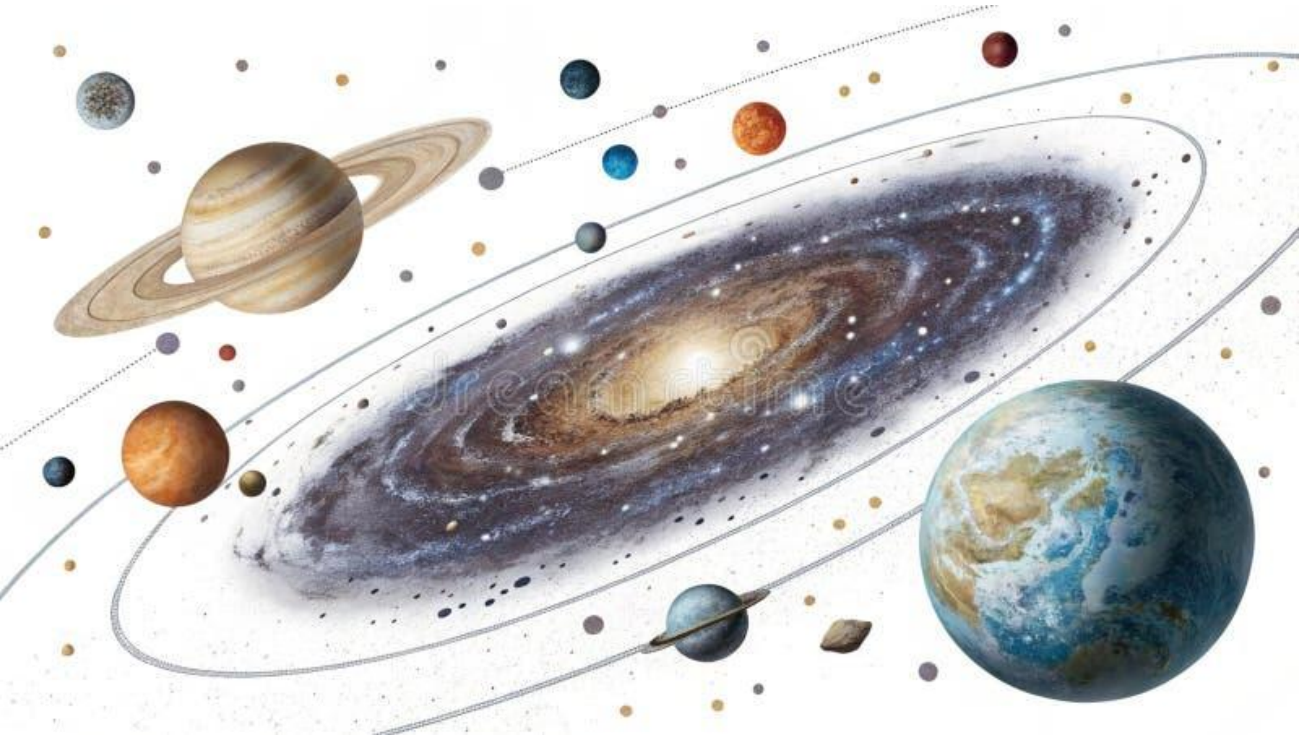
Status of muon EDM measurement at the Muon g-2 experiment in Fermilab

Katie Ferraby

On behalf of the g-2 collaboration

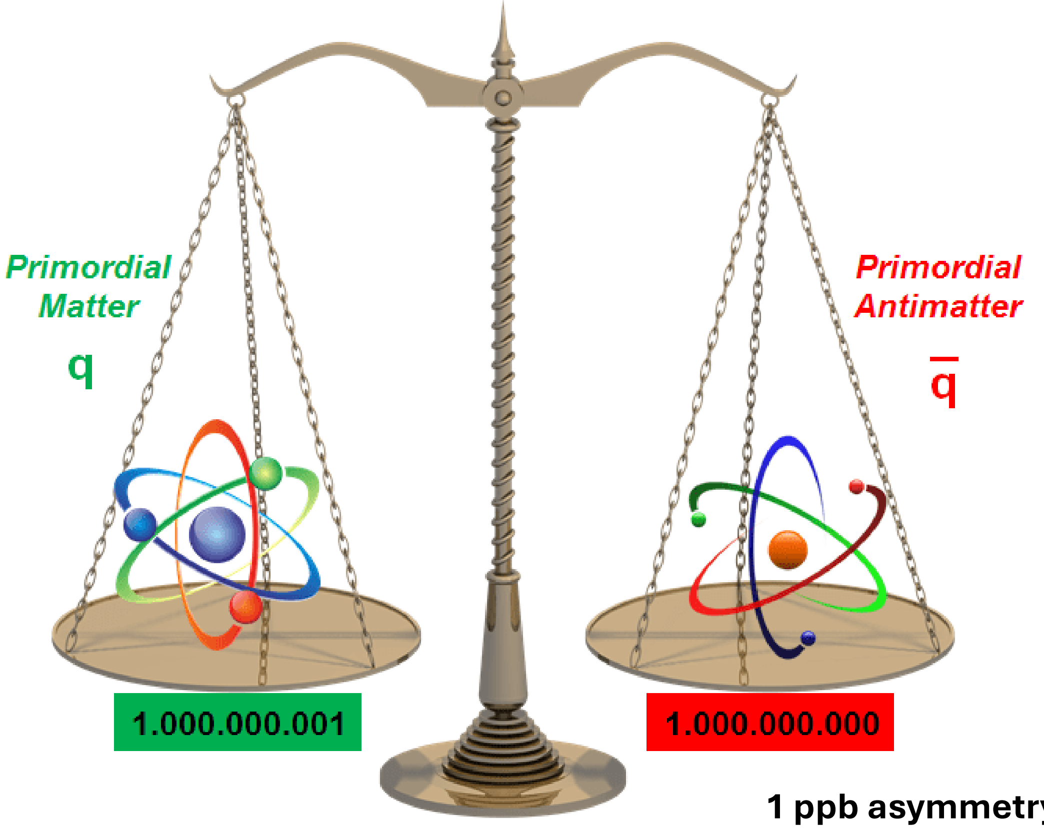
[1]

CP violation



CP violating sources are needed to explain the matter-antimatter asymmetry

The Big Bang should have produced equal amounts of matter and antimatter, which would annihilate and leave an emptry universe. However, out universe is full of matter. [2]



1 ppb asymmetry

...where can we find these extra sources?

CP violation

[3][4]

MDM:

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

EDM:

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

CP violation allowed under SM is not enough to explain the asymmetry.
More CP violation is needed.

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

⬇

[27]

	$\vec{\mu}$	$\vec{B}$	$\vec{d}$	$\vec{E}$	$\vec{S}$
C	-	-	-	-	+
P	+	+	+	-	+
T	-	-	-	+	-

Permanent particle EDM = CP violation

Why the muon?

$$\mathbf{SM:}\ |\mathbf{d}_e| < 10^{-39}\ e.cm$$ [6]

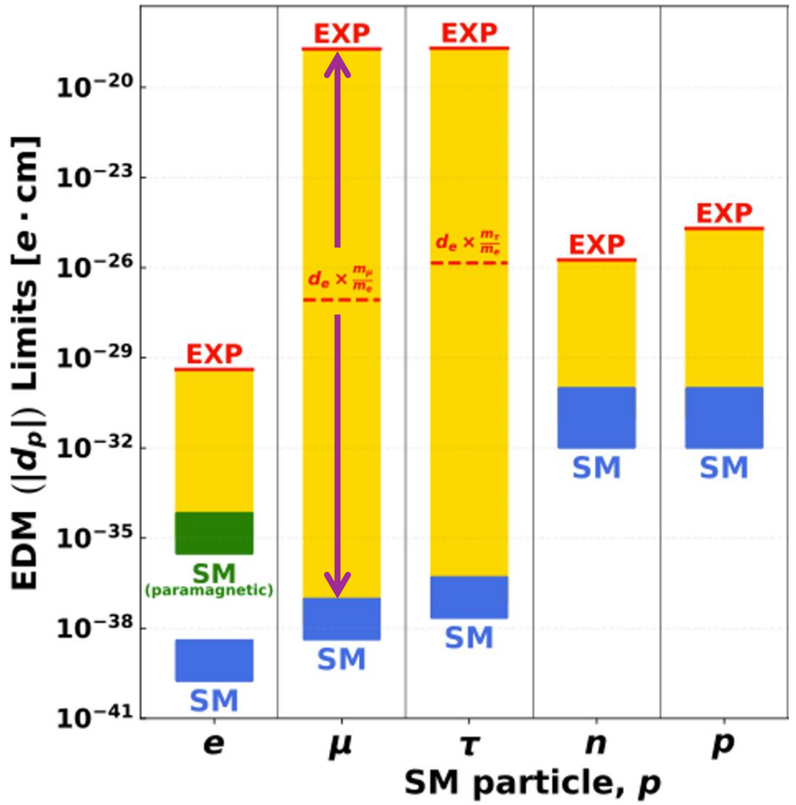
$$\mathbf{SM:}\ |\mathbf{d}_\mu| < 10^{-38}\ e.cm$$ [7]

$$\mathbf{SM:}\ |\mathbf{d}_\tau| < 10^{-35}\ e.cm$$ [8]

$$d_\mu \propto \frac{m_\mu}{m_e} d_e$$ [9] **?**

Test of lepton flavour universality

~ 19 orders of magnitude between experiment and theory



[5]

Lots of space to find new physics + can rule out lots of parameter space in BSM models

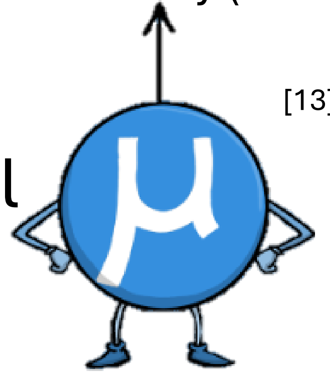
Current muon EDM limit


[11]

Brookhaven National Laboratory (BNL)


[12]

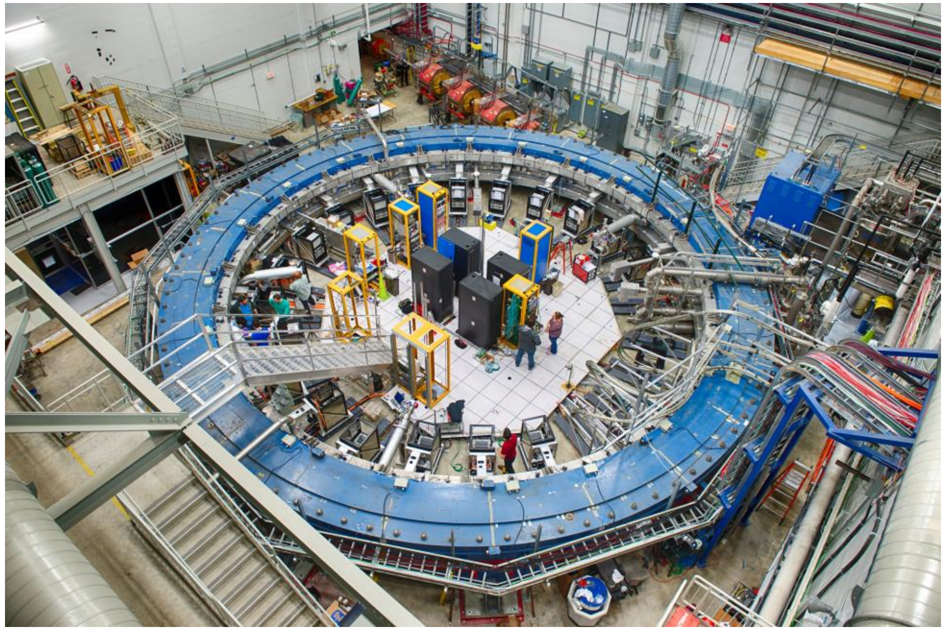
Fermilab National Accelerator Laboratory (FNAL)



