Recent results from MICE on multiple Coulomb scattering and energy loss

Author: John Nugent
Speaker: Daniel Kaplan
on behalf of the MICE Collaboration

University of Glasgow

john.nugent@glasgow.ac.uk

24/9/2019

MICE: Muon ionization Cooling Experiment

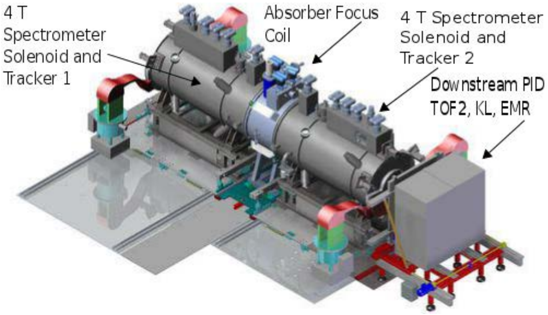
Why use muons?

- $\sim 200\times$ heavier than electrons $\implies$ rate of emission of synchrotron/bremsstrahlung radiation lower allowing more compact facilities
- With cooling could be used as high quality beam for Neutrino Factory
- μ has short lifetime 2.2 μs - only cooling technique which can be employed is ionization cooling

Goals of MICE

- Design, build, commission, and operate section of 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

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

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

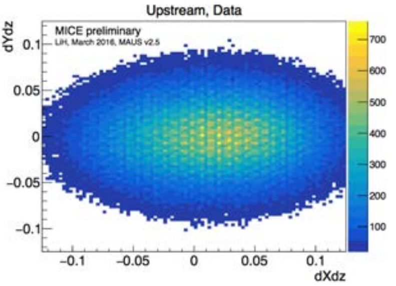
- Resulting distribution is non-Gaussian with the shape dependant on the thickness of the absorber
- Goal of MICE is to measure $d\varepsilon_n/dz$ to precision of 0.1%
- MUSCAT [3] showed poor agreement between GEANT simulations and low Z material scattering data
- MICE has taken scattering data for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

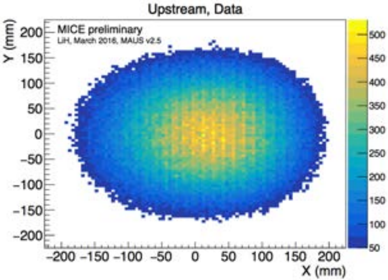
Overview of models of multiple Coulomb scattering

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

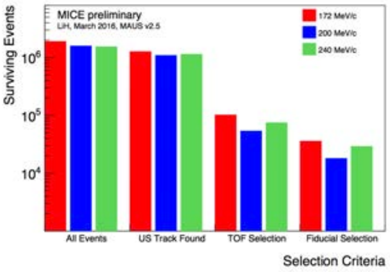
Scattering Data

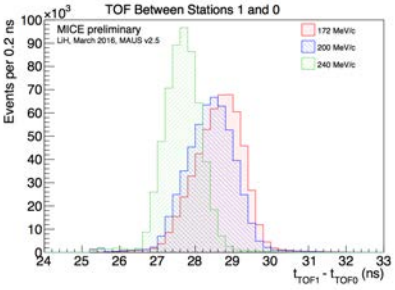
- Field off data sets were collected in ISIS run periods 2015/03 and 2015/04
- A momentum dependent multiple scattering measurement is made
- Measure empty channel scattering
  - Convolved with physics model of scattering in absorber $\rightarrow$ prediction.
- Measure absorber scattering
  - A Bayesian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





