

Recent results from MICE on multiple Coulomb scattering and energy loss

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13/8/2018

MICE: Muon Ionisation 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)

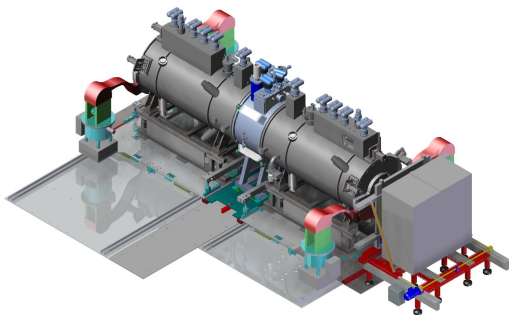
Why use μ s?

- μ s are ~ 200 heavier than electrons thus the rate of emission of synchrotron 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 2.2μ s - the only cooling technique which can be employed is ionisation cooling

Goals of MICE

- Design, build, commission, and operate a 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:

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

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 $\sim 11\%$)

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

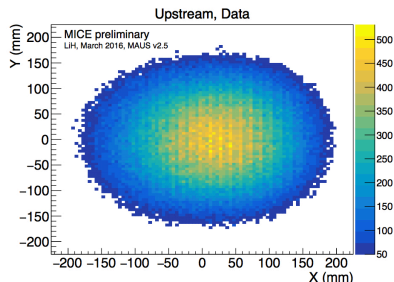
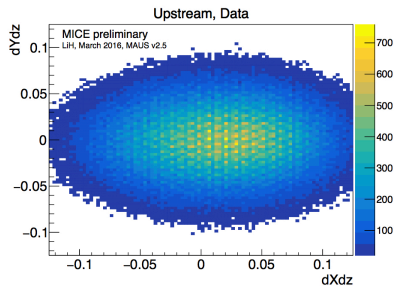
- The resulting distribution is non-gaussian with the shape dependant on the thickness of the absorber
- Goal of MICE is to measure $d\varepsilon_n/dz$ to precision of 0.1%
- MUSCAT [3] showed poor agreement between GEANT simulations and low Z material scattering data
- MICE has taken scattering data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

Overview of models of multiple Coulomb scattering

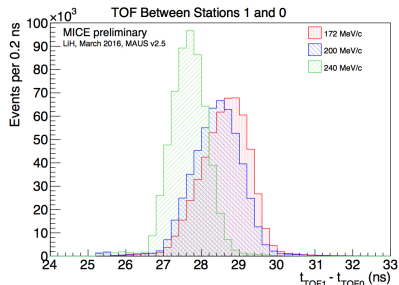
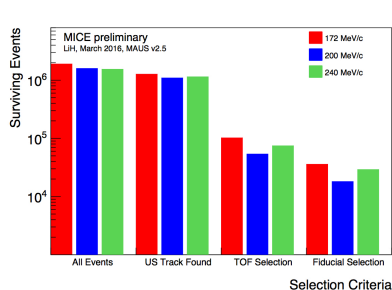
- GEANT4, full Legendre polynomial expansion & uses the Urban scattering model [4] for most particles and the Wentzel/Coulomb models for muons.
- Moliere [5] calculation solves the scattering transport equation describing the scattering distribution with a single variable χ_a , the resulting distribution is non-Gaussian
- ELMS covering both energy loss and multiple scattering (ELMS) 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. 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 - 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

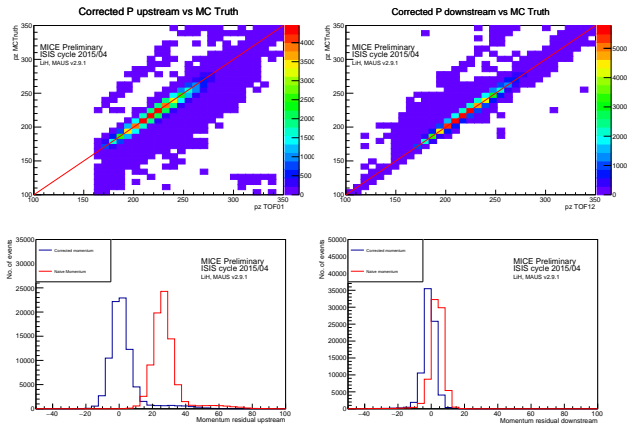


Procedure

- Require 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 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