[13]

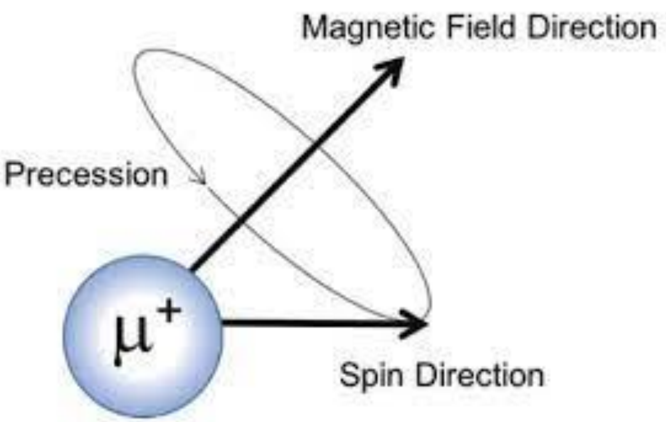
Previous best muon EDM limit was set at Brookhaven National Laboratory (BNL): $|\mathbf{d}_\mu| < \mathbf{1.8 \times 10^{-19}\ e \cdot cm\ (95\%\ CL)}$. [10]

Fermilab muon g-2 experiment

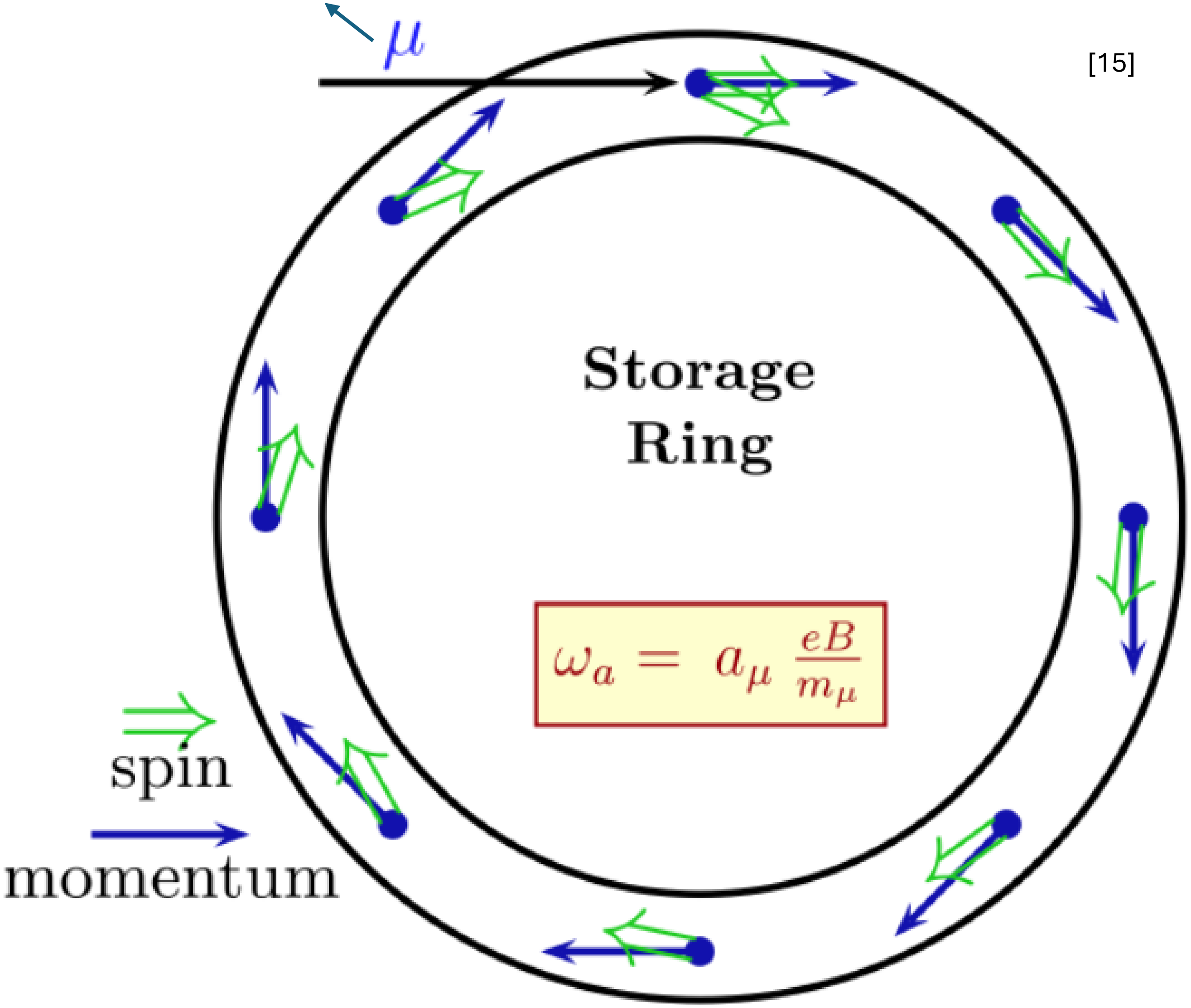


[14]

[16]



Polarised muon beam



[15]

Muon EDM in the g-2 experiment

BNL and FNAL both use this equation which is optimised for g-2, not EDM:

Field from the lab frame quadrupoles

[17]

Spin precession frequency

$$\vec{\omega} = -\frac{e}{m}\left[\underbrace{a_\mu\vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}}_{\text{g-2 term}} + \underbrace{\frac{\eta}{2}\left(\overbrace{\vec{\beta}\times\vec{B}}^{\text{“Motional” E-field}} + \frac{\vec{E}}{c}\right)}_{\text{EDM term}}\right]$$

Muons travel at the “magic momentum” (3.1 GeV) and so the term cancels out.

Muon EDM in the g-2 experiment

BNL and FNAL both use this equation which is optimised for g-2, not EDM:

Field from the lab frame quadrupoles

Spin precession frequency

$$\vec{\omega} = -\frac{e}{m}\left[\underbrace{a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}}_{\text{g-2 term}} + \underbrace{\frac{\eta}{2}\left(\overbrace{\vec{\beta}\times\vec{B}}^{\text{“Motional” E-field}} + \cancel{\frac{\vec{E}}{c}}\right)}_{\text{EDM term}}\right]$$

- $\vec{B}$ is 1.45 T and $\vec{E}$ is 18kV and therefore $\frac{\vec{E}}{c}$ is negligible in comparison to $\vec{\beta}\times\vec{B}$

Muon EDM in the g-2 experiment

BNL and FNAL both use this equation which is optimised for g-2, not EDM:

Spin precession frequency

$$\vec{\omega} = -\frac{e}{m}\left[\underbrace{a_\mu \vec{B}}_{\text{g-2 term}} + \underbrace{\frac{\eta}{2}\left(\vec{\beta} \times \vec{B}\right)}_{\text{EDM term}}\right]$$

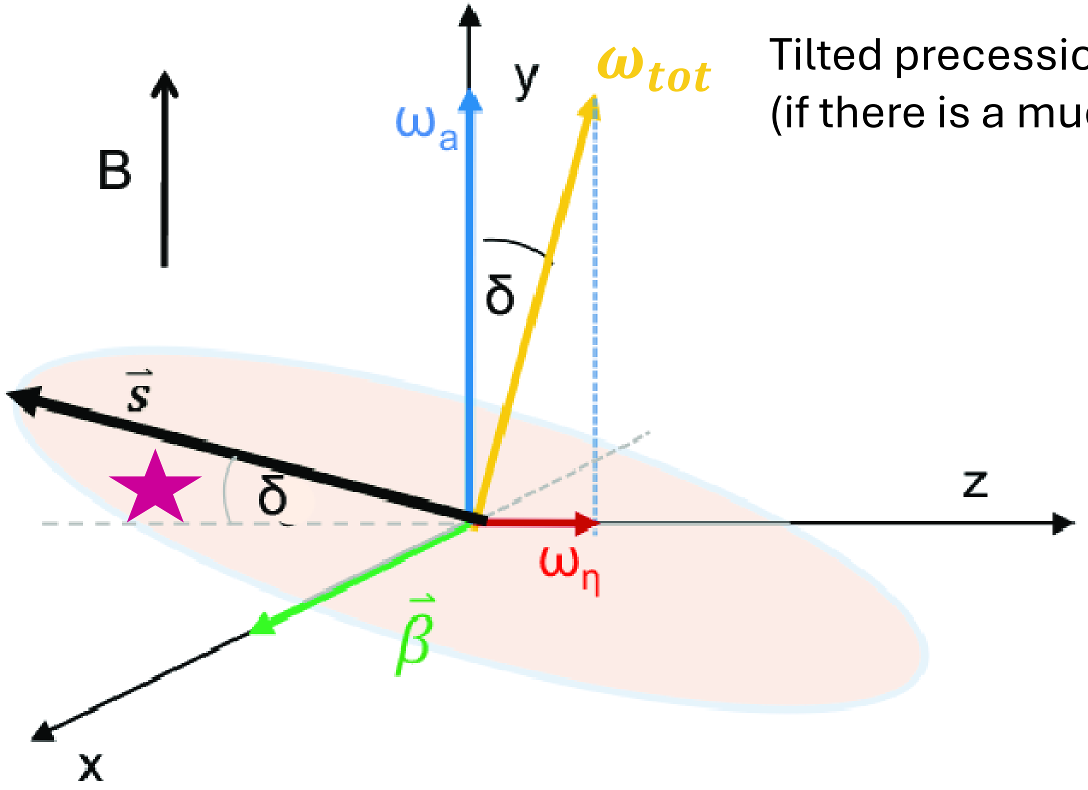
Aligned with $\vec{B}$

Perpendicular to $\vec{B}$

= tilted spin precession plane

Muon EDM in the g-2 experiment continued

[19]



Tilted precession plane
(if there is a muon EDM)

$$\vec{d} = \eta \frac{e}{2m} \vec{s}$$

$$\bigstar\ \delta = \tan^{-1}\frac{\omega_\eta}{\omega_a} \approx \frac{\omega_\eta}{\omega_a} = \frac{\beta\eta}{2a_\mu}$$

$$\overrightarrow{\boldsymbol{\omega_a}} = -\frac{\boldsymbol{e}}{\boldsymbol{m}}\left[\boldsymbol{a_\mu}\overrightarrow{\boldsymbol{B}}\right]$$

$$\overrightarrow{\boldsymbol{\omega_\eta}} = -\frac{\boldsymbol{e}}{\boldsymbol{m}}\left[\frac{\boldsymbol{\eta}}{2}\left(\vec{\boldsymbol{\beta}} \times \vec{\boldsymbol{B}}\right)\right]$$

