Muon EDM searches at FNAL and PSI

Exploring BSM physics with muons workshop, 30/09/2024

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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):

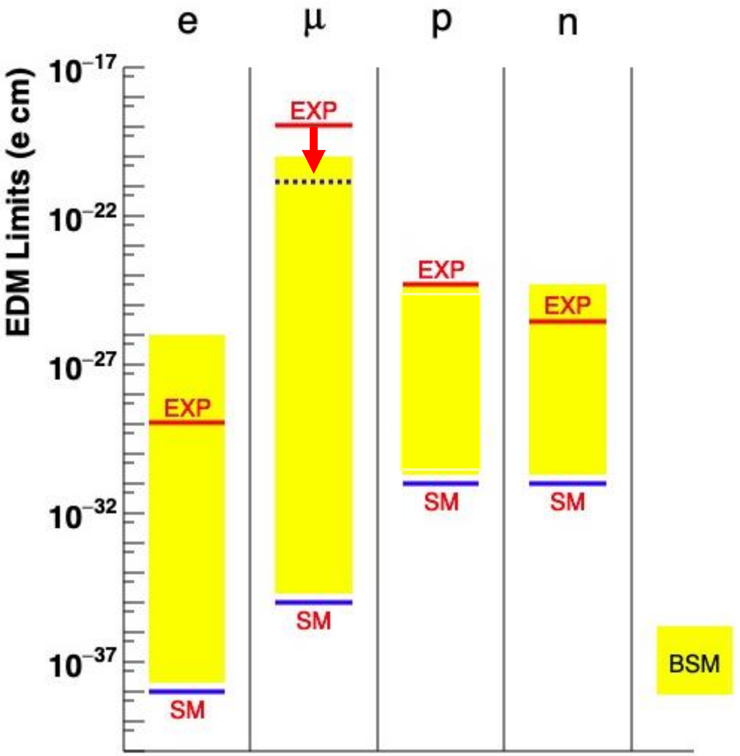
$$H = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$

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.

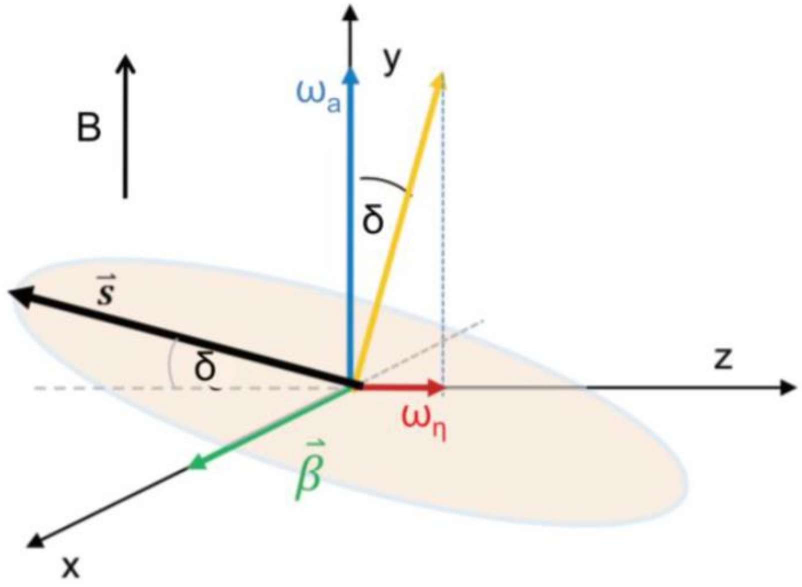
- Previous best limit was set at Brookhaven National Laboratory (BNL): **1.9** $\times$ **10^{-19}** $\boldsymbol{e \cdot cm}$.

Measuring the muon EDM

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

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

g-2 precession $\vec{\omega}_a$ EDM precession $\vec{\omega}_\eta$



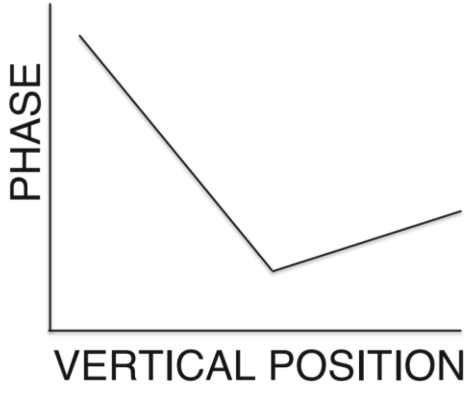
- **Two key effects:**
- A (very) small increase in the precession frequency.
- A second ‘tilt’ precession, π/2 out of phase with g-2 and perpendicular to it.

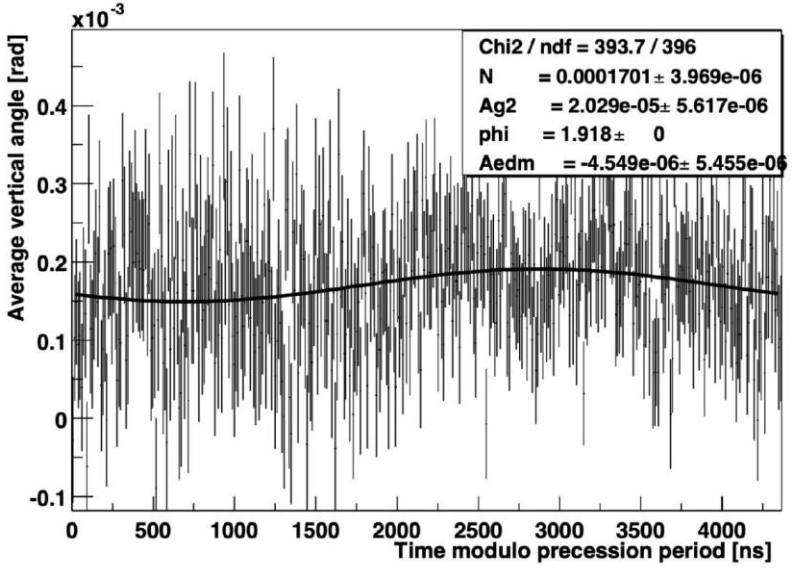
Fermilab g-2 experiment EDM signals

- **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.

- Tracker measurement periods match with g-2 analysis periods: Run 1, Run 2/3, and Run 4/5/6.





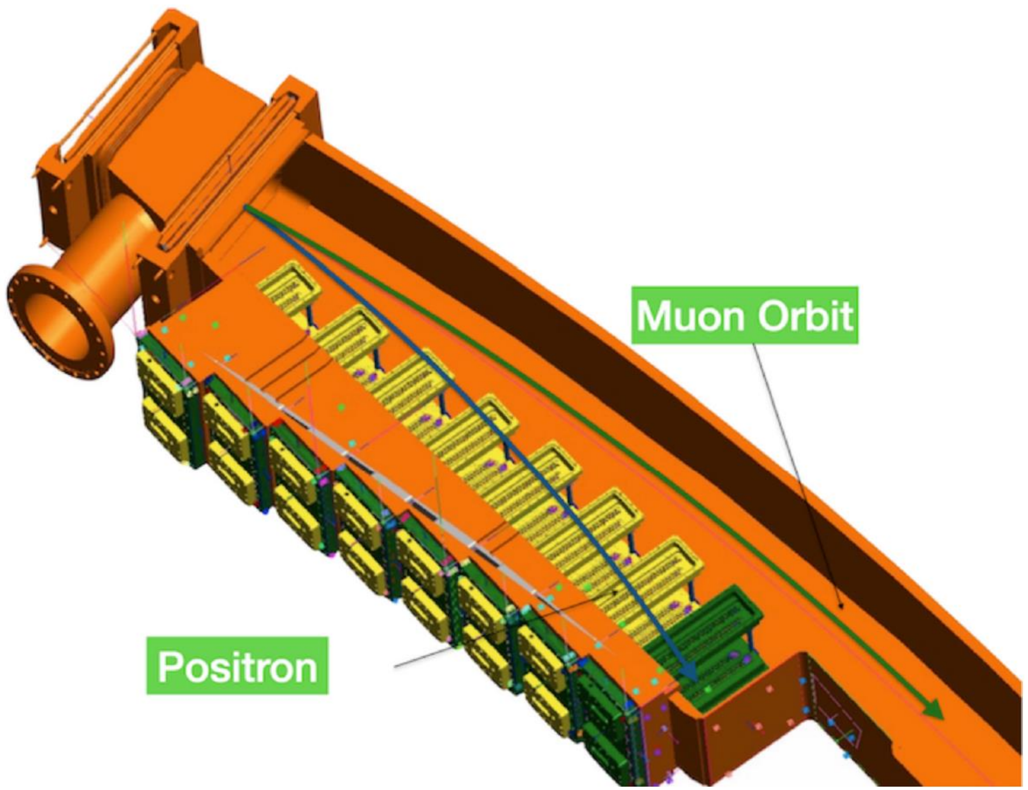
BNL 2000 data

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.

