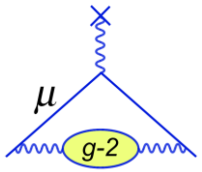
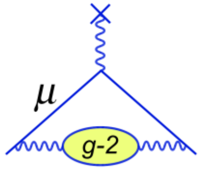


Searching for a muon EDM at the new g-2 experiment at Fermilab

IOP HEPP/APP conference, April 2022

Dominika Vasilkova

Muon dipole moments



- Particles in an electromagnetic field interact with it via an intrinsic magnetic dipole moment (MDM) and hypothetically could interact via an 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:

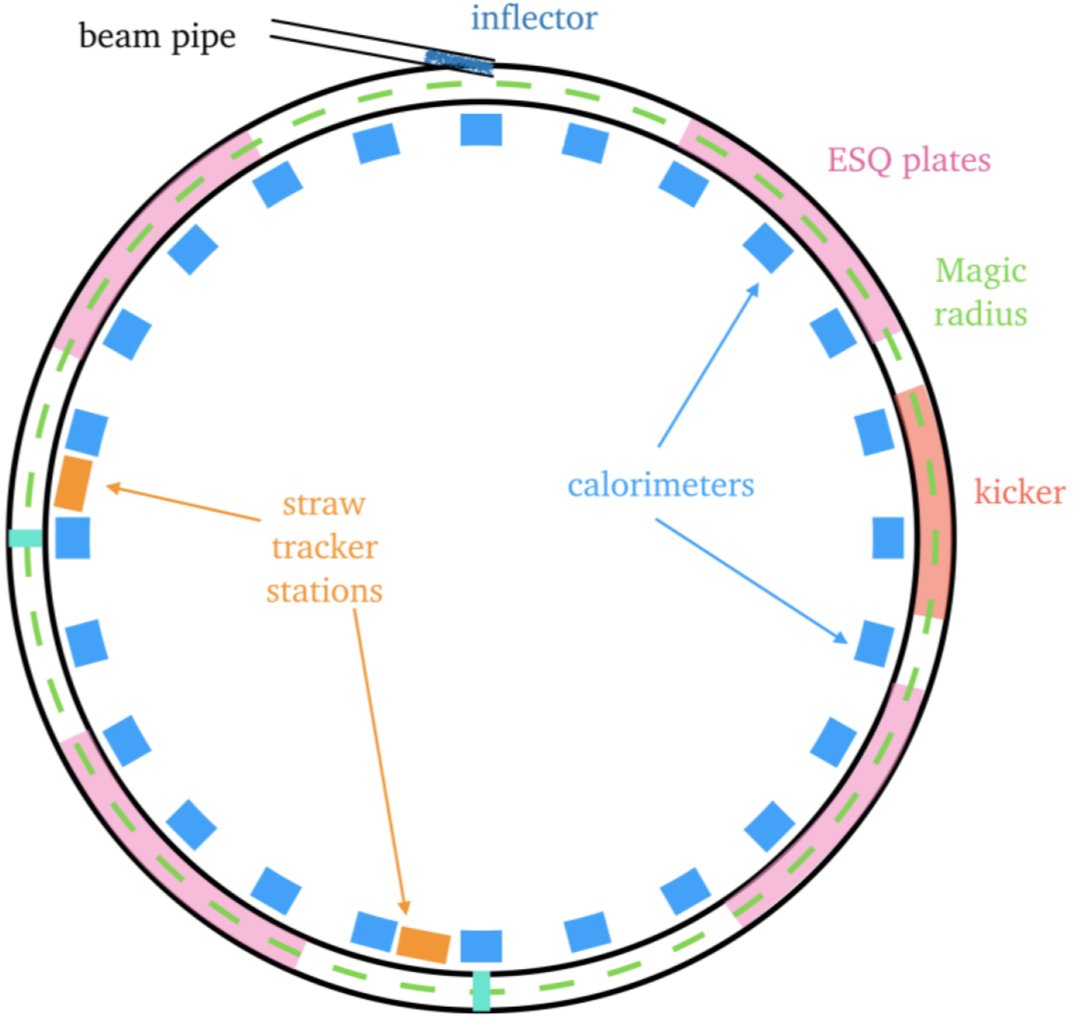
$$\vec{d} = \eta\frac{Qe}{2mc}\vec{S}$$

- The muon EDM is interesting because:
  - The electron EDM has a limit of $8.7\times10^{-29}\ e \cdot cm$ - suggests the muon EDM (via mass scaling) should be $< 10^{-27}\ e \cdot cm$ – well below the range of current experiments!
  - **d.E** is CP-odd, so an EDM observation would give a **new source of CP violation** in the lepton sector!

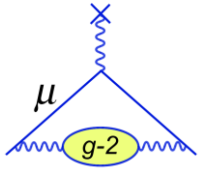
- For the muon, the previous best limit was set by Brookhaven National Laboratory (BNL) as **$1.9 \times 10^{-19}\ e \cdot cm$.**

The new g-2 experiment at FNAL

- Polarised 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 analyse the decay with 24 calorimeters + 2 straw tracker stations.



How do we look for an EDM?

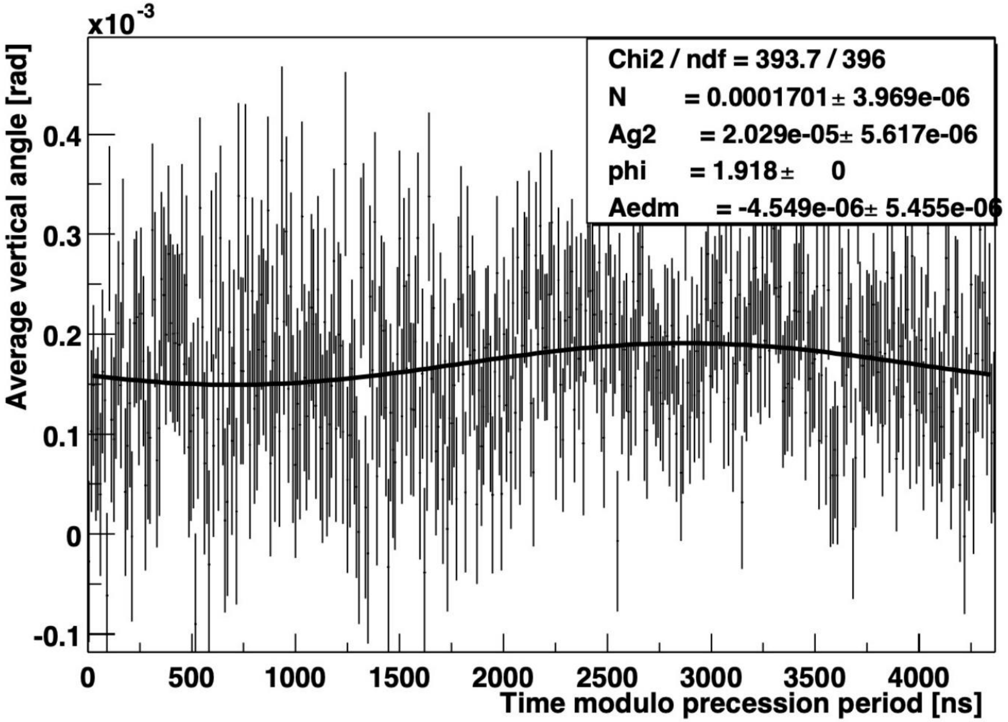


- An EDM tilts the precession plane – can detect by looking at the **average vertical angle in the trackers.**

- Previous tracker result statistically limited, and FNAL is aiming for a 21-fold improvement in stats.
    - Many more tracks – FNAL trackers can turn on sooner, are placed in the vacuum closer to the beam.

- FNAL EDM analysis aim is an improvement on the old limit of two orders of magnitude (~ 10^{-21} $e \cdot cm$).