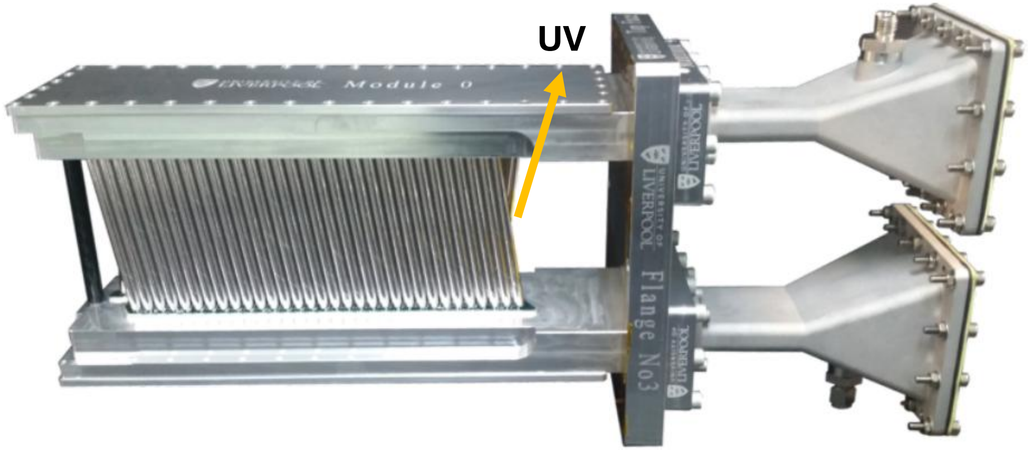
The spin precession plane tilts by an angle δ

- **Size of the tilt ∝ size of the EDM**

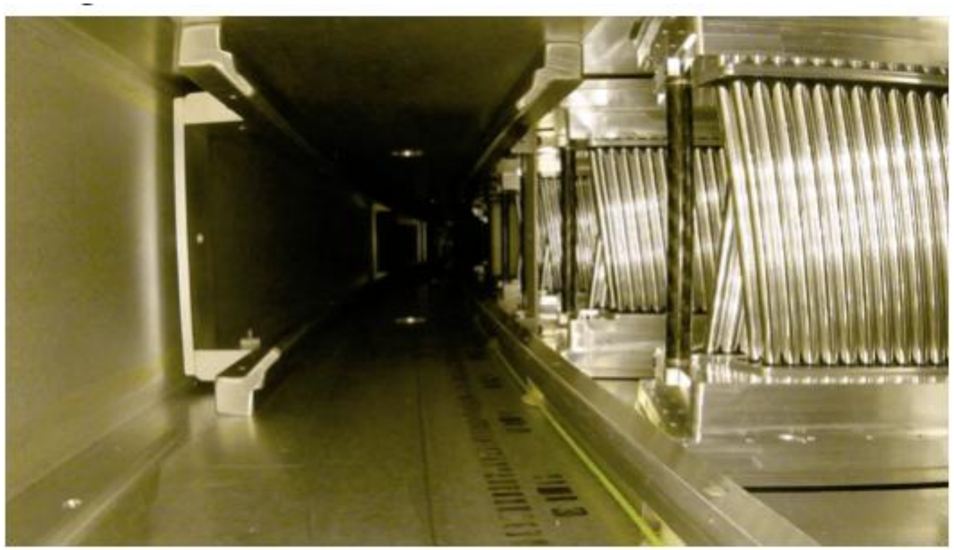
A muon EDM would increase the precession rate. We use the tilt to distinguish between the MDM and EDM. Using BNL limit of $d_\mu = 1.8 \times 10^{-19}$ e.cm gives Δa_μ = **189 ppb.**

Tracking station in Fermilab g-2

[20]

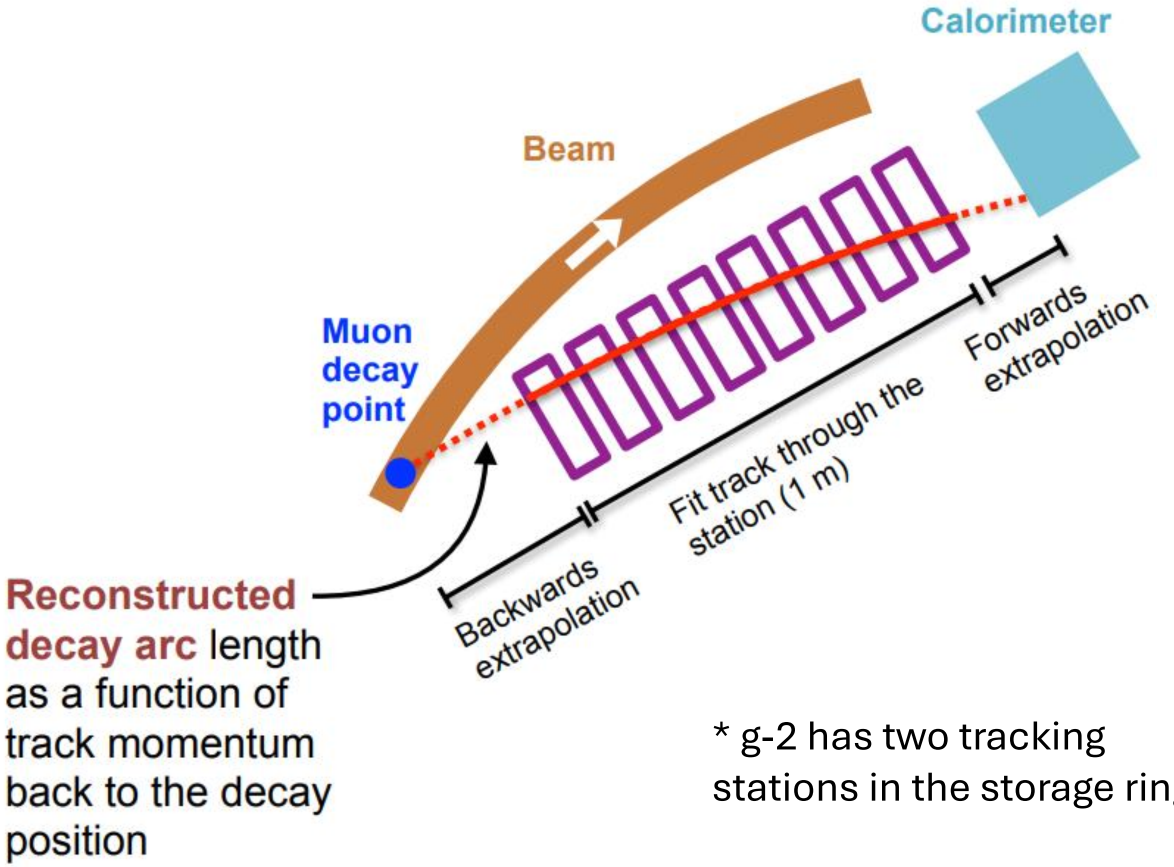


[15]



[15]

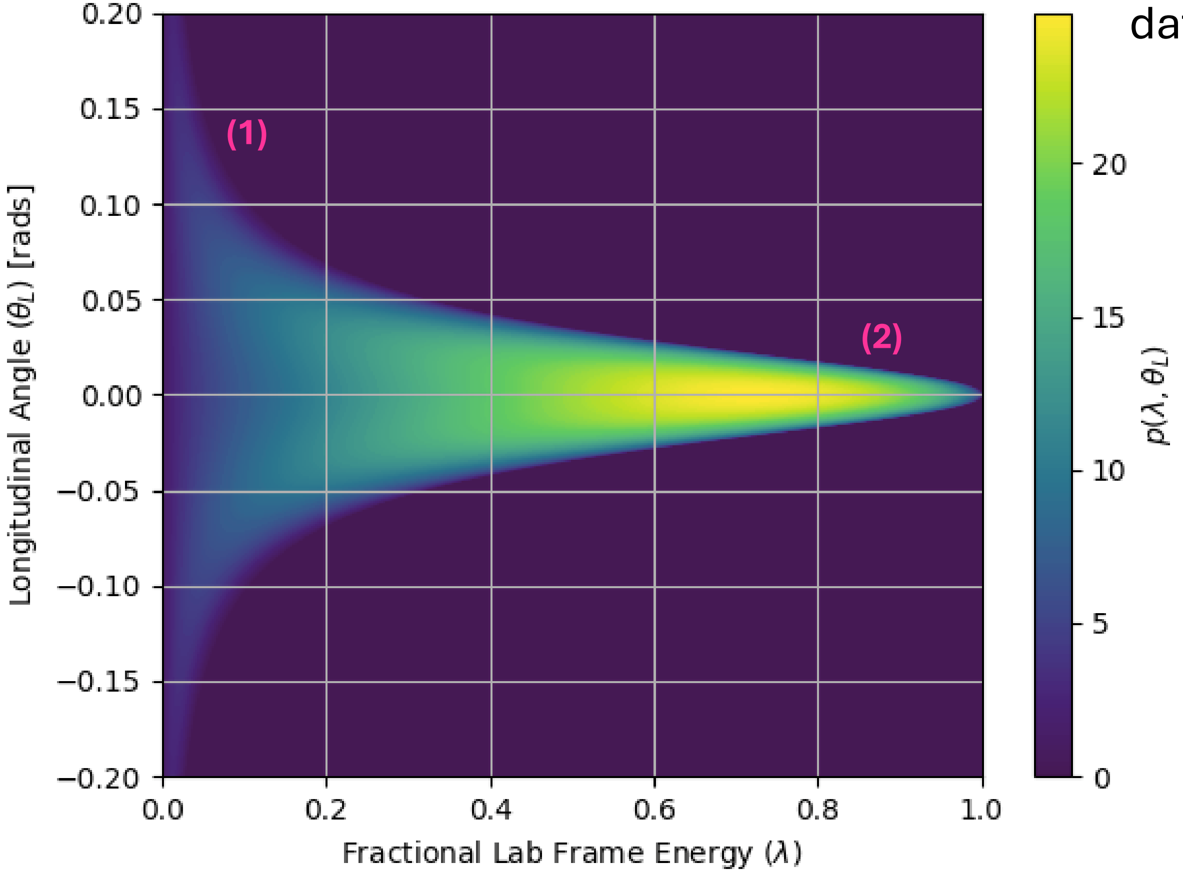
- We can't measure the spin directly, so we use the positron momentum as a proxy
- We measure the tilt at the decay vertex

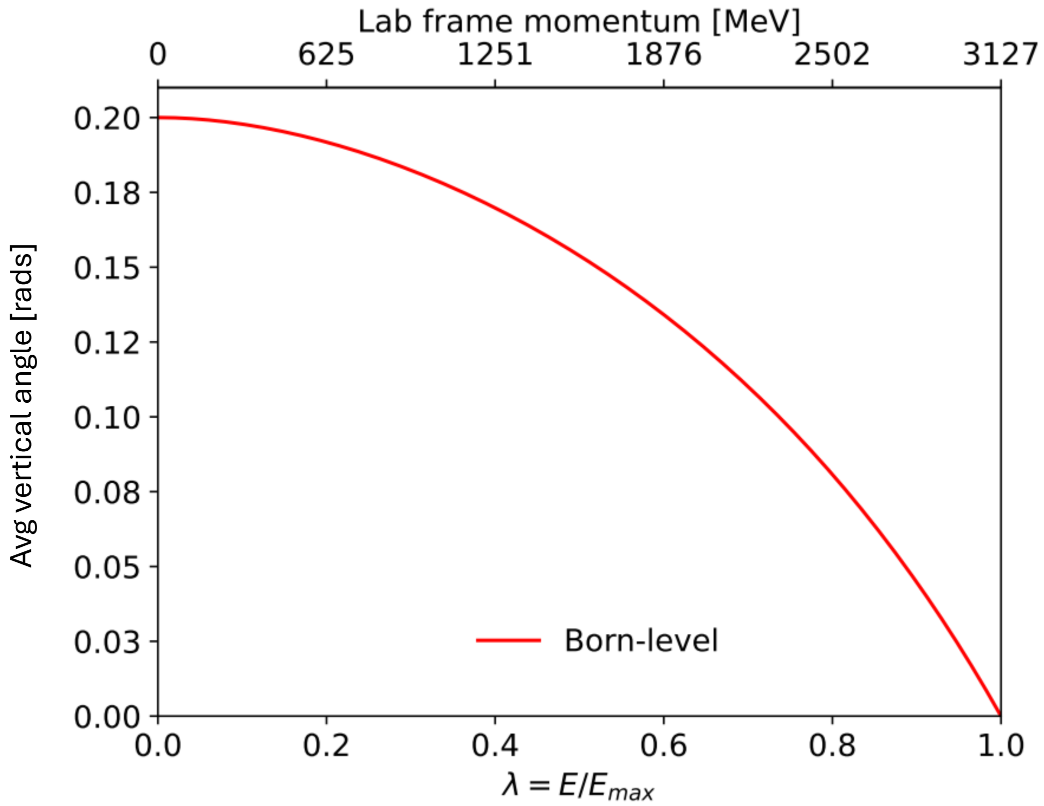


* g-2 has two tracking stations in the storage ring

Momentum dependence

The sensitivity to an EDM signal is dependent on momentum and therefore are split into a binned analysis. The analysis splits the data into 250 MeV bins going from 750-2750 MeV.





