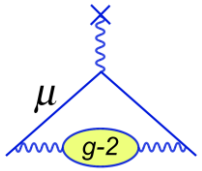


Muon EDM searches at the new g-2 experiment at Fermilab

New Perspectives, June 2022

Dominika Vasilkova

DOE report no: FERMILAB-SLIDES-22-043-PPD

Muon dipole moments

- 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:

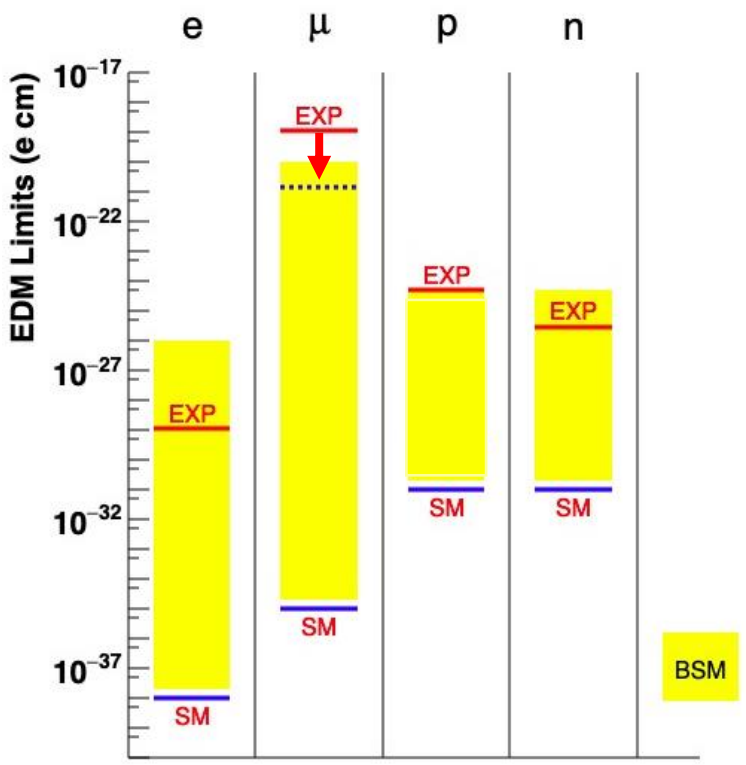
$$\vec{\mu} = g\frac{e}{2m}\vec{S}$$

EDM:

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

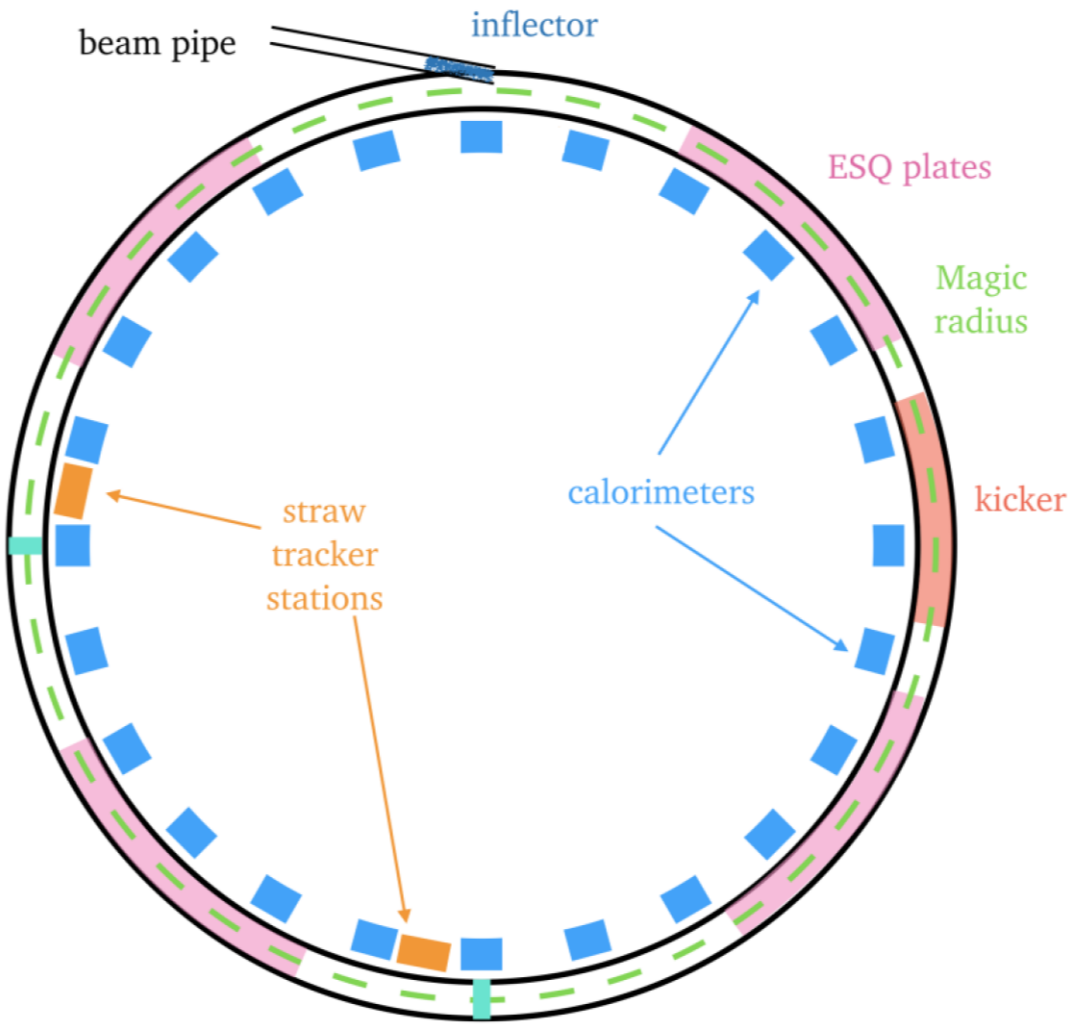
- Why muon EDM?
  - SM muon EDM well below the range of current experiments
  - **d**.**E** is CP-odd, so observation gives a **new source of CP violation** in the lepton sector

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



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.

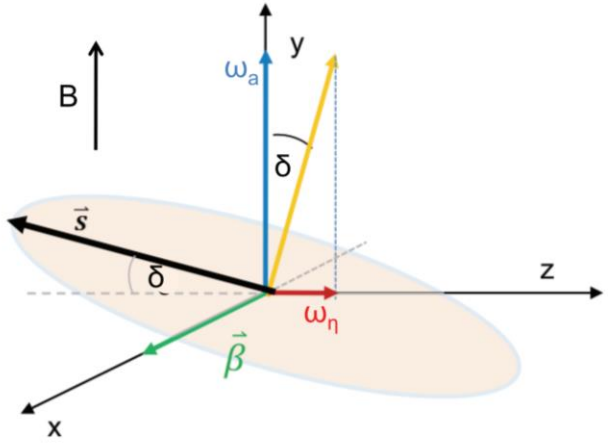


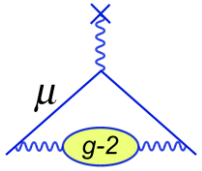
How do we look for an EDM?

