The Fermilab Muon g-2 straw tracking detectors and the muon EDM measurement

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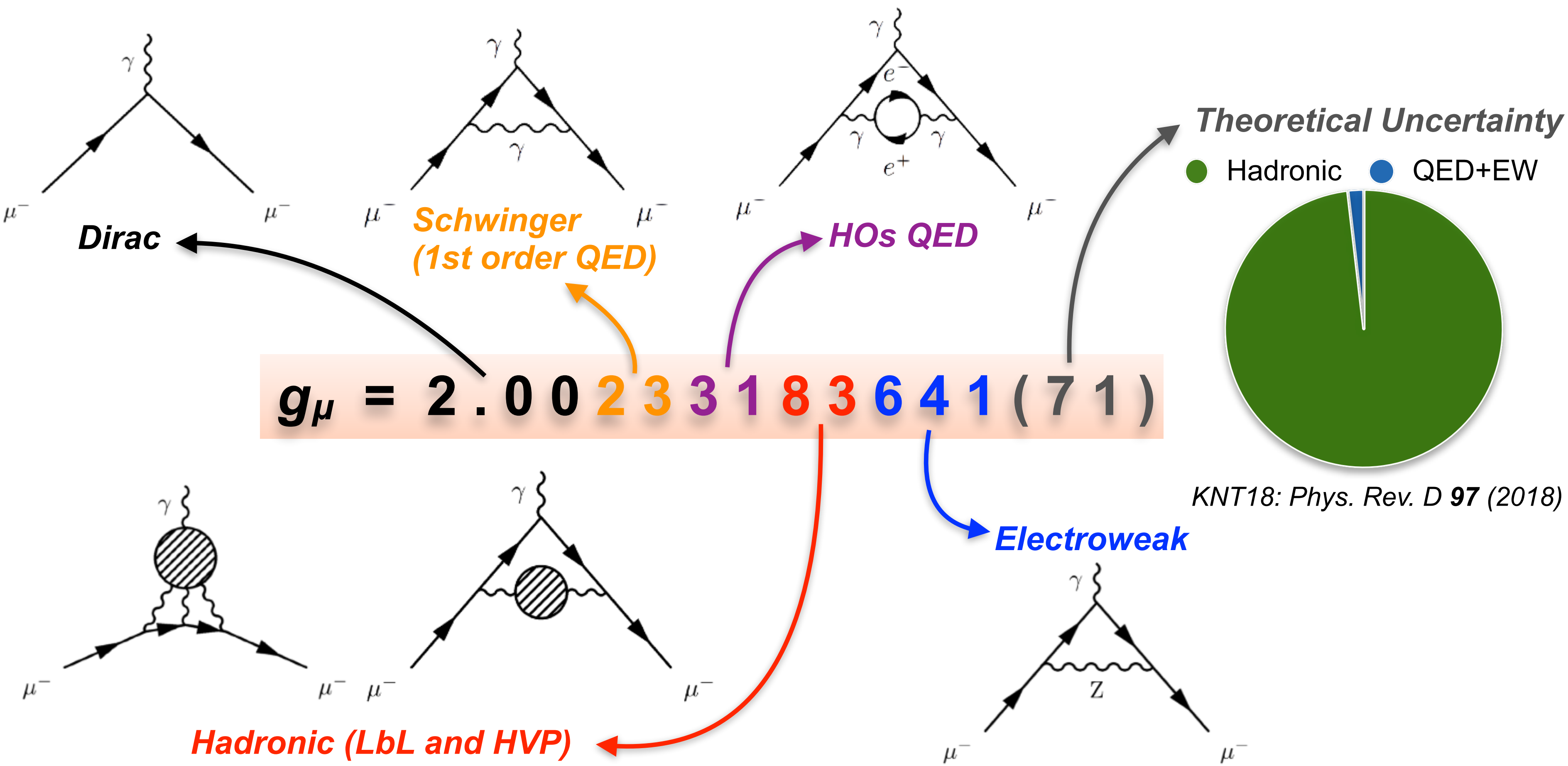
on behalf of the Fermilab Muon g-2 Collaboration

Meeting of the Division of Particles and Fields of the APS
29 July 2019
Boston

- The muon has an intrinsic magnetic moment, $\vec{\mu}$, that is coupled to its spin, $\vec{s}$, by the gyromagnetic ratio g_μ

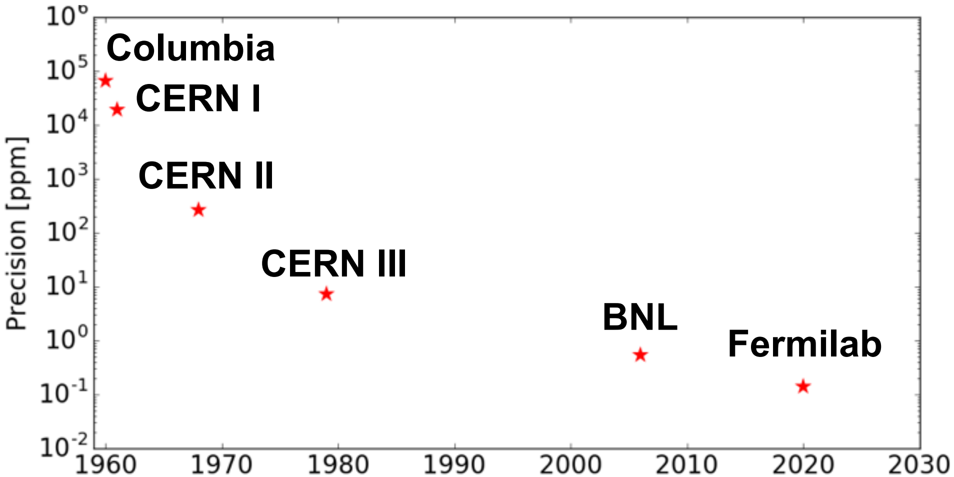
$$\vec{\mu} = g_\mu \left(\frac{e}{2m_\mu} \right) \vec{s}$$

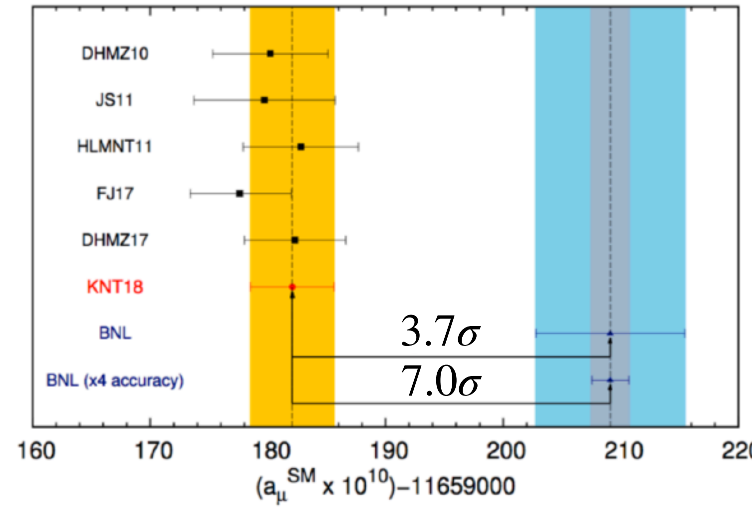
- Interactions between the muon and virtual particles alter this ratio



Physics Motivation

- The current discrepancy is at 3.7σ: $\delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 269(72) \times 10^{-11}$, with $a_\mu = \dfrac{g_\mu - 2}{2}$





- Assuming the central values of a_μ do not change, a 140 ppb measurement at Fermilab will yield a 7σ discrepancy. This will be achieved via reduction in:
  - statistical error via:
    - Improved beam duty cycle (12 Hz vs 1 Hz at BNL)
  - systematic error via:
    - **in-vacuum tracking system**, segmented calorimeters, field uniformity, laser calibration…

- Additionally, the *Muon g-2 Theory Initiative* will aim to reduce the uncertainty from hadronic contributions to a_μ

