# Field Off Scattering Studies: Current Status

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## Job List

- Number of comments at CM
- Requested boost to MC statistics $(\checkmark)$
- Investigating fiducial selection $(\checkmark)$
- Rotating vector definitions to cross-check $(\checkmark)$
- $P$ correction by Bethe-Bloch $(\checkmark)$
- Impact parameter plot $(\checkmark)$
- Include tracker acceptance into analysis $(\checkmark)$
- Update all plots and tables $(\checkmark)$
- Include MC Data comparison $(\checkmark)$

# Scattering Data

- Field off data sets were collected in ISIS run periods 2015/03 and 2015/04

- A momentum dependent multiple scattering measurement is made

    - Measure empty channel scattering
    - Convolved with physics model of scattering in absorber - prediction.
    - Measure absorber scattering
    - A Bayesian deconvolution algorithm unfolds absorber scattering distribution
    - $\chi^2$ comparison between data and prediction
    - Width of scattering distribution: $\Theta$ as a function of $P$
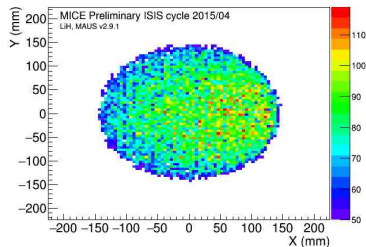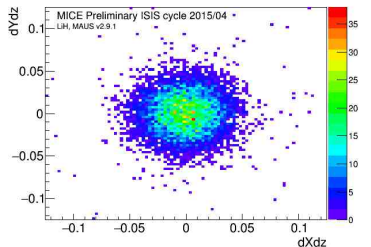
# Selection
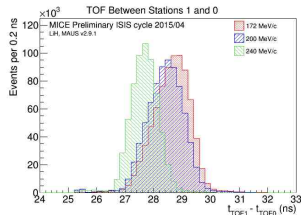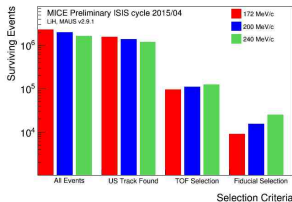


## Only minor changes to selection

- Require a US track. If a DS track not extant, statistics are set to overflow values.
- Analysis done in 200 ps bins, as shown in TOF plot
- Require projection of US tracks to appear, when 12 mrad radial angle is added, within central 140 mm radius of DS trkr plane 5
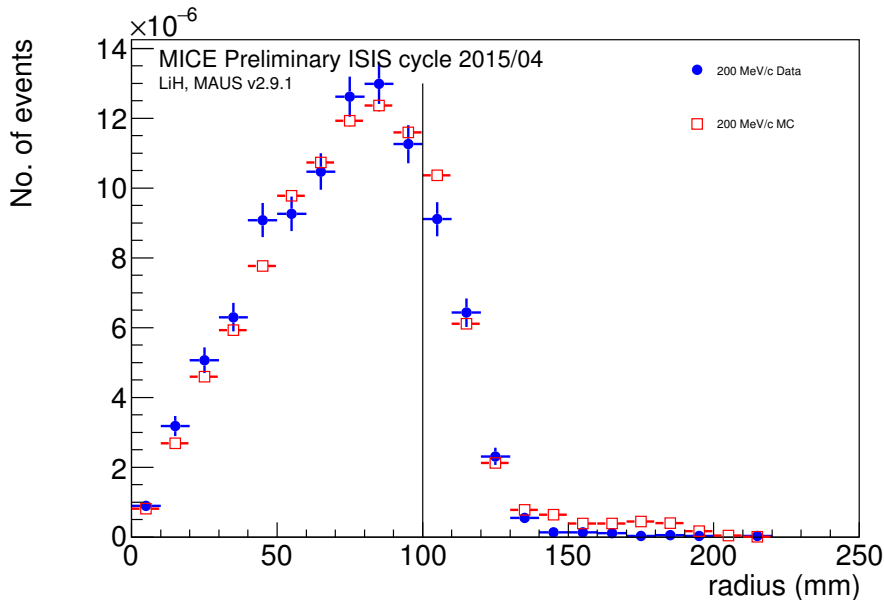- Tracks are projected to the upstream face of the diffuser, if track crosses the diffuser it is rejected