BNL
(2000 dataset)

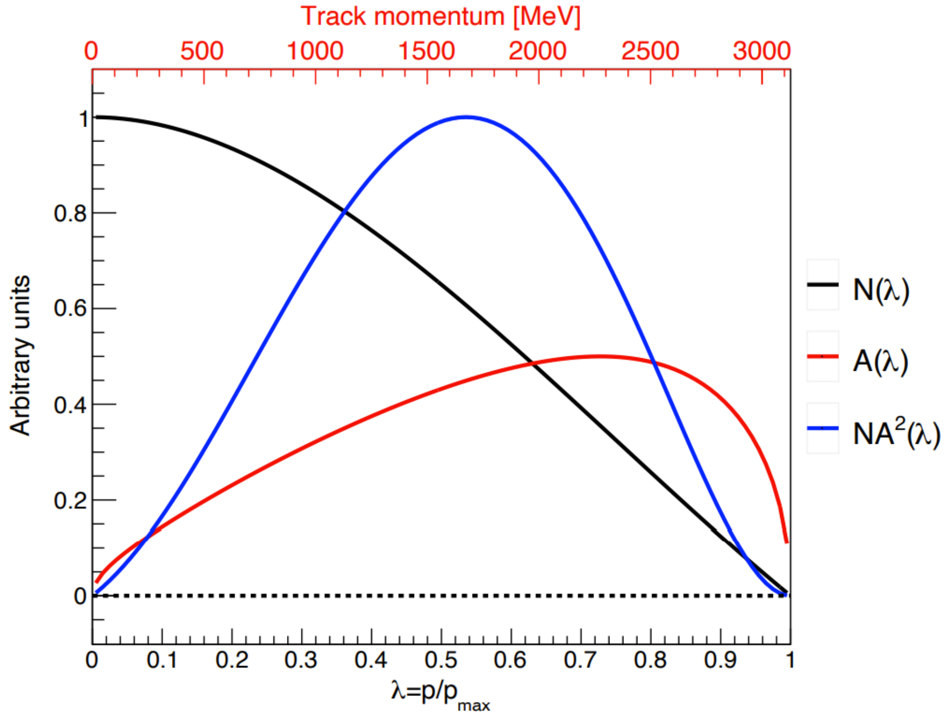


Largest hurdles for the tracker analysis

- **Radial field:**
  - Tilts the precession plane, introducing a 'fake EDM' signal.
  - Uncertainty on this tilt contributes to EDM uncertainty – important to measure well!

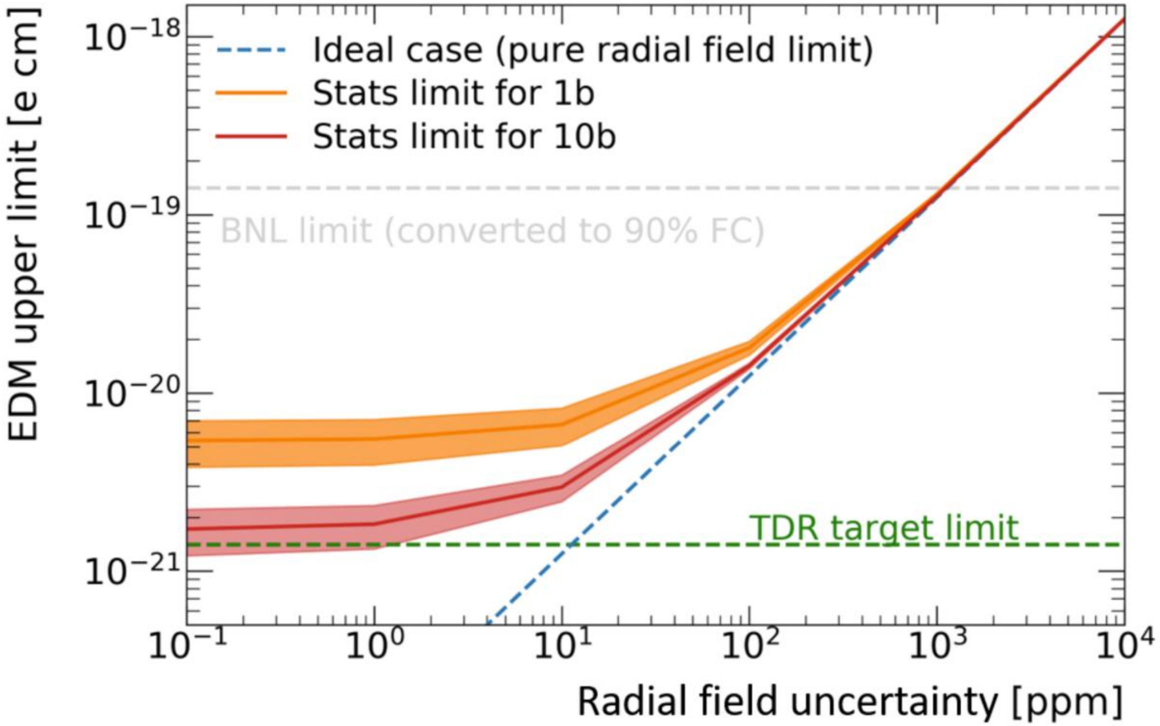
- **Acceptance and dilution:**
  - Not all positrons emitted along the direction of maximum tilt.
  - Not all positrons will reach the trackers and be detected.
  - Both effects momentum dependent and quite complex – correction estimated from simulation.

- **Statistical uncertainty –** need good quality tracks to reliably extrapolate to the vertex.



Predicted EDM sensitivity

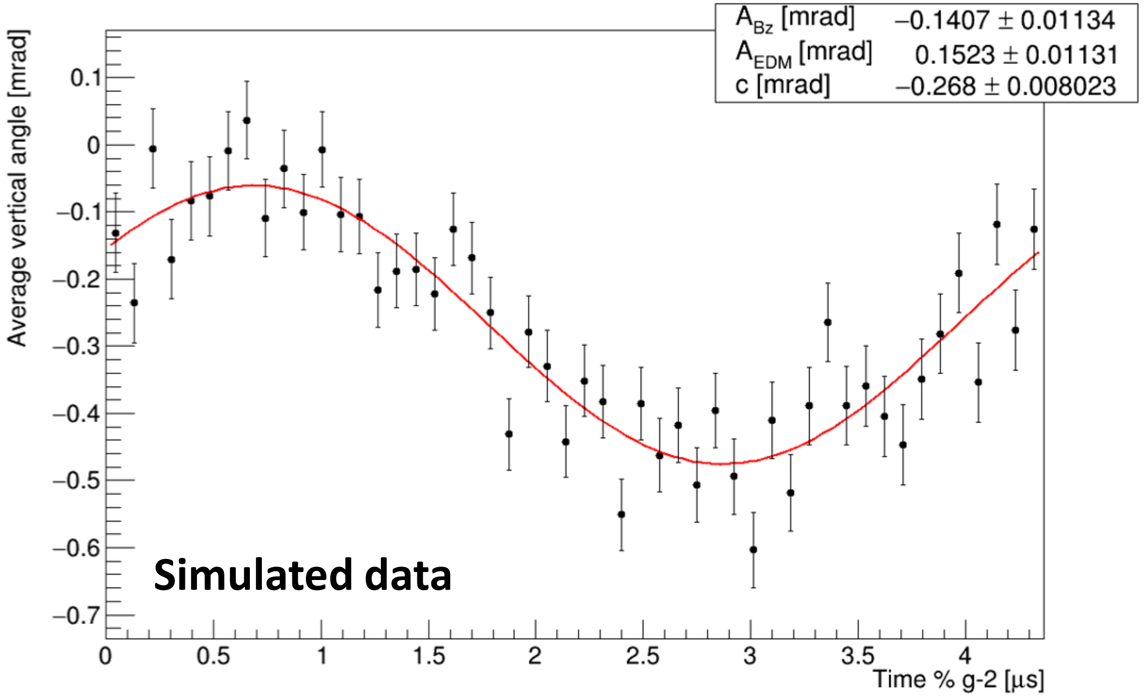
- Generate simulated tracks to make a 'whole experiment' size dataset + analyse.
- Simulate the impact of main sources of uncertainty to find which limits the analysis.
- Found we are limited by the radial field first, followed by the statistical uncertainty, so better measurements of the radial field were needed to achieve best results.
- Target limit of O(10^{-21} $e \cdot cm$) achievable.



Fitting the average vertical angle

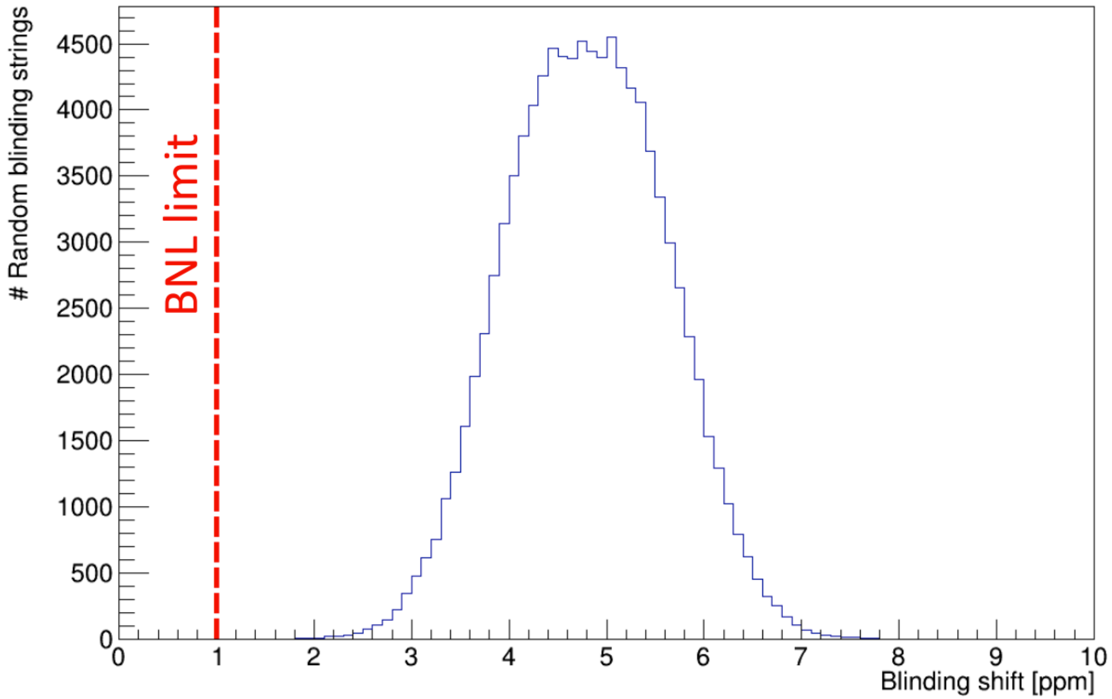
- Mid-momentum cuts to maximise the sensitivity.
- Plot modulo the g-2 period – overlays oscillation, and averages out any other oscillations at the wrong frequency (e.g. beam motions).
- Fix phase and frequency.
- Longitudinal magnetic field also tilts the plane, but in phase with g-2 – so fit simultaneously for both an in phase component and an out of phase component:

$$A_{EDM}\ \sin(\omega_a t + \ \phi) + A_{Bz} \cos(\omega_a t + \ \phi) + c$$



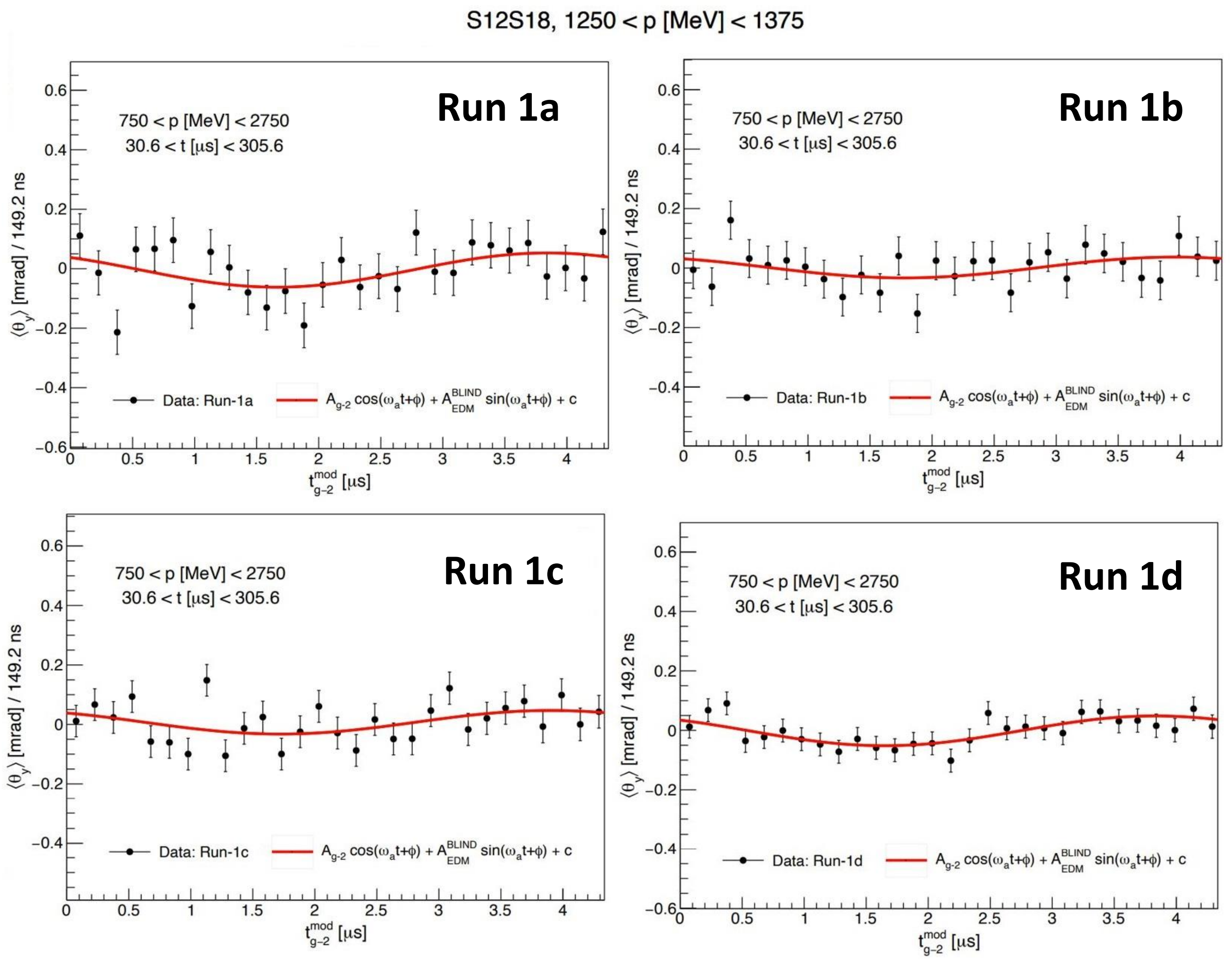
Keeping the analysis blind

- Important to not bias analysis, work ‘blind’ similarly to the MDM analyses.
- Hide ‘true’ oscillation by injecting fake signal of unknown amplitude – sampled from a distribution designed to give amplitude >> BNL limit.
- All analysis done with blinded data, once complete can unblind.
- Tested with MC data.



Status of analyses – Run 1

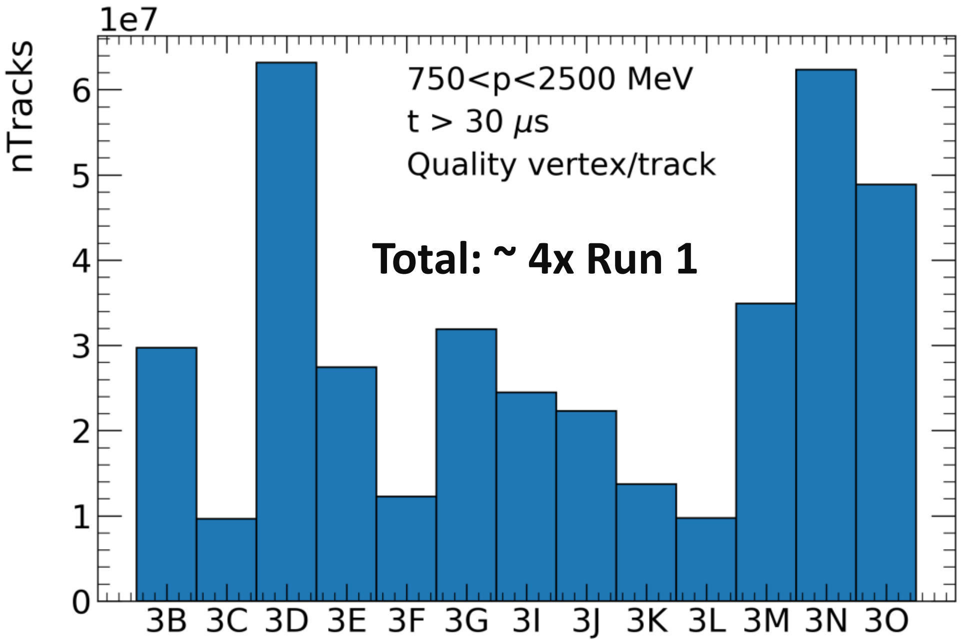
- Radial field estimated from mean vertical beam position – known to sufficient precision to be stats-limited.
- Blind fits for the EDM amplitude produced simultaneously in mid-range momentum bins.
  - Due to momentum-dependent dilution, this increases sensitivity to EDM
- Dilution factor from decay and tracker acceptance investigated in MC, corrections applied to data.
- **Final result expected to be as least as strong as BNL limit.**

