Recent Results from MICE on Multiple Coulomb Scattering and Energy Loss

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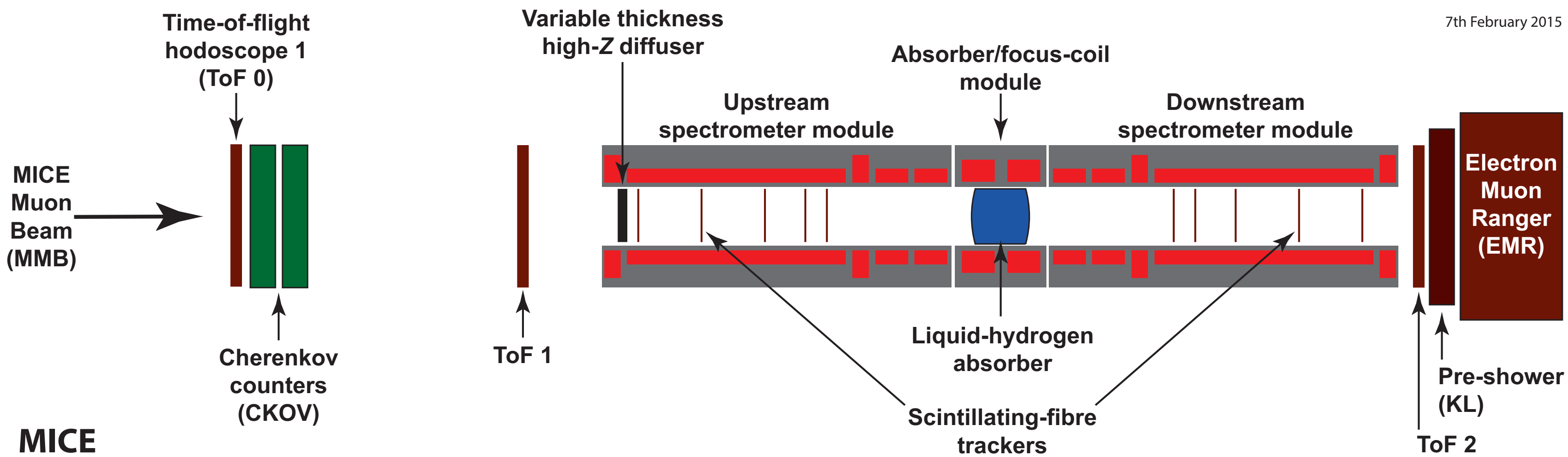
- Emittance change depends on energy loss and multiple Coulomb scattering
- Energy loss reduces momentum
- Scattering increases entropy of the beam
- RF re-acceleration restores p_L

$$\frac{d\epsilon_n}{dz} \approx -\frac{\epsilon_n}{\beta_{\mathrm{rel}}^2 E_\mu}\left\langle \frac{dE}{dz} \right\rangle + \frac{1}{\beta_{\mathrm{rel}}^3}\frac{\beta_\perp (13.6\ \mathrm{MeV})^2}{2E_\mu m_\mu X_0 c^2}$$

- We want to understand both energy loss and scattering terms

The MICE Detector



- TOF counters measure location and time of particle hits
- Trackers measure trajectories and momenta
  - Scattering and energy loss analyses have been done with no tracker field
  - Further studies are using data with tracker fields to refine measurements
- Absorber is Lithium Hydride or liquid Hydrogen

