

***dE/dx* and Time-of-Flight Considerations For Particle Identification in the Mu2e Detector**

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Abstract

Noise backgrounds present ambiguity in determining particle identity based on pad readout and signal strength within the Mu2e detector. This paper presents a study and discussion of the utility of examining energy losses and stopping power (dE/dx) to improve particle identification during analysis of Mu2e data. Simulated data show a distinction between pions, muons, and electrons in both the time-of-flight within the tracker and energy deposited in the tracker. This distinction between the behaviors of different particle species could prove to be a useful tool in determining the identity of particles observed in the Mu2e apparatus.

Introduction

The primary purpose of this study was to confirm whether or not the examination of a particle's energy loss while it travels through the Mu2e tracking chamber could help in eliminating ambiguity when attempting to discern between different particle species based on their recorded signals. The Mu2e experiment aims at accurately identifying a conversion electron: an electron with a momentum of 105 MeV/c that is the result of a muon converting into a lone electron. While inside the device, however, the presence of other particles may trigger false positive results. In order to take a closer look at this problem, a Monte Carlo simulation of the tracking system was generated to swim protons, electrons, pions, and muons through the drift chamber, recording expected initial and final energies as well as the time differences of each particle as they traversed the L-Tracker.

Methods

As previously stated, a Monte Carlo type tracking program was implemented for this study. The program was written in MATLAB, utilizing a fourth order Runge-Kutta

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algorithm to do numerical integrations. Specifications were taken from the Mu2e proposal for approximating the structure and makeup of the tracker. The project's intent is to create sections composed of tightly packed straws with thin Kapton walls, filled with a mixture of 80% Tetrafluoromethane (Freon 14) and 20% IsoButane². This design proved too intricate to reproduce efficiently in MATLAB, and so instead each tracker plane was treated as a homogeneous mixture of Kapton, Isobutane and Tetrafluoromethane with proportions consistent with the proposed Mu2e specifications.

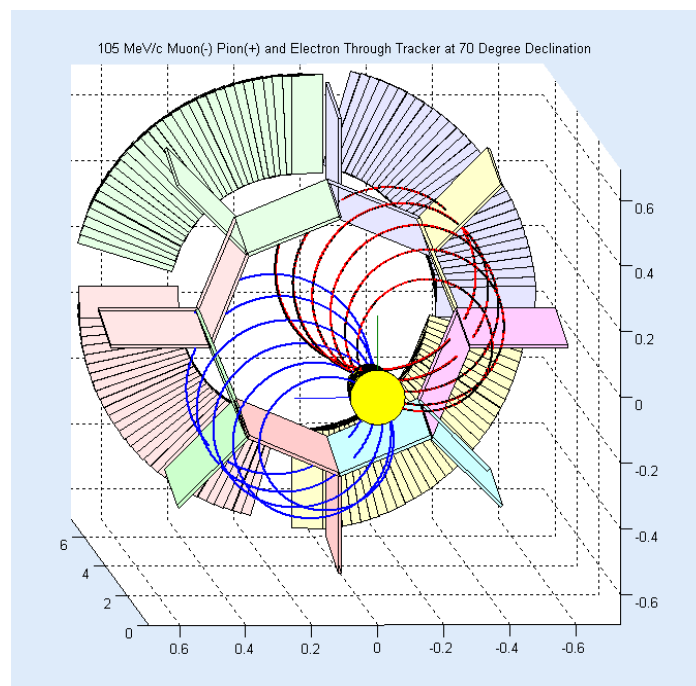
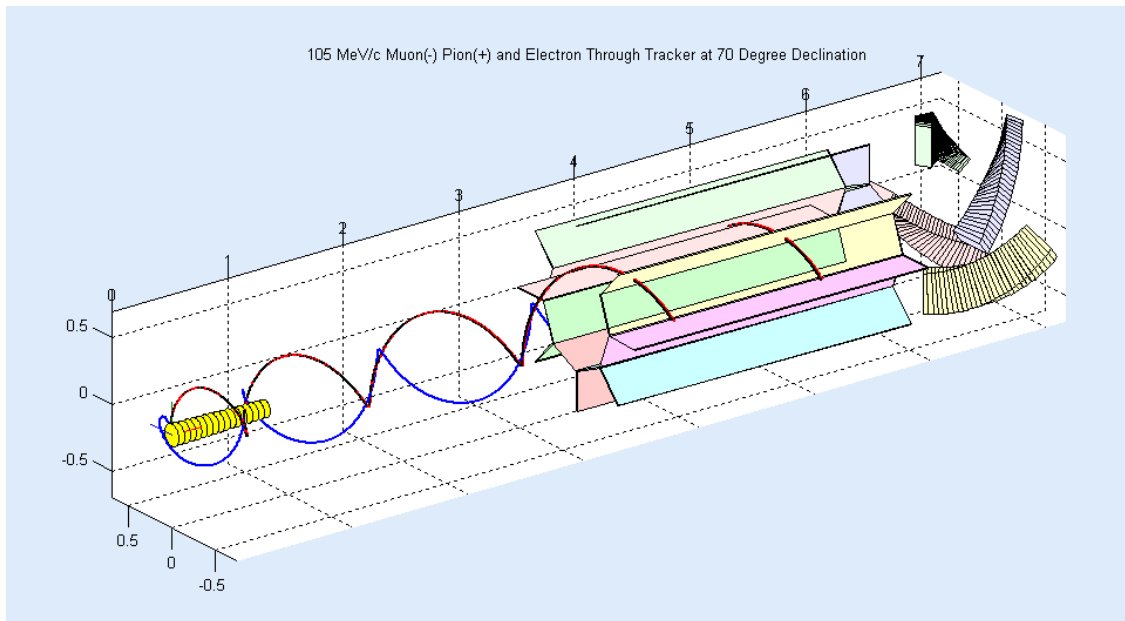