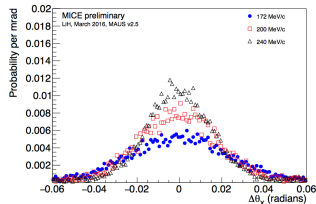
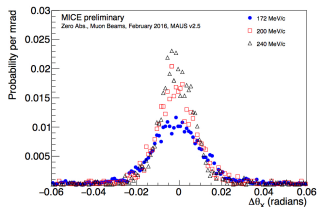
$$\theta_y = \text{atan} \left(\frac{p_{DS} \cdot (\hat{y} \times p_{US})}{|\hat{y} \times p_{US}| |p_{DS}|} \right) \quad (3)$$

and

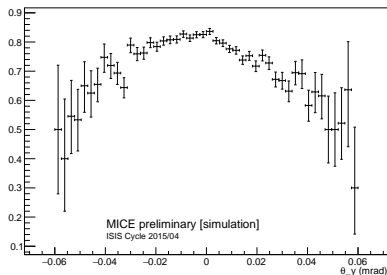
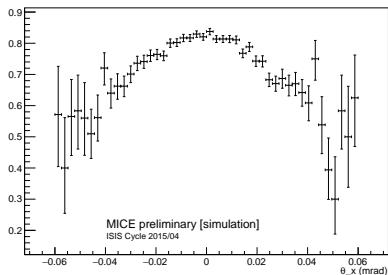
$$\theta_x = \text{atan} \left(\frac{p_{DS} \cdot (p_{US} \times (\hat{y} \times p_{US}))}{|p_{US} \times (\hat{y} \times p_{US})| |p_{DS}|} \right) \quad (4)$$

- 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



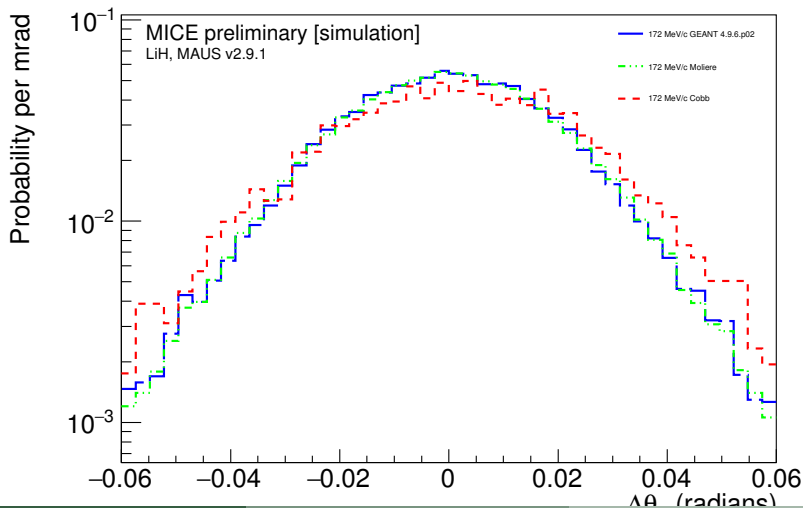
- Match track upstream and downstream
- TOF selection
- Calculate angle θ as per analysis
- Downstream acceptance is defined

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

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

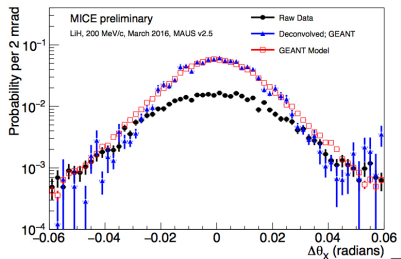
Physics Model & Scattering Prediction

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 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