See Jason Crnkovic's plenary talk on Monday for more information

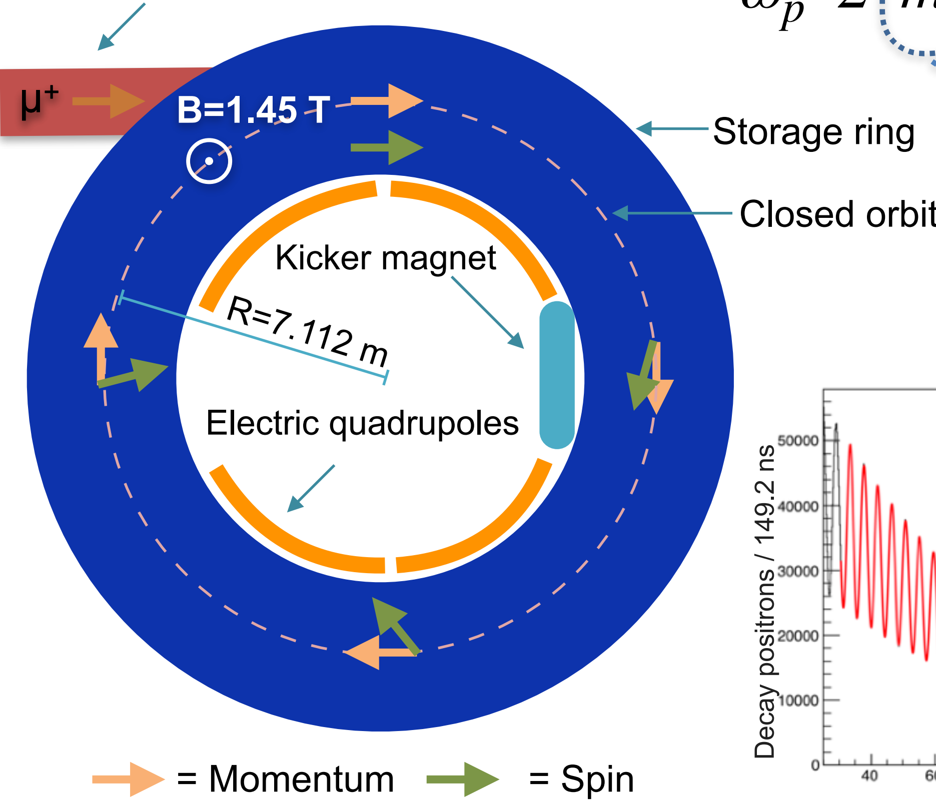
- The two frequencies that are measured in the experiment are

$$\omega_a = \omega_s - \omega_c = -a_\mu \frac{e}{m_\mu} B \qquad \omega_p \propto |B|$$

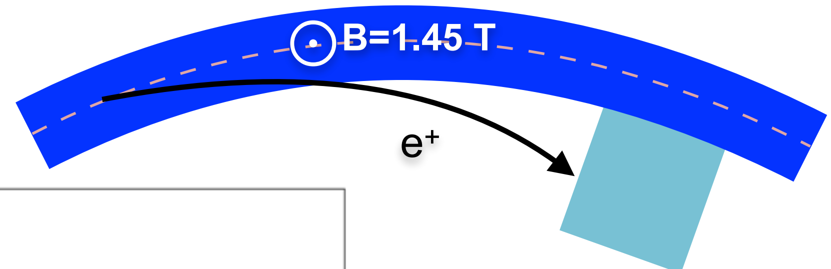
- The anomalous magnetic moment is then determined from the ratio

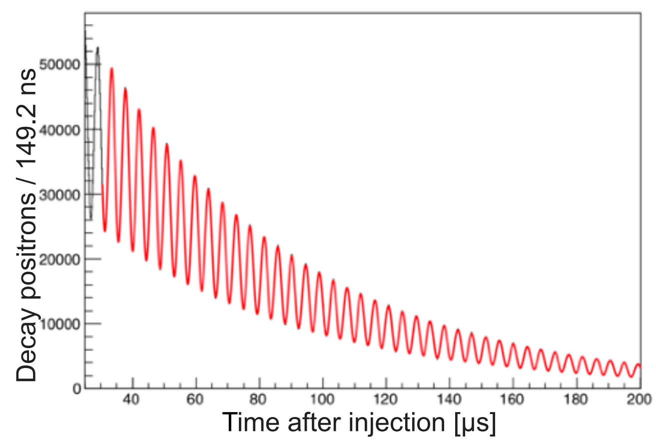
$$a_\mu = \frac{\omega_a}{\omega_p} \frac{g_e}{2} \frac{m_\mu}{m_e} \frac{\mu_p}{\mu_e}$$

g_e: 0.00026 ppb
μ_p/μ_e: 3.0 ppb *Rev. Mod. Phys.* ***88,*** 035009 (2016)
m_μ/m_e: 22 ppb



- The decay positron curls inwards, and is measured by one of the 24 calorimeters





- Histogram high energy positron events over time to extract ω_a from a fit
- CERN III precision (10 ppm) per hour

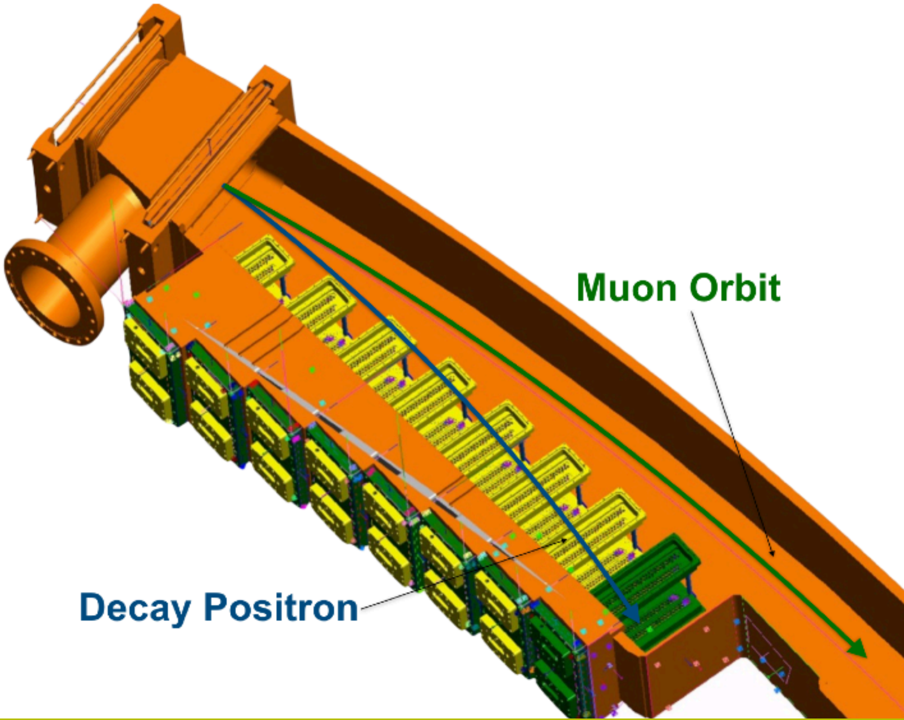
Tracker Overview

- Reduce the systematic uncertainty on the ω_a via measurements of
  - the muon beam profile
  - positron pile-up in calorimeters
  - independent gain cross-check

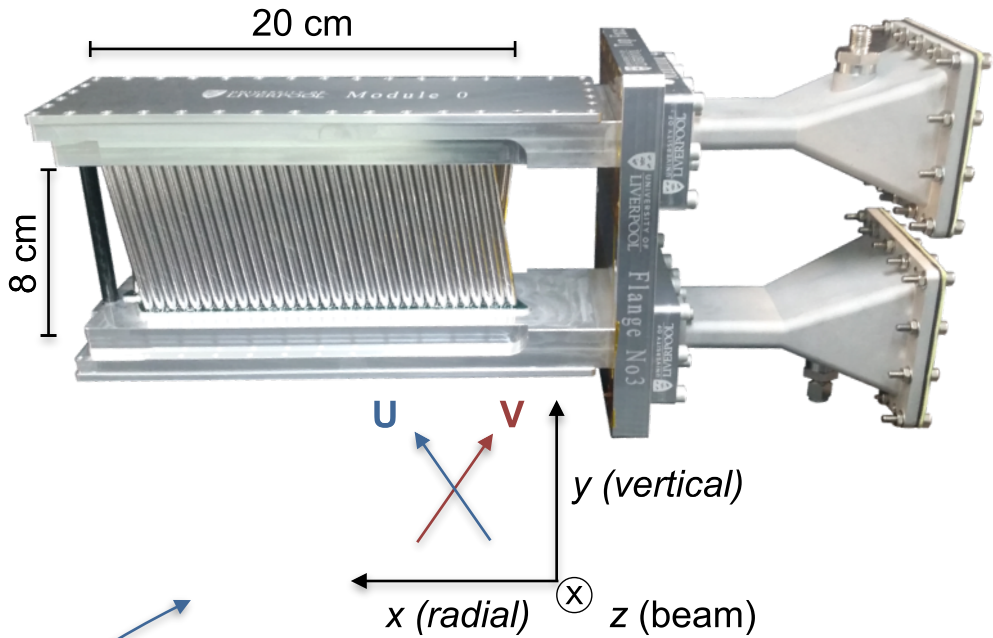
- Convolute the stored muon beam with the magnetic field, to determine $\tilde{\omega}_p$

