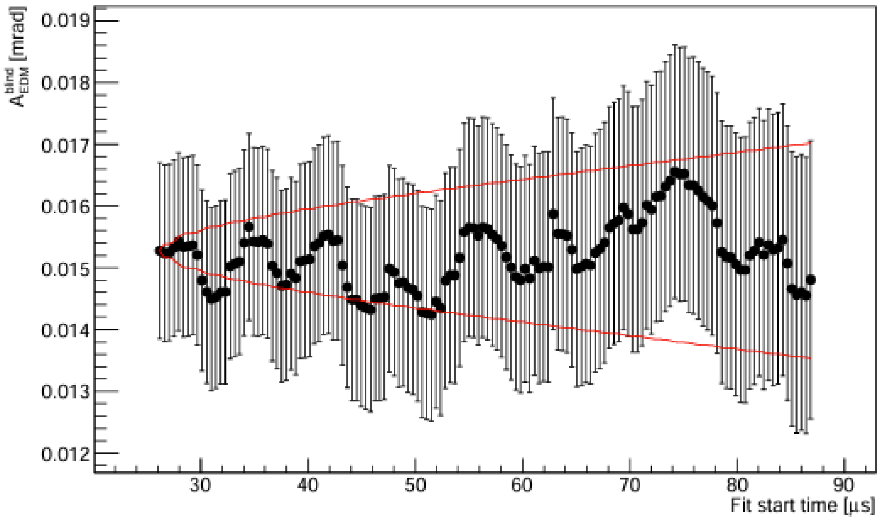


# Analysis cross-checks

- 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 << statistical uncertainty.