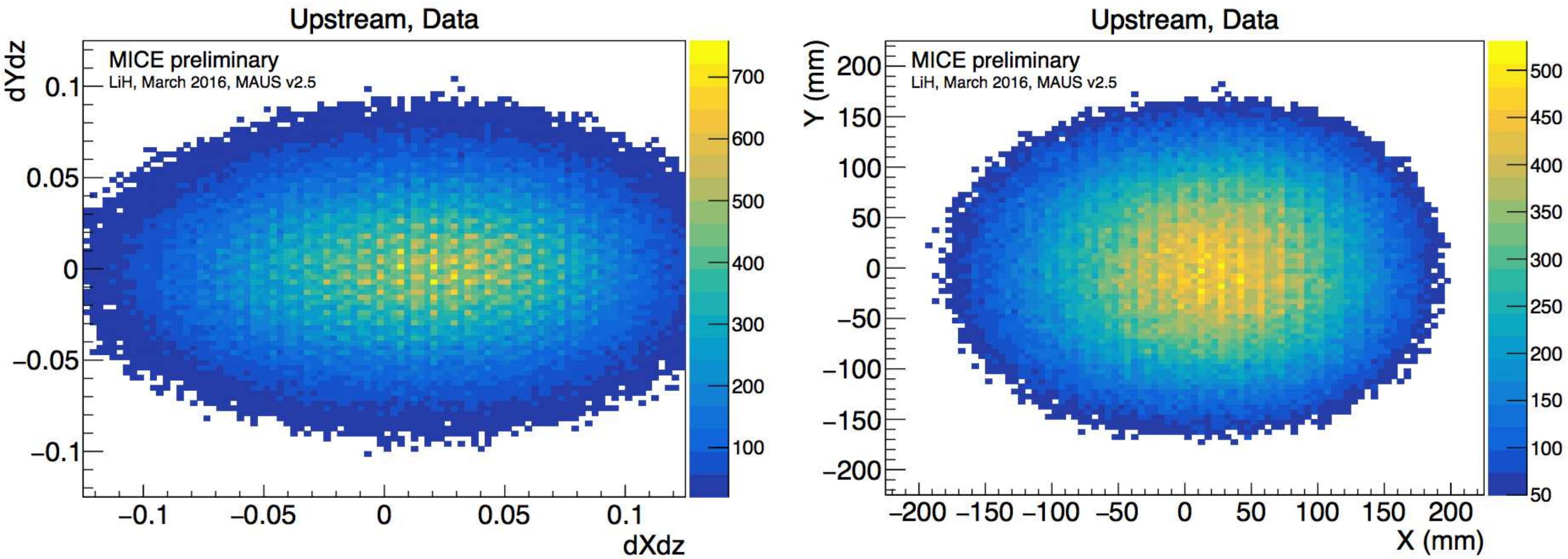
Overview of Multiple Coulomb Scattering

- The PDG recommends the formula

$$\theta_0 \approx \frac{13.6\text{MeV}}{p_\mu \beta_{\text{rel}} c} \sqrt{\frac{\Delta z}{X_0}} \left[1 + 0.038 \ln \left(\frac{\Delta z}{X_0} \right) \right]$$

- GEANT4 uses full Legendre polynomial expansion
- Other models also considered: Moliere, Cobb-Carlisle
- MUSCAT showed poor agreement between theory and low-Z material data
- MICE has taken scattering data on a LiH target:
  - 81% ^{6}Li, 4% ^{7}Li, 14% ^{1}H (traces of C, O, Ca)
- Results are compared to multiple theories and models

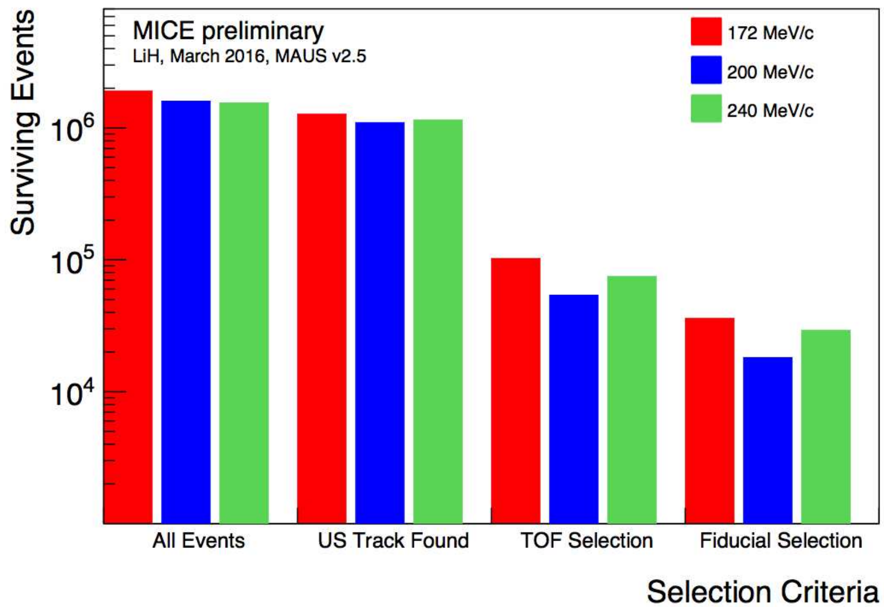
Scattering Data

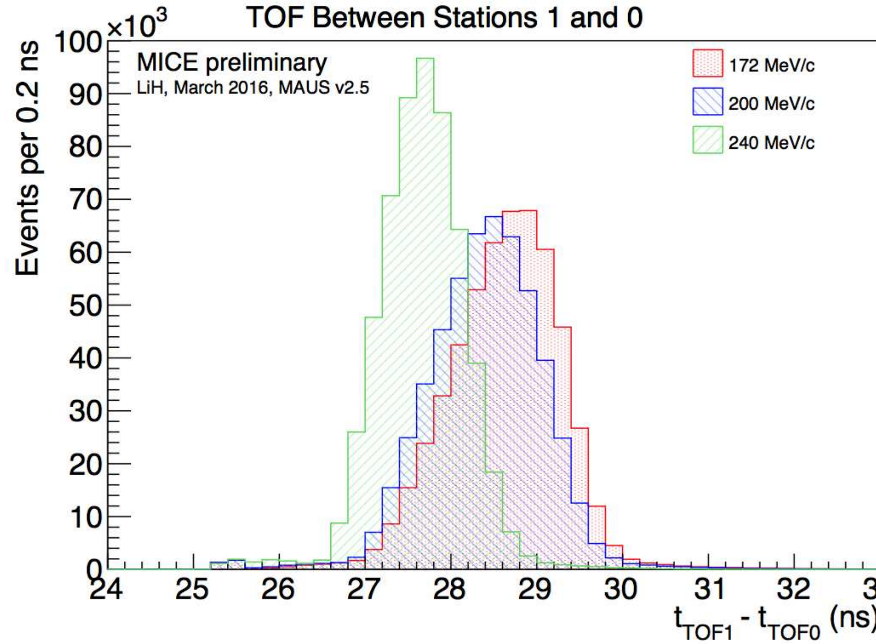


Field-off data sets from ISIS run periods 2015/03 and 2015/04

- Measure scattering with empty channel
- Prediction: convolve with physics model of scattering
- Measure scattering with absorber
- Deconvolve measured distribution
- χ^2 comparison between data and prediction
- Calculate width of scattering distribution: $\Theta(p)$

