Emittance Exchange in MICE

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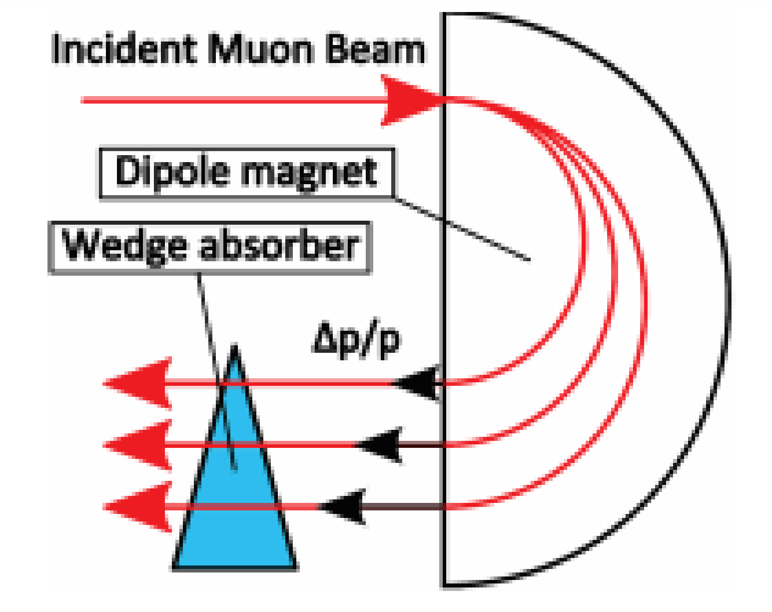
Aims



- Demonstrate Emittance Exchange and Reverse Emittance Exchange in the Wedge using MICE data
- Emittance Exchange can be demonstrated by looking at the change in phase space density of the particle selection before and after having passed through a Wedge absorber
- Emittance Exchange is shown by a decreased transverse phase space density (x, px, y, py) and increased longitudinal phase space density (z, pz), (and vice versa for Reverse Emittance Exchange)
- Can use a number of techniques to calculate phase space density: KDE, KNN, Voronoi Tessellations, etc.
- MICE beam only has a small natural dispersion → Use beam reweighing techniques to select beams with desired dispersion

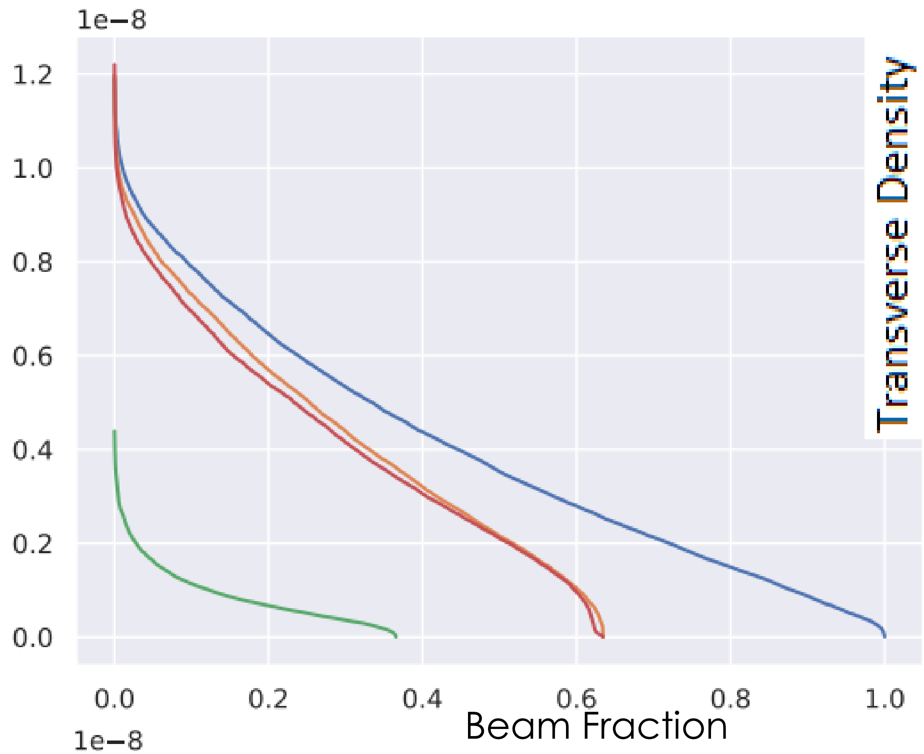
Previously

- Showed change in transverse phase-space density plots for various absorbers in two different ways. Both are however biased.

<u>Case 1: Biased by Transmission Losses</u>

- Cooling seen when the transverse downstream phase space density is greater than the upstream density.
- Bias is introduced by the missing particles being excluded from the downstream phase space volume calculation i.e comparing different volumes
- The current normalization doesn't account for the change in the particle distribution function.

Case 2: Biased by surviving beam particles



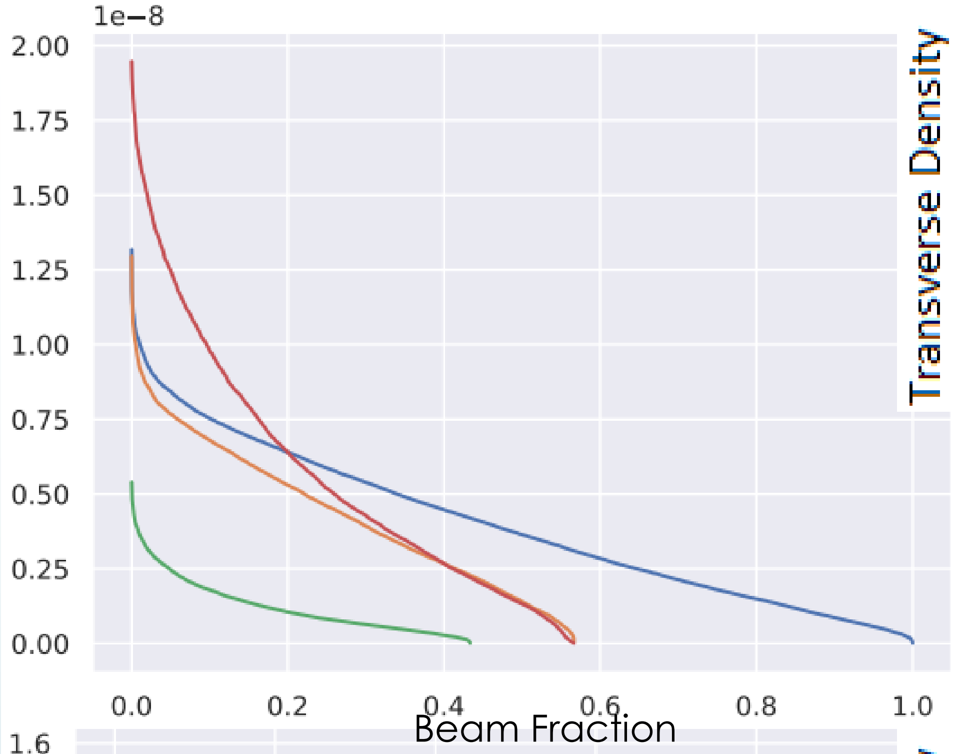
Fraction of beam above certain density

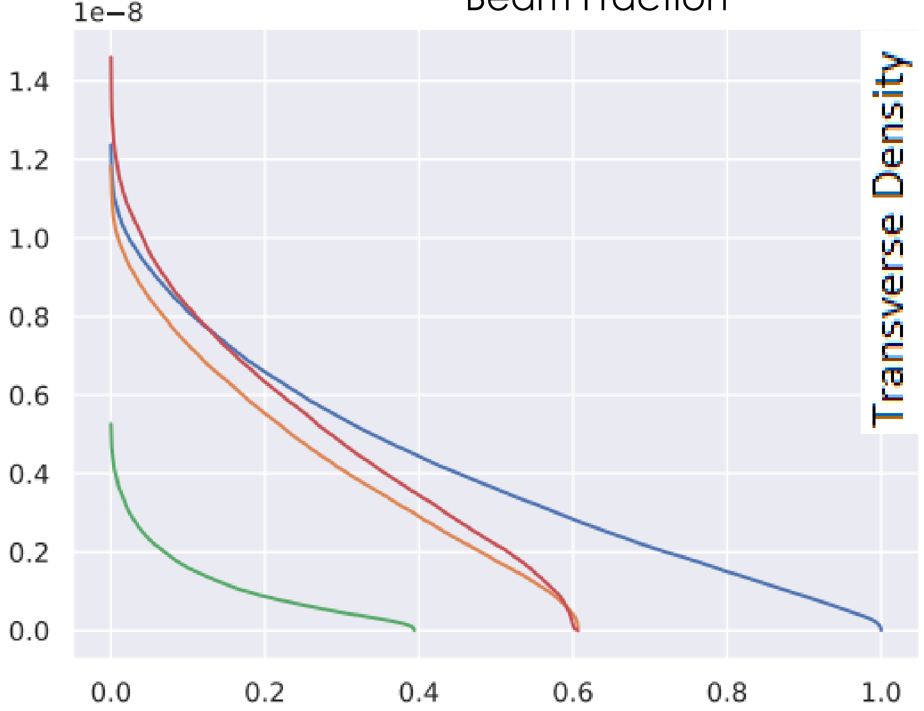
Top Left: No absorber

Top Right: Wedge

Bottom Left: LiH

Bottom Right: LH2



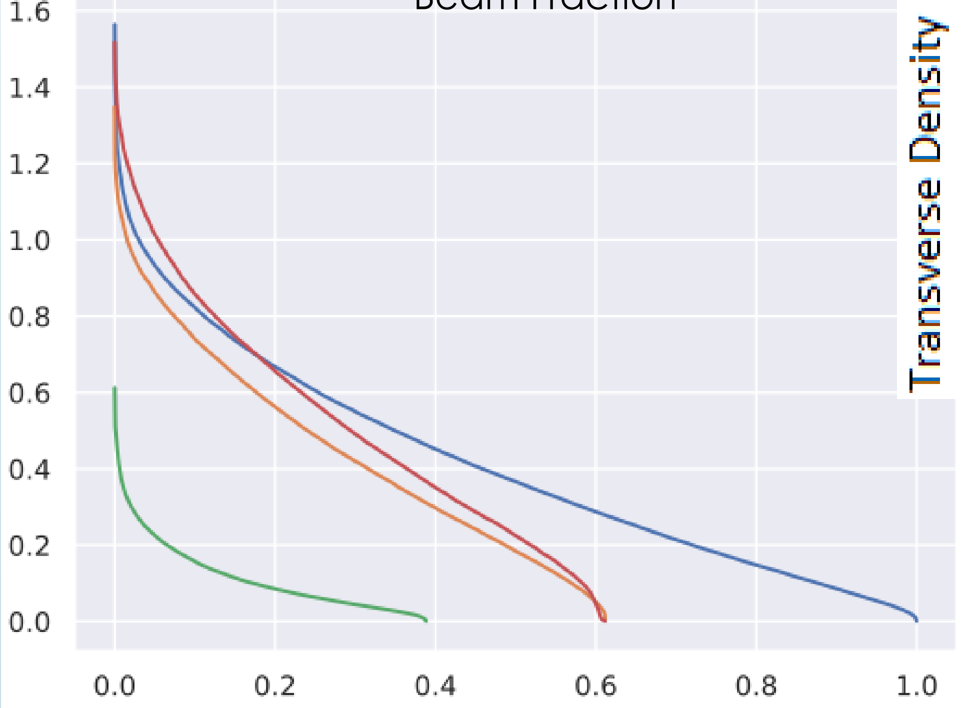


Blue – Full Upstream Sample

Red – Full Downstream Sample

Orange – Upstream Sample which made it Downstream

Green – Upstream Sample which doesn't make it downstream



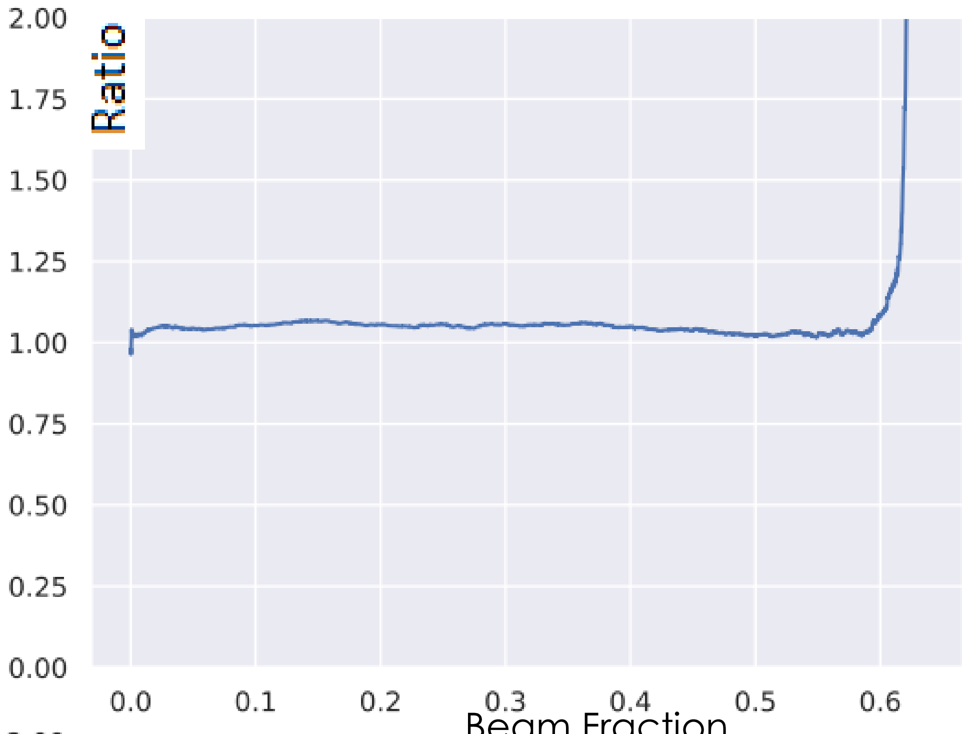
Previously

- Showed change in transverse phase-space density plots for various absorbers in two different ways. Both are however biased.