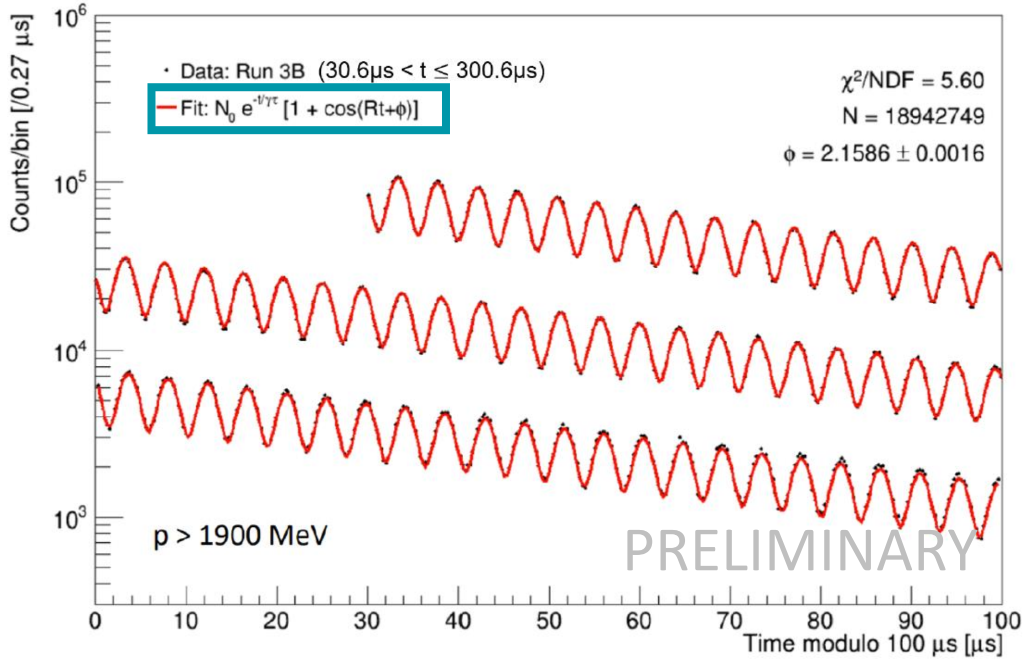
- Hits are fitted into tracks, which are then extrapolated back to the vertex of decay (used for the EDM analysis to measure the angle) and forward into the calorimeters.