Selection





- Require one upstream track and at most one downstream track (if no DS track, set scattering angle to overflow value)
- TOF cut to select muons at a target momentum
- Require US track to extrapolate to within DS tracker even if it scatters 12 mrad outward

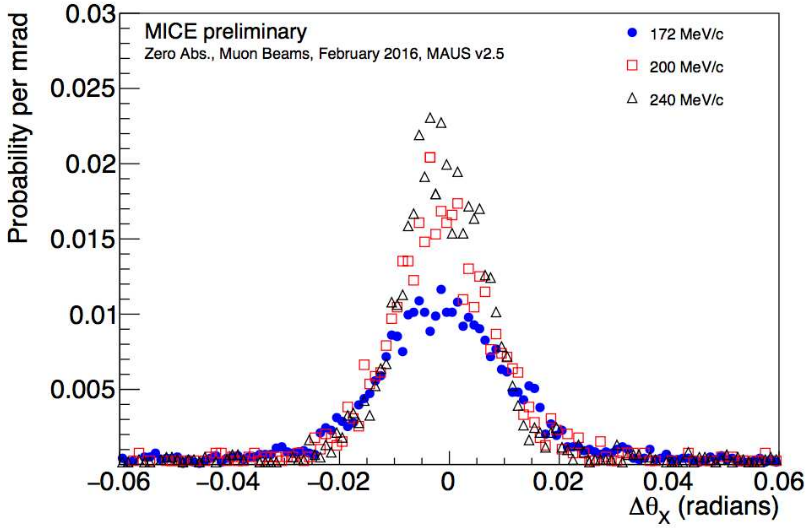
Define projection angles:

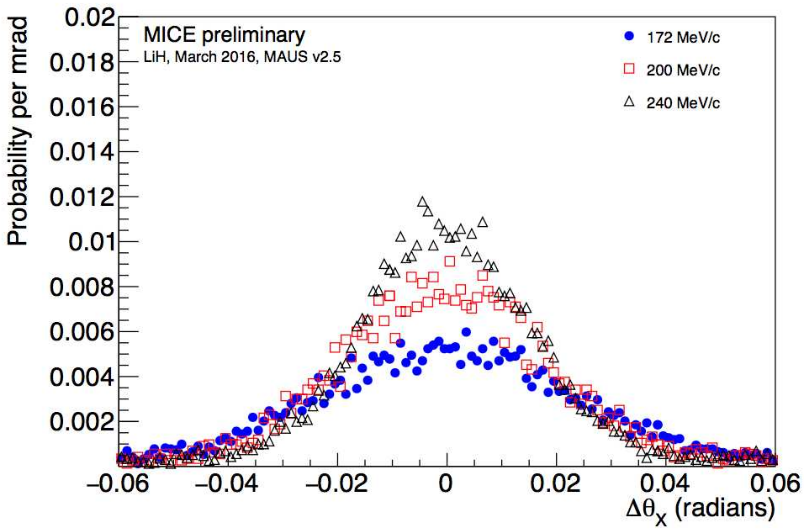
$$\theta_y = \mathrm{atan}\left(\frac{p_{\mathrm{DS}} \cdot (\hat{y} \times p_{\mathrm{US}})}{|\hat{y} \times p_{\mathrm{US}}||p_{\mathrm{DS}}|}\right)$$

$$\theta_x = \mathrm{atan}\left(\frac{p_{\mathrm{DS}} \cdot (p_{\mathrm{US}} \times (\hat{y} \times p_{\mathrm{US}}))}{|p_{\mathrm{US}} \times (\hat{y} \times p_{\mathrm{US}})||p_{\mathrm{DS}}|}\right)$$

so that $\theta_x^2 + \theta_y^2 \approx \theta_{\mathrm{scatt}}^2$ and:

$$\cos(\theta_{\mathrm{scatt}}) = \frac{p_{\mathrm{US}} \cdot p_{\mathrm{DS}}}{|p_{\mathrm{US}}||p_{\mathrm{DS}}|}$$