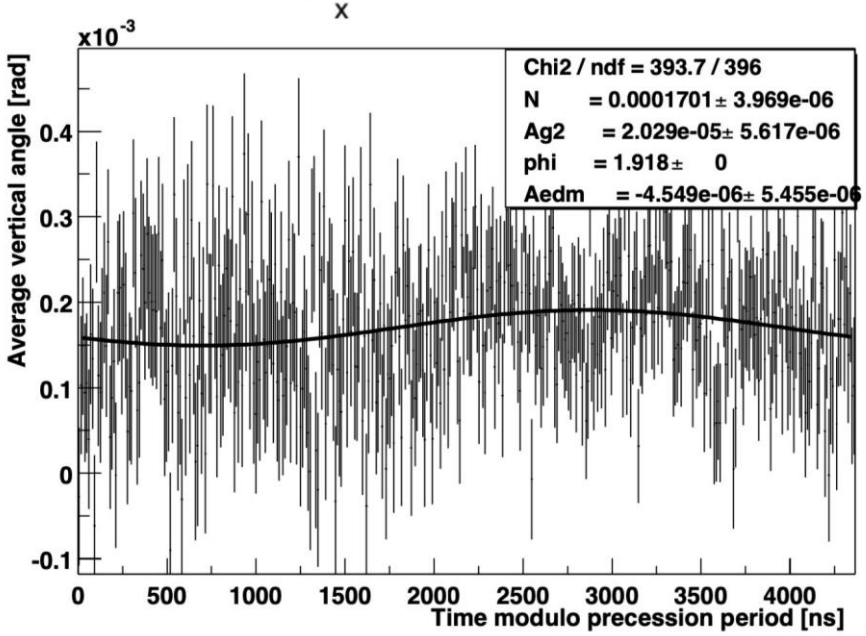
- An EDM tilts the precession plane – can detect by looking at the **average vertical angle in the trackers.**

- Previous result statistically limited, FNAL 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 (~ $10^{-21}\ e \cdot cm$).



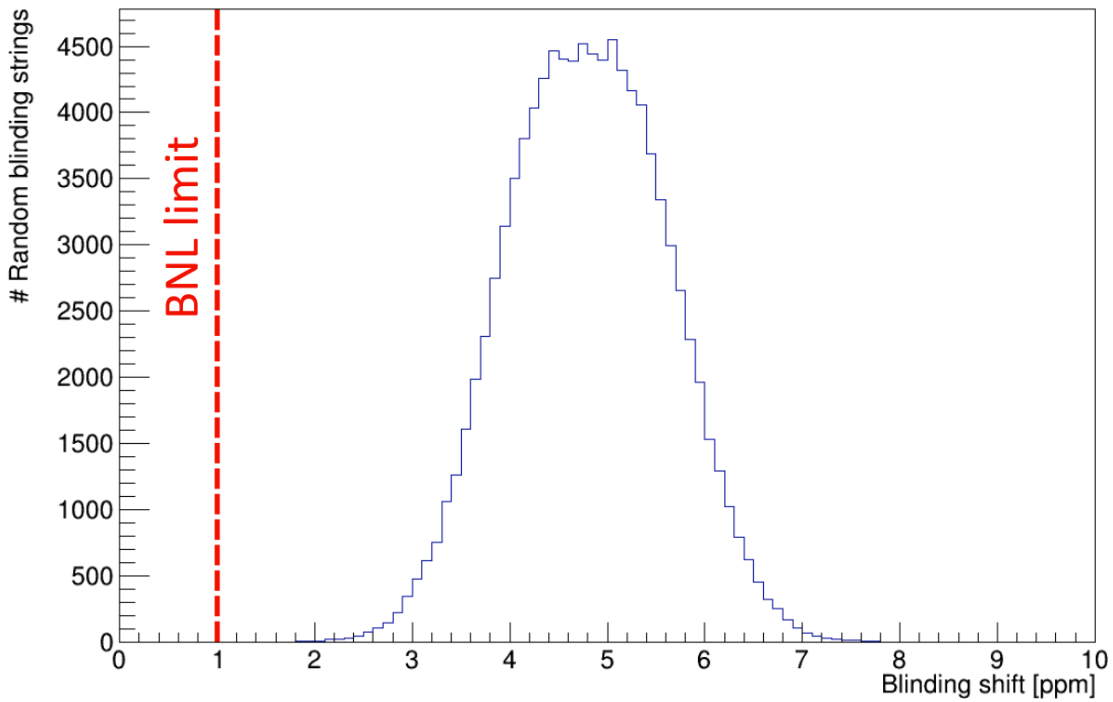




BNL
(2000 dataset)

Keeping the analysis blind

- 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.



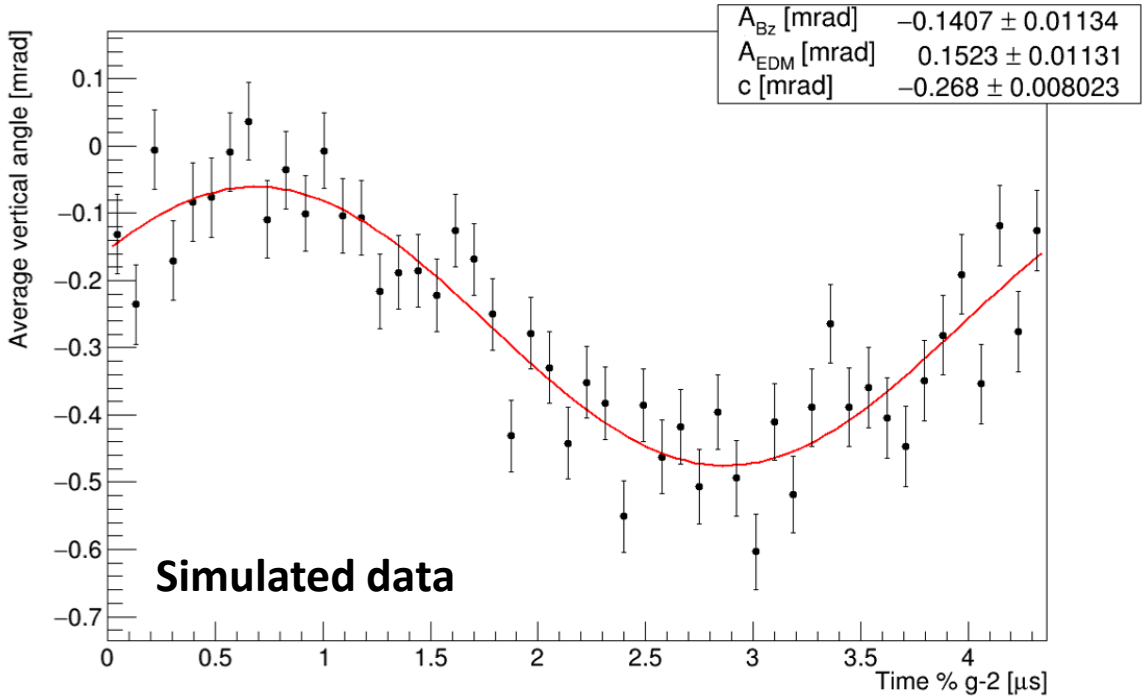
Fitting the average vertical angle

- 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.

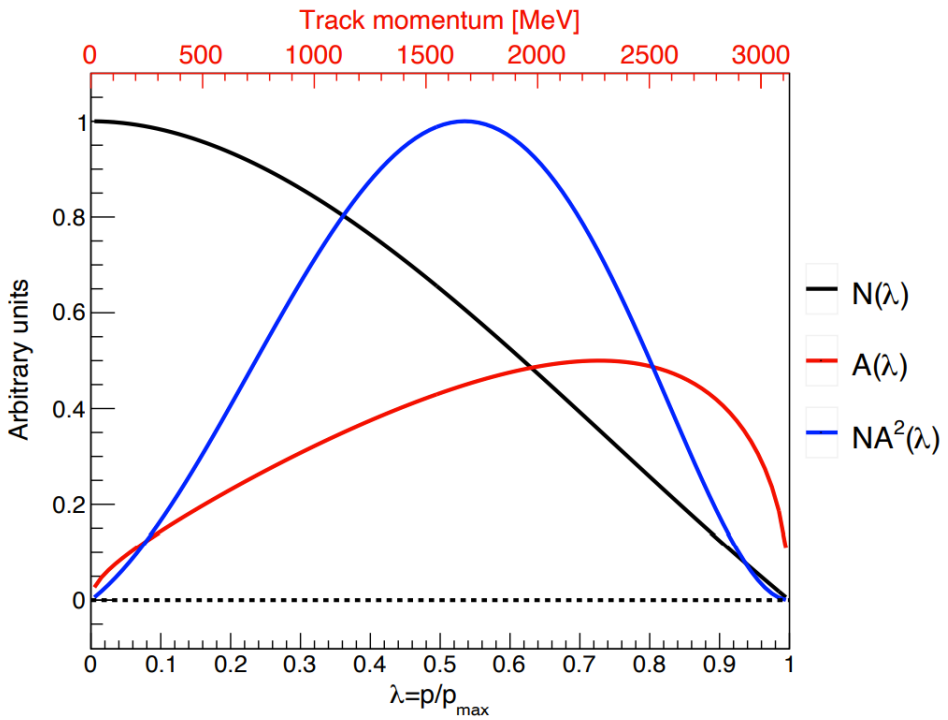
- Longitudinal magnetic field also tilts the plane, but in phase with g-2 – so fit simultaneously for both an in phase component and an out of phase component:

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



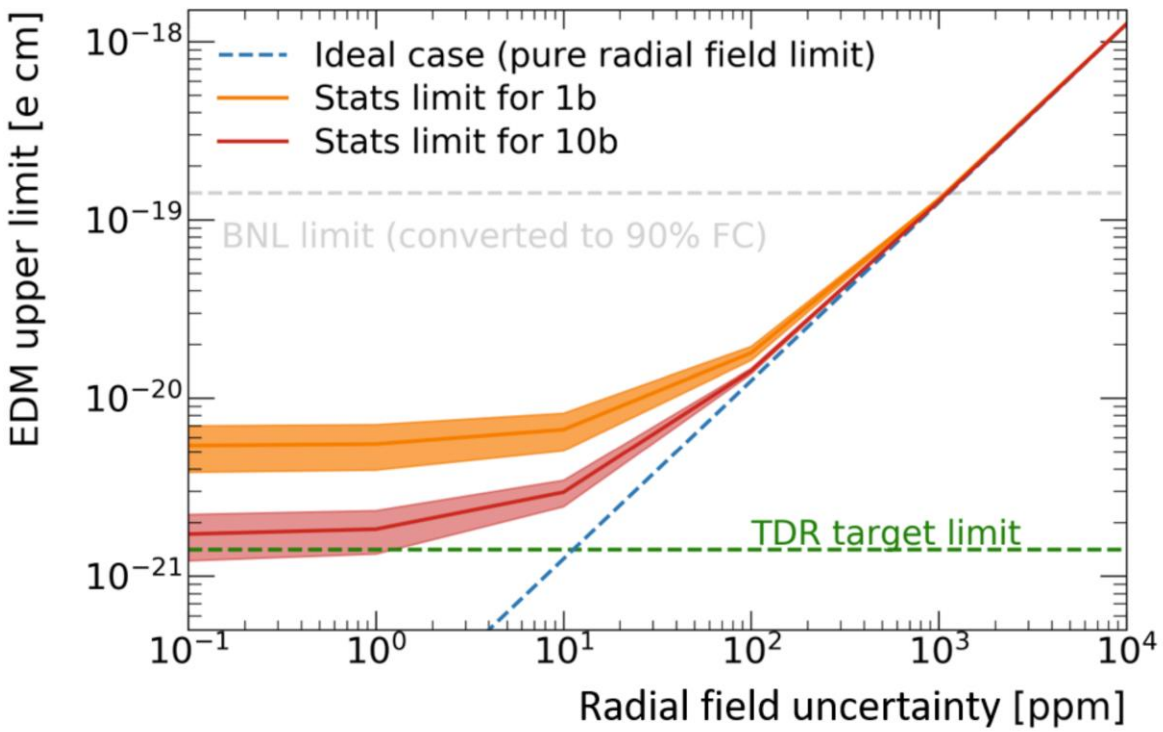
Largest hurdles for the tracker analysis

- **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:**
  - Amplitude of EDM oscillation is momentum dependent.
  - 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.
- Limited by the radial field, followed by the statistical uncertainty
  - Better measurements of the radial field needed to achieve best results!
- Target limit of O(10^{-21} $e \cdot cm$) achievable.



Measuring the radial field (B_r)

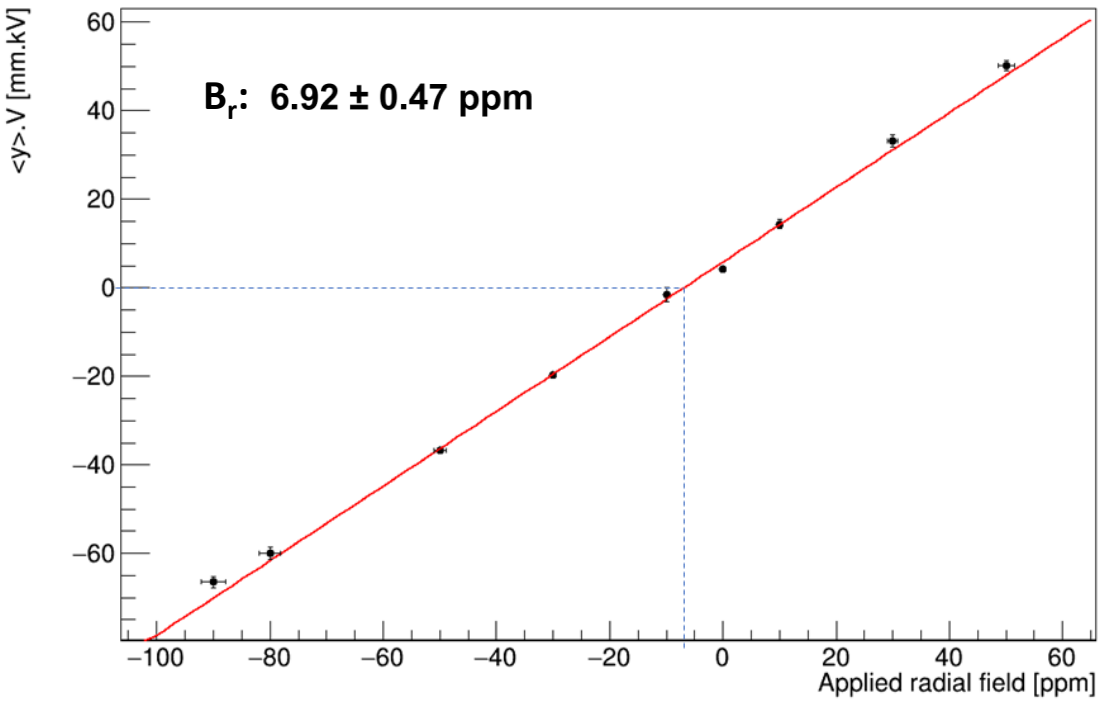
- Find surface coil setting which cancels out the background radial field.
  - This is the point where the beam <y> doesn't change with quad voltage.

$$< B_r^{Tot} > = 0 = < B_r^{App} > + < B_r^{Bkg} >$$

- Scans performed in run 4 and 5 – both achieved better than 1ppm precision target to not be radial field limited.

- Planning to cross-check this 'indirect' measurement with a hall probe measurement this summer.

