g-2 tracker systematic uncertainties

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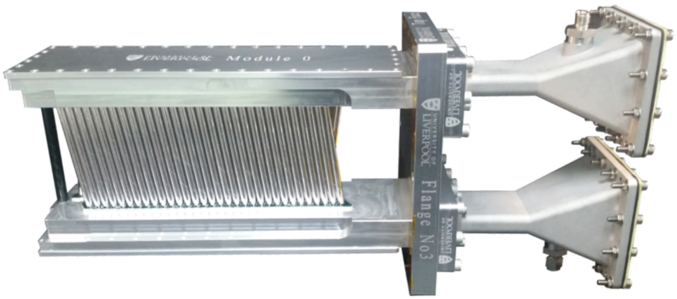
MUSE General Meeting

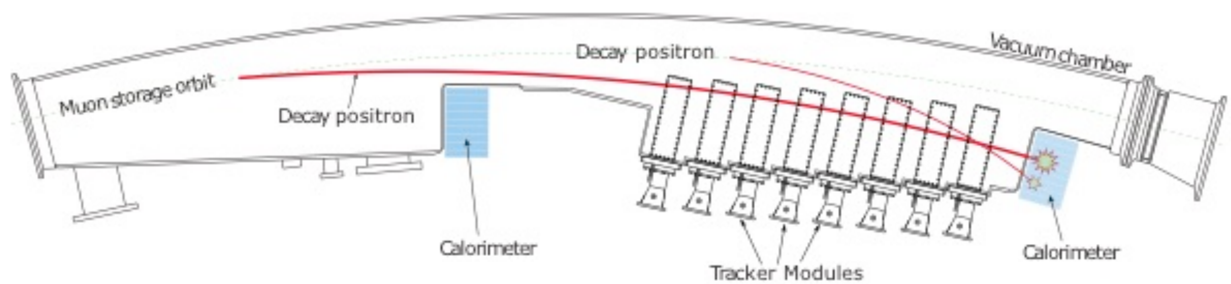
23rd October 2019

Introduction

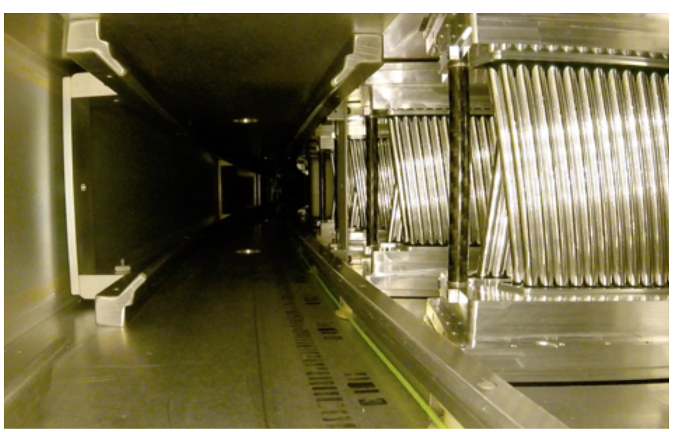
- The g-2 tracking detectors
- Precession frequency analysis
- Muon convolution
- Pitch correction
- Uncertainties
- Physics impact
- Conclusions

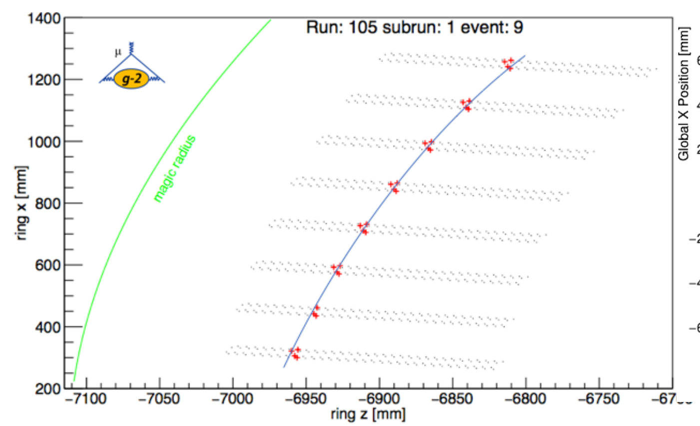
Tracking Detectors

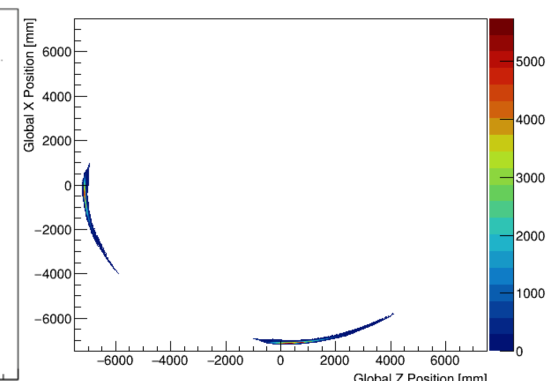




- Modules built at Liverpool University
- Measure e^+ tracks and reconstruct beam using traceback
- Reconstruct muon profile at 2 separate locations

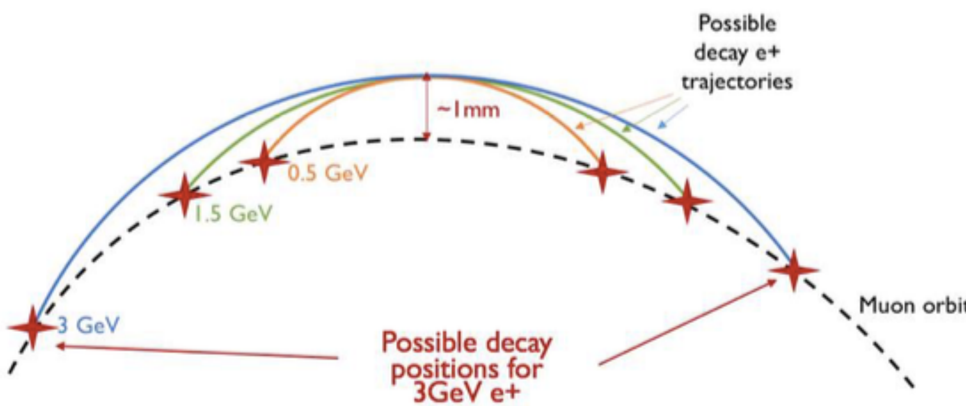






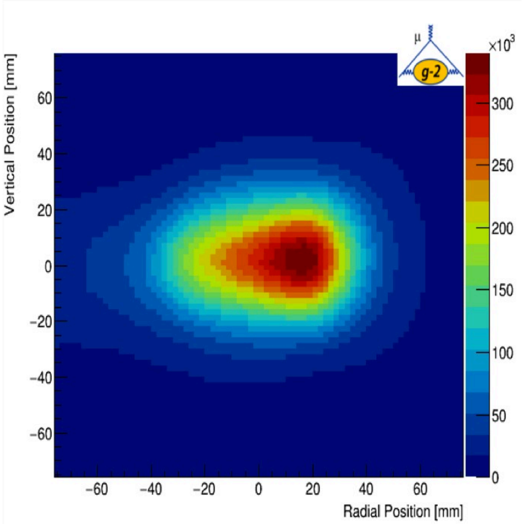
Measurements

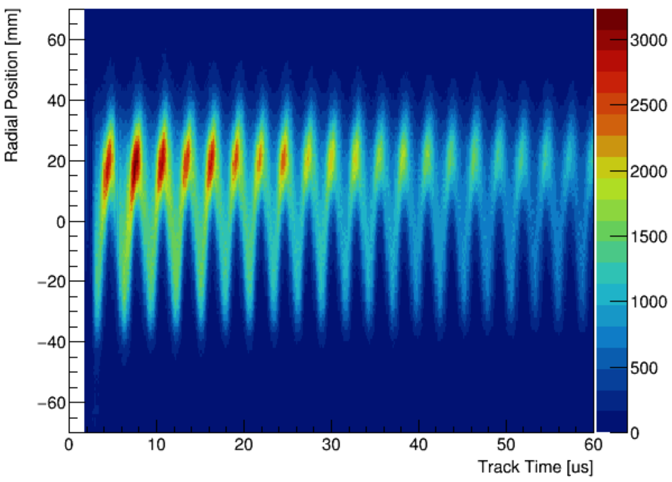
- Non destructive beam monitoring as a function of time in fill
- Measure the radial and vertical position at the extrapolated point of radial tangency as estimate of muon decay position

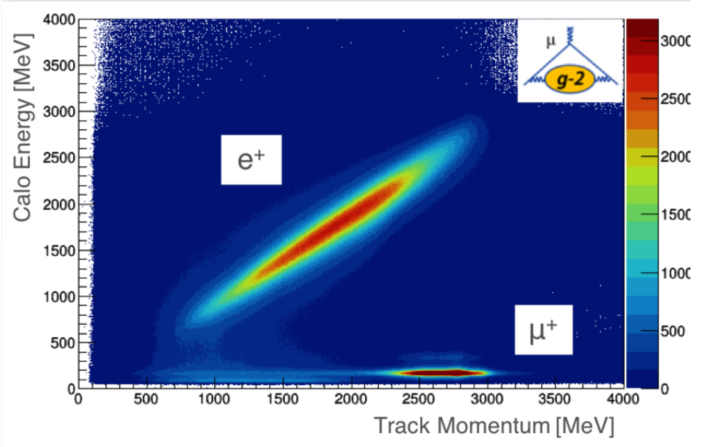


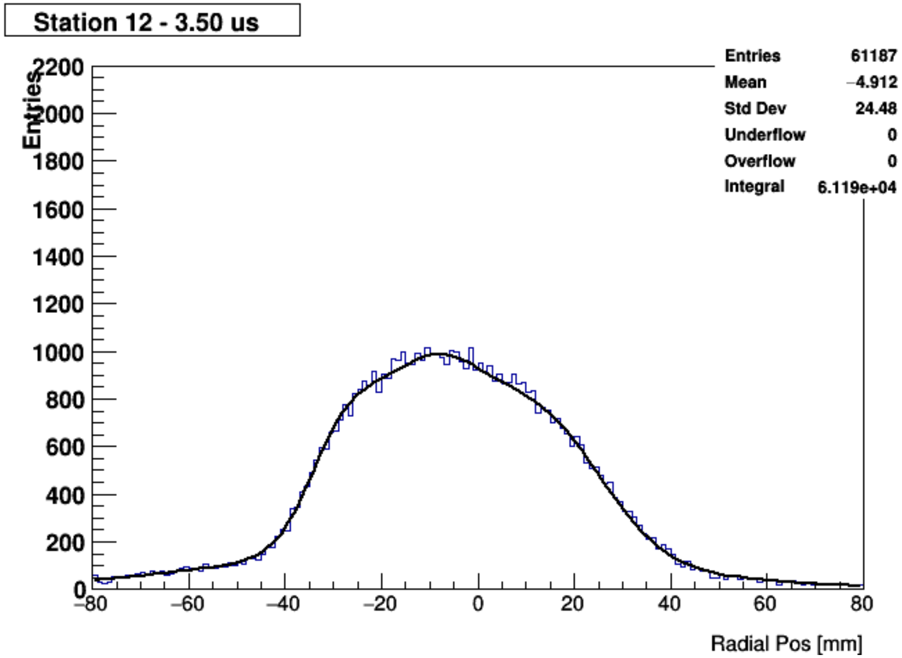
- Also measure the vertical angle of the positron
- Monitor any changes in fill crucial for ω_a analysis
- Provide muon map for convolution with B-field
- Measure vertical width needed for pitch correction