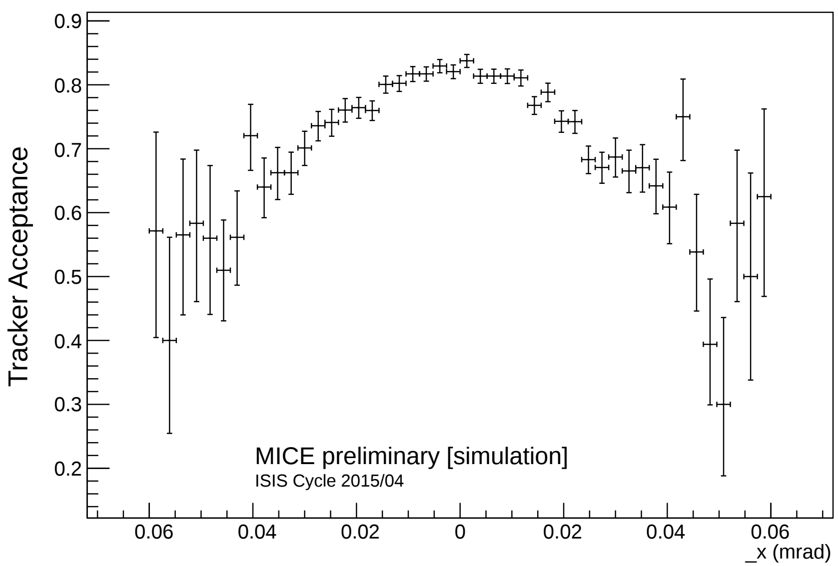


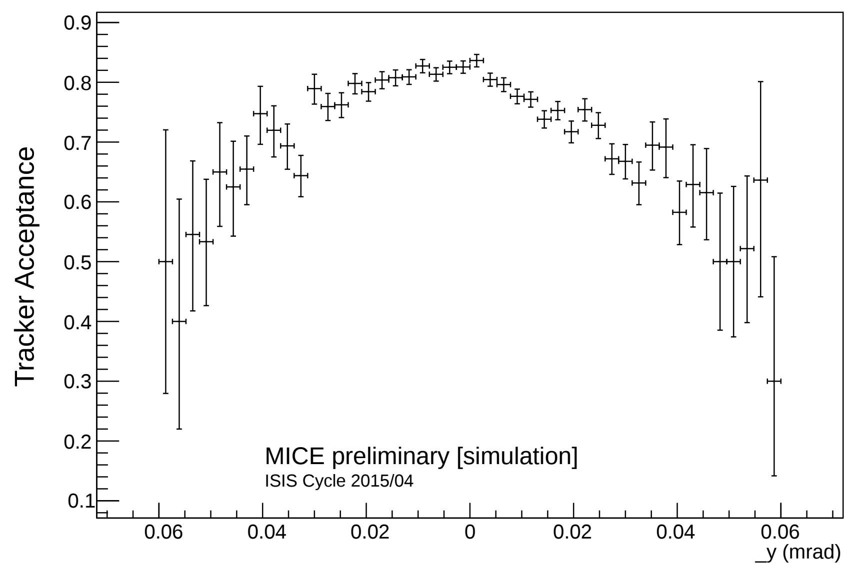


Tracker Acceptance

- Match upstream and downstream track
- TOF selection
- Calculate scattering angles θ_x and θ_y
- Define downstream acceptance:

$$\frac{\text{reconstructed tracks in MC truth } \theta \text{ bin}}{\text{tracks in MC truth } \theta \text{ bin}}$$