Case 1: Biased by Transmission Losses

Case 2: Biased by surviving beam particles

- The ratio of the downstream to upstream densities is a constant for the flat/no absorber case (expected when comparing same volumes)
- Lost particles are however excluded. Biased as it excludes some of the heating aspect



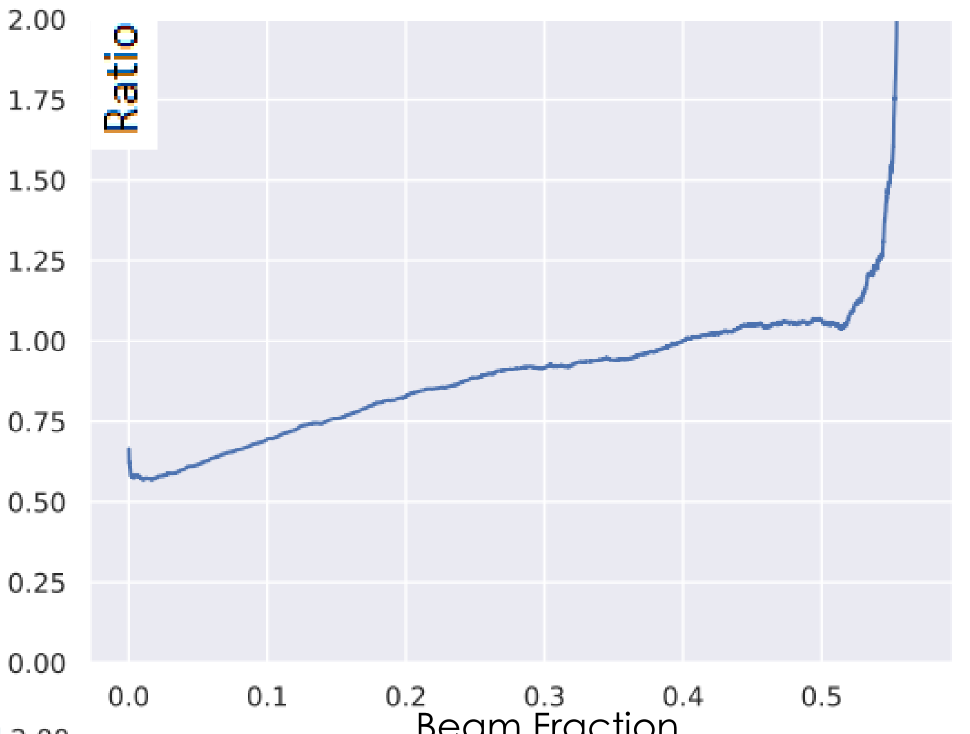
Ratio of the Downstream density to the Upstream density which makes it downstream

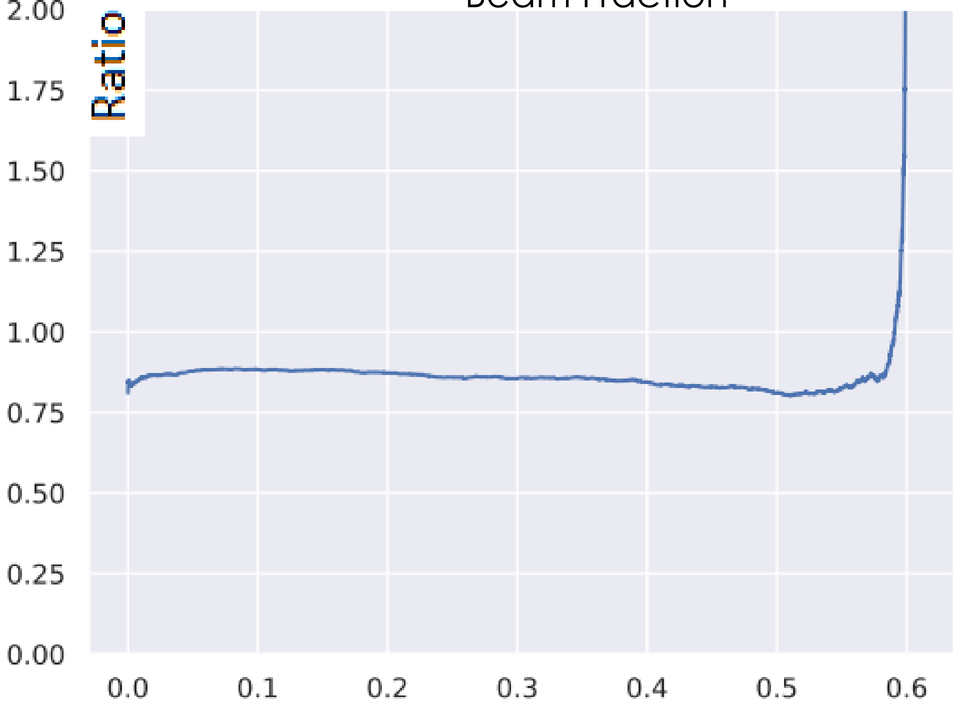
Top Left: No absorber

Top Right: Wedge

Bottom Left: LiH

Bottom Right: LH2

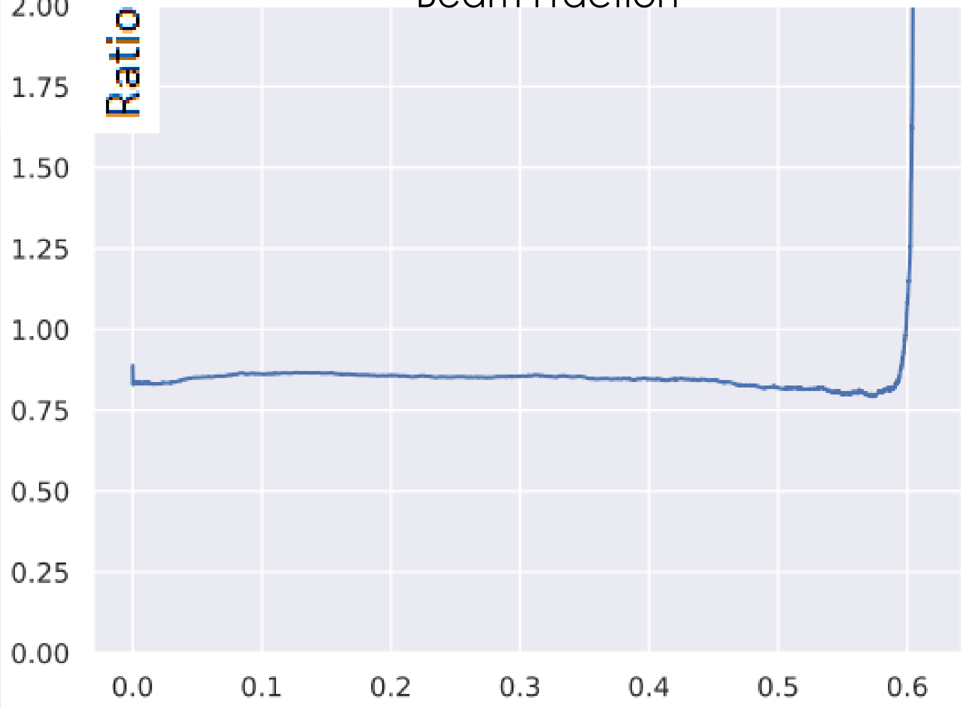




Ratio above one indicates heating while a ratio below one indicates cooling.

Transmission limits the beam to approximately 60% of the full upstream sample.

The min and max are limited by low sample size and scraping respectively



Classifying lost particles

- To get an unbiased result, the transmission losses need to be accounted for
- Will do this in terms of the no absorber case

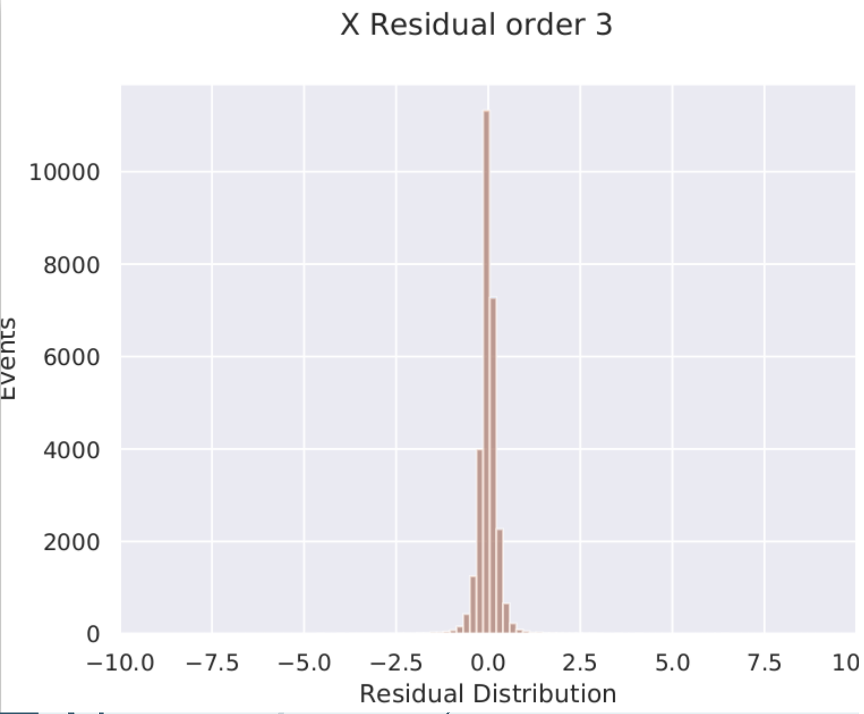
- Particles lost due to scraping of the aperture can be excluded as they are not relevant to the cooling performance of an absorber, they are only relevant to the experiment
- Particles lost due to Tracker inefficiencies can be excluded as they are missing completely at random (they should be)
- But it may be difficult to classify them e.g. if the propagated track is seen in some stations, but missing in others and doesn't pass all cuts
- Particles lost due to scattering with the absorber **cannot** be excluded. They are a source of heating, biasing the cooling performance.

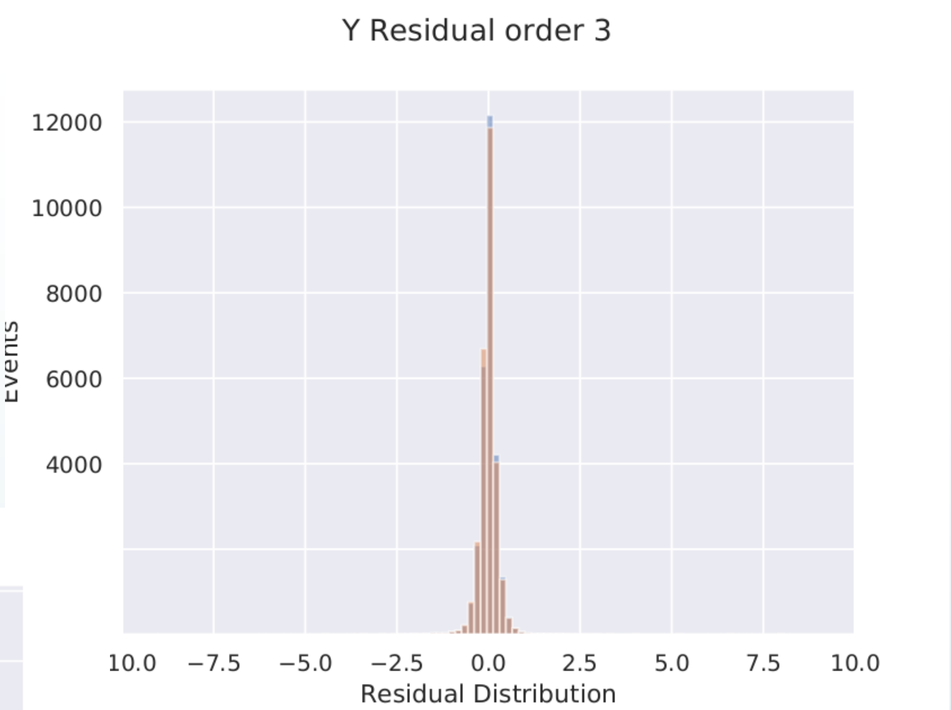
Classifying lost particles

- Lost particles will be propagated through the cooling channel (using Transfer matrix) to determine reason for loss. Should give tracker efficiency which is a source of error (Minor), but mostly used to safely reject scraped particles.
- For the absorber case, will propagate particles as if there were no absorber. This will identify particles not making it downstream due to scattering in the absorber.
- Investigation is to determine if there is a stable Transfer matrix for increasing beam fraction size, that can then be used to analyse the missing particle sample

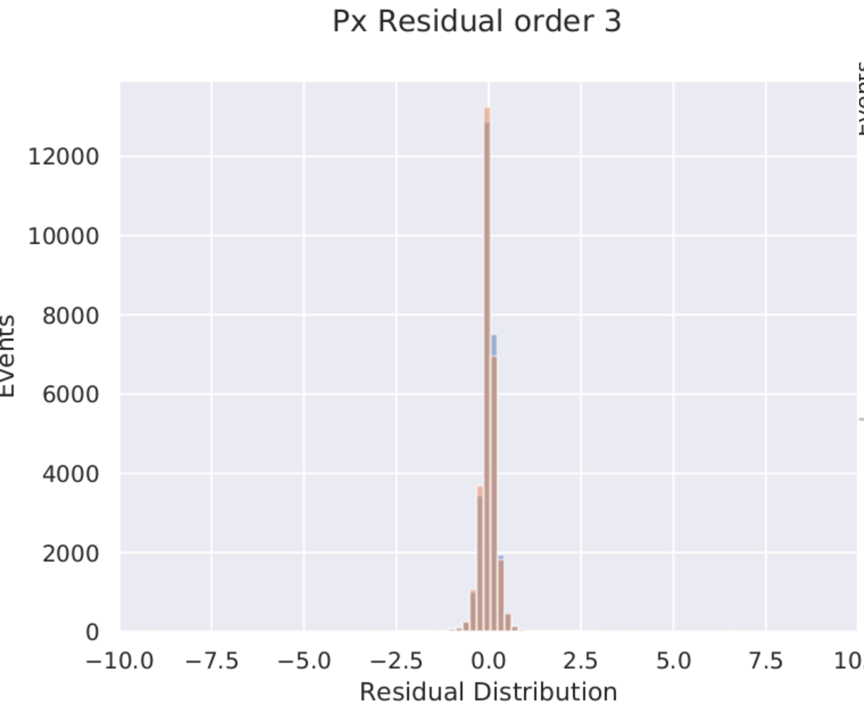
Sample case from TKU S2 to TKU S1

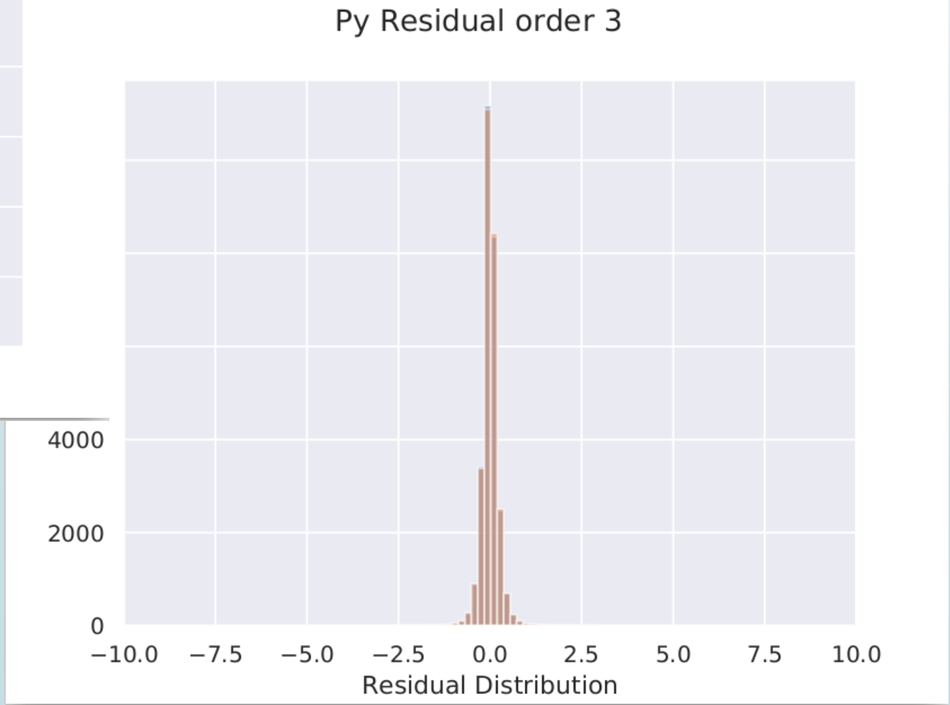
- Last analysis meeting, showed plots for a third order transfer matrix from TKU S2 to TKU S1 excluding ~1% of highly scattered particles, decays, etc, i.e. highly deviating particles.
- Applied transfer matrix to independent sample, and showed residuals from through position
- Residuals were on par with width of scintillating fibre
- Idea is to extend this for further distances and determine performance of transfer matrix from upstream to downstream.


X Residual order 3
Events
Residual Distribution


Y Residual order 3
Events
Residual Distribution


Pz Residual order 3
Events
Residual Distribution


Px Residual order 3
Events
Residual Distribution


Py Residual order 3
Residual Distribution

Concerns

- Advised results are too optimal due to Kalman actually pulling the spacepoints to desired location. Transfer matrix working too optimally by default.
- Not sure I agree (yet), as trackpoints should not be pulled beyond fibre width (and pulls be perhaps Gaussian like), although there may be inherent biases in trackpoint calculation

- Began investigating spacepoints and trackpoints
- Transfer matrix should apply on spacepoints just as on trackpoints.
- Became concerned about Kalman implementation as it is supposedly highly sensitive to the seed position, and the Pz discrepancy. Transfer matrix will be compromised by wrong Pz, but likely only a larger error.