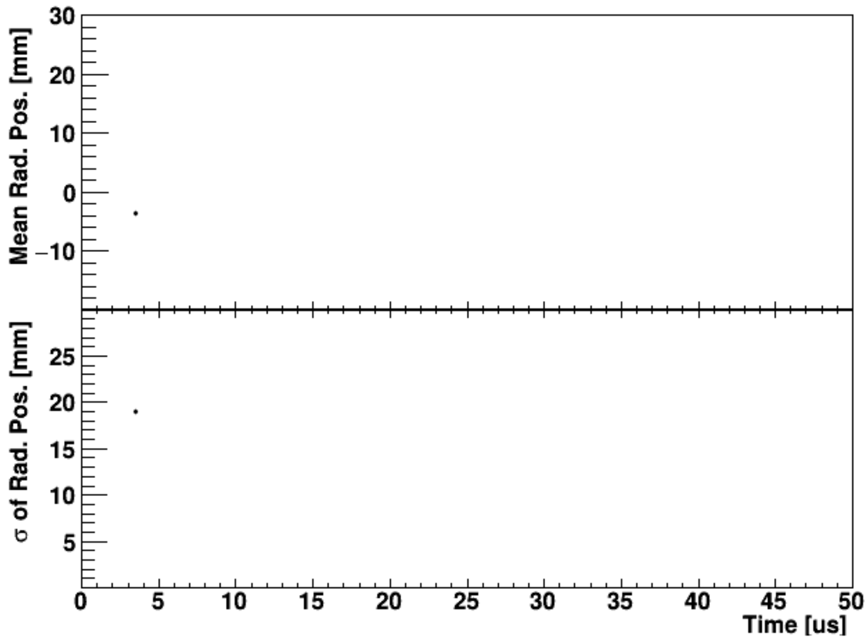
Tracking detectors





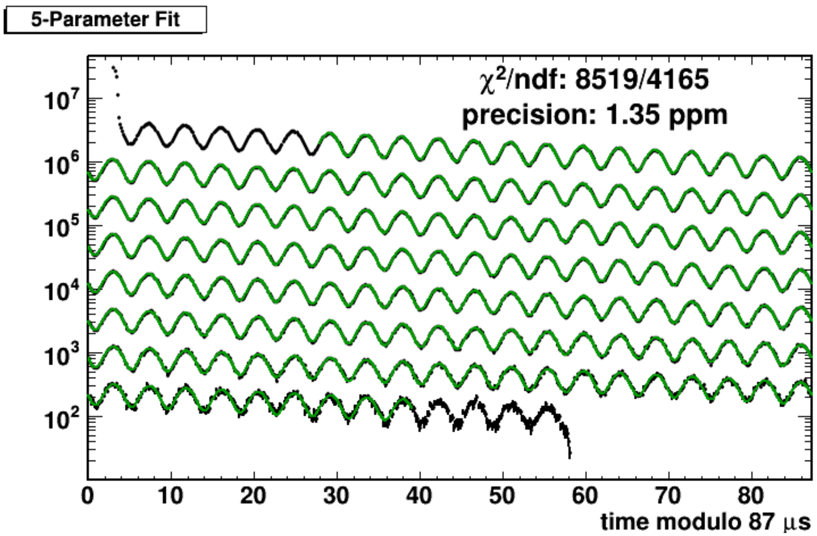




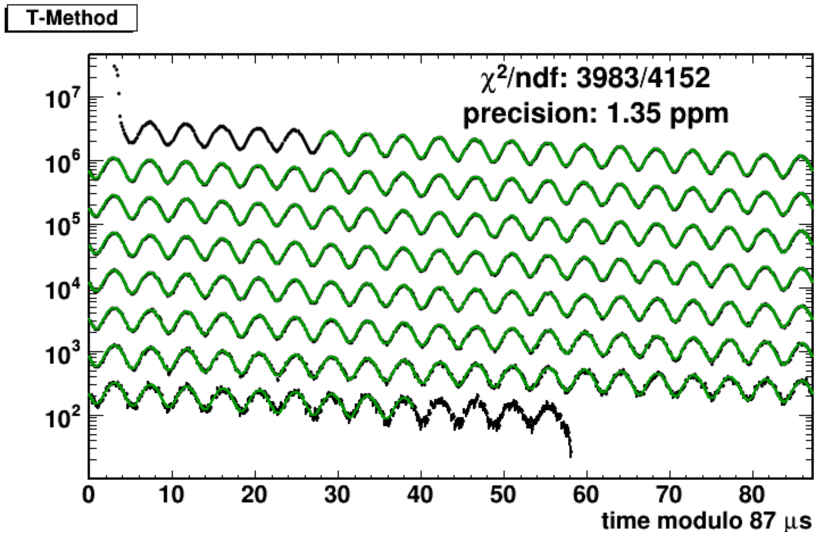


ω_a: impact of trackers

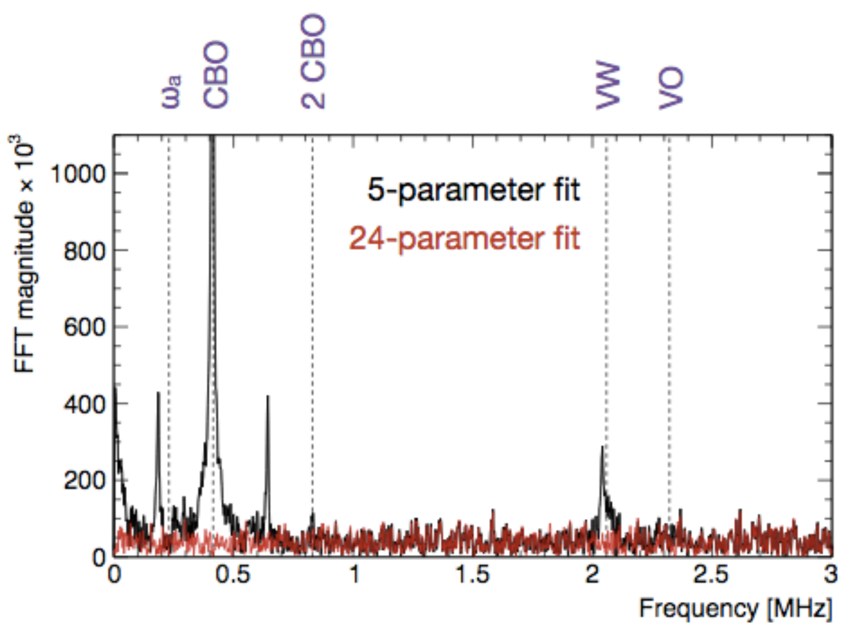
Improved fit procedure



beam frequencies

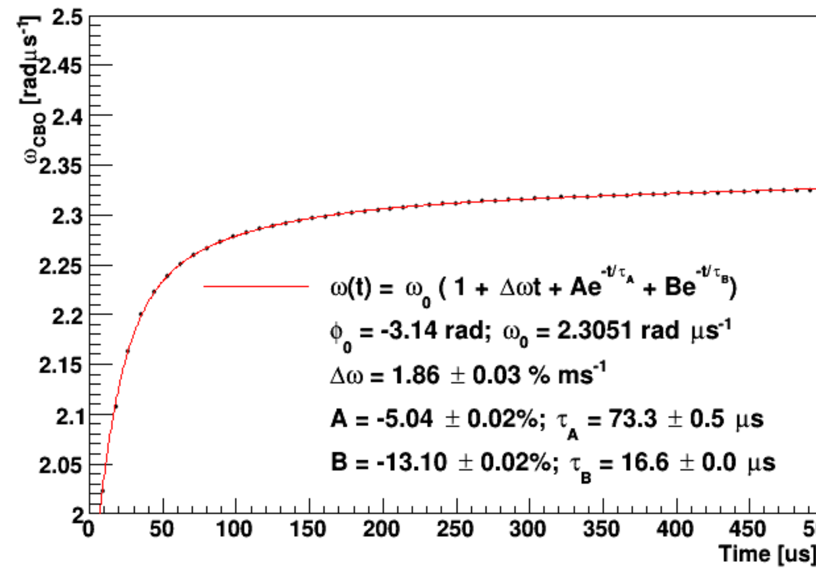


- Accounting for the beam oscillations improves the fits
- FFT of fit residuals flattened

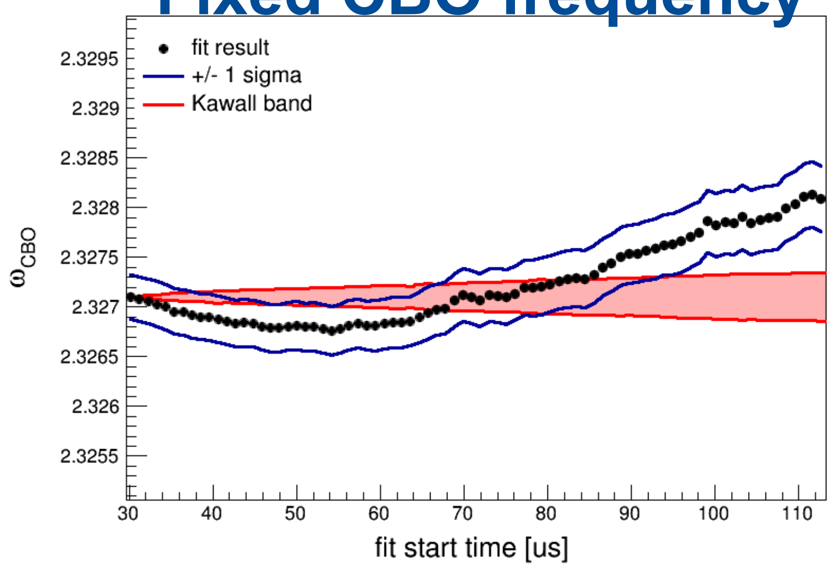


Tracking Detectors

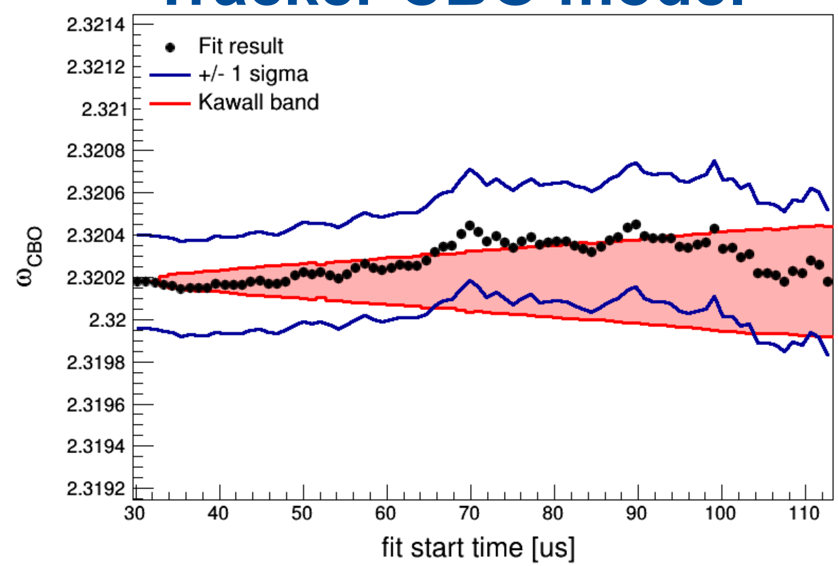
- The trackers are sensitive enough to measure beam frequencies changing throughout fill
- Accounting for these improves start time parameter scans



