Analysis of Multiple Coulomb Scattering of Muons in the MICE Liquid H_2 Absorber

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The Muon Ionization Cooling Experiment (MICE), is a multi-national accelerator physics experiment created to demonstrate Ionization Cooling (IC); a new, rapid beam-cooling technique suitable for the short-lived muon. The performance of IC depends on two key processes - energy loss due to collisional ionization, and Multiple Coulomb Scattering (MCS) - for which accurate models are crucial in enabling quantitative design studies for future muon accelerators. Experimental measurements of MCS of positive muons with momenta in the range 170-240 MeV/c in liquid hydrogen are reported in this paper.

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1. Introduction

High-brightness muon beams may be used in future accelerator physics facilities for a range of research topics [1, 2]. Although the muon is an attractive candidate due to reduced Bremsstrahlung losses, the primary challenge is its short life-time (2.2μs at rest) and the relatively long cooling periods required by the current techniques to obtain high-brightness beams.

1.1 Ionization Cooling

A rapid beam cooling technique that exploits momentum loss due to ionizing collisions when a focused beam passes through a low atomic number (Z), high energy absorbent material was recently demonstrated in a particle-by-particle measurement of emittance [3] by the MICE collaboration. To evaluate the performance of future proposed facilities utilising IC, accurate modelling of both collisional ionization and MCS are needed. Past comparisons of predictive models of MCS and experimental measurements have been shown to differ [4]. MCS is the phenomenon describing the multiple small-angle scatters a charged particle undergoes when traversing a material. Equation (1) describes the RMS scattering width (of the central 98% of the distribution) for the plane projected angle $\theta_{x,y}$ ($y-z$, $x-z$ plane projection respectively) for a beam with momentum p, velocity $\beta = v/c$ traversing some distance z within a material with atomic number Z and radiation length X_0 [5].

$$\theta_{RMS} = \frac{13.6 MeV/c}{\beta p} Z \sqrt{\frac{z}{X_0}} \left(1 + 0.038 \frac{zZ^2}{X_0\beta^2} \right) \tag{1}$$

2. Method

2.1 The MICE Apparatus

The muons reaching MICE, are decay products of pions provided by the ISIS proton beam colliding with a titanium target. The captured products are momentum selected by a series of magnets before reaching the MICE channel. The MICE Step IV configuration was used for this analysis comprising of the liquid hydrogen container (absorber) - holding 21 l of the material at a temperature of 20 K between the upstream (US) and downstream (DS) scintillating fibre (Sci-Fi) trackers. The cooling channel magnets were not used for the experimental measurements considered in this study (i.e. straight particle tracks in the vicinity of the absorber). Three time-of-flight detectors were also used velocity measurements (TOF0, 1 & 2).

2.2 Event Selection

MICE has gathered data with beamline settings configured to provide 170, 200 & 240 MeV/c muon momenta at the absorber with the vessel empty (but in place) and filled with liquid hydrogen. The data-sets are initially reduced through a set of selection criteria. Only particles that have single space-points (SPs) at each TOF, and a single reconstructed track at the US tracker (bins 2 and 3 of Fig. 1) are considered. Trajectories that are expected to have passed through excessive material (bin 4) or have low reconstruction quality (bin 5) are rejected. Finally, events that are directed at the edges of the DS tracker and those that are outside the selected TOF range are rejected (bin 6 & 7).
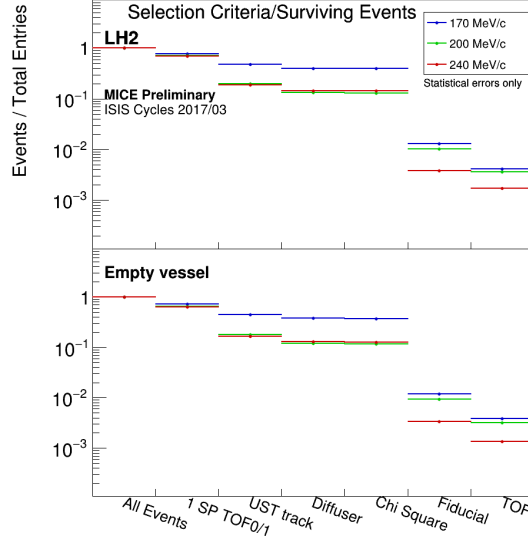
Figure 1: Ratio of events to total number of events (first bin) surviving each cut.

