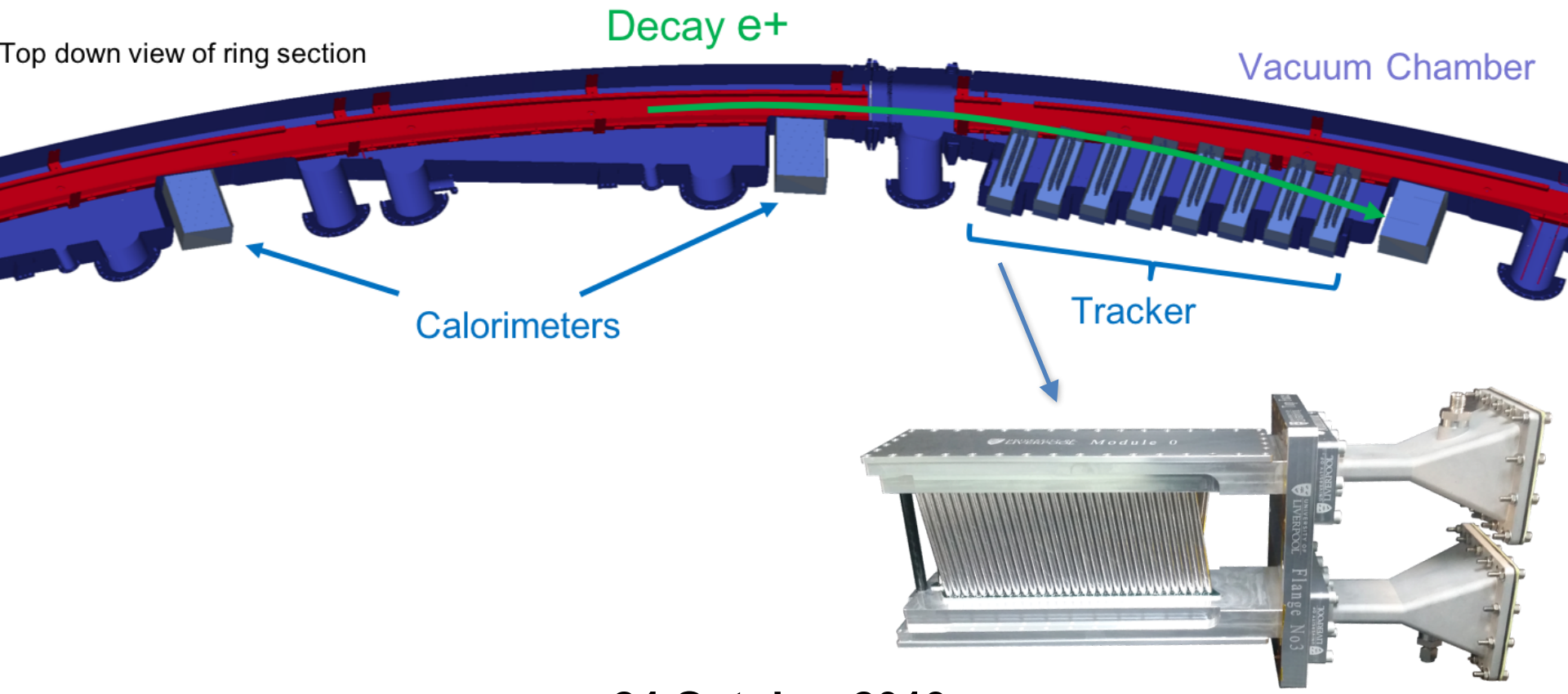
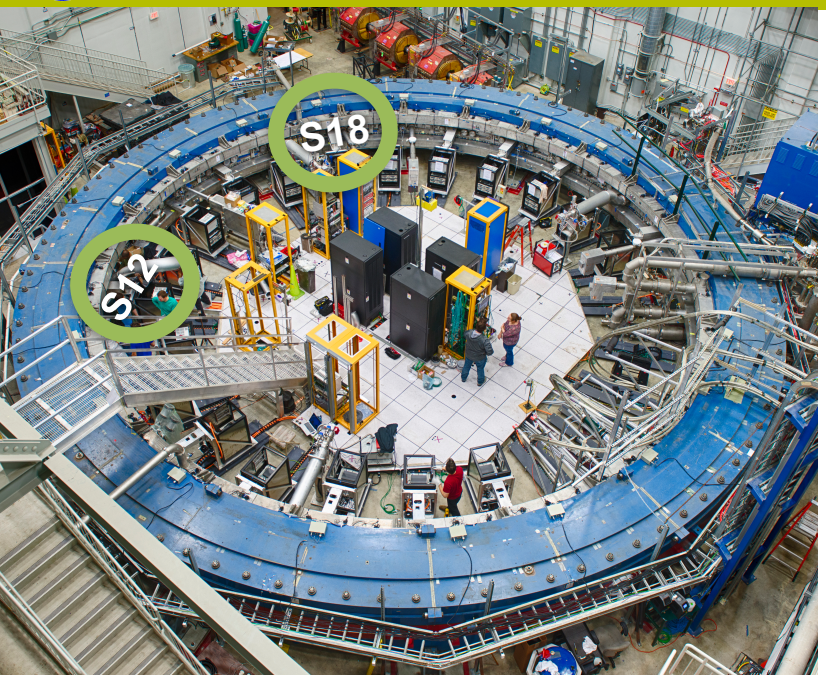
Gleb Lukicov

Straw tracker alignment



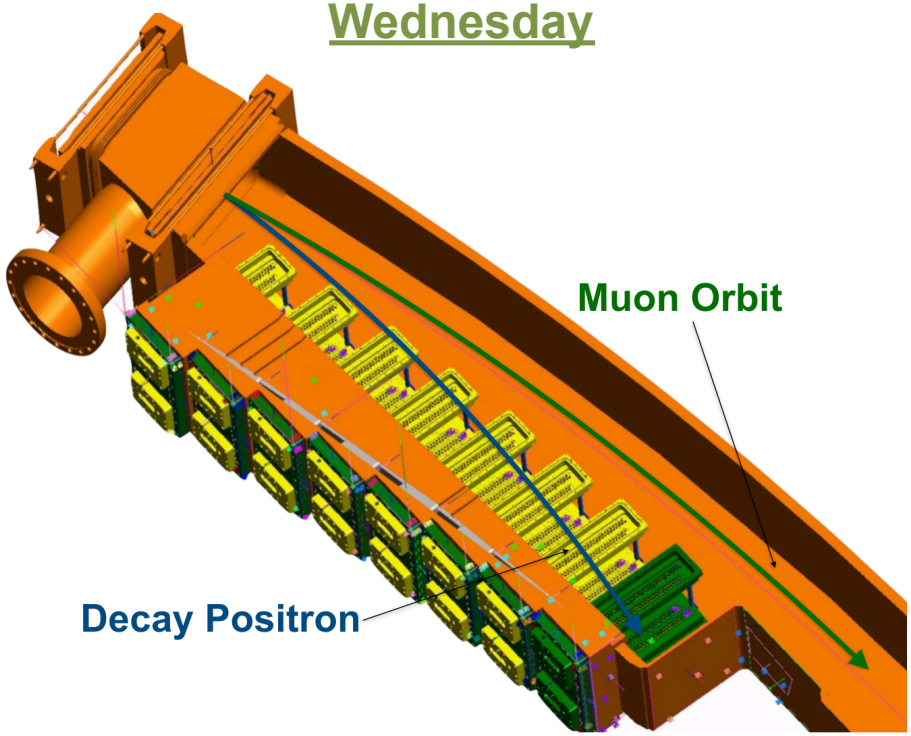
24 October 2019
MUSE General Meeting
Frascati

Tracker objectives



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

See Anna's talk on Wednesday

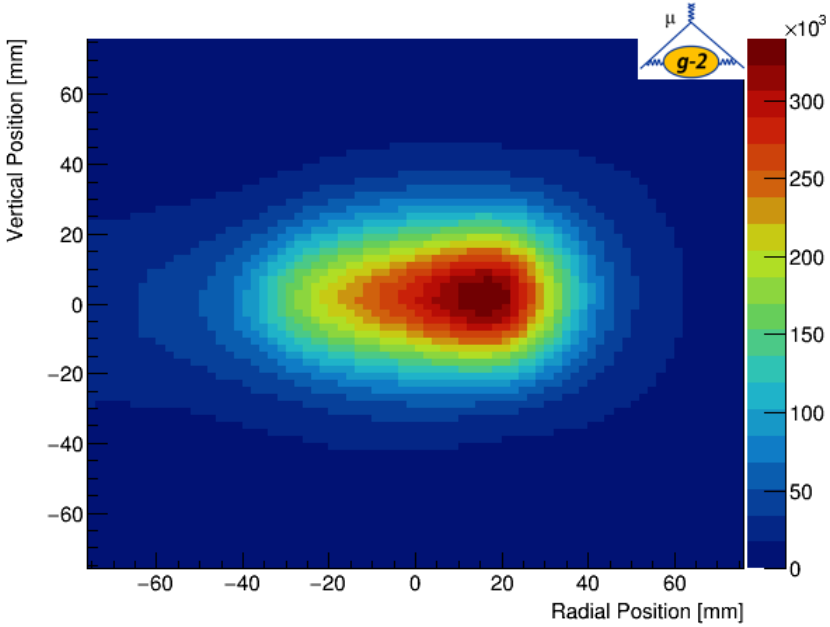


- Convolute the stored muon beam with the magnetic field, to determine $\tilde{\omega}_p$
- Access the beam dynamics via measurements of the betatron oscillations
- Improve on the sensitivity to the muon Electric Dipole Moment (EDM)