Fixed CBO frequency

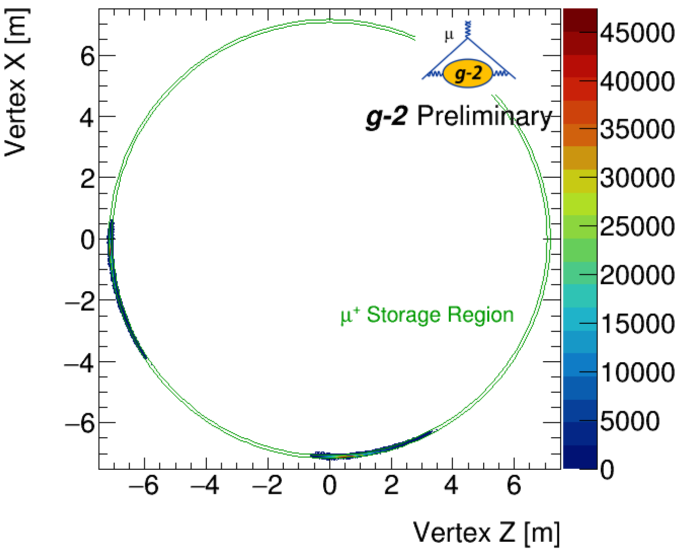


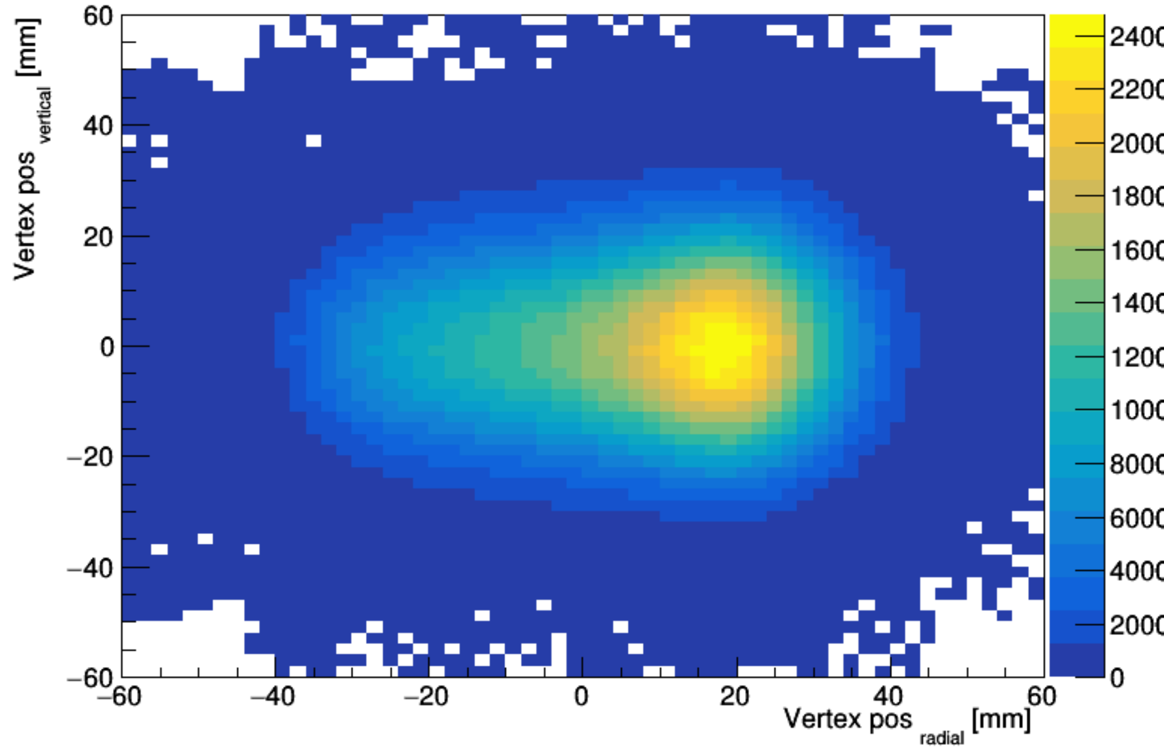
Tracker CBO model



convolution: impact of trackers

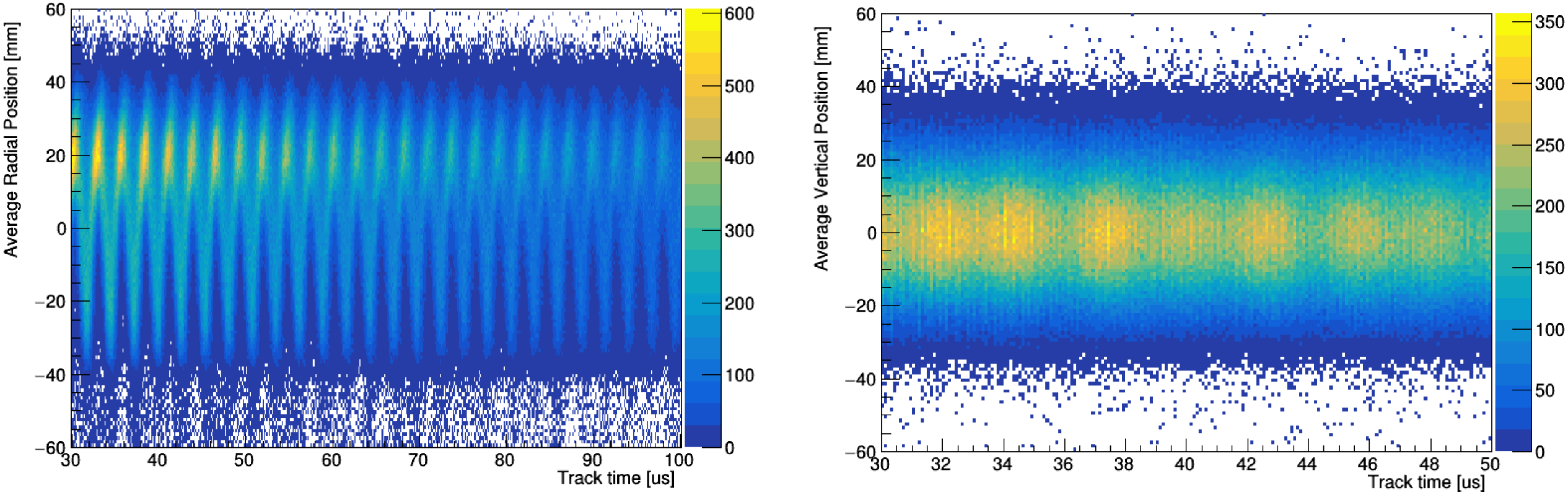
Tracker coverage





- Trackers located at 180° and 270°
- Each cover about 1m azimuthally
- Beam oscillations become apparent when plotted as a function of time in the fill...

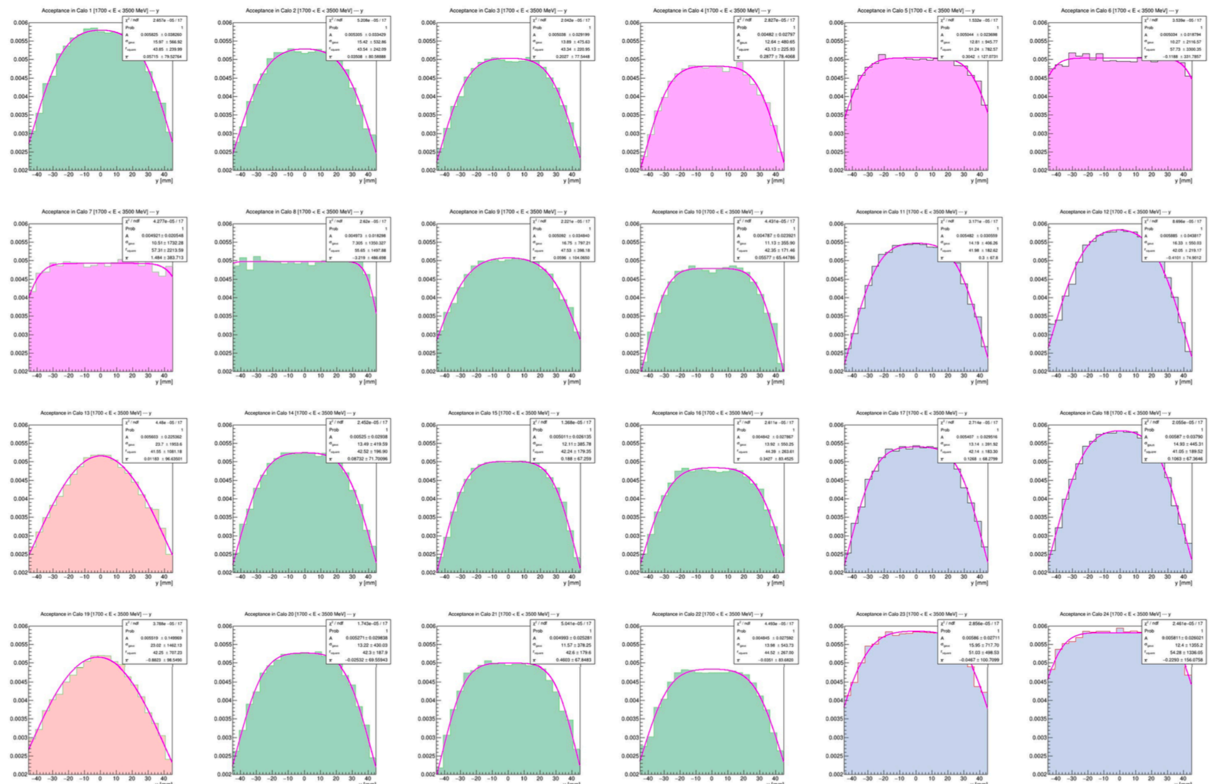
Oscillations



- Radial oscillation on a longer time scale than vertical
- Can fit individual time slices for mean and width for detailed studies
- For field convolution, only beam spot after 30 us matters

Calo Acceptance

- Final acceptance effect on calos will be smaller as high/low decays less likely to get into wiggle plot:



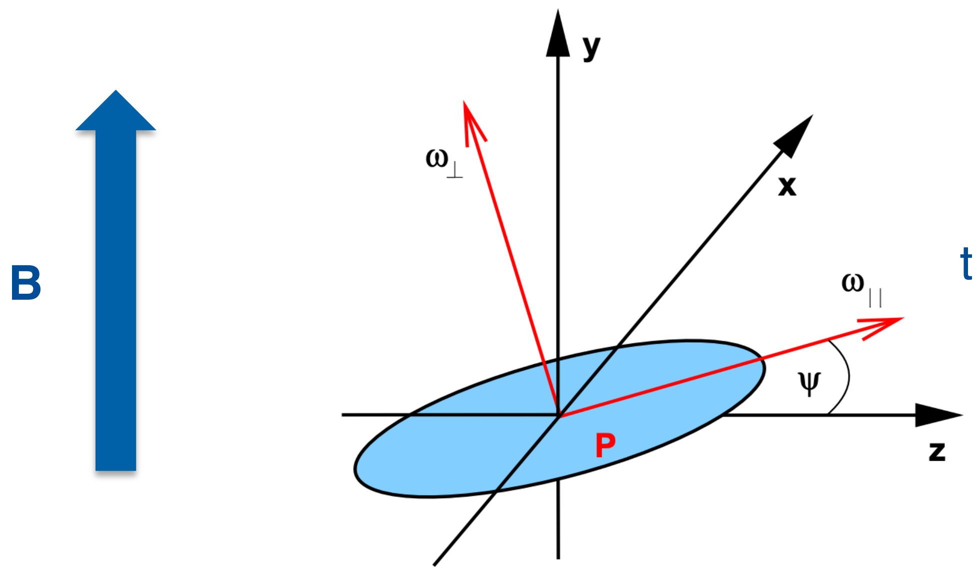
Vertical acceptance by calo

- Once we have corrected back to the beam we need to know what makes it into wiggle plot.

pitch correction: impact of trackers

Why do we need a pitch correction

- Muons are going up-and-down in the ring (focused by quads):



Muon going up at this time, but angle oscillates

- Field felt by the muons is reduced:

$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - a_\mu \left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}.\vec{B}\right)\vec{\beta}\right]$$