# Cut plot



TOF Between Stations 1 and 0
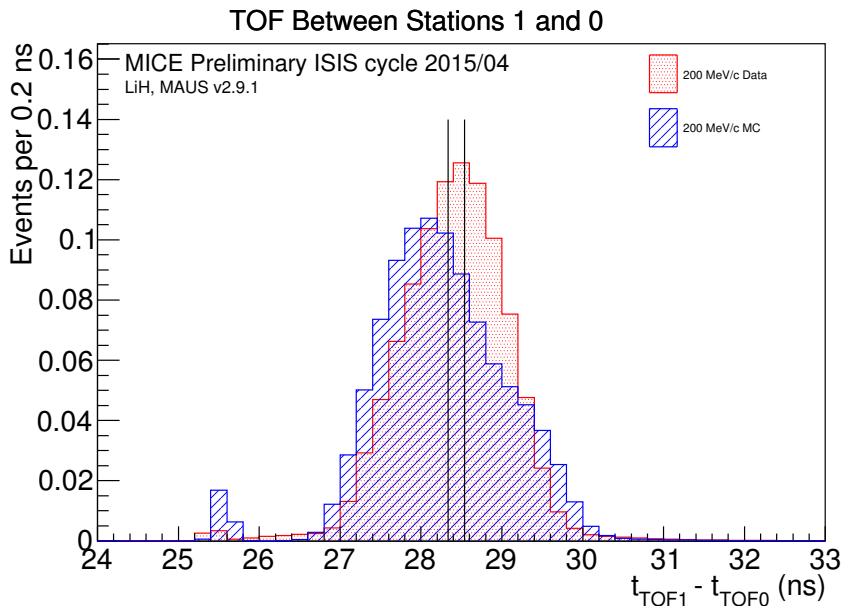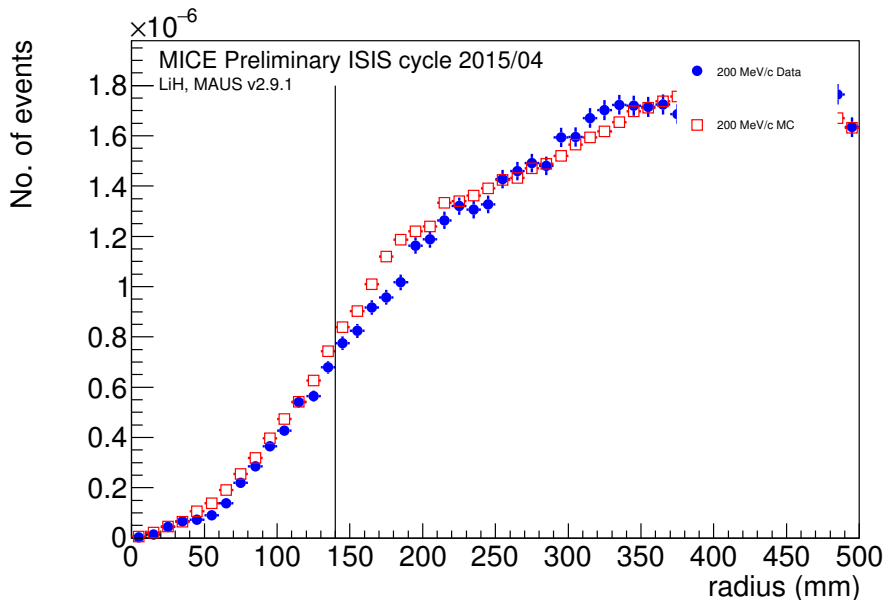
# Cut plot

# Cut plot

# Momentum Calculation

1. Momentum is measured with

$$p = \frac{m}{\sqrt{\frac{t_\mu^2}{t_e^2} - 1}} \tag{1}$$

2. If there is a hit in TOF2 this is done with TOF1+2 information

3. If there is no hit in TOF2 this is done with TOF0+1

4. Only in the case of TOF0+1 is a correction applied to account for the energy loss in the channel.

# Momentum Correction

- Developed analytic formula for momentum correction over the summer - works fine
- For greater transparency now use Bethe-Bloch most probable energy loss for known material budget in channel

