Recent results from MICE on multiple Coulomb scattering and energy loss

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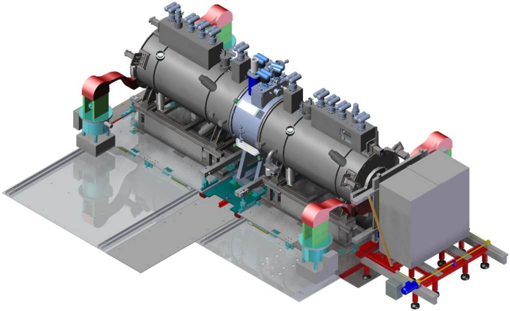
The MICE Experiment: Step IV



Ionisation Cooling

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

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

Overview 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%)

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

- Goal of MICE is to measure $d\varepsilon_n/dz$ to precision of 0.1%
- MUSCAT [3] showed poor agreement between theory and low Z material scattering data

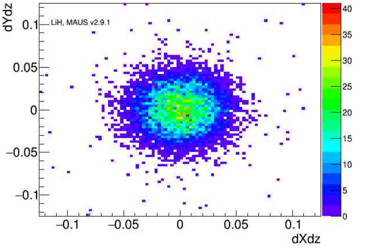
Overview of multiple Coulomb scattering

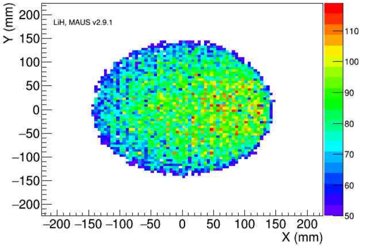
- GEANT4, full Legendre polynomial expansion & evaluates the Urban cross-section [4] for most particles and the Wentzel single-scattering cross-section for muons.
- Moliere [5] calculation solves the scattering transport equation describing scattering with a single variable χ_a
- ELMS covering both energy 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 seperate contributions from the nuclear and atomic electron scattering

$$\frac{\theta_0^2}{z} = 8\pi N_A \frac{Z^2}{A} r_e^2 \left(\frac{mc}{p_\mu \beta} \left[\ln\left(\frac{\theta_2}{\theta_1}^2 + 1 \right) - 1 \right] + \frac{1}{Z} \left[\ln\left(\frac{\theta_2^e}{\theta_1^e}^2 + 1 \right) - 1 \right] \right) \quad (3)$$

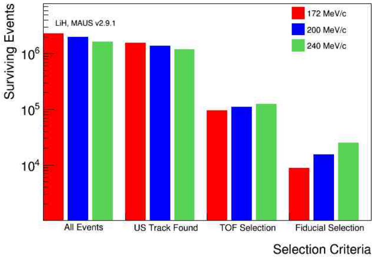
Scattering Data

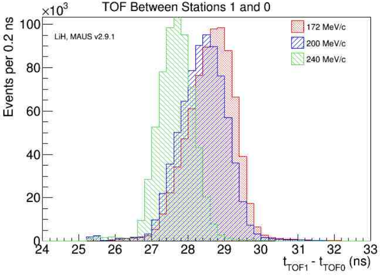
- Field off data sets were collected in ISIS run periods 2015/03 and 2015/04
- A momentum dependent multiple scattering measurement is made
  - Measure empty channel scattering
  - Convolved with physics model of scattering in absorber - prediction.
  - Measure absorber scattering
  - Prediction is response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





Selection



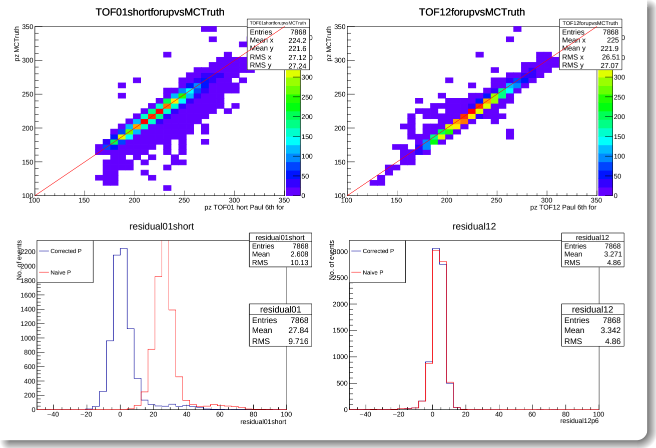


Procedure

- 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

`http://www.ppe.gla.ac.uk/~jnugent/TOFnote.pdf`

Scattering Data

- Define projection angles

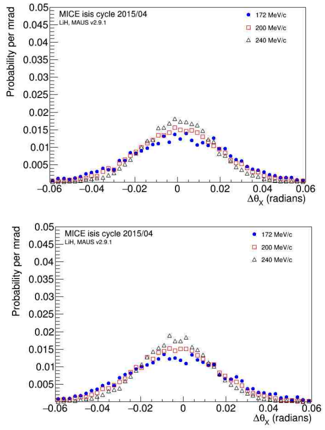
$$\theta_y = \text{atan}\left(\frac{p_{DS} \cdot (\hat{y} \times p_{US})}{|\hat{y} \times p_{US}||p_{DS}|}\right) \quad (4)$$