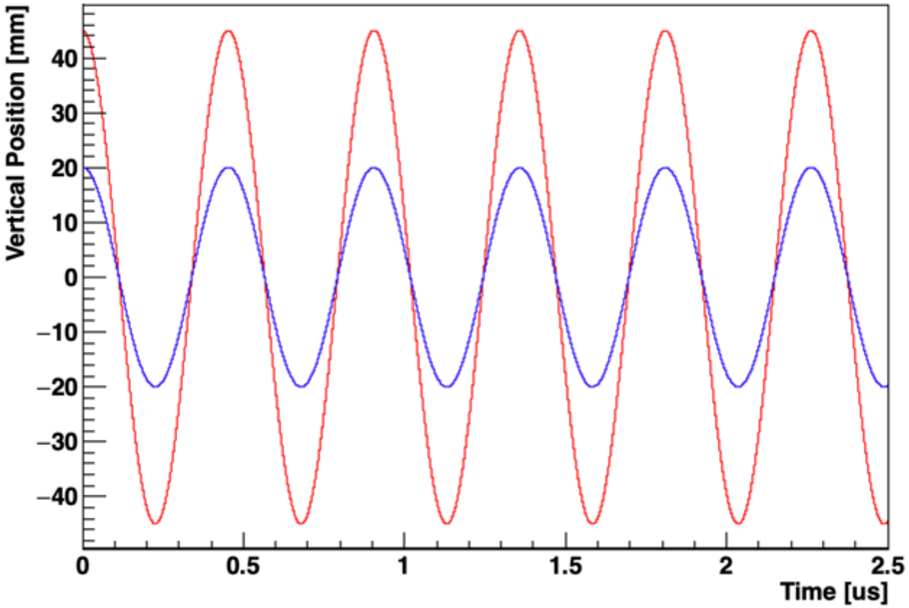
This is always positive for us (referring to $\left(\vec{\beta}.\vec{B}\right)$)

Angles and Positions

$$\left(\vec{\beta}.\vec{B}\right)\vec{\beta}$$

UNIVERSITY OF LIVERPOOL

- We really care about the vertical (pitch) angle of the μ^+
- But we measure e^+ so angle information is washed out a bit
- Instead, we measure position of decay and rely on the relation between amplitude & angle of oscillation:



Larger amplitude ⟷ Larger angle

Smaller amplitude ⟷ Smaller angle

$$C_P = \frac{\Delta\omega_a}{\omega_a} = -\frac{n}{2R_0^2}\left\langle y^2 \right\rangle$$

We'll actually use a beam dynamics model instead of this formula but it's close

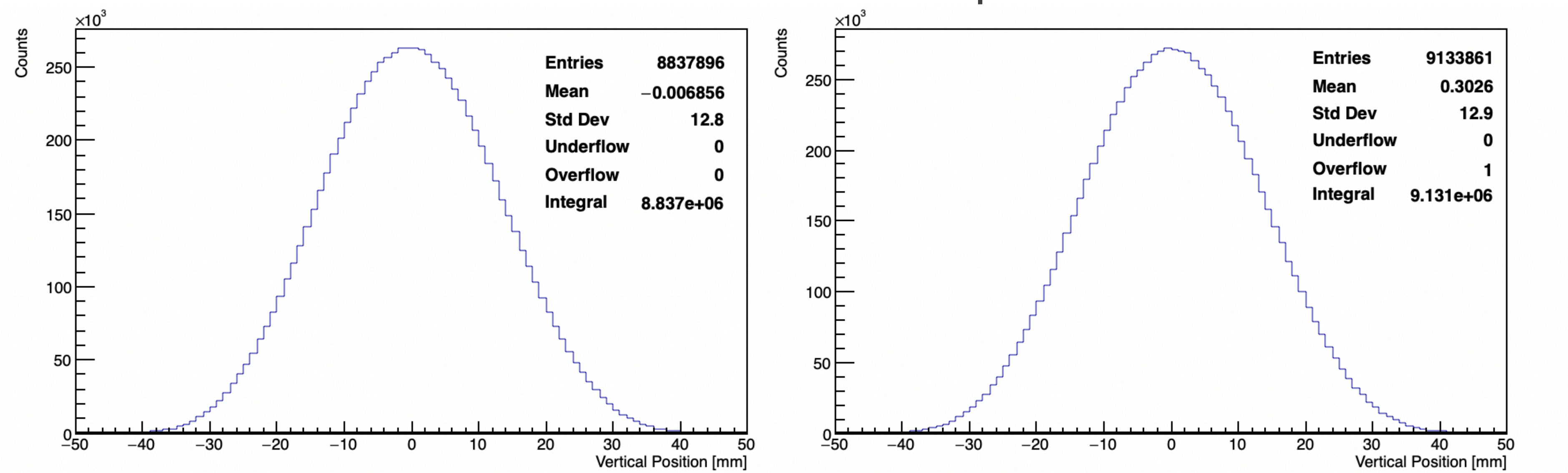
A Recipe for Pitch Correction:

Ingredients:

- **Tracker data**
- Beam dynamics (BD) model
- Calorimeter acceptance

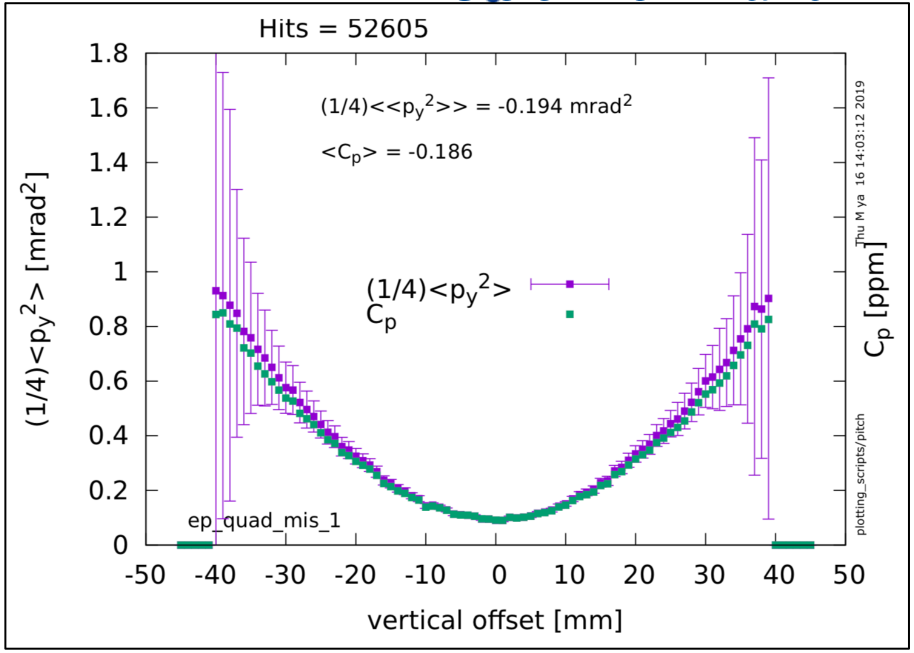
Steps:

1. Correct tracker measurements for acceptance & resolution:



A Recipe for Pitch Correction:

Stolen from David R.



Ingredients:

- Tracker data
- **Beam dynamics (BD) model**
- Calorimeter acceptance

Steps:

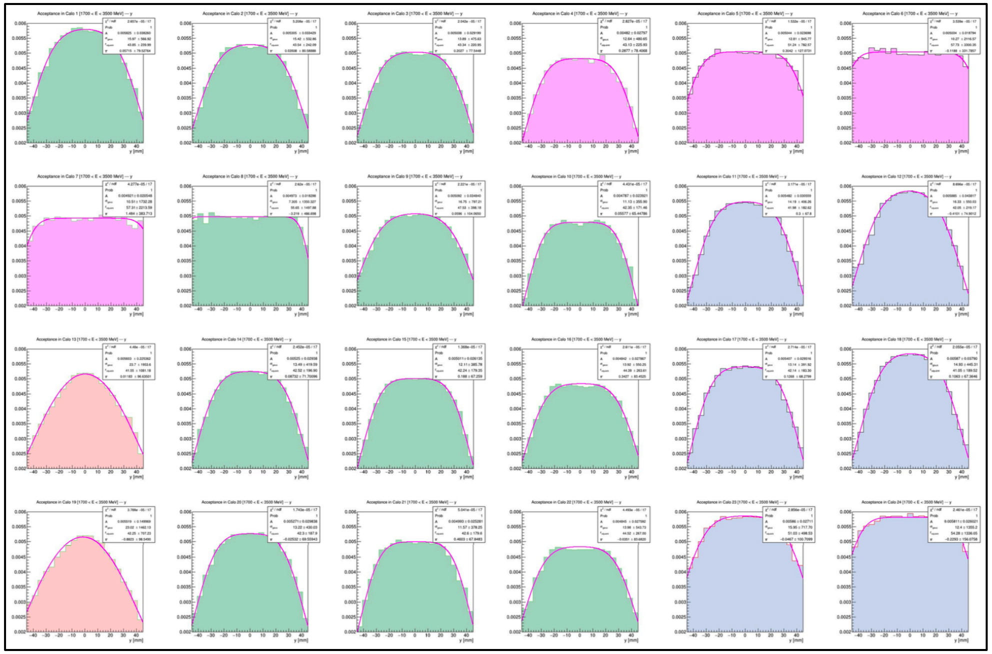
1. Correct tracker measurements
2. Tune BD model to match tracker data at two measurement points
3. Propagate μ^+ in model and get C_P for each decay

A Recipe for Pitch Correction:

Stolen from Josh

Ingredients:

- Tracker data
- Beam dynamics (BD) model
- **Calorimeter acceptance**



Steps:

1. Correct tracker measurements for acceptance & resolution.
2. Tune BD model to match tracker data at two measurement points
3. Propagate μ^+ in model and get C_P for each decay
4. Calculate C_P weighted by calo acceptance at each decay point

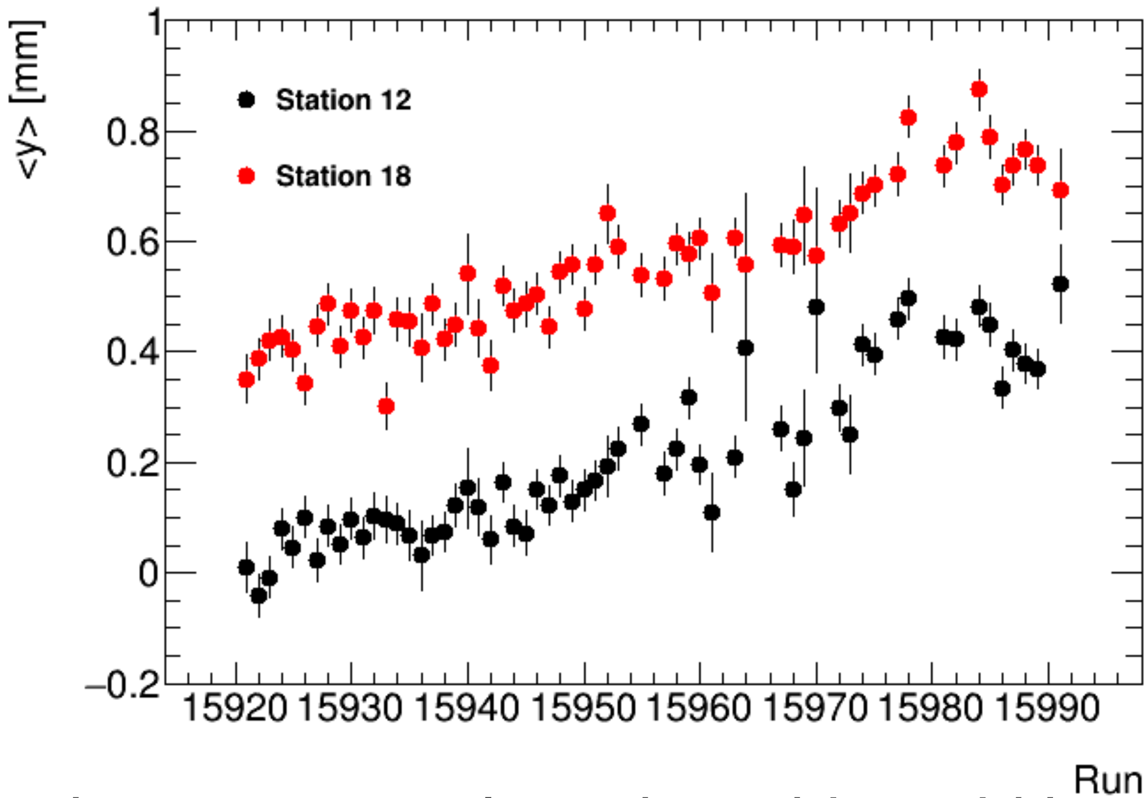
Tracking Uncertainties

Focusing on pitch correction since that is complete

Vertical Distribution: Changes vs Time

DocDB 14071

- We have 2 effects that could change our vertical distribution
    1. Changing radial magnetic field means the beam drifts up-and-down over the time scale of hours:



After alignment

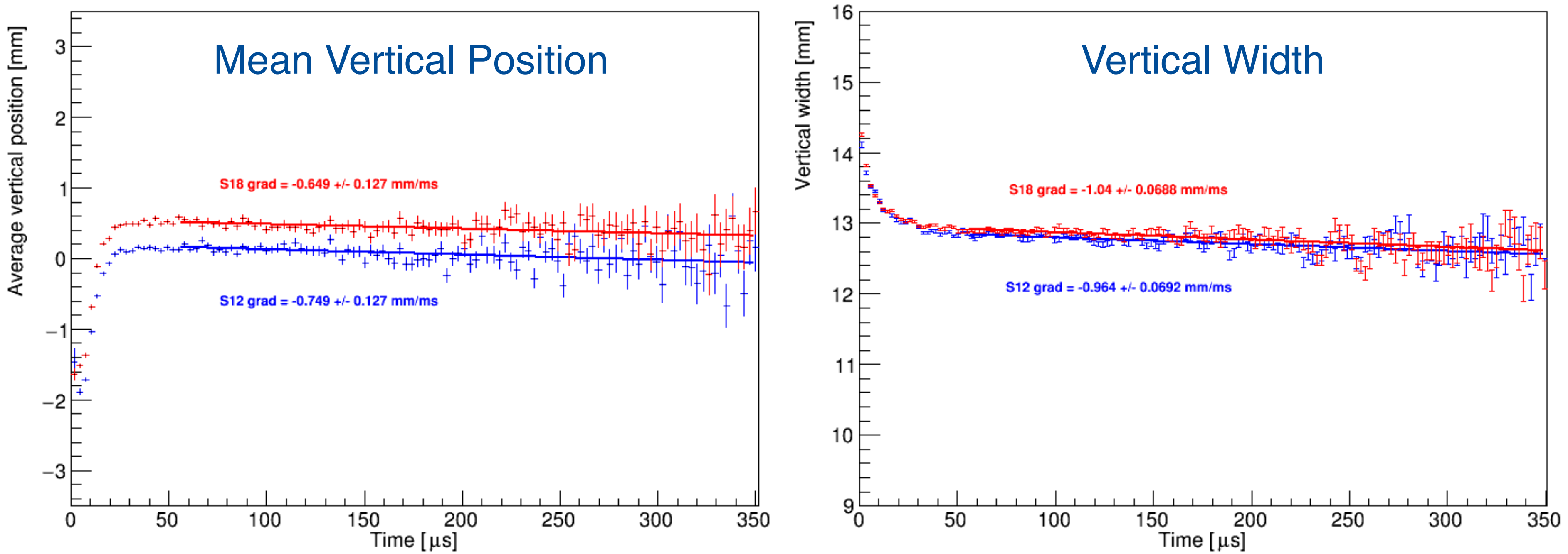
Difference could be from closed-orbit distortions or systematic shift

- We fit each run separately and combine widths

Vertical Distribution: Changes vs Time

- We have 2 effects that could change our vertical distribution

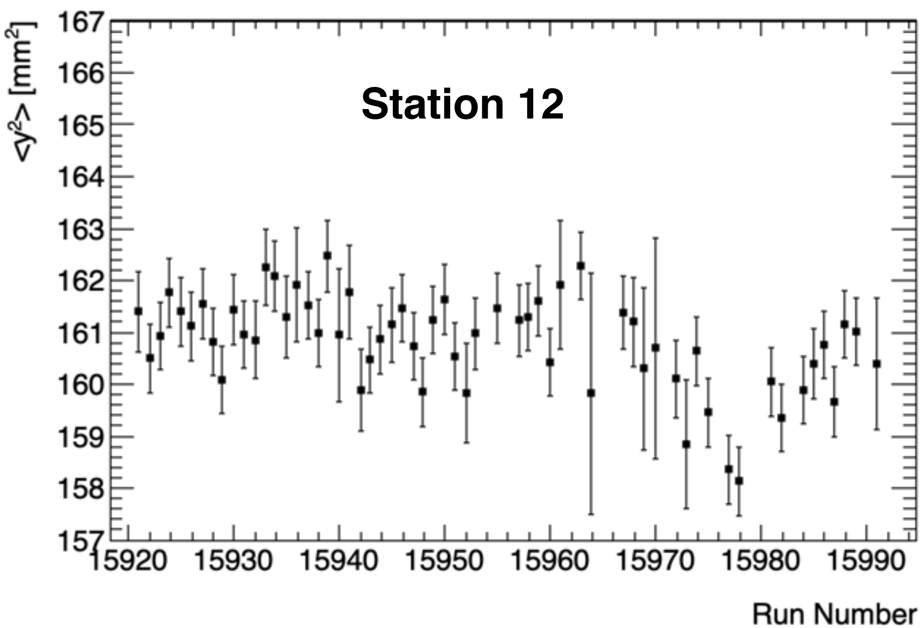
  2. Bad quad resistors mean the beam moves down and changes width over the course of each fill:

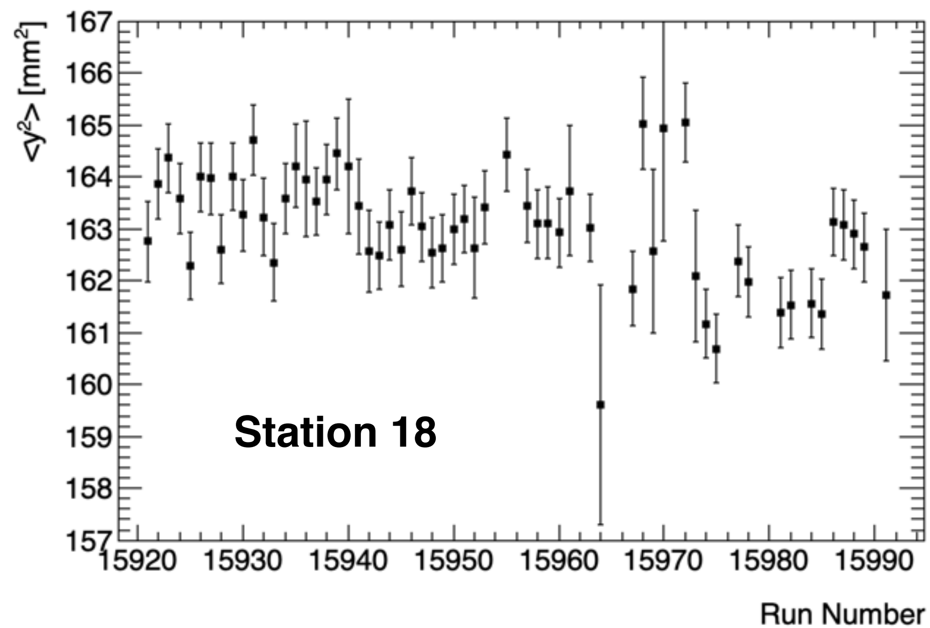


- Seems to be negligible for width measurement

$\langle y^2 \rangle$ over 60h dataset:

- Width is stable until run 15970, which is is thought to be related to the quads:





Remember
$1\ mm^2 \sim 1$ ppb

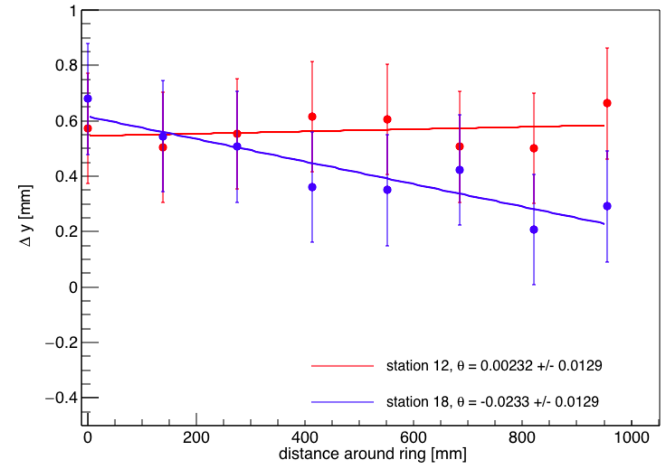
- Change after then is only a few ppb different
- Difference between stations combination of resolution & orbit distortions

Tracking Systematics

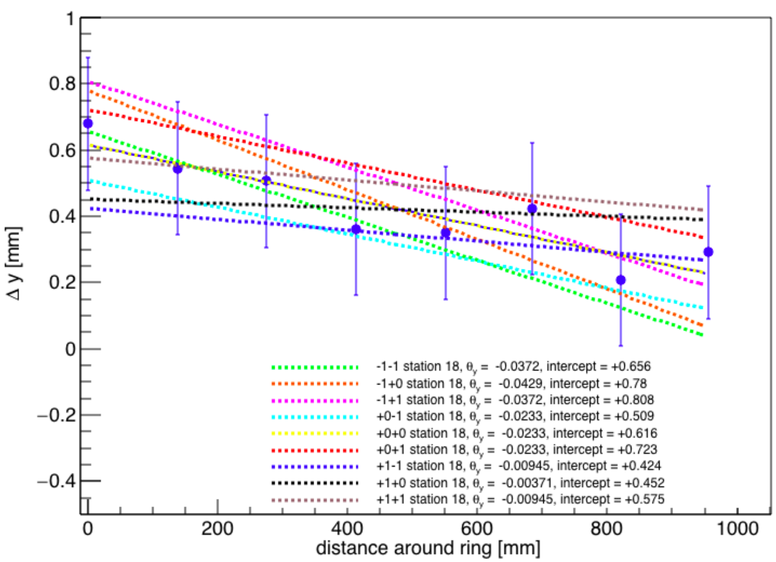
- Tracking systematics have been computed by whole team:
  - **Alignment**
  - **Tracking algorithm**
  - **Lost muons**
- We change parameters and see how μ_r , σ_r , μ_y , & σ_y change
- Generally, vertical width is not sensitive to most systematics
- Still missing fringe field estimate

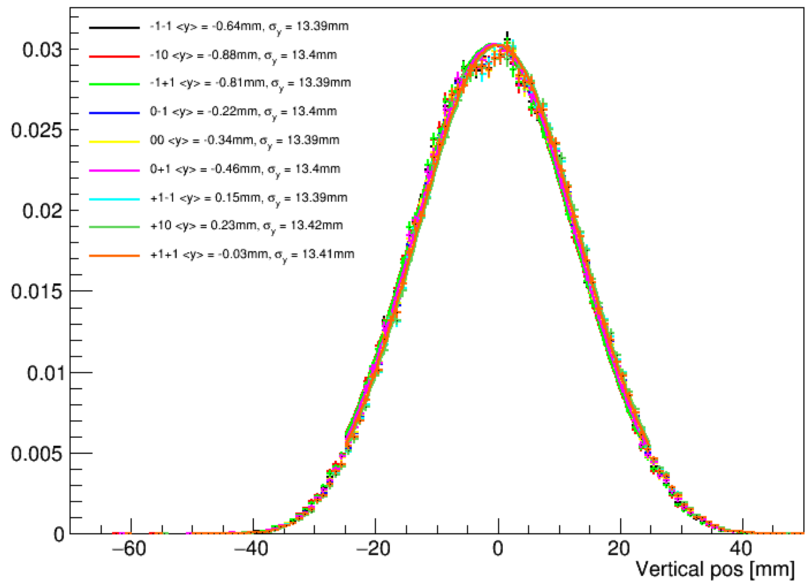
Alignment: External Alignment

- Use Horst's alignment measurements
- Fit for 'global alignment'
- Generate correlated shifts
- See doc-db 16063



Vertical difference from sim (e = ± 0.2mm)