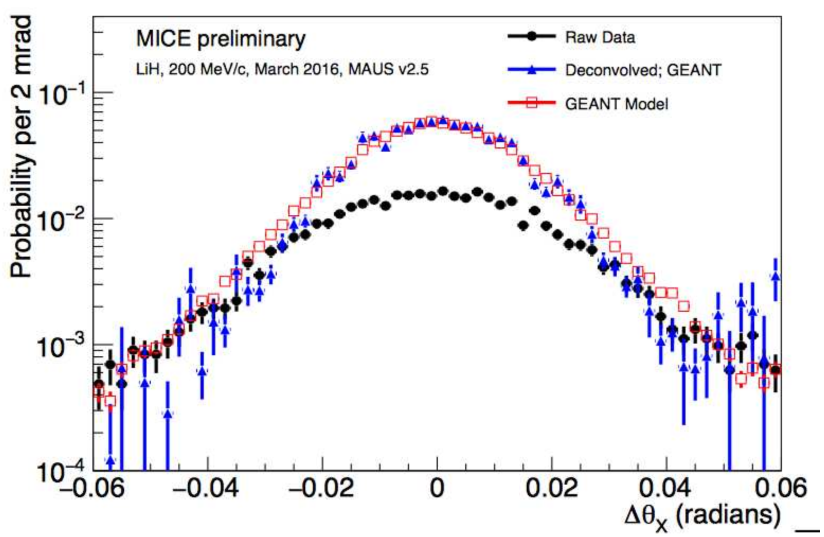


Deconvolution

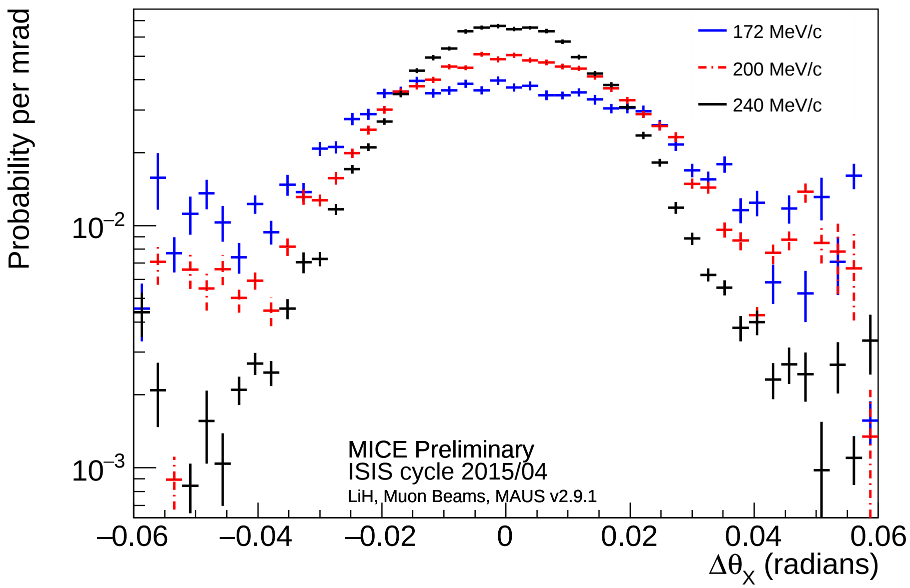
- Deconvolve observed scattering distribution to remove effects of detector resolution, etc
- Use an iterative algorithm that uses the conditional probability of a true scattering angle given an observed scattering angle

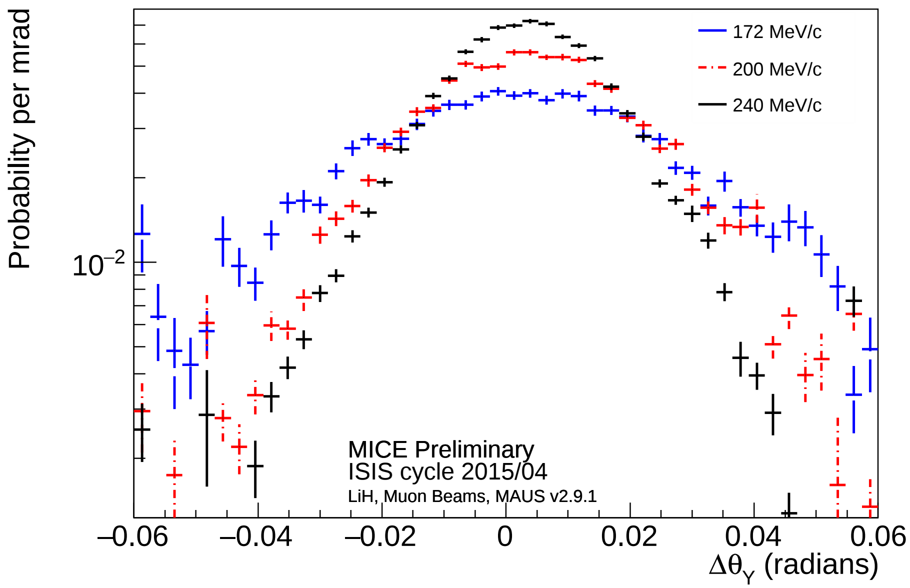
$$P(C_i|E_j) = \frac{P(E_j|C_i)P_0(C_i)}{\Sigma_{l=1}^{n_c} P(E_j|C_l)P_0(C_l)}$$

- We measure $E_j = \Delta\theta_y^{\text{tracker}}$, the measured deflection angle in the first tracker plane
- We want to know $C_i = \Delta\theta_y^{\text{abs}}$, the deflection angle in the absorber