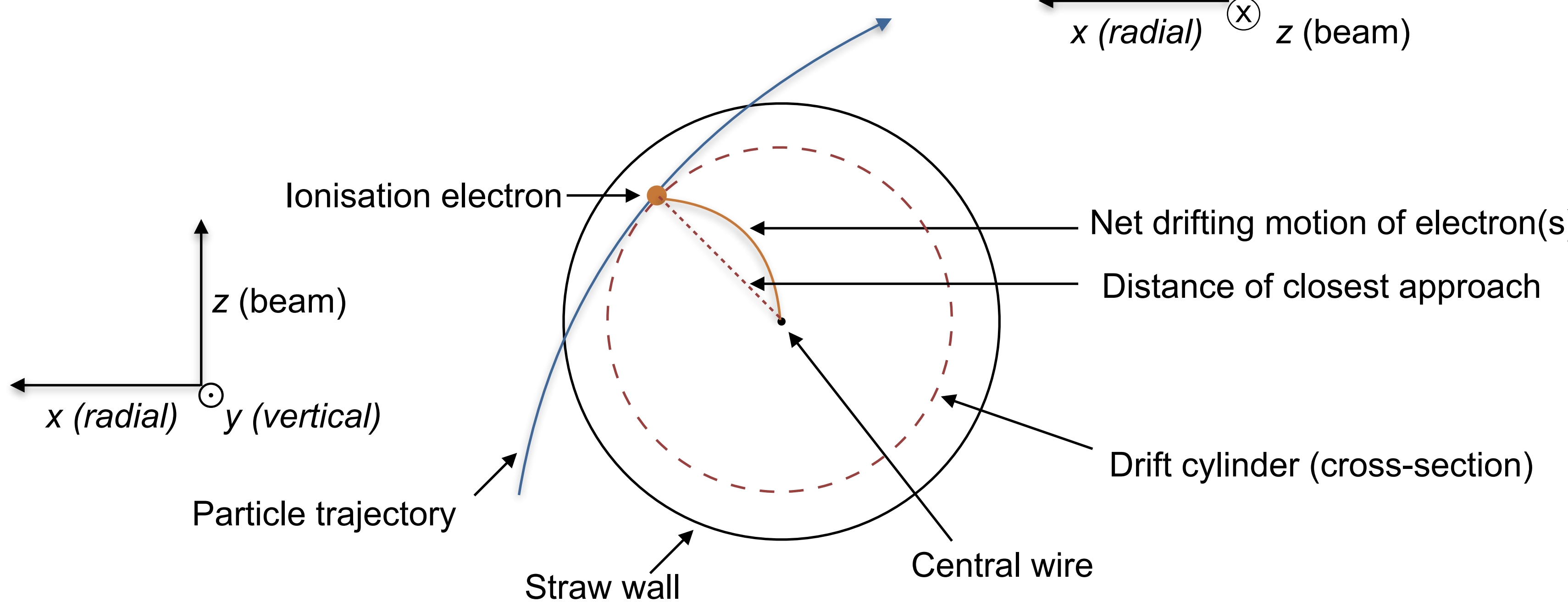
- Access the beam dynamics via measurements of the betatron oscillations

- Improve on the sensitivity to the muon Electric Dipole Moment (EDM)



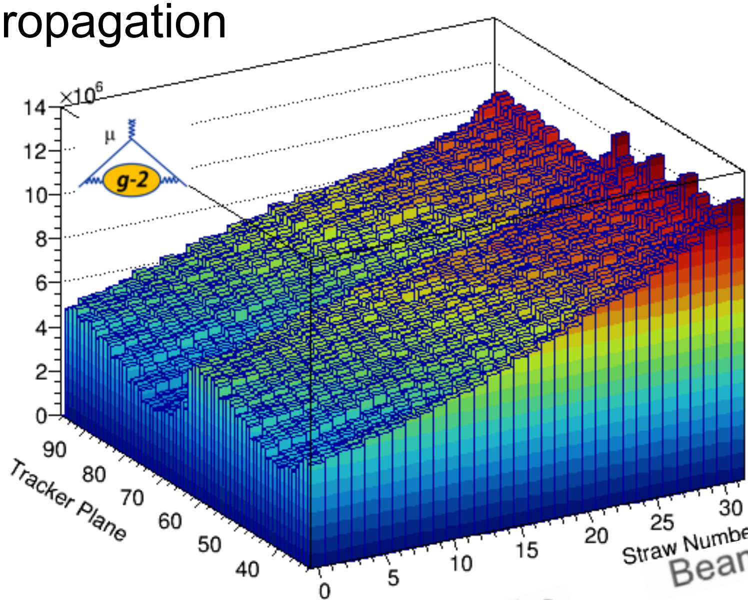
- 8 tracker modules per station
- 4 layers of 32 straws
- An angle of 15° between UV layers
- A straw is filled with 50:50 Ar:Ethane
- Central wire at +1.6 kV
- Module inside vacuum of 10^{-9} atm
- Straw is held at 1 atm
- Hit resolution of 100 μm

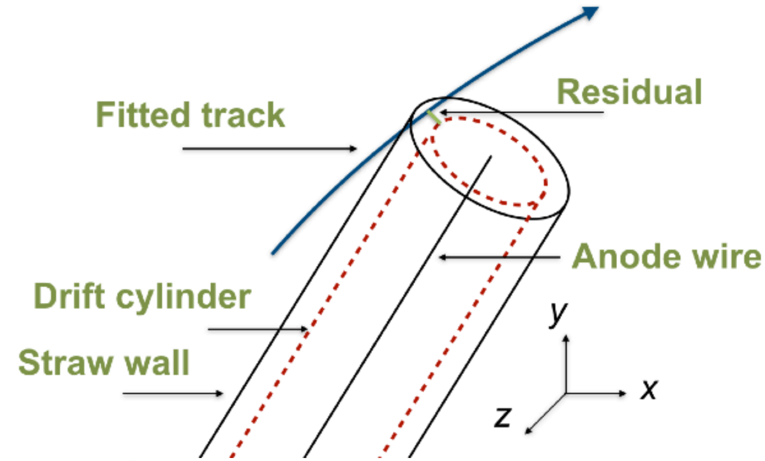


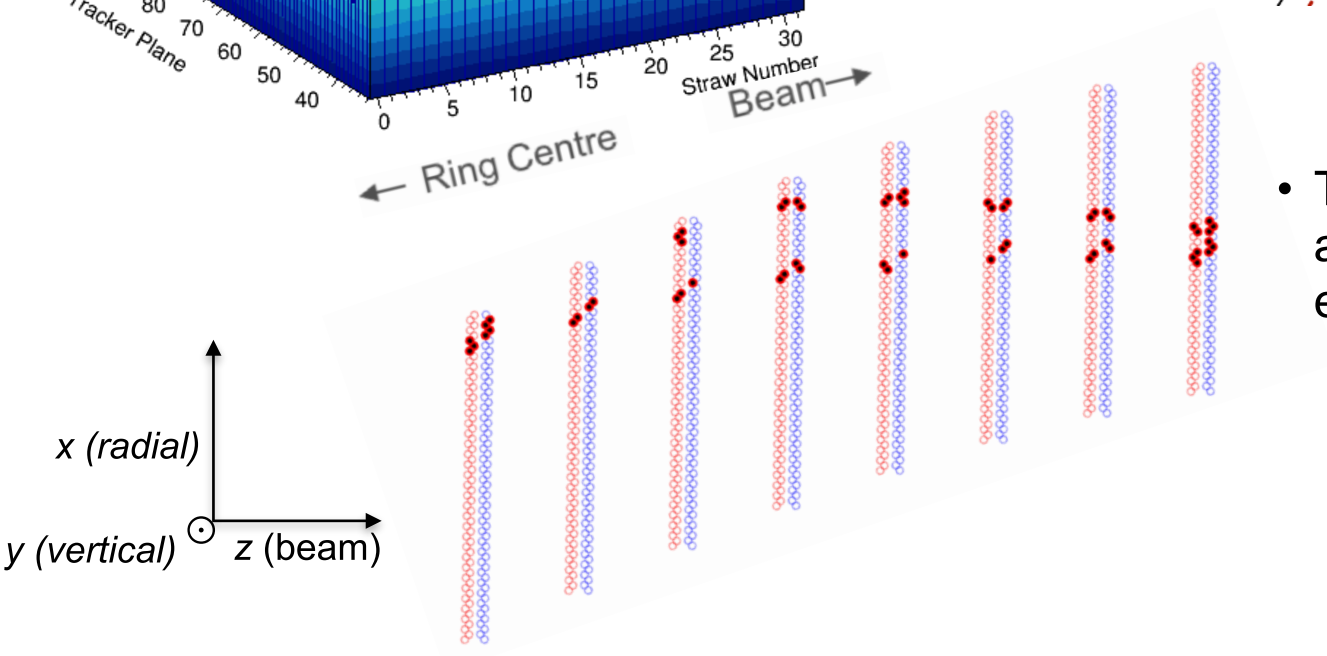


Tracking

- Track reconstruction is implemented with GEANE framework, which incorporates geometry, material, and field, utilising transport and error matrices for particle propagation



