Status of the muon EDM measurement at FNAL g-2

Workshop on Muon Precision Physics, 10/11/2023

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Muon EDM – why do we care?

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

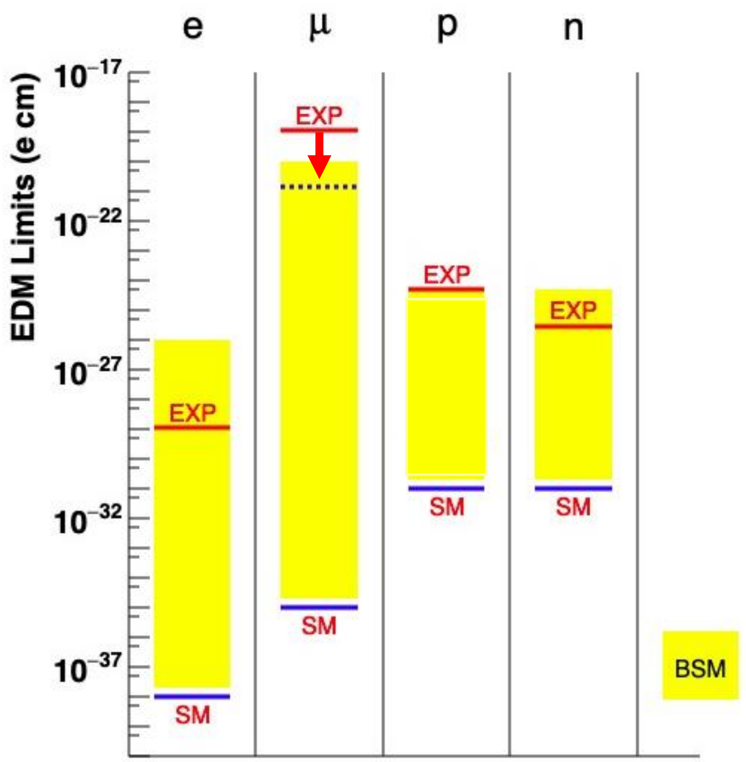
$$H = -\underline{\vec{\mu}\cdot\vec{B}} + \underline{\vec{d}\cdot\vec{E}}$$

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.
  - **d.E** is CP-odd, so observation gives a **new source of CP violation** in the lepton sector.

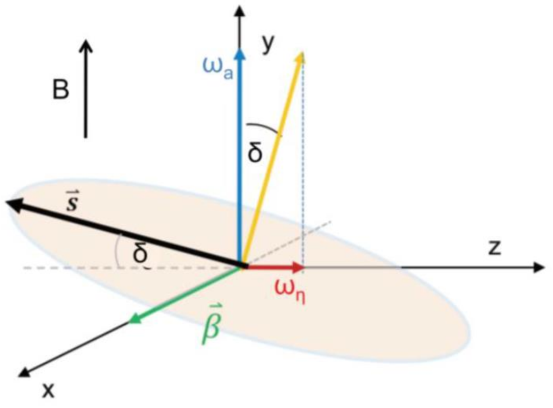
- Previous best limit was set at Brookhaven National Laboratory (BNL): **1.9 × 10^{-19}** $\boldsymbol{e\cdot cm}$**.**

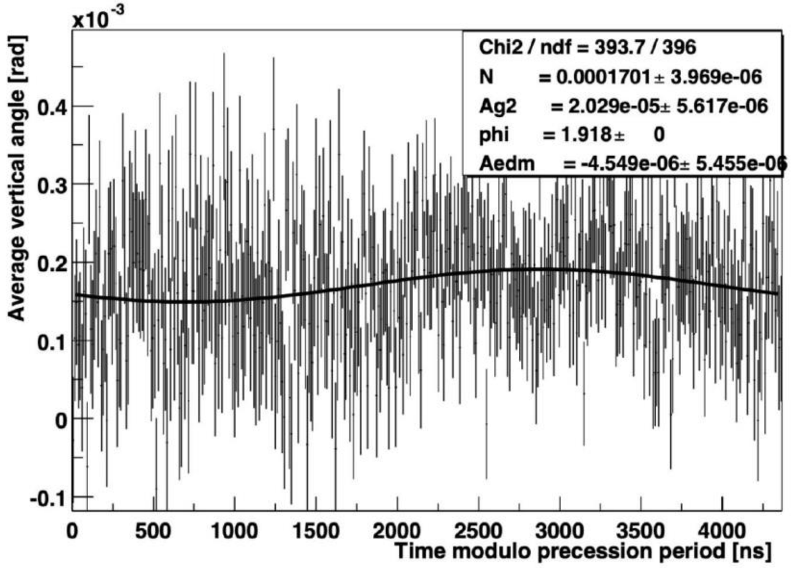
Measuring the muon EDM at FNAL

- Non-zero EDM introduces a tilt to the precession plane of the muons.

- Two main methods possible to search for a tilt:
  - **Phase difference:** using calorimeters to look for a vertical asymmetry between ingoing and outgoing positrons.
    - Systematically limited at BNL/FNAL.
  - **Direct measurement:** either trackers or calorimeters.
    - Trackers better for this as statistically limited.
    - Calorimeter measurement still systematically limited.

- Currently, two sets of data being actively analysed: Run 1, and Run 2/3.

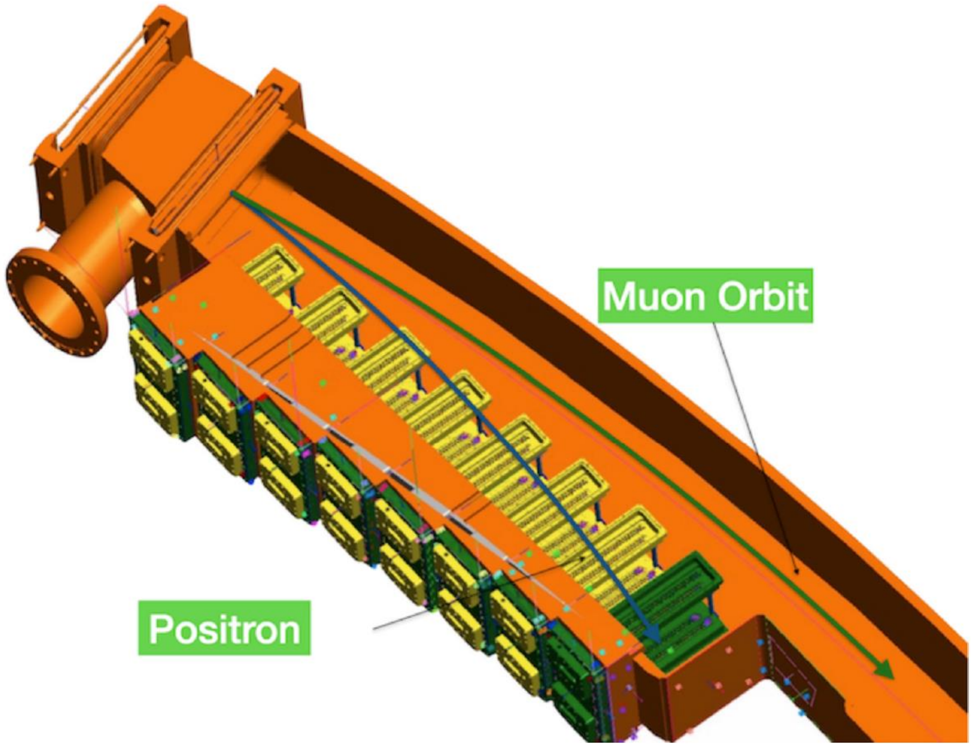




BNL 2000 data

The straw trackers at FNAL g-2

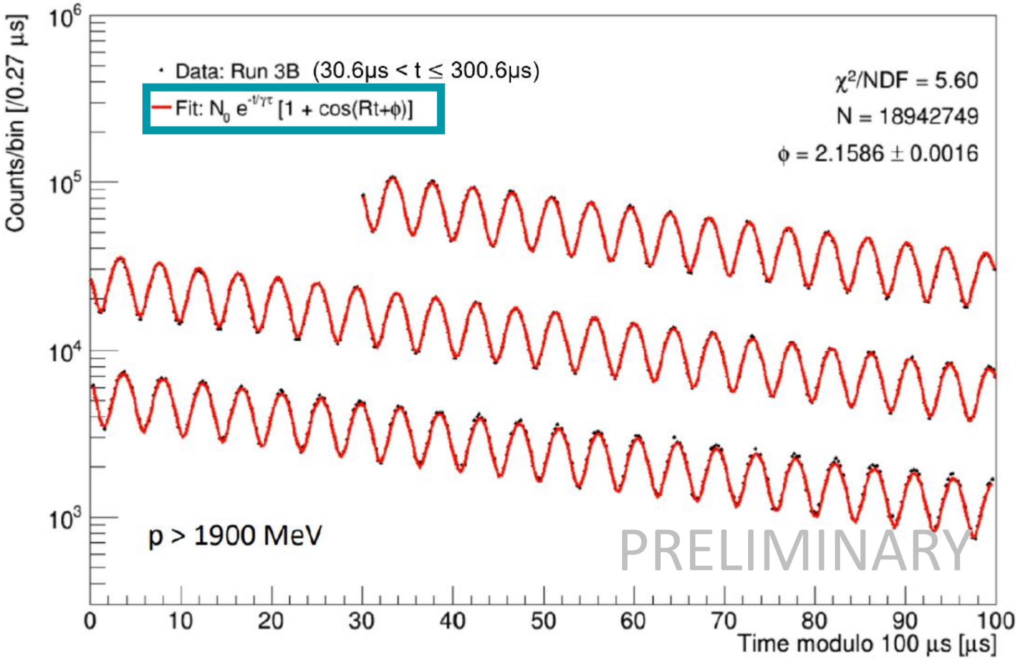
- Argon-Ethane straw trackers, straw hit resolution of ~ 100 µm.
- Two 'stations' (12 and 18) of 8 straw modules each, designed to operate inside the vacuum chambers.
- Hits are fitted into tracks, which are then extrapolated back to the vertex of decay (used for the EDM analysis to measure the angle) and forward into the calorimeters.