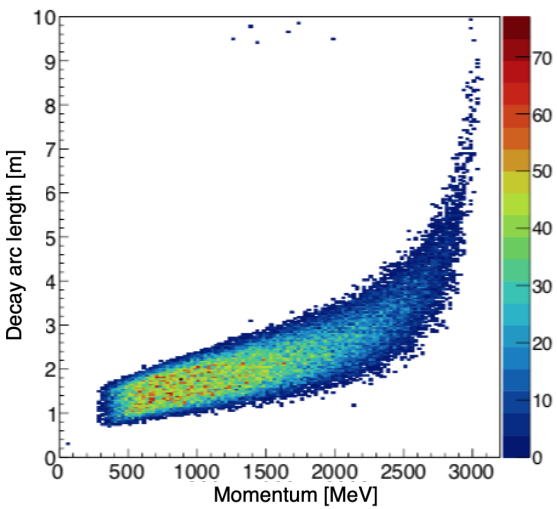
See Becky's talk on Wednesday

Track extrapolation

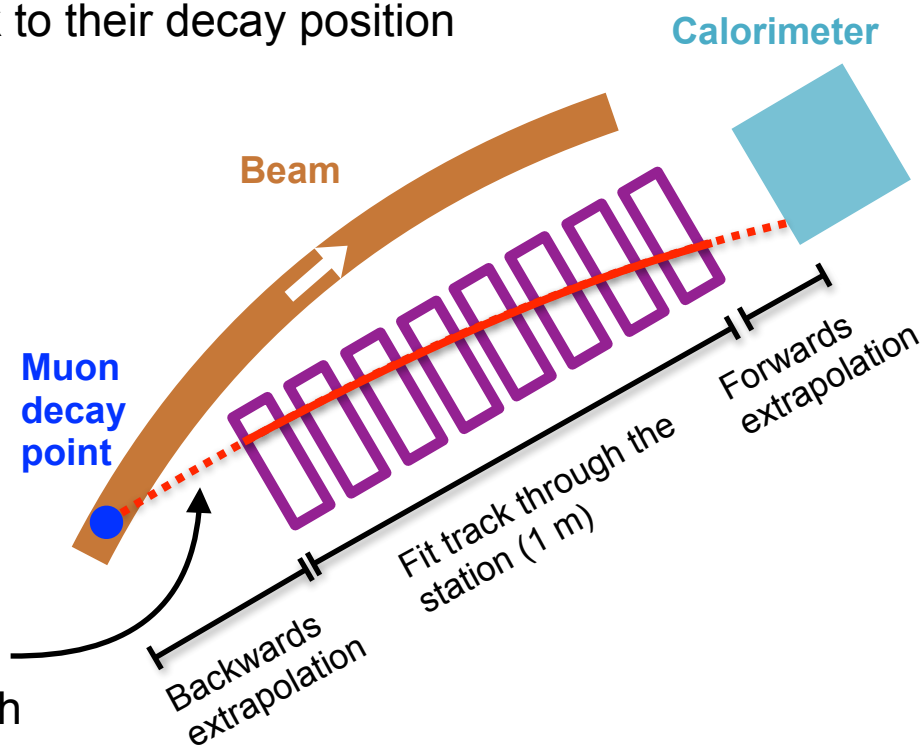
- Fitted tracks [1] are extrapolated [2] back to the decay point using a *Runge-Kutta* algorithm that propagates the tracks through the varying magnetic field



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



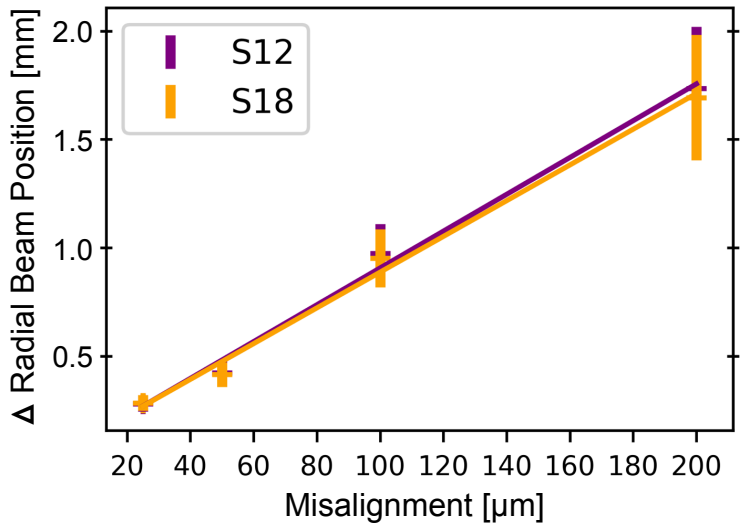
- **Reconstructed decay arc** length as a function of track momentum back to the decay position



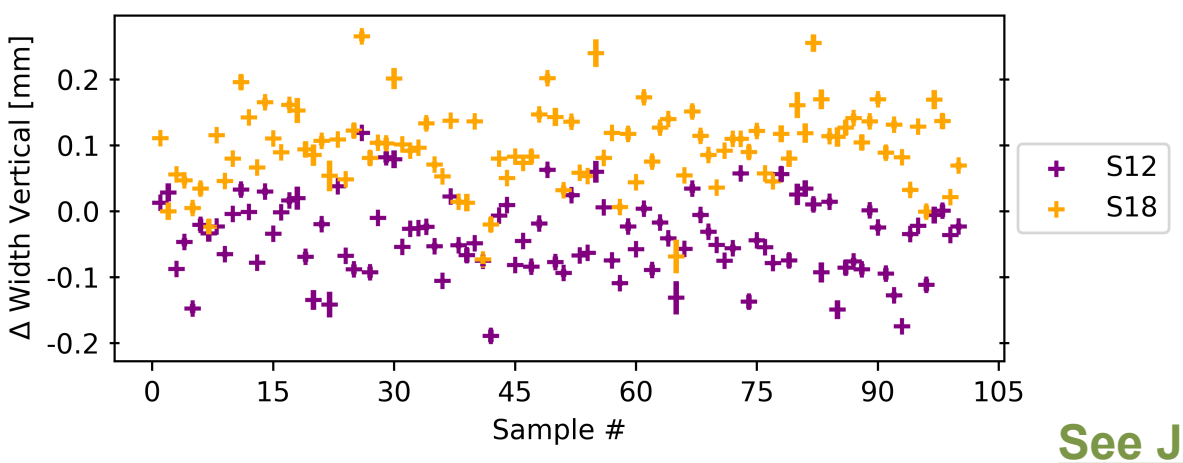
[1] N. Kinnaird, http://meetings.aps.org/link/BAPS.2018.APR.D17.1 (2018).
[2] S. Charity, PhD thesis, University of Liverpool (2018).

Motivation for tracker alignment

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



- The contribution of misalignment, at 100 μm scale (as seen in data), to the <u>systematic uncertainty related to the pitch correction</u> was estimated at 2 ppb, and is reducible!

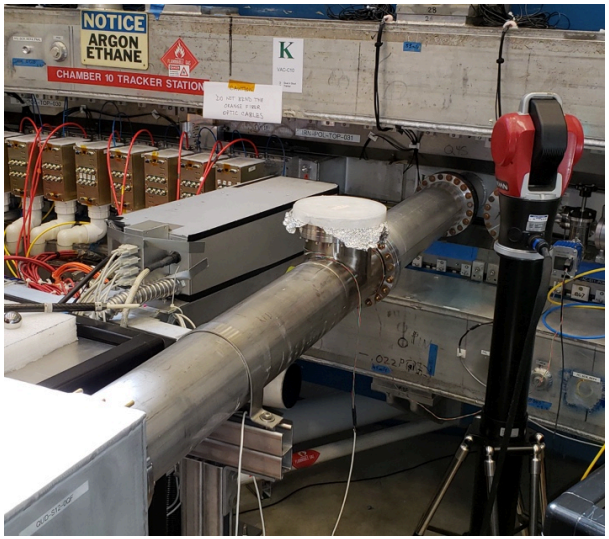


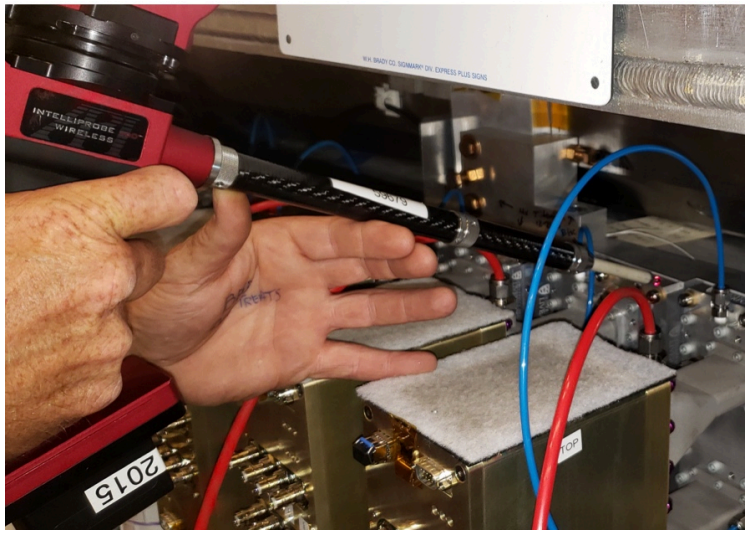
$$\frac{\Delta\omega_a}{\omega_a} \propto \sigma^2_{\text{vertical}}$$