and

$$\theta_x = \text{atan}\left(\frac{p_{DS} \cdot (p_{US} \times (\hat{y} \times p_{US}))}{|p_{US} \times (\hat{y} \times p_{US})||p_{DS}|}\right) \quad (5)$$

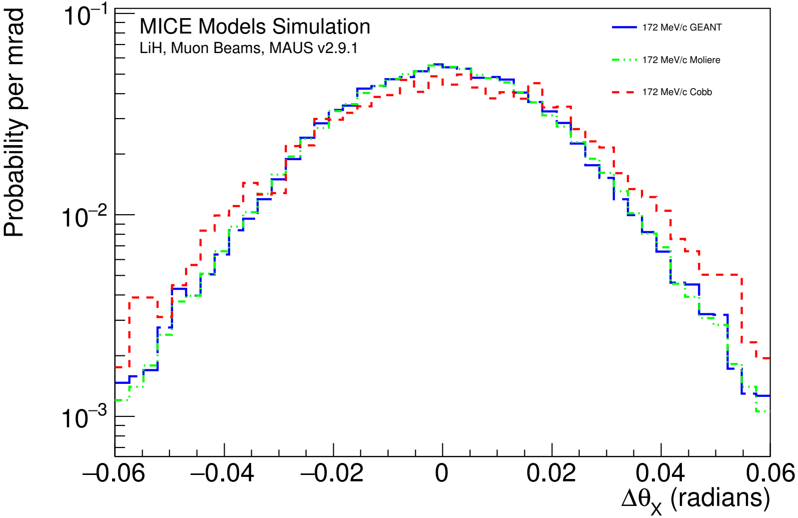
- Where $\theta_x^2 + \theta_y^2 \approx \theta_{scatt}^2$ with

$$\cos\theta_{scatt} = \frac{p_{US} \cdot p_{DS}}{|p_{US}||p_{DS}|} \quad (6)$$



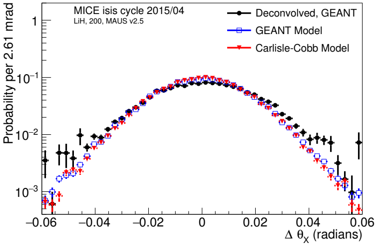
Physics Model

Three different physics models are used to make the scattering prediction, GEANT4, Carlisle-Cobb & Moliere



Deconvolution of Raw Scattering Data

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

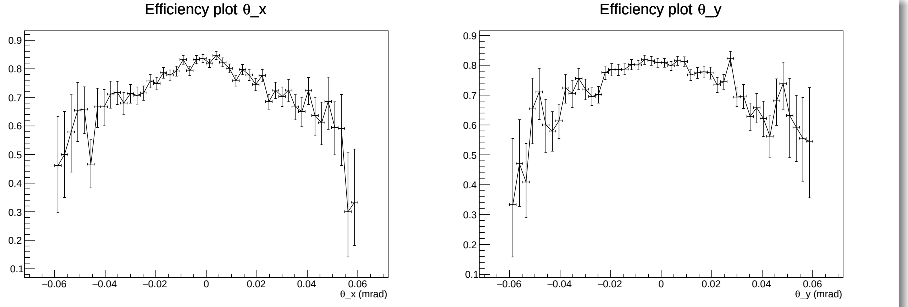


Bayes Theorem

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

- 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 Efficiency



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

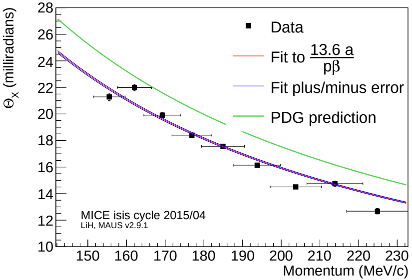
$$\frac{\text{No. of tracks in } \theta \text{ bin MC Truth that are reconstructed}}{\text{No. of tracks in } \theta \text{ bin MC Truth}} \quad (7)$$