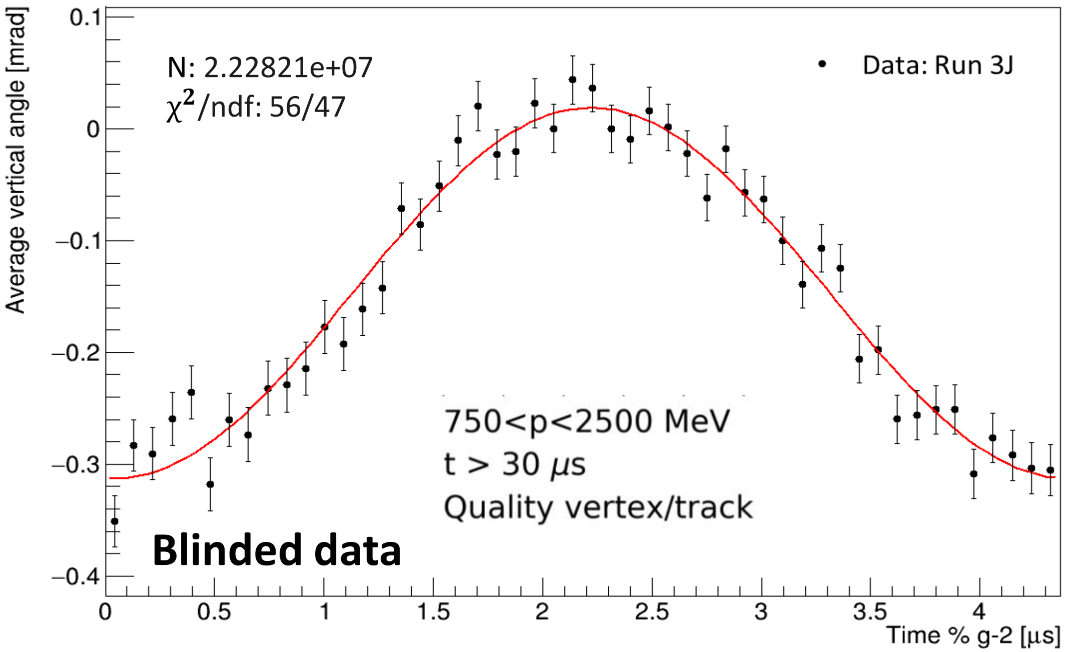


Status of analyses – Run 2 and 3

- Run 2/3 analysis just started - expected to have significant increase in tracks vs Run 1, likely still statistics-limited but systematics become more important.

- Simple mid-momentum fits for EDM amplitude and longitudinal field produced:



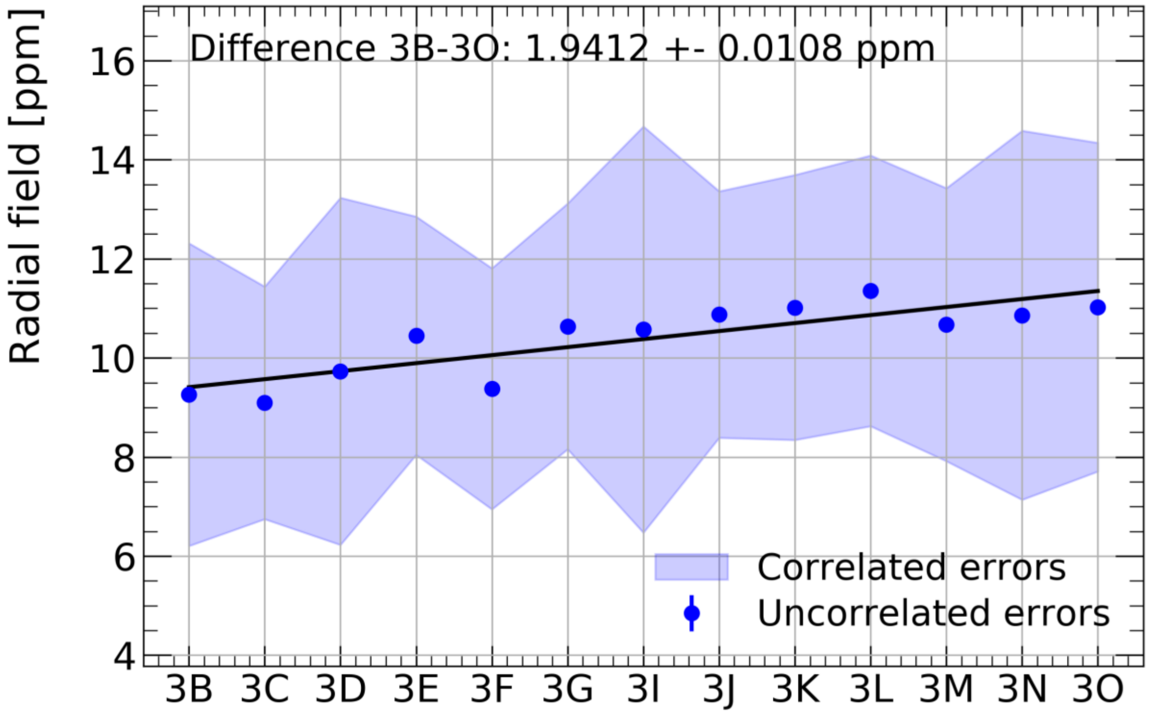


Status of analyses – Run 2 and 3

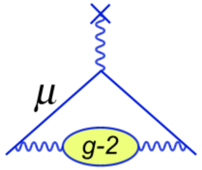
- Radial field estimated for Run 2 and Run 3, with a drifting radial field found in Run 3.

- Very small change, but does move the beam vertically, which leads to a changing tracker acceptance.
  - Needs to be well understood, as leads to drifts in other fit parameters as well as a change in the correction needed.

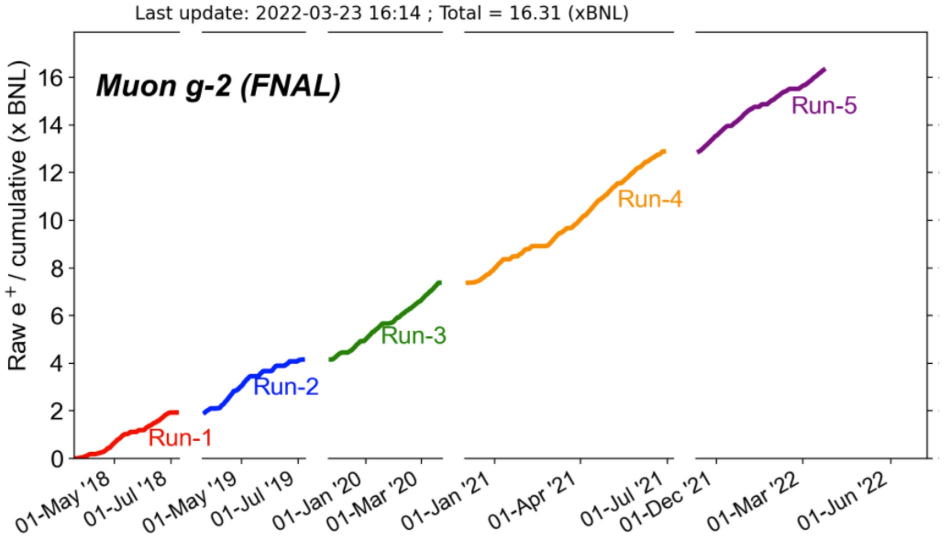
- Once this is understood, a full momentum-binned analysis can be performed.