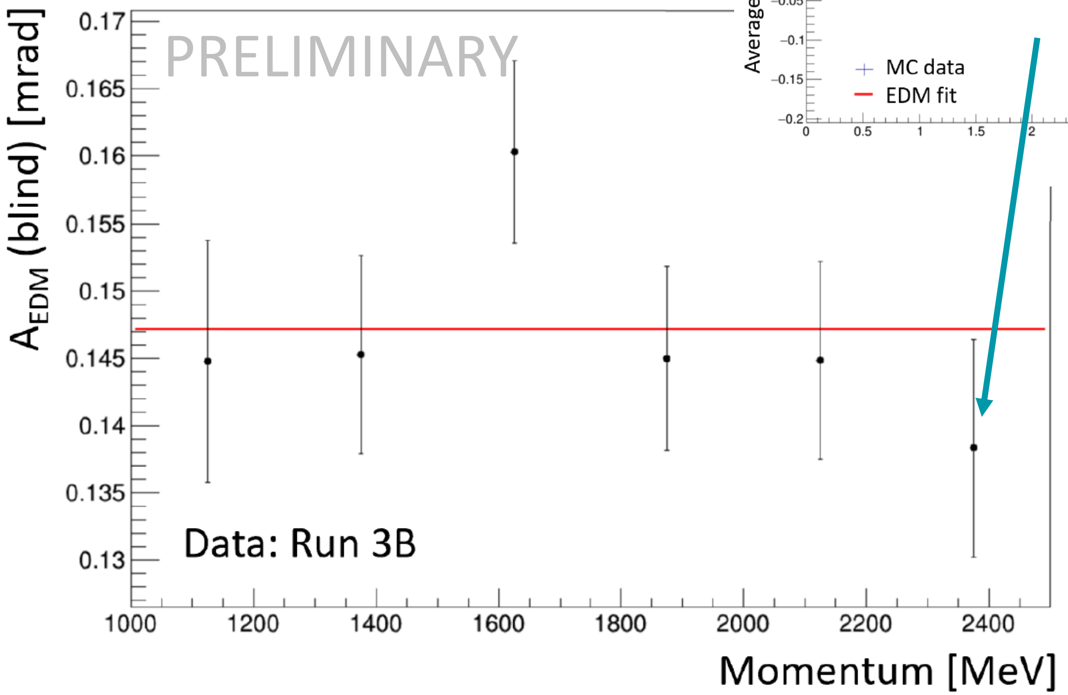


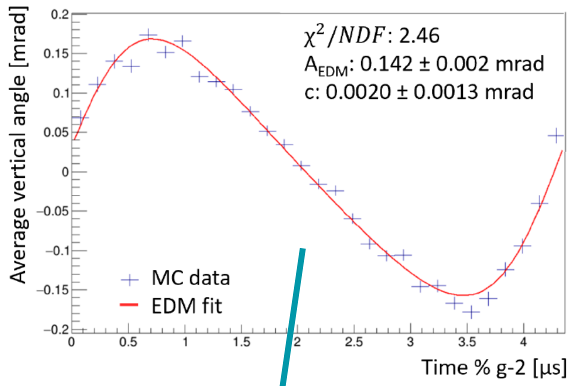
Extracting the EDM signal

- Plot the vertical angle modulo the g-2 period in central momentum bins + fit.

$$f(t) = \frac{A_{g-2}\ \cos\left(\omega_a t + \phi_{g-2}\right) + A_{EDM}^{blind}\ \sin\left(\omega_a t + \phi_{g-2}\right) + c}{N(t)}$$



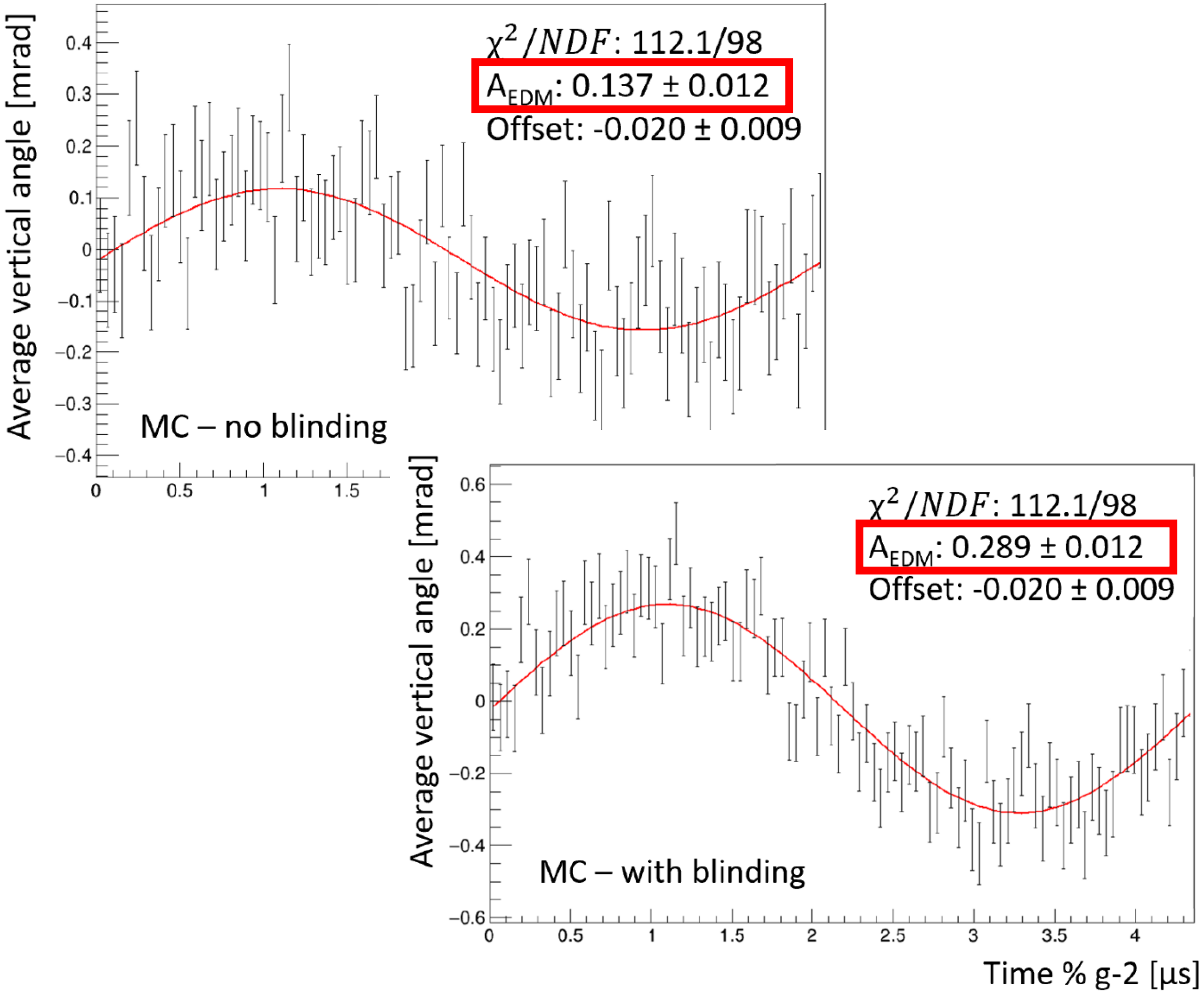




Blinding

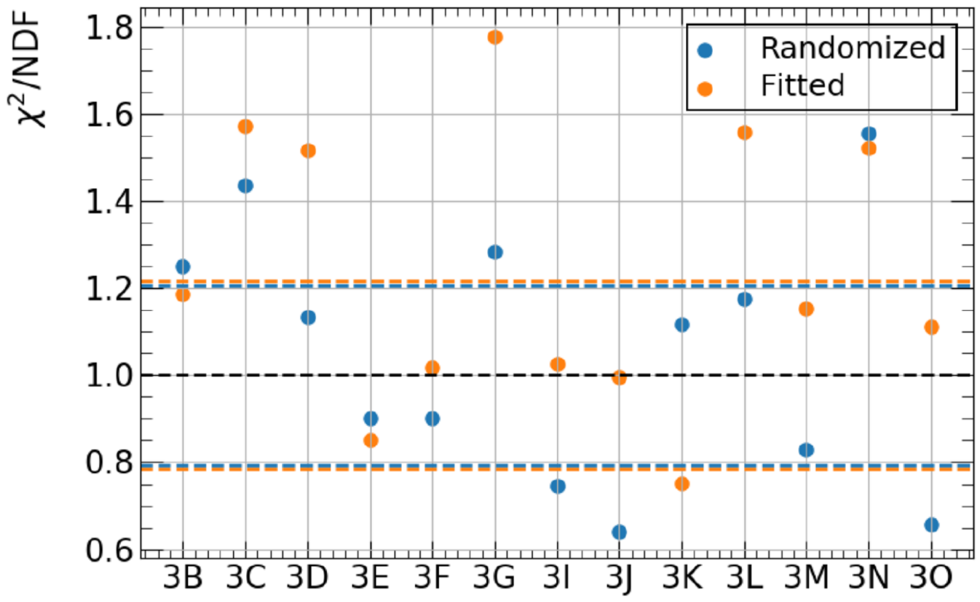
- Need to blind the vertical angle oscillation to prevent bias in the analysis.