Selection



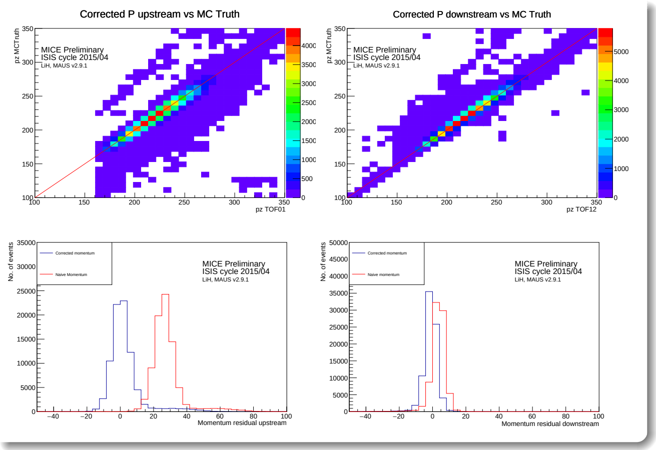


Procedure

- 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, including scattering, to appear within central 140 mm radius of DS tracker

Momentum Correction

Correction must be applied to the p as reconstructed by the TOF to account for additional path length and energy loss in channel



- Exact P at centre of absorber described by an analytic expression which is second order expansion of the Taylor series in p/mc
- Assume constant energy loss

Scattering Data

- Define projection angles

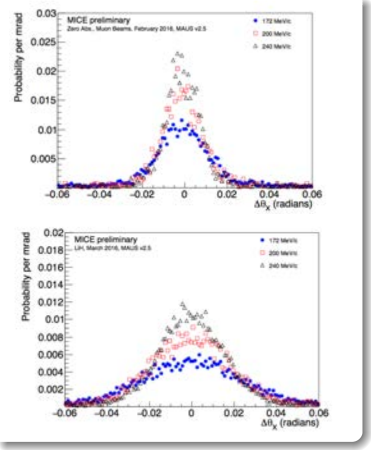
$$\theta_y = \text{atan}\left(\frac{p_{DS} \cdot (\hat{y} \times p_{US})}{|\hat{y} \times p_{US}||p_{DS}|}\right) \quad (3)$$

and

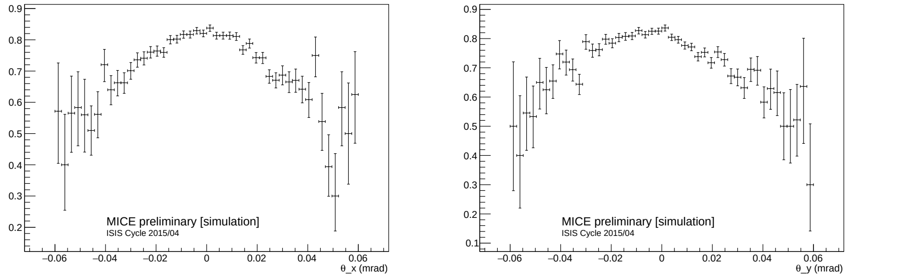
$$\theta_x = \text{atan}\left(\frac{p_{DS} \cdot (p_{US} \times (\hat{y} \times p_{US}))}{|p_{US} \times (\hat{y} \times p_{US})||p_{DS}|}\right) \quad (4)$$

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

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



Tracker Acceptance



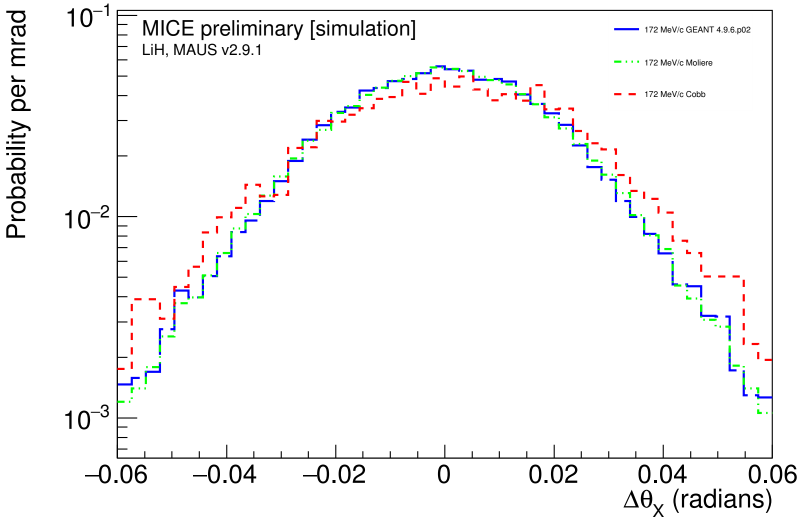
- Pair an US & DS track
- Acceptance is not 100% due to apertures in the channel
- Calculate angle θ as described in slide 9
- Downstream acceptance is defined