$$\Delta_p = \xi \left[ \ln \frac{2mc^2\beta^2\gamma^2}{I} + \ln \frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma) \right] \qquad (2)$$
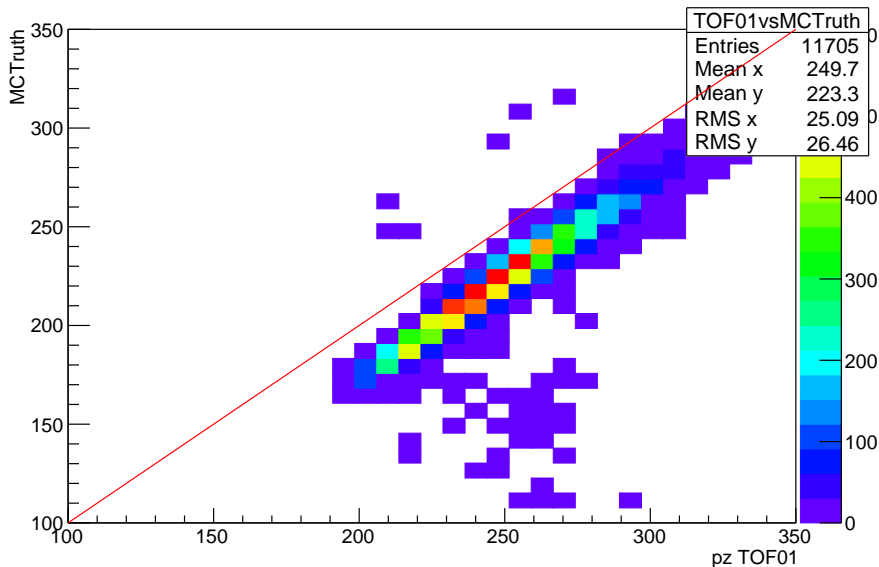
where

$$\begin{aligned}
\xi &= (K/2)\langle Z/A \rangle z^2 (x/B^2) \\
I &= \text{mean excitation energy} \qquad (3) \\
j &= 0.2
\end{aligned}$$

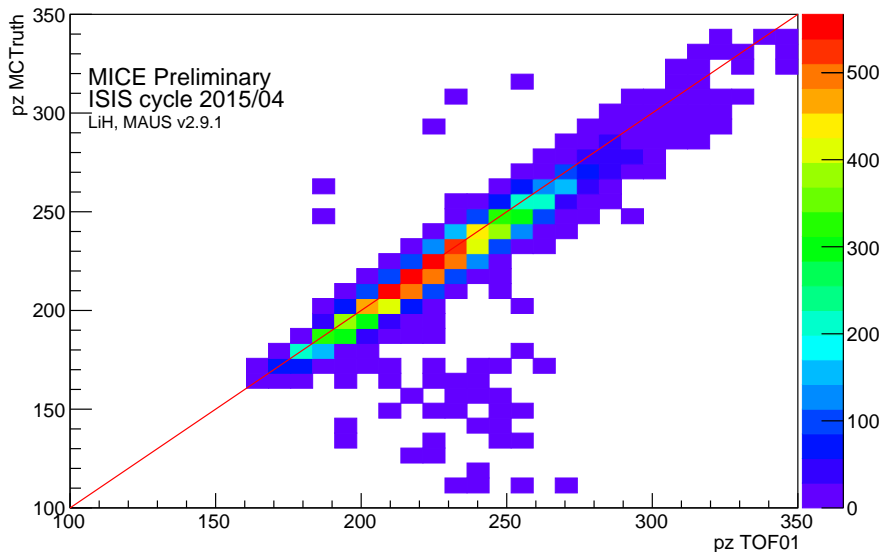- Tracks crossing the diffuser ring are cut

# Compare Before Correction with MC



TOF01vsMCTruth

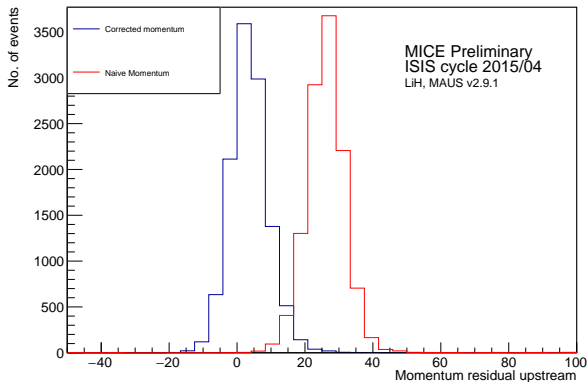| TOF01vsMCTruth | |
|---|---|
| Entries | 11705 |
| Mean x | 249.7 |
| Mean y | 223.3 |
| RMS x | 25.09 |
| RMS y | 26.46 |