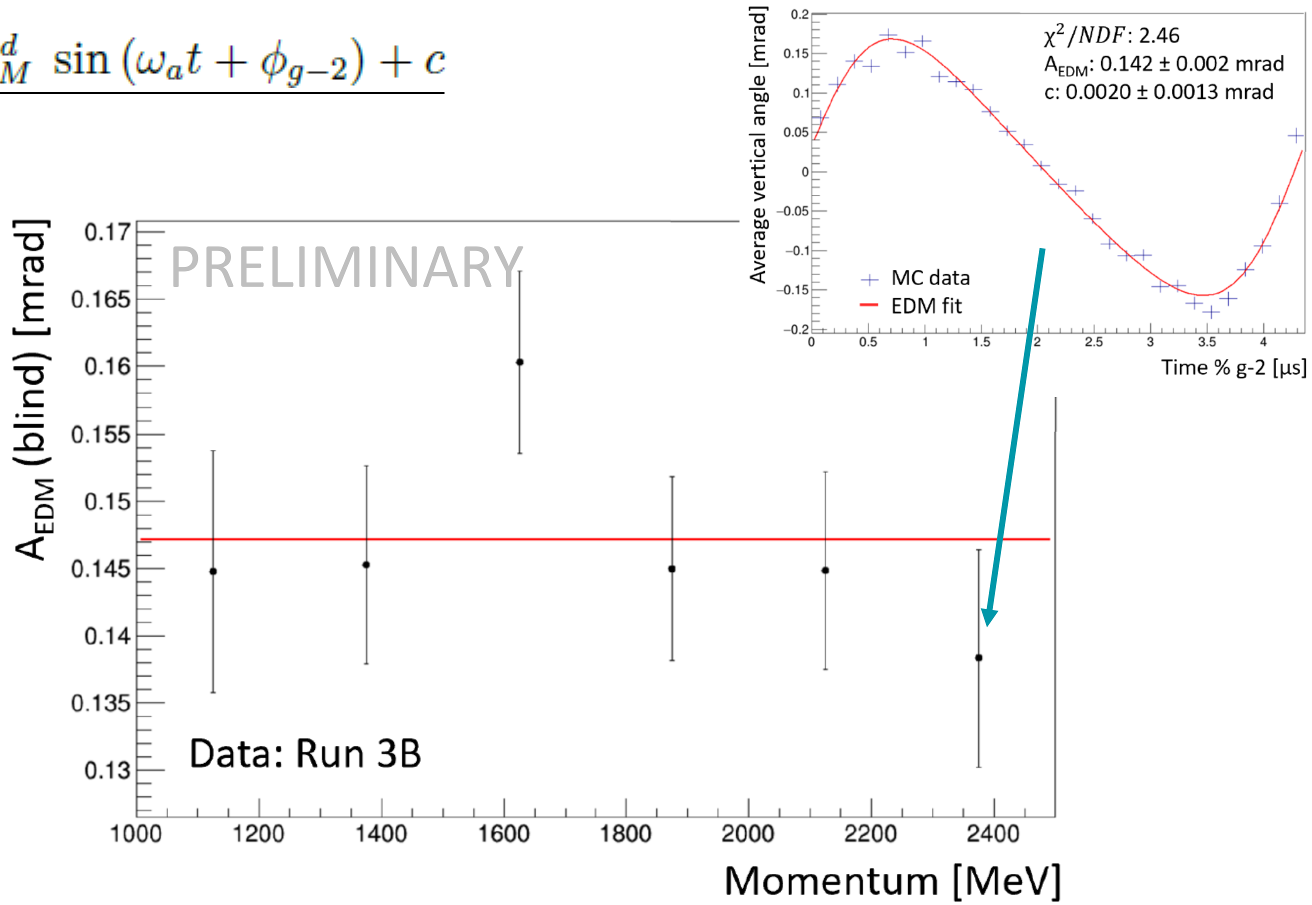


Extracting the EDM signal

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

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

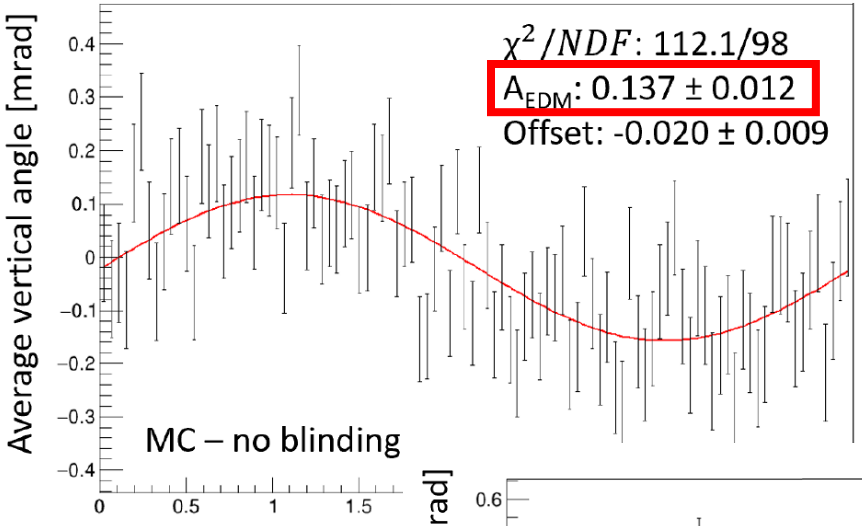


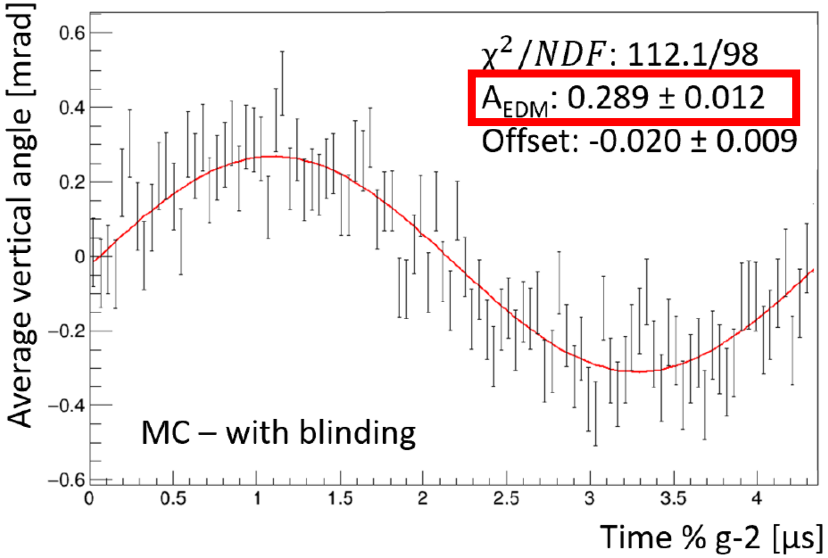


Blinding

- 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.



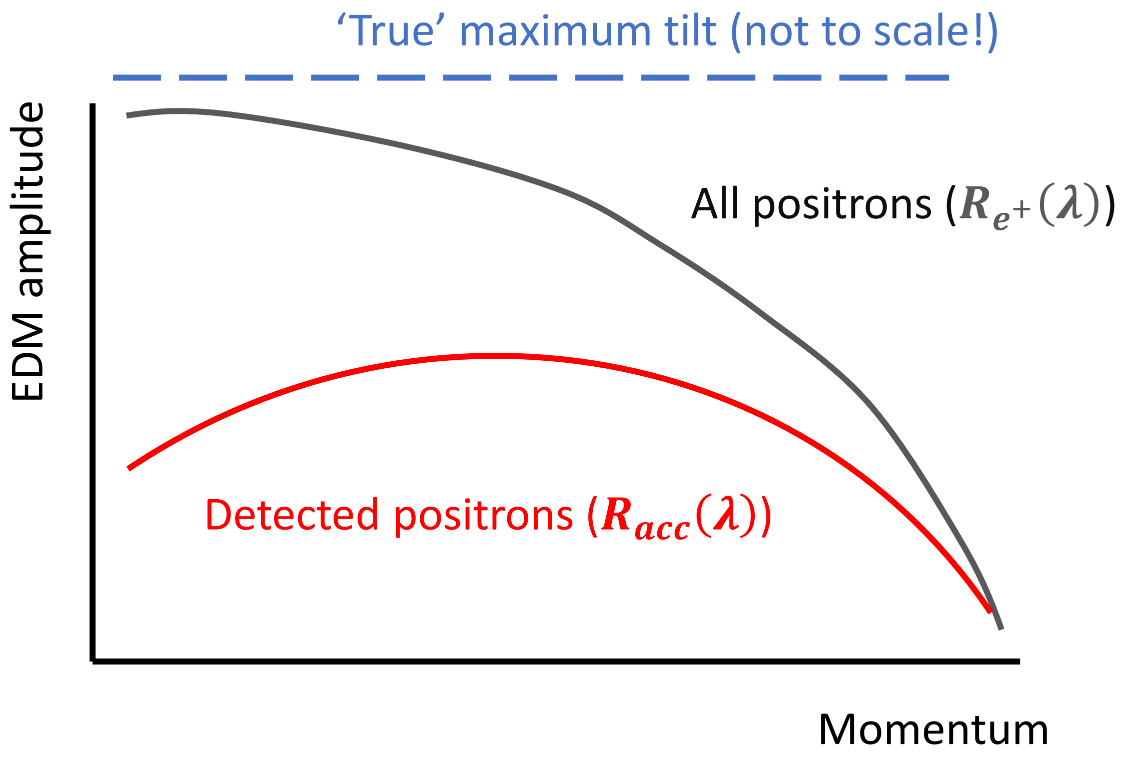


Reductions to the measured vertical angle

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

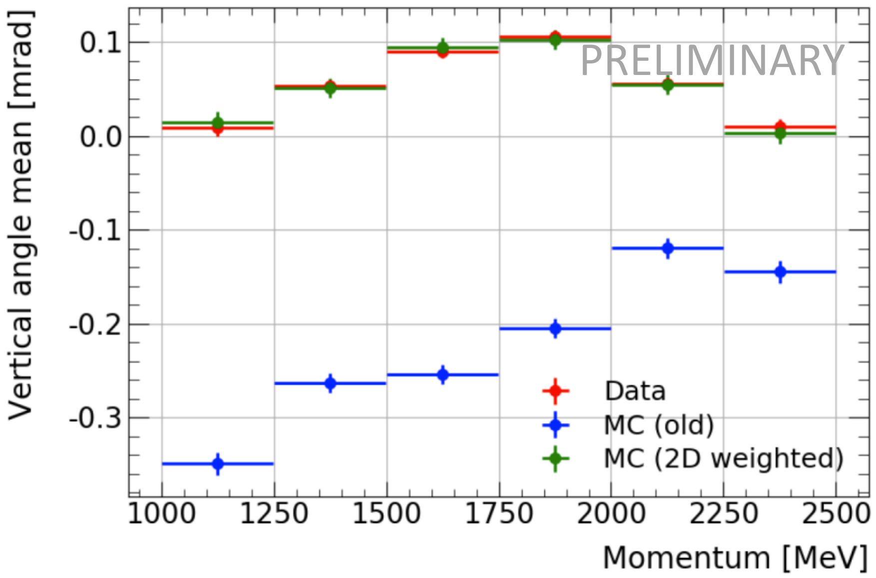
$$\text{Measured tilt} = R_\gamma \, R_{e^+}(\lambda) \, R_{acc}(\lambda) \text{ True tilt}$$

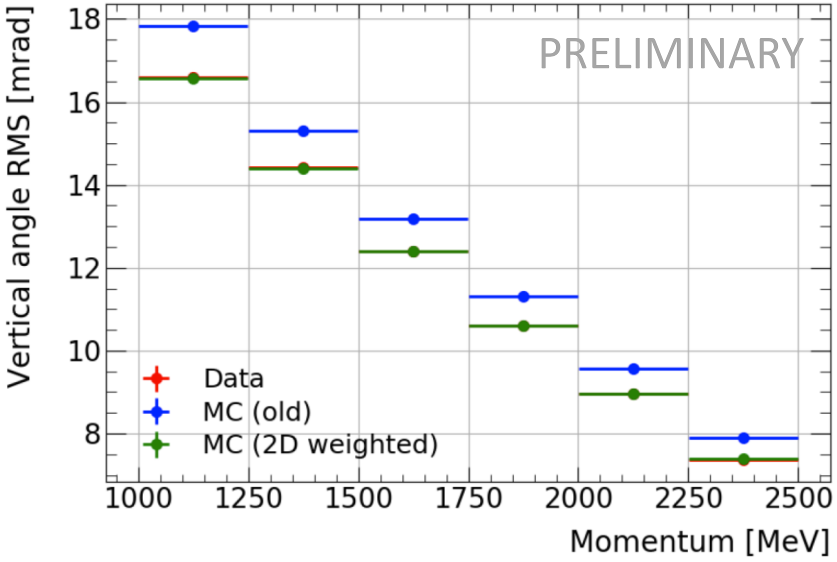
- R_γ : boost factor from muon rest frame to lab frame.
  - Factor is 1/γ, so ~ 1/29.
- $R_{e^+}(\lambda)$: muon decay asymmetry shape.
  - Has an analytical form, f(λ) where λ is fractional momentum, calculated up to first order radiative corrections.
- $R_{acc}(\lambda)$: acceptance effects, from the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



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%).