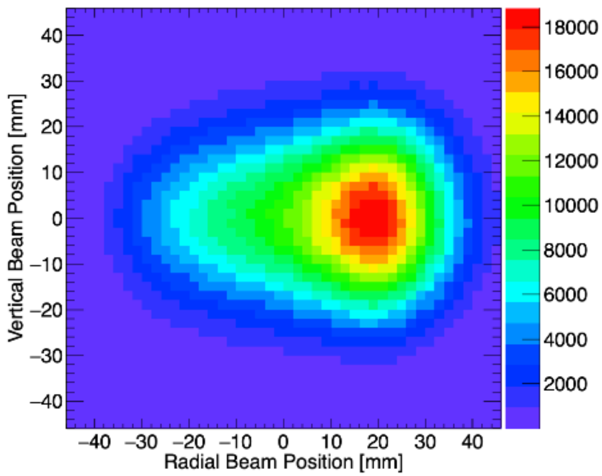




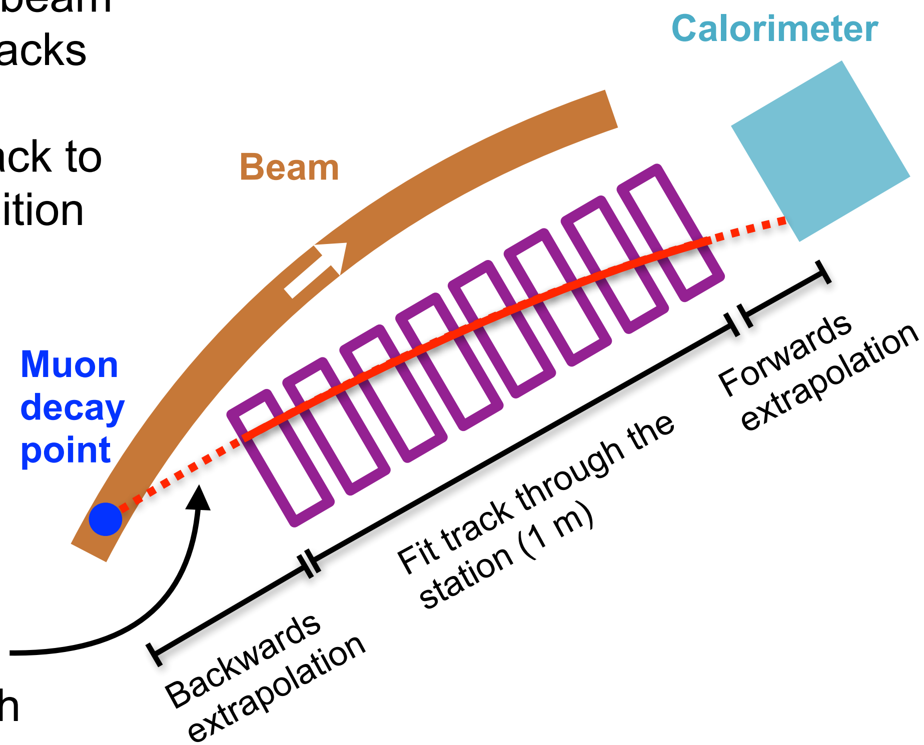
- Two tracks close in time as seen by the online event display

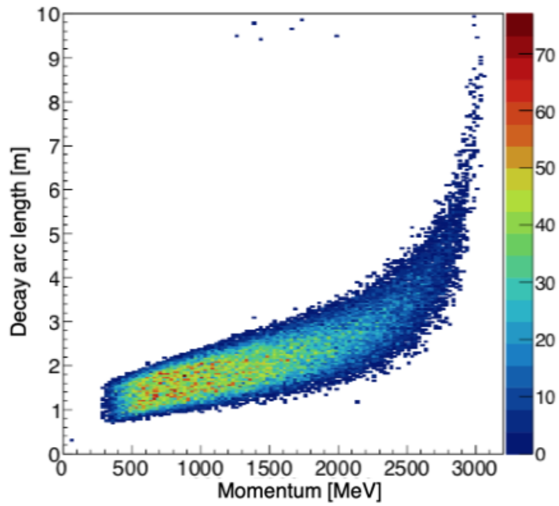
Track Extrapolation

- Fitted tracks are extrapolated back to the decay point using a *Runge-Kutta* algorithm that propagates the tracks through the varying magnetic field
- Only tracks that are not to passing through material (e.g. vacuum chamber) are used in extrapolation



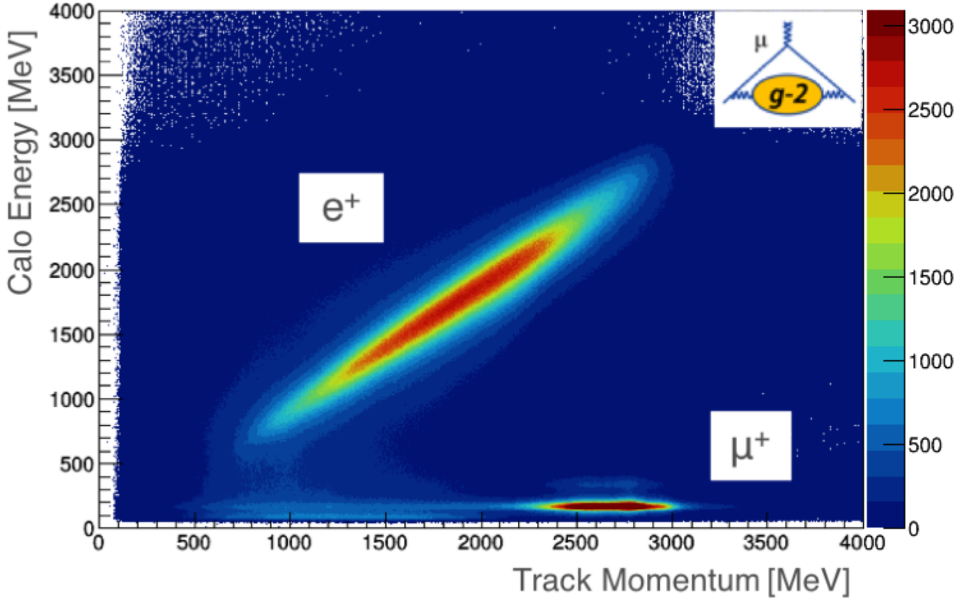
- Reconstructed beam position from tracks that have been extrapolated back to their decay position





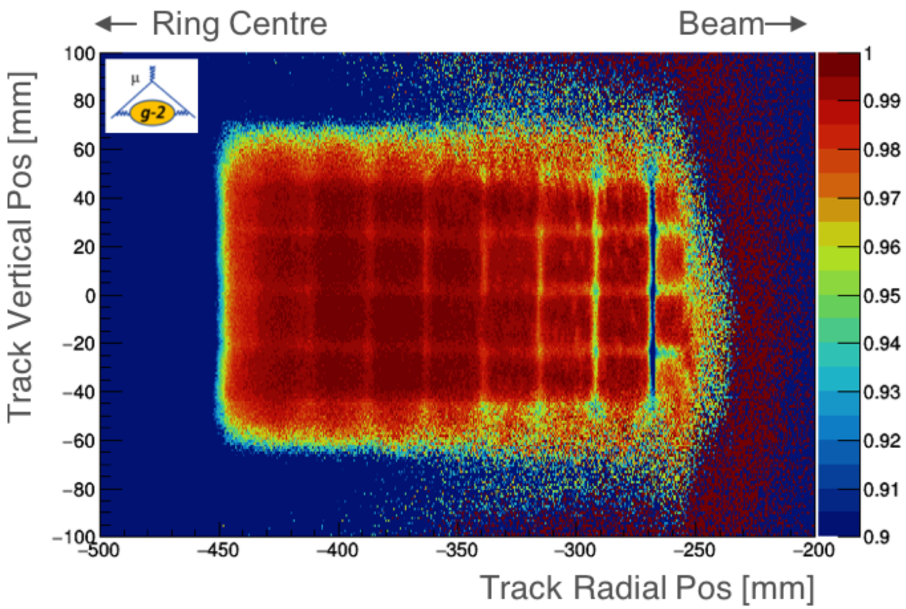
- **Reconstructed decay arc** length as a function of track momentum back to the decay position