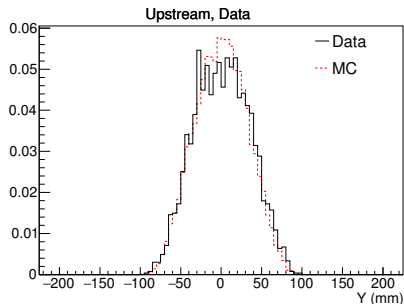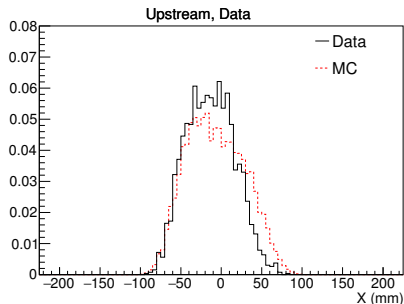# Compare Bethe Bloch Correction with MC



Corrected P upstream vs MC Truth
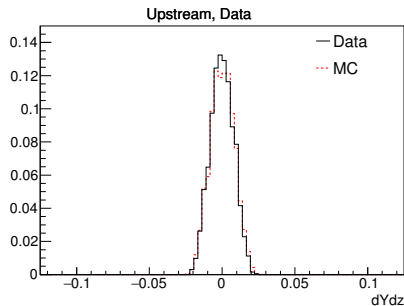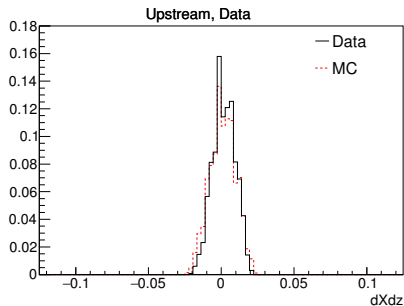
# Before After Correction Residuals

# MC Data comparison



- 200 MeV/c case
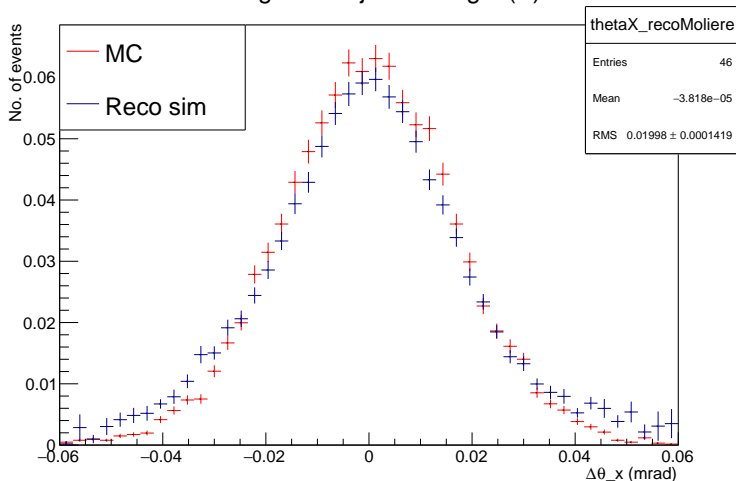- Compare MC recon and data

# MC Data comparison



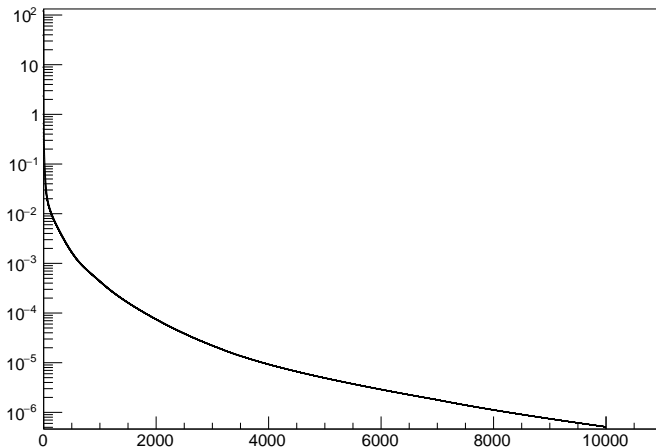- 200 MeV/c case
- Compare MC recon and data