The trade off between wanting high statistics (1), low angular spread (2) and high signal sensitivity (3) means that the mid-momentum range are the best bins to use.

High energy positrons are emitted along the muon spin direction.

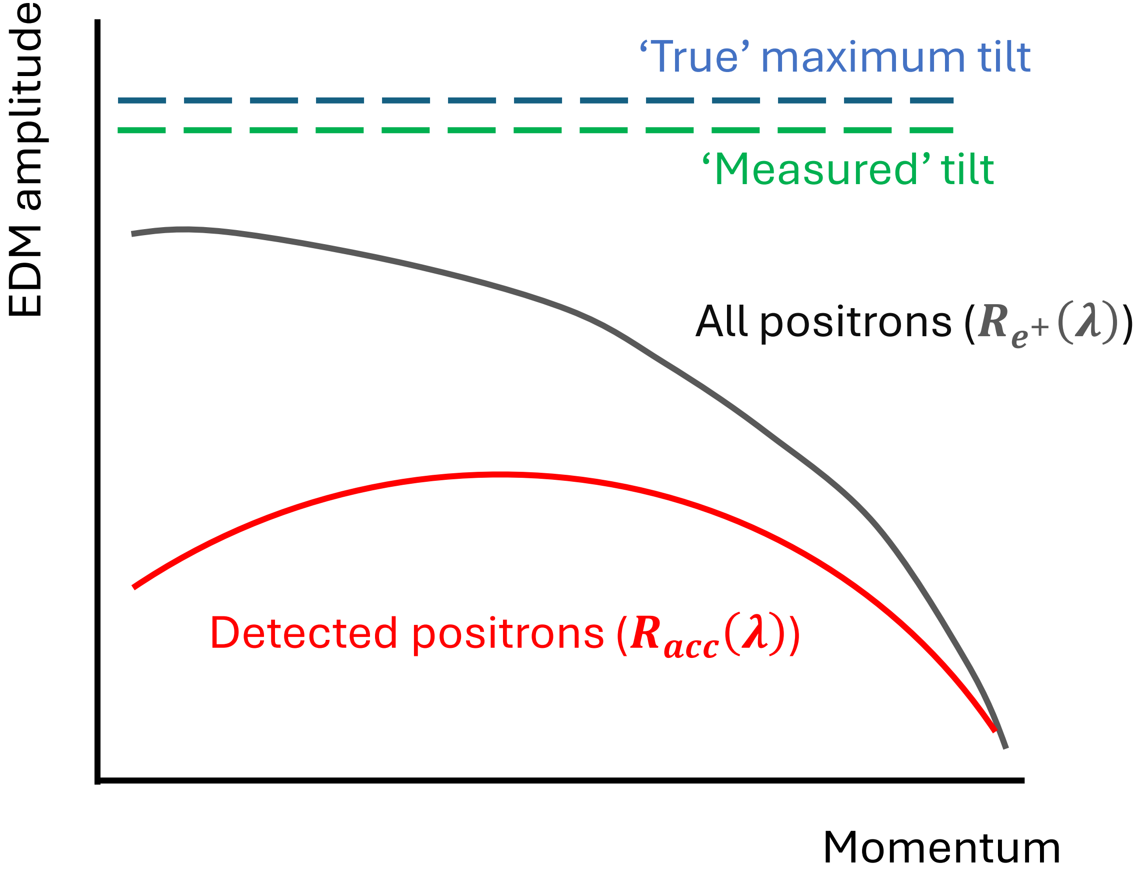
Reductions to the measured vertical angle

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

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

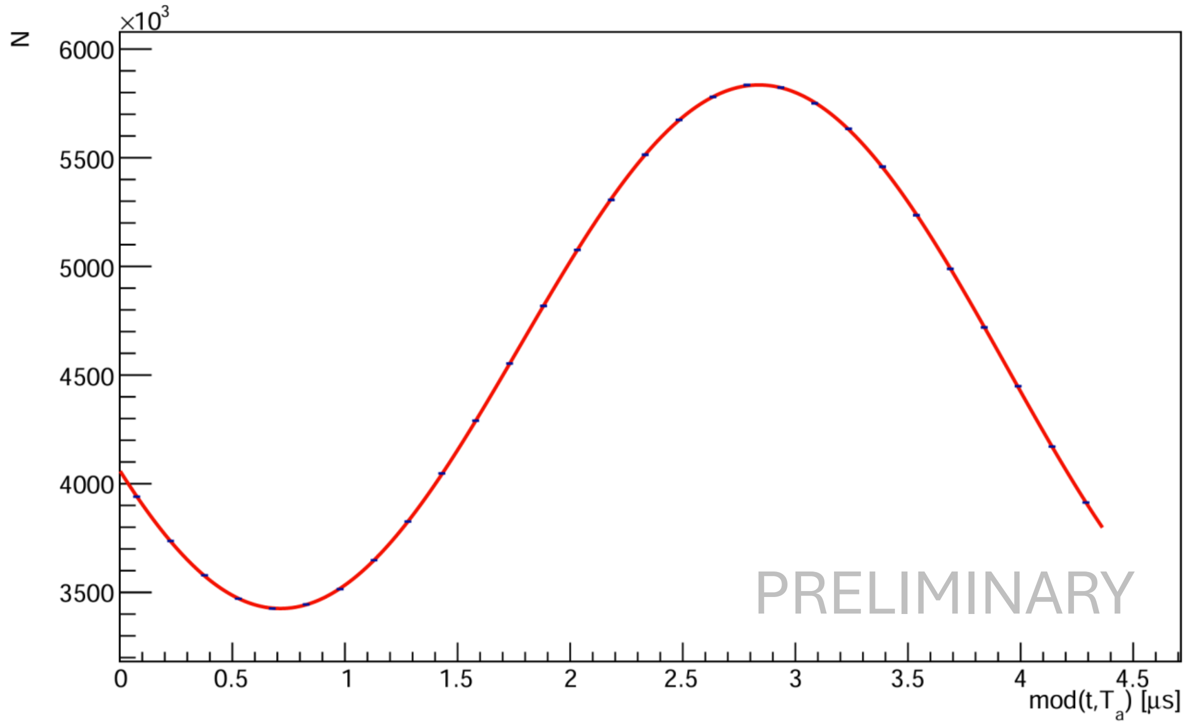
- $\boldsymbol{R_\gamma}$ **:** boost factor from muon rest frame to lab frame.
  - Factor is 1/γ, so ~ 1/29.
- $\boldsymbol{R_p}$ **:** beam polarization reduction (as is < 100%).
- $\boldsymbol{R_{e^+}(\lambda)}$ **:** muon decay asymmetry shape.
  - Has an analytical form, f(λ), where λ is fractional momentum, calculated up to first order radiative corrections.
- $\boldsymbol{R_{acc}(\lambda)}$ **:** acceptance effects, from the finite size of the tracker + reconstruction capabilities.
  - Determined from MC ratios.

(Tilts not to scale)



How do we look for an EDM signal

- Step 1: Need to know the g-2 phase
  - EDM signal is π/2 out of phase with it.
- So, fit the g-2 oscillation from the trackers
  - Momentum cut > 1700 MeV.
- Other parameters used in main g-2 analysis not needed.
  - Uncertainty propagated through to the impact on EDM as a systematic.

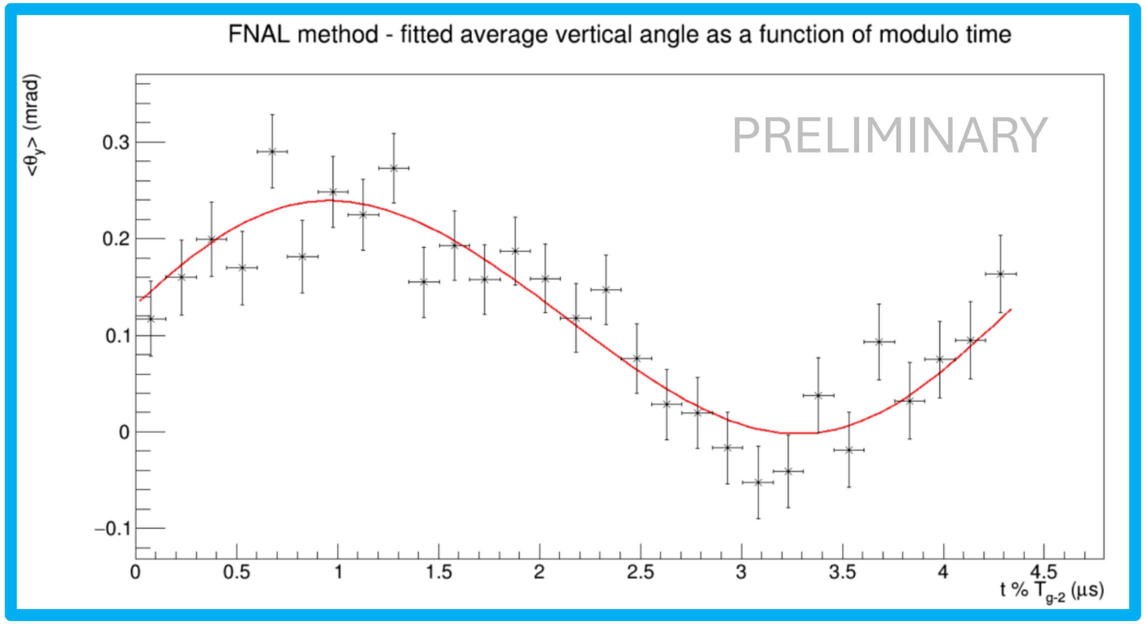


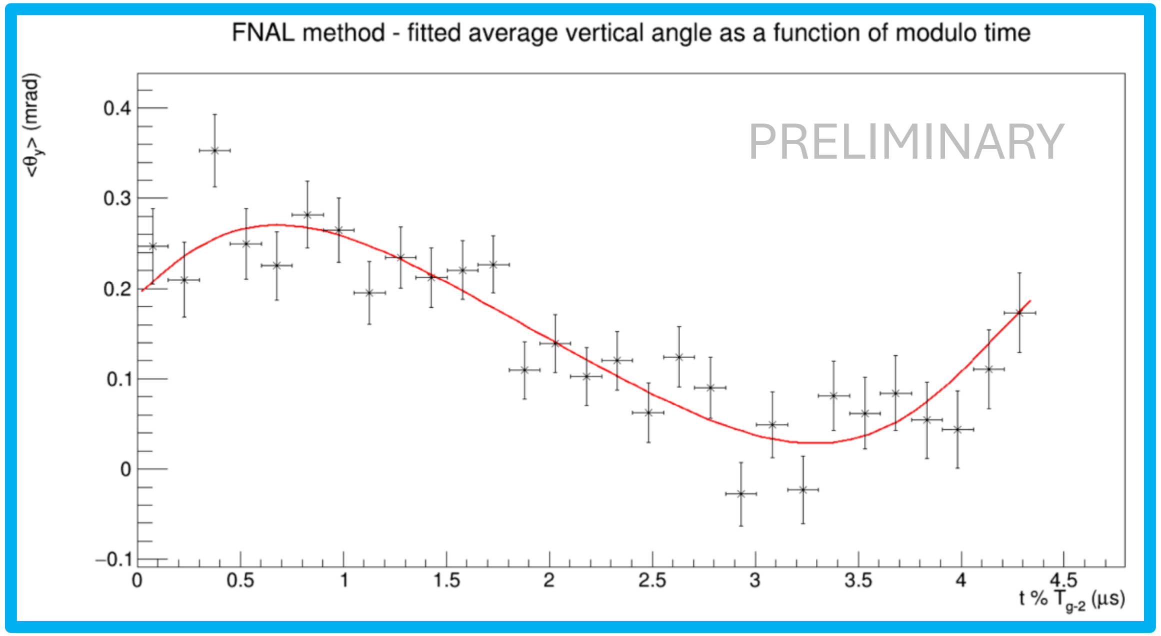
[5]

$$N(t) = N_0 e^{-t/\gamma\tau}\underbrace{(1+A_N\cos(\omega_a t+\phi_a))}_{\text{g-2 wiggle}}$$

Number of positrons

Extracting the EDM signal





1500-1750 MeV, station 12

Mostly sinusoidal

2000-2250 MeV, station 12

Not sinusoidal

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

Then, fit the average vertical angle oscillation using the g-2 phase.