Trackpoints and Spacepoints

- Trackpoints are in a global reference frame
- Spacepoints are in a local reference frame
- Local coordinates are transformed to global coordinates by taking account of tracker misalignments
- **Residuals between local Spacepoints and Global Trackpoints should be straight lines of each tracker misalignment**
- Residual between Global Spacepoints and Global Trackpoints at each station should be random unless there is an inherent bias

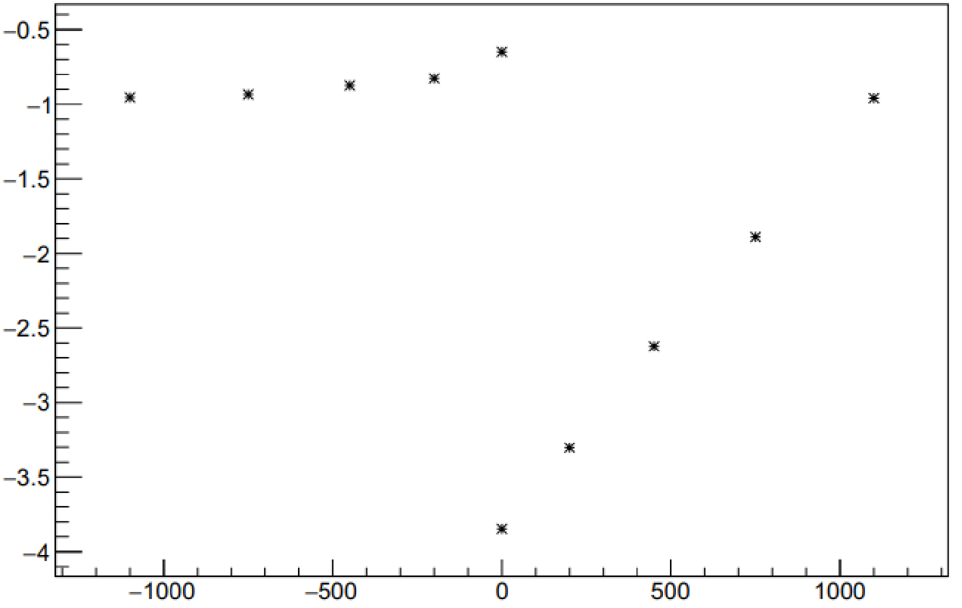
X Residual

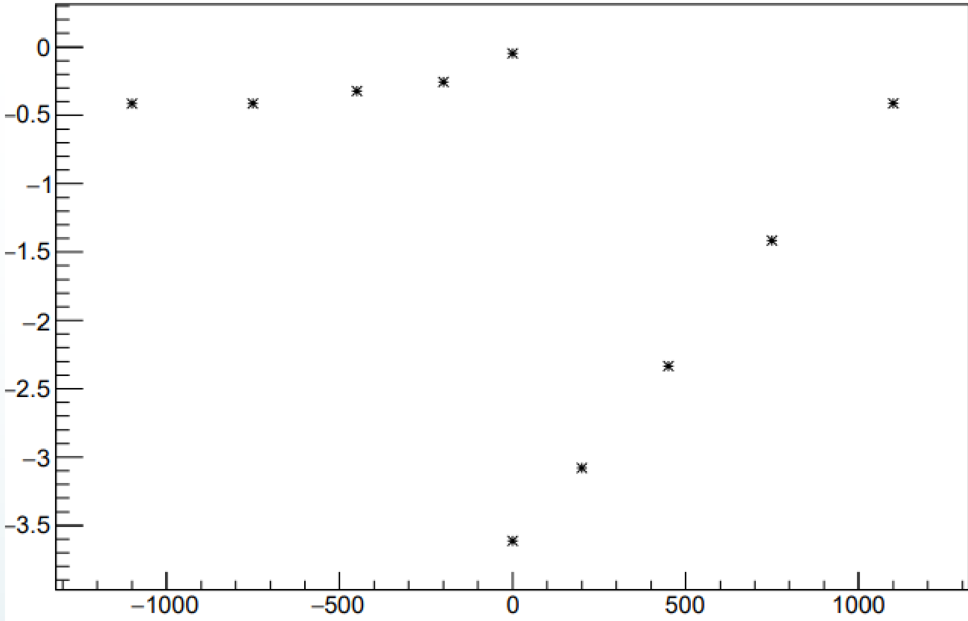
X Axis: Local Station Coordinates (mm)
Y Axis: Residual (mm)

Top Left: No absorber
Top Right: Wedge
Bottom Left: LiH
Bottom Right: LH2

X Residual is between Global X position Track point and local X position Space point

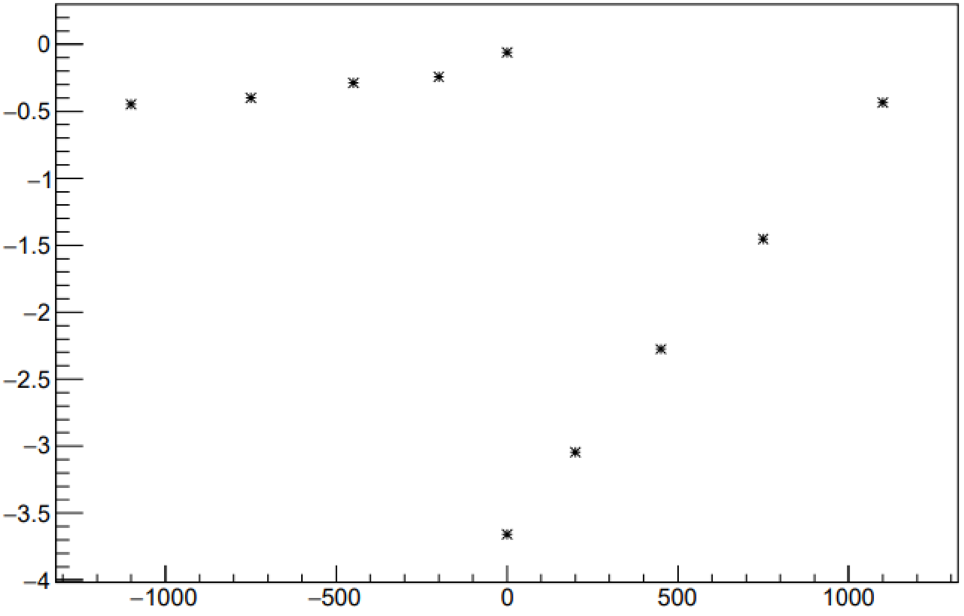
Residual should simply show the input Tracker misalignment. Should it be equal?

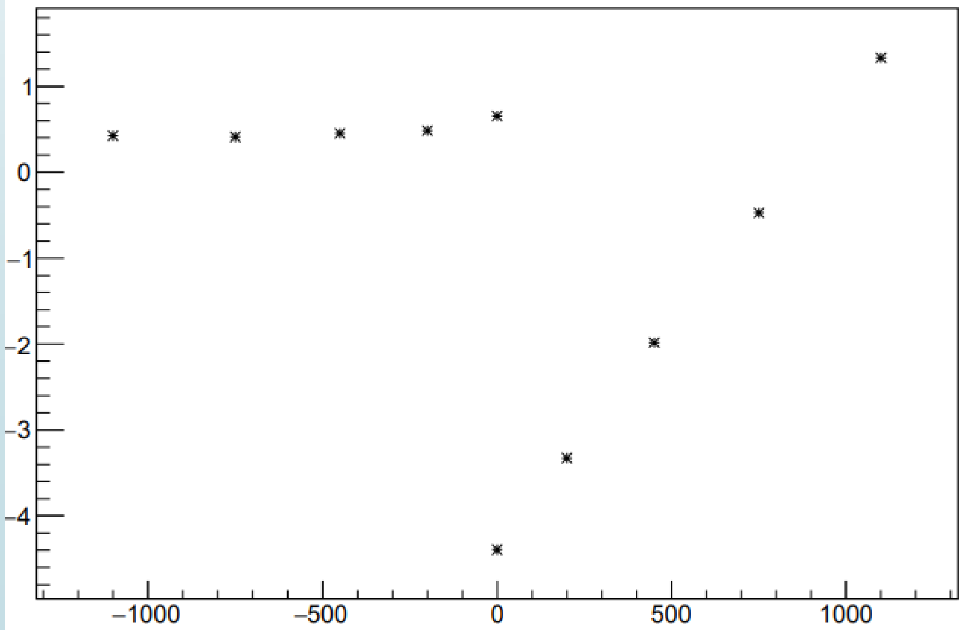




TKU TKD

TKU TKD





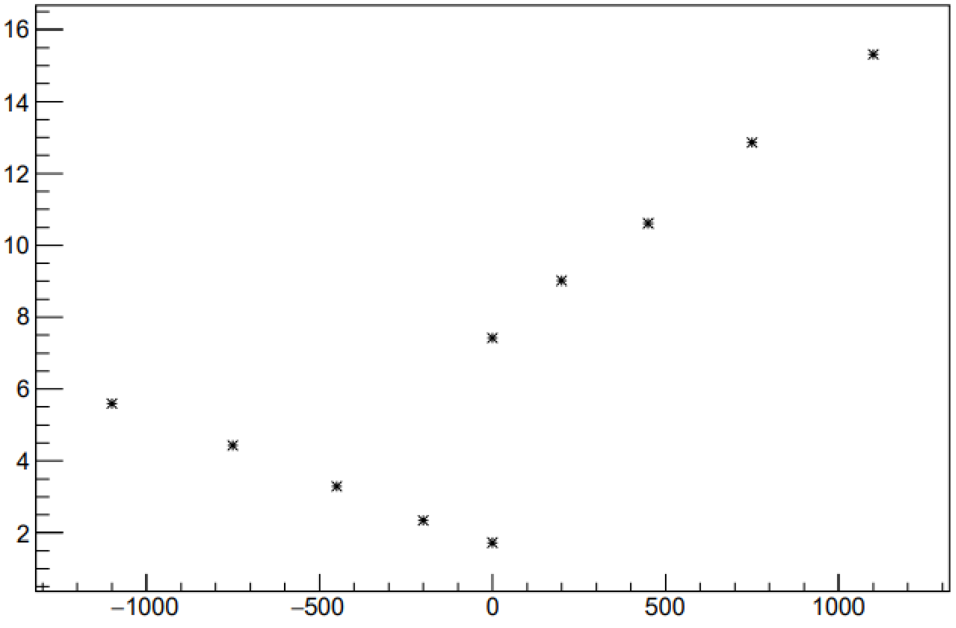
Y Residual

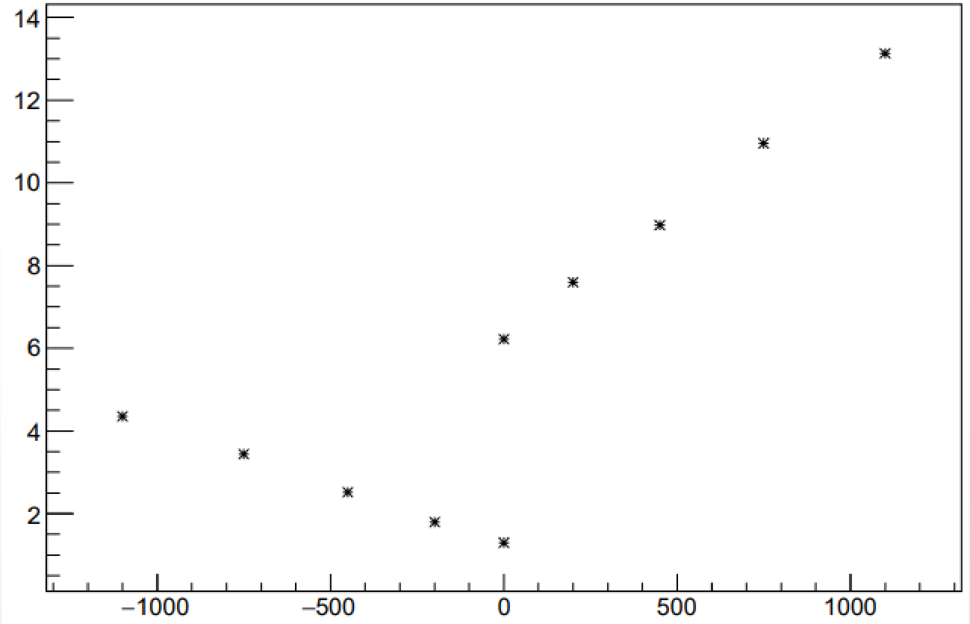
X Axis: Local Station Coordinates (mm)
Y Axis: Residual (mm)

Top Left: No absorber
Top Right: Wedge
Bottom Left: LiH
Bottom Right: LH2

Y Residual is between Global Y position Track point and local Y position Space point

Residual should simply show the input Tracker misalignment. Should it be equal?





TKU TKD

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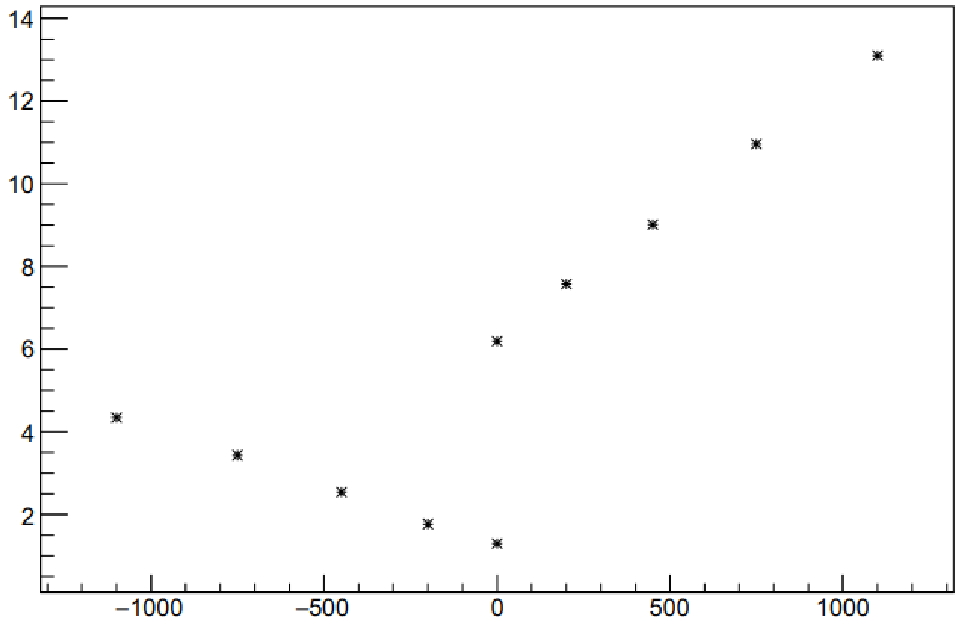

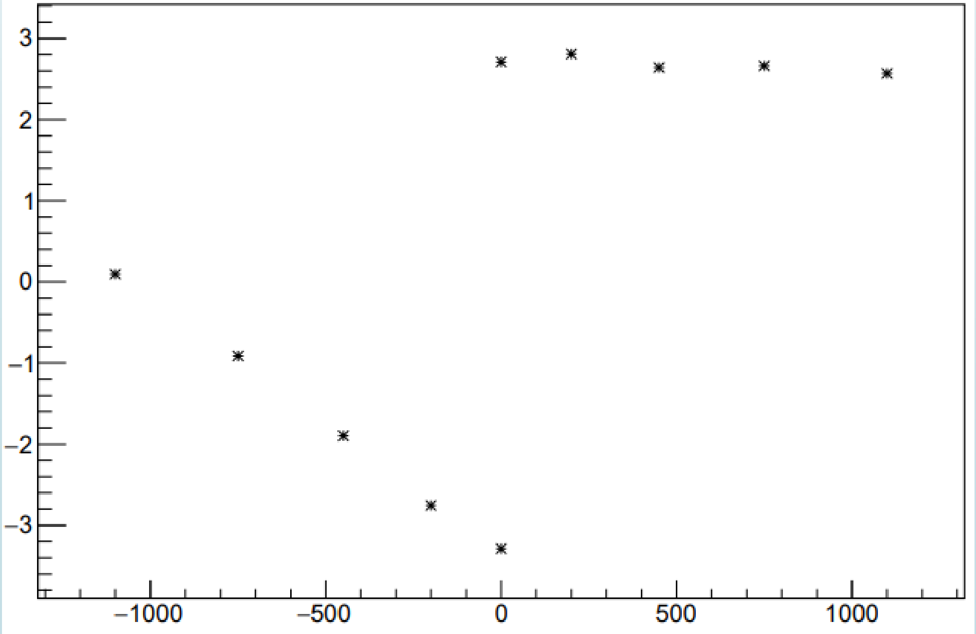

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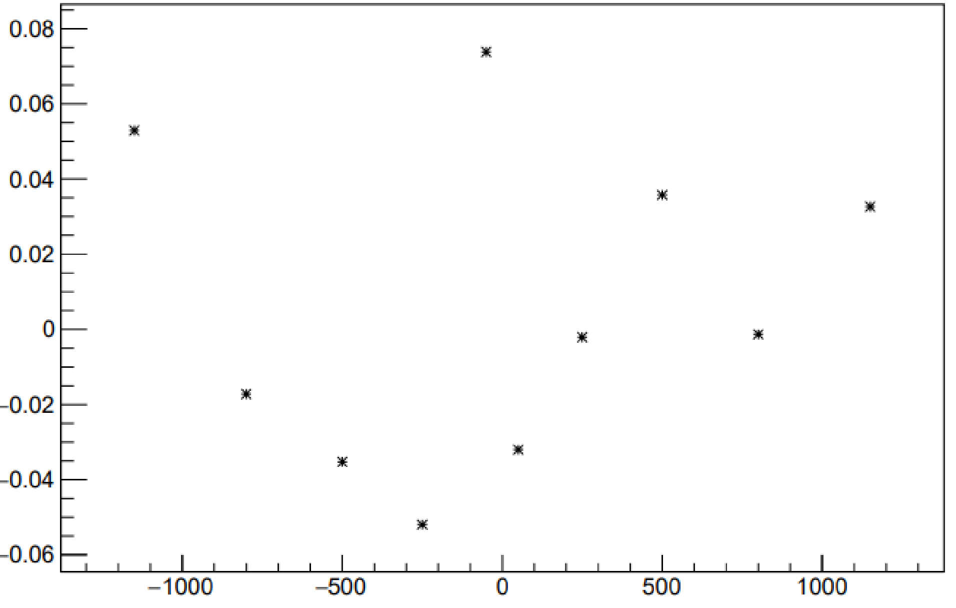
- **Residual between Global Spacepoints and Global Trackpoints at each station should be random unless there is an inherent bias**