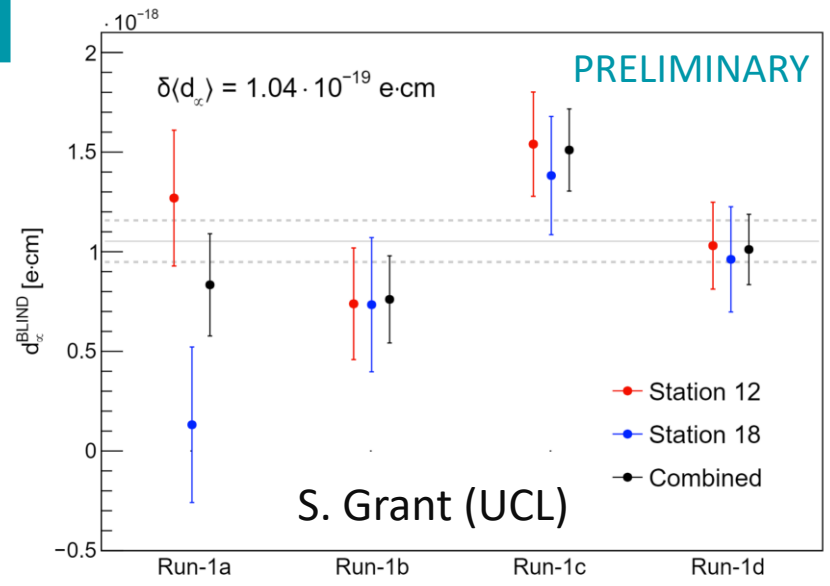
Run 5 scan

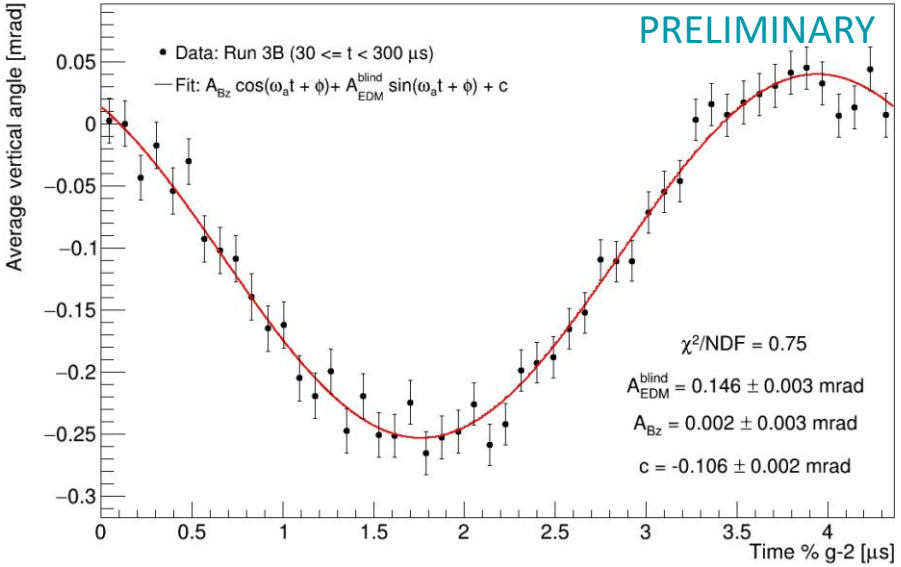


Analysis status

- **Run 1** – nearly complete, unblinding soon, result expected to be **at least as strong as BNL**.
  - All 4 sub-datasets analysed.
  - Radial field estimated to sufficient precision.
  - Acceptance corrections calculated from MC.
  - Final systematics considerations in progress.

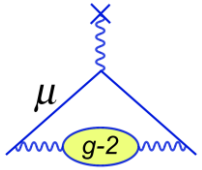
- **Run 2/3** analysis – currently underway
  - Higher stats so systematic effects become more important.
  - Combination will have sufficient stats to **improve on BNL limit**.



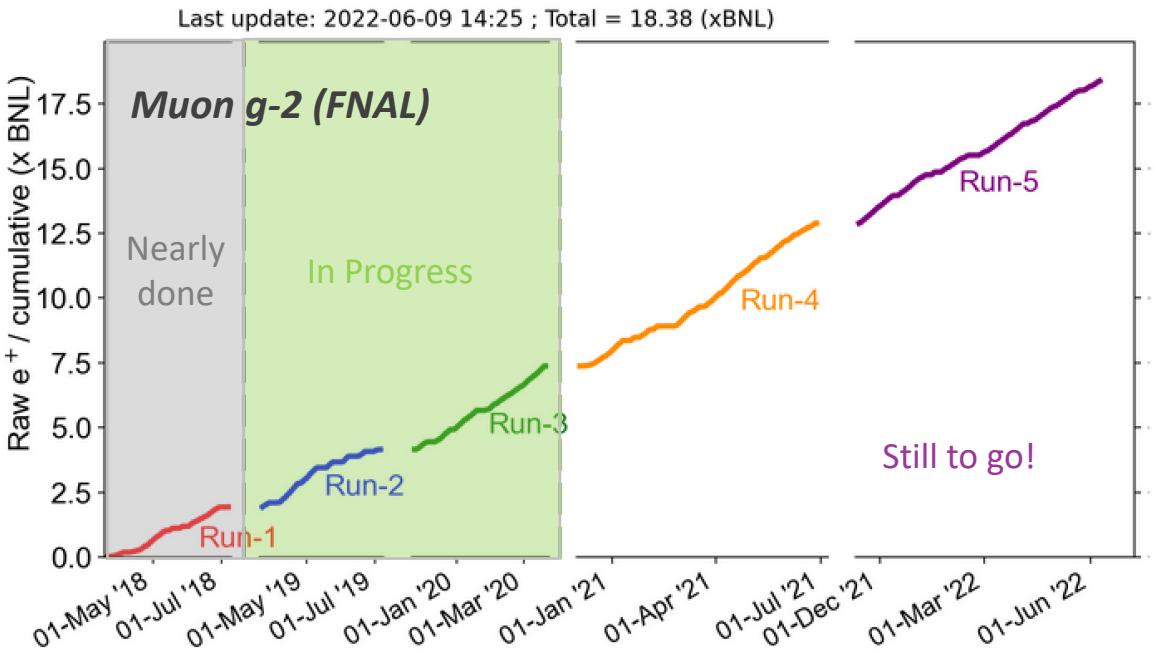


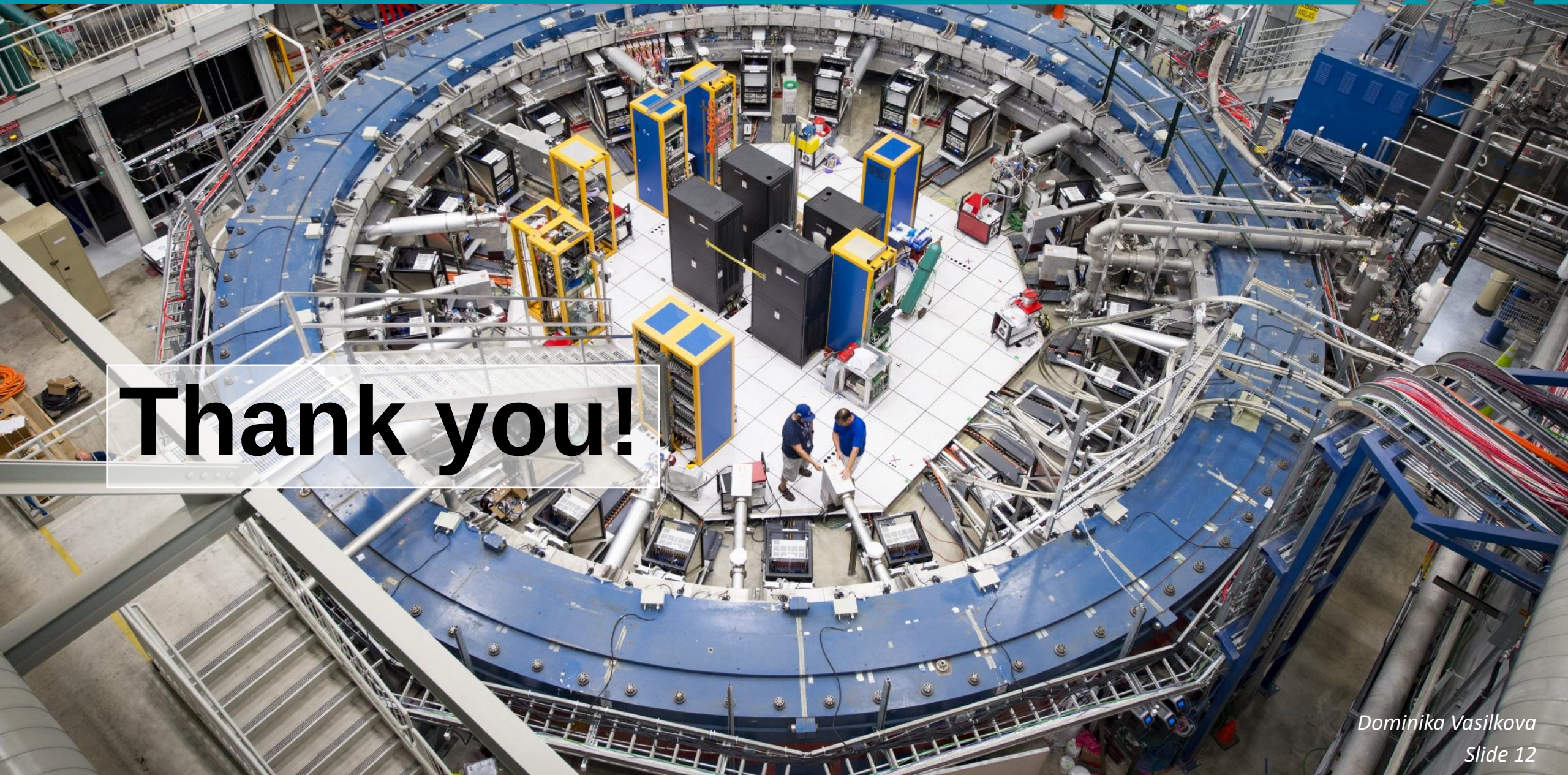
Conclusions and outlook

- 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 Run 2/3 analyses underway, together will improve on the BNL limit.
- Still lots more data to go – Run 4 and Run 5.
  - Final EDM result will be a combination.
- Overall, on track to set a world-leading limit on the muon EDM – so watch this space!