# MC Data comparison



Change in Projected Angle (X)

- 200 MeV/c case
- Compare MC recon and data

# MC Data comparison

Graph



- 200 MeV/c case
- $\chi^2$ between iterations

## Fiducial Scan

- Ultimately want bin by bin correction for acceptance in $\theta$
- $\therefore$ MC must be used, takes into account the efficiency, tracker resolution + selection. MC is treated in idential manner to data.

$$\text{acceptance} = \frac{\text{No. of tracks in } \theta \text{ bin MC Truth that are reconstructed}}{\text{No. of tracks in } \theta \text{ bin MC Truth}}$$

(4)

- Detector efficiency know to be $\sim 100\%$ $\therefore$ selection acceptance must be $\sim 100\%$. If not then there is geometric acceptance effect which is a bias in scattering measurement
- Track upstream is propagated to most downstream plane in DSS, nominal scattering fixed 40 mrad.
- Scan cut applied to analysis and calculate track acceptance
- Justify cuts based on acceptance scan

# Fiducial Scan



Scan radial selection
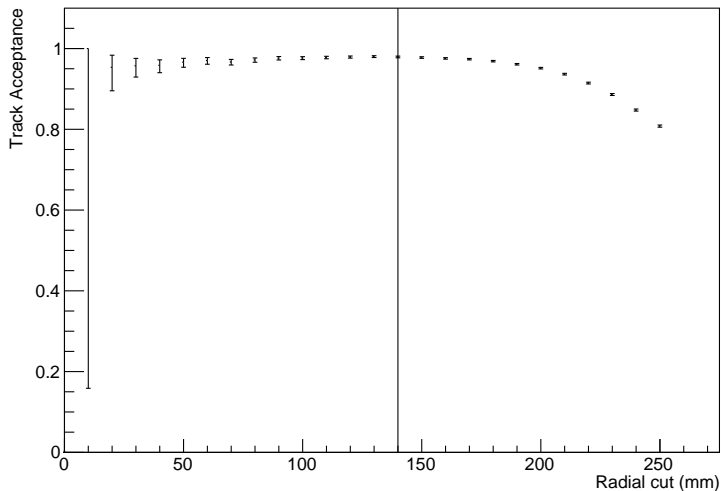
# Forward convolution
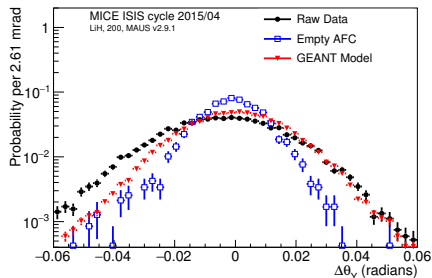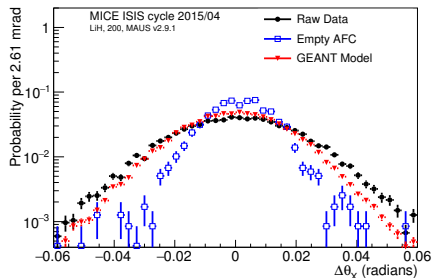


- Discussed asymmetries on Monday - investigating geometries that were used for reconstruction

# Deconvolution of Raw Scattering Data

- Use a iterative algorithm that uses the conditional probability to characterize the response of the reconstructed scattering angle to the true scattering angle
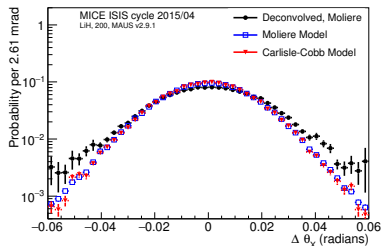


### Bayes Theorem

$$P(C_i|E_j) = \frac{P(E_j|C_i)P_0(C_i)}{\sum_{l=1}^{n_c} P(E_j|C_l)P_0(C_l)}$$

- We want $C_i = \Delta\theta_Y^{abs}$ the deflection angle in the absorber material.
- We measure $E_j = \Delta\theta_Y^{tracker}$ the deflection angle measured at the first tracker plane.