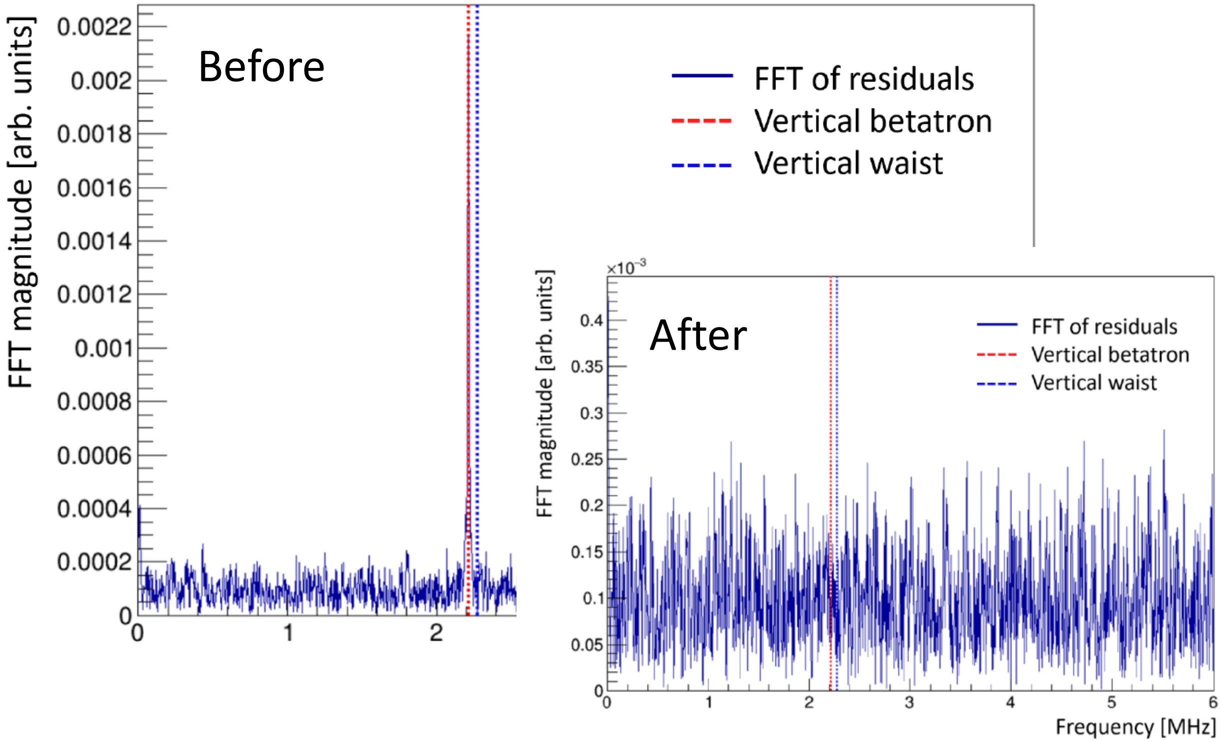
- Achieve this by injecting a very large fake signal in each momentum bin.
  - Amplitude is sampled randomly from a gaussian distribution, chosen to be >> BNL limit.
  - Includes the momentum-dependence.



Beam dynamics corrections

- Muon beam has a fast vertical oscillation that shows up in the FFTs of the fit residuals.
  - To improve fit quality, must be dealt with.
  - Two possible ways to deal with this: include in fit, or randomize out. Both equally effective, but randomization is simpler.

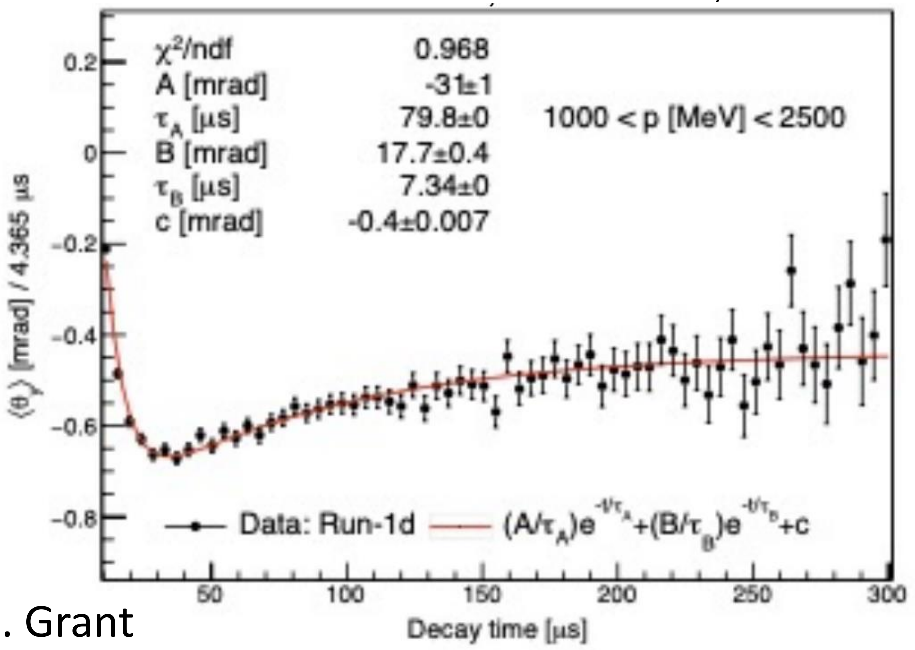




Behaviour at early times

- Run 1: dominated by the effects of faulty resistors, which increase the time taken for the beam to stabilize.
- Run 2/3: with the resistors fixed, now dominated by a faster rise caused by a space-charge effect in the trackers.
  - Both dealt with by fitting the data to remove the effect.

Run 1D, Station 18



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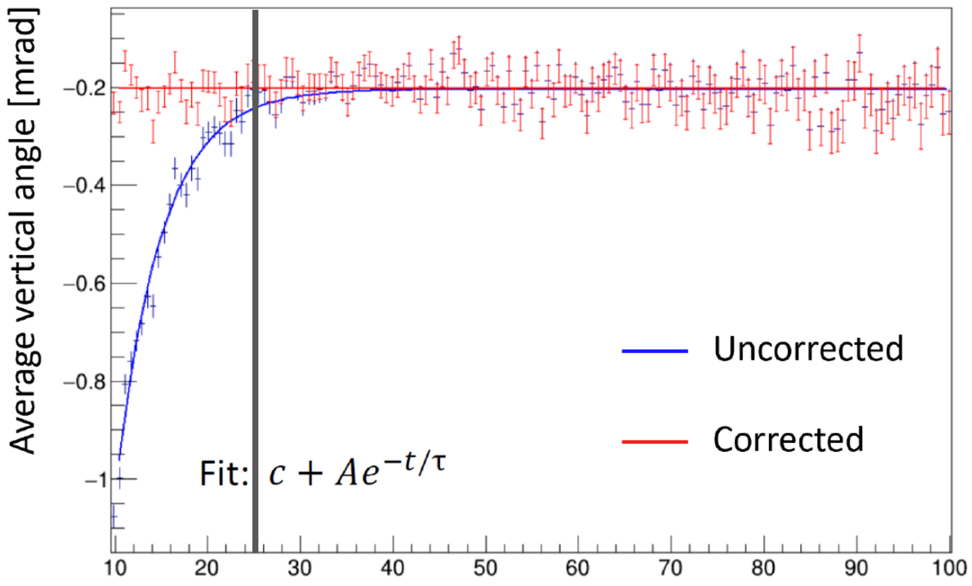
Run 3B, Station 12