3. Results

The resulting scattering distributions of the surviving events (Fig 2) are expressed as the difference of angles between the US and DS momentum vectors ($\vec{P}_{US}$, $\vec{P}_{DS}$) when projected into corresponding orthogonal planes. The first plane is defined as the plane containing the US vector and the Y experimental axis, and the second plane is defined as its orthogonal that contains $\vec{P}_{US}$. This means that the two planes required for the projected angle calculations are defined on a particle by particle basis. This definition would be equal to using the Y-Z and X-Z planes (from experimental coordinates) if all particles moved parallel to the experimental Z-axis. Because this is not the case the following definitions are established for scattering studies:

$$\theta_y = \arctan\left(\frac{\vec{P}_{DS} \cdot (\hat{Y} \times \vec{P}_{US})}{|\hat{Y} \times \vec{P}_{US}||\vec{P}_{DS}|}\right) \tag{2}$$

$$\theta_x = \arctan\left(\frac{\vec{P}_{DS} \cdot (\vec{P}_{US} \times (\hat{Y} \times \vec{P}_{US}))}{|\vec{P}_{US} \times (\hat{Y} \times \vec{P}_{US})||\vec{P}_{DS}|}\right) \tag{3}$$

4. Conclusions & Future work

This paper presents experimental measurements of MCS of muons crossing a mean of 33 cm of liquid hydrogen with approximate beam momenta 170, 200, 240 MeV/c in the MICE channel. The same measurement with identical selection criteria is performed with the liquid hydrogen vessel empty. The scattering distributions for the empty absorber configuration (Fig. 2 bottom) shows the scattering of particles from the intermediate material of the trackers and vessel, mainly scintillator material (BCF-10 plastic fibres), helium and aluminium. The top row shows the added effect of liquid hydrogen. The decrease in width can be observed as the beam momenta increases, whilst the
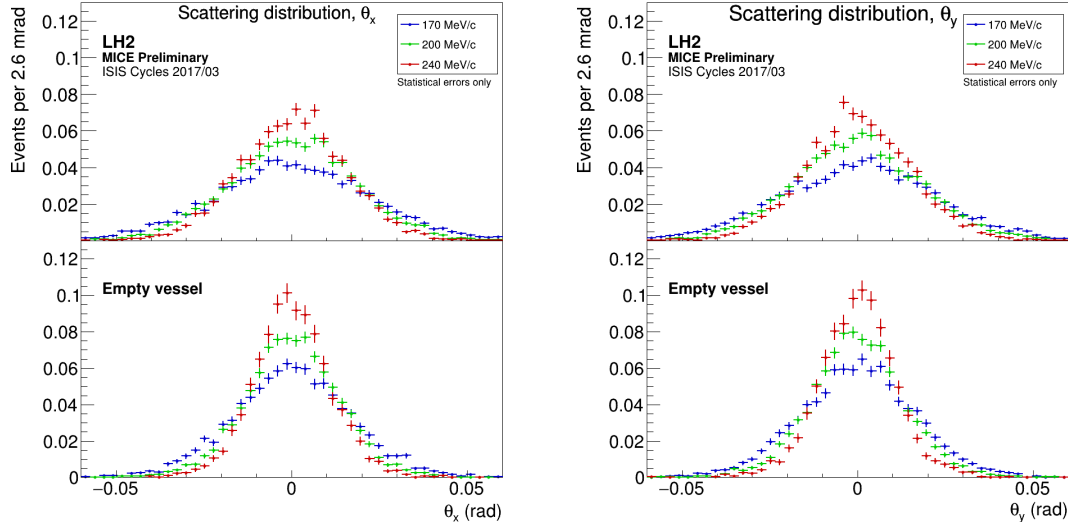
Figure 2: Distribution of θ_x (left) and θ_y (right) for the three momenta settings. For vessel full (top) and empty (bottom) configurations.

width increases at all settings when liquid hydrogen is added in the beam path. The future aim of this analysis is to compare the experimental measurements with the predictions of equation 1, the GEANT4 [6] simulation and the Moliere [7] MCS model.

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