Fig 1,2. Approximate paths of a pion, muon and electron through the tracker. Particles were propagated at an angle of 70 degrees from the beam line.

The code that was used to project the image of the tracker onto a MATLAB figure defines each tracker vane by its eight vertices, organized neatly into a three dimensional matrix. From there, color is added in order to visually define each face of the tracker by way of the *patch* function. The succinct organization of section vertices proved to be crucial in building an efficient method of tracking a particle as it enters and exits each vane of the tracker. The vertex matrices were used to construct individual coordinate systems for each section, defined as three orthogonal unit vectors. With each iteration of a particle's path approximation, a coordinate transformation was performed to the new coordinate system of each individual section. By way of simple vector analysis, the program was then able to recognize whether or not a particle was within the interior volumes of any of the 16 tracker vanes.

When a charged particle traverses any layer of matter, it loses some of its energy through various means. For heavy particles, losses are the primarily due to ionization and atomic excitation. The rate of energy loss (also called stopping power) can be approximated by the Bethe-Bloch³ formula

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 \right]$$

where

$$T_{\max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e / M + (m_e / M)^2}.$$

For electrons, on the other hand, *bremsstrahlung* losses dominate at energies above a few tens of MeV. The average rate of energy loss⁴ in this case may be described by

$$\frac{1}{E} \frac{dE}{dx} = \frac{4N_0 Z^2 r_e^2}{137A} \left[\ln \left(\frac{183}{Z^{1/3}} \right) + \frac{1}{18} \right]$$

for an electron with initial energy E. If the last term of this formula is neglected, yielding a loss of precision of only 1% in the final result, one may now write,

$$\frac{dE}{E} = -\frac{dx}{X_0}$$

where

$$\frac{1}{X_0} = \frac{4N_0 Z^2 r_e^2}{137A} \left(\ln \frac{183}{Z^{1/3}} \right).$$

Whenever a particle was recognized as being within the material of the tracker, energy losses were accrued for that iteration according to the appropriate equations above. Energy loss equations above provide measurements of the average energy losses of a

particle as it passes through matter. Energy loss, however, is a stochastic process and so there are fluctuations in total energy loss. These fluctuations were taken into account after the total average energy loss had been calculated for the entire simulation. When deciding how to model fluctuations, the value of κ^5 was examined by the simulation:

$$\kappa = \frac{0.150 \rho x z^2 Z (1 - \beta^2)}{A \beta^4}.$$

For each particle that was observed, the above formula yielded results satisfying $\kappa < .01$, indicating the necessity for use of a Landau distribution for the energy loss^{5,6}. Landau distributions are asymmetric, with a long high-side tail for large values of energy loss. This is the case because for certain absorbers, it is very unlikely that a particle will have an interaction that yields an energy loss close to that of T_{\max} , the largest possible energy that may be transferred to a free electron in a single collision^{7,8}. Instead, it is typically the case that a particle will experience energy losses much less than their total energy. The parameterization used to describe the Landau distribution⁹ is as follows:

$$f(\lambda) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(\lambda + e^{-\lambda})}$$

where

$$\lambda = \frac{(\Delta E - \Delta E_{m.p.})}{C \frac{m_e c^2 Z z^2}{\beta^2 A} \rho \Delta x}$$

In addition to energy loss, Moliere scattering³ was calculated during each iteration where the scatter away from the direction of propagation is defined as:

$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{x/X_0} [1 + 0.038 \ln(x/X_0)].$$

In order to do this, another coordinate transformation was done to shift to a system where the particle's path vector was a primary axis. A random angle on the interval $[0, 2\pi]$ was generated to be the scattering angle in a plane perpendicular to the particle's path while θ_0 was the scattering angle away from the direction of motion. Once the particle's path vector had been rotated by the scattering angles, another transformation was done back to the Mu2e tracker coordinate system.