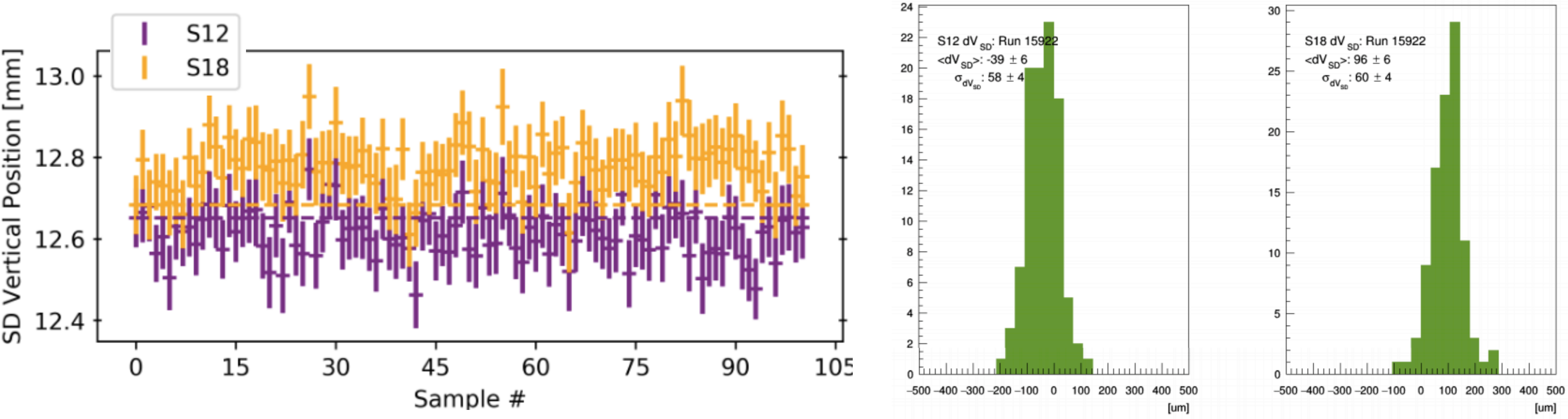




- $\langle y \rangle$ changes by +/- 0.6 mm, and $\langle y^2 \rangle$ +/- 0.01 mm^2
- Corresponds to a **ΔC_p = 0.3 ppb**

Alignment: Internal Alignment

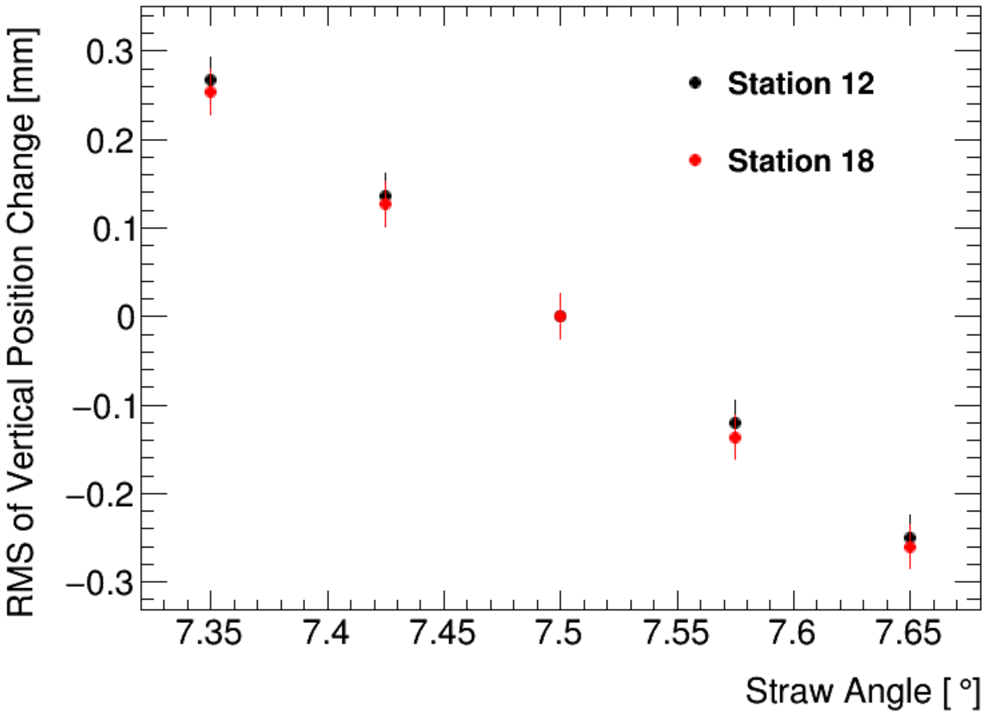
- Internal alignment is the movement of the individual modules in a station

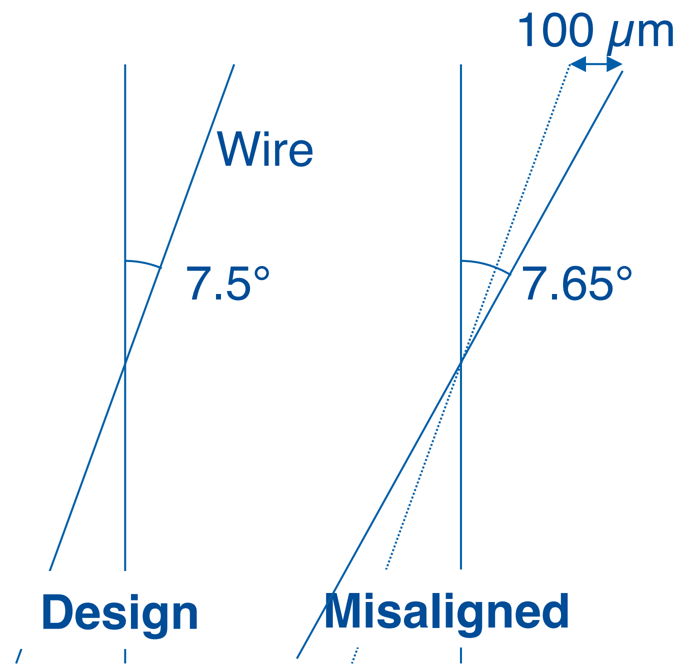


- Generate randomly mis-aligned modules +/- 100μm
- Reconstruct data and calculate $\langle y^2 \rangle$
- Details in doc-db 16685
- $\Delta\sigma_y$ = 0.06 mm, giving $\mathbf{\Delta C_p = 1.5}$ **ppb**

Gleb Lukicov (UCL)

Alignment: Straw Angle Alignment



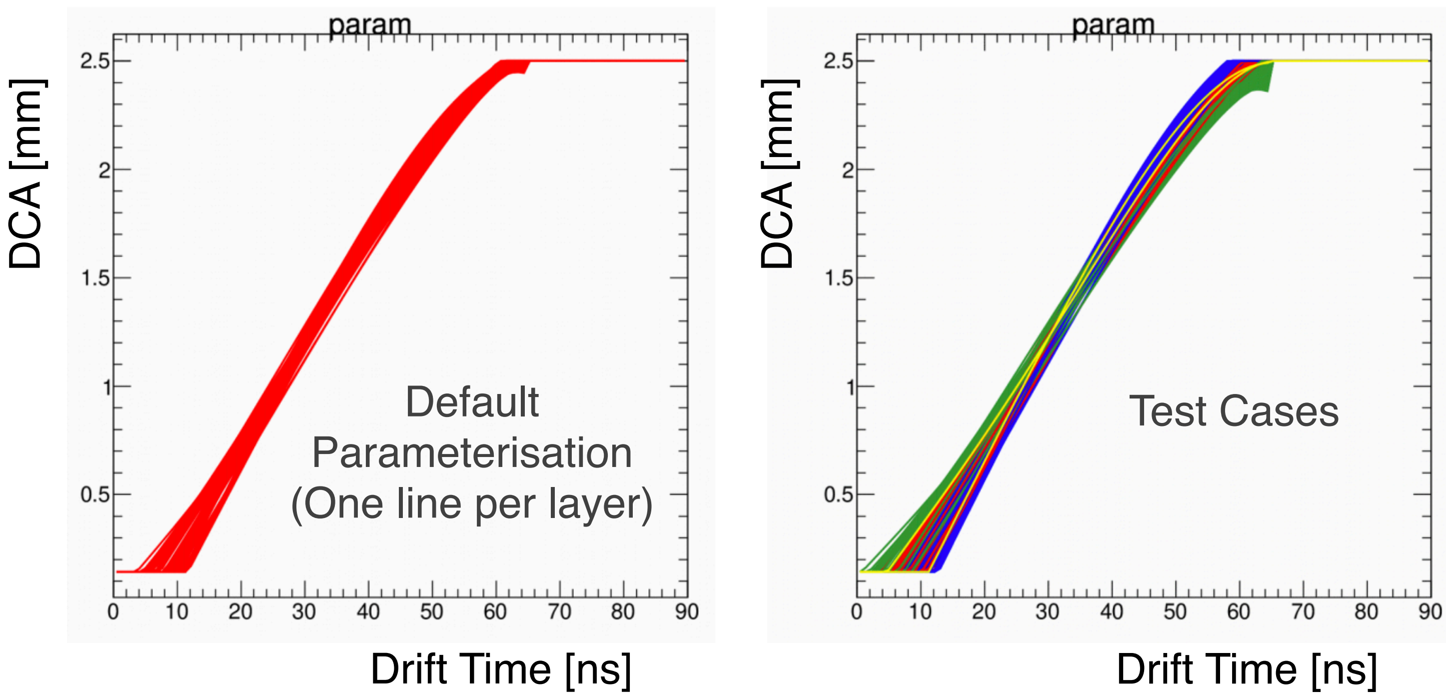


- Wire position at end of straw known to ~100 μm
- Conspiracy theory: all are misaligned in same way due to some machining error
- Uncertainty on vertical width of **0.25 mm → ΔC_P = ± 6.9 ppb**

Tracking Algo: T-to-R

DocDB 17746

- Have function for going between drift-time and track impact parameter
- Changed slope of this curve to that of steepest & shallowest layers:



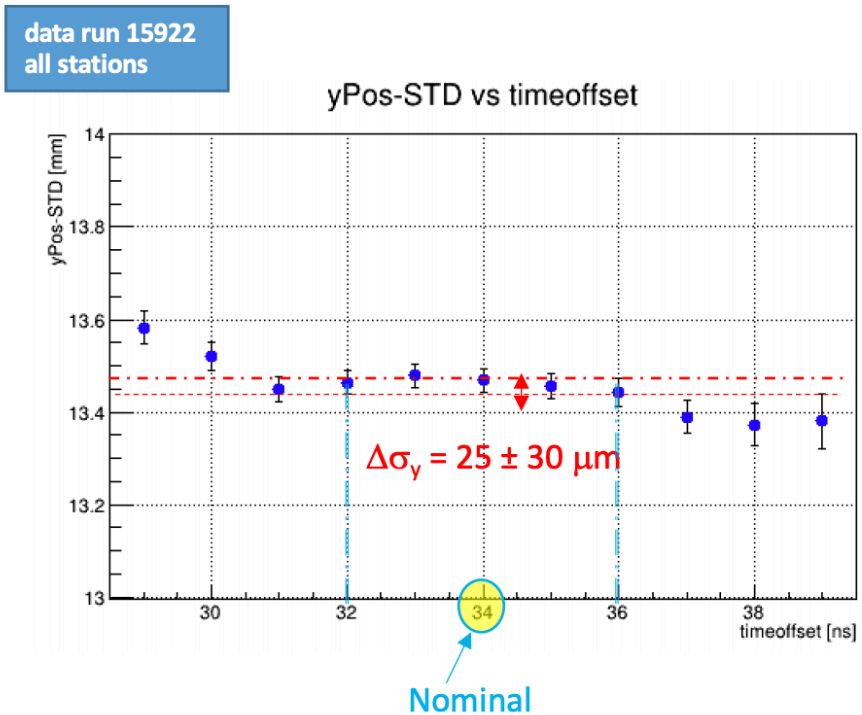
- $\Delta\sigma_y$ = 0.1 mm, giving $\mathbf{\Delta C_p = 2.7}$ **ppb**

