Recent results from MICE on multiple Coulomb scattering and energy loss

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MICE: Muon ionization Cooling Experiment

For a complete introduction to MICE and an overview of all of the latest results see P. Soler's talk: MICE Results (Thu 11:50)

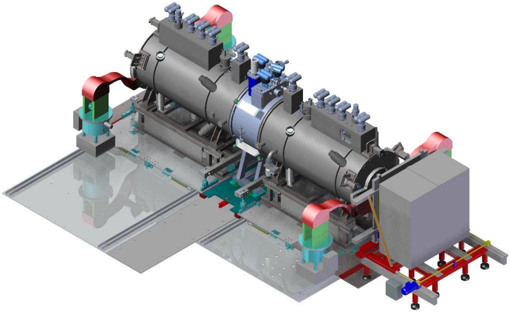
Why use muons?

- muons are ∼200 heavier than electrons thus the rate of emission of synchrotron/bremsstrahlung radiation is lower allowing for more compact facilities
- Could be used as a high quality beam for a Neutrino Factory
- The μ has a short lifetime 2.2 μs - the only cooling technique which can be employed is ionization cooling

Goals of MICE

- Design, build, commission, and operate a section realistic cooling channel
- Measure its performance in a variety of modes of operation and beam conditions
- Measure material properties of potential absorbers (LiH and liquid hydrogen)

The MICE Experiment: Step IV



Ionization Cooling

The rate of change of normalised emittance due to ionization cooling is:

$$\frac{d\varepsilon_n}{dz} \approx -\frac{\varepsilon_n}{\beta^2 E}\left\langle \frac{dE}{dz} \right\rangle + \frac{\beta_\perp (13.6\mathrm{MeV})^2}{2\beta^3 E m X_0} \quad (1)$$

Overview of models of multiple Coulomb scattering

- The PDG recommends this formula, based on work by Lynch and Dahl [1, 2] incorporating path length effects (accurate to $\sim$11%)

$$\theta_0 = \frac{13.6\,\mathrm{MeV}}{p_\mu c \beta_{\rm rel}} Z \sqrt{\frac{\Delta z}{X_0}} \left[1 + 0.038 \ln\left(\frac{Z^2 \Delta z}{\beta_{\rm rel}^2 X_0}\right)\right] \tag{2}$$

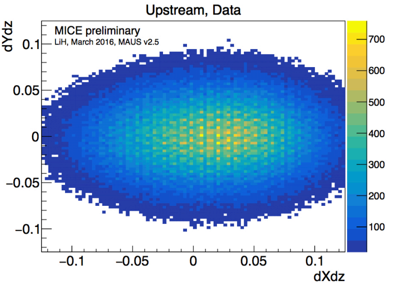
- The resulting distribution is non-Gaussian with the shape dependant on the thickness of the absorber
- Goal of MICE is to measure $d\varepsilon_n/dz$ to precision of 0.1%
- MUSCAT [3] showed poor agreement between GEANT simulations and low Z material scattering data
- MICE has taken scattering data for muons on a LiH target.
  - LiH composition: 81% ^{6}Li, 4% ^{7}Li, 14% ^{1}H (trace of C, O, and Ca)

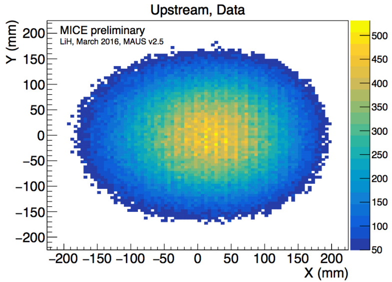
Overview of models of multiple Coulomb scattering

- GEANT4, full Legendre polynomial expansion & uses the Urban scattering model [4] for most particles and the Wentzel/Coulomb models for muons.
- Moliere [5] calculation solves the scattering transport equation describing the scattering distribution with a single variable χ_a, the resulting distribution is non-Gaussian
- ELMS covering both energy loss and multiple scattering based on electromagnetic first principles, was developed by Allison and Holmes [6, 7] and shows good agreement with hydrogen data.
- Cobb-Carlisle model [8, 9], samples directly from the Wentzel single-scattering cross-section and simulates all collisions with nuclei and electrons. Includes a cut-off for the nuclear cross-section and separate contributions from the nuclear and atomic electron scattering

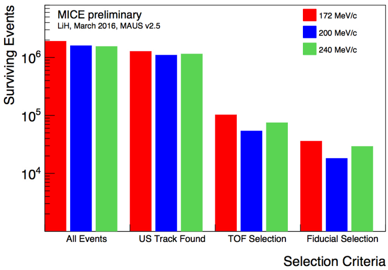
Scattering Data

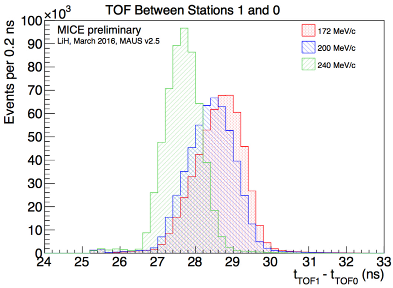
- Field off data sets were collected in ISIS run periods 2015/03 and 2015/04
- A momentum dependent multiple scattering measurement is made
- Measure empty channel scattering
  - Convolved with physics model of scattering in absorber $\rightarrow$ prediction.
- Measure absorber scattering
  - A Bayesian deconvolution algorithm unfolds absorber scattering distribution
- χ^2 comparison between data and prediction
  - Width of scattering distribution: Θ as a function of P