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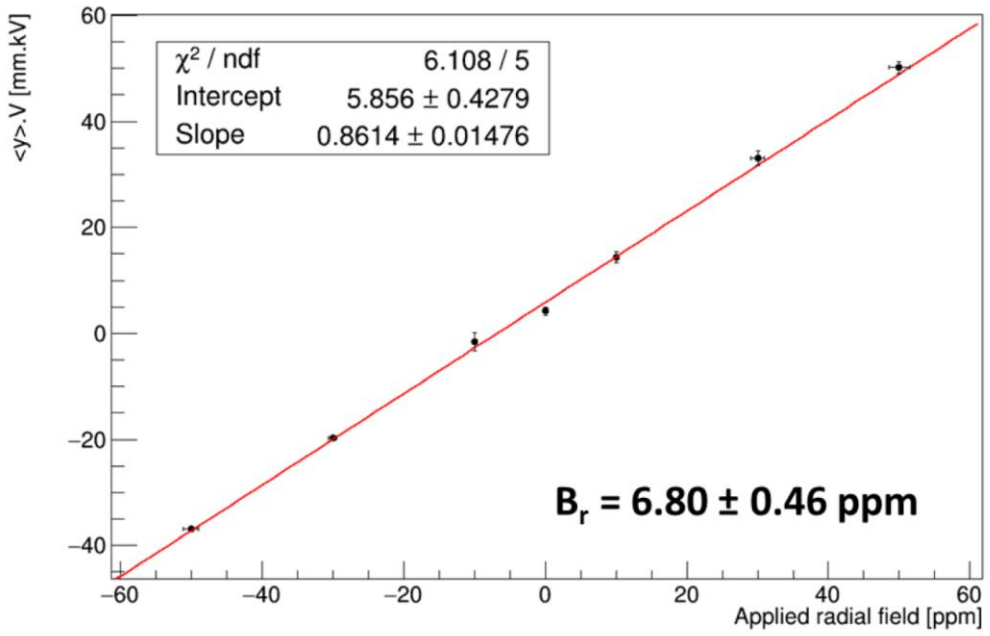
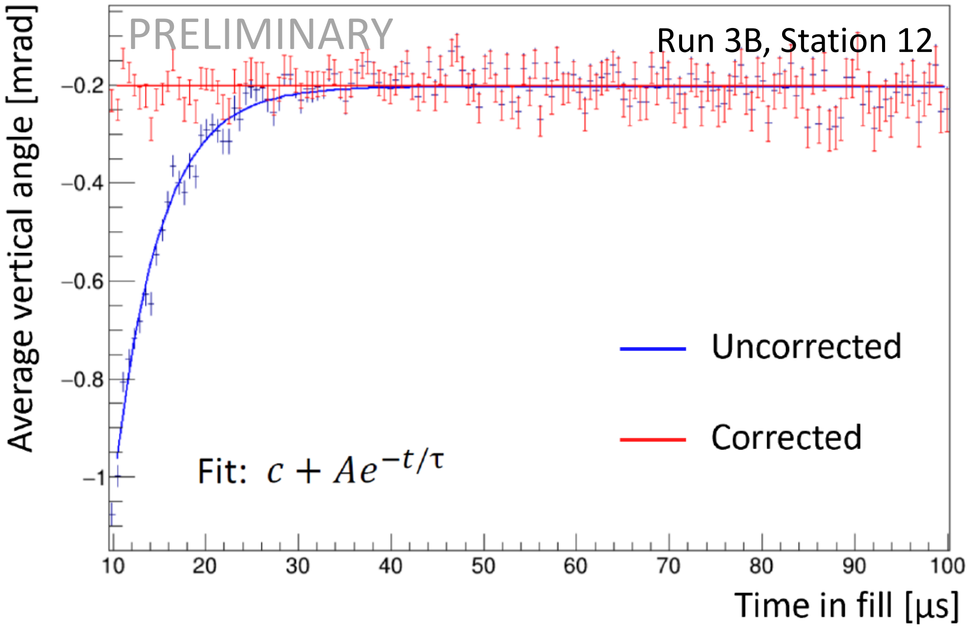
Other systematic uncertainties

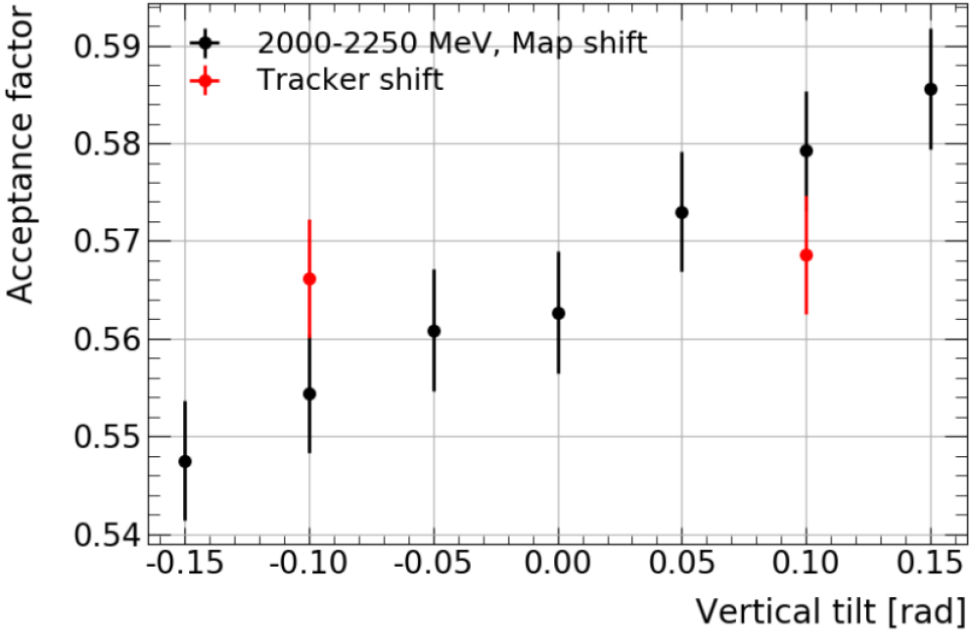
- A non-zero radial field component will also tilt the precession plane:
  - Must be measured very precisely – dedicated ‘radial field scans’ were run during data taking for this.
  - Scans give an uncertainty < ~ 1ppm, which is good enough to not limit the analysis.
- Recent beam dynamics studies show the impact of the radial field is ~ 30x smaller than naïve B_r/B tilt – good news!
- Other potential sources of fake EDM being investigated, such as an interplay between a varying tracker efficiency and acceptance.
  - Aim is to put an upper bound on any effects like these.