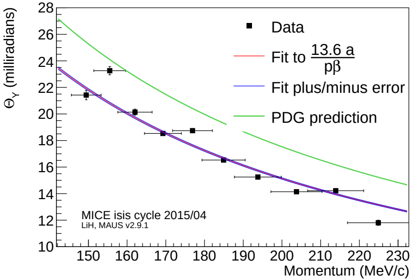
Results slide - deconvolution

p (MeV/c)		Meas. (mrad)	G4 Pred.	χ^2/DoF	CC Pred.	χ^2/DoF
171.89±0.07	θ_X	22.82±0.33±0.85	19.27±0.1	1074.4 / 34	19.45±0.1	961.8 / 34
171.89±0.07	θ_Y	23.13±0.39±0.63	19.05±0.1	1657.6 / 34	19.18±0.1	1475.0 / 34
199.3±0.06	θ_X	18.7±0.18±0.6	16.61±0.07	1306.7 / 34	16.21±0.07	1635.6 / 34
199.3±0.06	θ_Y	17.91±0.17±0.84	16.39±0.07	1825.5 / 34	16.04±0.07	1884.2 / 34
243.73±0.08	θ_X	14.33±0.08±0.55	13.29±0.04	1327.2 / 34	13.06±0.03	1617.2 / 34
243.73±0.08	θ_Y	14.4±0.09±0.55	13.1±0.04	4064.5 / 34	13.03±0.03	3297.4 / 34
171.89±0.07	θ^2_{Scatt}	32.92±1.23±0.31	26.91±0.23	2647.0 / 46	27.17±0.23	2735.6 / 46
199.3±0.06	θ^2_{Scatt}	25.34±0.52±0.69	23.19±0.15	1012.3 / 46	22.71±0.15	1152.2 / 46
243.73±0.08	θ^2_{Scatt}	20.14±0.2±0.68	18.61±0.07	1337.9 / 46	18.42±0.07	1393.5 / 46

- Measurement of scattering at each nominal momentum point following the deconvolution proceedure - gaussian fit is performed on 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
- Comparison with PDG formula is made and the fit is made for $a = \sqrt{\frac{z}{X_0}}(1 + 0.038 \ln \frac{z}{X_0})$

Conclusions

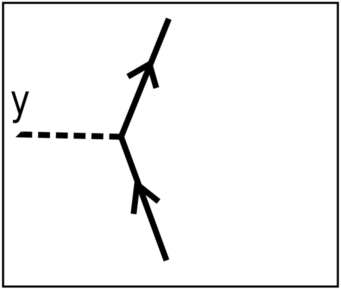
- MICE has taken data measuring multiple Coulomb scattering of μ with $140 < P < 240$ MeV/c off LiH
- Data has been compared to popular simulation packages such as GEANT4 and other relevant models such as Moliere and Carlisle-Cobb
- Future work will inlcuding a measurement of multiple Coulomb scattering off liquid hydrogen, measurement with magnetic field in the cooling channel and also system check of energy loss measurement

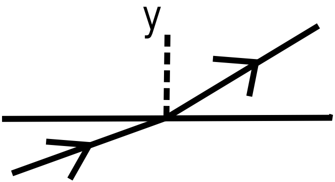
- All data and MC processed with MAUS v2.9.1
- Analytic expression used to correct momentum calculated from TOF system
- Moliere model fully incorporated into analysis
- Tracker efficiency now incorporated into scattering distributions
- Final results and figures updated to reflected changes

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





Selection

Selection	Description	μ Beams, LiH abs. 172	200	240	π Beam 240
TOF1 trigger	At least two raw TOF slab hits exist and at least one in each TOF plane.	1.	1.	1.	1.
Upstream track selection	There is one US track and at most one track in the DS tracker (If is are no DS track $\theta_X = \theta_Y = 45°$).	66.8%	68.4%	74.1%	59.0%
TOF timing selection	Select muons from run at the target momentum.	3.8%	5.4%	7.5%	35.0%
Fiducial selection	For projected US tracks $\sqrt{x^2+y^2} < r_0$ at DS ref plane, 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.	0.3%	0.5%	0.8%	2%

[1]

[1] Taken from MCSNote

[1] K. A. Olive et al. Review of Particle Physics. *Chin. Phys.*, C38:090001, 2014.

[2] Gerald R. Lynch and Orin I. Dahl. Approximations to multiple Coulomb scattering. *Nucl. Instrum. Meth.*, B58:6–10, 1991.

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[5] G. Moliere. Theory of the scattering of fast charged particles. 2. Repeated and multiple scattering. *Z. Naturforsch.*, A3:78–97, 1948.

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[8] Thimothy 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.