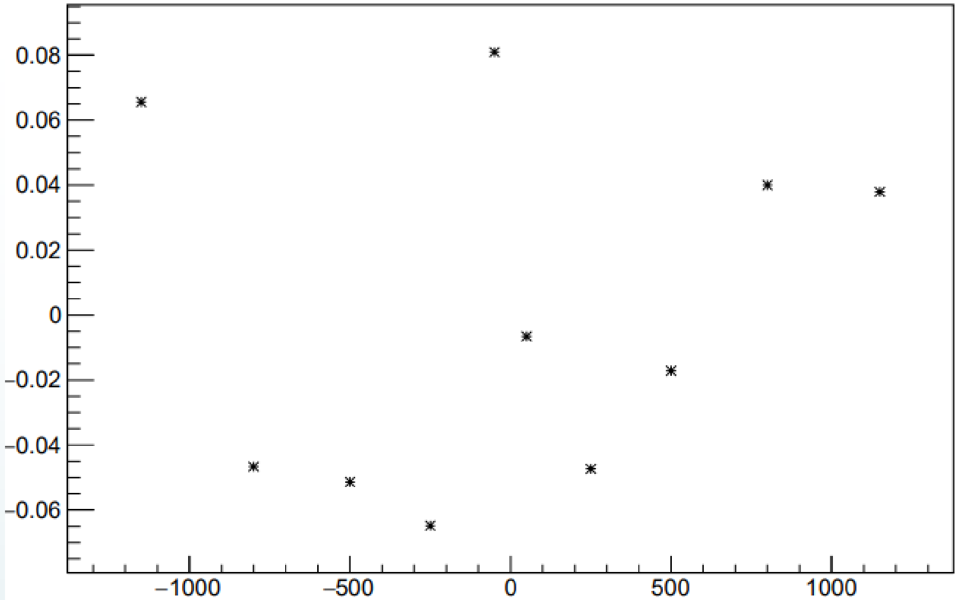
X Residual Global

X Axis: Local Station Coordinates (mm)
Y Axis: Residual (mm)

Top Left: No absorber
Top Right: Wedge
Bottom Left: LiH
Bottom Right: LH2

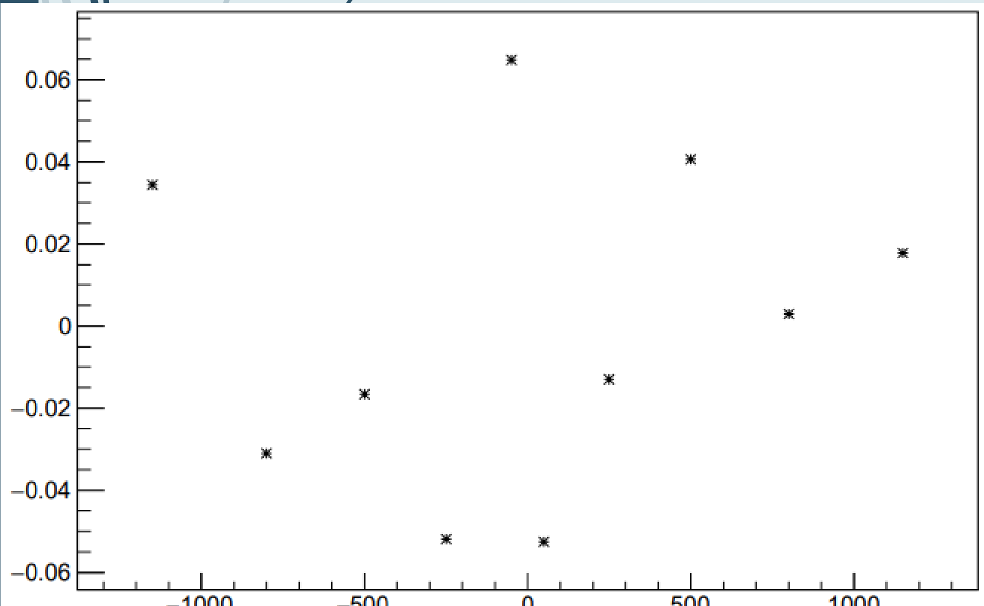
X Residual is between Global X position Track point and Global X position Space point (+/- 50 mm Offset introduced for TKU and TKD respectively)

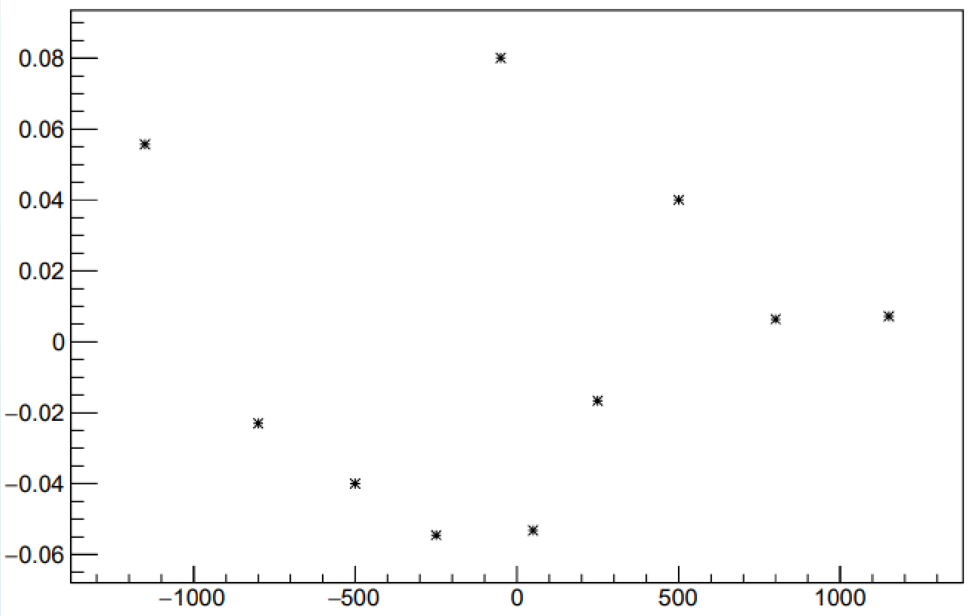
If there is no inherent bias, they should be randomly distributed

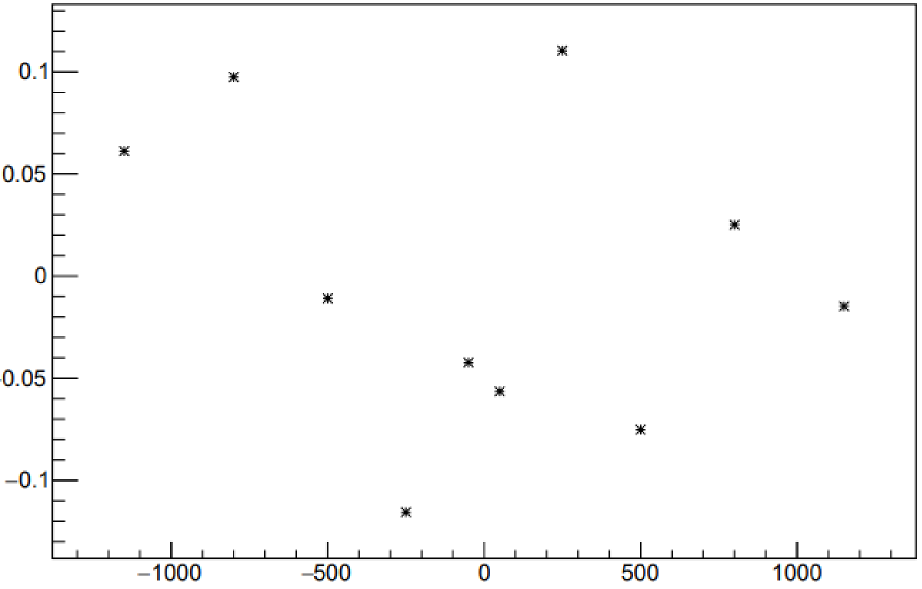


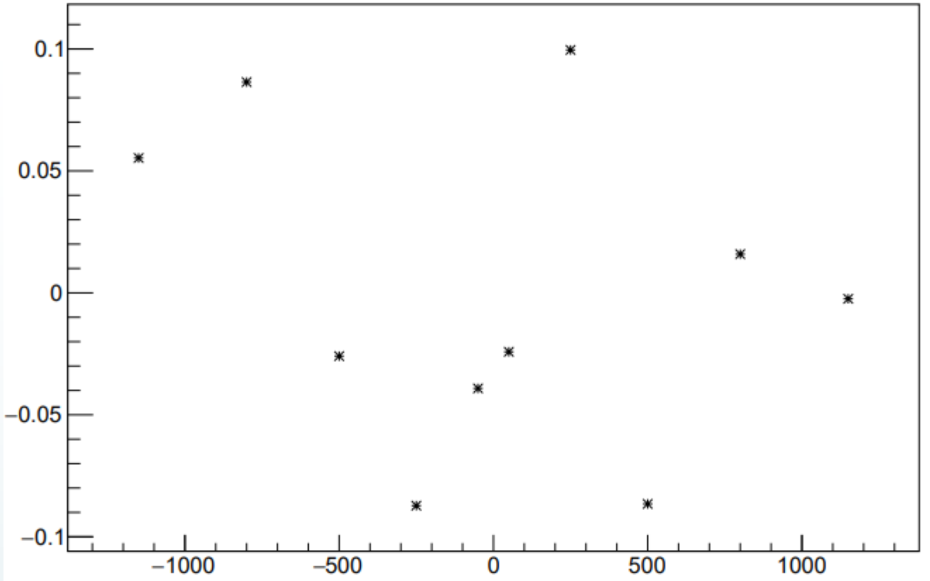
TKU TKD

TKU TKD









Y Residual Global

X Axis: Local Station Coordinates (mm)
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Top Left: No absorber
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TKU TKD

TKU TKD

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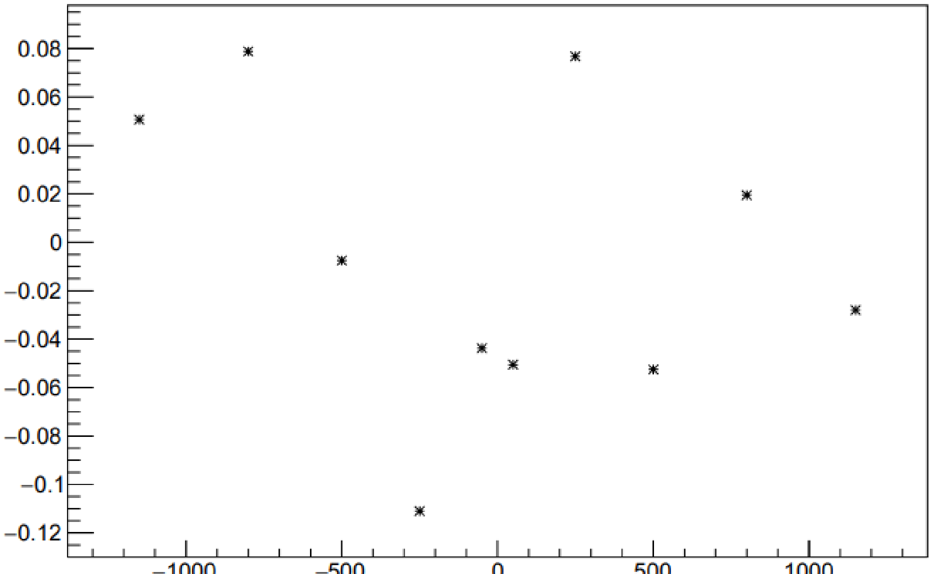
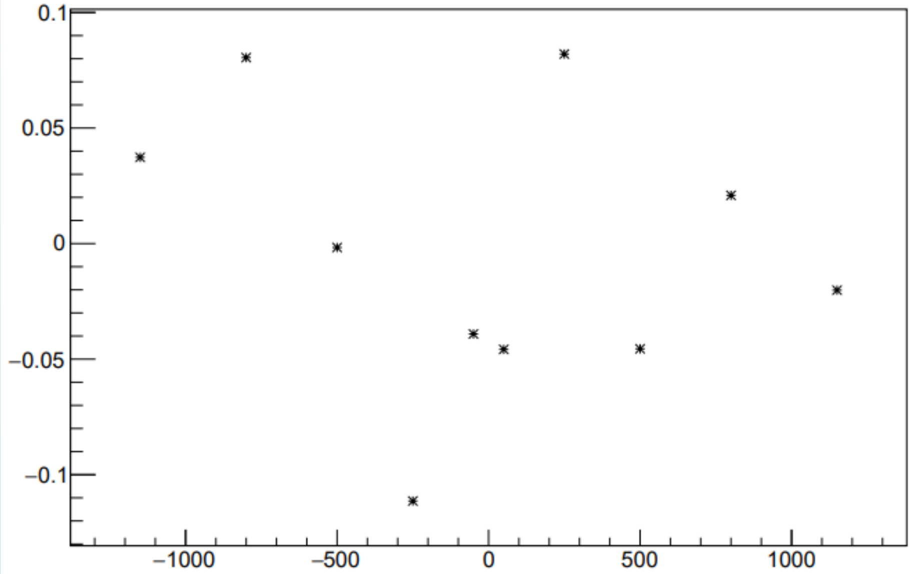
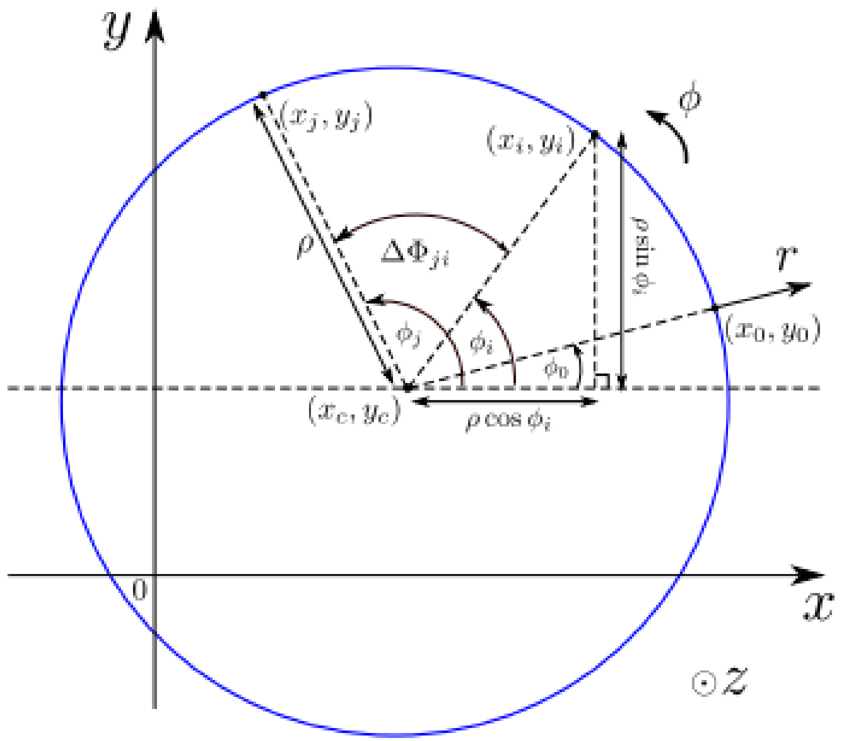
If there is no inherent bias, they should be randomly distributed