Other systematic uncertainties

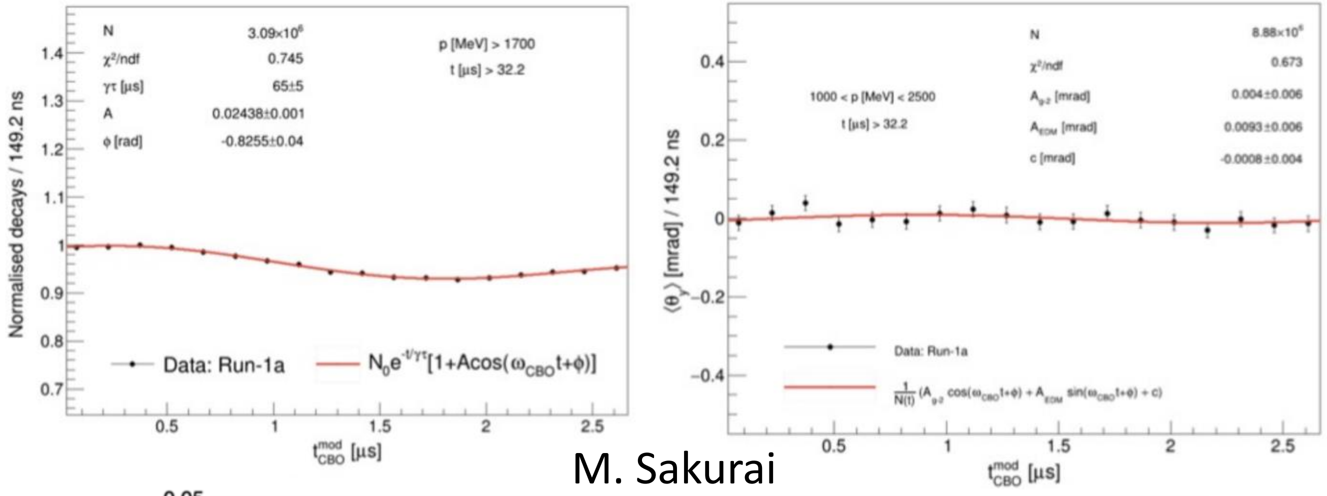
- Current dominant systematic uncertainty is from the $R_{acc}(\lambda)$ correction.
  - This is essentially a statistical uncertainty on the MC run to calculate the relevant ratios.
- Plenty of other systematics: correction fit uncertainties, tracker alignment, tracker resolution.
  - All << statistical uncertainty, refinements still ongoing for anything ~ $R_{acc}(\lambda)$!

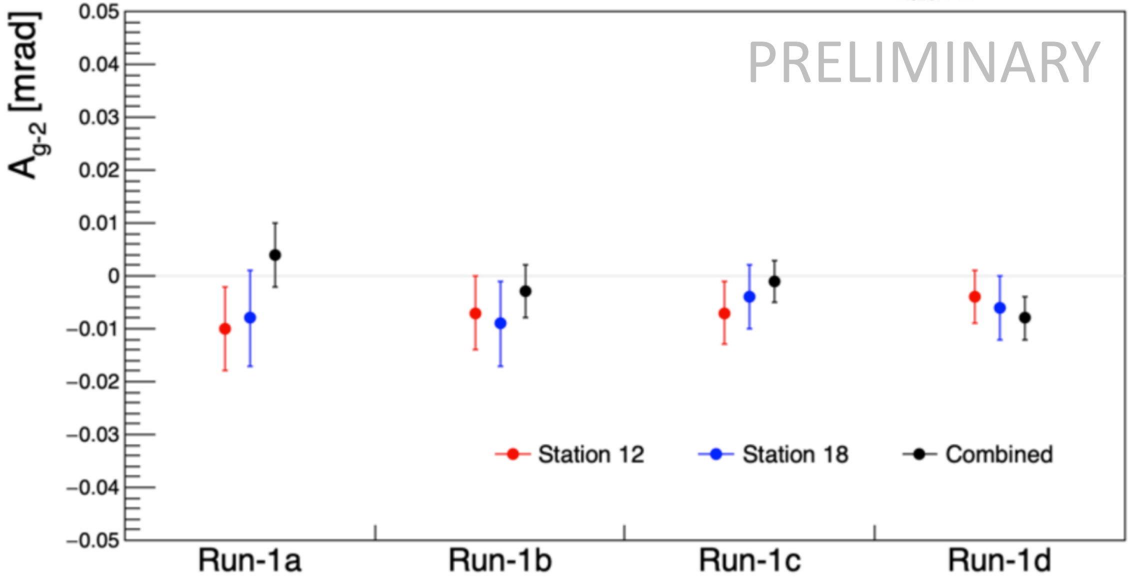




The ω_{CBO} cross-check

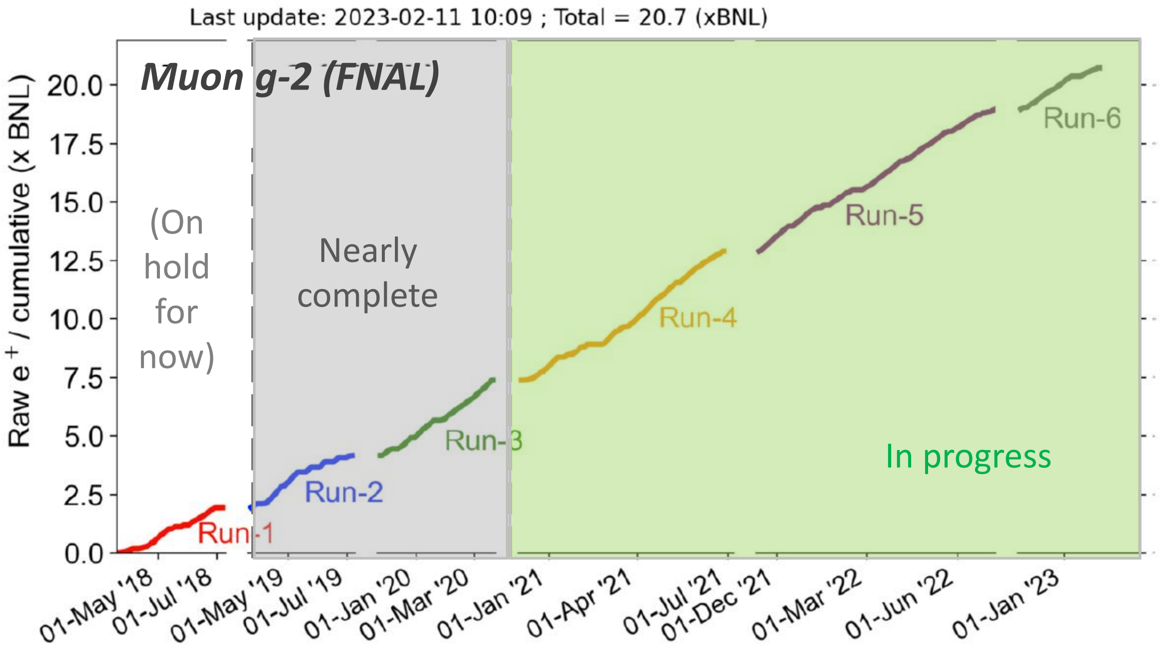
- Plot the vertical angle modulo another frequency and fit for an oscillation at that frequency but out of phase with it.
- We choose a known radial beam frequency, the coherent betatron oscillation (CBO) for this.
- Should give amplitudes of zero!
- For Run 1: unblinded fits do indeed give zero amplitude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