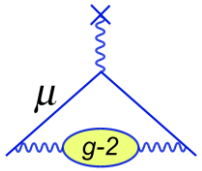


EDM analysis status summary:





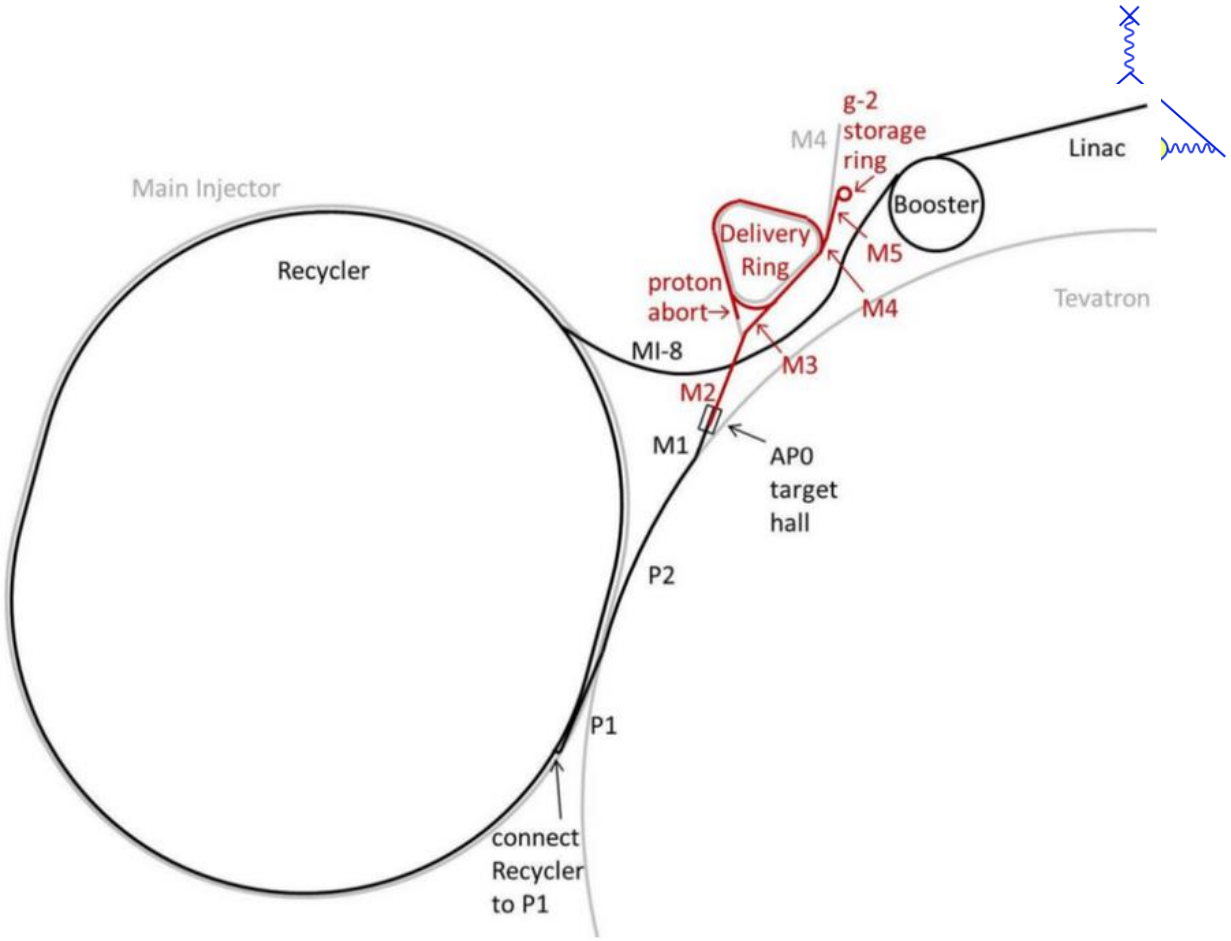
Thank you!



Backups

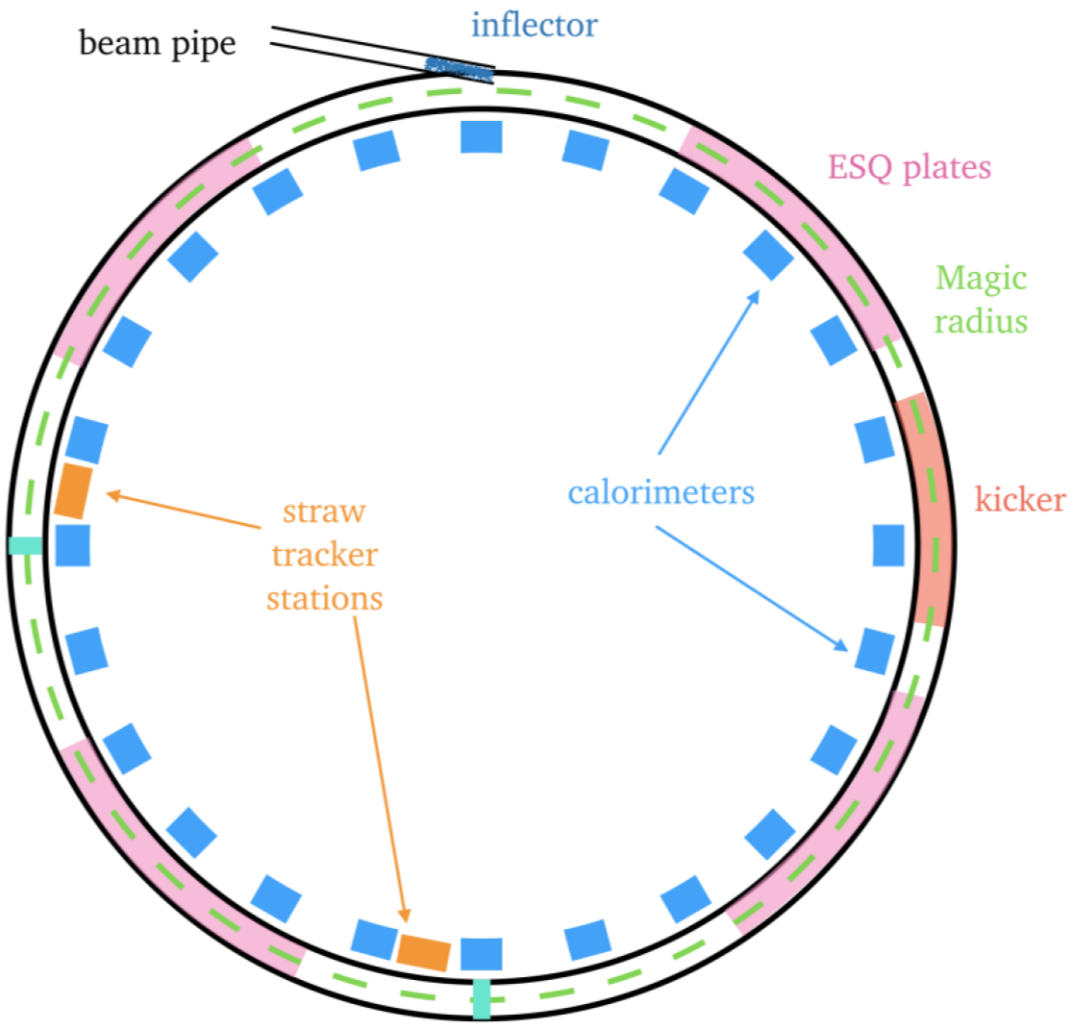
The FNAL g-2 beamline

- 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.)