Scattering Results

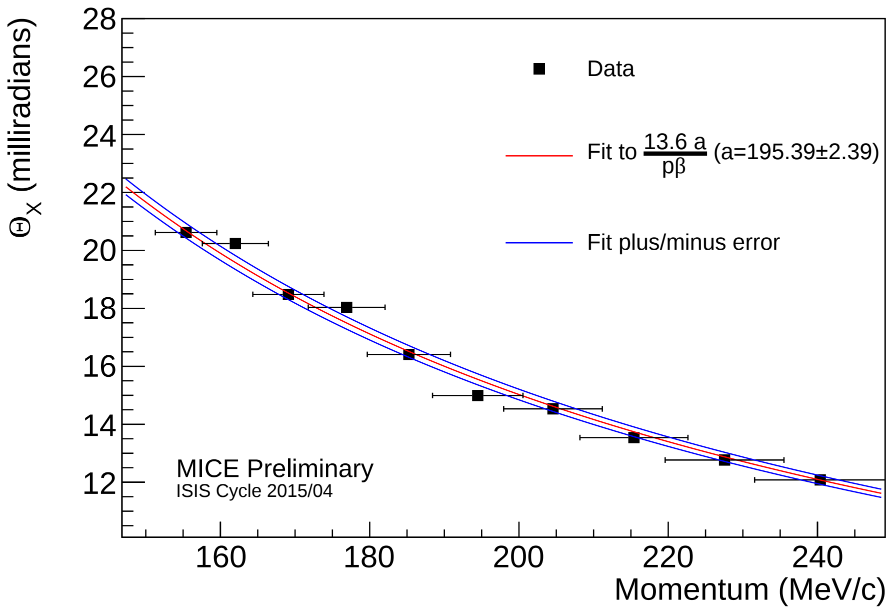


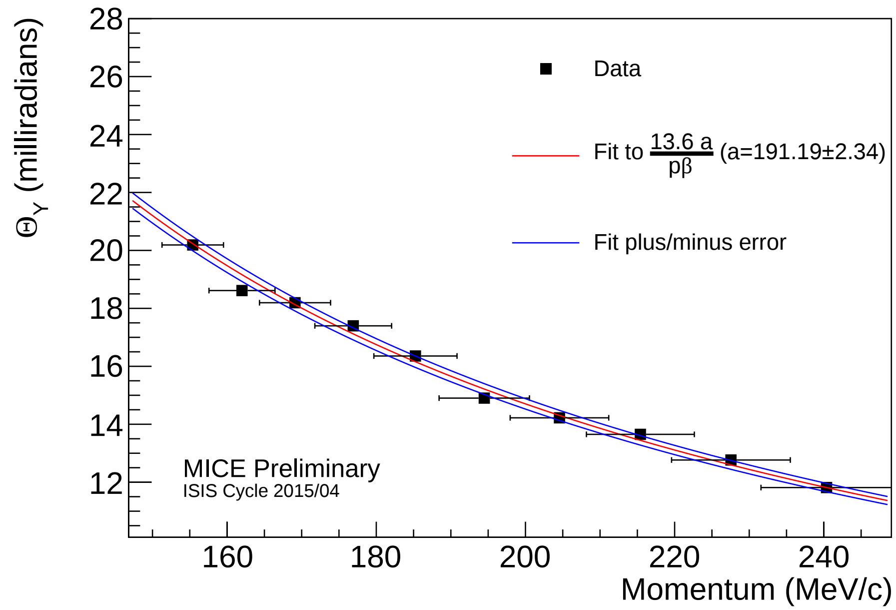


- θ_x and θ_y measured at each momentum point using deconvolution
- Final value is $\Theta =$ width of gaussian fit from $+40$ to -40 mrad

Θ as a Function of Momentum

- Scan across momentum range and measure Θ_x and Θ_y in each bin
- Compare to PDG formula with fit for $a = \sqrt{\frac{z}{X_0}}(1 + 0.038 \ln \frac{z}{X_0})$





- Preliminary analysis shows that scattering is higher than predicted by GEANT and lower than predicted by the PDG model

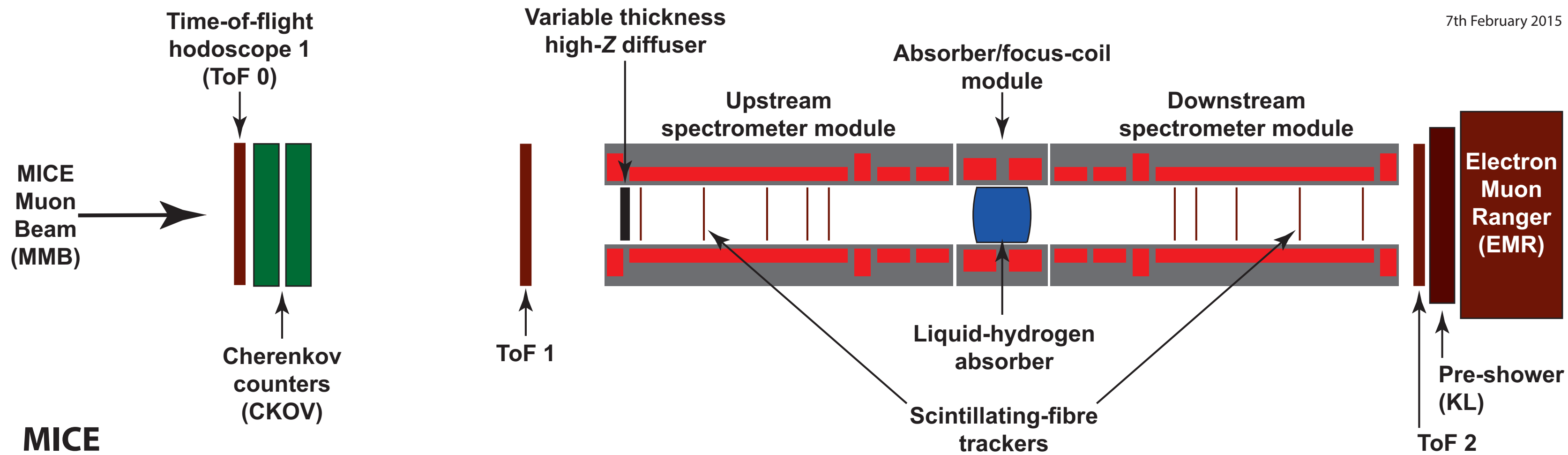
Overview of Energy Loss

- The Bethe-Bloch formula gives

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0} \right)^2 \left[\ln \left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