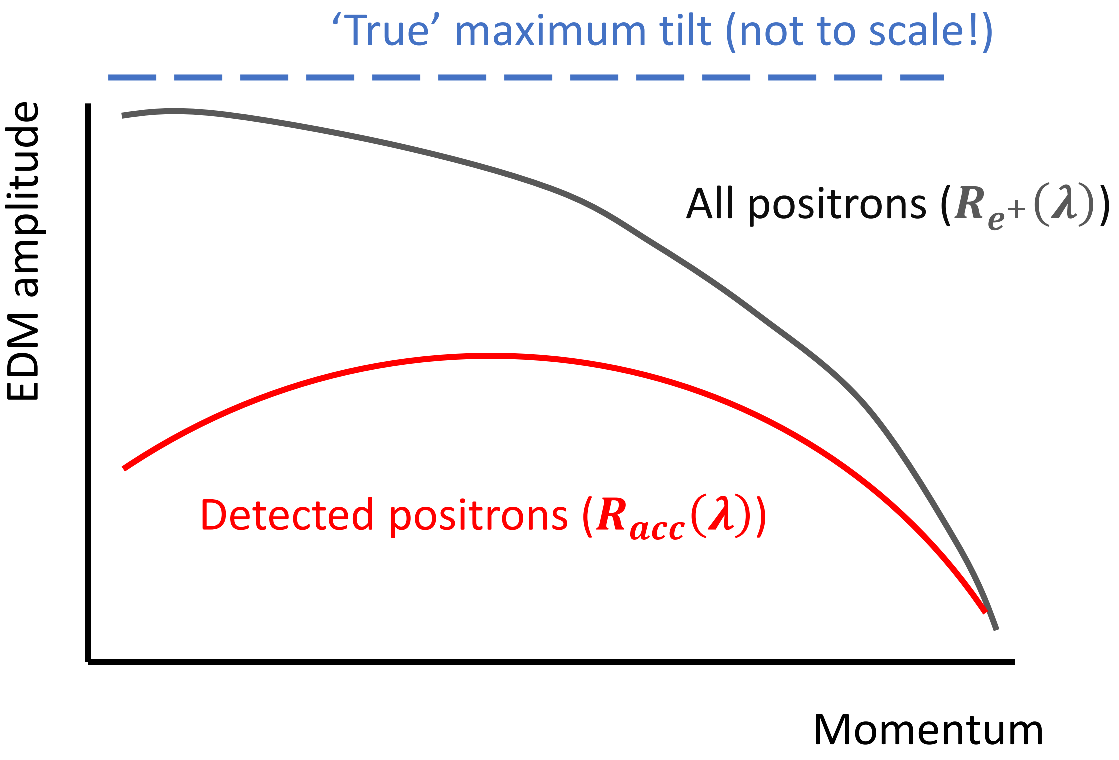
(Fit from 26.2μs)

Reductions to the measured vertical angle

- The vertical angle measurable in the trackers is reduced by three effects, which need to be corrected:

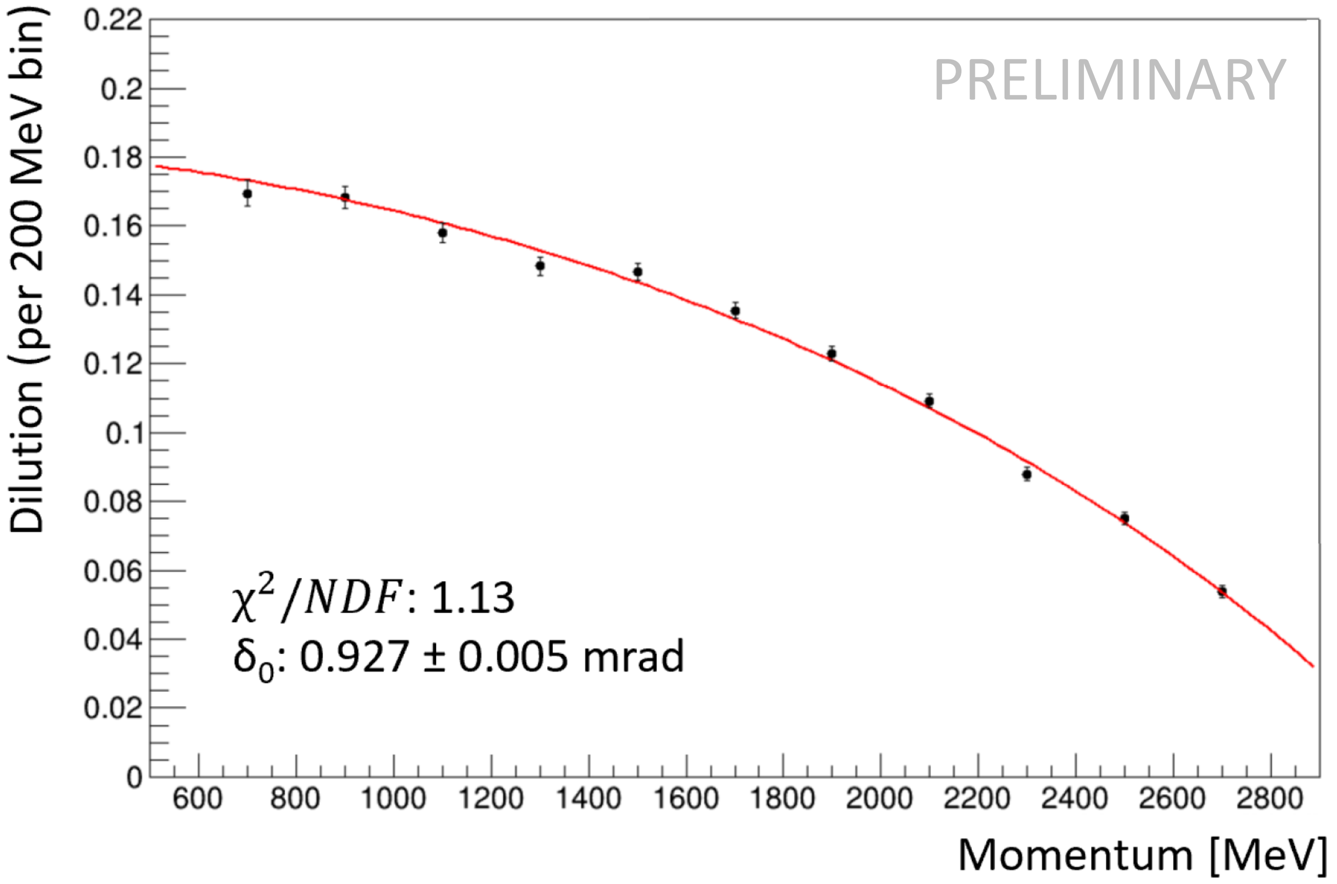
Measured tilt = $R_\gamma\, R_{e^+}(\lambda)\, R_{acc}(\lambda)$ True tilt

- R_γ **:** boost factor from muon rest frame to lab frame.
  - Factor is 1/γ, so ~ 1/29.
- $R_{e^+}(\lambda)$ **:** muon decay asymmetry shape.
  - Has an analytical form, f(λ) where λ is fractional momentum.
  - Accounts for radiative corrections via a scaling factor.
- $R_{acc}(\lambda)$ **:** acceptance effects, from the finite size of the tracker + reconstruction capabilities.
  - No analytical form, determined from MC ratios.



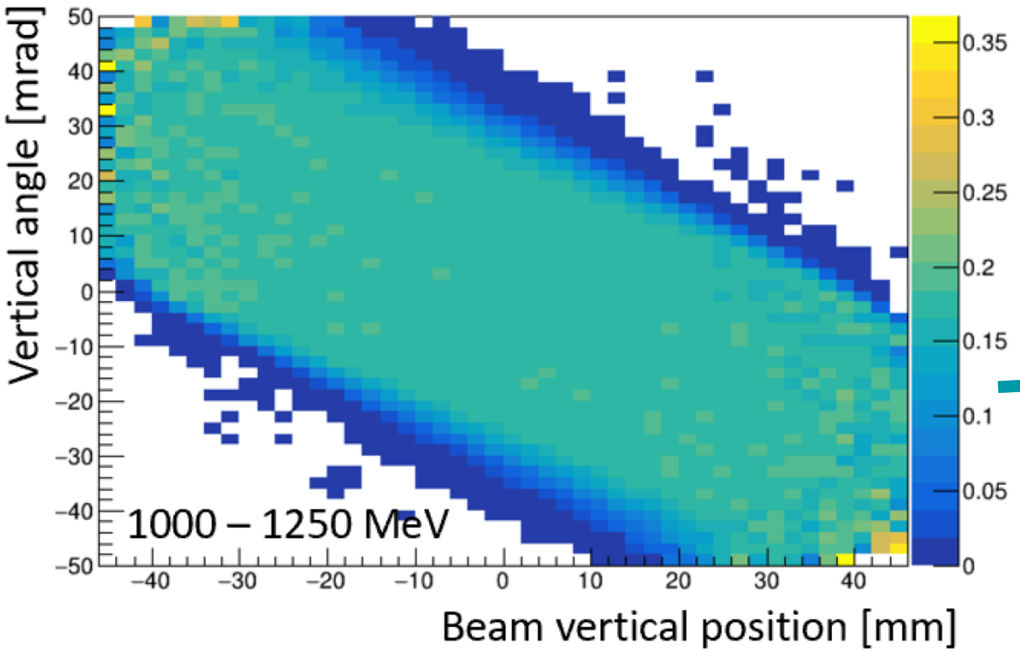
Momentum dependence ($R_{e^+}(\lambda)$) factor

