Recent results from MICE on multiple Coulomb scattering and energy loss

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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
- $\mu$ has short lifetime 2.2 $\mu$s - 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:

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

(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 $\sim 11\%$)

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

\[ (2) \]

- 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\% $^6\text{Li}$, 4\% $^7\text{Li}$, 14\% $^1\text{H}$ (trace of C, O, and Ca)
  - Other absorbers: liquid hydrogen & plastic wedge
Overview of models of multiple Coulomb scattering

- Moliere [5] calculation solves scattering transport equation describing scattering distribution with single variable $\chi_a$ – 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 → prediction.
- Measure absorber scattering
  - A Bayesian deconvolution algorithm unfolds absorber scattering distribution
- $\chi^2$ comparison between data and prediction
  - Width of scattering distribution: $\theta$ as a function of $p$
**Selection**

![Graph showing survival events and TOF between stations 1 and 0](image)

**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

\[
\theta_y = \arctan\left( \frac{p_{DS} \cdot (\hat{y} \times p_{US})}{|\hat{y} \times p_{US}| |p_{DS}|} \right)
\]  

(3)

and

\[
\theta_x = \arctan\left( \frac{p_{DS} \cdot (p_{US} \times (\hat{y} \times p_{US}))}{|p_{US} \times (\hat{y} \times p_{US})| |p_{DS}|} \right)
\]  

(4)

- A simple cross check is that

\[
\theta_x^2 + \theta_y^2 \approx \theta_{\text{scatt}}^2
\]

where \( \theta_{\text{scatt}} \) is defined as:

\[
\cos \theta_{\text{scatt}} = \frac{p_{US} \cdot p_{DS}}{|p_{US}| |p_{DS}|}
\]  

(5)
• Pair an US & DS track
• Acceptance is not 100% due to apertures in the channel
• Calculate angle $\theta$ as described in slide 9
• Downstream acceptance is defined

\[
\text{No. of tracks in } \theta \text{ bin MC Truth that are reconstructed} \quad \frac{\text{No. of tracks in } \theta \text{ bin MC Truth}}{\text{No. of tracks in } \theta \text{ bin MC Truth}}
\] (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.

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**MICE preliminary [simulation]**
LiH, MAUS v2.9.1

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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

\[
P(C_i|E_j) = \frac{P(E_j|C_i)P_0(C_i)}{\sum_{l=1}^{nc} P(E_j|C_l)P_0(C_l)}
\]

- 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
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 $\mu$ 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.