# Tracker Acceptance
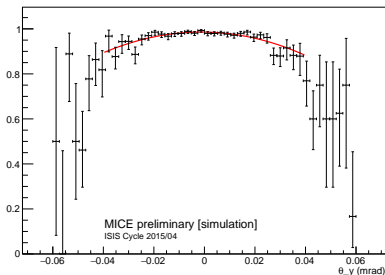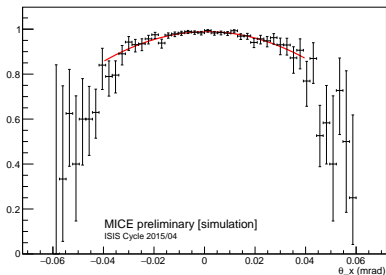


- 200 MeV/c case
- Match track upstream and downstream
- TOF selection
- Calculate angle $\theta$ as per analysis
- Downstream acceptance is defined

$$\frac{\text{No. of tracks in } \theta \text{ bin MC Truth that are reconstructed}}{\text{No. of tracks in } \theta \text{ bin MC Truth}} \quad (5)$$

# Systematic Errors

- Several sources have been considered
  - Material thickness uncertainties - comments from referees on Monday about this cut
  - Alignment uncertainties
  - TOF uncertainties
  - Fiducial volume uncertainties
- TOF systematic affects the momentum scale and is the dominant systematic
- All systematics are combined and included in final result

# Results - deconvolution

| p (MeV/c) | | Meas. (mrad) | G4 Pred. | $\chi^2$/DoF | CC Pred. | $\chi^2$/DoF |
|---|---|---|---|---|---|---|
| 171.89±0.07 | $\theta_X$ | 22.82±0.33±0.54 | 19.27±0.1 | 1074.5 / 34 | 19.45±0.1 | 963.8 / 34 |
| 171.89±0.07 | $\theta_Y$ | 23.13±0.39±0.61 | 19.05±0.1 | 1657.4 / 34 | 19.18±0.1 | 1475.5 / 34 |
| 199.3±0.06 | $\theta_X$ | 18.7±0.18±0.46 | 16.61±0.07 | 1306.3 / 34 | 16.21±0.07 | 1635.8 / 34 |
| 199.3±0.06 | $\theta_Y$ | 17.91±0.17±0.76 | 16.39±0.07 | 1825.9 / 34 | 16.04±0.07 | 1885.4 / 34 |
| 243.73±0.08 | $\theta_X$ | 14.33±0.08±0.49 | 13.29±0.04 | 1327.3 / 34 | 13.06±0.03 | 1617.4 / 34 |
| 243.73±0.08 | $\theta_Y$ | 14.4±0.09±0.5 | 13.1±0.04 | 4064.4 / 34 | 13.03±0.03 | 3297.5 / 34 |
| 171.89±0.07 | $\theta_{Scatt}^2$ | 32.92±1.23±0.25 | 26.91±0.23 | 2647.9 / 46 | 27.17±0.23 | 2744.9 / 46 |
| 199.3±0.06 | $\theta_{Scatt}^2$ | 25.34±0.52±0.69 | 23.19±0.15 | 1011.5 / 46 | 22.71±0.15 | 1154.8 / 46 |
| 243.73±0.08 | $\theta_{Scatt}^2$ | 20.14±0.2±0.72 | 18.61±0.07 | 1338.1 / 46 | 18.42±0.07 | 1394.5 / 46 |

# Θ as a Function of Momentum
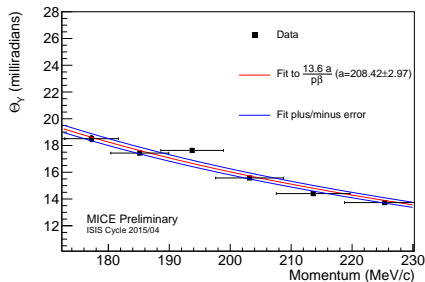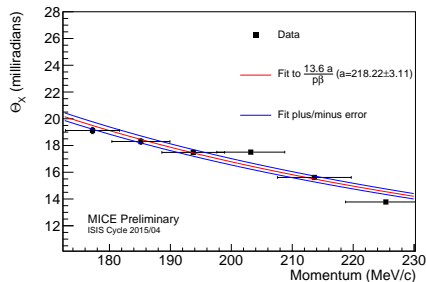


- Scan across the entire momentum range and measure scattering in both projections in each bin
- Comparison with PDG formula is made and the fit is made for
  $a = \sqrt{\frac{z}{X_0}}(1 + 0.038 \ln \frac{z}{X_0})$