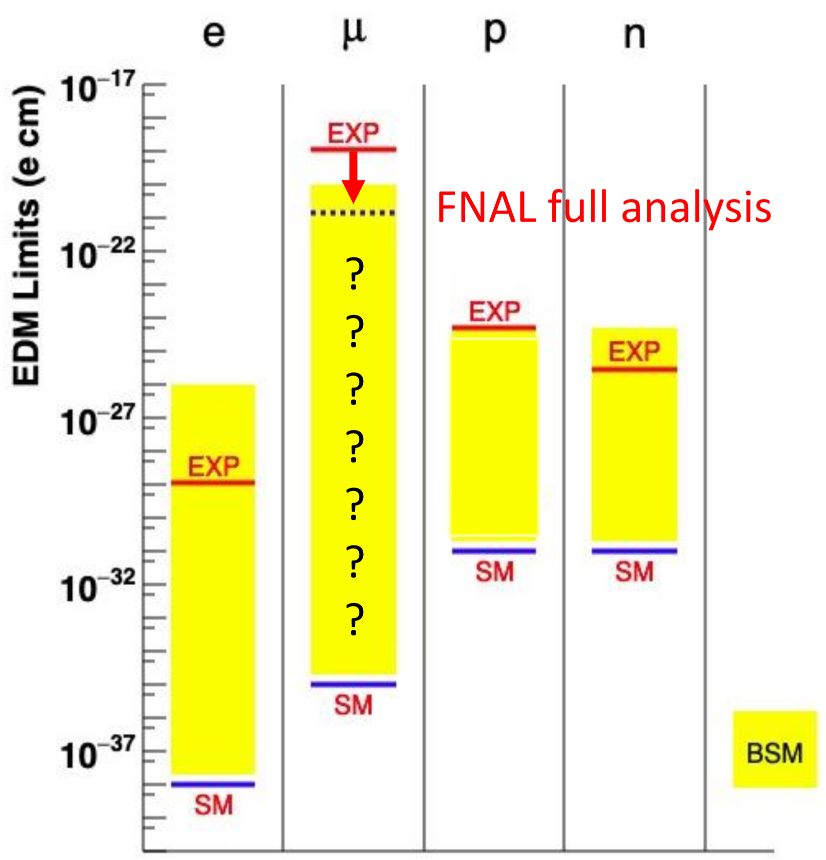
Timelines for FNAL analysis

- Run 1: ‘complete’, but still blinded
  - Collaboration review completed, feedback mostly feeding into improvements for Run 2/3.
- Run 2/3: the main focus, nearing completion
  - ~ 3x better limit than BNL as-is, up to ~ 4x better after retracking + improvements.
  - First draft note being sent for collaboration review soon.
- Run 4/5/6 + full dataset:
  - Analysis started, but focusing on Run 2/3 currently to get our first EDM result out.
  - Final result expected to improve vs BNL by an order of magnitude: ~ $2.0 \times 10^{-20}\ e \cdot cm$ (in the absence of a signal).



The next step: muEDM at PSI

- The FNAL measurement will set new world limits, but plenty of BSM phase space to go!
- FNAL method nearing its boundaries of what is ‘measurable’ – EDM signal is small and challenging to detect.
- Next step needs to be a dedicated muon EDM experiment, designed to maximise the signal – muEDM at PSI.



How to get more sensitive?

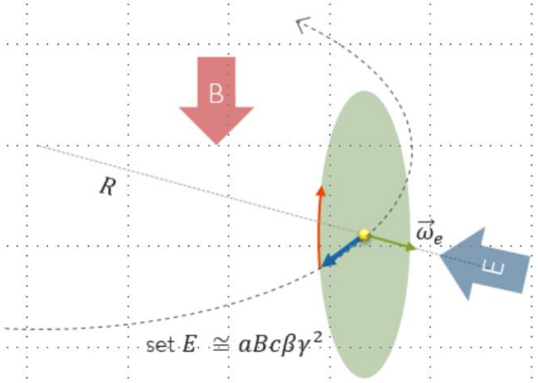
- Frozen spin method designed to improve the sensitivity to an EDM by ‘removing’ the g-2 oscillation with radial E fields:

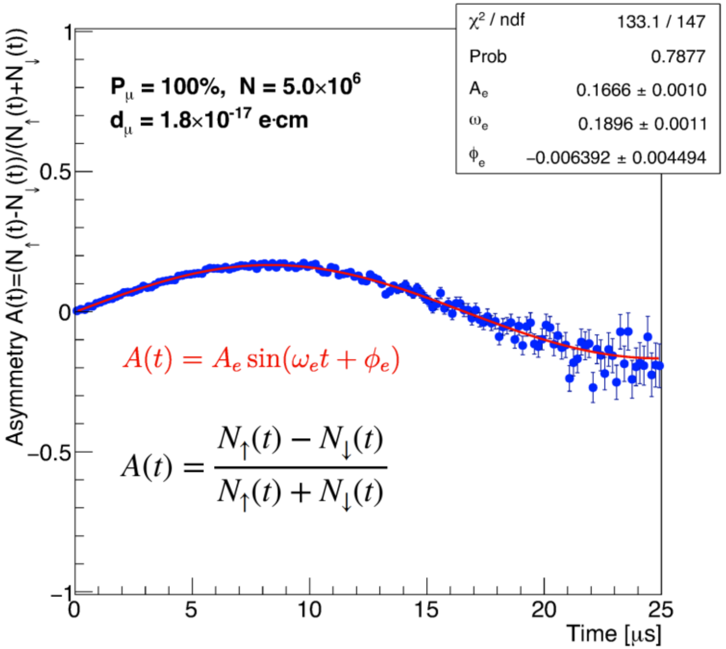
$$\vec{\omega} = -\frac{q}{m}\left[a_\mu \vec{B} + \left(\frac{1}{1-\gamma^2} - a_\mu\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{2d_\mu mc}{q\hbar}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

g-2 precession $\vec{\omega}_a$ EDM precession $\vec{\omega}_\eta$

- Spin then ‘follows’ the momentum, and the vertical precession moves in a perpendicular circle.

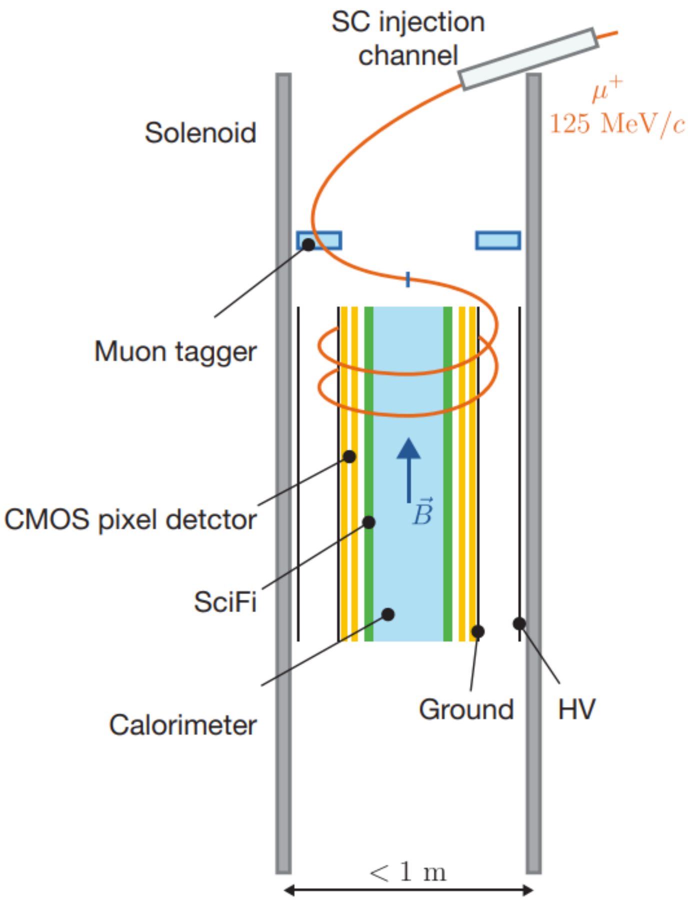
- Signal is a slowly varying vertical asymmetry:
  - Due to frozen g-2 precession, every positron contributes – need fewer overall decays for good sensitivity.