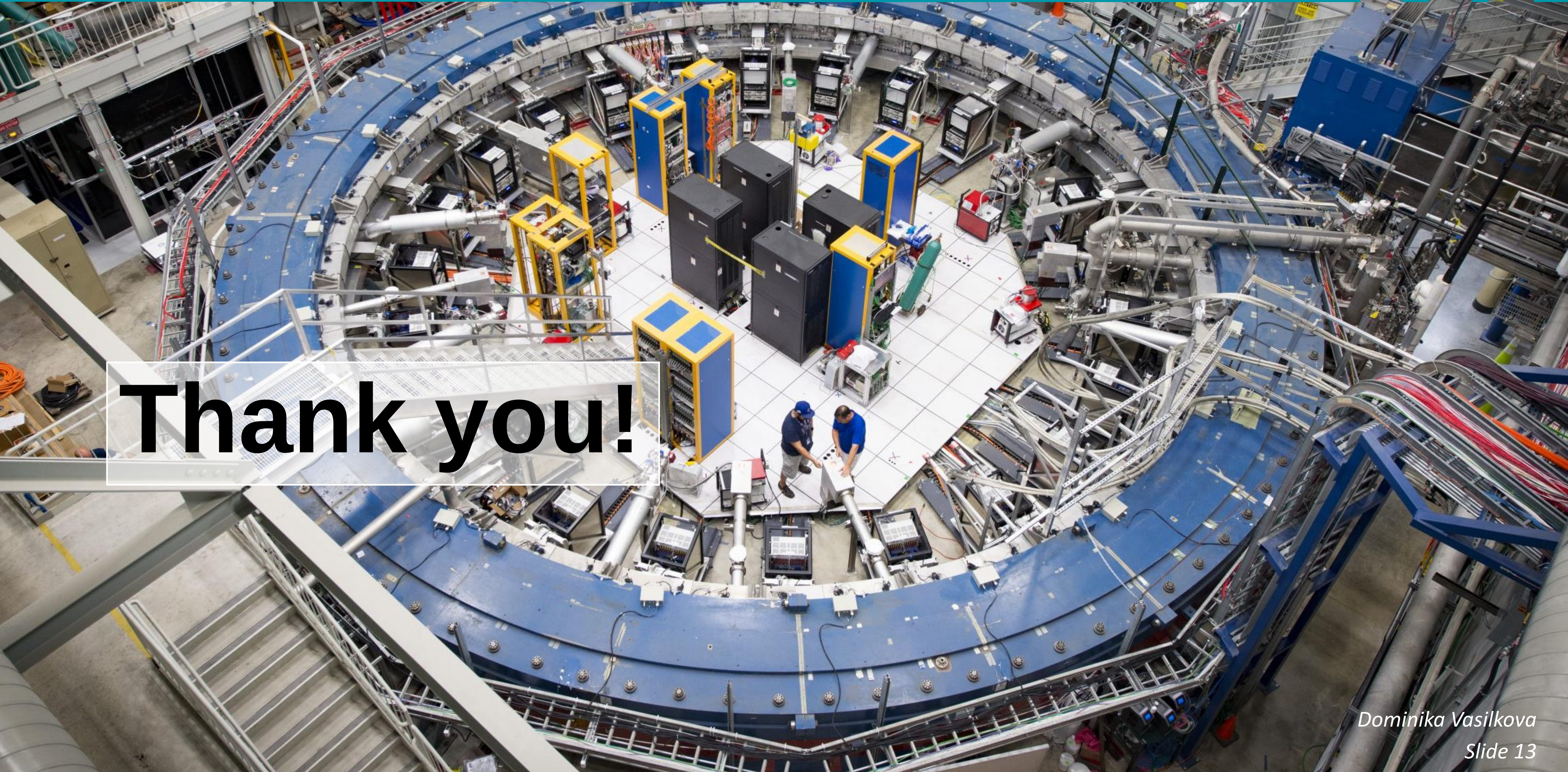
Conclusions and outlook



- A secondary physics goal of FNAL g-2 is to measure the muon EDM, to improve the previous limit set at BNL.
- Run 1 and Run2/3 analyses underway, together will improve on the BNL limit.
- Still lots more data to go – Run 4 and Run 5.
- Overall, on track to set a world-leading limit on the muon EDM.



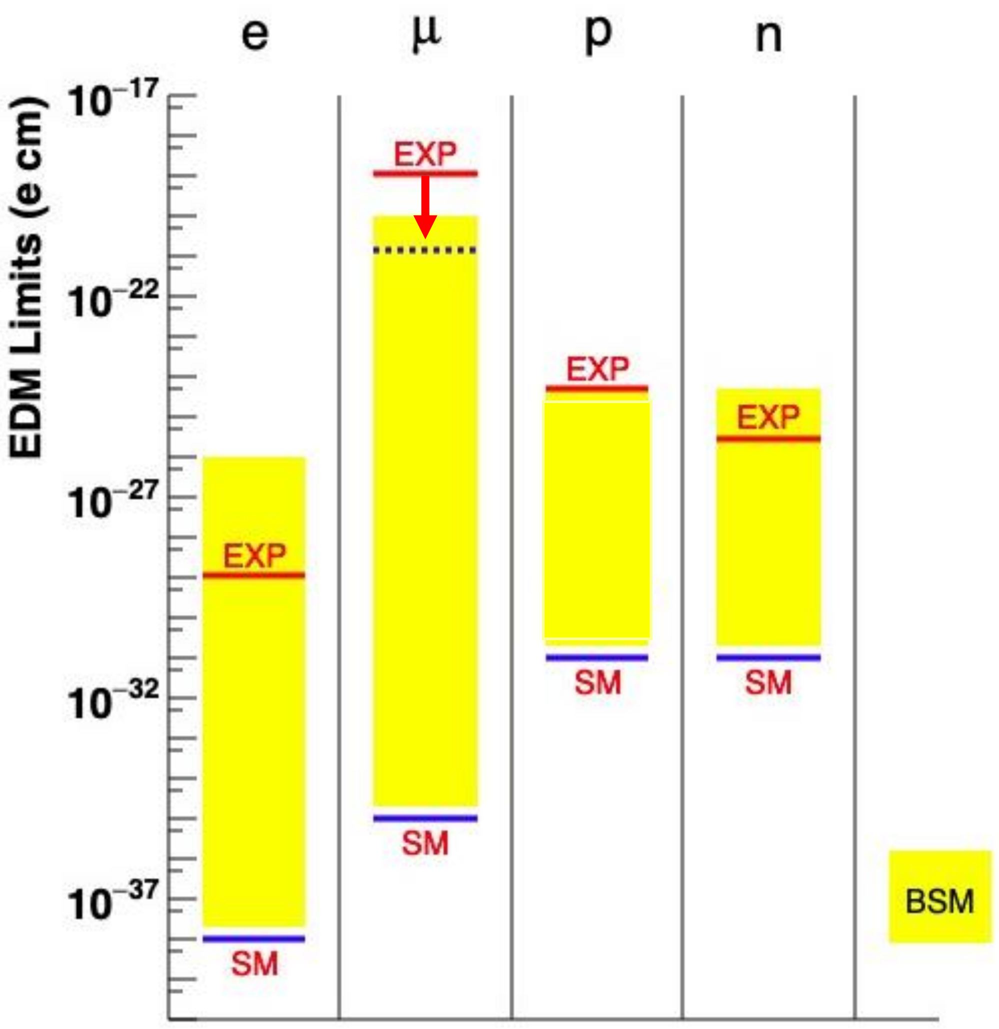
Thank you!

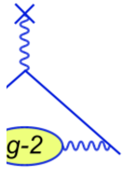


Backups

EDM searches

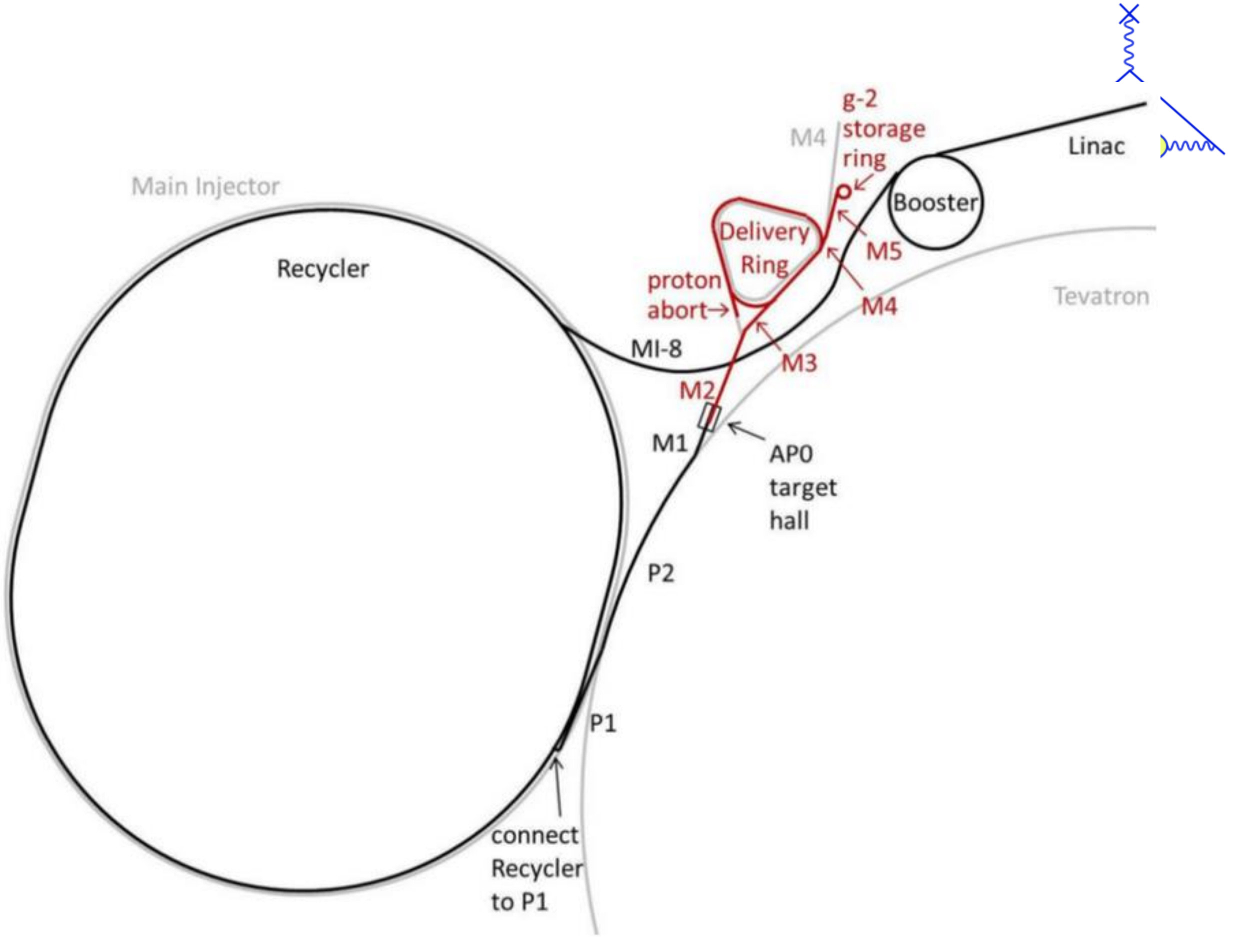
- Electron EDM is already constraining BSM physics.
- Muon EDM not quite there yet – BNL limit shown on this plot.
- Target FNAL limit is the black dashed line.