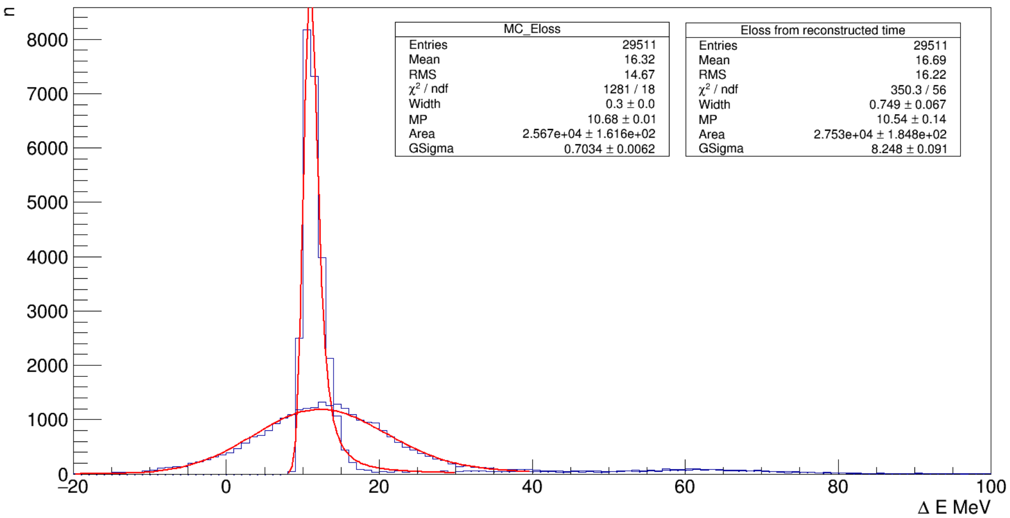
- GEANT includes Bethe-Bloch and corrections, but MICE is firmly in Bethe-Bloch energy range

Energy Loss Measurement Using TOF



- Assume energy loss in TOF and tracker is known
- $t_{\mathrm{TOF1}} - t_{\mathrm{TOF0}}$ gives initial velocity
- Assume energy loss in TOF1 and US tracker to find v_{ua} = velocity before absorber
- Guess v_{ad} = velocity after absorber, assume energy loss in DS tracker
- With known velocity at every point between TOF1 and TOF2, calculate t_{TOF2}
- Refine guess of v_{ad} until t_{TOF2} time matches observed value

Energy Loss Results using TOF



	MPV Energy Loss
MC Truth	9.18 ± 0.01 MeV
MC Reco	9.12 ± 0.04 MeV
Data Reco	9.23 ± 0.13 MeV

- MC studies show good reconstruction of peak energy loss, but not shape
- Good agreement between MC and data

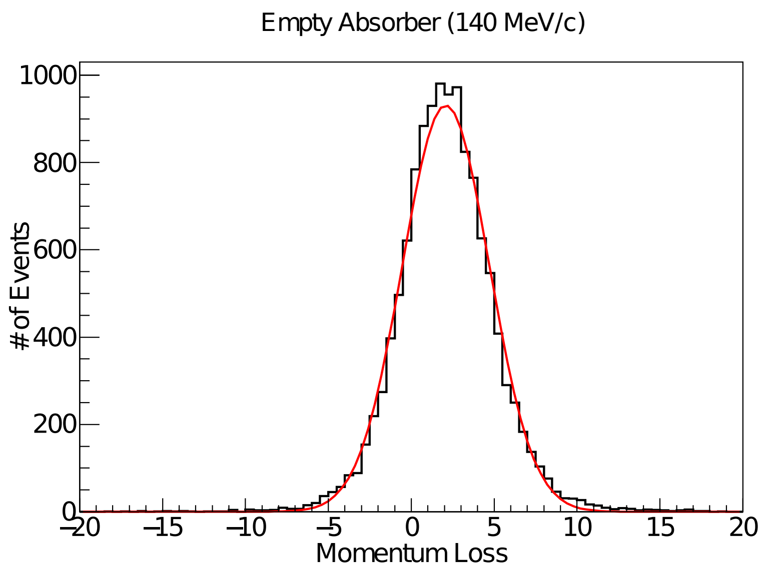
Field-On Energy Loss Measurement

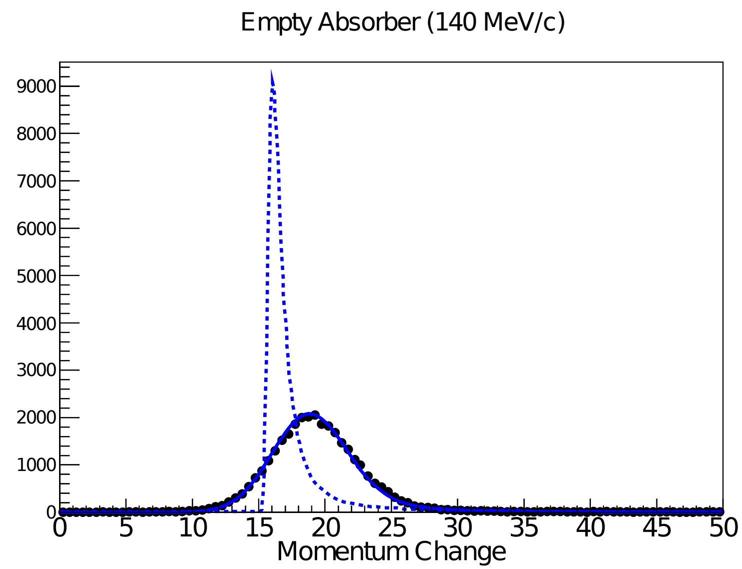
- Data taken from ISIS run period 2017/02 and 2017/03
- Require one upstream track and one downstream track
- Require tracks to have $p_t/p > 0.1$
- Use two-dimensional TOF/tracker cut to select muons