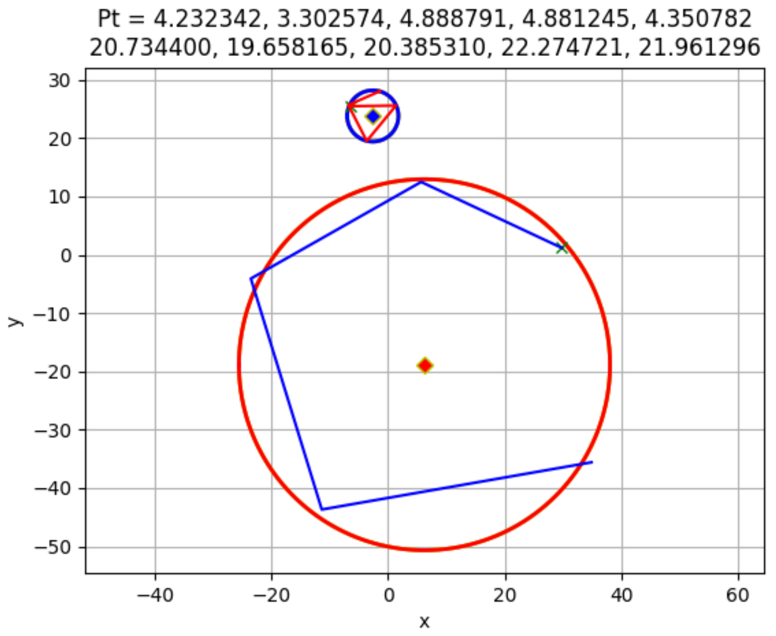




Circle Fit of spacepoints

- Currently spacepoints are fitted to a circle, accepted if χ^2 are small enough
- A straight line is also made in s-z plane, accepted if it passes Roadcut
- Radius of circle determines transverse momentum i.e. ~ $p_t = cBQR$
- Longitudinal momentum determined through $^{p_z}/_{p_t} = {}^{\Delta z}/_{R\Delta\varphi}$
- For circle fit R and p_t doesn't change until Kalman does its smoothing. Therefore p_z is determined mostly by the phase advance until it is Kalman smoothed
- Kalman is sensitive to the seed position, so the question is how the seed position is determined and used (haven't figured it out yet)



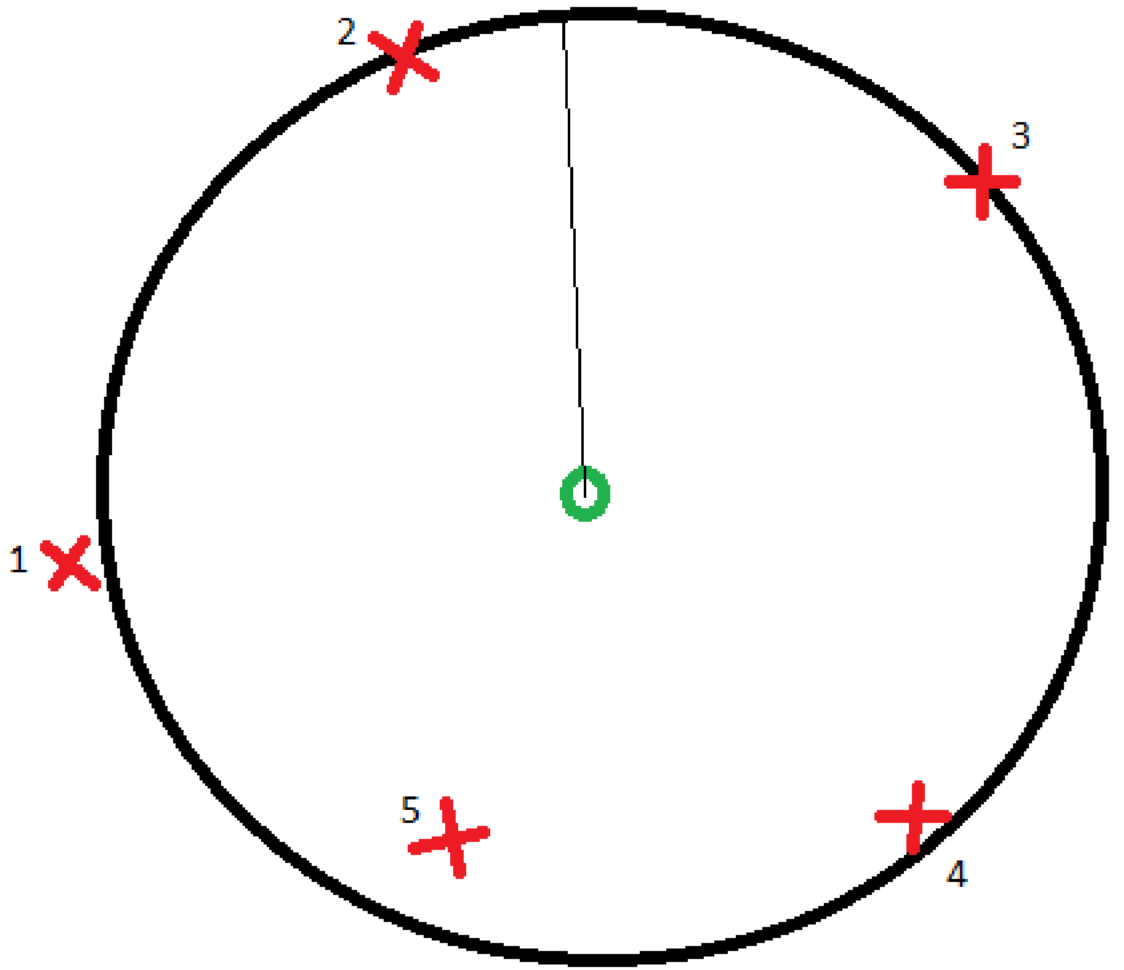


Path of particle in ideal solenoid

- If there is no Energy Loss, then the particle will follow a constant radius path
- If there is a constant Energy Loss with no scattering, then the particle will spiral towards a centre with radius $r = a\varphi$, where φ is the turning angle and a is angle of the polar slope (between tangent and polar circle, dictates expansion of spiral).
- dE/dx is fairly constant through the stations as the Energy Loss is small (or as implemented by MAUS)
- In MICE we have 5 stations per tracker. Between stations the particles follow a helical path (with no Energy Loss, assume perfect vacuum) and are deviated at the station.
- At the station, Energy Loss occurs, and the particle is deviated to a lower radius path but remains tangential to the circle centre unless scattered.
- This in turn creates a new circle centre along the radial path. The radius change is proportional to the Energy Loss.

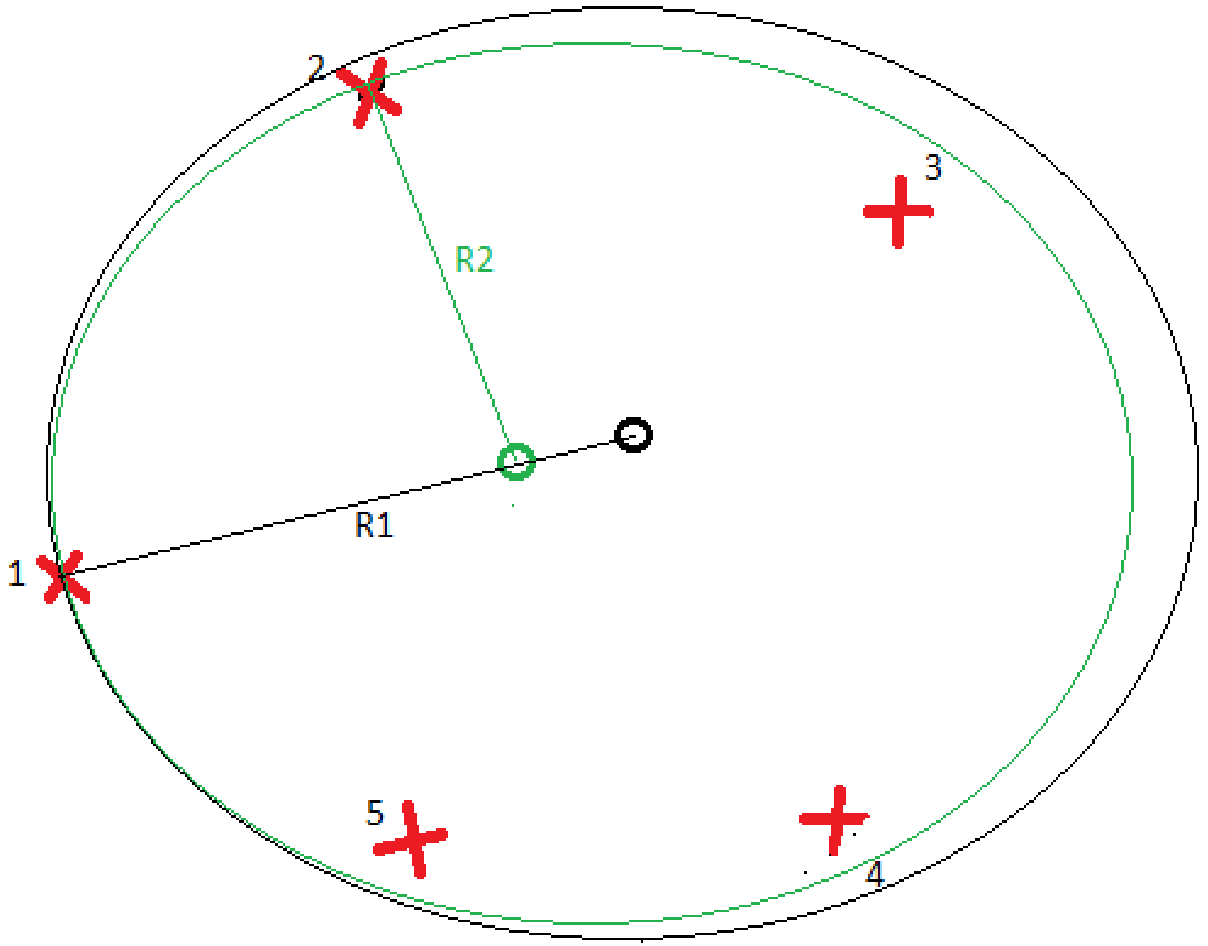
Exaggerated case – not to any scale

Circle fit radius of five stations



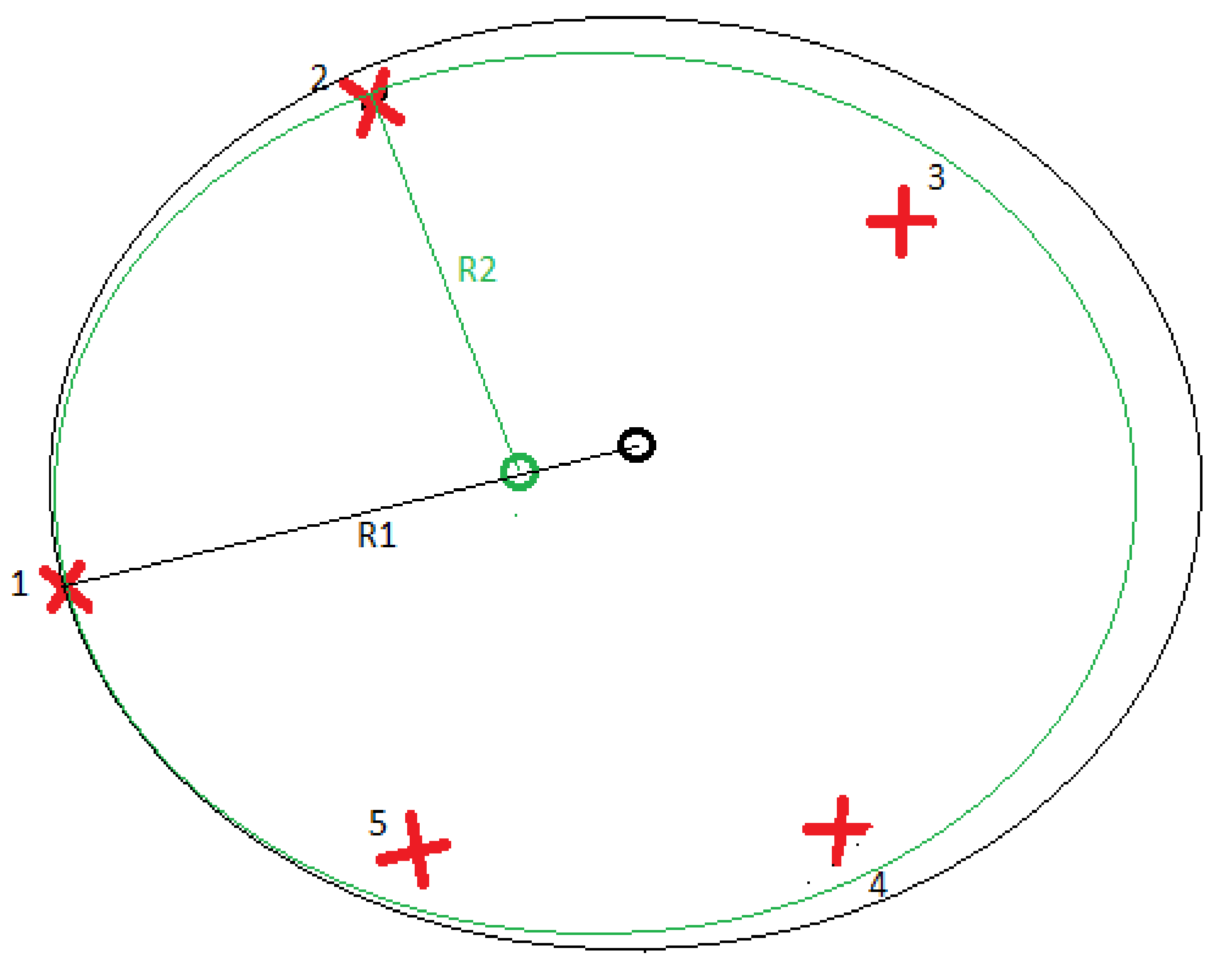
R1 true radius of initial particle

R2 true radius of particle after Energy Loss through 1st station, with new centre