Design of PSI experiment

- Inject polarized μ+ at p = 125 MeV/C – one at a time - into a solenoid, which provides a weak focusing field for storage.
- Magnetic kicker to guide muons into stable orbit
  - Pulsed ~ 80ns after injection to cancel longitudinal motion along the cylinder.
- Radial E field tuned to cancel g-2 precession, generated by cylindrical electrodes.
- Positrons from decay follow a circular path outwards, detect and measure to analyse the decay:
  - Measure momentum to detect g-2 precession (to confirm/tune frozen spin).
  - Measure position along the cylinder to determine asymmetry.



MuEDM's two phases

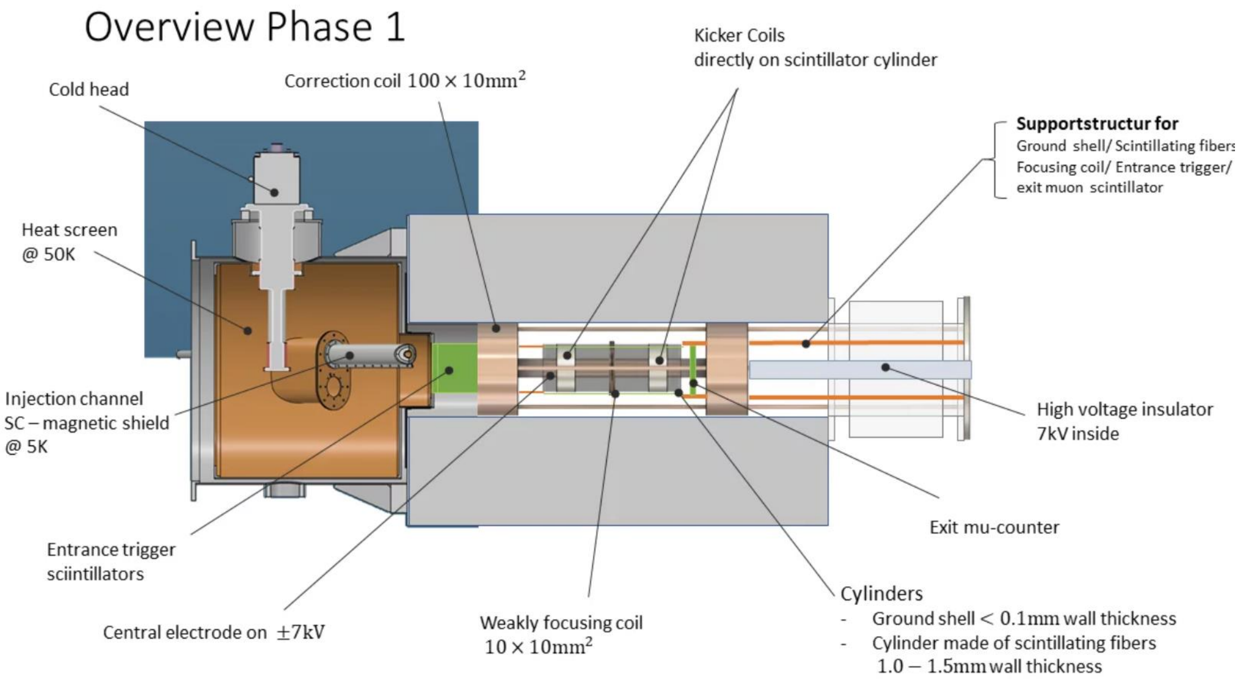
- **Phase I (ongoing):**
- Precursor experiment, to demonstrate that the spin can be frozen, and to make a first measurement of the muon EDM.

- **Phase II:**
- Using a dedicated magnet with a large bore hole and excellent temporal stability and spatial uniformity.
- Set final limit ~ 10^{-23} e.cm – only needs ~ a year of data taking to achieve this!

(Something like this one!)

Phase I in more detail

- Using existing solenoid magnet at PSI, field of 3T.
- Muons at ~ 28 MeV/c (due to limits in size of the magnet's central hole).
- 'Simpler' detector solutions – scintillating fibres and tiles.
- Aim to set limit ~ $3 \times 10^{-21}\ e \cdot cm$ with initial measurement – already an order of magnitude better than FNAL's limit.

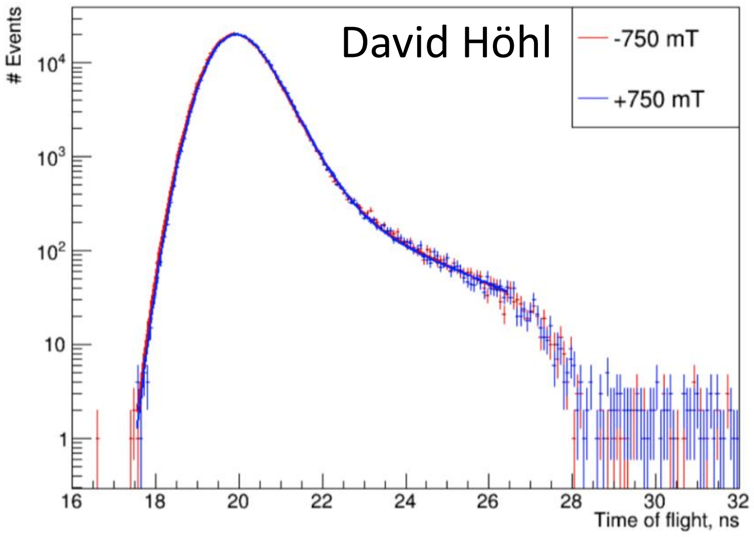


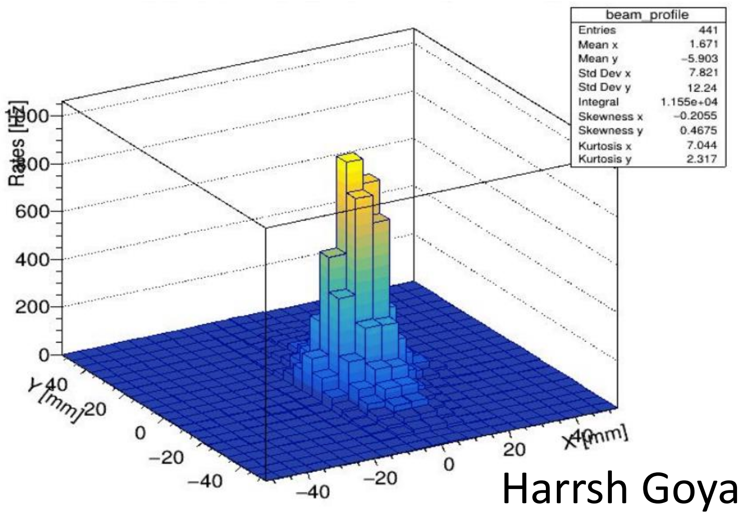
Lots of recent activity!

- Test beams at PSI over the past year + simulation work for beamlines, potential systematics:
  - Major systematic from E field with a perpendicular component (tilts precession, so g-2 precession looks like EDM).
  - Mitigated by comparing counter-rotating beams (needs momentum/field stability in both B-field setups).

- Last December: testing injection momentum control, beam monitoring, fringe fields and shielding.
  - Tests suggest 0.5% momentum control is achievable.
  - +tive/-tive beam time of flight distributions within 0.2%.