Gavin Hesketh (UCL)

Tracking Algo: t_0 Offset

DocDB 16787

- t_0 offset is fixed time difference between estimate of t_0 and the mean of hits in the track
- Getting it wrong increases/decreases the drift circles of the straw hits



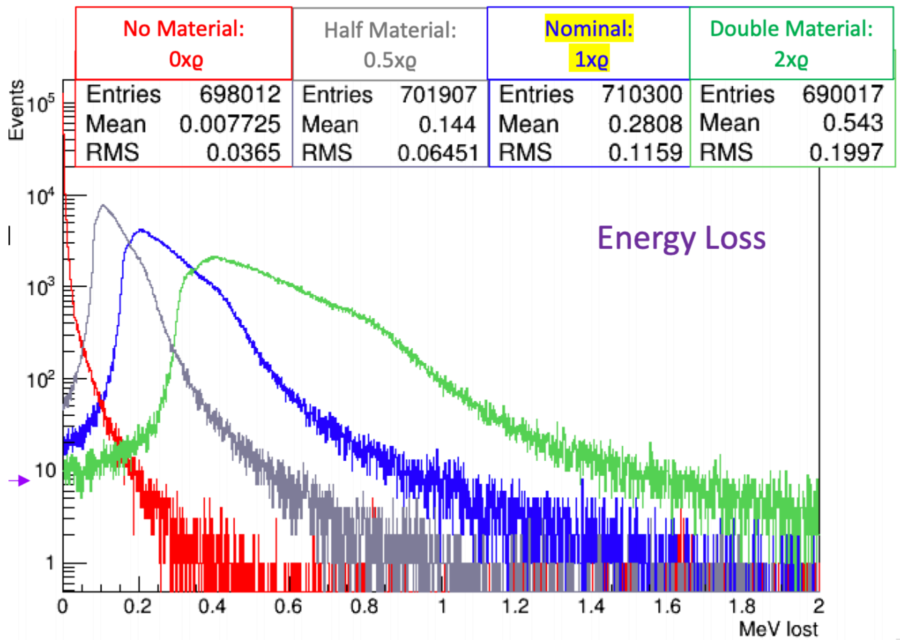
- Take ± 2 ns as uncertainty
- No clear shift in width of y distribution, but we take uncertainty as **25 μm [0.6 ppb]**

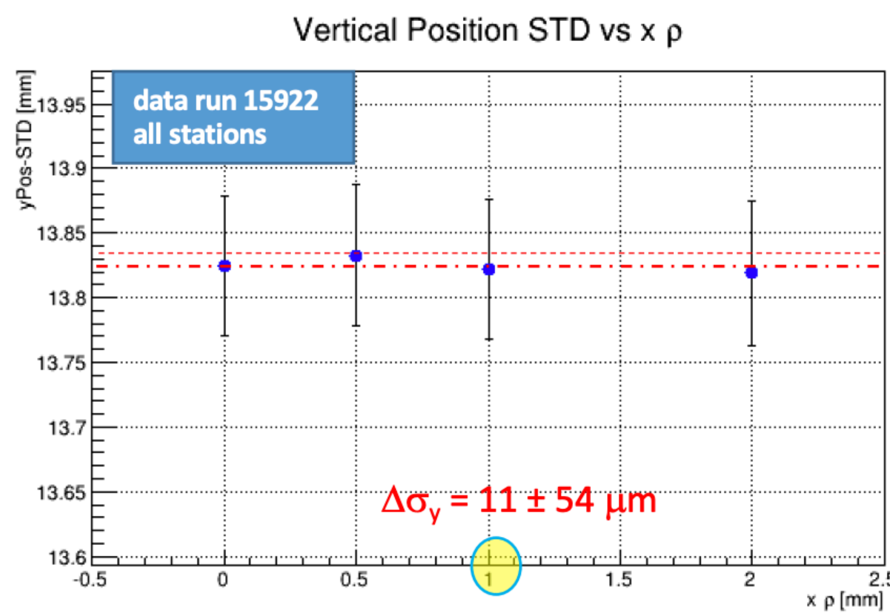
Alessandra Lucà (FNAL)

Tracking Algo: Material Density

[DocDB 16787]

- Amount of material in tracker is used to calculate energy loss
- Getting it wrong means we get our track curvature wrong



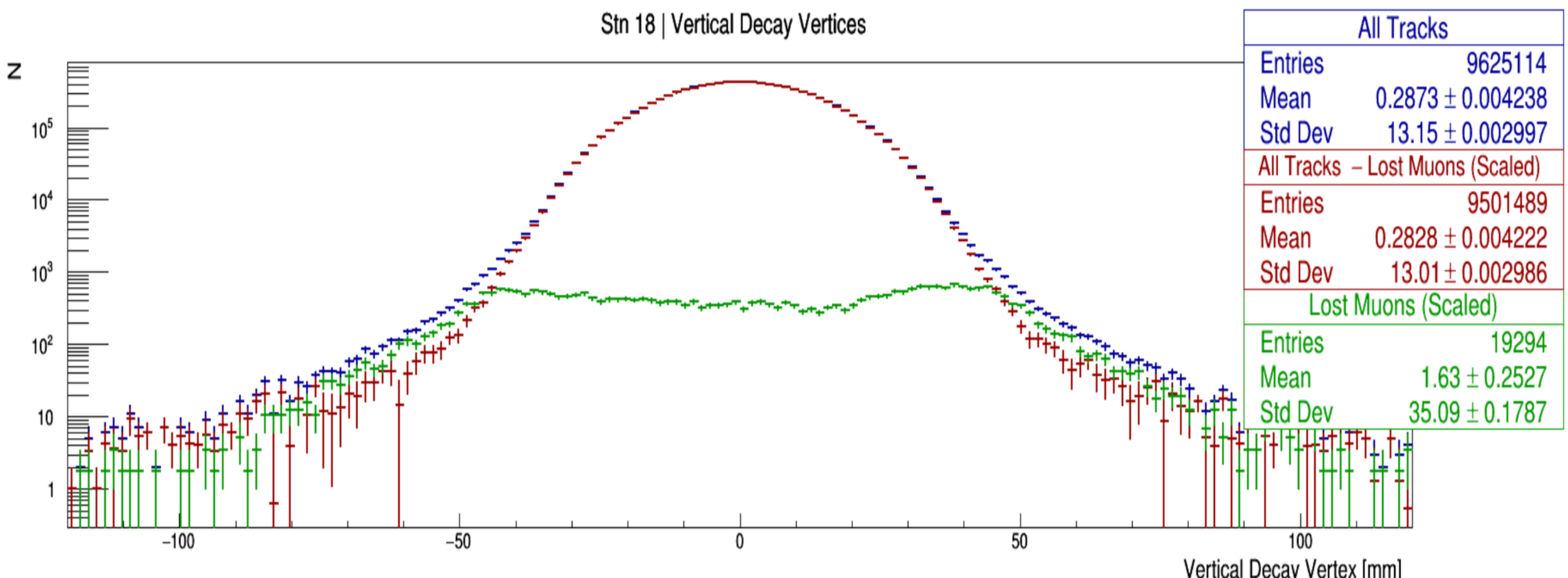


- Tested reconstruction with 0, 0.5, 1, 2x nominal density.
- No clear shift in width of y distribution, but we take uncertainty as **11 μm [0.3 ppb]**

Alessandra Lucà (FNAL)

Lost Muons

- Lost muons look like high momentum e^+ in the tracker
- Many removed by quality cuts, but some survive.
- Estimate how many make it through by using calorimeter to tag e^+/μ^+:



$$\Delta \text{ Vertical Width [mm]} \mid -0.109 \pm 0.004$$

± 60 mm Range

[2.9 ppb]

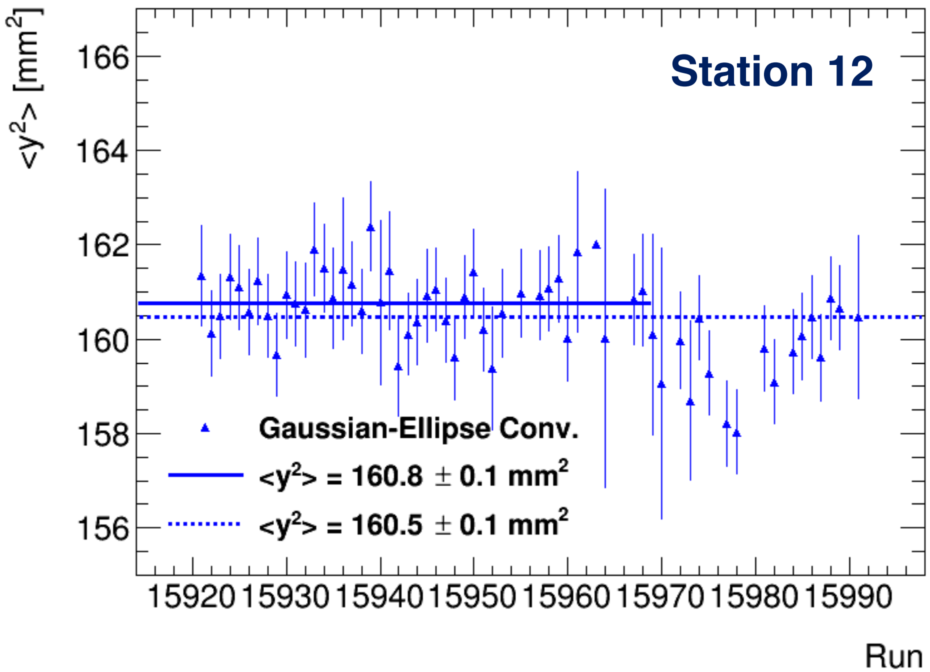
Sam Grant (UCL)

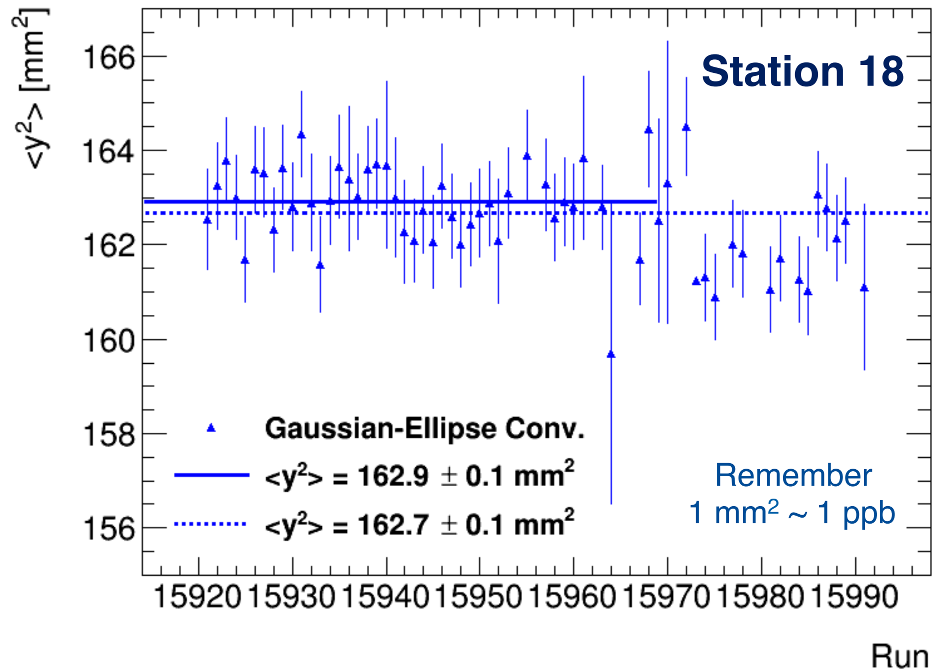
Uncertainties from Tracking:

Systematic	σ_y systematic [mm]	C_p systematic [ppb]
Alignment (Internal)	0.06	1.5
Alignment (External)	0.01	0.3
Alignment (Curvature)	0.1	2.7
Straw Stereo Angle	0.25	6.9
t_0	0.03	0.6
Track Finding	0.01	0.3
Hit resolution	0.01	0.3
R to T	0.1	2.7
Material Effects	0.01	0.3
Magnetic fringe field	?	?
Cross-talk	< 0.005	< 0.1
Lost muon contamination	0.11	2.9
Total	**0.32 + ?**	**8.6 + ?**

- Find that all tracking uncertainties together give ~ 9 ppb
- Need to make sure last outstanding systematic is not significant
- Should be able to check straw stereo angle alignment with tracks

Vertex Resolution Removal: Data





- Using fit over whole range of 60h:

$$\langle y^2 \rangle^{S12}_{meas} = 160.5 \pm 0.1 \text{ mm}^2 \qquad \langle y^2 \rangle^{S18}_{meas} = 162.7 \pm 0.1 \text{ mm}^2$$

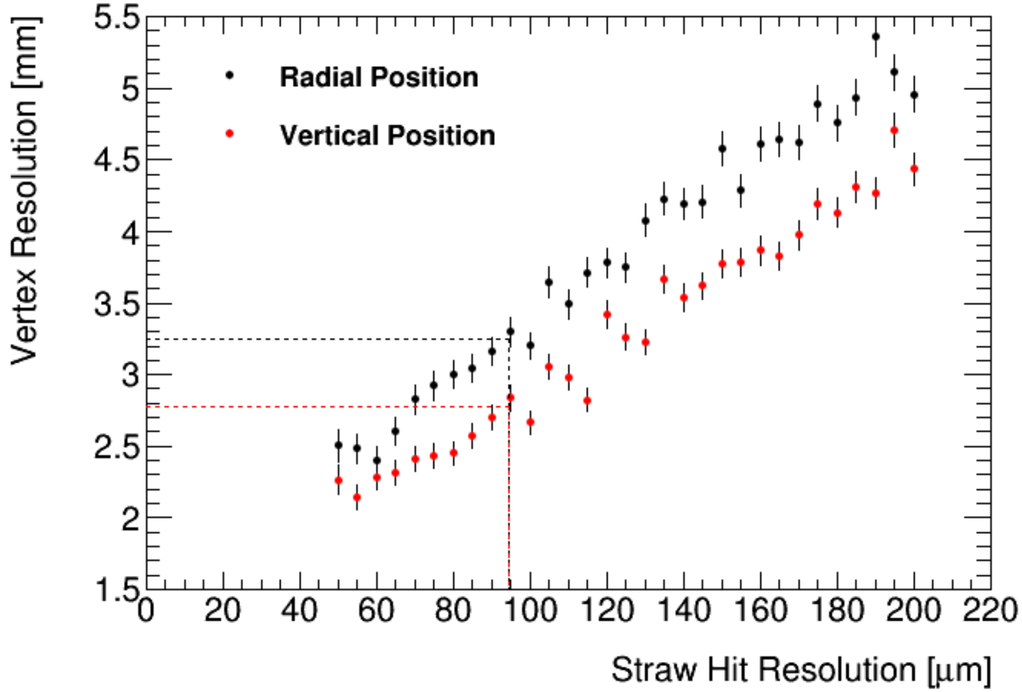
Stat. errors only

$$\langle y^2 \rangle^{S12}_{calc} = 153.2 \pm 0.1 \text{ mm}^2 \qquad \langle y^2 \rangle^{S18}_{calc} = 155.4 \pm 0.1 \text{ mm}^2$$

- Relatively small change from resolution (~8 ppb)

Vertex Extraction Resolution: Systematic

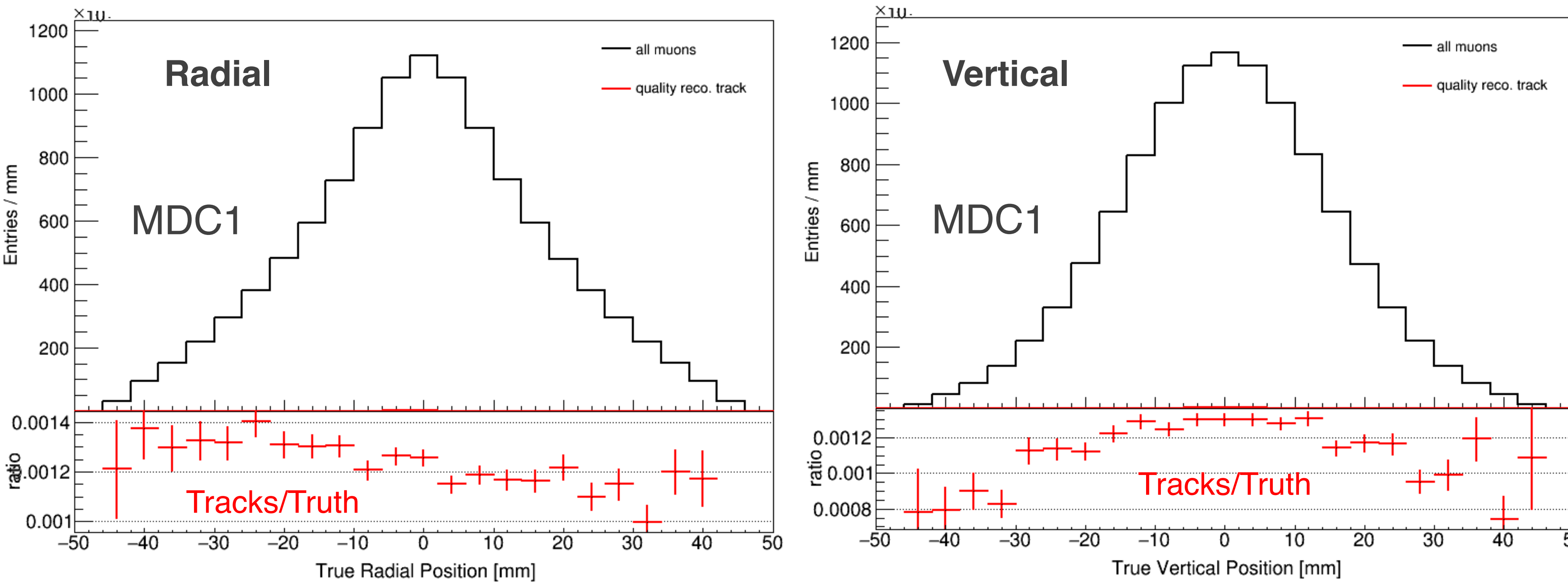
- How wrong could our resolution estimate be?



- Conservatively, I think we know our hit resolution to ~ 30 μm
- Vertical resolution known to 0.5 mm → $\Delta C_P = \pm 3$ ppb

Tracker to beam: acceptance

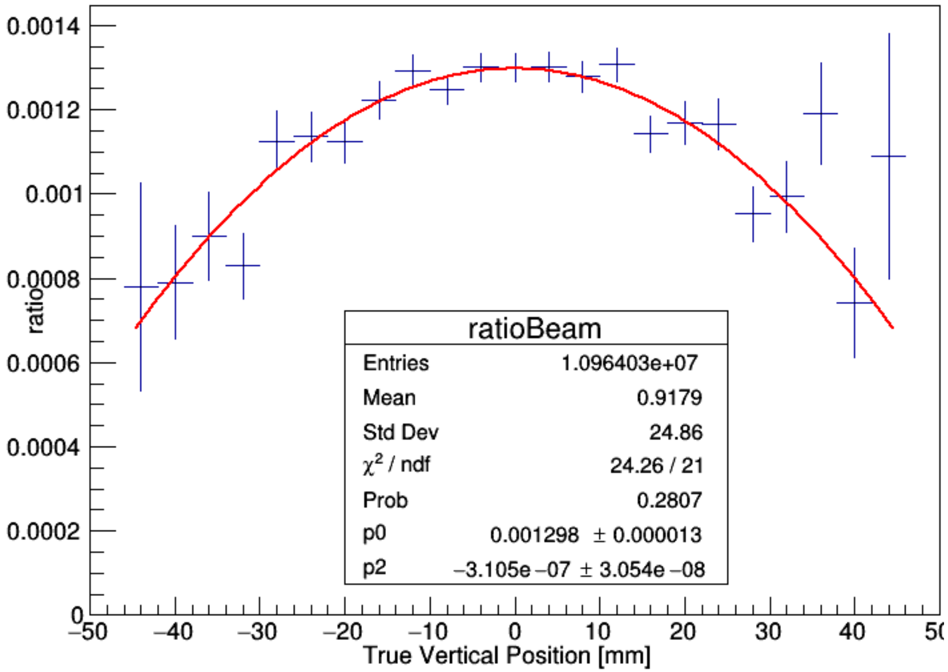
- How does what trackers measure compare to true beam?

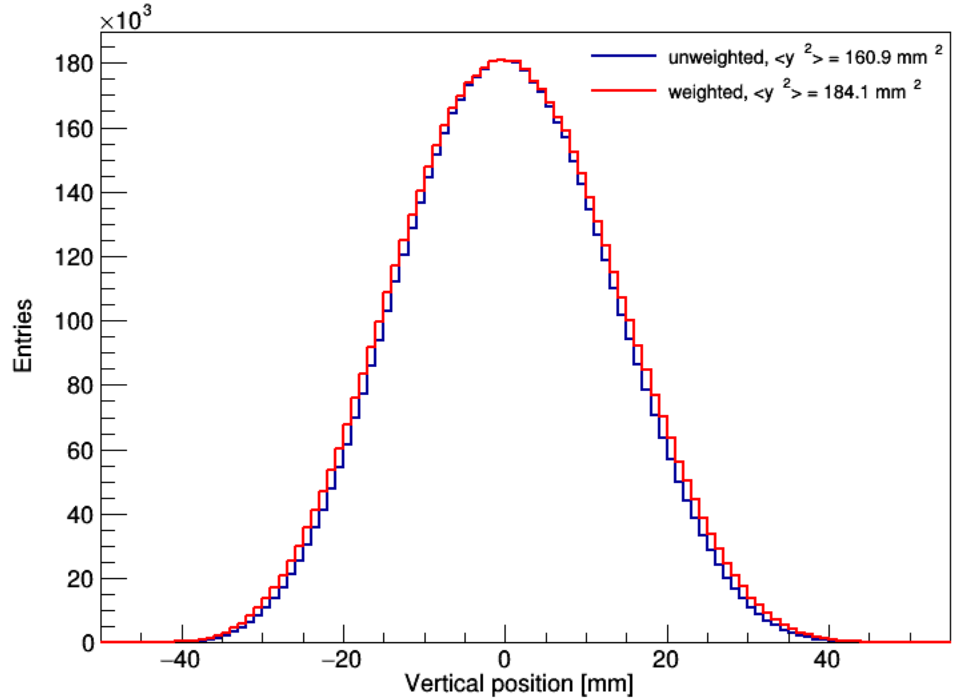


- See more tracks at lower radius (closer to tracker)
- See fewer tracks that decay near top and bottom of ring – means we underestimate vertical width

How much do we underestimate width?

- Take the tracker measurement and weight it by the acceptance curve (2nd order polynomial fit)





- $\langle y^2 \rangle$ increases from 161 to 184 mm² [14%]
- Including resolution increase is reduced by ~ 3 mm²
- Will correct for acceptance & resolution together

Remember
1 mm² ~ 1 ppb

Uncertainties Summary:

Systematic	C_p systematic [ppb]
Tracking	8.6 + ?
Vertex Resolution	3
Total	**9.1 + ?**

- Uncertainty excluding acceptance is ~10 ppb
- Acceptance correction itself will be less than 20 ppb with small error
- Simulation/Model uncertainty is also 10 ppb
- Total correction expected to be **~160 ± 15 ppb**.

Conclusions

- Systematics assessed for pitch correction
  – Straw stereo angle dominates
- Same uncertainties apply to convolution, radial component important
  – Assessment underway
- For $\omega_{a,}$ the tracker model is used for variation of field index throughout the fill
  – Uncertainties negligible compared to changes in beam dynamic frequency lifetimes