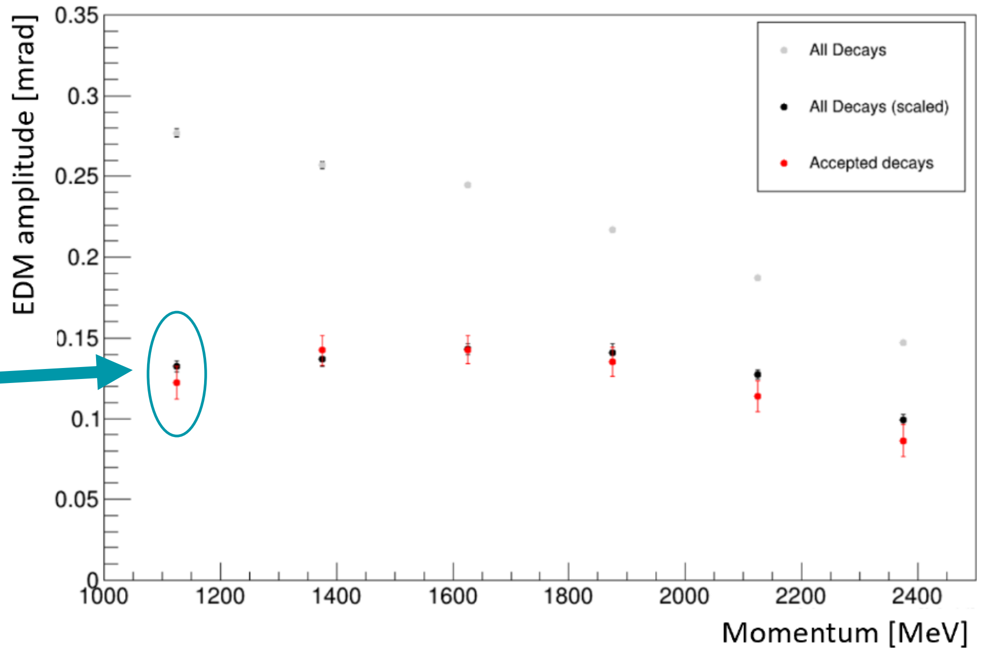
- Analytical form is only first-order: radiative corrections lead to a small reduction in the tilt seen.
- Currently, extract this from MC by plotting and fitting the 'all decays' sample:
  - Use a factor to quantify the reduction seen.
- Now moving to an updated function that includes the radiative 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.

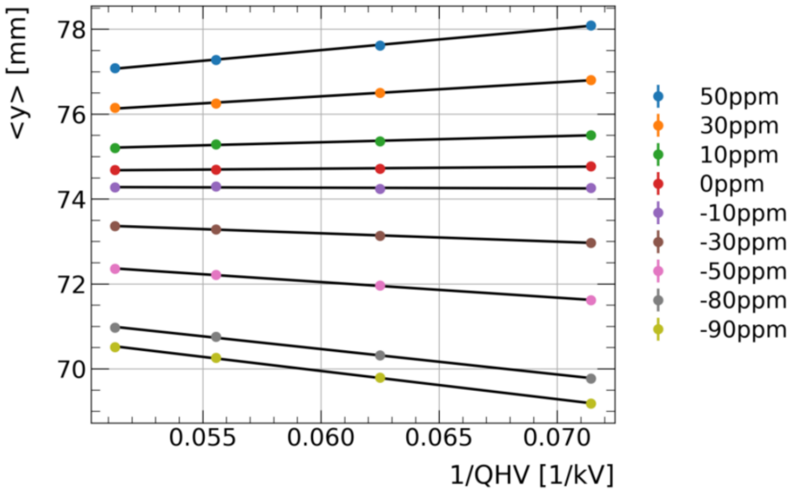


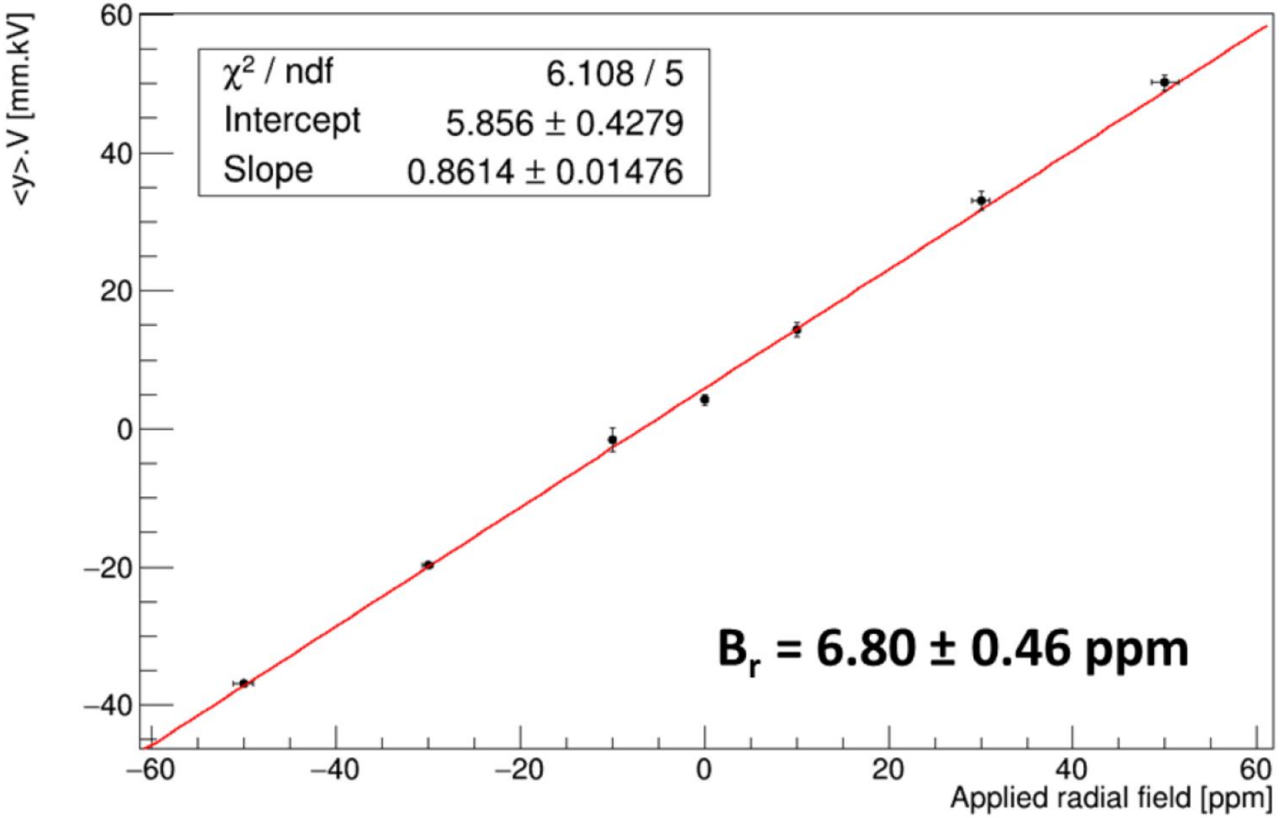


The radial field - measurement

- 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:





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

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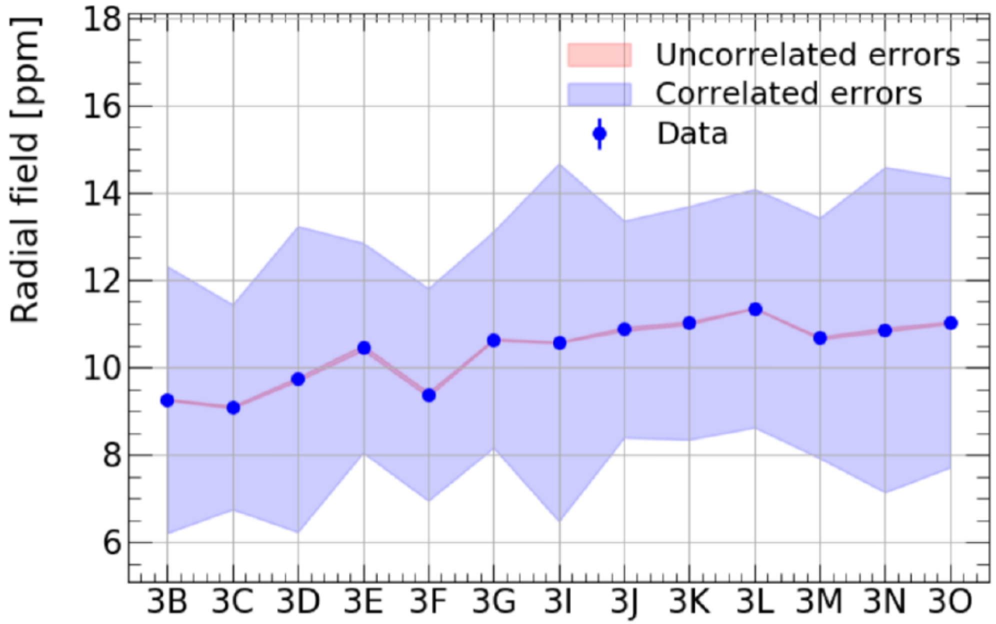


Other systematics

- Drift uncertainty: comes from the fit uncertainties of the early time drift correction

All values are preliminary, work ongoing to improve methods!

Unc. [mrad]	Statistical	Radial field	Acceptance	Drift	MC weighting	Alignment	Total
2B	0.0578	0.00363	0.00281	0.0000600	0.00245	0.00128	0.0581
2C	0.0265	0.00393	0.00273	0.0000504	0.00330	0.00208	0.0272
2D	0.0285	0.00626	0.00274	0.0000510	0.00409	0.00586	0.0295
2E	0.0459	0.00360	0.00208	0.0000641	0.00247	0.00178	0.0461
2F	0.0467	0.00363	0.00273	0.0000572	0.00281	0.00339	0.0471
2G	0.0992	0.00492	0.00276	0.0000947	0.00363	0.000508	0.0994
2H	0.0855	0.00498	0.00274	0.0000912	0.00271	0.00321	0.0858

- MC weighting: vertical angle distributions are slightly different in data and MC – apply a weighting, residual differences are included here.