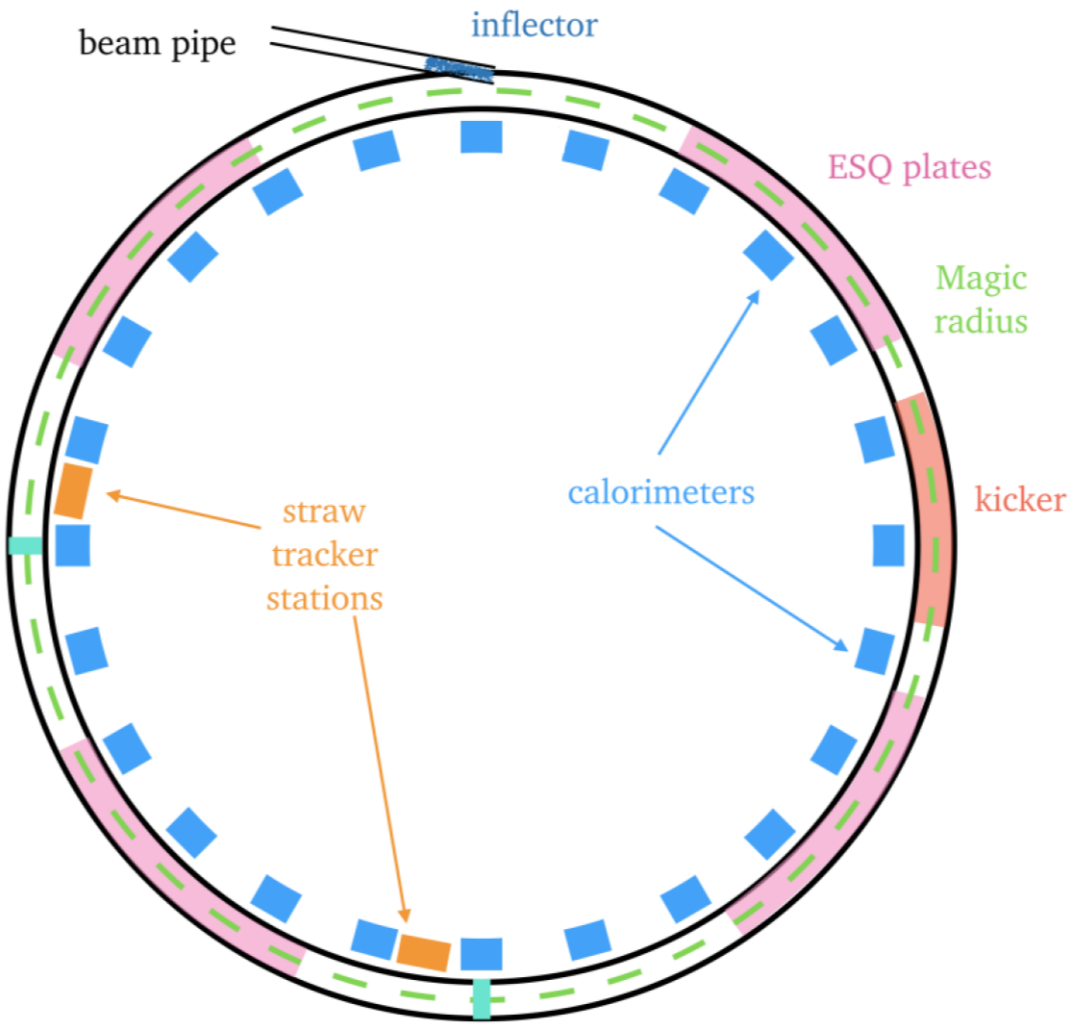
- Also need to know the magnetic field to high precision for the precession frequency:

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

- 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.

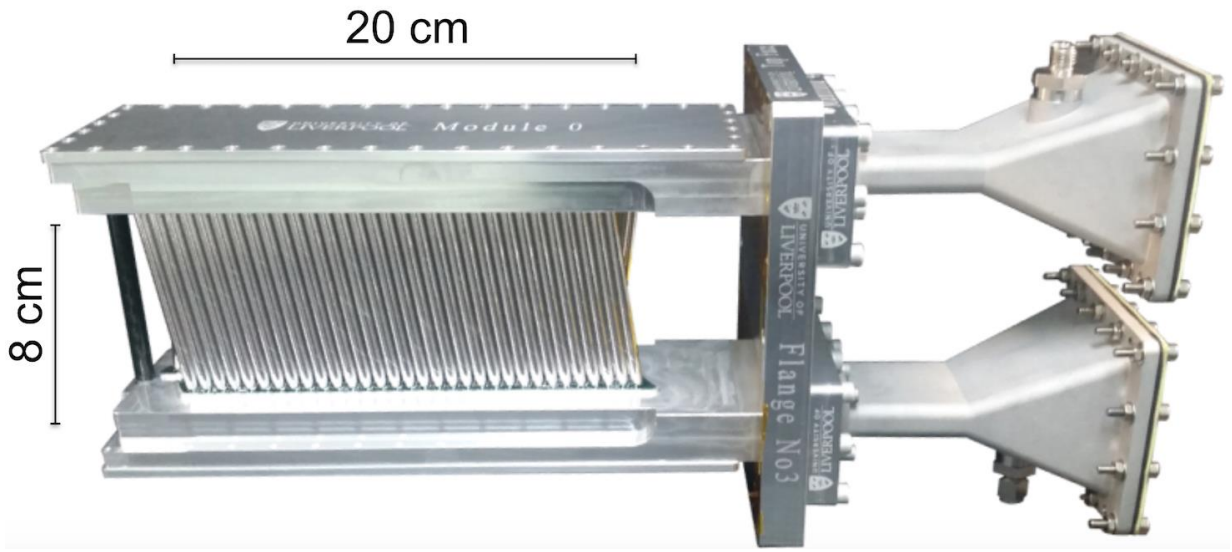


The g-2 trackers (more detail)

- 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.