# Job List

- Note has been updated, draft of paper has been prepared
- Update plots colour scheme/format etc
- Comments from referees on Monday, list of actions that will incorporated over next 2-3 weeks

# Selection

| Selection | Description | $\mu$ Beams, LiH abs. | | |
|---|---|---|---|---|
| | | 172 | 200 | 240 |
| TOF1 trigger | At least two raw TOF slab hits exist and at least one in each TOF plane. | 1. | 1. | 1. |
| Upstream track selection | There is one US track and at most one track in the DS tracker (If there is no DS track $\theta_X = \theta_Y = 45°$). | 66.84 % | 68.05 % | 74.15% |
| TOF timing selection | Select muons from run at the target momentum. | 4.1 % | 5.42 % | 7.77 % |
| Fiducial selection | For projected US tracks $\sqrt{x^2 + y^2} < r_0$ at plane 5 of DS tracker, where $x = x_0 + (\frac{dx}{dz} + a_0 \cos\phi)\Delta z$, $y = y_0 + (\frac{dy}{dz} + a_0 \sin\phi)\Delta z$, and $\phi = \tan^{-1}\frac{dy/dz}{dx/dz}$. $r_0 = 150$ mm and $a_0 = 0.012$ assumed. | 0.09 % | 0.19 % | 0.41 % |
| Diffuser cut | US tracks are projected to the diffuser position any track within the radius of the diffuser annulus is rejected | 0.07 % | 0.16 % | 0.36 % |

# Selection
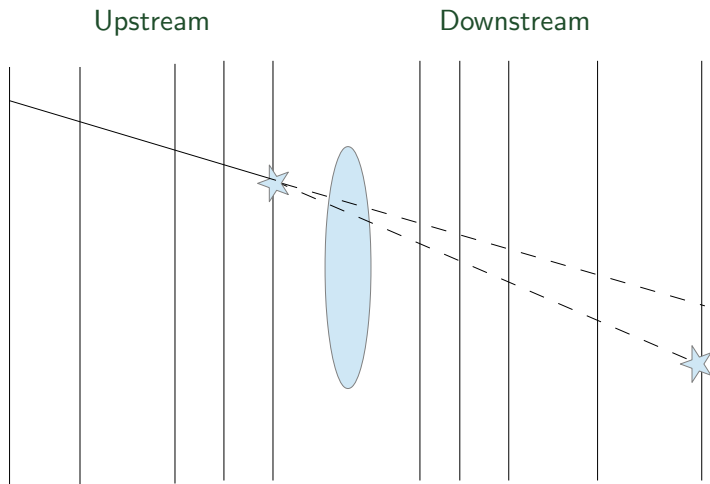


Upstream

Downstream

# Transverse Distance at Absorber

Request to understand distance between projected tracks at absorber centre

Project tracks to centre of absorber and calculate transverse distance



Data Projection
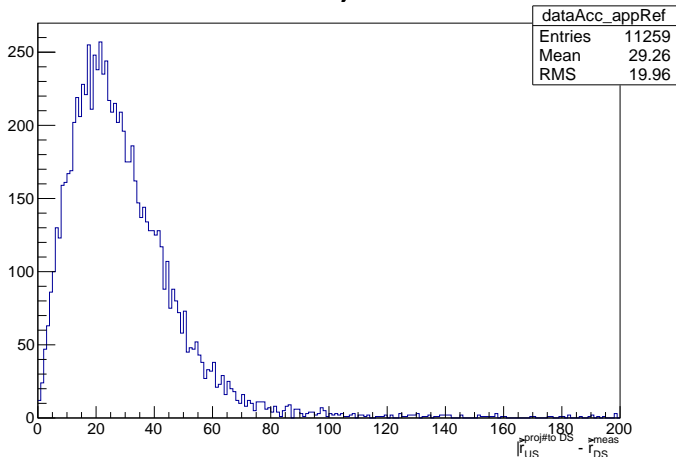
# Transverse Distance at Absorber