Track Extrapolation

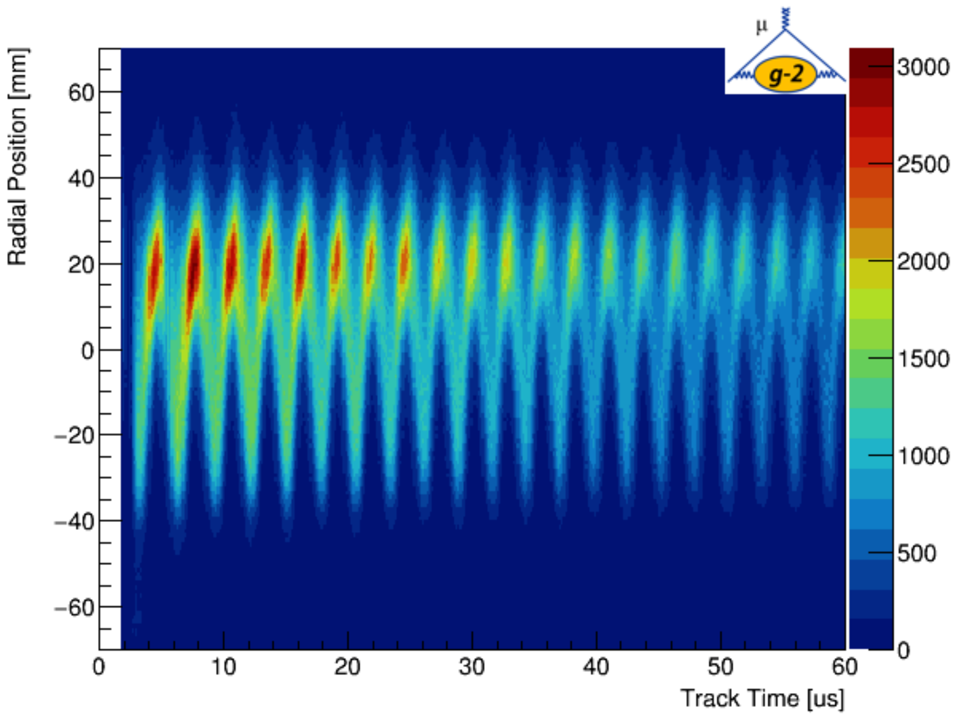


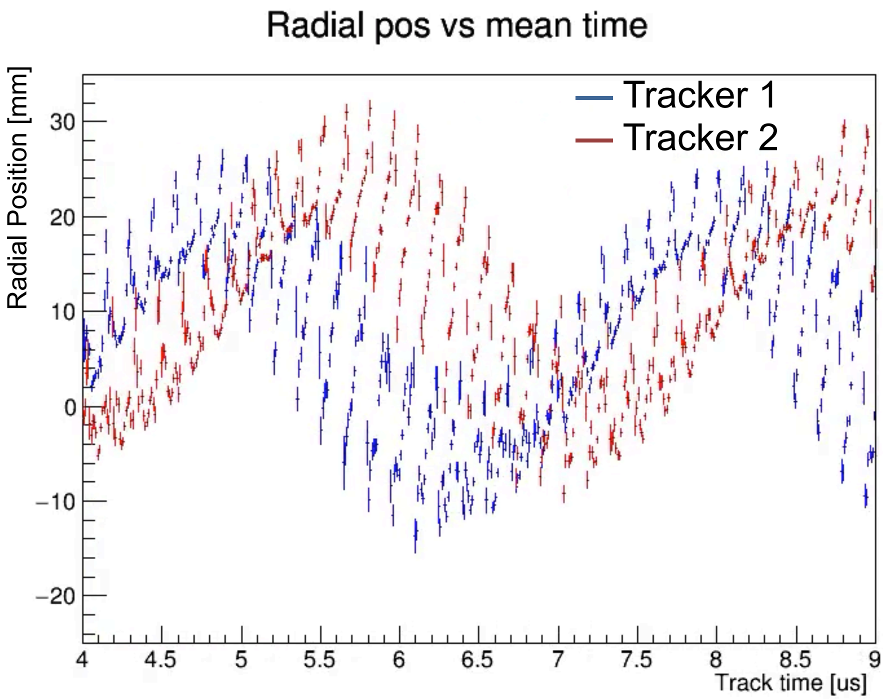
- Tracks and calorimeter clusters are matched up based on time proximity (10 ns)

- Extrapolated tracks to the front face of the calorimeter. Tracker provides trajectory information at the face of the calorimeter, which is used to inform the clustering algorithms



- Reconstructed **radial position** of the decay point plotted against time. The oscillations are the radial betatron oscillations

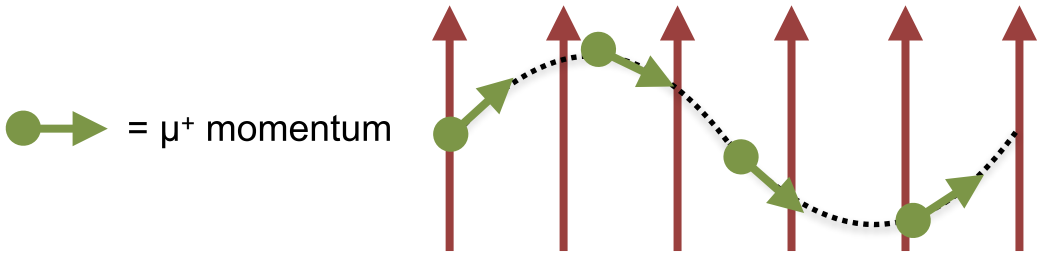




Pitch Correction

- Muons are going up-and-down in the ring (focused by electrostatic quadruples), reducing the effective field, as the momentum vector now has a (vertical) component along the field

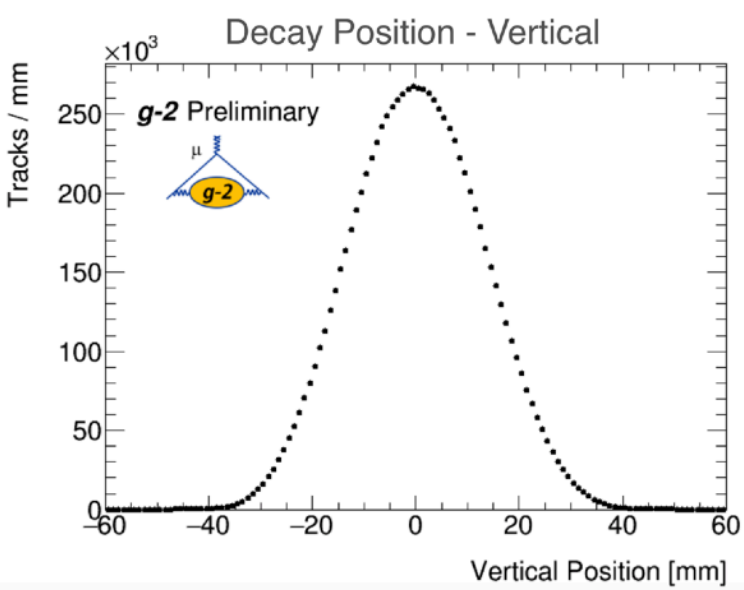
$$B_{\text{vertical}} = 1.45\ \text{T}$$



$$\boldsymbol{\omega_a} = \frac{e}{m_\mu}\left[a_\mu \boldsymbol{B} - \frac{\gamma a_\mu}{\gamma+1}(\boldsymbol{B}\cdot\boldsymbol{\beta})\boldsymbol{\beta}\right]$$