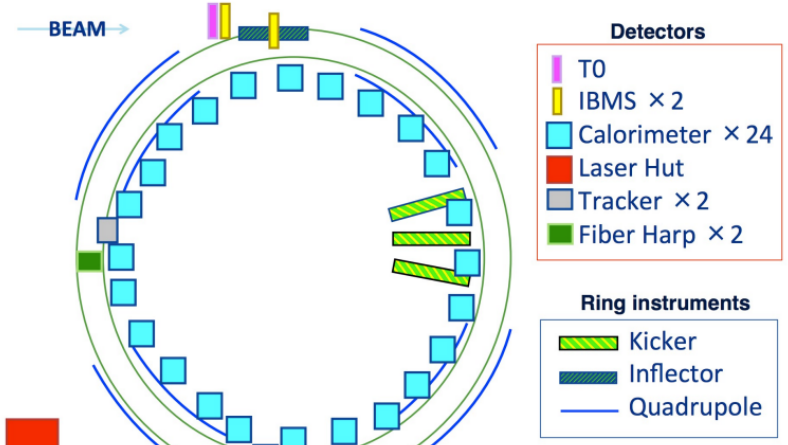


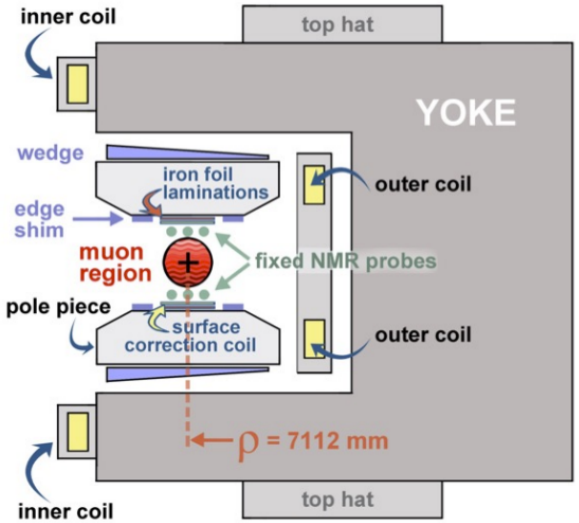
How we measure the radial field

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

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

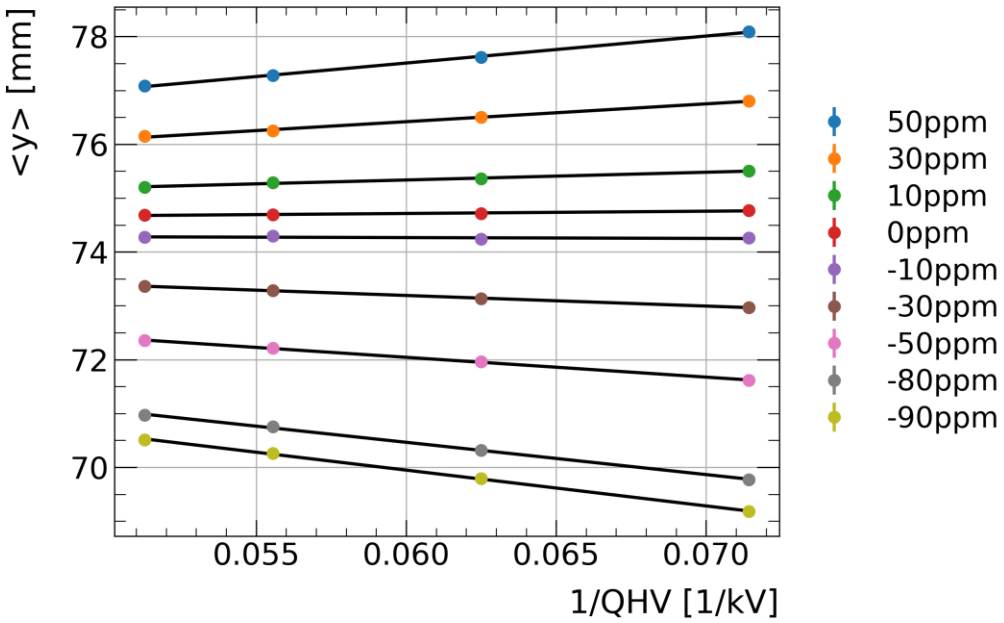
- $\langle y \rangle$: average vertical cluster position
- $\langle B_r{}^{App} \rangle$: applied field from surface correction coils
- QHV: electrostatic quadrupole HV
- $\langle B_r{}^{Bkg} \rangle$: background field (what we measure)



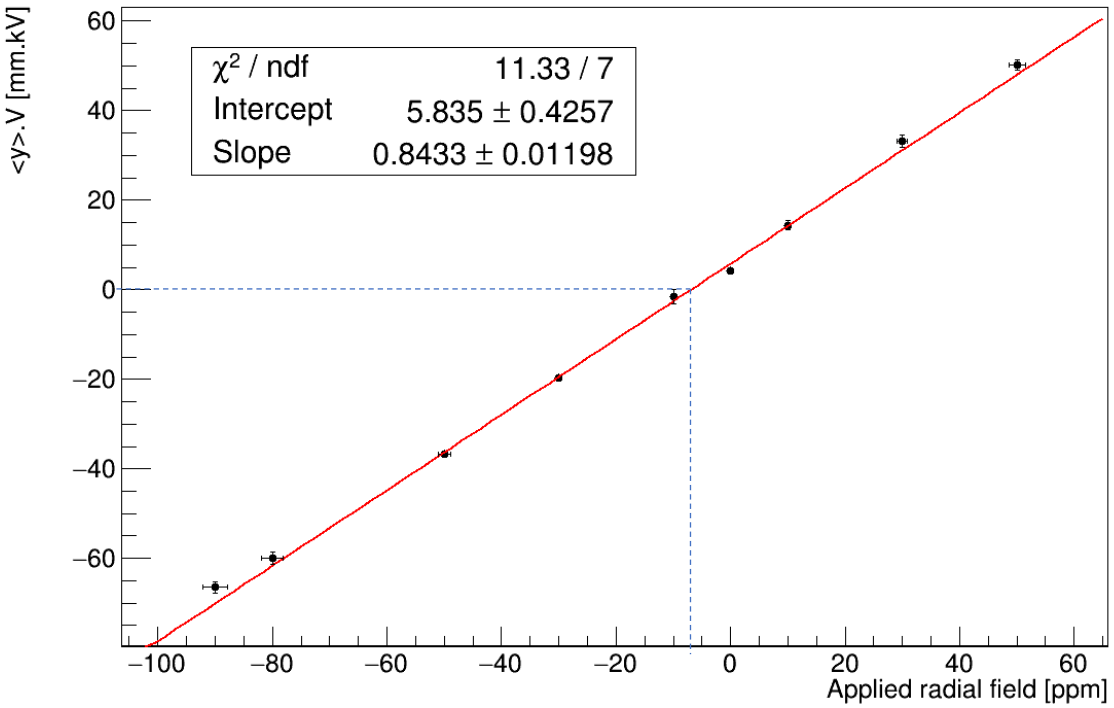


How we measure the radial field, part 2

- 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.