Request to understand distance between projected tracks at absorber centre

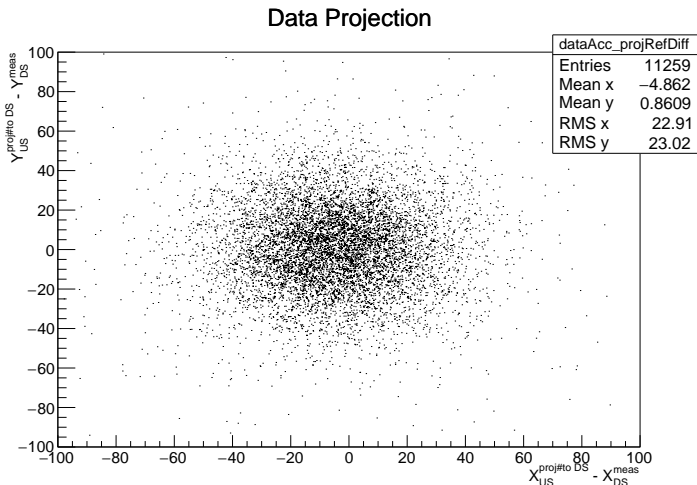Project tracks to centre of absorber and calculate transverse distance

## Rotate Angle Definitions

Definition of scattering angles comes from Cobb Note

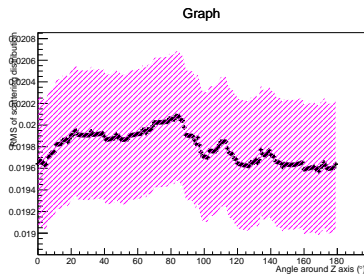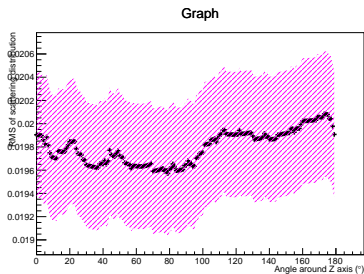$$\tan \theta_p = \frac{\vec{d} \cdot \vec{v'}}{\vec{d} \cdot \vec{u}} \tag{6}$$

where

$$\vec{v} = \vec{s} \times \vec{u} \tag{7}$$

where $\vec{s}$ is arbitrary defined as $\vec{s} = (0, -1, 0)$

Test that this definition is arbitrary by rotating around the $z$-axis and plot RMS of scattering distribution

# Rotate Angle Definitions



Left: $\theta_{"x"}$ Right: $\theta_{"y"}$

# Scattering Data

## Scattering Angle Definitions

- In the top diagram both the solid vectors are in the plane of the square i.e. the plain of the board. The y-axis is coming out of the board

- If both the up- and downstream vector were in the same plane then the subtraction of the simple projected angle would be sufficient

- The bottom figure is a side on view of the top figure. If the up- and downstream vectors are in two different planes then a more consider apporach is required as detailed in http://www.ppe.gla.ac.uk/~jnugent/Projected-angles.pdf by John Cobb
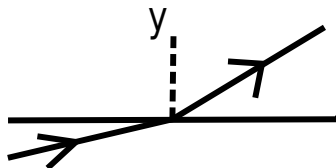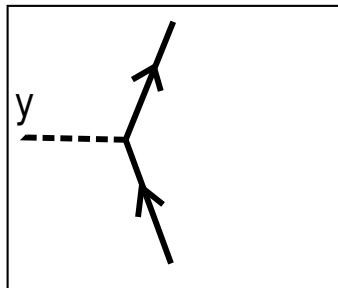
# MC Truth After Deconvolution

- Want to correct absorber scattering distribution bin by bin in the $\theta_{\text{scat}}$
- Bin by bin correction can not be done in data, if the track is not measured down stream then we never measure the scattering angle
- Can only be done in MC truth
- $\therefore$ correction must be done on final deconvolved distribution, raw distributions include tracker resolution + interstitial material
- We calculate the acceptance of the tracker system (Up+down)
- MC selection == data selection
- Apply acceptance correction to final deconvolved scattering distributions