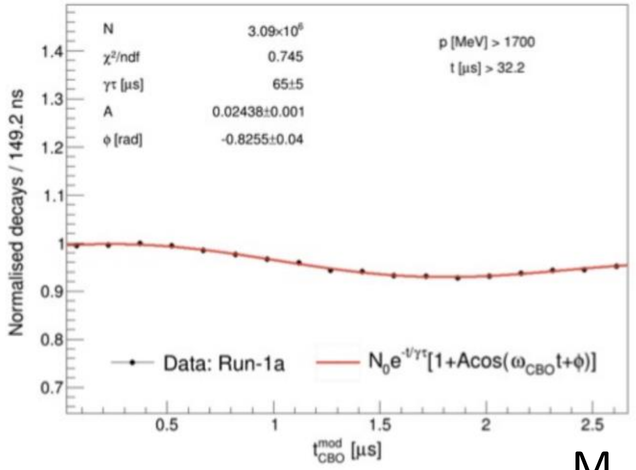
- Alignment: vertical shifts and tilts of the trackers themselves introduce uncertainties

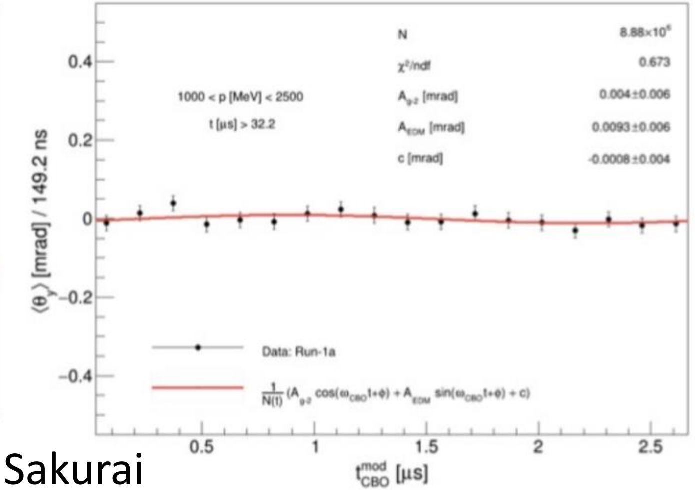
Uncertainty [mrad]	Dilution	Tracker resolution	Phase
All runs	0.0000212	0.000140	0.0000274

- Phase: impact of getting the phase wrong in the 5-parameter fit

The ω_{CBO} cross-check

- Plot the vertical angle modulo another frequency and fit for an oscillation at that frequency but out of phase with it.
- We choose a known radial beam frequency, the coherent betatron oscillation (CBO) for this.
- Should give amplitudes of zero!
- For Run 1: unblinded fits do indeed give zero amplitude modulo the CBO frequency for all 4 datasets.





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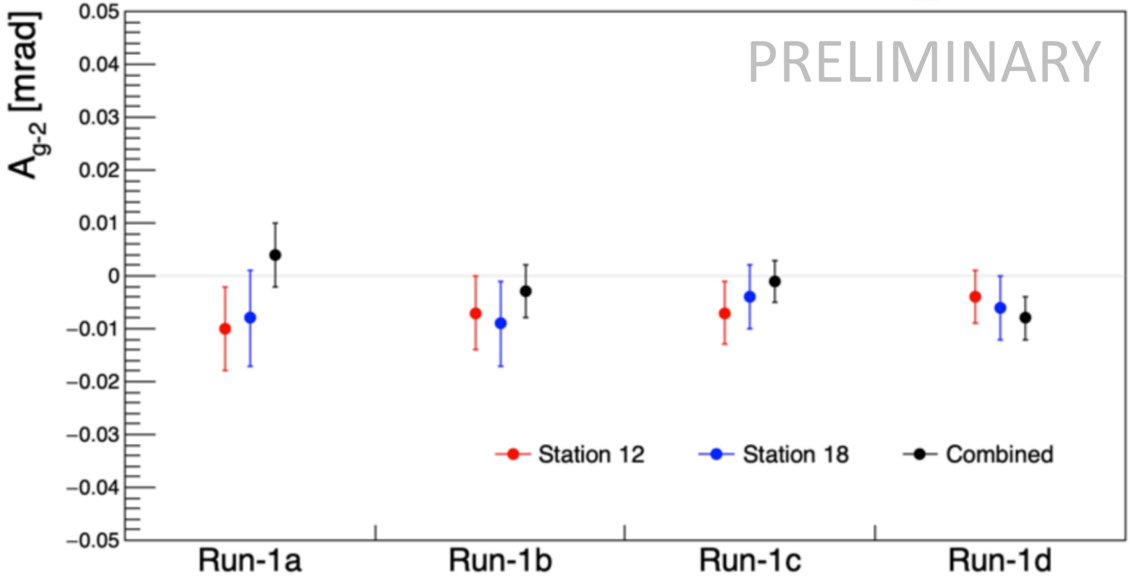
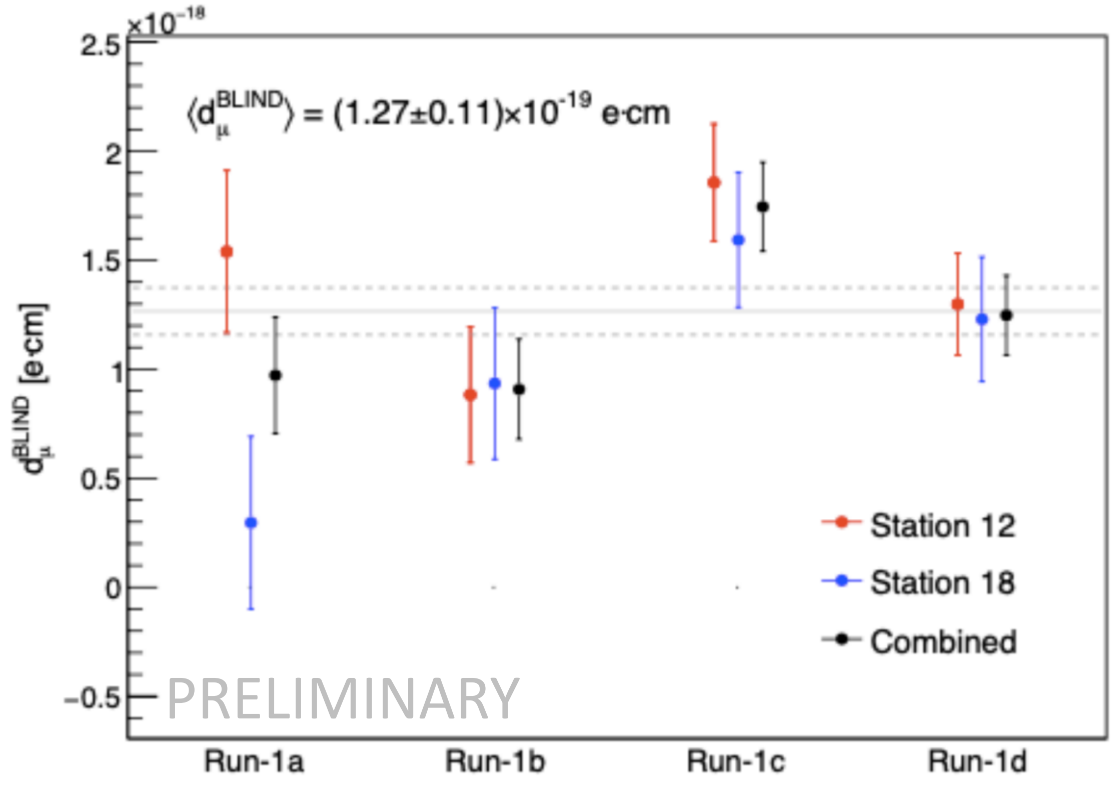


Run 1 – a preliminary look

- Fits to the 4 datasets give a final limit ~ $2.0 \times 10^{-19}\ e \cdot cm$, assuming the central value is zero.
- Currently still blinded!
- Some changes have been made to the analysis procedure:
  - These plots use a simpler fit function than the full one, so this is being updated.