An EDM signal would be π/2 out of phase with the g-2 phase.

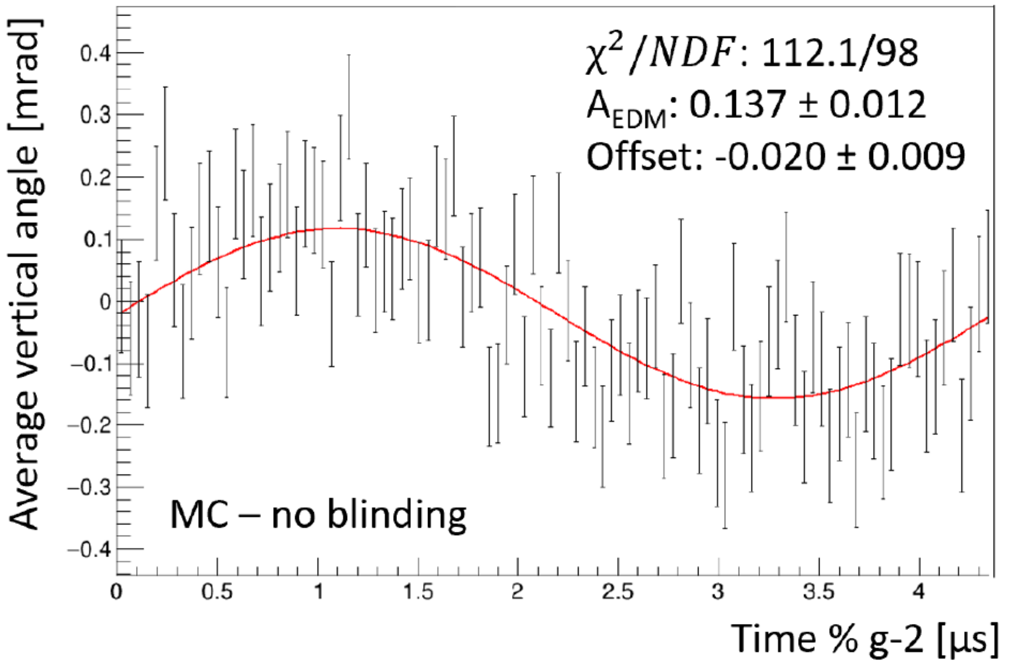
Blinding in the muon EDM analysis

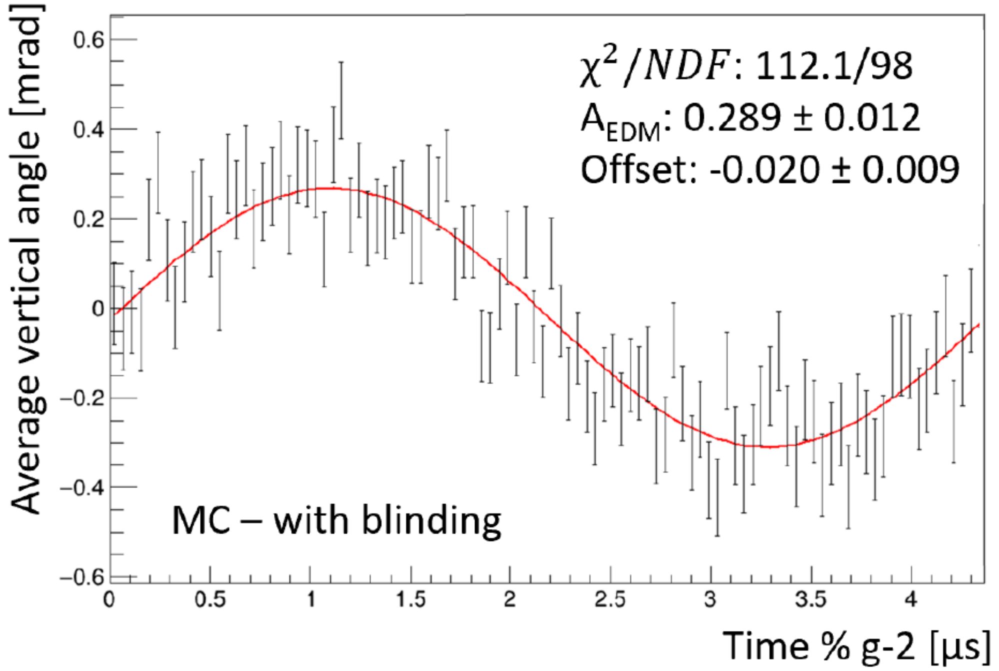
- A blinding was added to not bias the analysis. An EDM signal of unknown size was added to the data using MC and the fake EDM added is much larger than the BNL muon EDM limit.

- If there was no EDM, and no blinding applied, the average vertical angle would be flat.

Test blinding

[24]





Average radial field

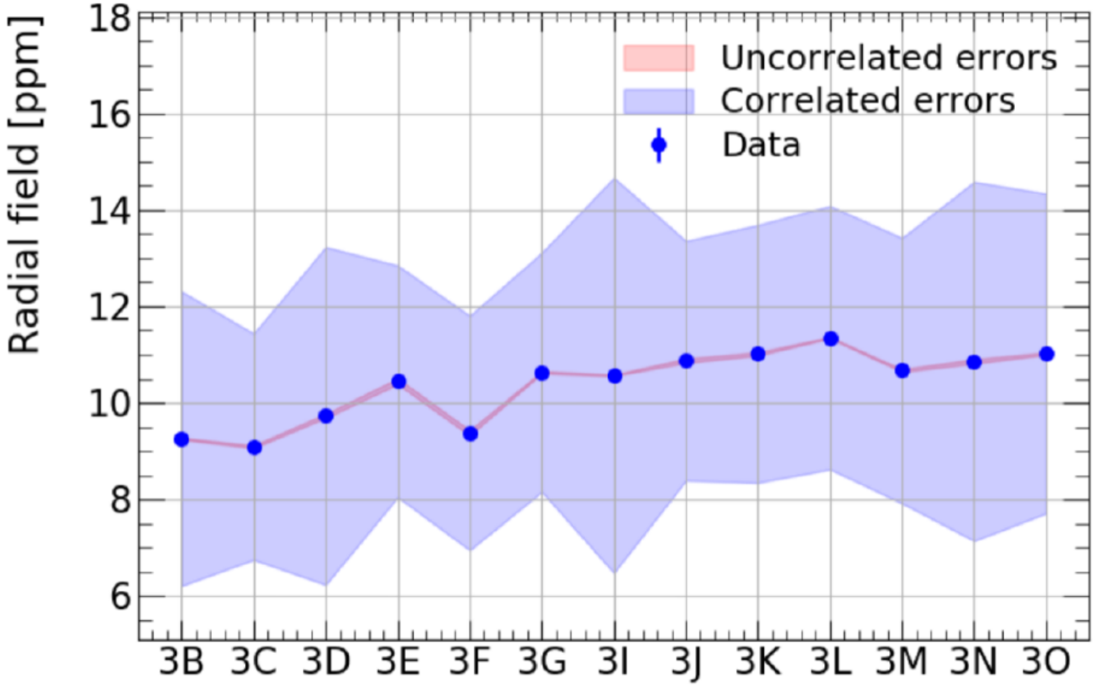
A non-zero average radial field can mimic an EDM signal as it also tilts the precession plane.

Scans are performed in Run 4/5/6 – so need to extrapolate the measurements to Runs 1/2/3 using the vertical beam position.

Radial field scans can achieve 1ppm uncertainty and therefore the average radial field is measured precisely enough to not be the limiting systematic.

The average radial field mimic ended up being a small effect.

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



[5]

Systematic limitations

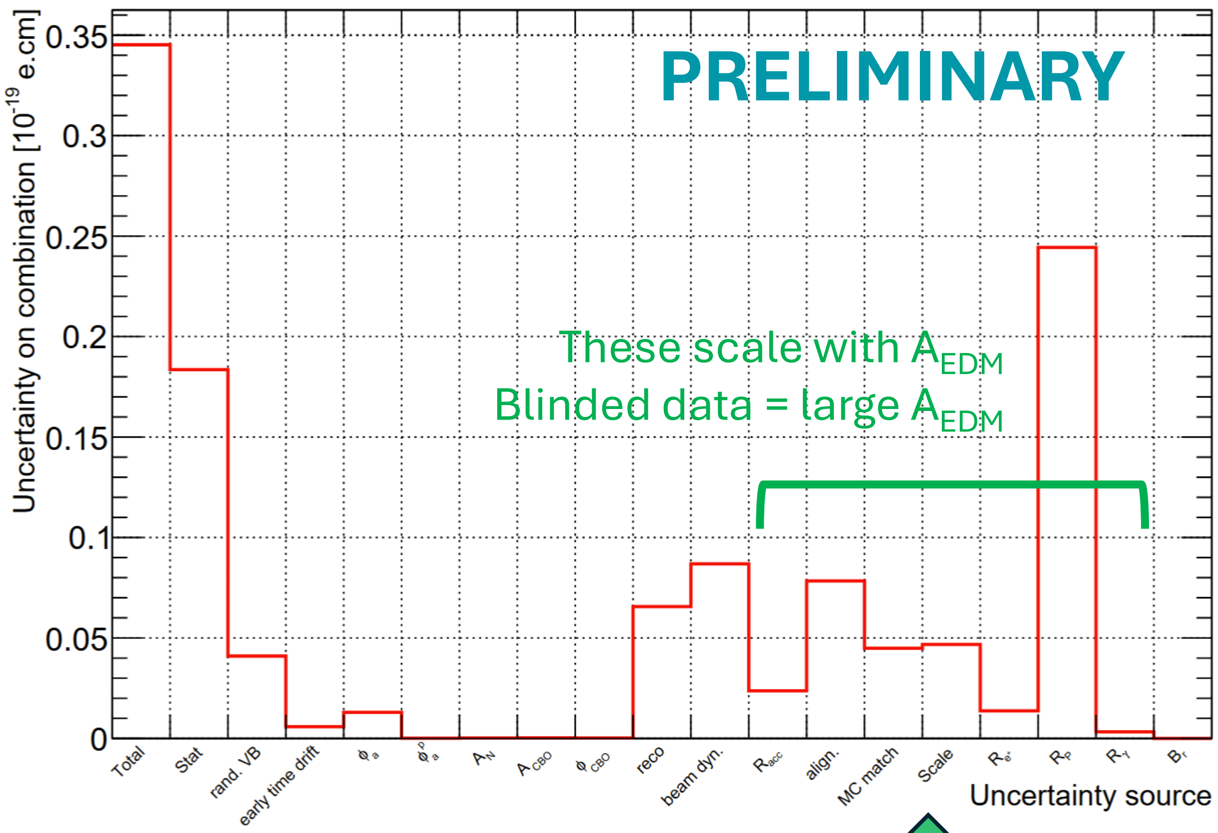
Plot abbreviations:

- Align: alignment
- Beam dyn (beam dynamics): CBO beam oscillation

The analysis is expected to be statistically limited.