See Joe's talk on Wednesday

Survey (external) alignment

- The ***survey alignment*** of the two stations was undertaken [1]





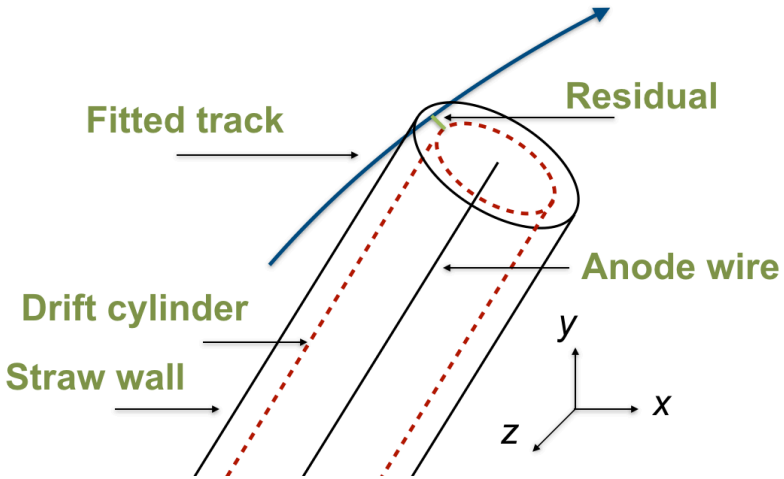
- Putting the measured offsets into the geometry [2,3] results in a shift in the mean radial extrapolated beam position of
  - 350 μm for station 12
  - 330 μm for station 18

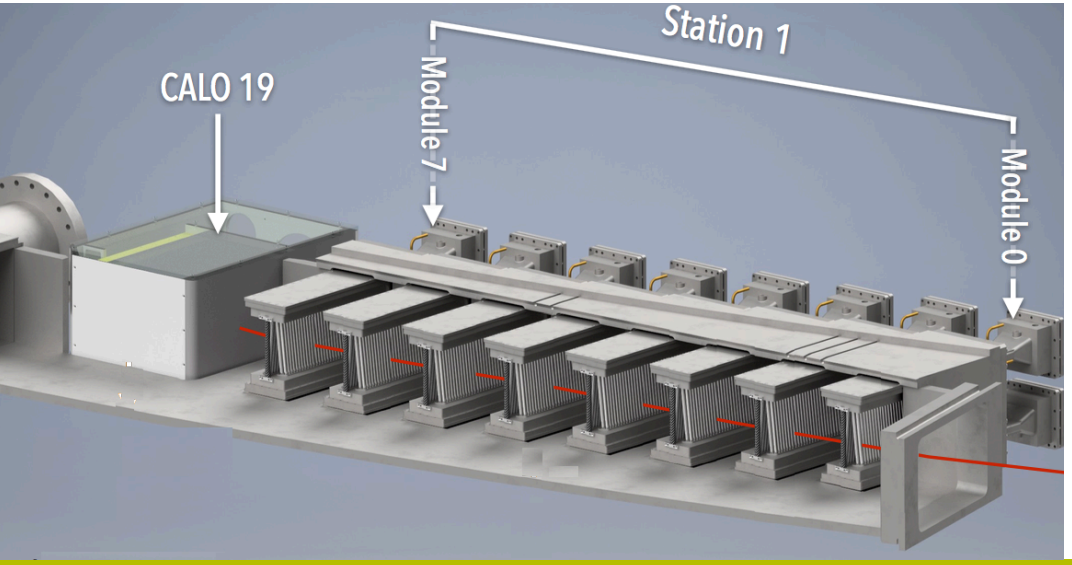
- The track-based (internal) alignment will improve upon the accuracy

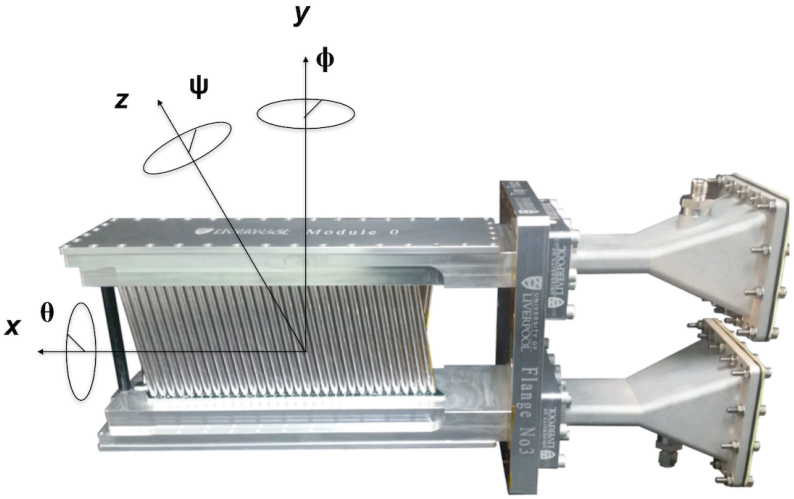
[1] H. Friedsam, *Alignment results*, g – 2 DocDB:5955 (2017).
[2] L. Welty-Rieger, *Alignment studies*, g – 2 DocDB:15322 (2018).
[3] J. Price, *Tracker global alignment*, g – 2 DocDB:16063 (2019).

Track-based alignment

- The alignment was implemented using the *Millepede II* framework, minimising $\chi^2(\boldsymbol{a},\boldsymbol{b}) = \sum_j^{tracks} \sum_i^{hits} \frac{\left(r_{i,j}(\boldsymbol{a},\boldsymbol{b}_j)\right)^2}{(\sigma^{\mathrm{det}})^2}$
- Inputs are:
  - residual between the track and the hit
  - the rate of change of residual with module position
  - the rate of change of residual with track parameters
- Alignment was be done to predict:
  - translations: radial (*x*) and vertical (*y*)
- Total of **32 alignment parameters**

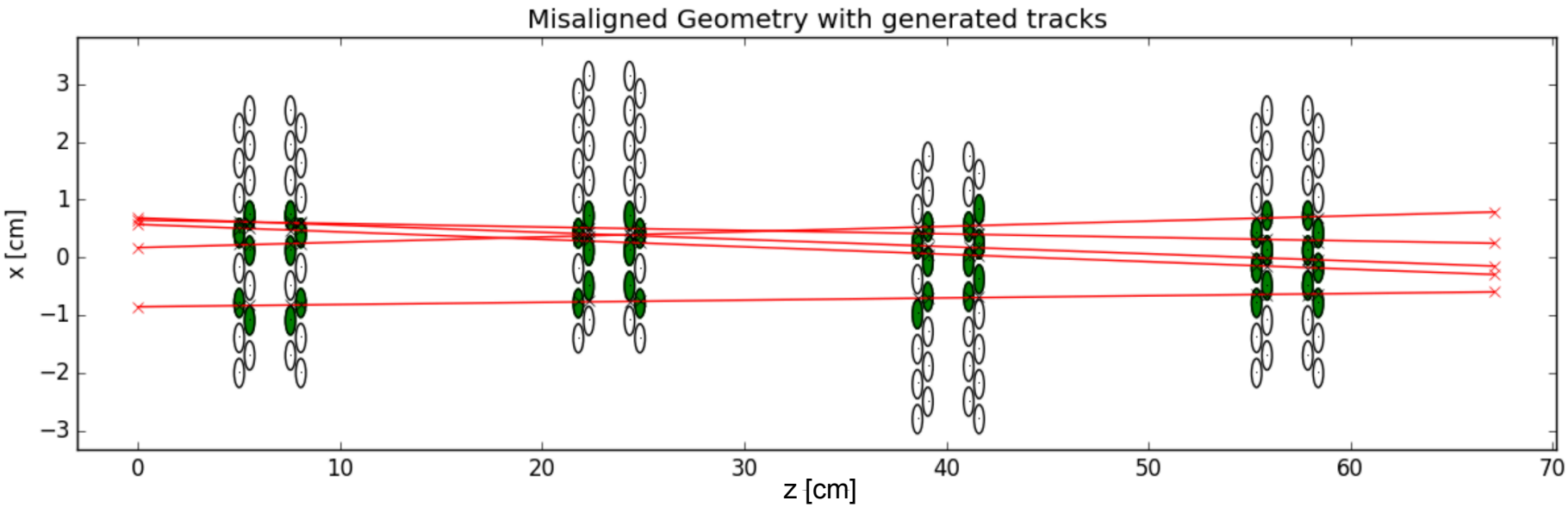


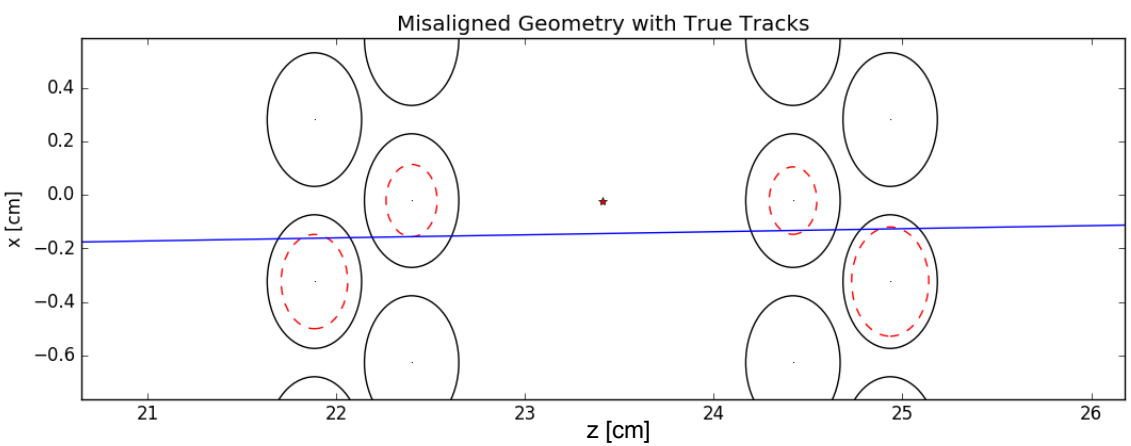




Toy model simulation

- A standalone simulation was developed to understand the detector geometry.
- Straight tracks (no magnetic field), and no scattering effects (no detector material)