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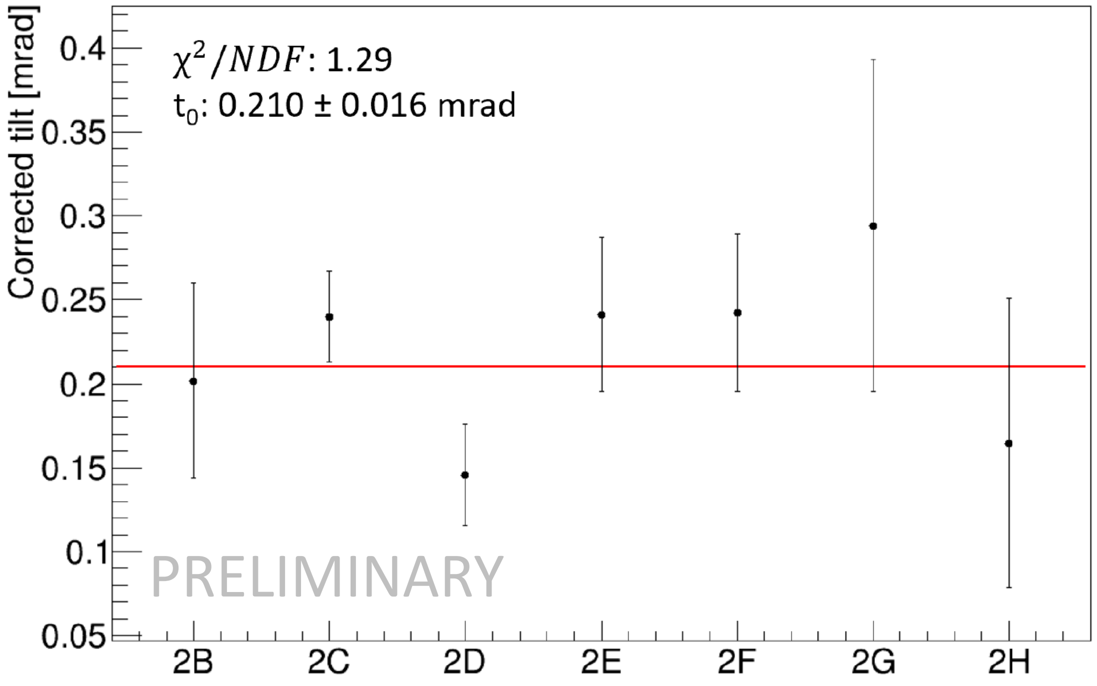
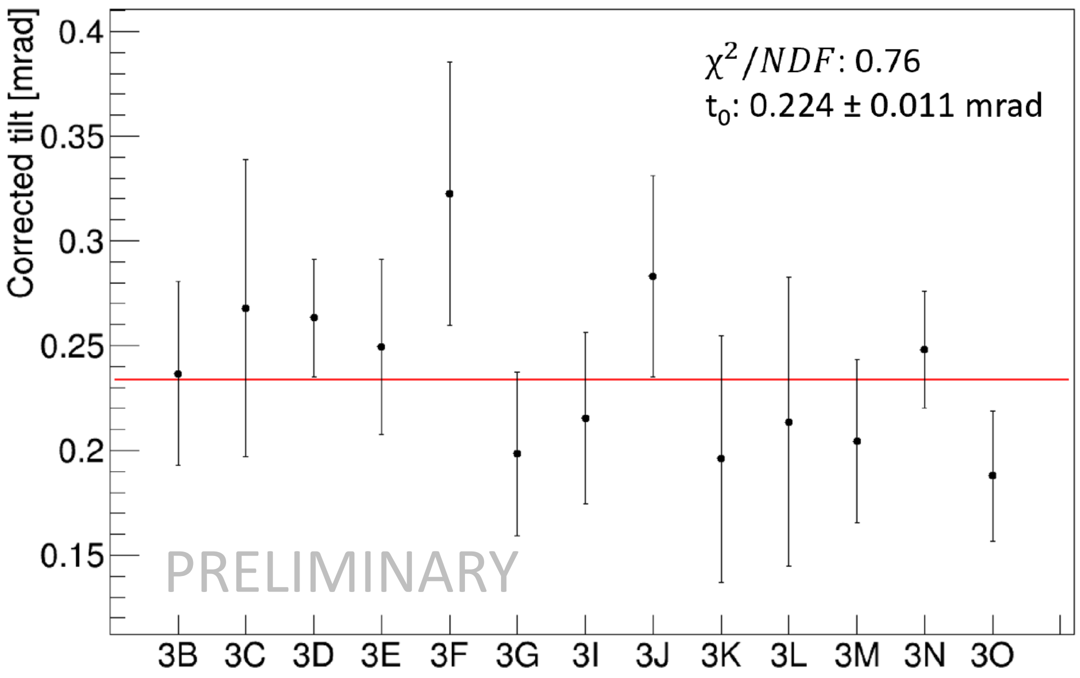
Run 2/3 – a preliminary look

- Work to fully quantify systematics is still ongoing, but expect ~ 3x better limit on the muon EDM from Run 2/3 based on initial fits.
  - Dominated by statistical uncertainty, acceptance still largest systematic, but improved by a factor of ~ 3.5 due to the map method.





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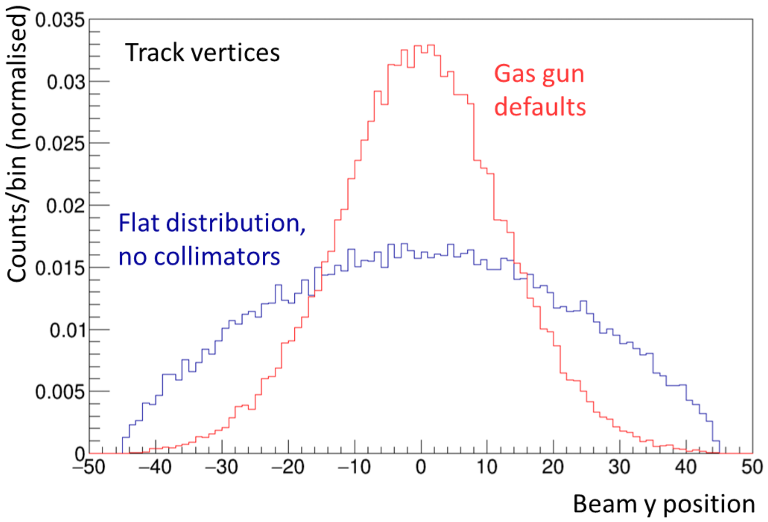
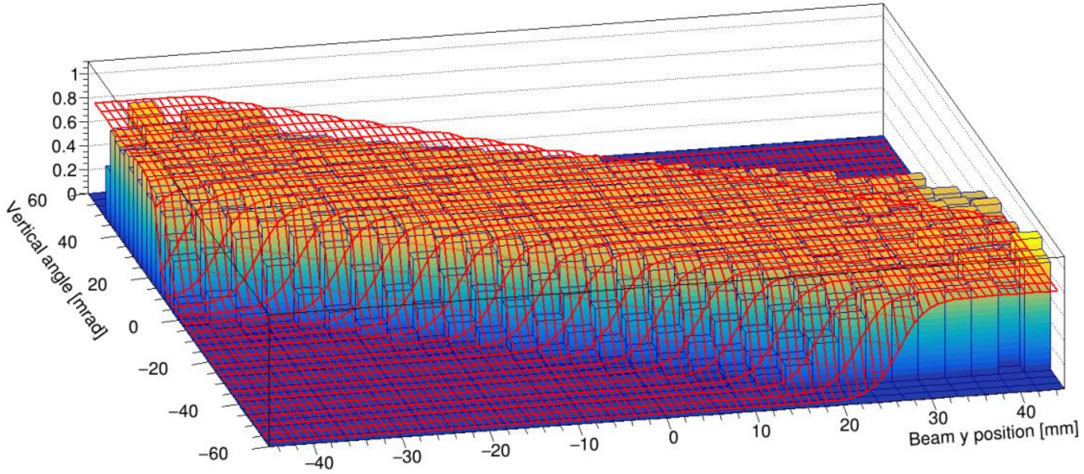
Work in progress: improvements for Run 2/3

- Since Run 2/3 were processed, improvements to the tracking have been made.
  - Vertex efficiency 2x better: so worth retracking!

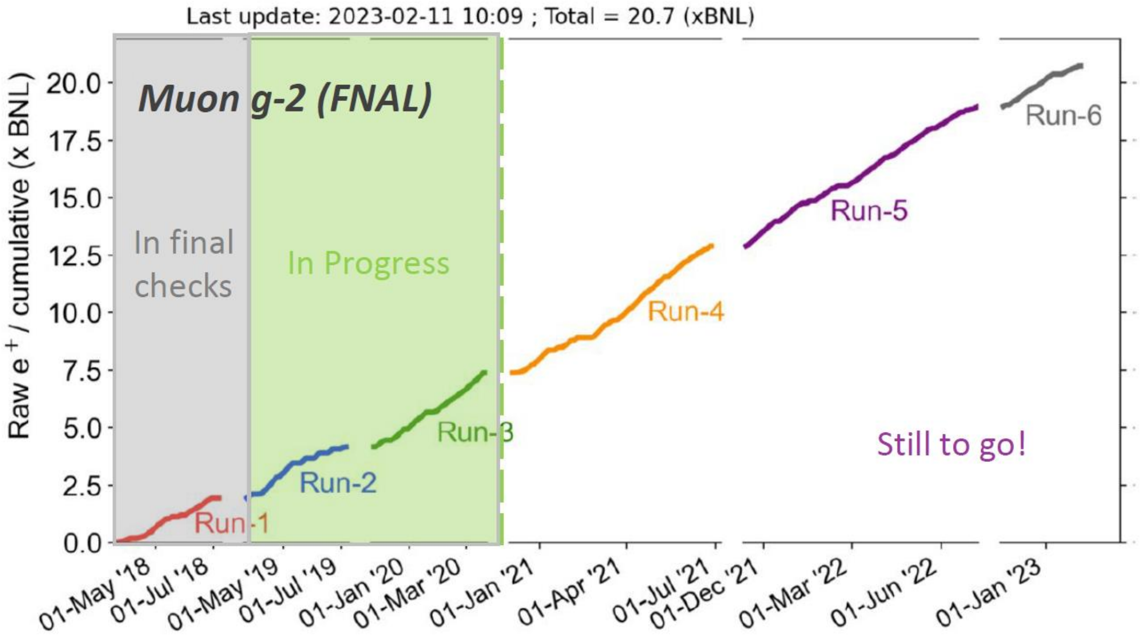
- Further refinements to the acceptance correction:
  - Maps limited by the statistics of the 'track vertex' MC sample.
  - Vary beam shape to selectively improve edge bins: maps become 2-3x more efficient.
  - Fitting maps to extract shape rather than interpolating between bins.