- The statistically uncertainty is 2 times larger than any systematic for run 2-3.
- The group is still investigating the alignment uncertainties and are subject to change.

[5]



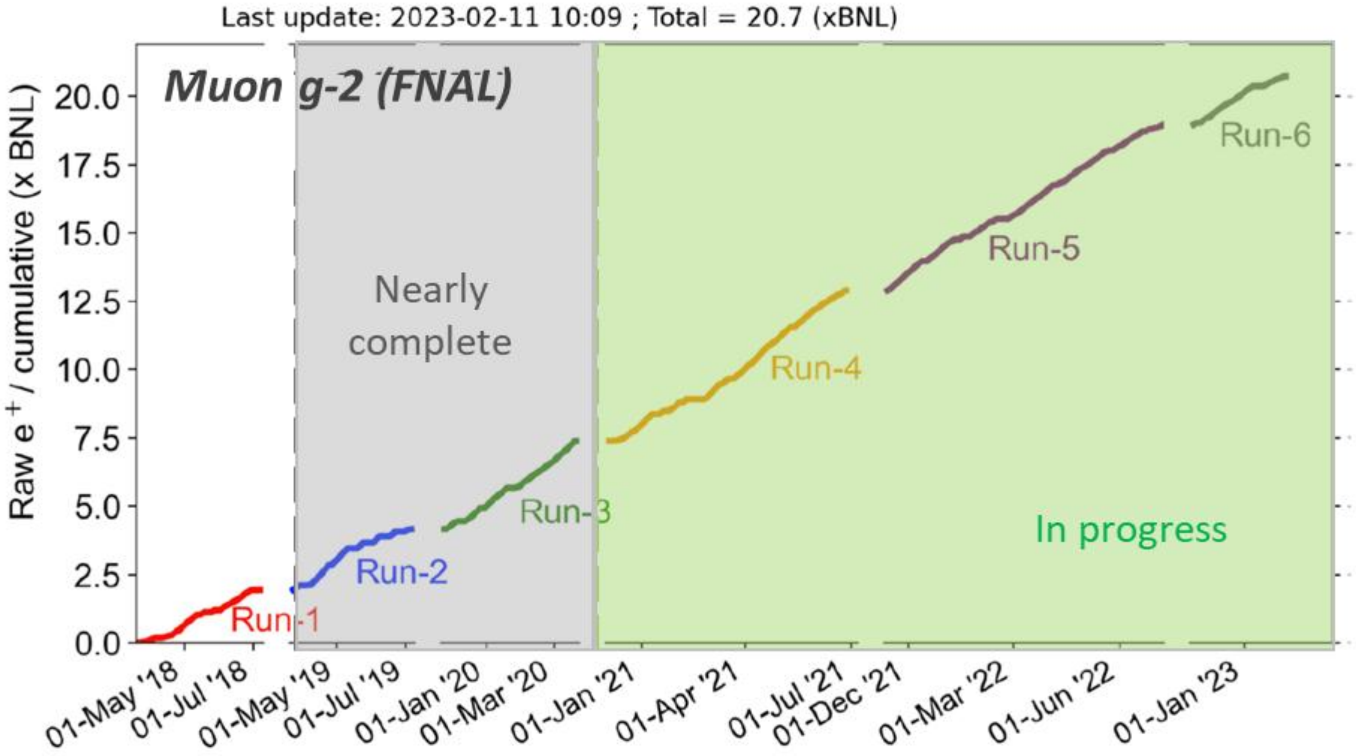
Alignment and R_p scale with A_{EDM} and therefore will change (decrease) once the large blinding factor is removed.

Analysis timeline

Run 2/3 status:

- Analysis mostly complete, in collaboration review.
- Full dataset:
  - Expected to improve on BNL limit by ~ an order of magnitude.

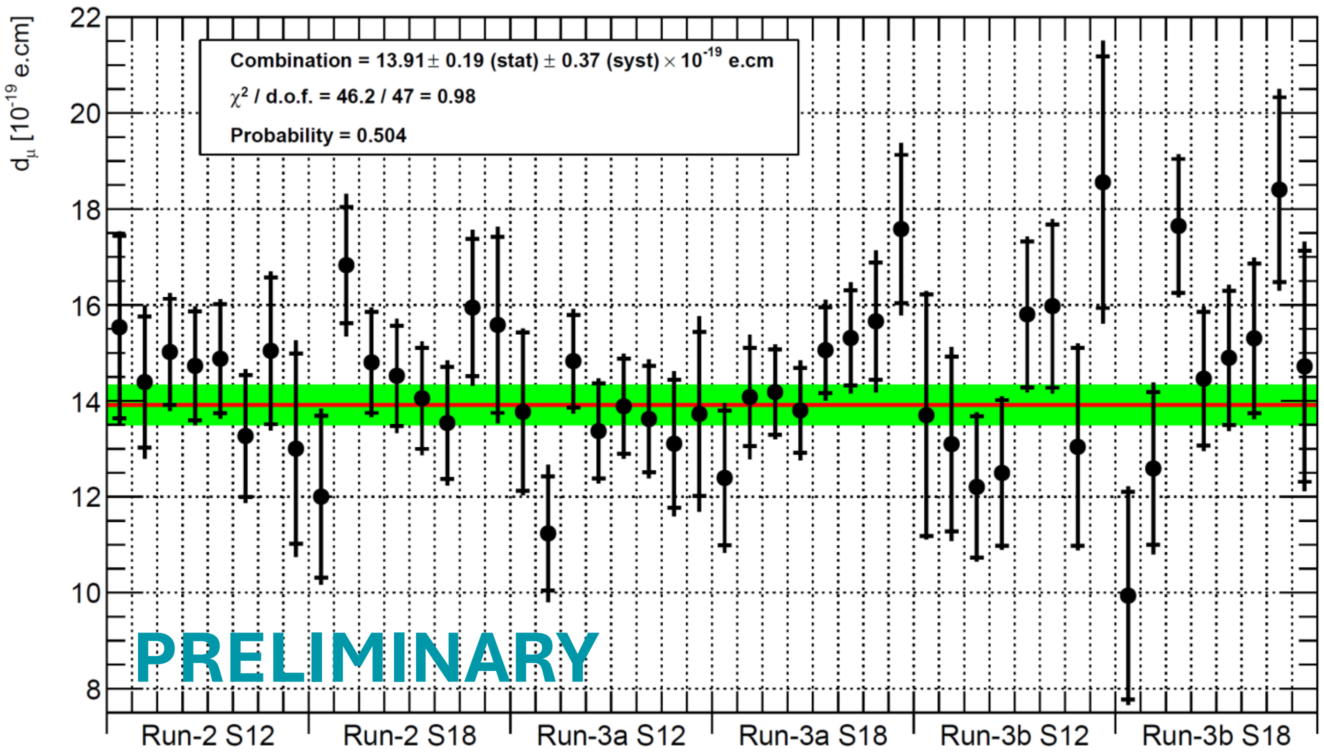
[5]



Preliminary blinded Run 2/3 results

Points combined + fitted using the Best Unbiased Linear Estimator (BLUE) method to account for correlations

- Assuming zero signal is observed, plan to set limit using the Feldman-Cousins method.
    - Matches most recent electron EDM results so easier to compare!

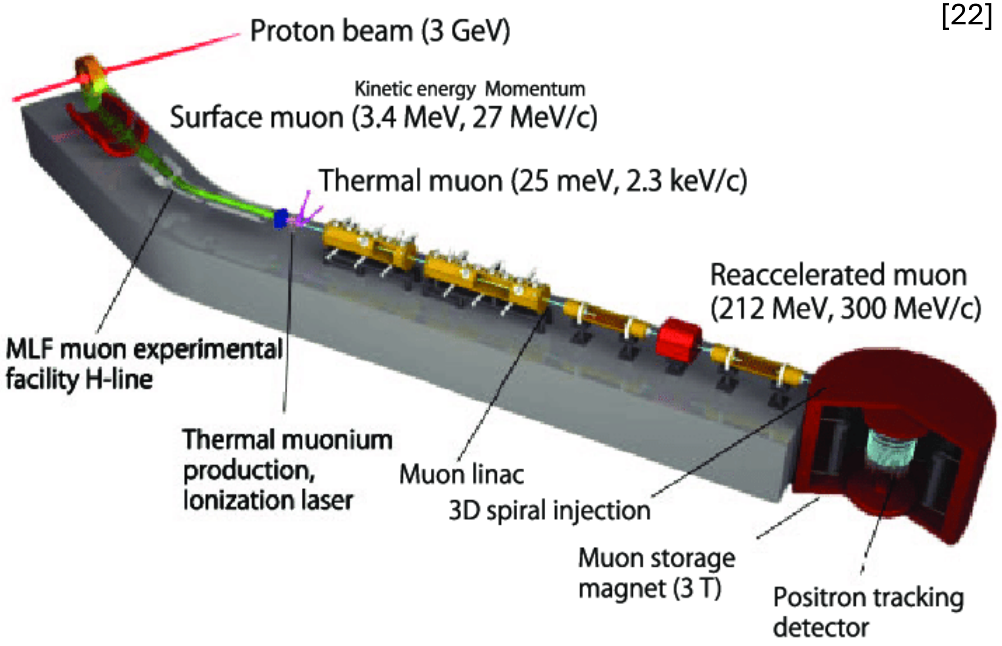


[5]

8 momentum bins x 2 tracker stations x 3 subsets = 48

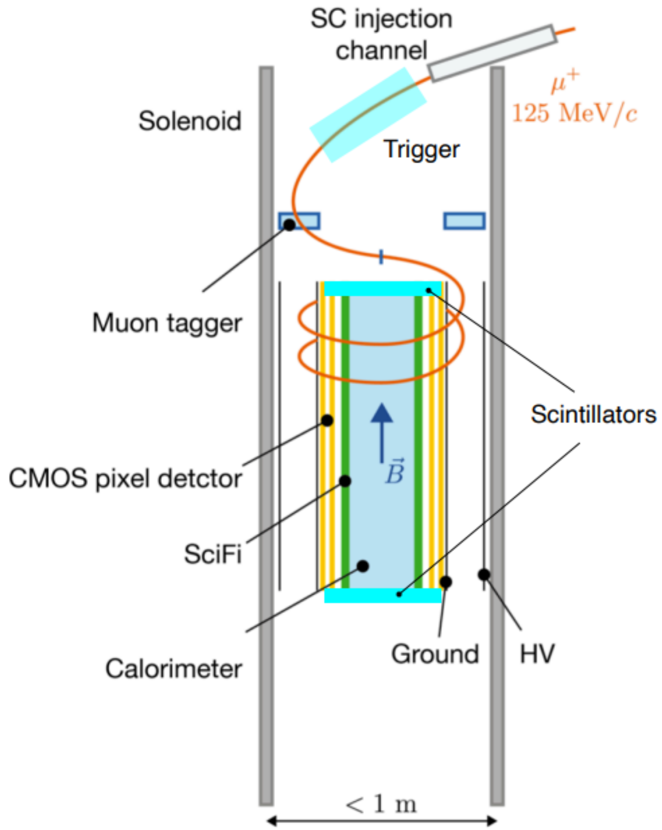
48 statistically independent EDM measurements