A zoom-in in module 2 shows fitted track through generated drift circles

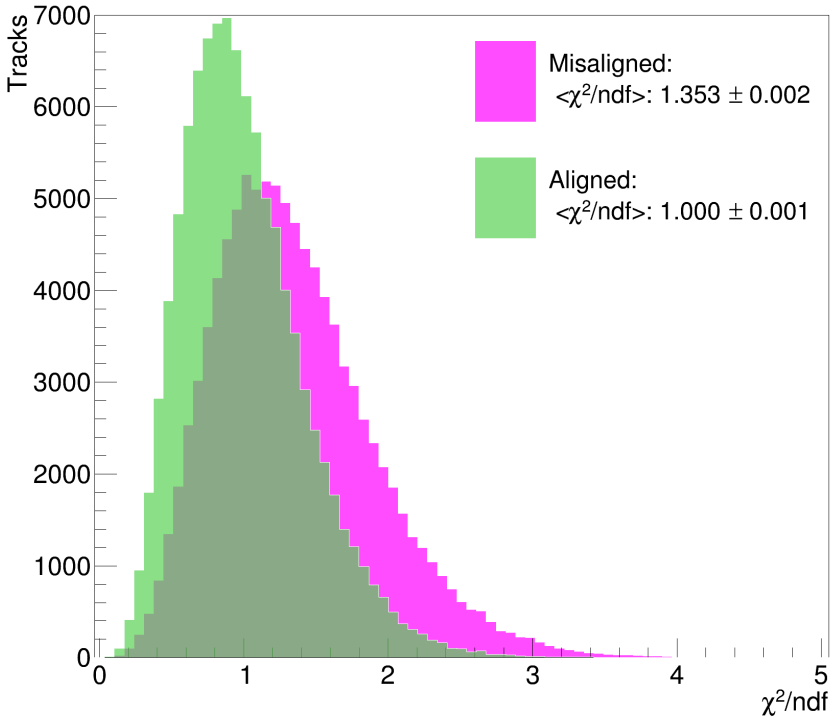
Toy model simulation

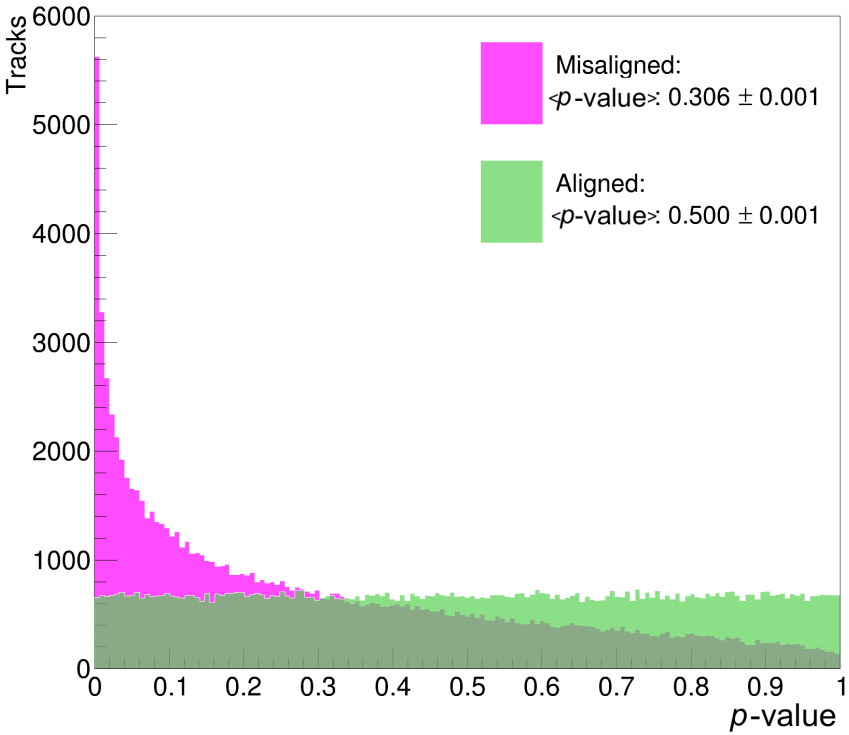
Before Alignment:

χ^2 and *p*-value distributions are indicative of a poor detector alignment

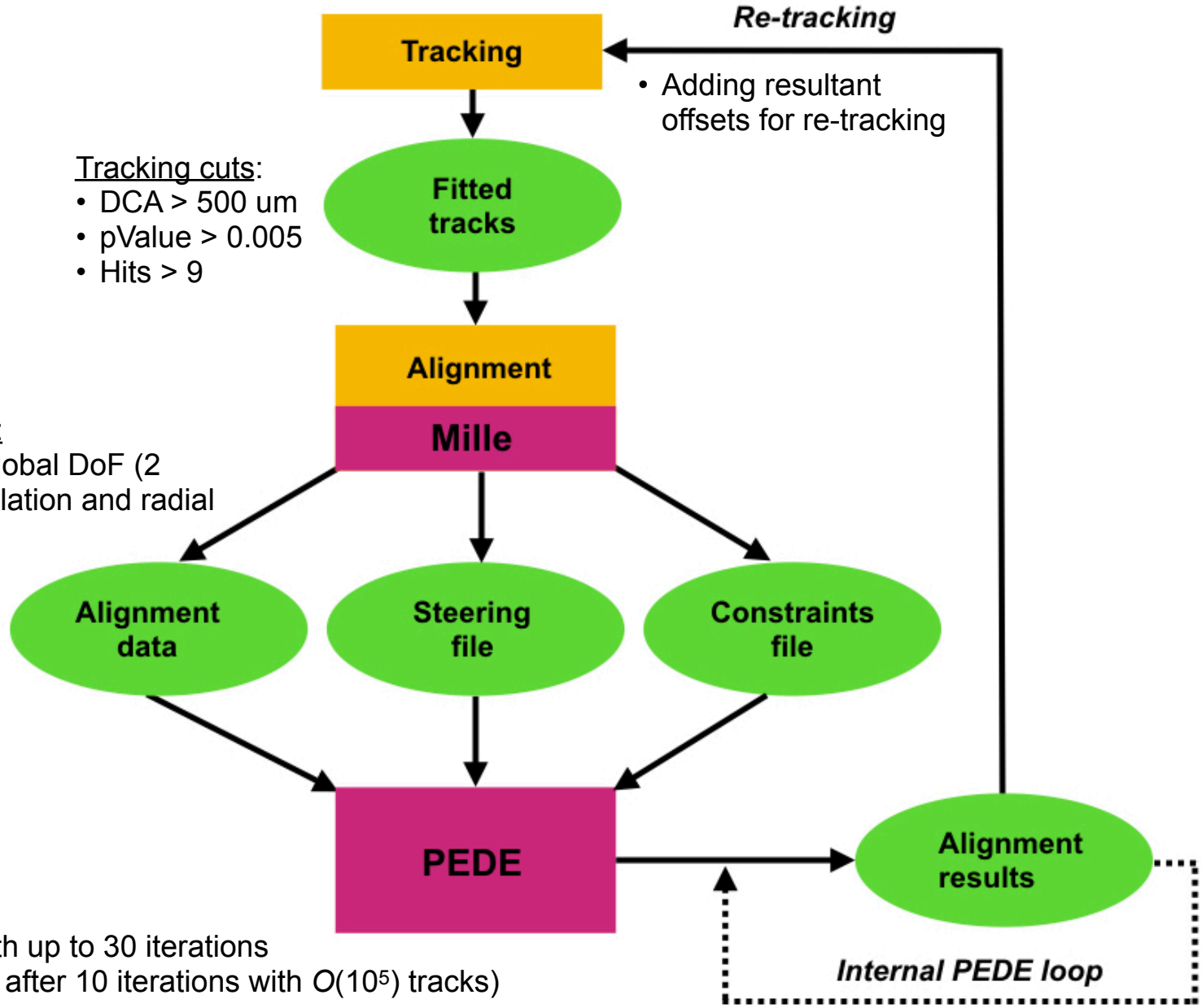
After Alignment:

The predicted offsets from Millepede were added to the assumed geometry of the tracker, and re-fitting of the tracks was done





Alignment cuts and methods



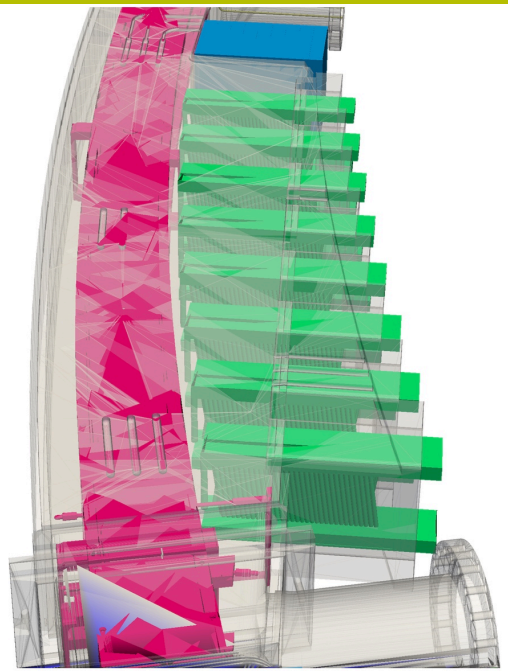
- Adding resultant offsets for re-tracking

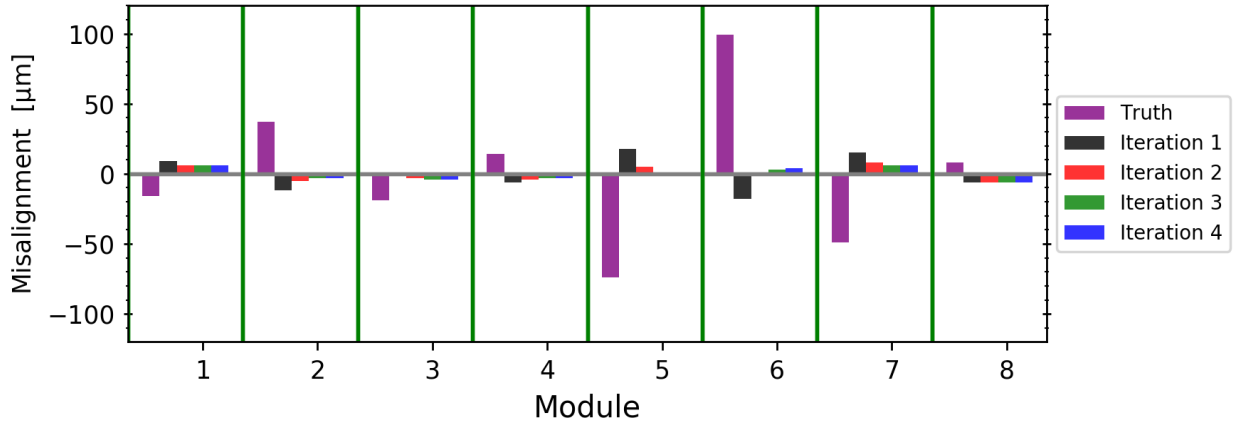
Tracking cuts:
- DCA > 500 um
- pValue > 0.005
- Hits > 9

Alignment method:
- Constraining 5 global DoF (2 rotations, 2 translation and radial curvature)

PEDE Method
Matrix inversion with up to 30 iterations
(usually converges after 10 iterations with $O(10^5)$ tracks)

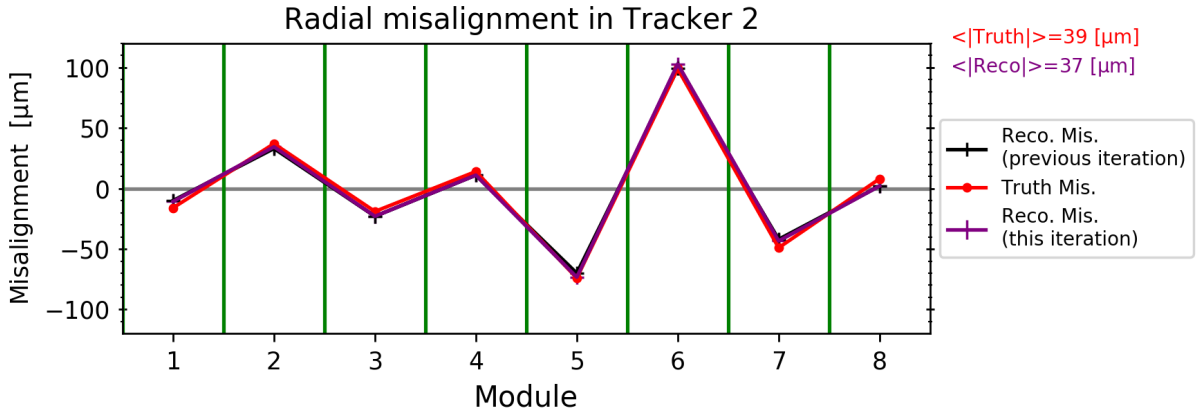
Full ring simulation





- The **truth** (input) misalignment, and the results of the reconstructed misalignment (shown as the **difference with respect to the truth**).

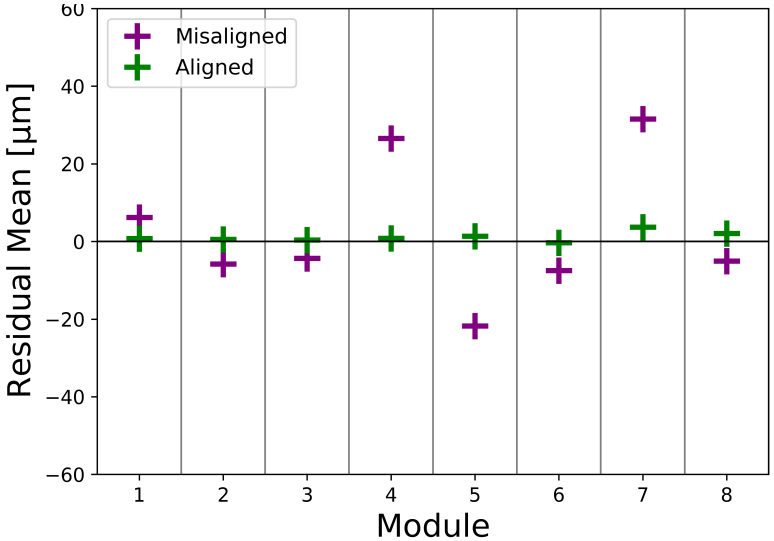
- Alignment convergence in simulation was reached within 2 μm and 10 μm radially and vertically, respectively.



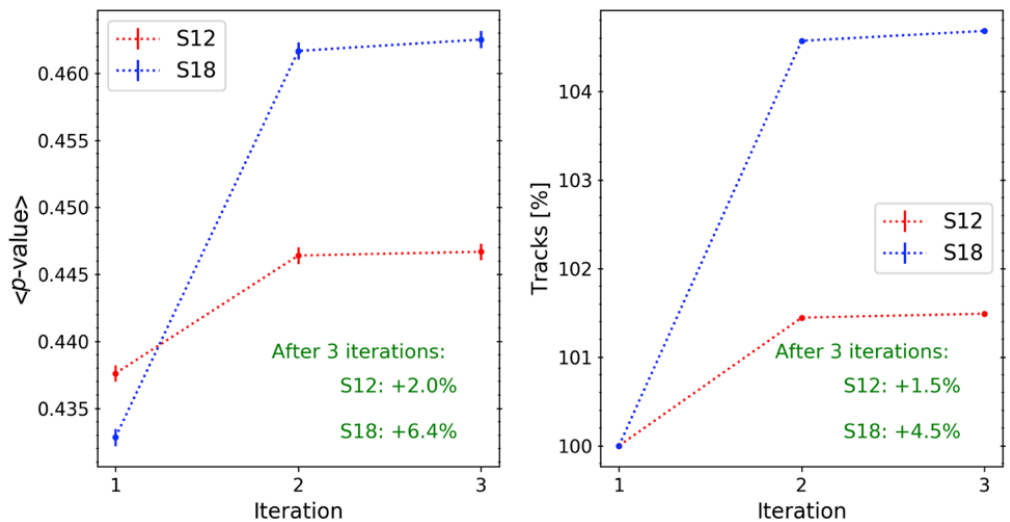
Alignment results with data

- With data, the number of reconstructed tracks has increased by up to 5% due to the position calibration from the alignment