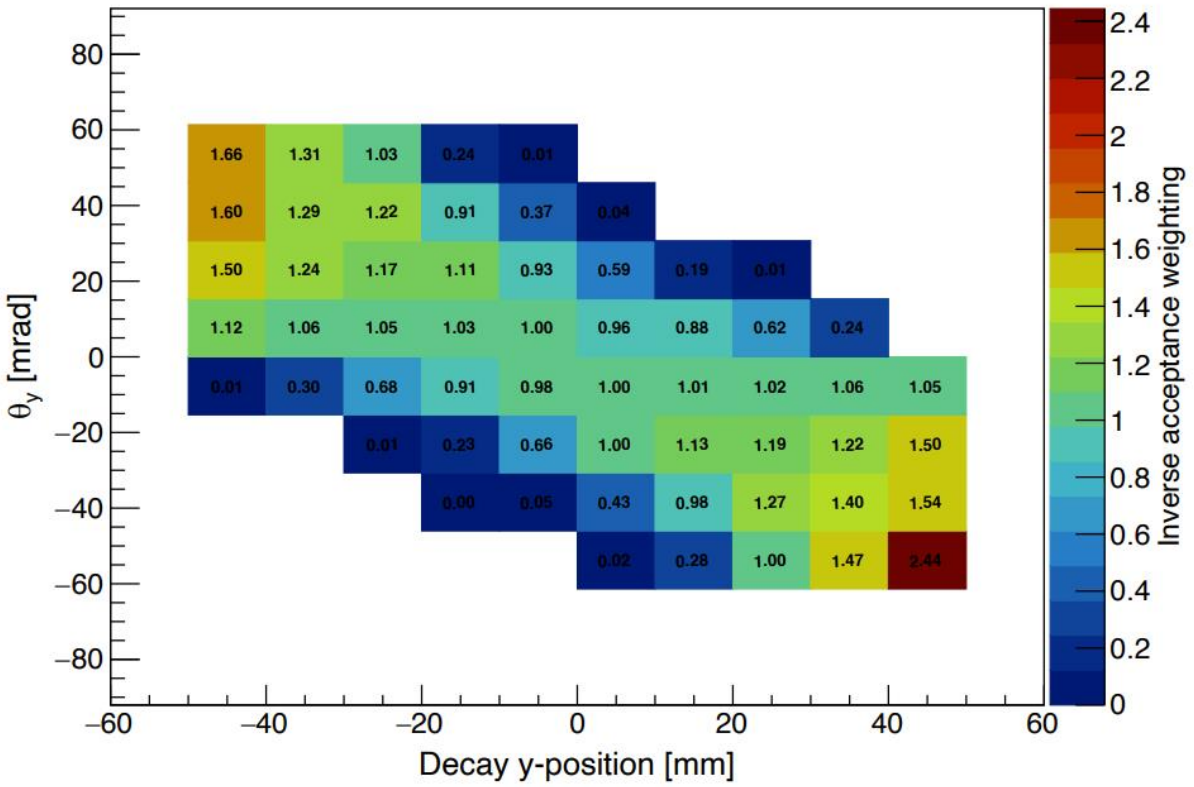
Data from Run 5 scan



Acceptance correction

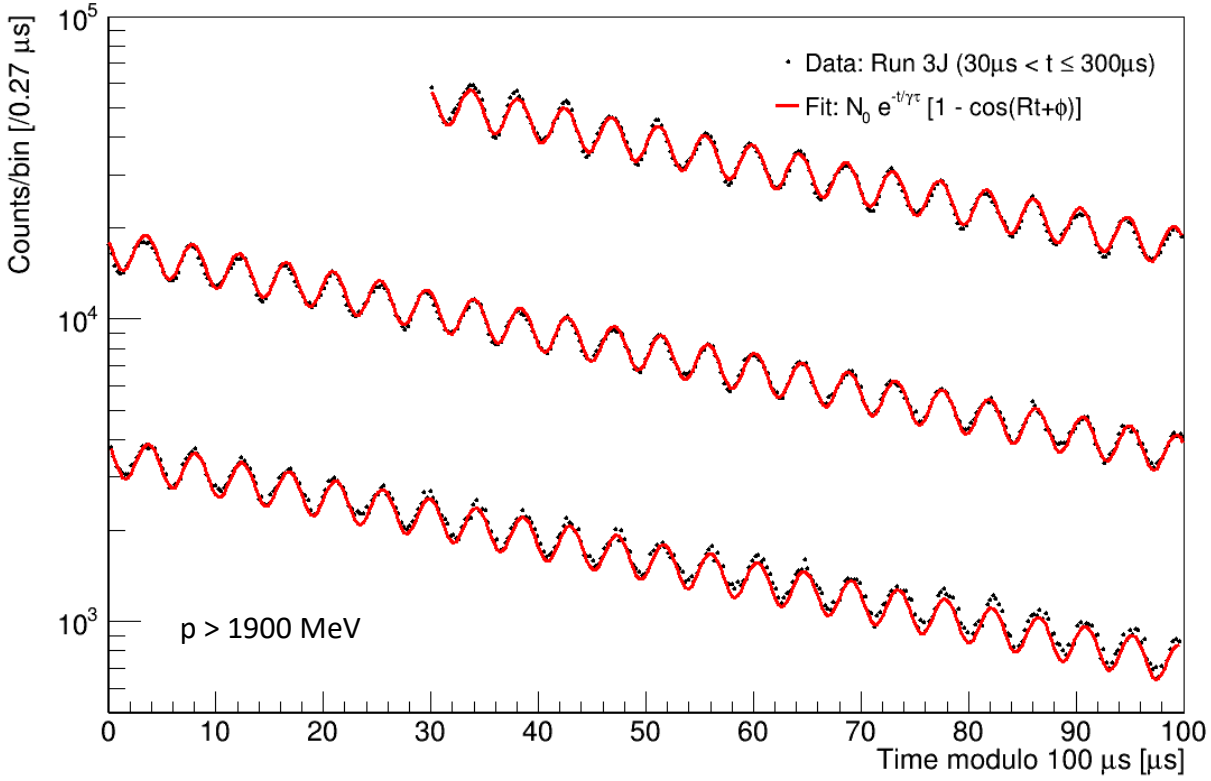
- Use MC (with full g-2 geometry) to study the difference between positions that hit the trackers and all decays.

- Leads to a 2D map of correction factors based on the vertical position of the decay, and the angle of the decay.

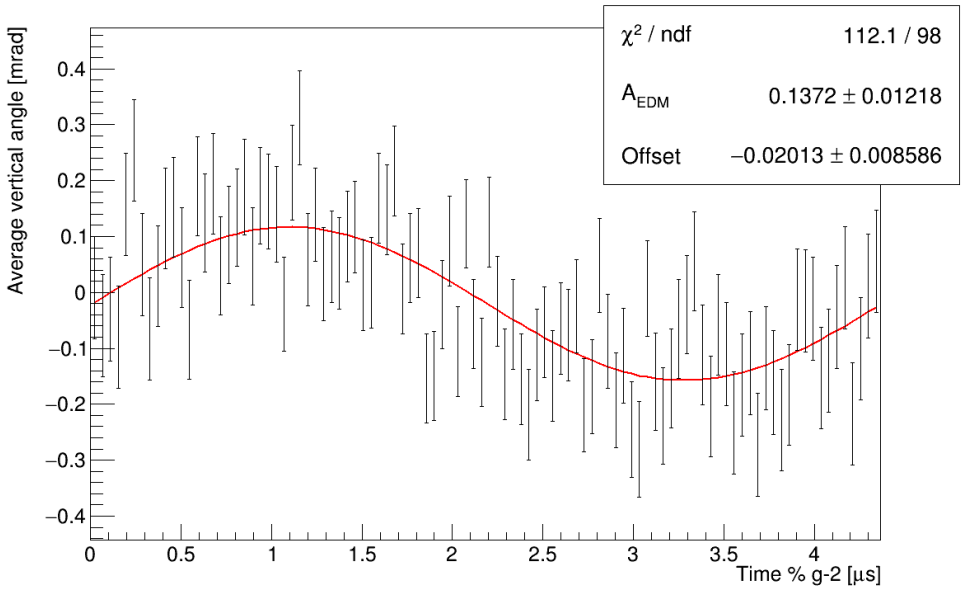


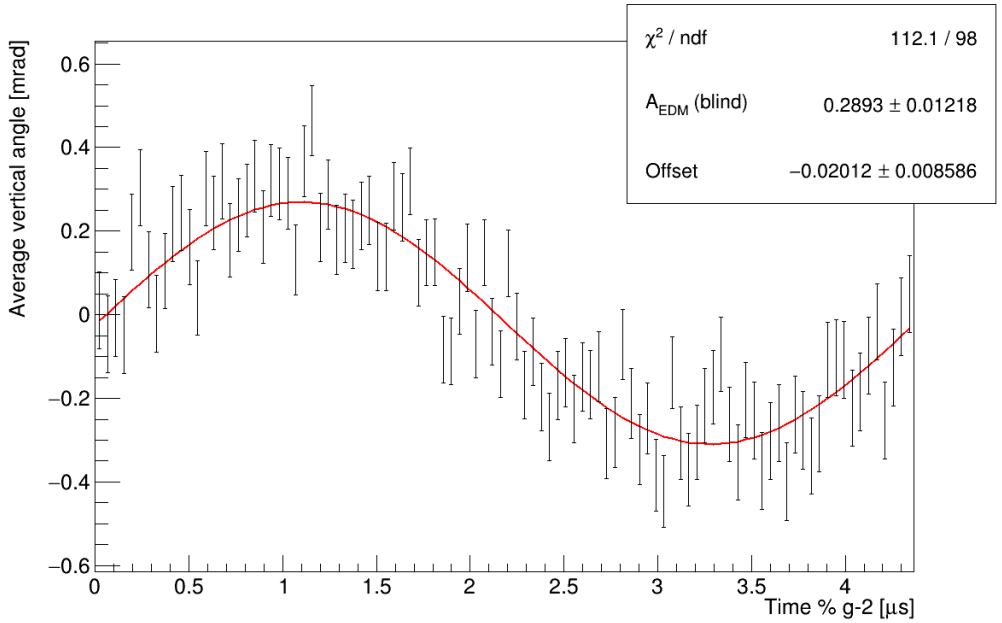
EDM analyses – wiggle fits

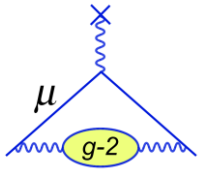
- We do a similar wiggle fit to the ω_a analysis to get the phase.
- Use the BNL value for ω_a itself as Run 2/3 are not unblinded.



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.