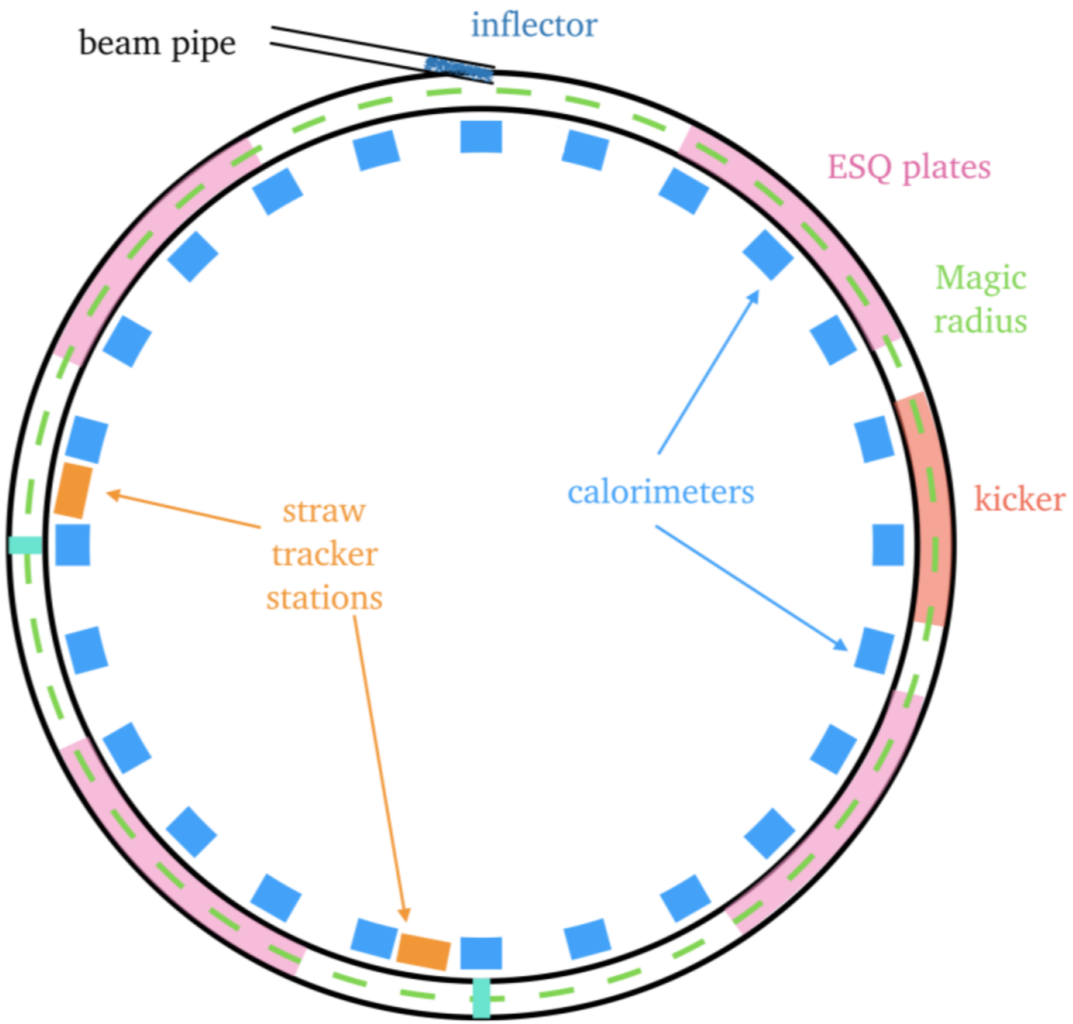
The FNAL g-2 beamline

- 8 GeV Protons in FNAL's recycler ring delivered to muon campus in 'bunches'.
- Protons → Target (Ni-Fe alloy) → Pions → Delivery ring → Decay to muons → Storage ring.
- Lithium lens to focus the pions, pulsed magnet to select 3.1 GeV muons.



FNAL g-2 in more detail

- Muon storage – ring magnet provides radial restoring force, so need a set of electrostatic quadrupoles (ESQ) to keep beam stored vertically.
- Inflector shields muons from ring field as injected, so that they enter with minimal deflection.
- Kickers used to push beam into optimal orbit.
- Variety of detector systems:
  - Calorimeters to measure energy/momentum
  - Trackers allow beam distribution measurements + EDM vertical angle studies
  - Also have destructive beam measurement tools like fiber harps that are placed in the beamline occasionally.



FNAL g-2 in more detail (cont.)

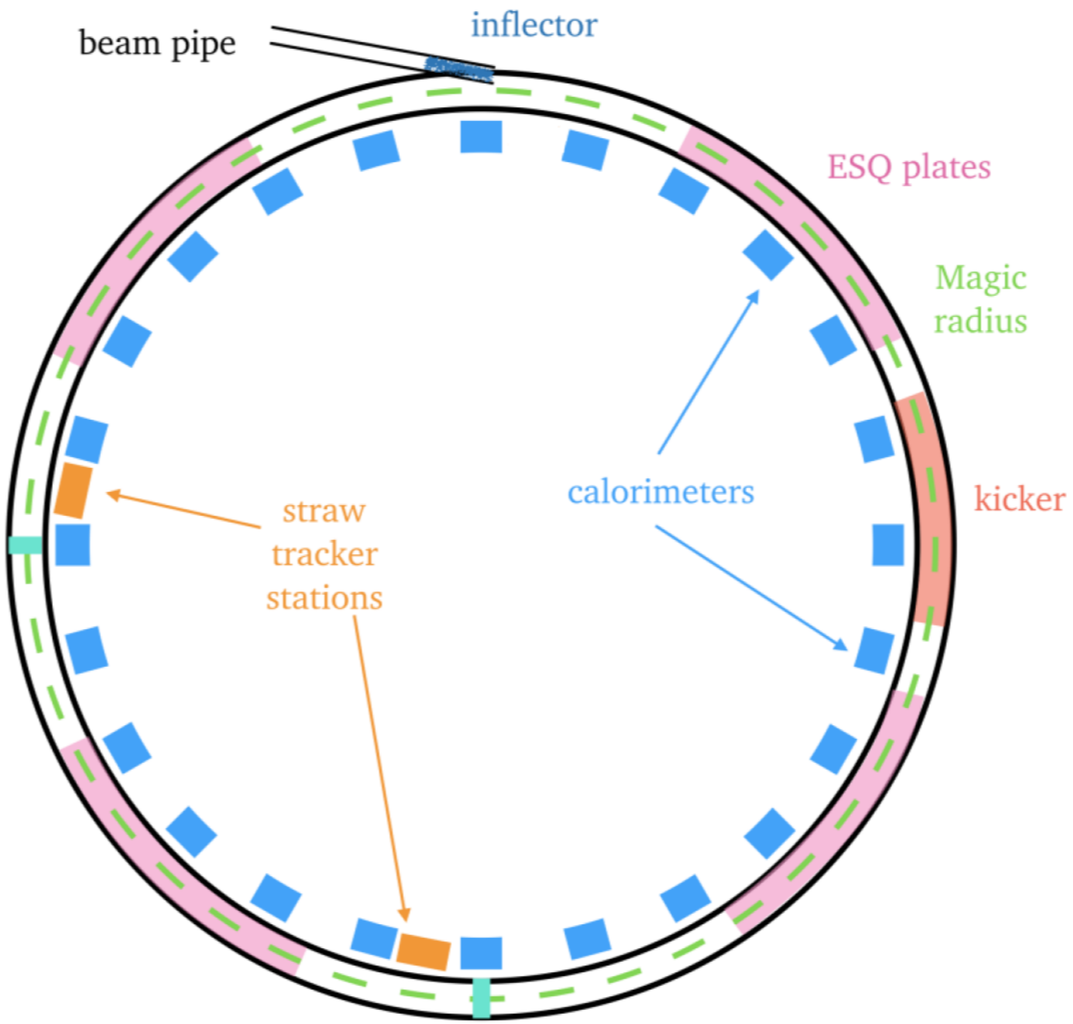
- Also need to know the magnetic field to high precision for the precession frequency:

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

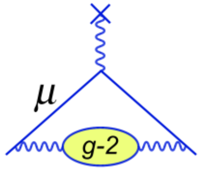
- Trolley – contains an array of NMR probes and can travel freely around the ring to map out the field seen by the muons.

- Fixed probes – also NMR probes but placed on the ring to monitor the field while muons are in the ring.