- Residual mean per module **before** and **after** alignment in S18



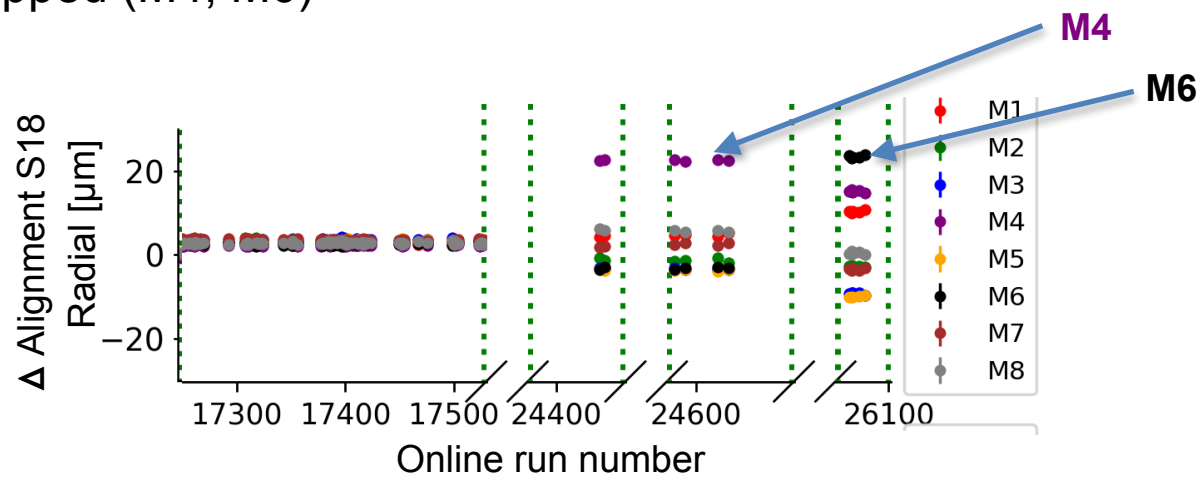
- The mean *p*-value and percentage of tracks as a function of iteration number



- Extrapolated tracks have a radial shift towards the centre of the ring of 0.50 mm and a vertical shift of 0.14 mm

Production DB: Internal alignment

- Alignment constants are now loaded from the database (DB) **automatically** for experiment-wide data *production*
- There are three intervals of validity (IoV), corresponding to the two occasions when a module was swapped (M4, M6)



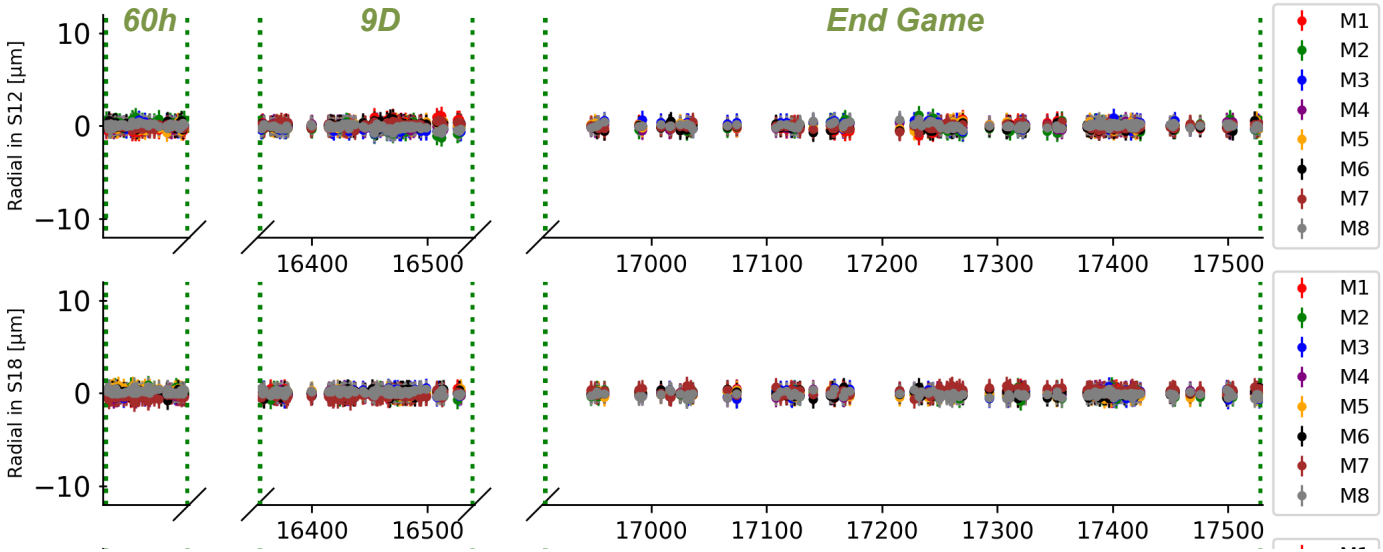

```
gm2_conditions_dev=> select * from tracker_align_internal_module_data;
 __iov_id | channel |   m1    |   m2    |   m3    |   m4    |   m5    |   m6    |   m7    |   m8
----------+---------+---------+---------+---------+---------+---------+---------+---------+---------
        4 |       3 |  0.0207 | -0.0185 |  -0.021 |  0.0148 | -0.0134 |  0.0014 |  0.0481 | -0.0323
        4 |       4 |  -0.025 | -0.0306 |  0.0542 |  0.0277 |  0.0153 | -0.0124 | -0.0439 |  0.0148
        4 |       5 |  0.0153 | -0.0182 | -0.0107 |  0.0371 | -0.0534 | -0.0039 |  0.0752 | -0.0413
        4 |       6 | -0.0711 | -0.0919 |  0.0645 |  0.0744 |  0.0581 |  0.1186 |   0.018 | -0.1705
        5 |       1 |       0 |       0 |       0 |       0 |       0 |       0 |       0 |       0
        5 |       2 |       0 |       0 |       0 |       0 |       0 |       0 |       0 |       0
        5 |       3 |  0.0207 | -0.0185 |  -0.021 |  0.0148 | -0.0134 |  0.0014 |  0.0481 | -0.0323
        5 |       4 |  -0.025 | -0.0306 |  0.0542 |  0.0277 |  0.0153 | -0.0124 | -0.0439 |  0.0148
        5 |       5 |  0.0153 | -0.0182 | -0.0107 |  0.0651 | -0.0534 | -0.0039 |  0.0752 | -0.0413
        5 |       6 | -0.0711 | -0.0919 |  0.0645 |  0.0803 |  0.0581 |  0.1186 |   0.018 | -0.1705
        6 |       1 |       0 |       0 |       0 |       0 |       0 |       0 |       0 |       0
        6 |       2 |       0 |       0 |       0 |       0 |       0 |       0 |       0 |       0
        6 |       3 |  0.0207 | -0.0185 |  -0.021 |  0.0148 | -0.0134 |  0.0014 |  0.0481 | -0.0323
        6 |       4 |  -0.025 | -0.0306 |  0.0542 |  0.0277 |  0.0153 | -0.0124 | -0.0439 |  0.0148
        6 |       5 |  0.0153 | -0.0182 | -0.0107 |  0.0651 | -0.0534 |  0.0275 |  0.0752 | -0.0413
        6 |       6 | -0.0711 | -0.0919 |  0.0645 |  0.0803 |  0.0581 |   0.157 |   0.018 | -0.1705
```

IoV ID links the constants to the run range

```
 __iov_id | channel |  run  | status
----------+---------+-------+--------
        1 |       1 | 15921 |      1
        2 |       1 | 19028 |      1
        3 |       1 | 25086 |      1
        4 |       1 | 15921 |      1
        5 |       1 | 19028 |      1
        6 |       1 | 25086 |      1
(6 rows)
```

Run-1: Monitoring and Summary

- **Alignment - <Alignment> per module is stable throughout Run-1**
- 230 runs with track cut of 250K per station



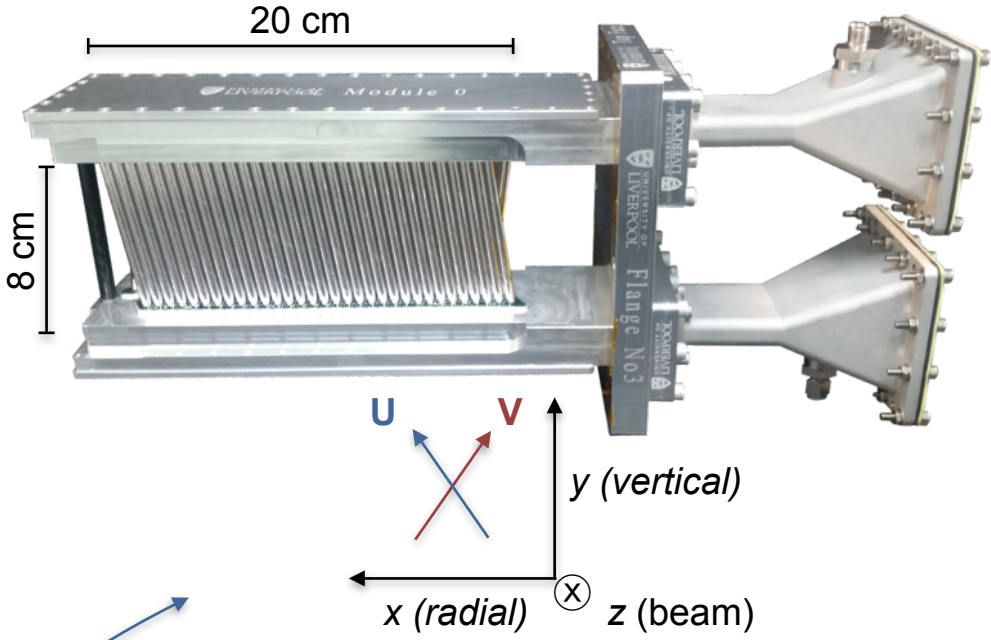
Summary:

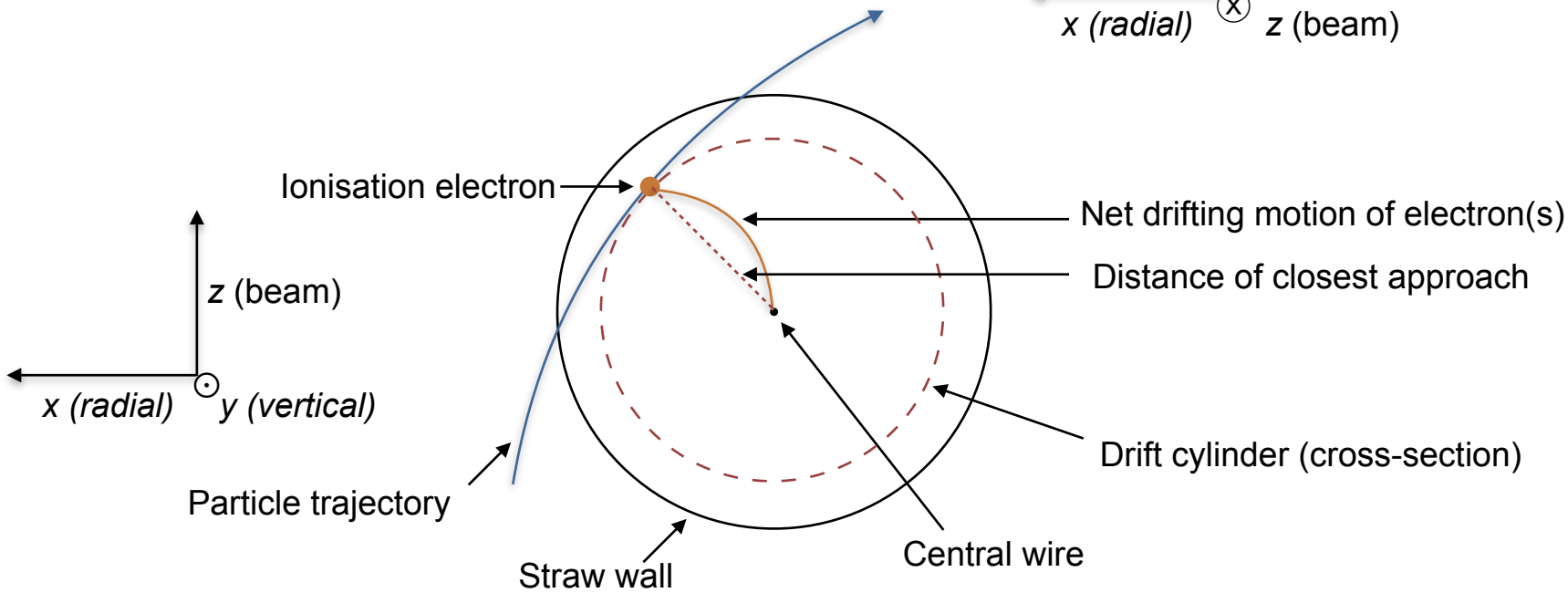
- Misalignment affects the radial and vertical extrapolated beam distributions
- Aligned tracking detector is required to accurately estimate the uncertainties on ω_a
- Internal and external alignment on the *g—2* straw tracking detector was performed
- Alignment convergence in simulation was reached within 2 μm and 10 μm radially and vertically
- With data, the number of reconstructed tracks has increased by up to 6% and <*p*-value> of the tracks has increased by up to 5%.
- Stable alignment results throughout the Run-1 and Run-2
- Alignment constants are being read-out from the production DB

BACKUP

Tracker overview

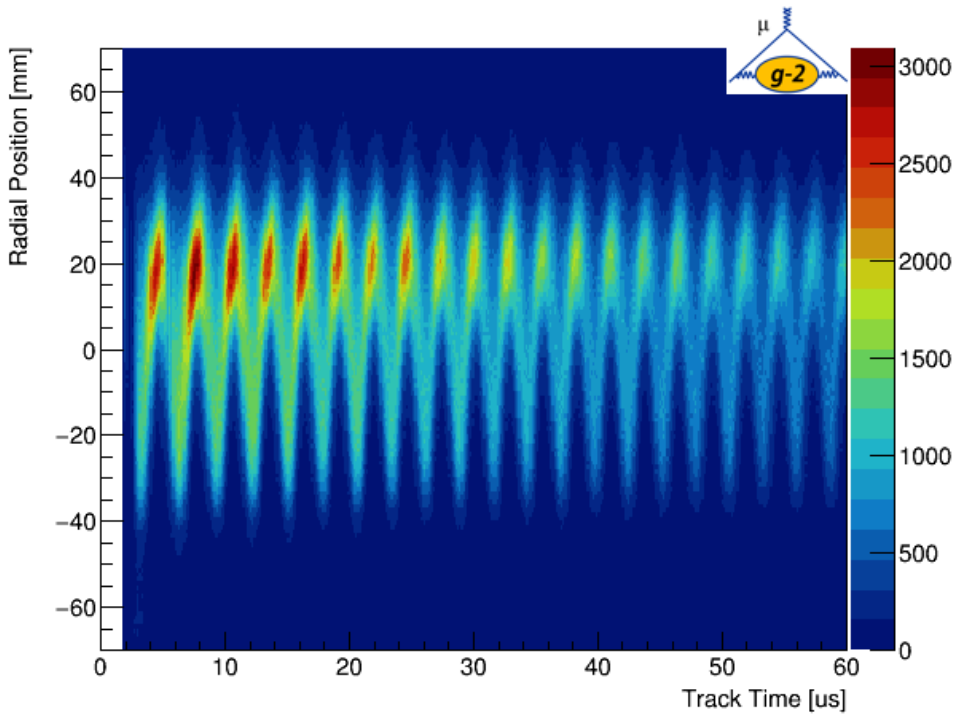
- 8 tracker modules per station
- 4 layers of 32 straws
- An angle of 15° between UV layers
- A straw is filled with 50:50 Ar:Ethane
- Central wire at +1.6 kV
- Module inside vacuum of 10^{-9} atm
- Straw is held at 1 atm
- Hit resolution of 100 μm