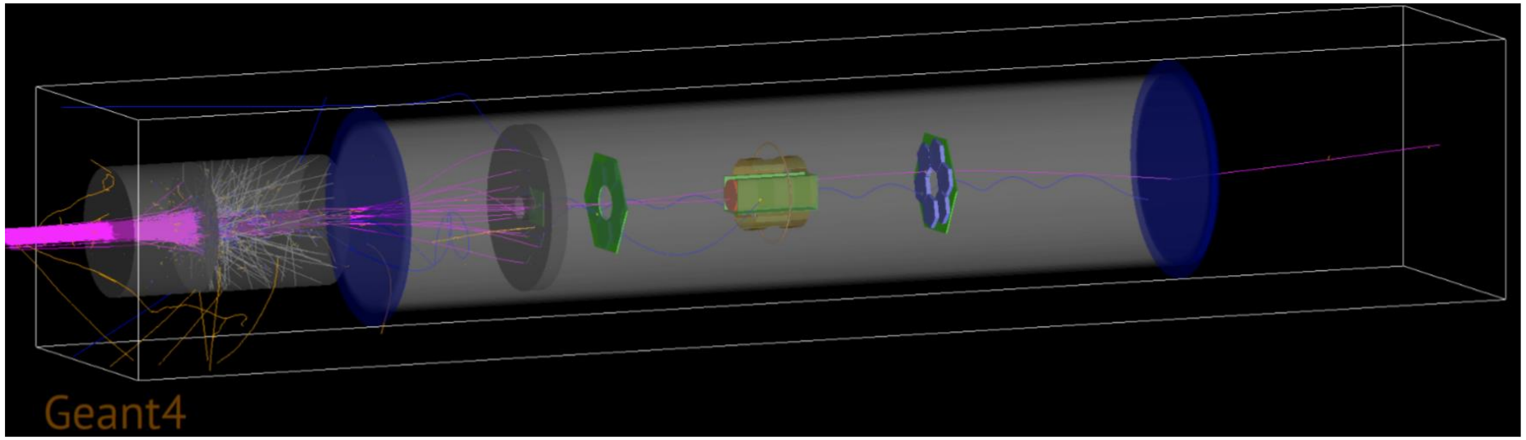
- June: PSI muE1 ‘z-configuration’ beam 4D phase space characterisation – investigating feasibility of running multiple experiments (including muEDM) on one beamline.
  - Twiss parameters etc. successfully extracted.

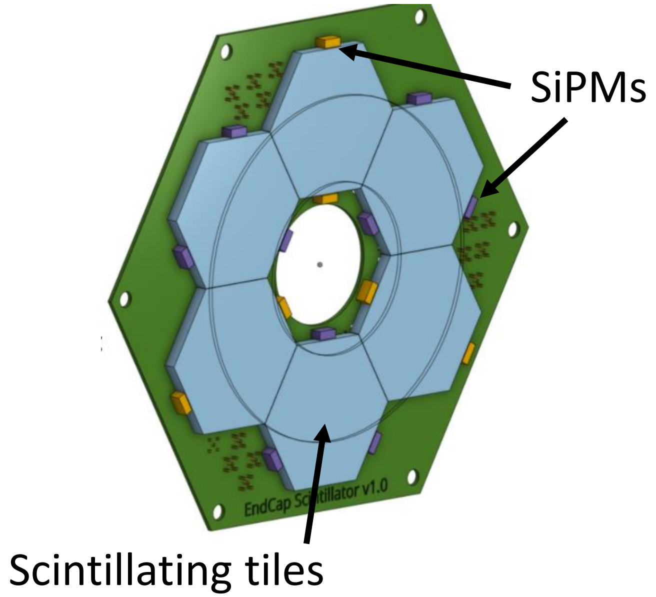




Lots of recent activity!

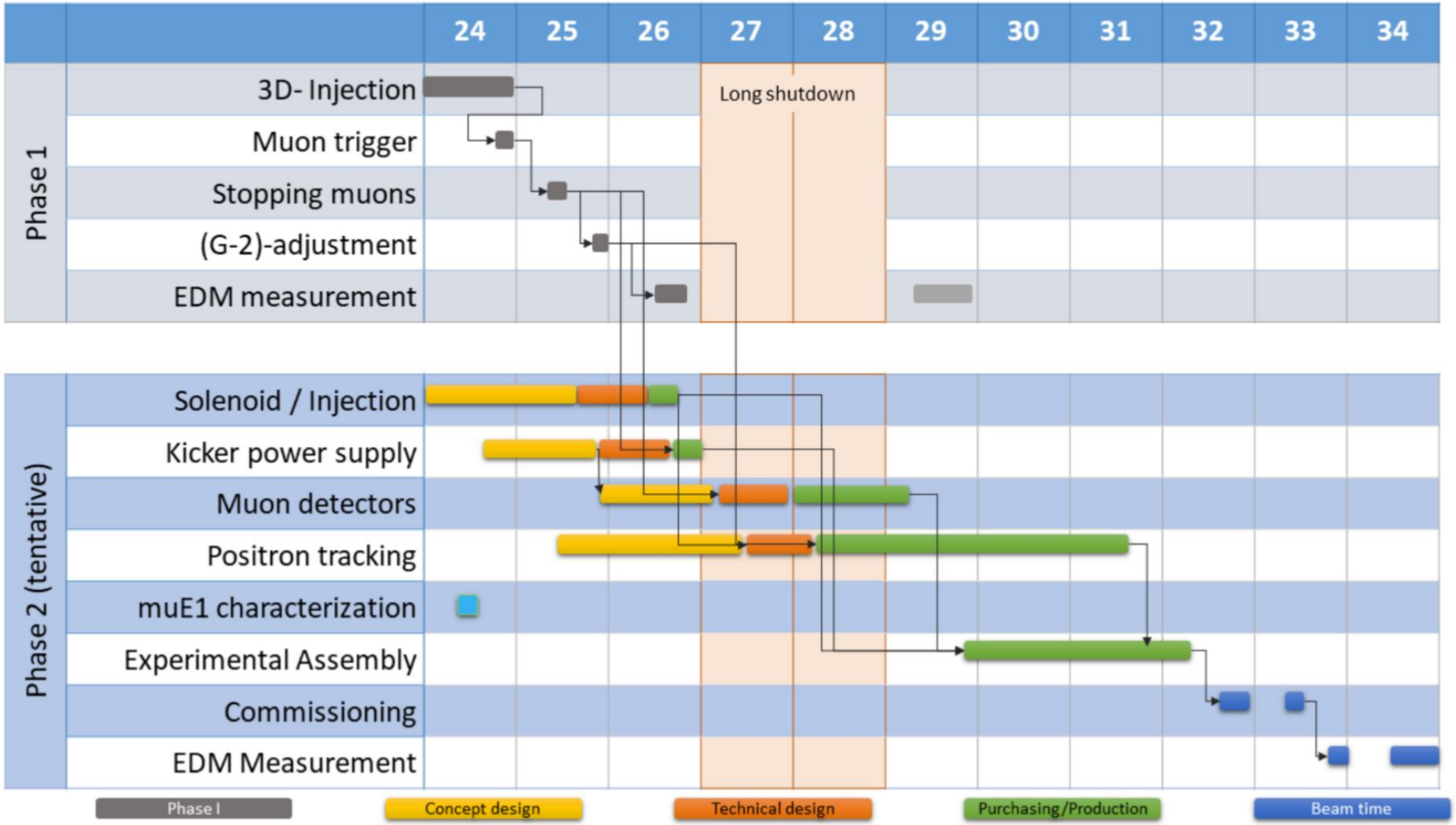
- Sept (now!): Measure potential asymmetry changes in upstream/ downstream detectors due to kicker pulsing.
  - Could give a slow time effect which looks like an EDM asymmetry.





Tentative muEDM schedule

- Targeting a first EDM measurement with phase I before the PSI long shutdown.



Conclusions and outlook for muon EDM

- Muon EDM measurement at Fermilab:
  - Run 2/3 analysis the current focus, expecting to complete final checks in the next few months.
  - First EDM result with improve on BNL limit by factor of ~ 3-4.
  - Final result from Runs 2-6 in the next year or so, final limit ~ $2.0 \times 10^{-20}\ e \cdot cm$.

- Muon EDM measurement at PSI:
  - Lots of R&D ongoing for phase I currently, which will demonstrate frozen spin + set a new EDM limit ~ $3 \times 10^{-21}\ e \cdot cm$.
  - Planned phase II with dedicated magnet + best possible detectors: final limit ~ $6 \times 10^{-23}\ e \cdot cm$.

- An exciting time for muon EDMs, with many improvements over the next few years!