Other muon EDM experiments



[22]

J-PARC g-2/EDM experiment: $\mathrm{d}_\mu \sim 10^{-21} e.cm$

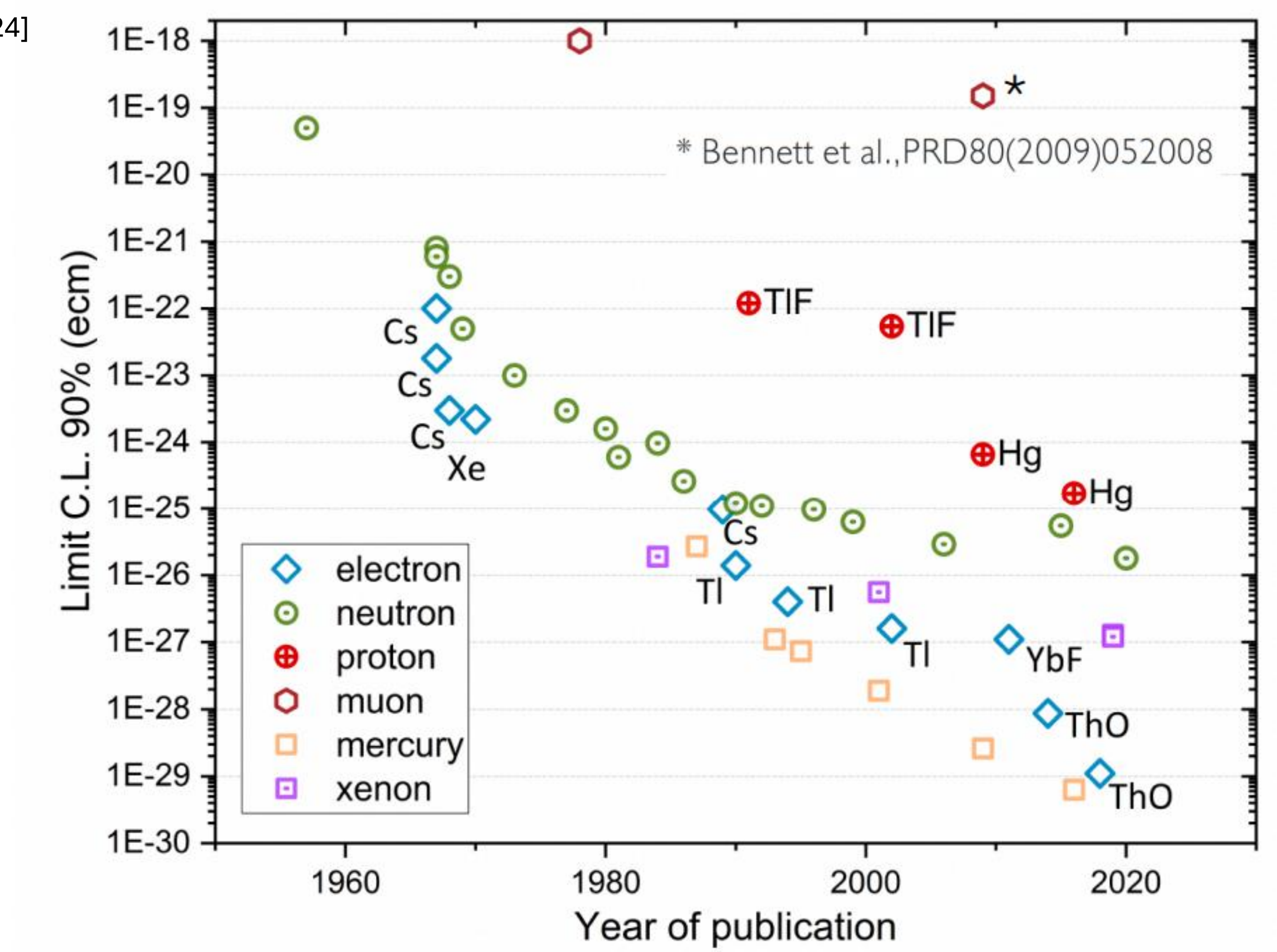


[23]

PSI muEDM: $\mathrm{d}_\mu \sim 10^{-23} e.cm$

Other EDM experiments

[24]



Full dataset: the run 2-3 limit will likely improve by a factor of 2 because of the increased statistics.

Dedicated EDM experiments will sharply improve the muon EDM limit as every muon will be used – in non-dedicated experiments, muons are optimised for the g-2 analysis.

Thank you!

References

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Back up

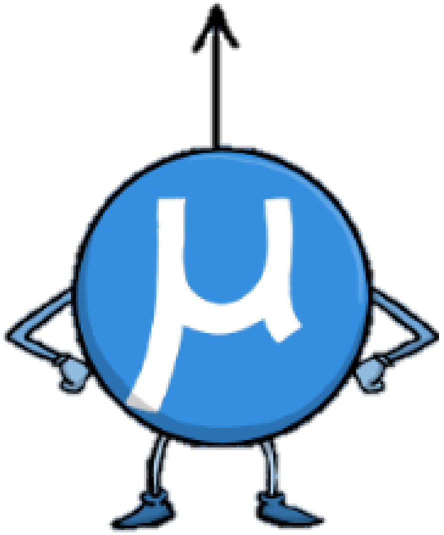
Definitions

MDM

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

g-2 investigates the behaviour of the muons in a B-field.

The g-factor relates the magnetic dipole moment (MDM) of a particle to its spin.



EDM

$$\vec{d} = \eta\frac{\mathrm{e}}{2m}\vec{s}$$

η is analogous to the g-factor.

It relates the electric dipole moment (EDM) of a particle to its spin.

Electron EDM ACME Experiment

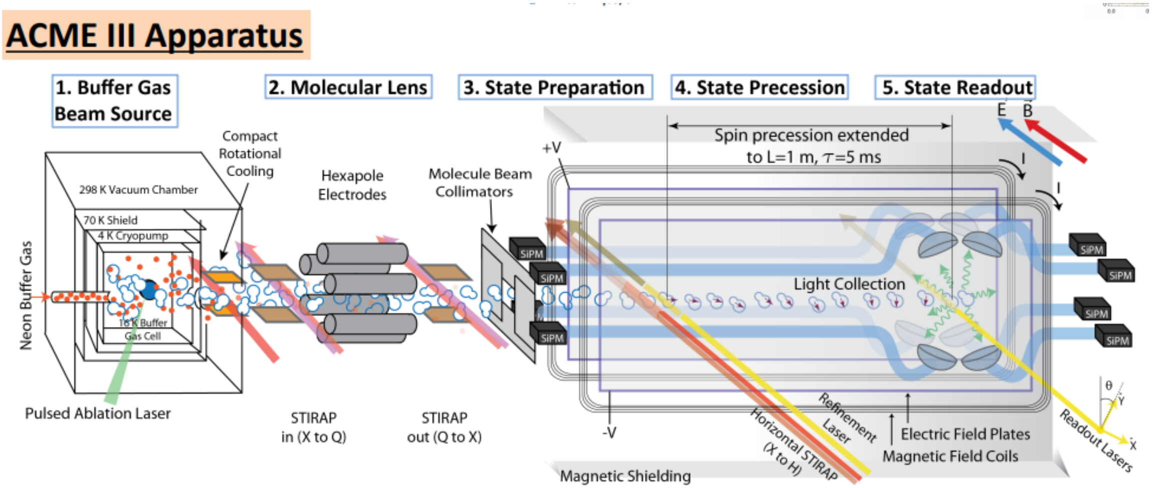
[25] [26]

- The ACME experiment searches for the electron's electric dipole moment (EDM) using a beam of cold, metastable thorium monoxide (ThO) molecules.

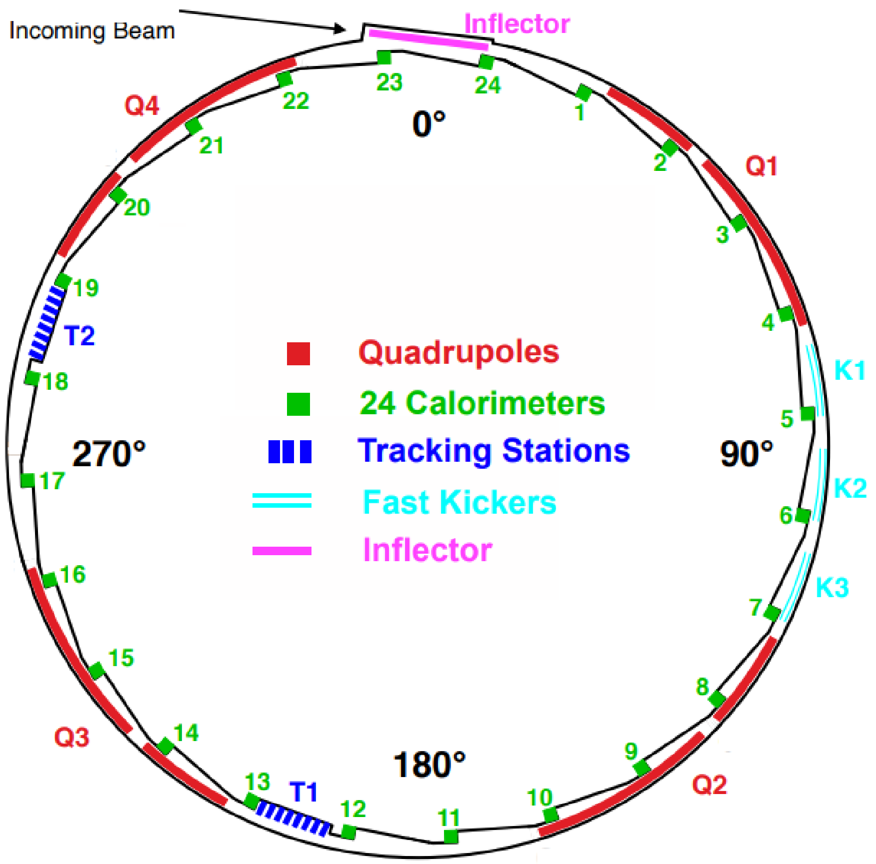
- In these molecules, there is an effective internal electric field which can interact with the molecular electrons' EDM. A particular metastable state of ThO is used and the electron's spin precession is measured as they travel through controlled electric and magnetic fields.