Timelines and what's next?

- Run 1: currently in collaboration review.
  - Still blinded, but unblinding soon (hopefully!)
  - Expecting a limit ~ BNL limit if zero central value.
- Run 2/3: still working on improvements.
  - ~ 3x better limit than Run 1 as-is, up to ~ 4x better after retracking + improvements.
- Run 4/5/6 + full dataset:
  - Our best data, both stats-wise and radial field measurement-wise.
  - Analysis starting soon, as data processing is recently complete.
  - Final result expected to improve vs BNL by an order of magnitude: ~ $2.0 \times 10^{-20}\ e \cdot cm$.

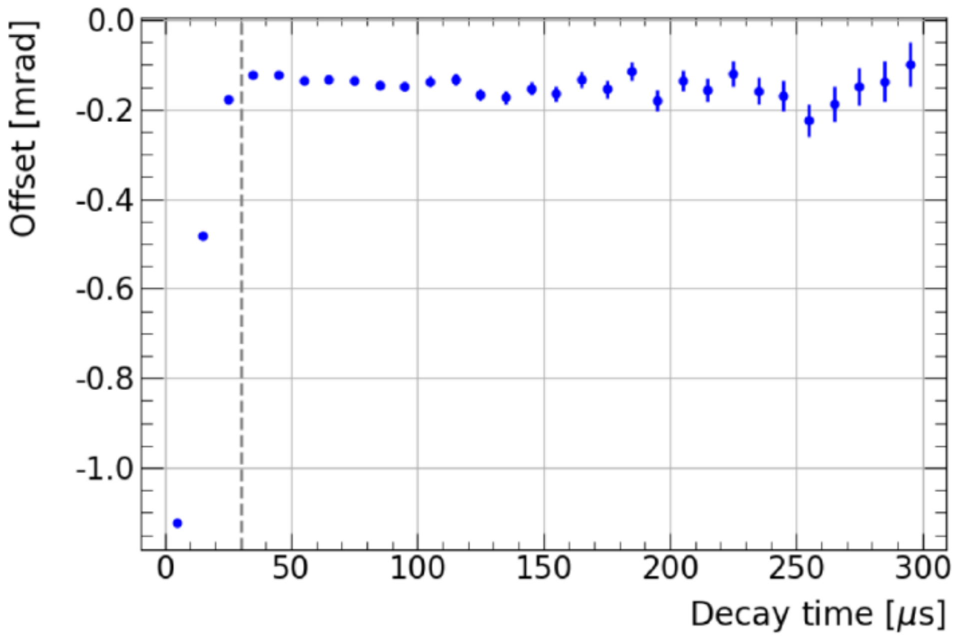


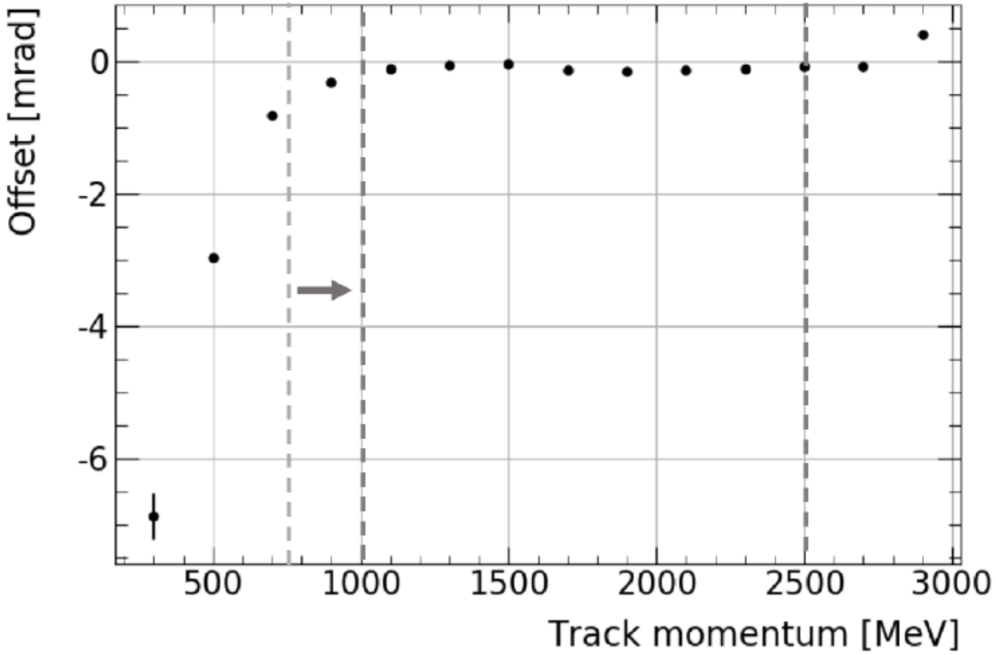
Bonus slides

Analysis cuts

- Most sensitive to an EDM in the mid-momentum ranges, so cut to maximise that sensitivity.

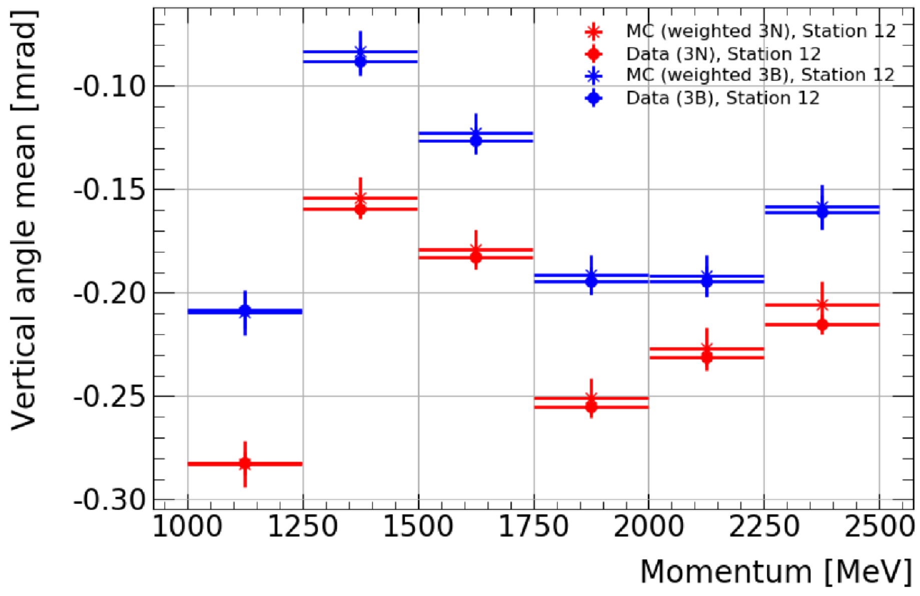
- Cut on time to minimise beam dynamics effects at early times, and statistical fluctuations at late times.

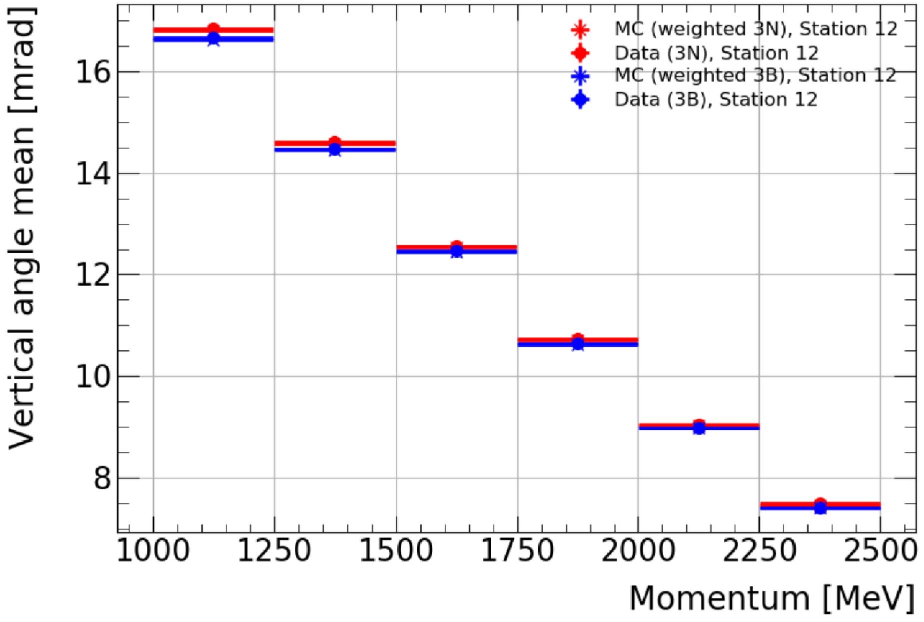




Data/MC differences

- 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.