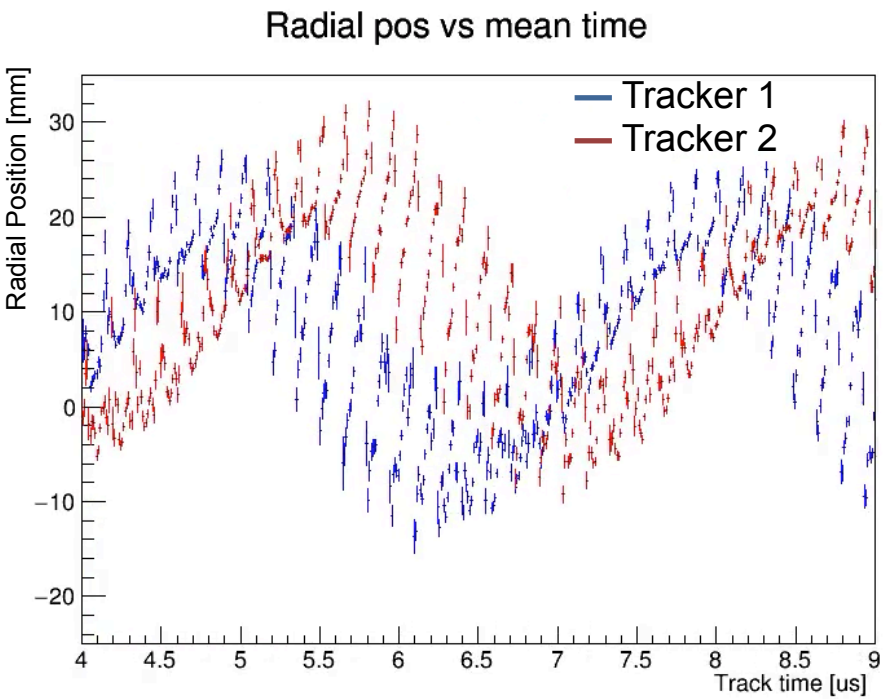




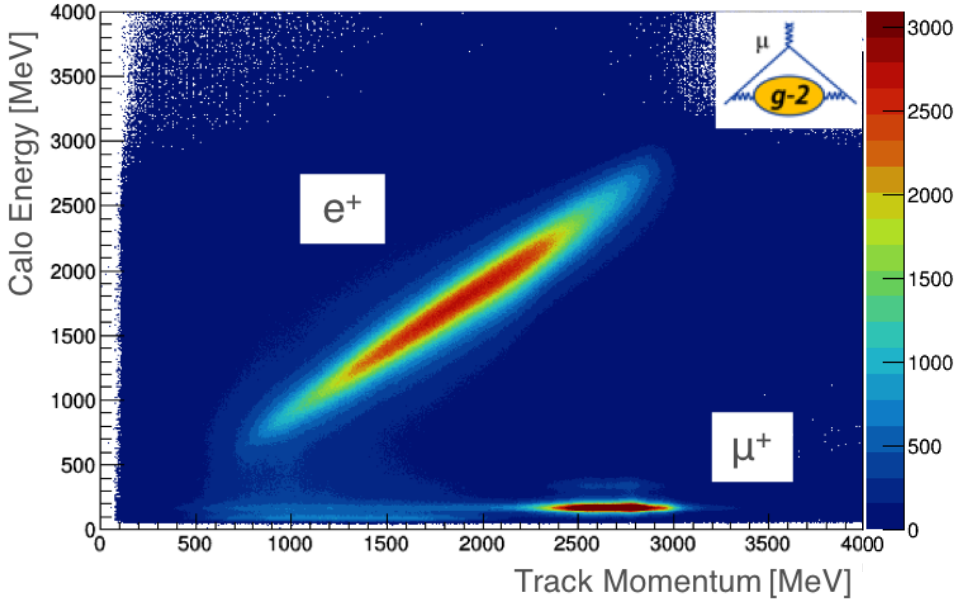
Beam profile over time

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



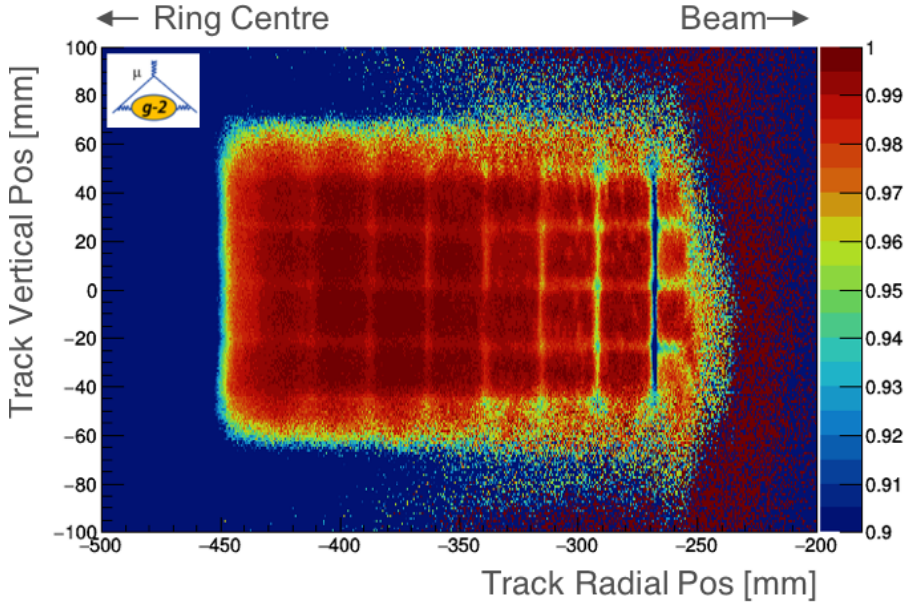


Track extrapolation



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

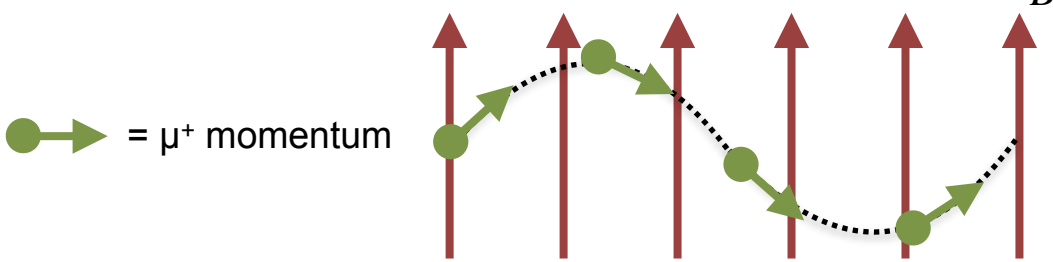
- Extrapolated tracks to the front face of the calorimeter. Tracker provides trajectory information at the face of the calorimeter, which is used to inform the clustering algorithms



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

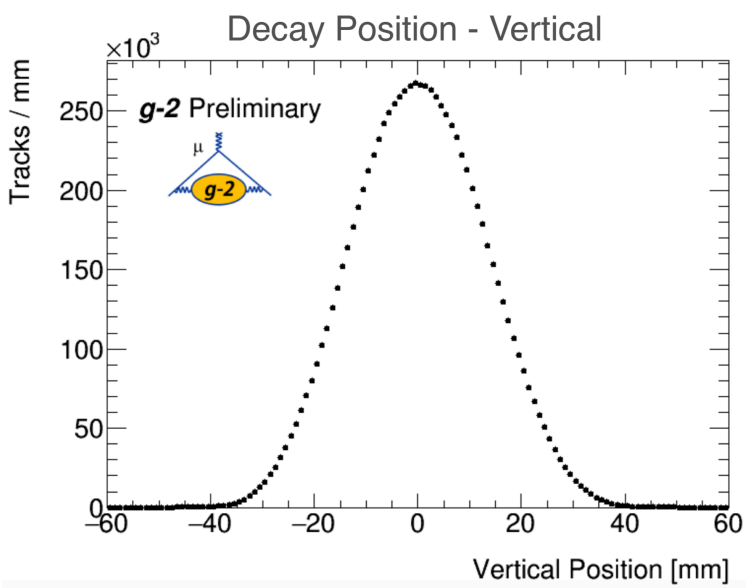
$B_{\text{vertical}} = 1.45\ \text{T}$



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

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

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

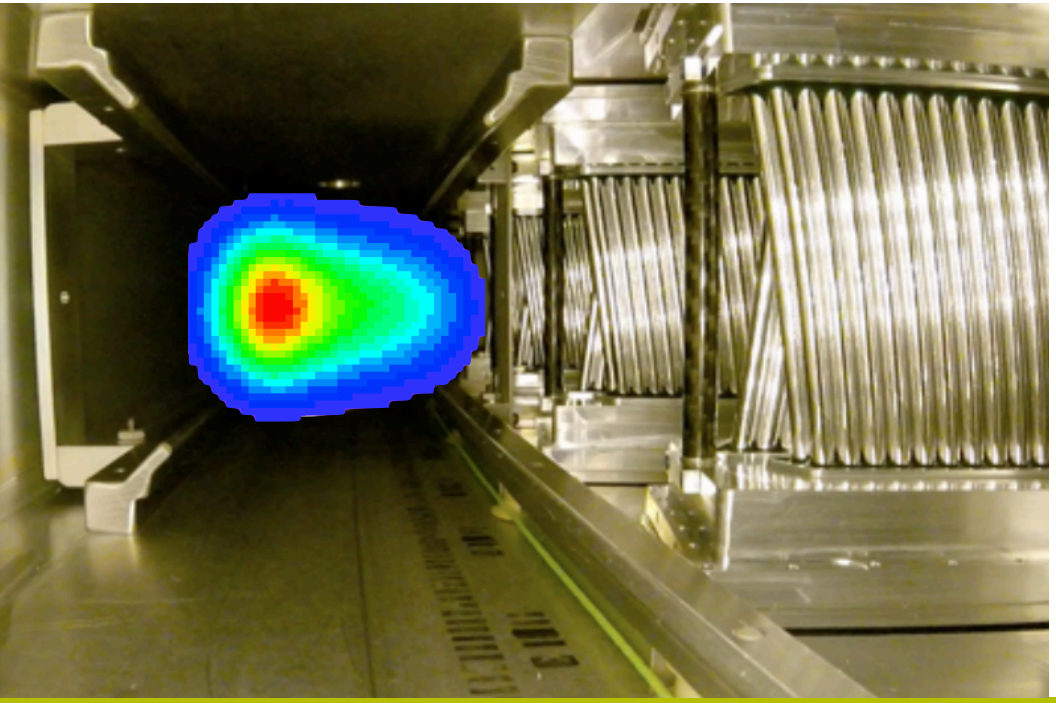


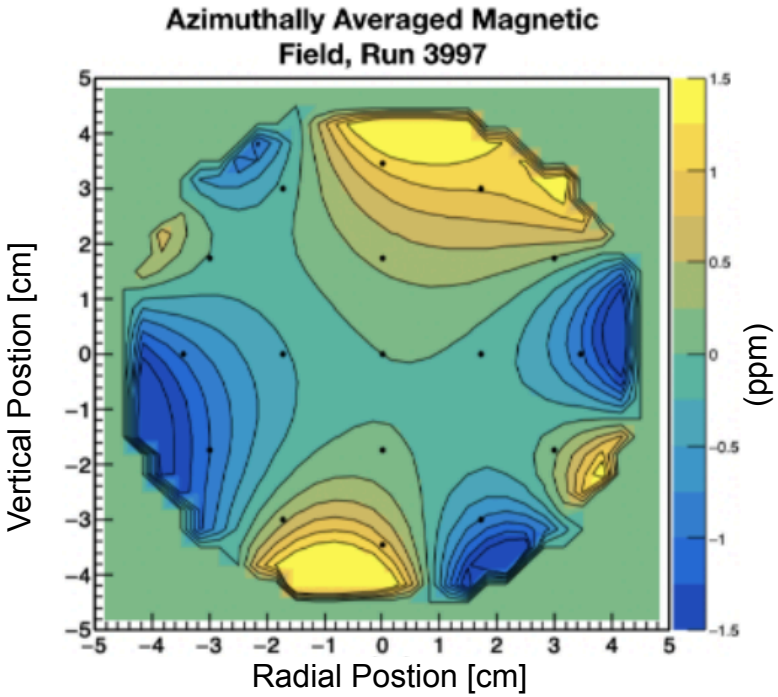
- Trackers measure the **vertical width** of the beam precisely. Uncertainty on the correction is < 30 ppb, in line with the designed expectation

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

- **Beam profile from the trackers**





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