Data/Results

Simulated data presented here were generated only for pions, muons and electrons. Protons were stopped by the tracker about half-way through their trajectory, and are

easily recognized through their opposite charge to that of the electron.

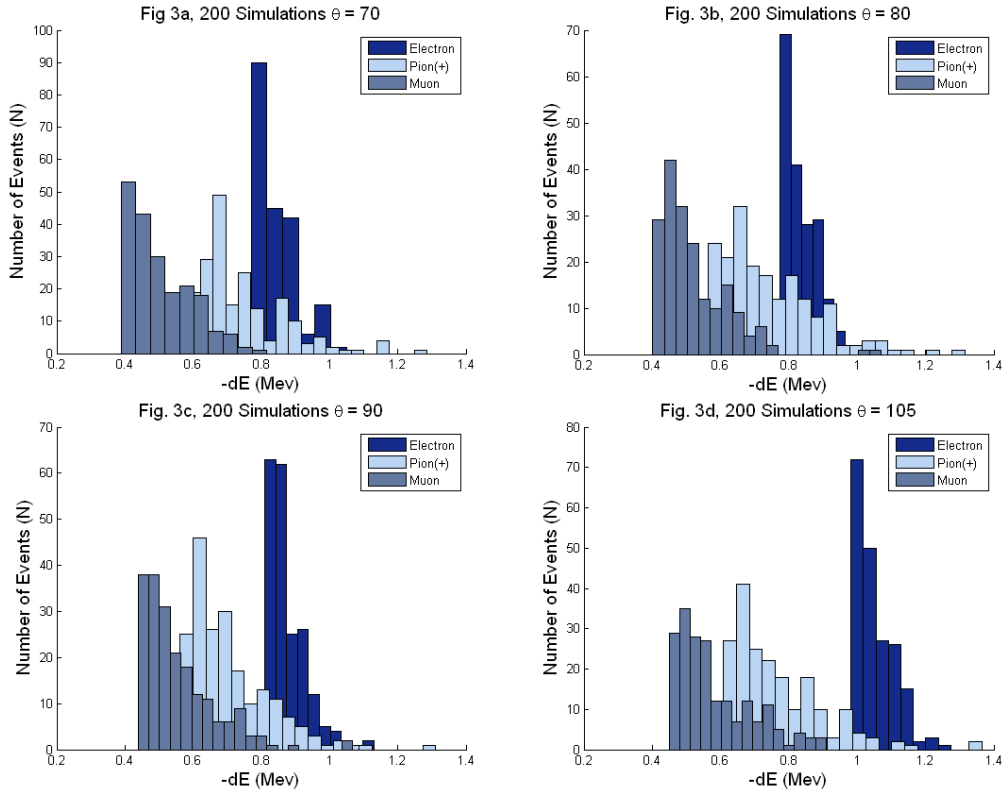


Fig. 3a-d, Histograms representing number of events per total energy loss. Data were calculated for pions, muons, and electrons at angles from the beam line of (a) 70 degrees (b) 80 degrees (c) 90 degrees (d) 105 degrees. Data represents 200 simulations per particle at each angle.

It is apparent that the distributions in Figures 1-4 are exhibit some overlap. Typical energy losses for electrons and pions tend to differ by only about 200keV. Muon energy losses, on the other hand, differ by 350-400keV from electron energy loss, and show almost no overlap aside from very unlikely, high end energy loss fluctuations.