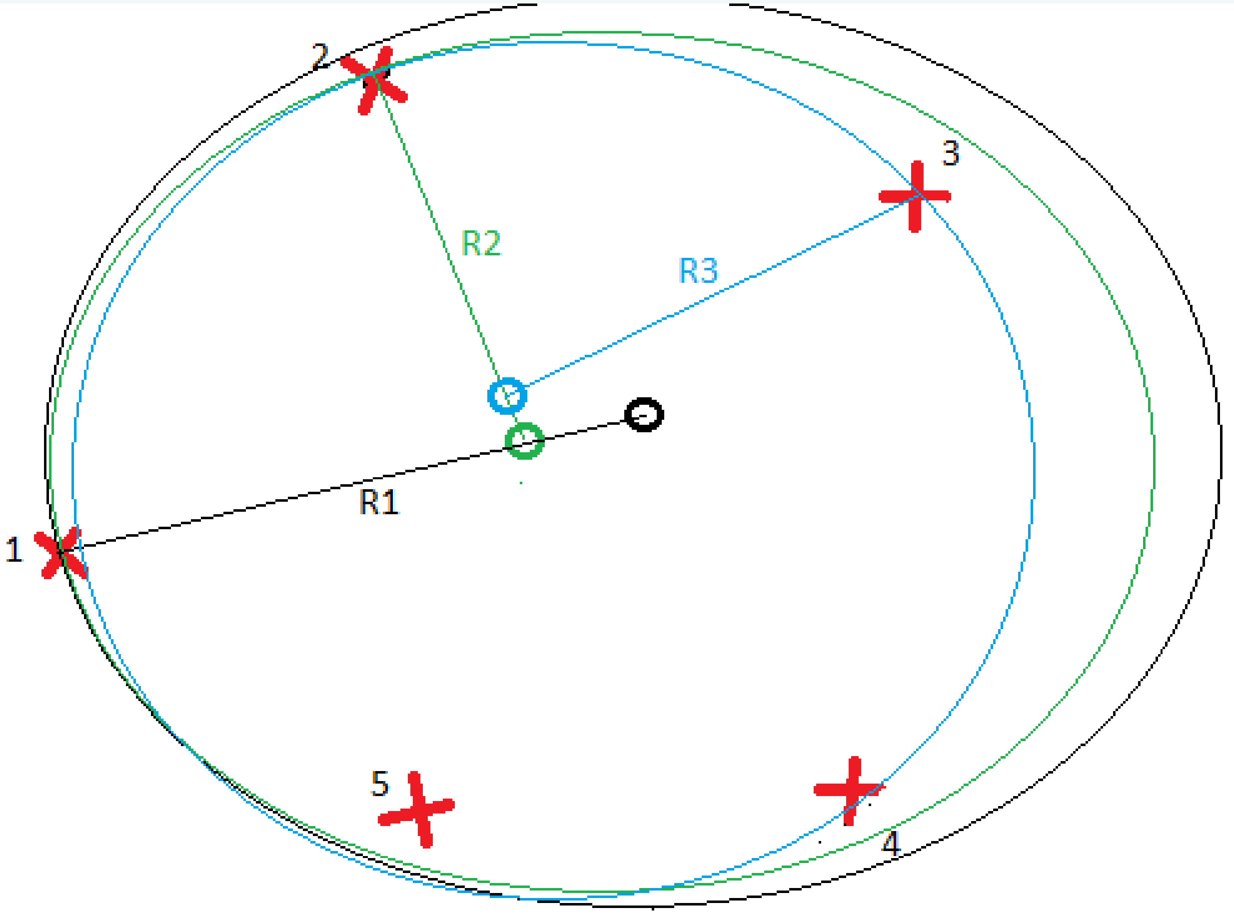


Before Station 2 to after Station 2

R2 true radius of particle after Energy Loss through 1st station, with new centre



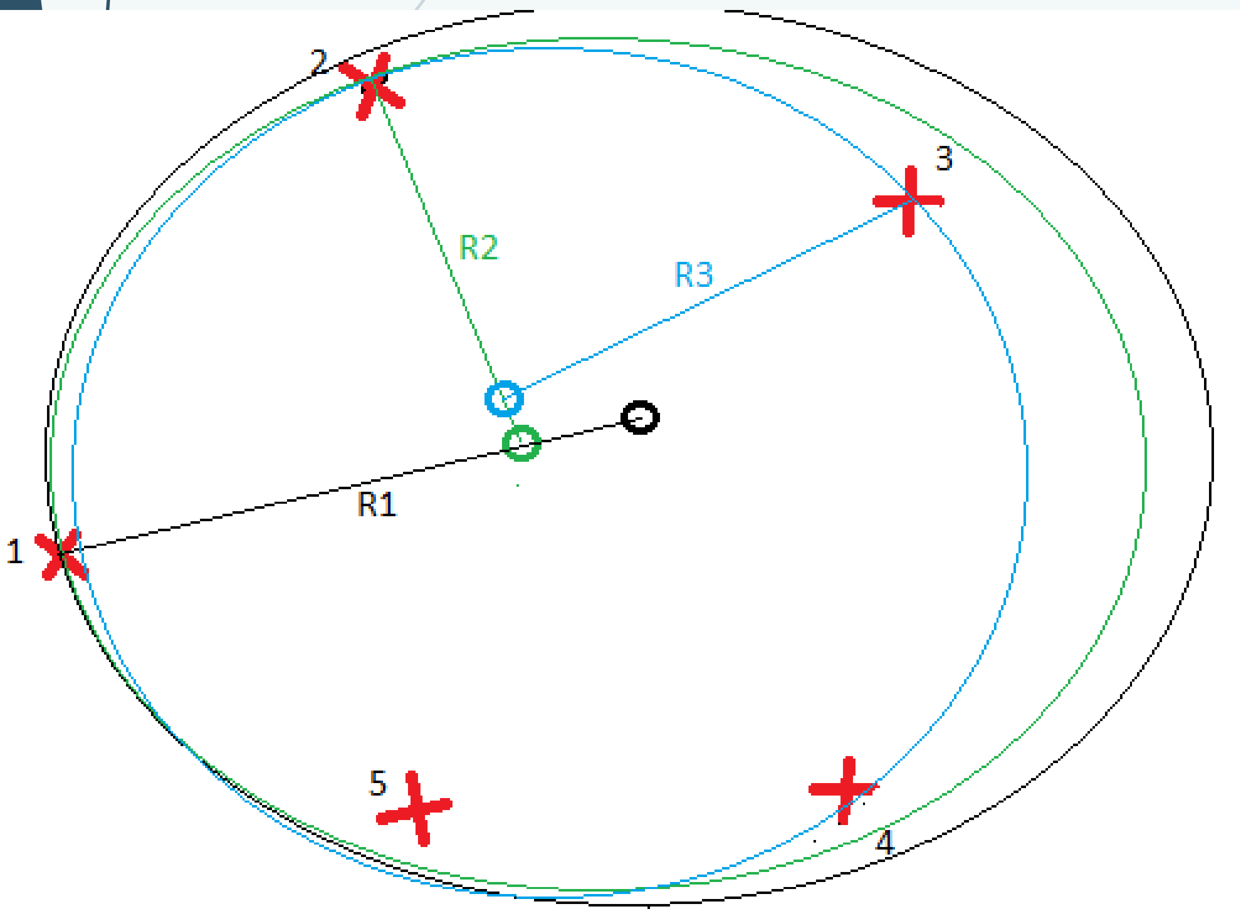
R3 true radius of particle after Energy Loss through 2nd station, with new centre

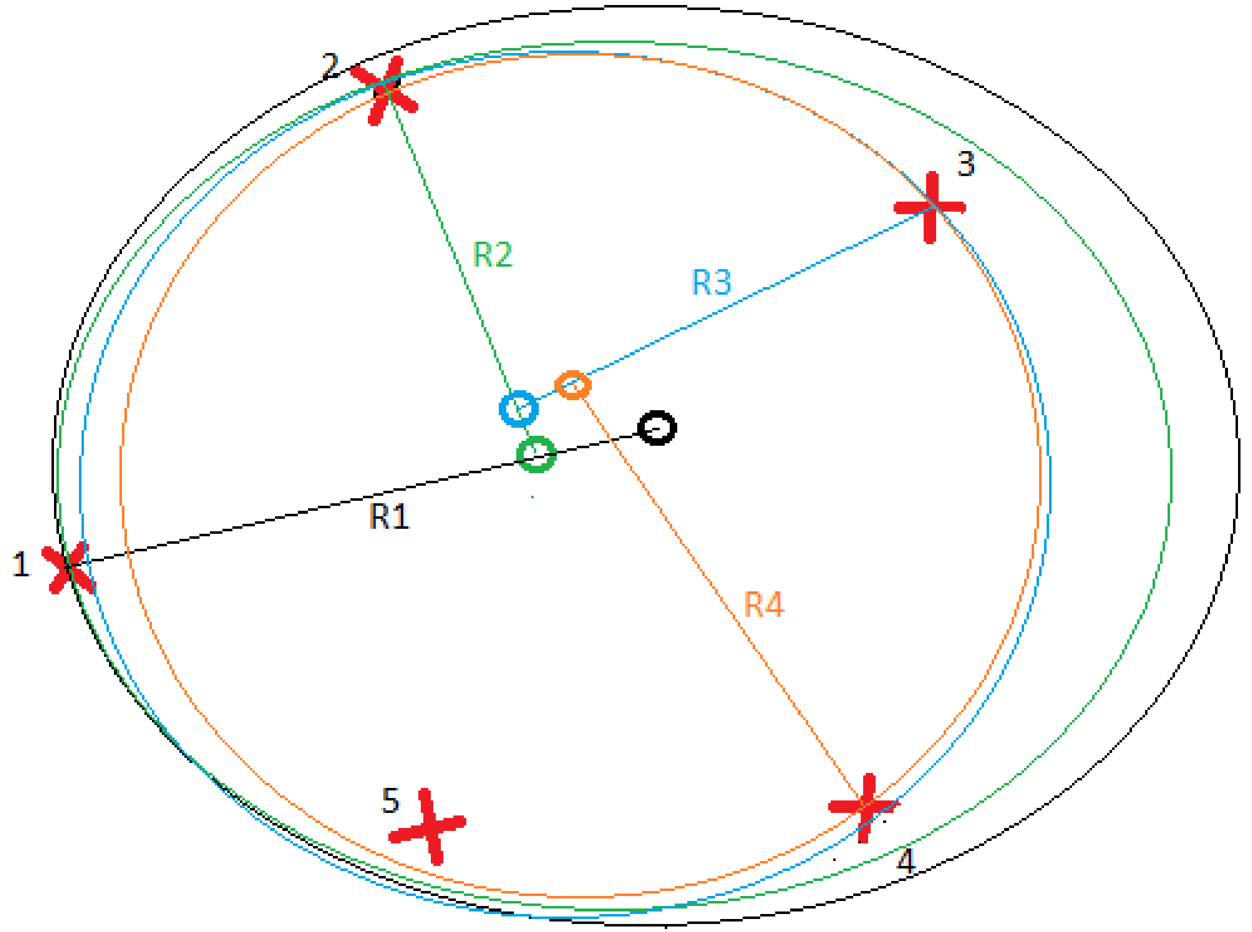


Before Station 3 to after Station 3

R3 true radius of particle after Energy Loss through 2st station, with new centre

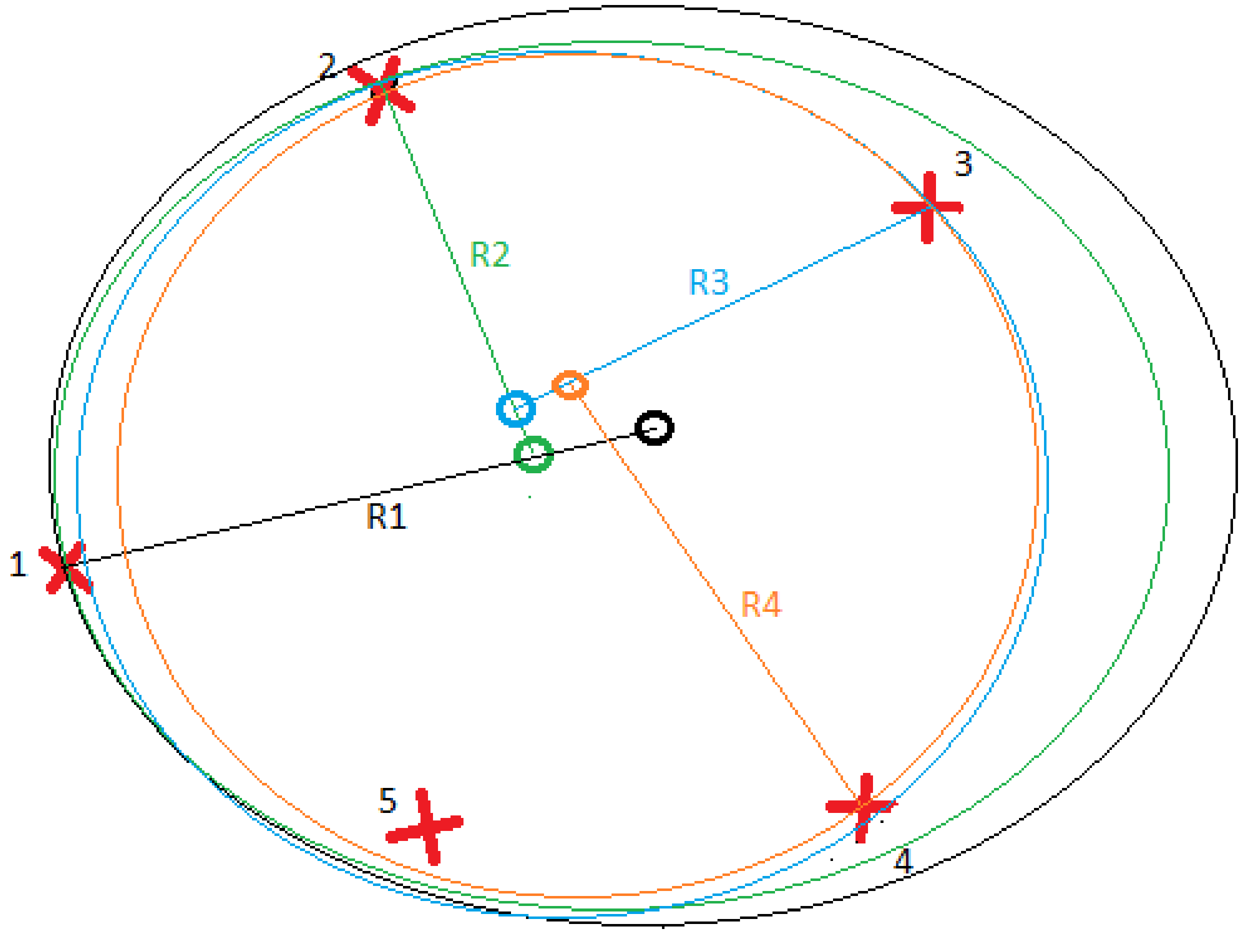
R4 true radius of particle after Energy Loss through 3rd station, with new centre



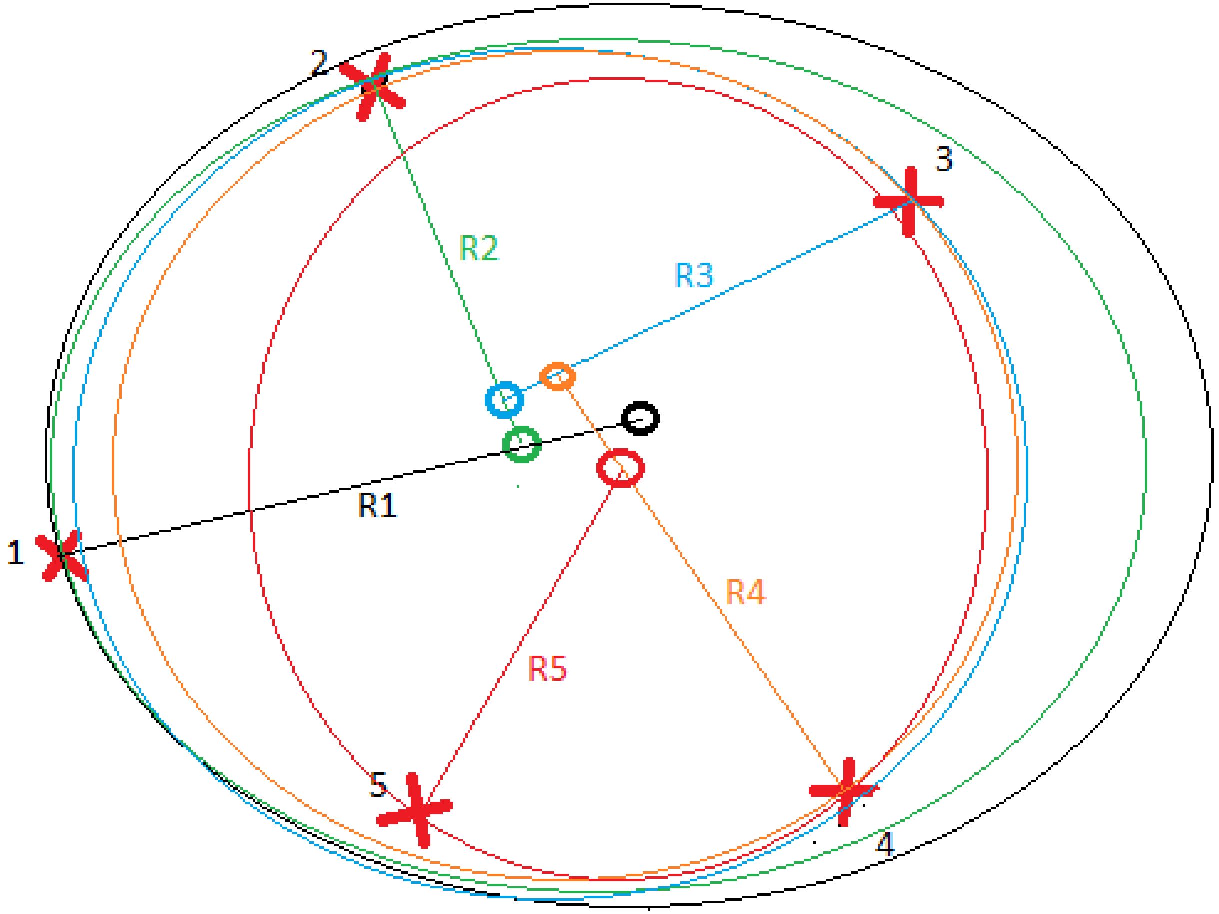


Before Station 4 to after Station 4

R4 true radius of particle after Energy Loss through 3rd station, with new centre