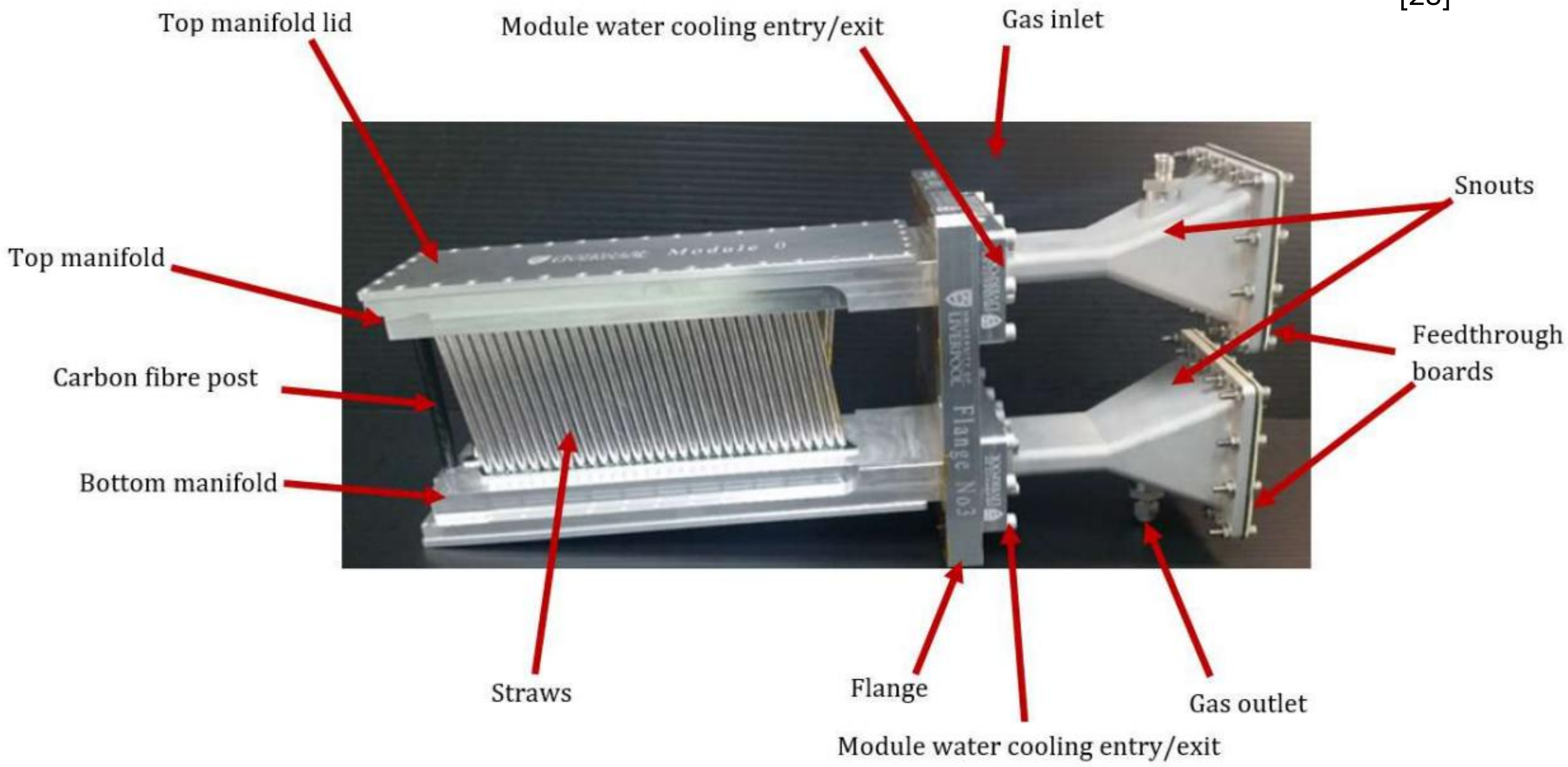
- ACME can detect tiny differences in spin orientation that would indicate a nonzero EDM.

- By performing the experiment many times with different relative directions of the applied electric and magnetic fields, they are able to isolate the amount of precession accumulated due the electron EDM.



g-2 straw trackers





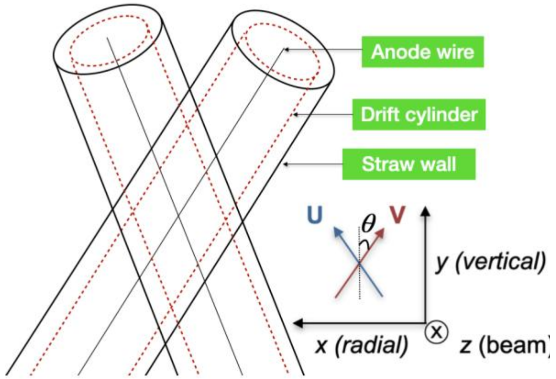
Each tracking station:

- 8 identical tracking 'modules'

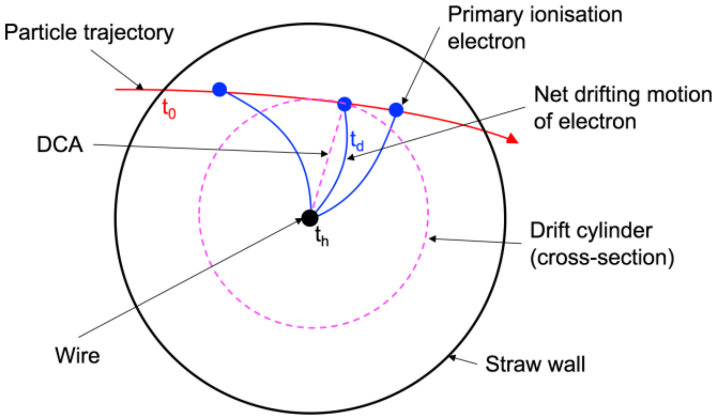
Each tracking 'module':

- 4 layers of 32 straws, grouped into two pairs of 'UV' layers
- The pairs are staggered by half a tube diameter to aid in resolution and minimise dead regions

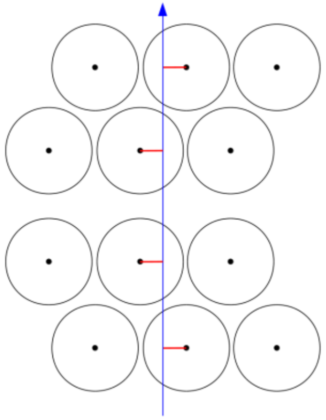
g-2 straw trackers



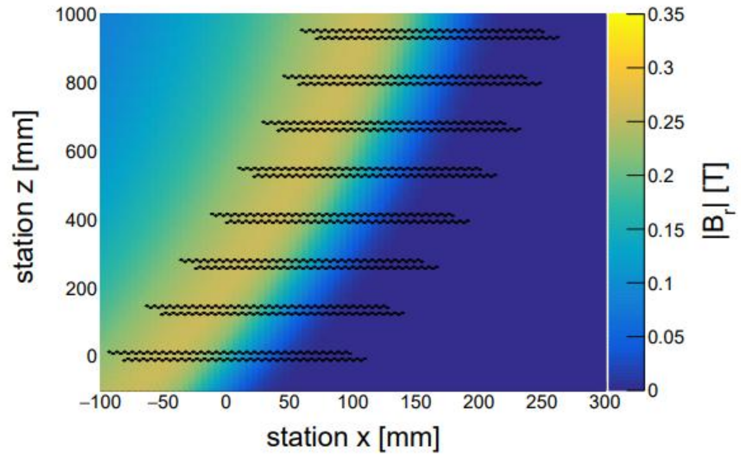
+/- 7.5° stereo angles



(a) Single drift cylinder.



(b) Multiple drift cylinders.



(c) Radial, $y = 45.0$ mm.

Radial B-field

Straws filled with 50:50 mixture of argon-ethane:

- Good resolution
- Minimum leak rate

Each straw contains a wire under high voltage:

- Ionisation electrons drift inwards but then are deflected by the ring's B-field
- The drifting electrons induce avalanches which produce ions which induce a signal in the wire

Motivation for future plans

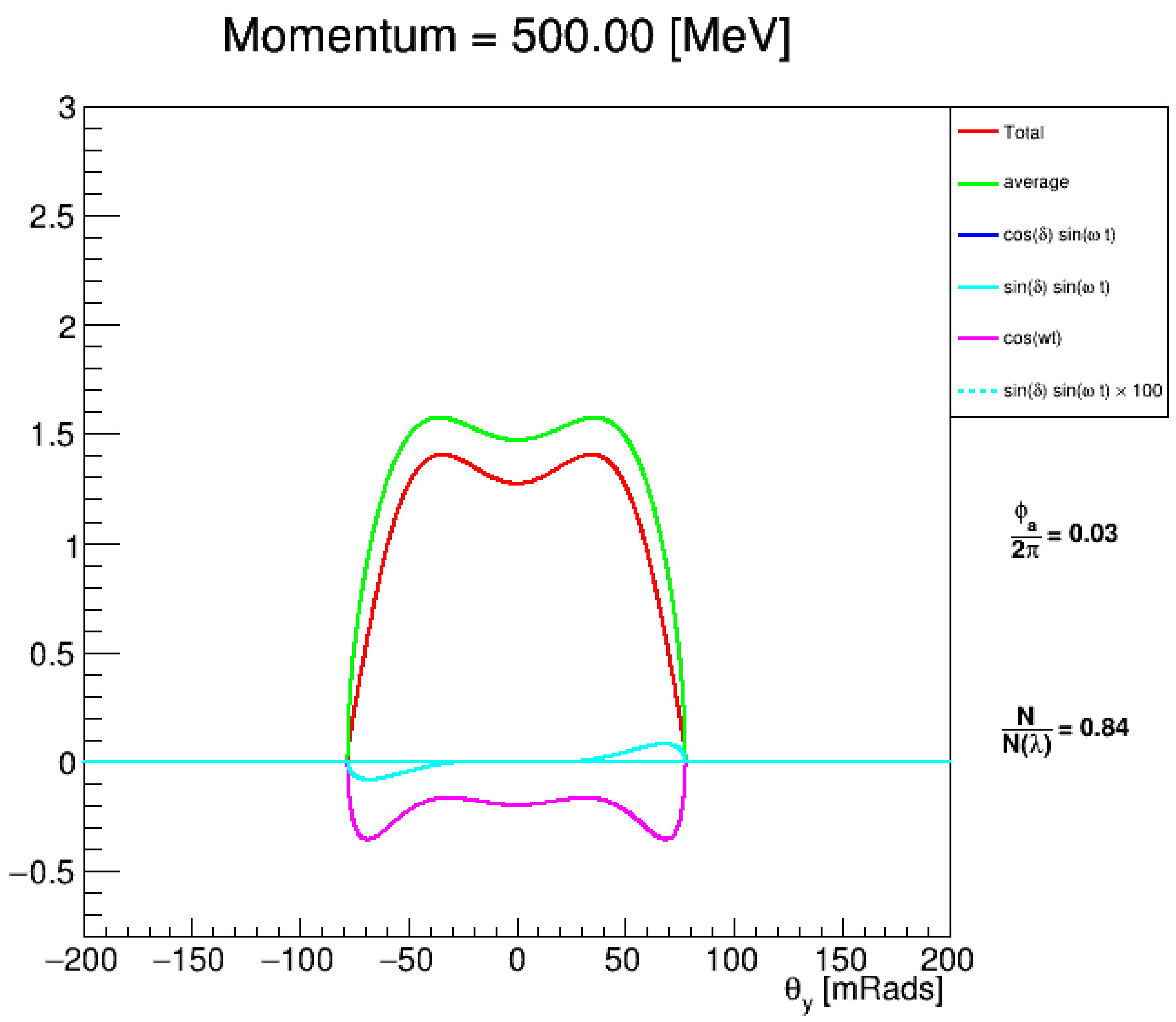
- We've seen that using the average angle method is ~40% better than using the asymmetry method.
- We now want to test a weighted average angle method and calculate its FOM.

New weighting terms

$$\{\theta_y\}_\lambda = \frac{\sum \theta p(\theta,\lambda)\omega(\theta,\lambda)}{\sum p(\theta,\lambda)\omega(\theta,\lambda)}$$

- We will weight based on the most sensitive vertical angles to an EDM for a given positron momentum

Visualising the oscillation



Visualising the oscillation