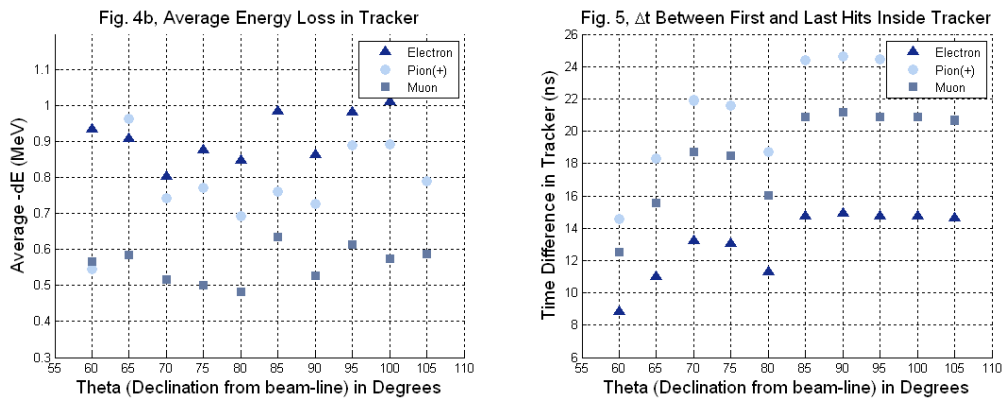


Fig. 4b, Average total energy loss for pions, muons, and electrons propagated at 10 different angles from the beam line.

Fig. 5, Time difference between first and last hits on tracker walls for pions, muons, and electrons propagated at 10 different angles from the beam line.

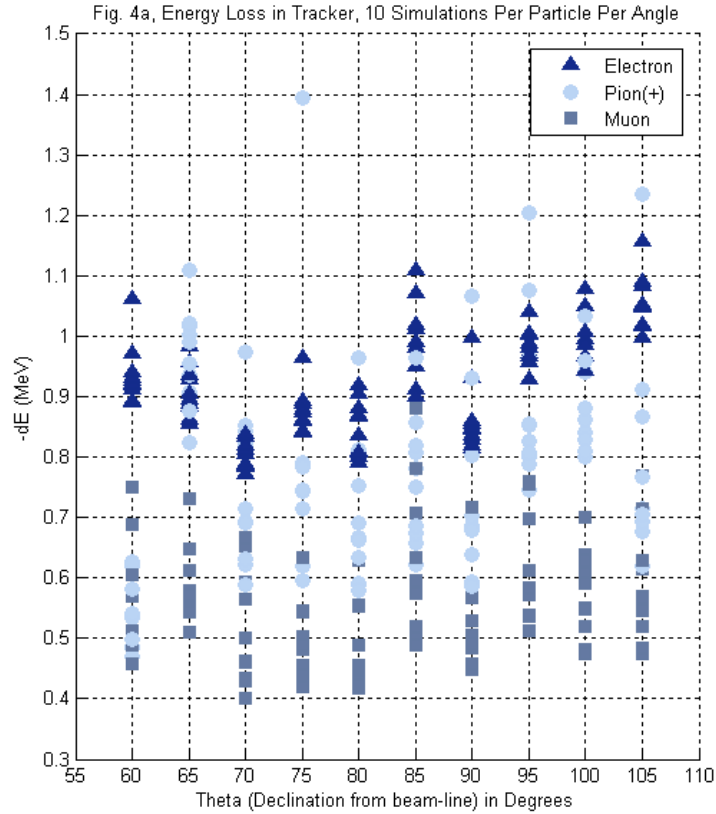


Fig. 4a, Total energy loss calculated for 10 Simulations each for pions, muons, and electrons propagated at 10 different angles from the beam line.

Theta	$\langle \Delta E_{\pi} \rangle / \langle \Delta E_e \rangle$	$\langle \Delta E_{\mu} \rangle / \langle \Delta E_e \rangle$
70	0.8886	0.5991
80	0.8865	0.6208
90	0.8106	0.6368
105	0.7290	0.5521

Fig. 6, Average ratios of energy loss between pions and electrons, and muons and electrons for N events. Values calculated by:

The ratio of the average energy losses between pions and electrons showed pions losing anywhere from 73-89% as much energy as electrons (Fig 6). Depending on a particle's initial angle of travel with respect to the beam direction, there were some instances of drastic jumps in total energy loss. An example of this can be seen with pions at a 65 degree declination. Detailed observation of simulations yielding these results revealed a sort of skimming where a particle would graze just inside the wall of a tracker vane and continue to bend along its helical trajectory, still within the tracker material instead of passing completely through the section. Time data at any given angle shows a difference of at least 2ns for any particle at that declination; at large enough angles, the timing data is nearly constant across about a 20 degree spectrum.

Conclusions

Obvious differences in typical energy losses between particles leads one to believe if data were filtered to only retain particles losing more than about 85-90% of the typical loss for an electron, almost all muons and most pions could be rejected, while only eliminating an insignificant number of conversion electrons. This would streamline processes of analysis and increase confidence levels of a positive ID of conversion electrons. Also, cases of skimming that result in misinterpretation of a particle that has lost abnormally large amounts of energy may be resolved through timing data within tracker sections, taken from pad readouts from copper pads on each large face of tracker vanes. This may help eliminate false positive results further.

Works Cited

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