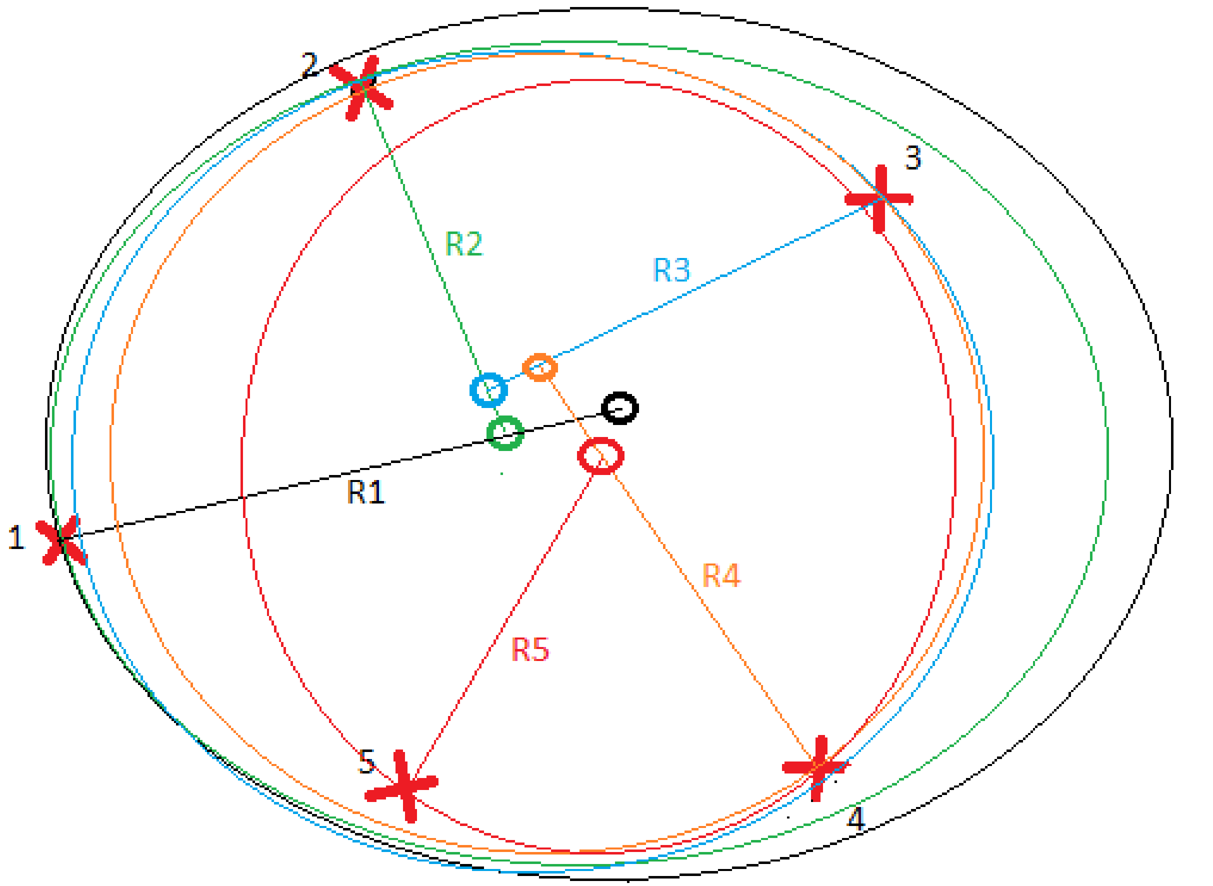


R5 true radius of particle after Energy Loss through 4th station, with new centre

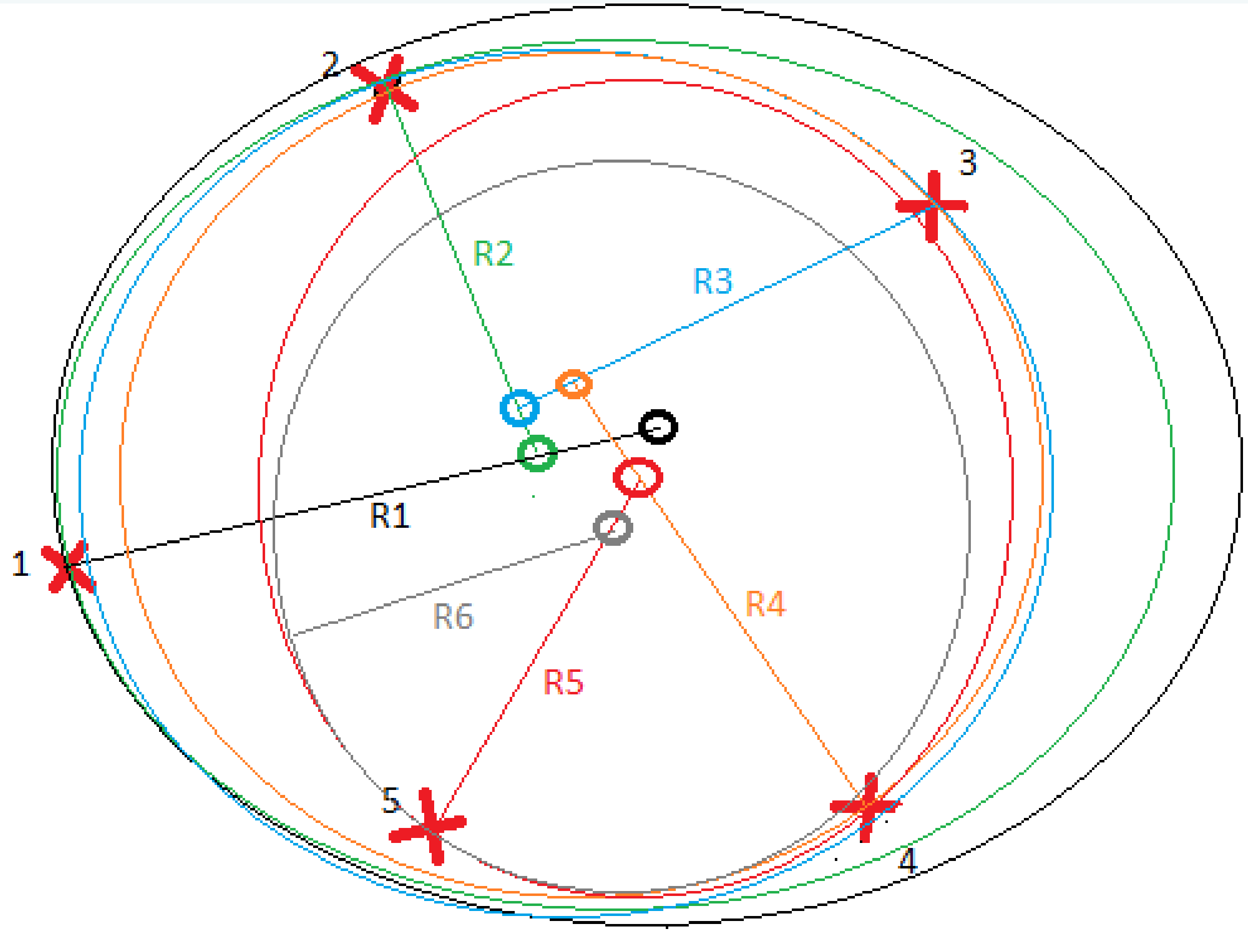


Before Station 5 to after Station 5

R5 true radius of particle after Energy Loss through 4th station, with new centre



R6 true radius of particle after Energy Loss through 5th station, with new centre



What affect does it have on Pt and Pz

- $p_t = cBQR$
- c, B and Q are constant (should be), so transverse momentum changes by radius loss
- A particle loses approximately 0.6 MeV per station, so ~ 3 MeV per tracker, which for a 140 MeV particle is ~2%. Energy loss is same percentage in each direction
- Therefore the radius from start to finish reduces by ~2%
- For a high radius particle, e.g. 100mm, this radius reduction would be more than a few widths of fibres, leading to a poor χ^2 value for the circle fit and thus being excluded

What effect does it have on Pt and Pz

- z-s plane
- Another χ^2 cut is made in the z-s plane, if the fit in the z-s plane fits a straight line.
- $z = \frac{dz}{ds} s - s_0 \; with \; s = R\varphi$, however if the radius is not constant, or not the appropriate radius (wrong circle centre), then the phase advance will be wrong.
- Should have straight line between stations in s-z plane, however a small deviation at each station. That deviation should be similar at each station (i.e. angle change)
- A too strict straight line χ^2 cut may exclude valid particles, but more importantly:

$$^{p_z}/_{p_t} = {}^{\Delta z}/_{R\Delta\varphi}$$

- The p_t to R ratio should be fairly constant and thus p_z is heavily influenced by the phase advance.
- If the movement of circle centre isn't accounted for, then will have the wrong phase advance angle

To investigate

- Identify calculation and use of seed position for Kalman filter. Kalman filter may appropriately smooth p_t and p_z, then there is no problem.
- Although the residuals between trackpoints and spacepoints are small, they appear to work in the same way, an inherent bias
- Circle fit, and line-fit in z-s plane may exclude particles (especially high radius particles) by using χ^2 cut when not appropriate.

- Test and apply transfer matrix routine from upstream to downstream. Check if it is consistent across the beam fraction of the beam. Extend from 4D to 5D and maybe infer 6D
- Classify lost particles, determine an appropriate volume that lost particles should occupy
- If not possible may need to use beam weighting techniques (although inherent biases may not be eliminated)
- Use to classify Transvere and longitudinal phase-space density change. Can be used to quantify cooling performance of a particular material
- Determine overall 6D change to quantify the Emittance Exchange achieved by the wedge

The End

Separating into components

- For a symmetric absorber/no absorber the upstream sample can be separated into the sample which makes it downstream and the sample that is lost

$$N_1\Sigma_1 = N_2\Sigma_2 + N_3\Sigma_3$$

- The determinant of a matrix can be separated into parts using:

$$|\Sigma_1| = \sum_{i=0}^{n} \Gamma_n^i \left| {}^{\Sigma_2}\!/\!_{\Sigma_3}{}^{i} \right| = |\Sigma_2| + |\Sigma_3| + \sum_{i=1}^{n-1} \Gamma_n^i \left| {}^{\Sigma_2}\!/\!_{\Sigma_3}{}^{i} \right|$$

Potential next step

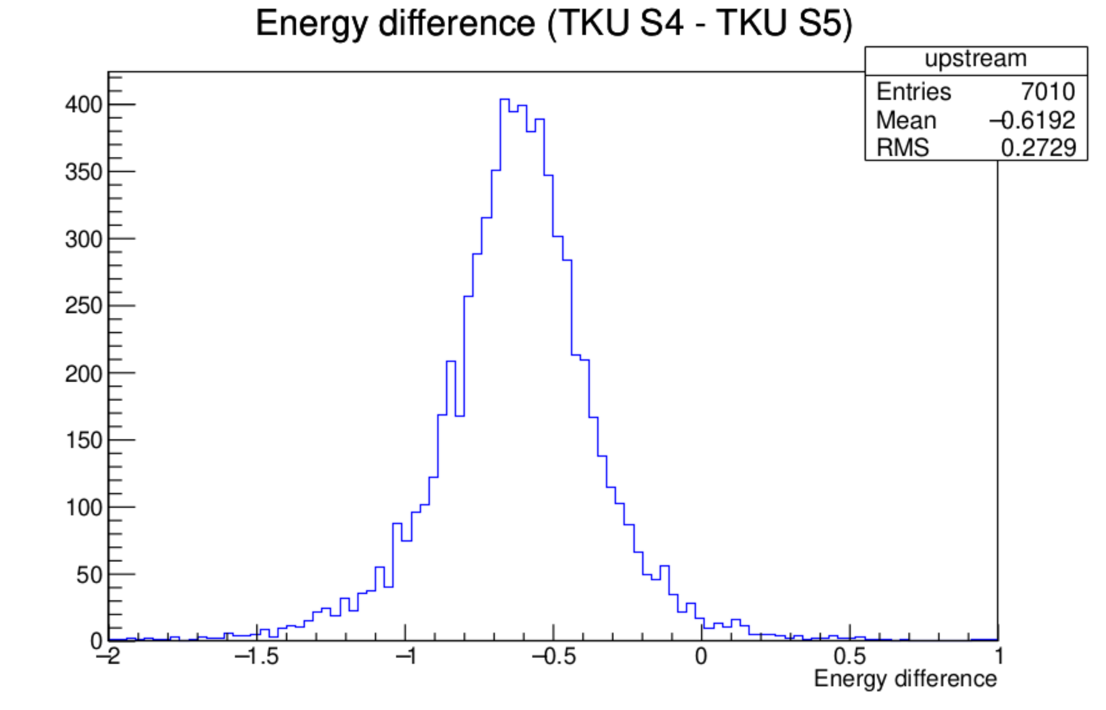
- The missing data downstream is inaccessible, however the upstream sample which makes it downstream can be compared to the downstream sample
- The transport, M, of a covariance matrix from upstream to downstream can be given by:

$$\Sigma_{down} = \langle X_{down}\tilde{X}_{down}\rangle = \langle MX_{up}\tilde{M}\tilde{X}_{up}\rangle = M\langle X_{up}\tilde{X}_{up}\rangle\tilde{M} = M\Sigma_{up}\tilde{M}$$

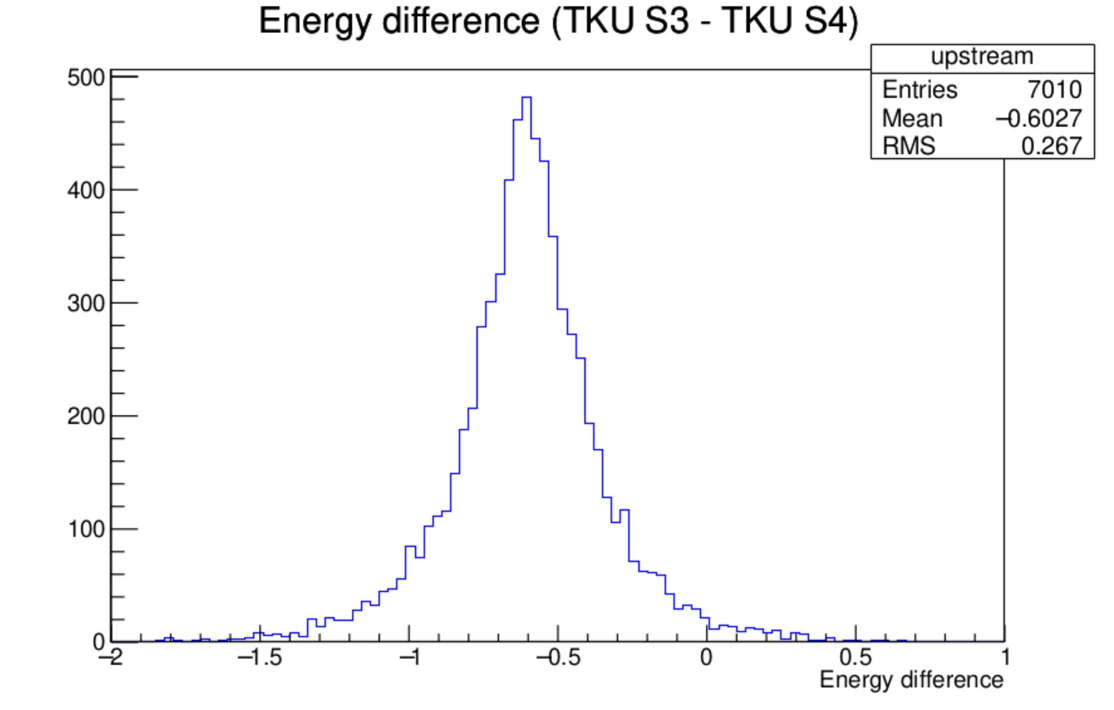
- The determinant is given by:

$$|\Sigma_{down}| = \left|M\Sigma_{up}\tilde{M}\right| = |M|^2\left|\Sigma_{up}\right| = \left|\Sigma_{up}\right|$$