- Need to correct for vertical μ⁺ angle but we measure an ensemble of decay e⁺

$$\frac{\Delta\omega_a}{\omega_a} \propto \sigma^2_{\text{vertical}}$$

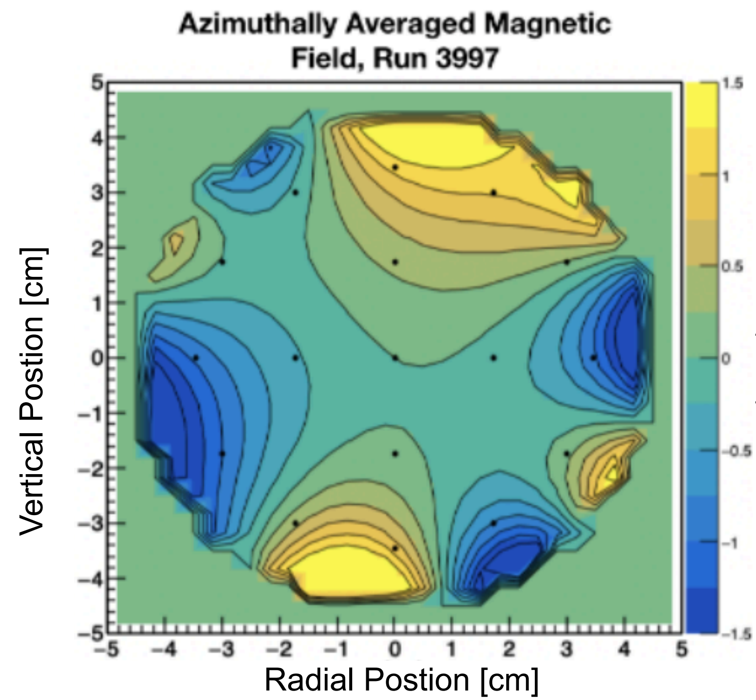


- Trackers measure the **vertical width** of the beam precisely. Uncertainty on the correction is < 30 ppb, in line with the designed expectation

Field Convolution

- Trackers measure the beam profile as a function of time
- Storage region field is measured by a trolley (when muons are not present)
- This is cross-calibrated by the fixed probes outside the storage region
- Convolution finds shapes common in beam and field profiles and projects these shapes to estimate the field experienced by the muons

- **The storage region near the tracker station**



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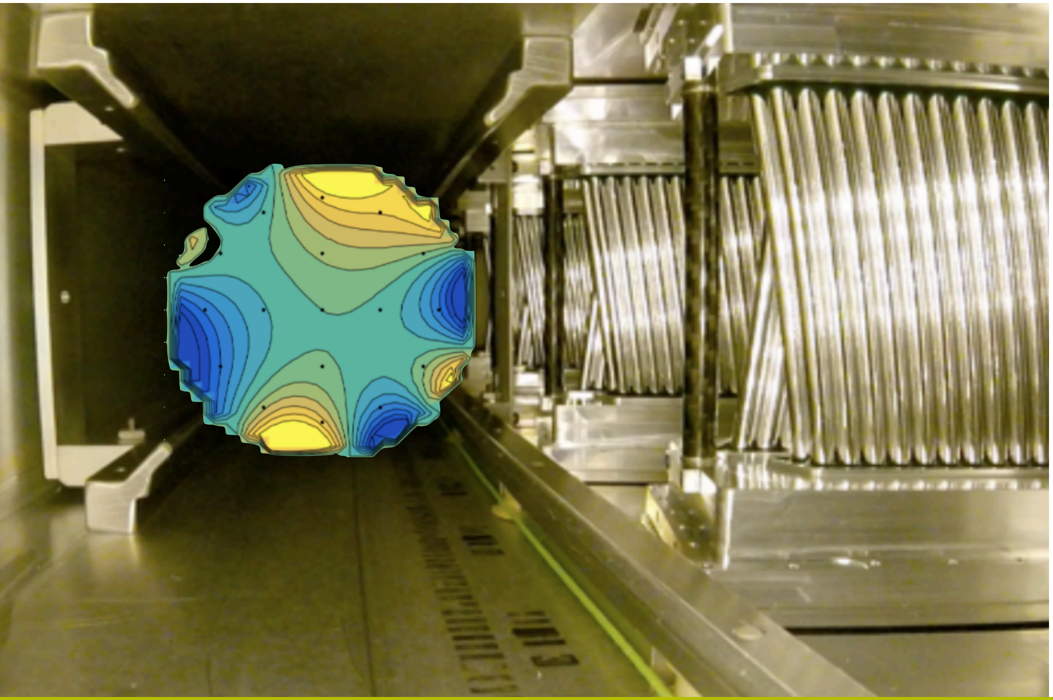
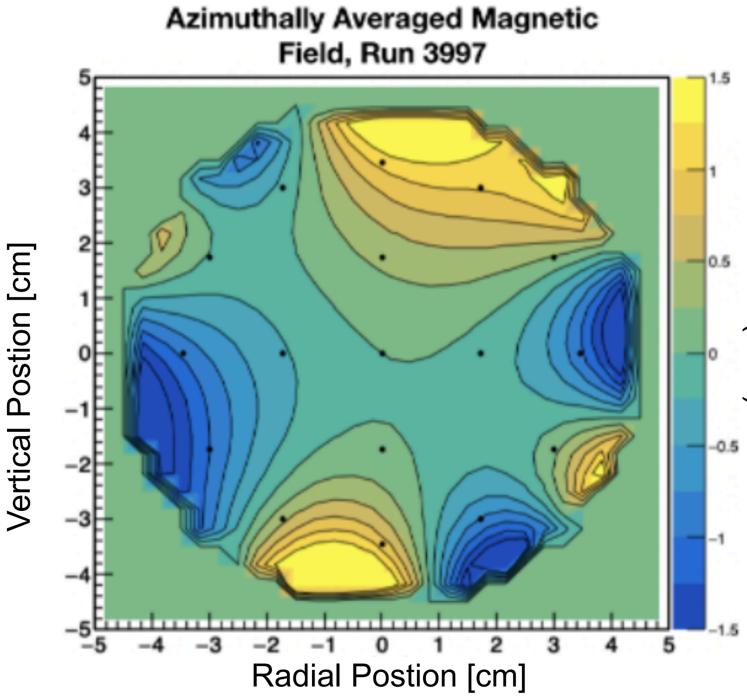
- **Field measurement by the trolley**





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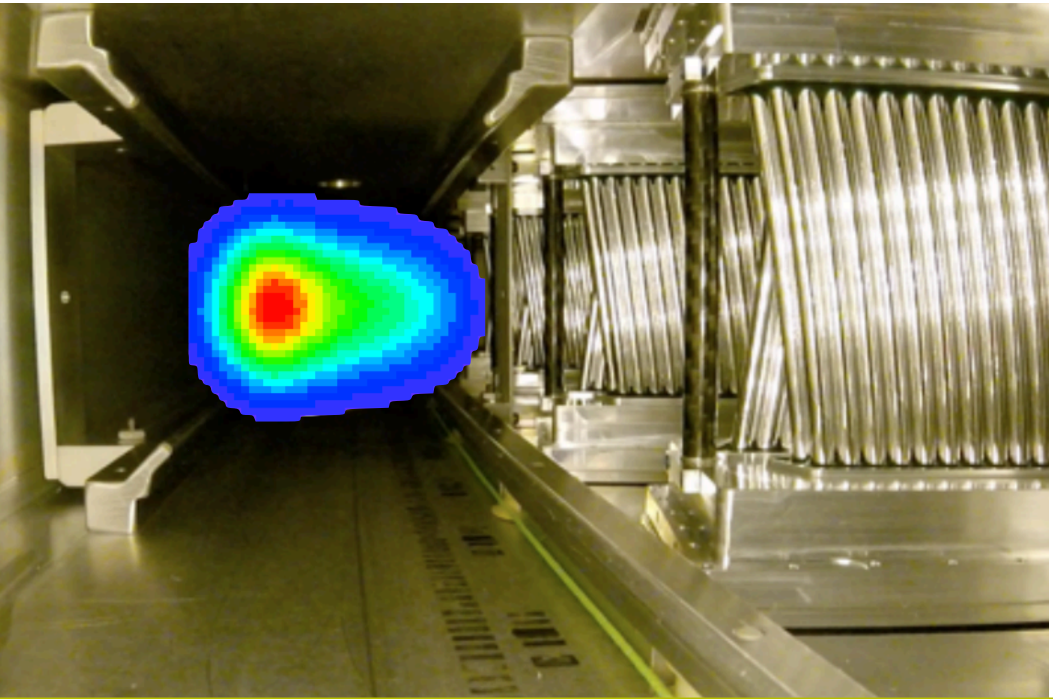
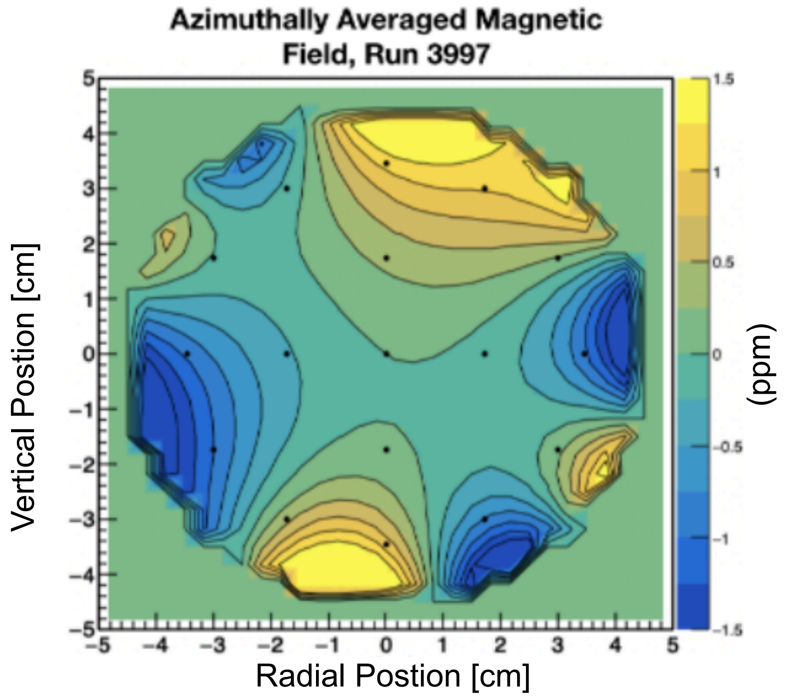
- **Beam profile from the trackers**