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

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

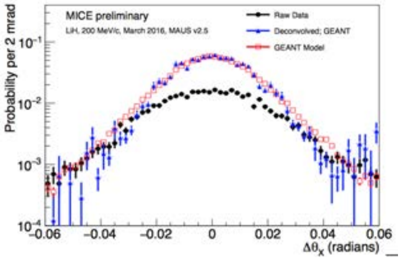
Physics Model & Scattering Prediction

Three different physics models are used, GEANT4, Carlisle-Cobb & Moliere, convolved with the empty channel data



Deconvolution of Raw Scattering Data

- Measure scattering in LiH
- Empty channel data convolved with model
- RooUnfold [10] uses Bayesian conditional probability to deconvolve
- Right: example output from this algorithm



Bayes' Theorem

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

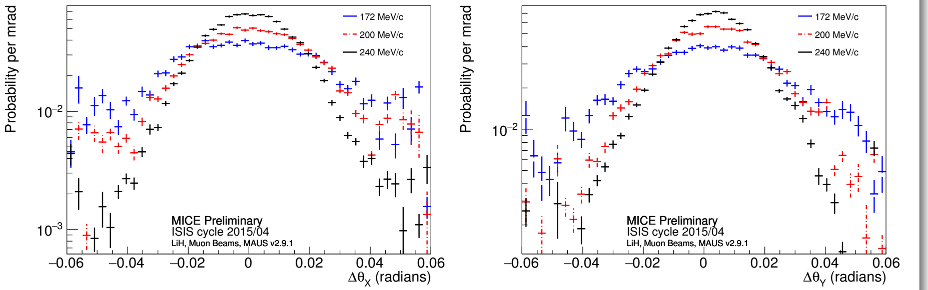
- We want $C_i = \Delta\theta^{abs}$ the deflection angle in the absorber material.
- We measure $E_j = \Delta\theta^{tracker}$ the deflection angle measured at the first tracker plane

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

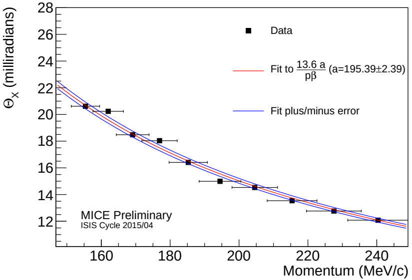
Results slide - deconvolution

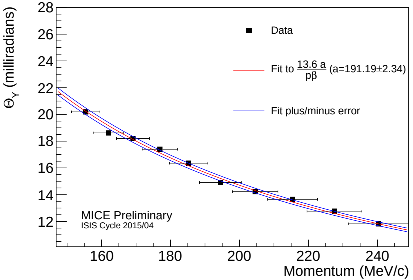
Preliminary MICE result



- Measurement of scattering at each nominal momentum point following the deconvolution procedure - fit Gaussian to the central -40 to +40 mrad
- Report the width of the fitted distribution

θ as a Function of Momentum





- Scan across the entire momentum range and measure scattering in both projections in each bin

Conclusions

- MICE has measured multiple Coulomb scattering of μ with $140 < P < 240$ MeV/c in 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 in liquid hydrogen, measurement with magnetic field in the cooling channel and energy loss measurement

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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.

[10] G. D'Agostini. A Multidimensional unfolding method based on Bayes' theorem. *Nucl. Instrum. Meth.*, A362:487–498, 1995.