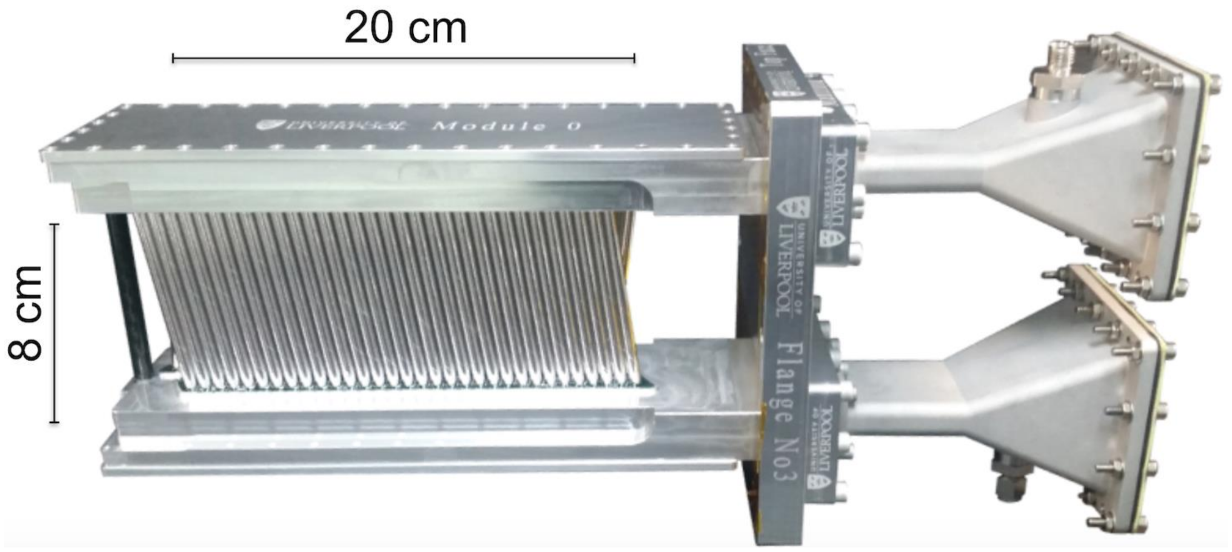
- Extra 'plunging' probes for calibration.



The g-2 trackers (more detail)

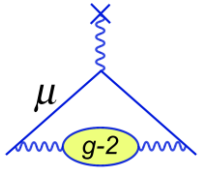


- Straw trackers with argon-ethane gas.
- Hits in straws are reconstructed into a track, extrapolated backward to decay vertex, forward into calorimeters.
- Multipurpose:
  - Monitoring the muon beam profile during runs.
  - EDM analysis – vertical angle.
  - Track and Calorimeter hit matching – can compare measurements of momentum/energy.
  - Pileup studies – easier to see in trackers than the calorimeters.



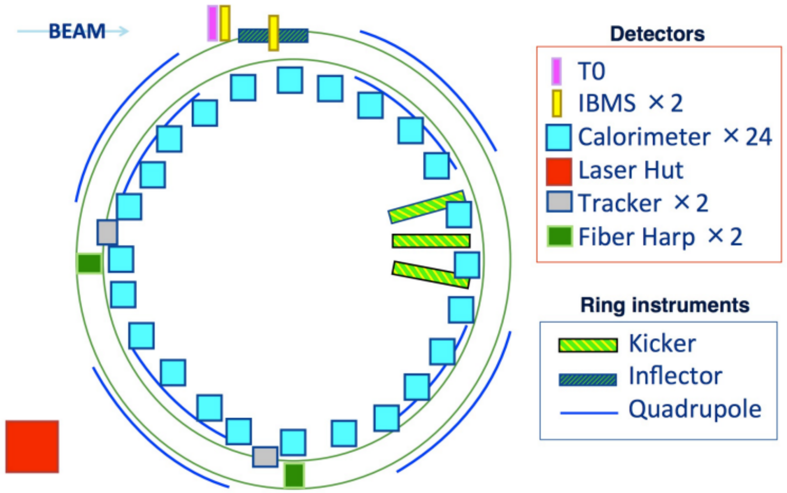
How we measure the radial field

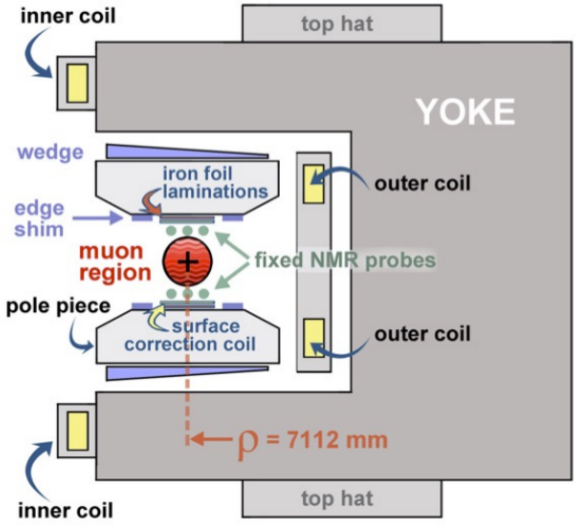
Exploit the interaction between the vertical beam position, the total radial field, and the electric fields



$$\langle y \rangle \sim \frac{\langle B_r \rangle}{QHV} \rightarrow \frac{\langle B_r^{App} \rangle + \langle B_r^{Bkg} \rangle}{QHV}$$

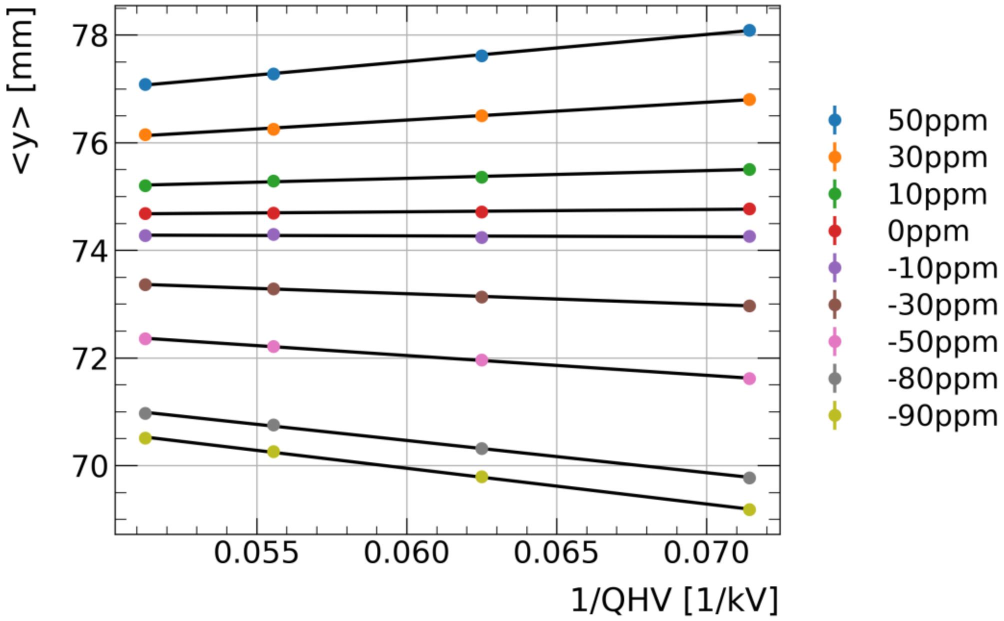
- $\langle y \rangle$: average vertical cluster position
- $\langle {B_r}^{App} \rangle$: applied field from surface correction coils
- QHV: electrostatic quadrupole HV
- $\langle {B_r}^{Bkg} \rangle$: background field (what we measure)

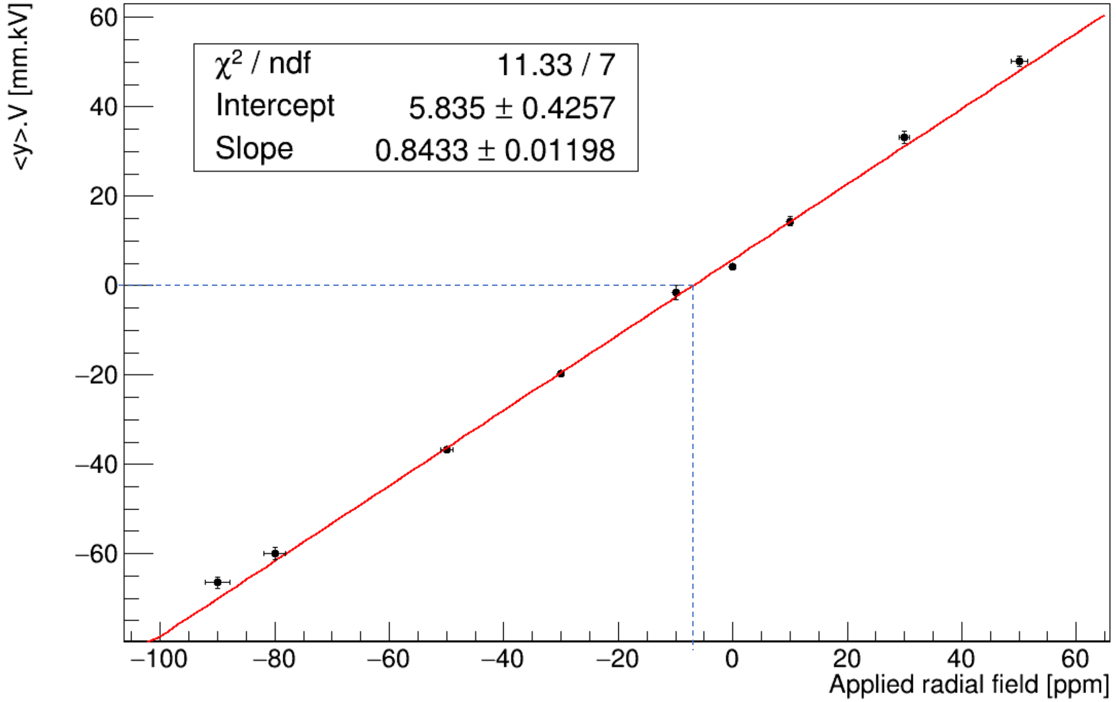




How we measure the radial field, part 2

- Find the point where gradient = 0 (x-intercept).
  - Radial field is then equal in size, opposite in sign.
  - Extrapolate to any data by comparing the mean vertical beam position.