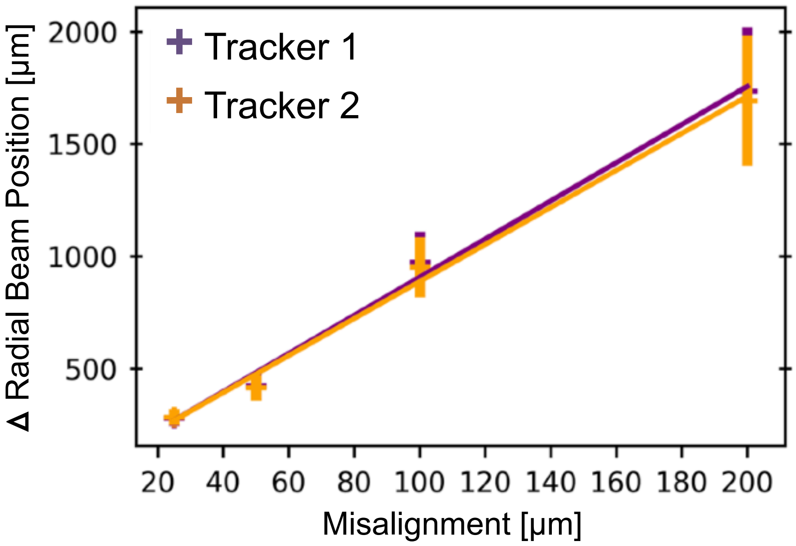




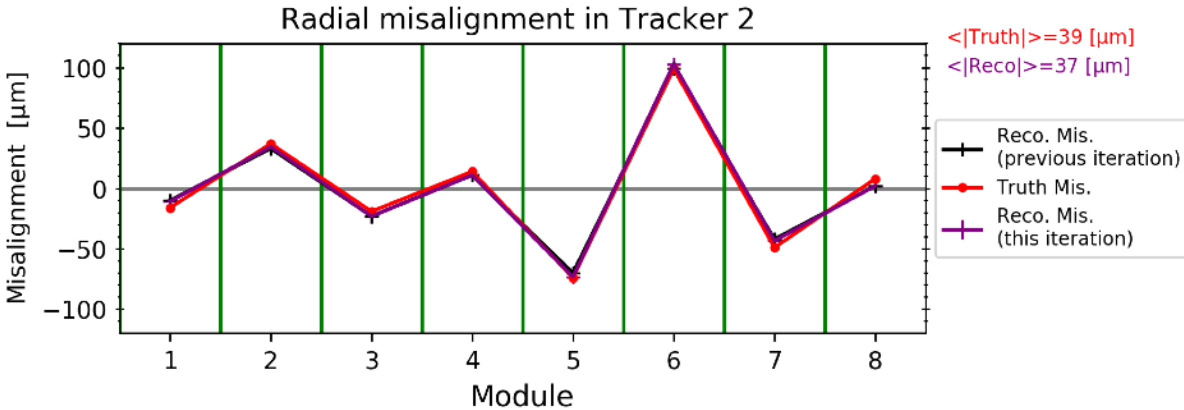
- The reconstructed beam distribution is affected by the the internal alignment of individual modules

- The alignment was implemented using the *Millepede II* framework, minimising

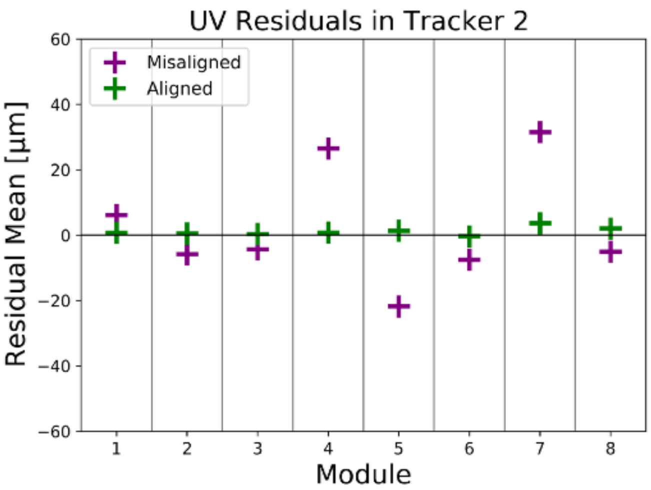
$$\chi^2(\boldsymbol{a},\boldsymbol{b}) = \sum_j^{tracks} \sum_i^{hits} \frac{\left(r_{i,j}(\boldsymbol{a},\boldsymbol{b}_j)\right)^2}{(\sigma^{\det})^2}$$



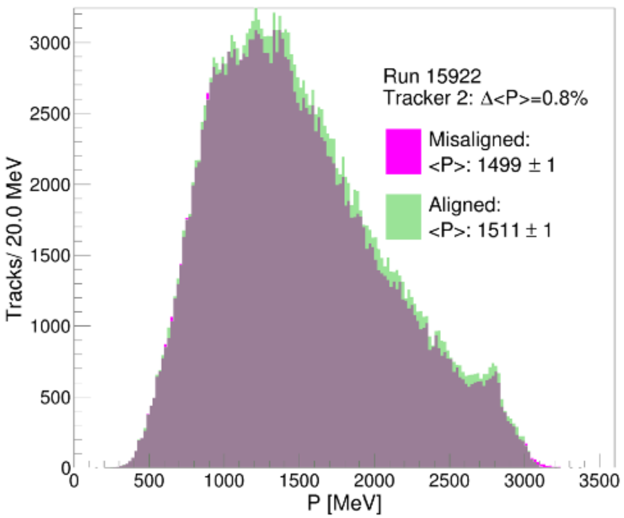
- Alignment convergence in simulation was reached within 2 μm and 10 μm radially and vertically, respectively. Simulation results were obtained with *O*(10^5 tracks) with 3 iterations



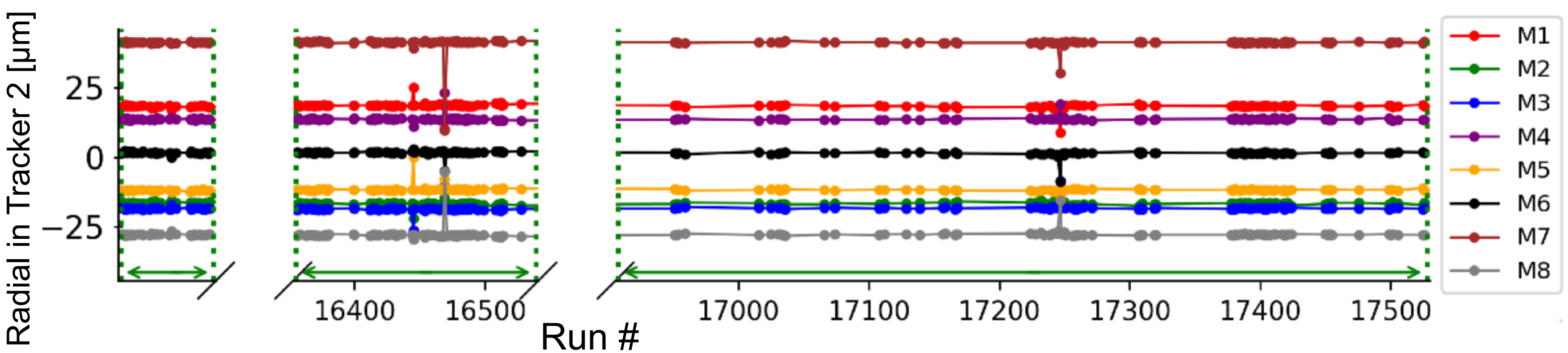
- With data, the number of reconstructed tracks has increased by 6% due to the position calibration from the alignment
- Extrapolated tracks have a radial shift towards the centre of the ring of 0.50 mm and a vertical shift of 0.14 mm



