# Recent results from MICE on multiple Coulomb scattering and energy loss

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## The MICE Experiment: Step IV



Ionization Cooling

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

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

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  $\sim 11\%$ )

$$\theta_0 \approx \frac{13.6 \,\mathrm{MeV}}{p_\mu \beta_{\mathrm{rel}}} \sqrt{\frac{\Delta z}{X_0}} \left[ 1 + 0.038 \ln\left(\frac{\Delta z}{X_0}\right) \right]$$
(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
- MICE has taken scattering data for muons on a LiH target.
  - ▶ LiH composition: 81% <sup>6</sup>Li, 4% <sup>7</sup>Li, 14% <sup>1</sup>H (trace of C, O, and Ca)

### 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  $\chi_a$
- 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

$$\frac{\theta_0^2}{z} = 8\pi N_A \frac{Z^2}{A} r_e^2 \left( \frac{mc}{p_\mu \beta} \left[ \ln \left( \frac{\theta_2^2}{\theta_1}^2 + 1 \right) - 1 \right] + \frac{1}{Z} \left[ \ln \left( \frac{\theta_2^e}{\theta_1^e}^2 + 1 \right) - 1 \right] \right)$$
(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
  - A Bayesian deconvolution algorithm unfolds absorber scattering distribution
  - ▶  $\chi^2$  comparison between data and prediction
  - Width of scattering distribution:
     Θ as a function of P



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### 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

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### Scattering Data

• Define projection angles

$$heta_y = \mathsf{atan}igg(rac{p_{DS} \cdot (\hat{y} imes p_{US})}{|\hat{y} imes p_{US}||p_{DS}|}igg)$$

and

٠

$$\theta_{x} = \operatorname{atan}\left(\frac{p_{DS} \cdot (p_{US} \times (\hat{y} \times p_{US}))}{|p_{US} \times (\hat{y} \times p_{US})||p_{DS}|}\right)$$
(5)
Where  $\theta_{x}^{2} + \theta_{y}^{2} \approx \theta_{scatt}^{2}$  with

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



(4)

(6)

### Tracker Acceptance



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

No. of tracks in  $\theta$  bin MC Truth that are reconstructed

#### No. of tracks in $\theta$ bin MC Truth

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(7)

### 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 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.

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### 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
- 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 proceedure - final value is a Gaussian fit to the central -40 to +40 mrad

### $\Theta$ 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  $a = \sqrt{rac{z}{X_0}}(1+0.038 \ln rac{z}{X_0})$

### Conclusions

- MICE has measured multiple Coulomb scattering of  $\mu$  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 including 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 apporach is required as detailed in http://www.ppe.gla.ac.uk/ ~jnugent/Projected-angles.pdf by John Cobb



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