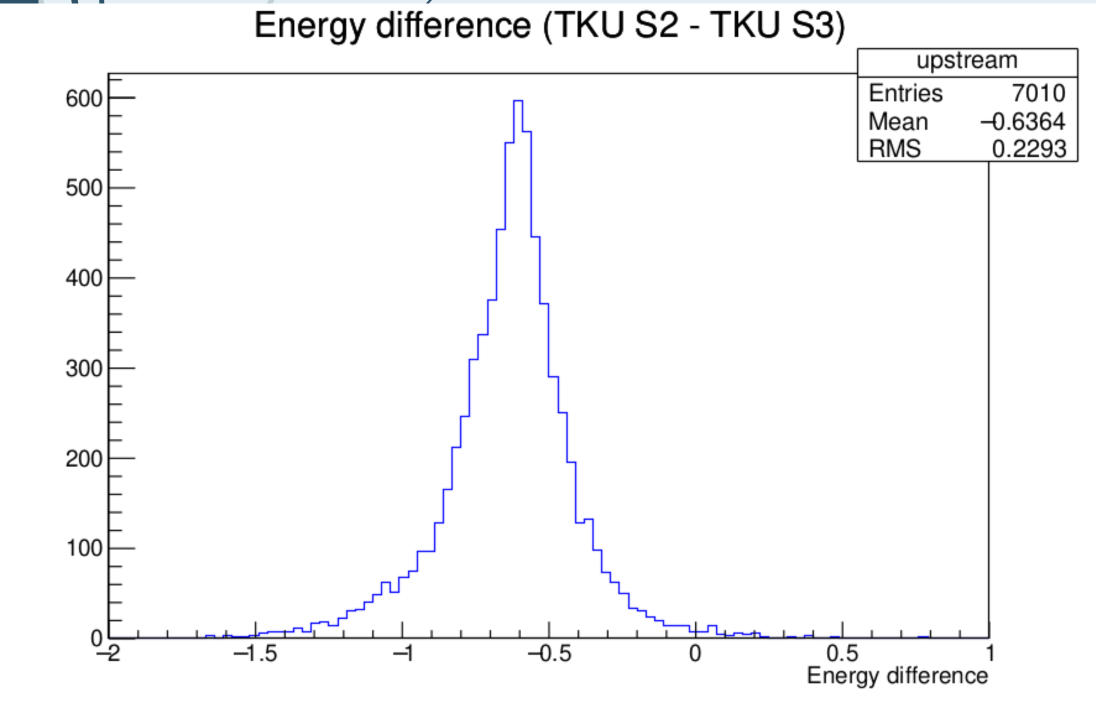
- The transfer matrix M has been previously investigated by Sophie Middleton and Chris Rogers
- A potential investigation would be to investigate the change in M for different fraction sizes of the beam. If stable it could be used to investigate the missing data downstream to see if it is due to scraping and magnet misalignment affects and nothing else



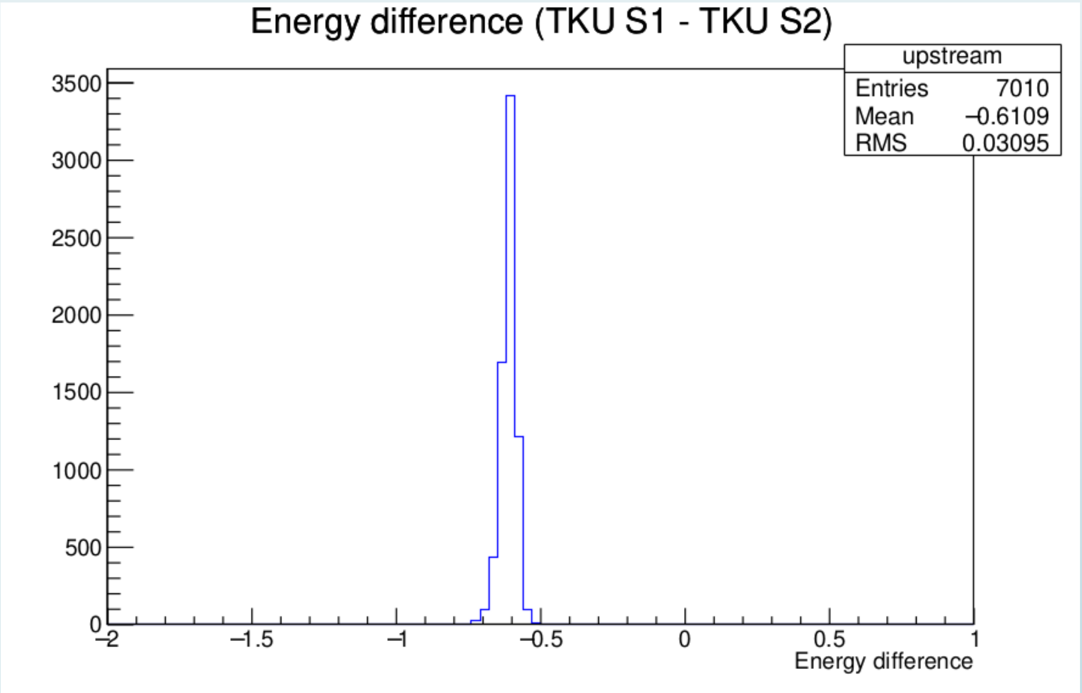
Energy difference (TKU S4 - TKU S5)
upstream
Entries 7010
Mean −0.6192
RMS 0.2729
Energy difference



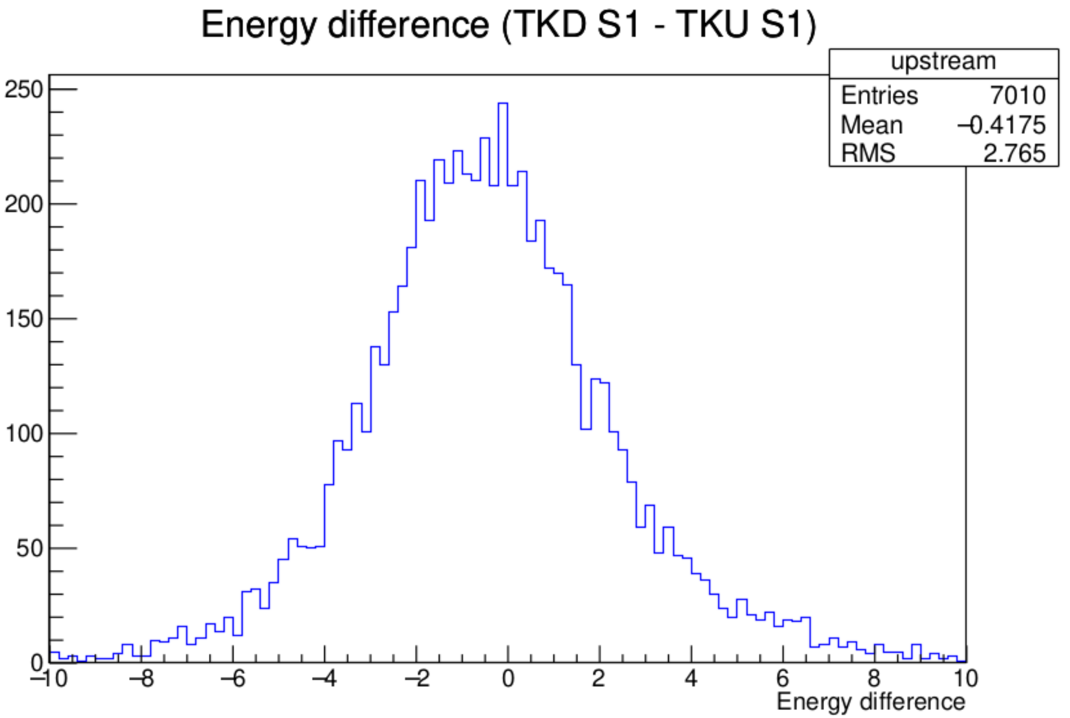
Energy difference (TKU S3 - TKU S4)
upstream
Entries 7010
Mean −0.6027
RMS 0.267
Energy difference

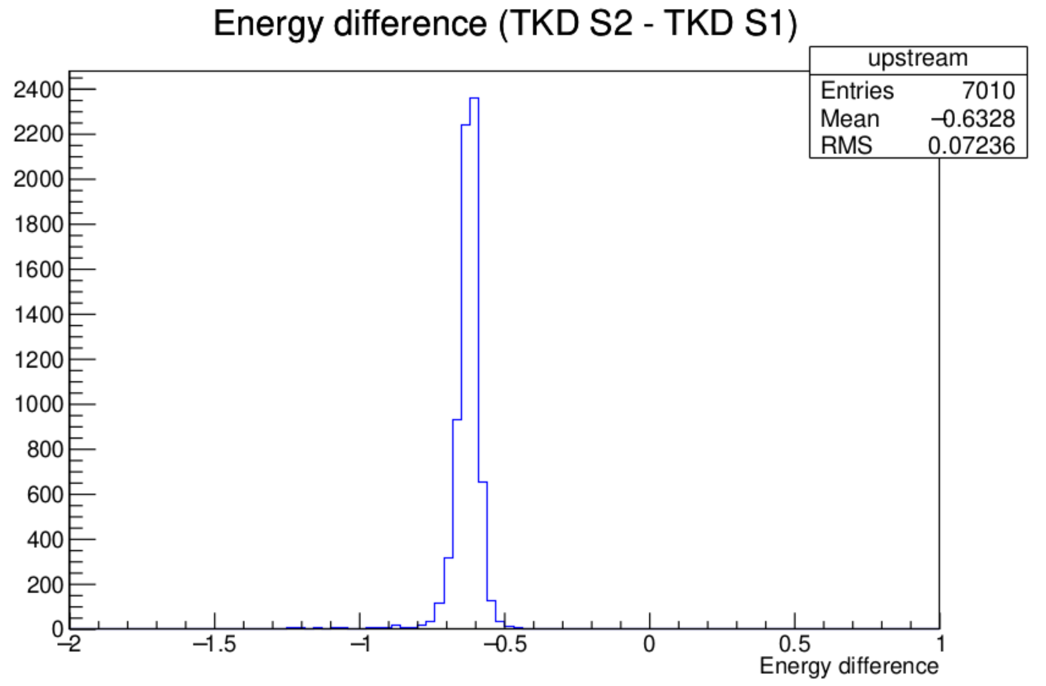


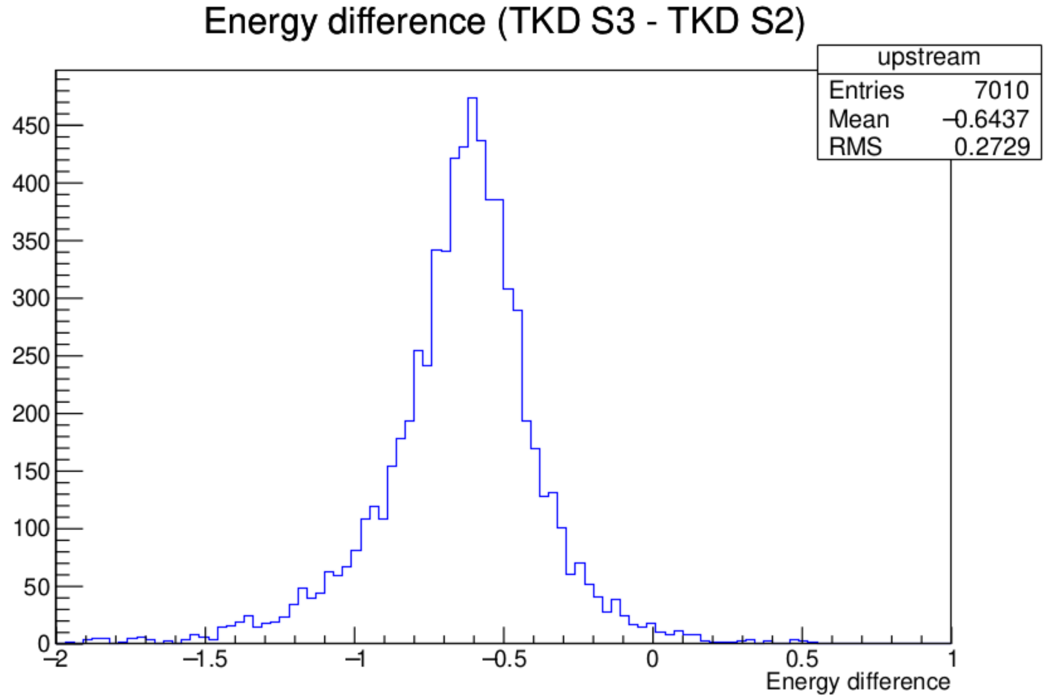
Energy difference (TKU S2 - TKU S3)
upstream
Entries 7010
Mean −0.6364
RMS 0.2293
Energy difference

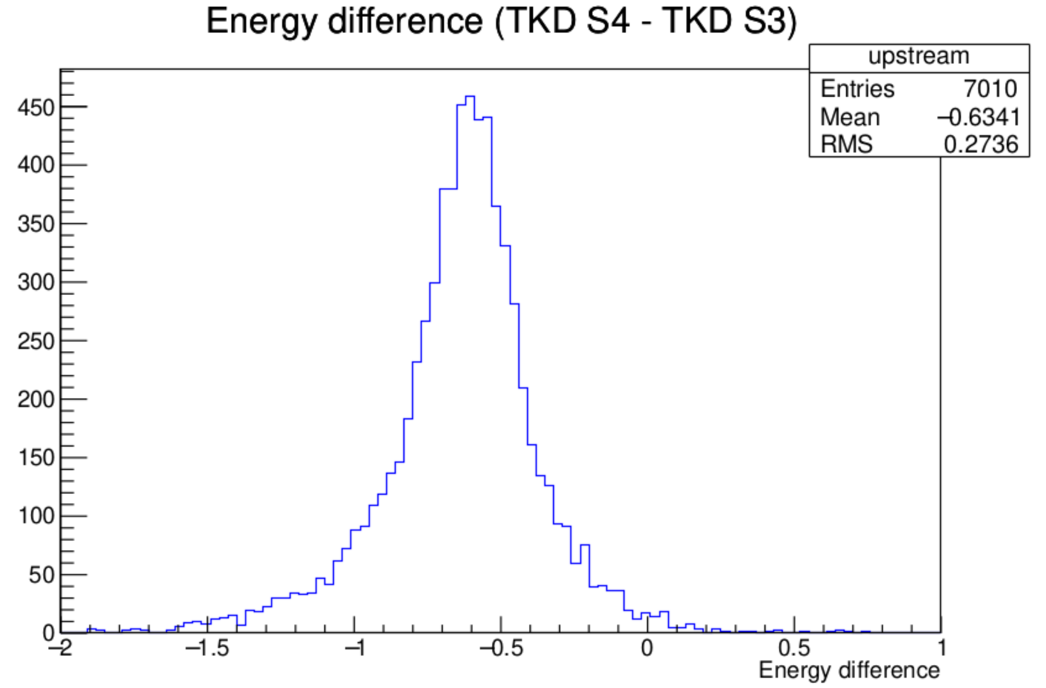


Energy difference (TKU S1 - TKU S2)
upstream
Entries 7010
Mean −0.6109
RMS 0.03095
Energy difference


Energy difference (TKD S1 - TKU S1)
upstream
Entries 7010
Mean −0.4175
RMS 2.765
Energy difference


Energy difference (TKD S2 - TKD S1)
upstream
Entries 7010
Mean −0.6328
RMS 0.07236
Energy difference


Energy difference (TKD S3 - TKD S2)
upstream
Entries 7010
Mean −0.6437
RMS 0.2729
Energy difference


Energy difference (TKD S4 - TKD S3)
upstream
Entries 7010
Mean −0.6341
RMS 0.2736
Energy difference