Combining TOF and Tracker Measurements

- Combine TOF01 and US Tracker to get US momentum
- Use DS Tracker to measure DS momentum
- Slightly improved US measurement, significantly improved DS measurement
- Measure energy loss distribution with and without absorber

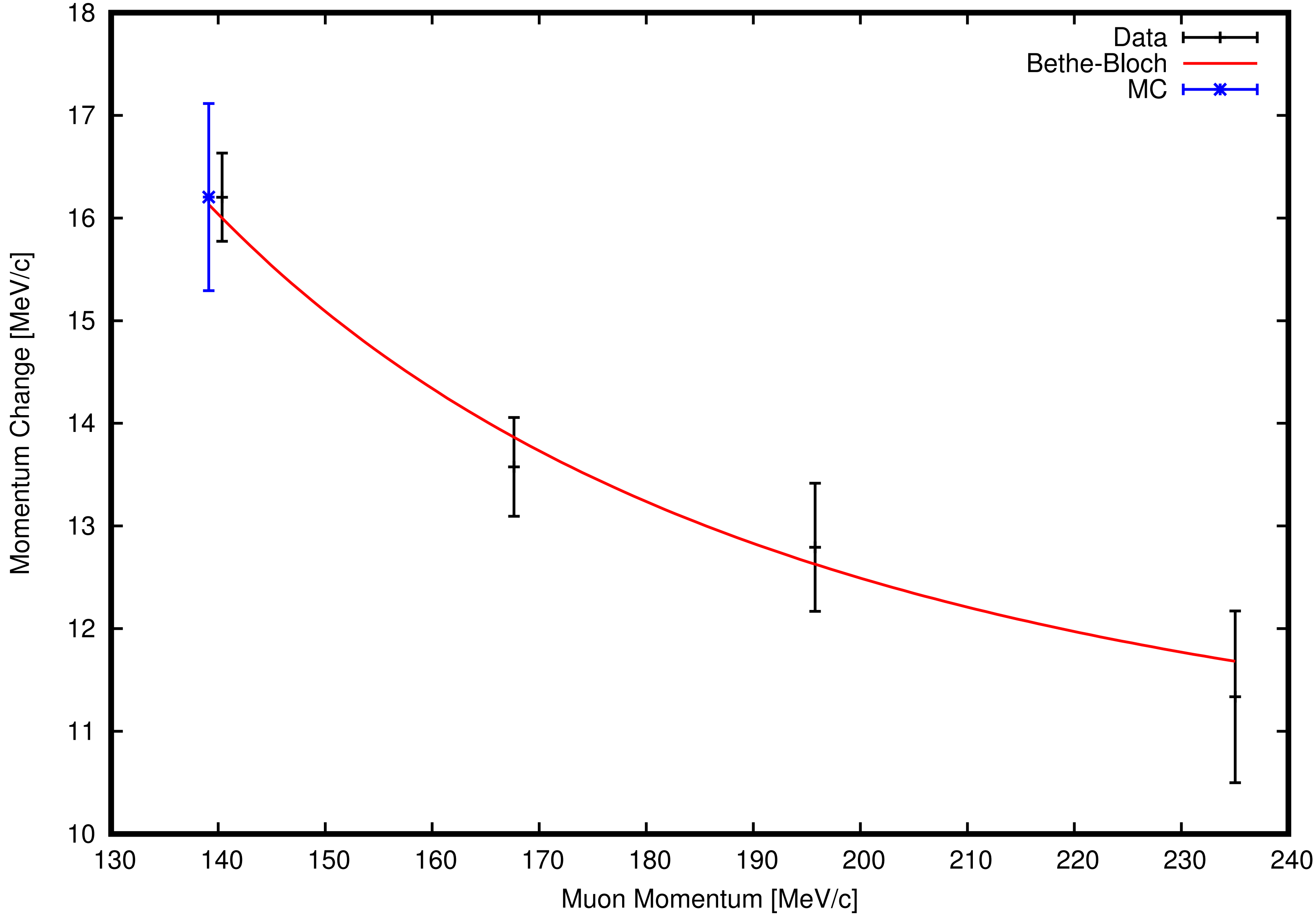
Convolution Fit





- Measure energy loss with no absorber, fit distribution to a gaussian $G_0(\Delta p)$
- Measure energy loss with absorber
- Fit distribution to $L_{\text{true}} \times G_0(\Delta p)$
  L_{true} is a Landau distribution of the true energy loss

Field-On Energy Loss Results



- Preliminary results: MC (energy loss modeled by GEANT) agrees with data
- Also seems to agree well with Bethe-Bloch prediction
- Systematic uncertainties are preliminary

Conclusions

- MICE has measured Coulomb scattering and energy loss of muons in LiH with 140 MeV/$c < p <$ 240 MeV/c
- Data has been compared to simulation packages such as GEANT and other relevant models
- Multiple publications in the works (MCS paper forthcoming, energy loss in Rhys Gardener's thesis at Brunel)
- Work is ongoing to refine measurements with field-on data and expand measurements to liquid Hydrogen