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

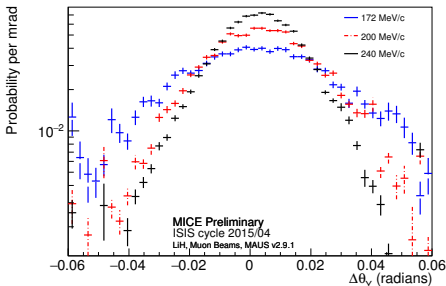
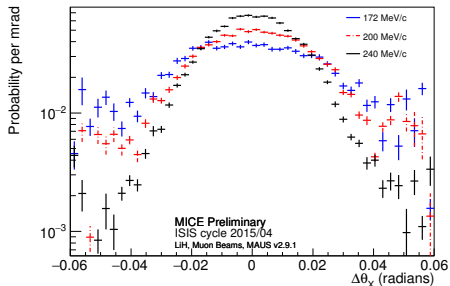
- We want $C_i = \Delta\theta_Y^{abs}$ the deflection angle in the absorber material.
- We measure $E_j = \Delta\theta_Y^{tracker}$ the deflection angle measured at the first tracker plane

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

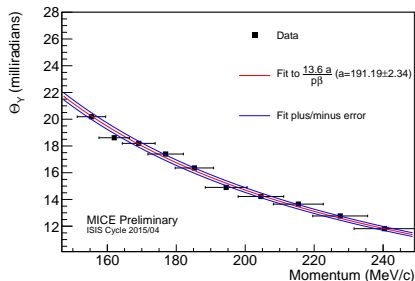
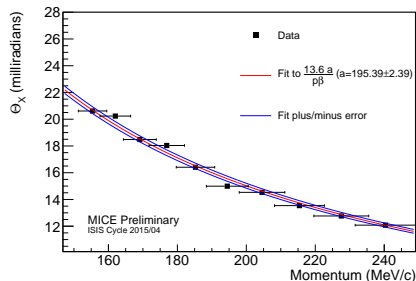
Results slide - deconvolution

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 fit is made for $a = \sqrt{\frac{z}{X_0}} (1 + 0.038 \ln \frac{z}{X_0})$

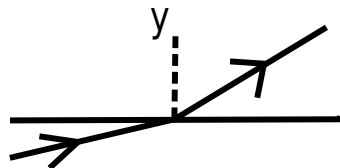
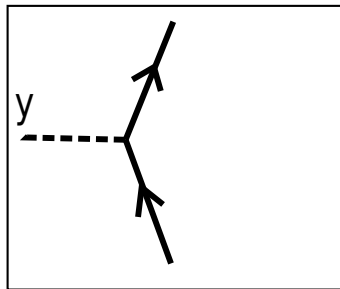
Conclusions

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



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- [2] Gerald R. Lynch and Orin I. Dahl. Approximations to multiple Coulomb scattering. *Nucl. Instrum. Meth.*, B58:6–10, 1991.
- [3] D. Attwood et al. The scattering of muons in low Z materials. *Nucl. Instrum. Meth.*, B251:41–55, 2006.
- [4] S. Agostinelli et al. GEANT4: A Simulation toolkit. *Nucl. Instrum. Meth.*, A506:250–303, 2003.
- [5] G. Moliere. Theory of the scattering of fast charged particles. 2. Repeated and multiple scattering. *Z. Naturforsch.*, A3:78–97, 1948.
- [6] W. W. M. Allison. Calculations of energy loss and multiple scattering (ELMS) in molecular hydrogen. *J. Phys.*, G29:1701–1703, 2003.
- [7] Simon Holmes. The Physics of Muon Cooling for a Neutrino Factory. *DPhil thesis, University of Oxford*, 2006.
- [8] Timothy Carlisle. Step IV of the Muon Ionization Cooling Experiment (MICE) and the multiple scattering of muons. *DPhil thesis, University of Oxford*, 2013.
- [9] T. Carlisle, J. Cobb, and D. Neuffer. Multiple Scattering Measurements in the MICE Experiment. *Conf. Proc.*, C1205201:1419–1421, 2012.