Selection



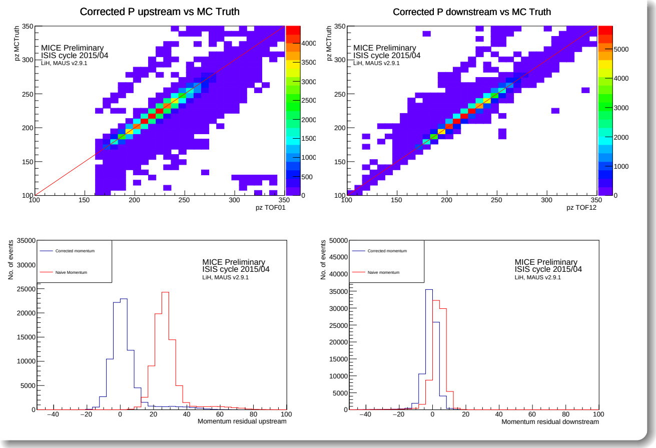


Procedure

- Require an US track. If a DS track not extant, statistics set to overflow values.
- Analysis done in 200 ps TOF 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 plane 1 projected

Momentum Correction

A correction must be applied to the P as reconstructed by the TOF to account for the additional path length and energy loss in the channel



- The exact P at the centre of the absorber can be described by an analytic expression which is the second order expansion of the Taylor series in p/mc
- Caveat is constant energy loss is assumed in derivation

Scattering Data

- Define projection angles

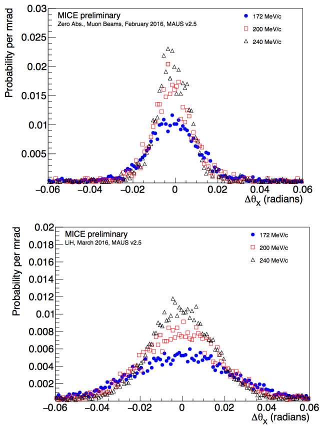
$$\theta_y = \text{atan}\left(\frac{p_{DS} \cdot (\hat{y} \times p_{US})}{|\hat{y} \times p_{US}||p_{DS}|}\right) \quad (3)$$

and

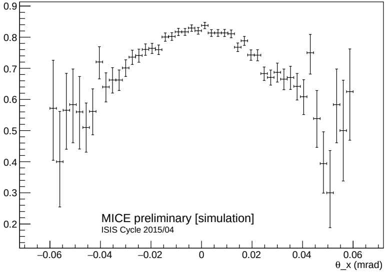
$$\theta_x = \text{atan}\left(\frac{p_{DS} \cdot (p_{US} \times (\hat{y} \times p_{US}))}{|p_{US} \times (\hat{y} \times p_{US})||p_{DS}|}\right) \quad (4)$$

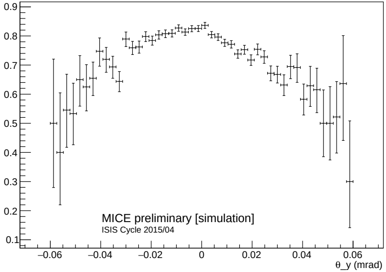
- A simple cross check is that $\theta_x^2 + \theta_y^2 \approx \theta_{scatt}^2$ where the θ_{scatt} is defined as:

$$\cos\theta_{scatt} = \frac{p_{US} \cdot p_{DS}}{|p_{US}||p_{DS}|} \quad (5)$$



Tracker Acceptance





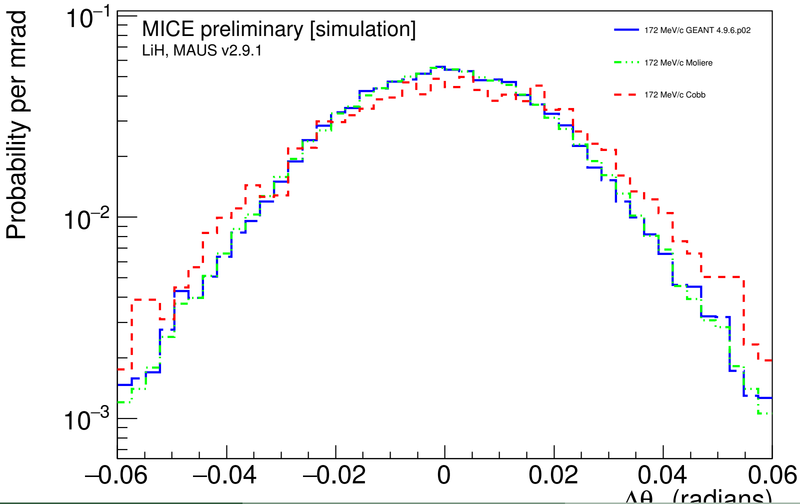
- Match track upstream and downstream
- TOF selection
- Calculate angle θ as described in slide 9
- Downstream acceptance is defined

$$\frac{\text{No. of tracks in } \theta \text{ bin MC Truth that are reconstructed}}{\text{No. of tracks in } \theta \text{ bin MC Truth}} \tag{6}$$