- The uncertainty contribution from the tracker misalignment to the pitch correction is now negligible

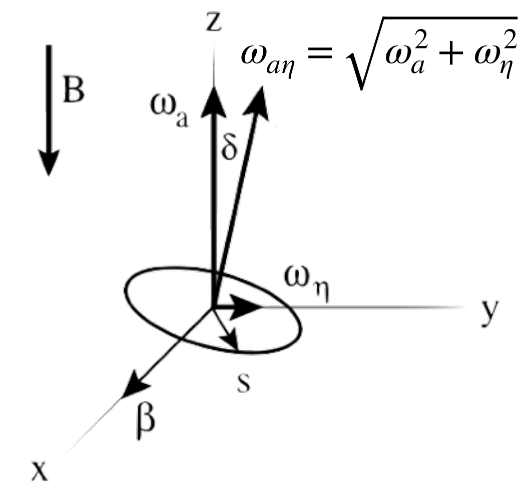


- Alignment monitoring results (single iteration) are stable throughout the entire Run-1

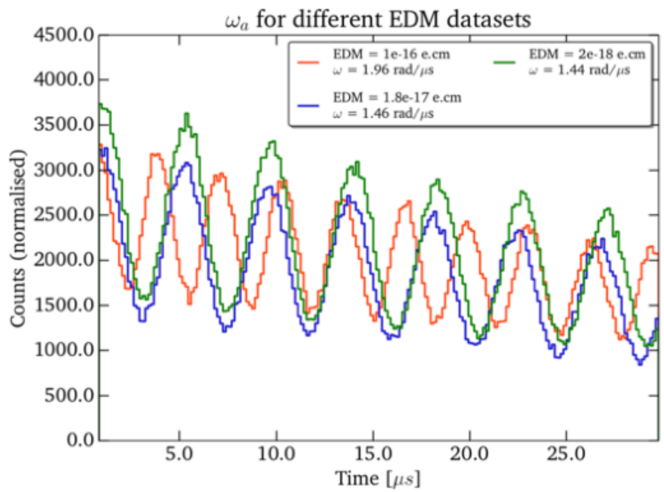


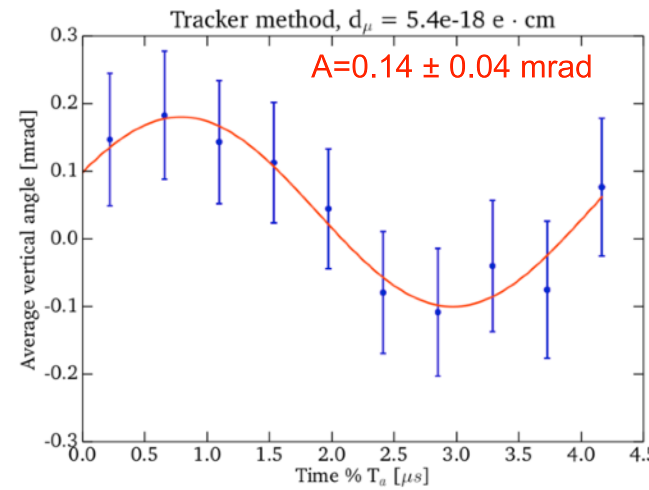
Electric Dipole Moment (EDM)

- A measurement of the muon EDM (d_μ) would provide clear evidence of CP violation
- The tracker will realise an EDM measurement through the direct detection of oscillation in the average **vertical angle** of the decay e+



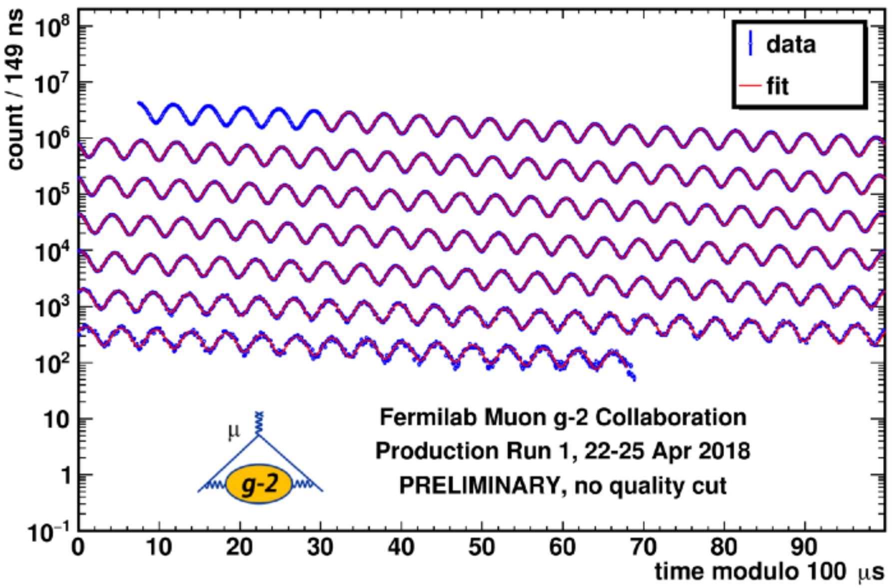
- Simulation results with large EDM signal



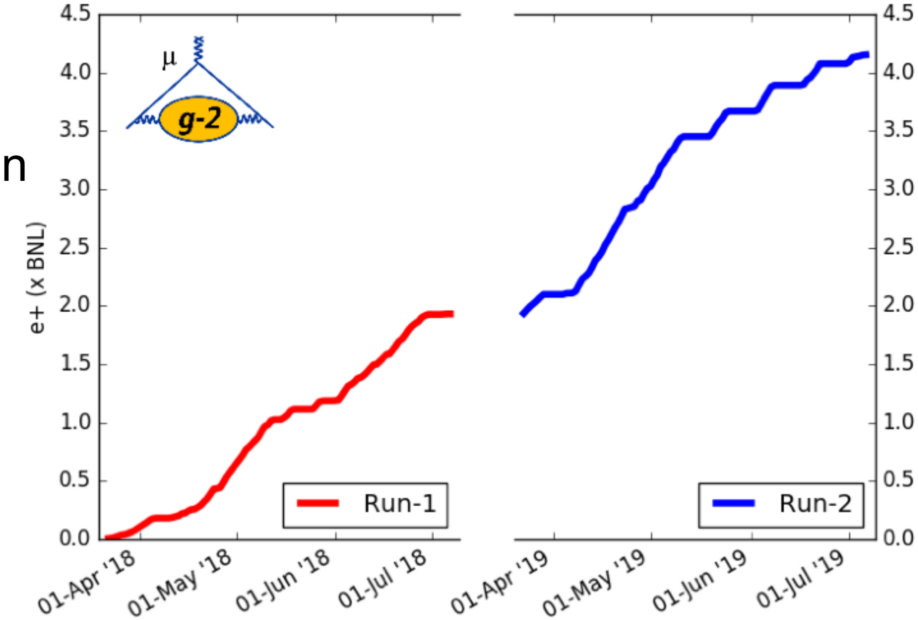


- SM limit of d_μ ~10^{-25} *e*·cm (mass-scaling the measured electron EDM)
- Some SM extensions predict a limit of ~10^{-23} *e*·cm
- Current experimental limit is < 1.8×10^{-19} *e*·cm *Phys. Rev.* ***D*** *80, 052008 (2009)*
- Goal: Measure δ to within 0.4 μRad to place a new limit on the muon EDM, with a sensitivity of 10^{-21} *e*·cm, a 100 fold improvement on the Brookhaven result.

- This figure has 1 billion positrons. The number of wiggles is similar to the one achieved by BNL in 1999



- Run-1 (2018): analysing collected data
- Run-2 (2019): just finished production
- Analysis of Run1 data is nearing completion
- **First publication at the end of 2019**
- **Expecting to accumulate another x17 BNL in the next two years**



ω_a systematic uncertainty summary

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

Muon (g-2) Technical Design Report, arXiv:1501.06858 (2015)

- Total systematic uncertainty on ω_p: 70 ppb
- Total statistical uncertainty: 100 ppb