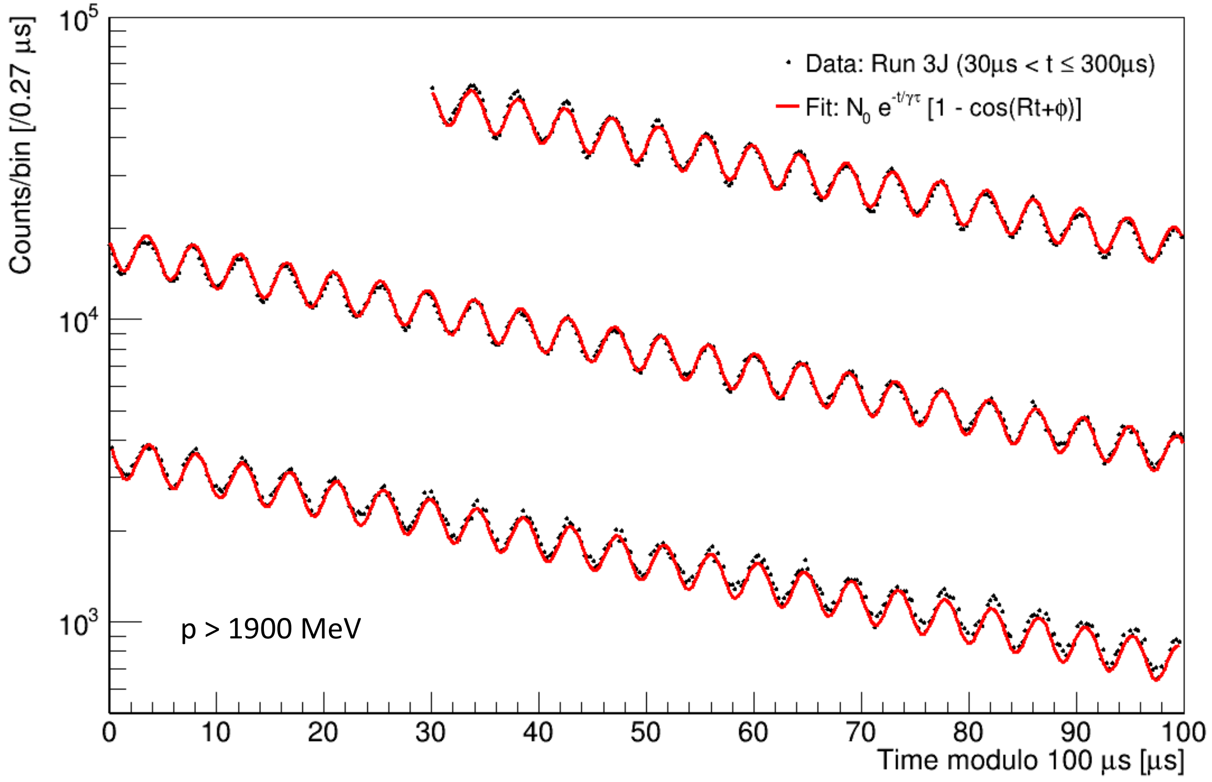


Data from Run 5 scan

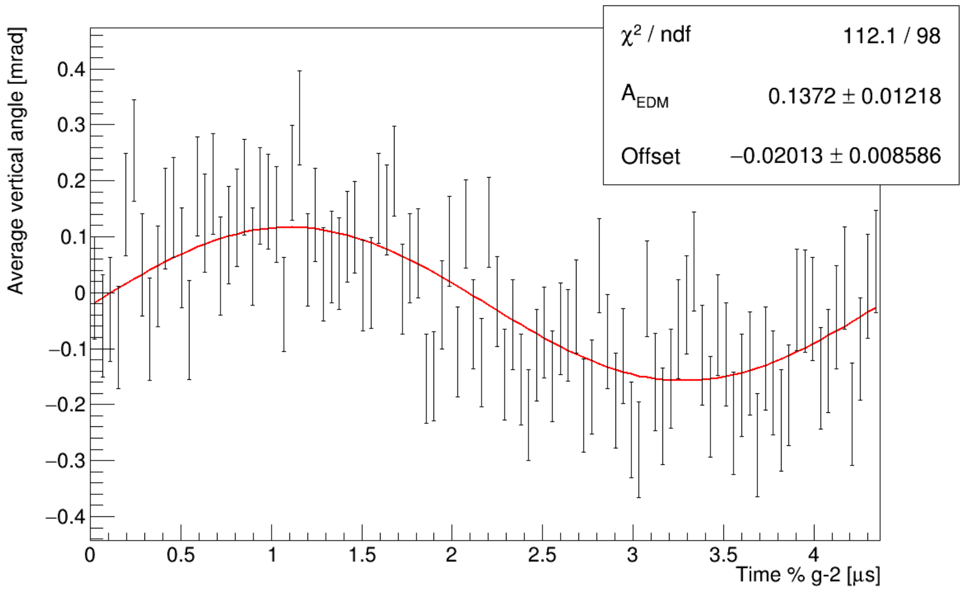
EDM analyses – wiggle fits

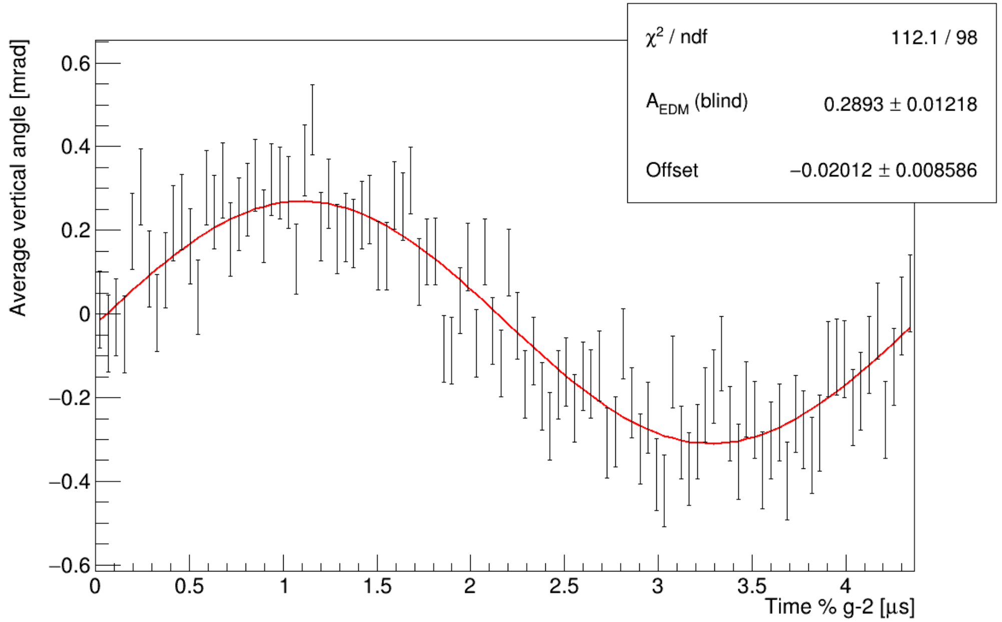
- We do a similar wiggle fit to the ω_a analysis to get the phase.

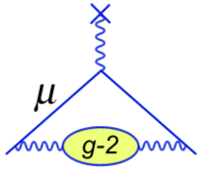
- Use the BNL value for ω_a itself as Run 2/3 are not unblinded.



EDM analysis – checking the blinding







- Shift in A_{EDM} parameter – increased by +tive definition of the blinding amplitude.
- Offset slightly increased (MC has a net –tive offset, injected blinding has 0 offset).
- Fit quality unchanged.