- Correction done on bin-by-bin basis dividing by measured acceptance

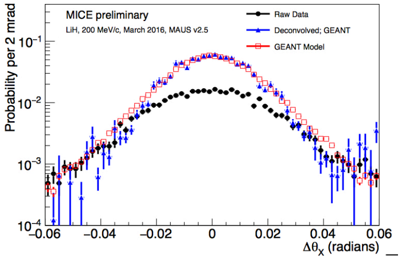
Physics Model & Scattering Prediction

Three different physics models are used to make the scattering prediction, GEANT4, Carlisle-Cobb & Moliere, these are convolved with the empty channel data



Deconvolution of Raw Scattering Data

- Use an iterative algorithm from RooUnfold [10] that uses the Bayesian conditional probability to characterize the response of the reconstructed scattering angle to the true scattering angle
- Right: example output from this algorithm



Bayes Theorem

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

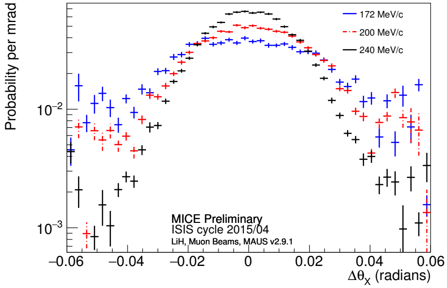
- We want $C_i = \Delta\theta_Y^{abs}$ the deflection angle in the absorber material.
- We measure $E_j = \Delta\theta_Y^{tracker}$ the deflection angle measured at the first tracker plane

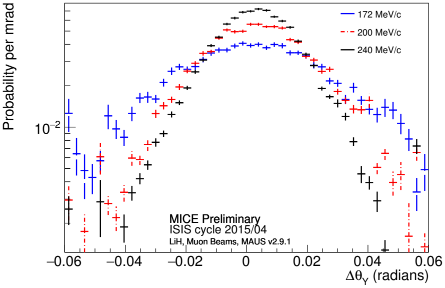
Systematics

- A study of the systematics is in progress
- The results remain preliminary
- Several sources have been considered
  - Material thickness uncertainties
  - Alignment uncertainties
  - TOF uncertainties
  - Fiducial volume uncertainties
  - Pion contamination
  - Definition of scattering angles
  - Channel acceptance
- Further work is required to clarify the various contributions

Results slide - deconvolution

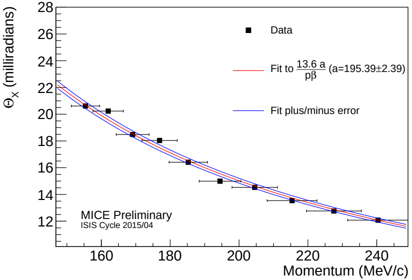
Preliminary MICE result

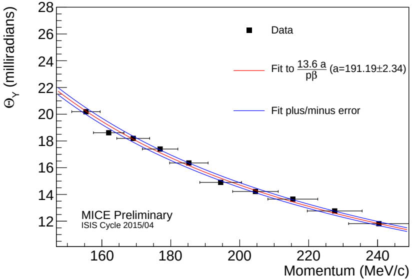




- Measurement of scattering at each nominal momentum point following the deconvolution procedure - final value is a Gaussian fit to the central -40 to +40 mrad

Θ as a Function of Momentum





- Scan across the entire momentum range and measure scattering in both projections in each bin
- The fitted a is compared to $\sqrt{\frac{z}{X_0}}(1 + 0.038\ln\frac{z}{X_0})$

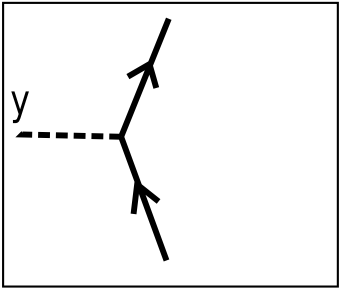
Conclusions

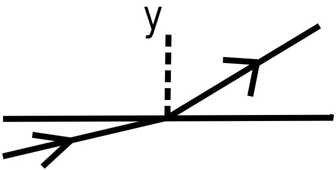
- MICE has measured multiple Coulomb scattering of μ with $140 < P < 240$ MeV/c off lithium hydride
- Data has been compared to popular simulation packages such as GEANT4 and other relevant models such as Moliere and Carlisle-Cobb
- A study of the systematics is in progress, a MICE publication is currently being prepared
- Future work will include a measurement of multiple Coulomb scattering off liquid hydrogen, measurement with magnetic field in the cooling channel and energy loss measurement

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 vectors 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 considered approach is required as detailed in `http://www.ppe.gla.ac.uk/~jnugent/Projected-angles.pdf` by John Cobb





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