2D Michel Reconstruction in MicroBooNE

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Abstract

This paper describes an algorithm that can be applied to cosmic data in MicroBooNE to identify and cluster Michel electron showers and reconstruct their energy using only 2D reconstruction information. It takes into account charge and position information from the collection plane only. An accurate reconstruction of the Michel energy spectrum will be useful as a calibration method in the early stages of data collection.

1 Introduction

1.1 The Standard Model of Particle Physics

The Standard Model aims to describe the elementary particles responsible for all of the visible matter in the universe and its fundamental forces. Under the Standard Model there are twelve elementary particles with spin $\frac{1}{2}$ known as fermions, each with a corresponding anti-particle. These fermions fall into two main categories: quarks (up, down, charm, strange, top, bottom) and leptons (electron, electron neutrino, muon, muon neutrino, tau, tau neutrino), each of which is further divided into three generations (see Fig. 1). There are also the force carriers; gluons, $W^\pm$ and $Z^0$, and photons, which mediate the strong, weak, and electromagnetic forces respectively.

Quarks carry fractional charges ($+\frac{2}{3}$ or $-\frac{1}{3}$) and are grouped according to flavor. They are bound together to form hadrons. Hadrons can be further described as baryons, composed of three quarks, and

Figure 1: The Standard Model of Particle Physics [1]. Increasing generations of fermions (reading from left to right) correspond to increasing masses.
mesons, composed of a quark and an anti-quark. Neutrons and protons are both examples of baryons while a pion is an example of a meson, and all of these particles are hadrons. Because quarks only exist in bound states they are only observable indirectly.

Leptons have only integer charges (−1 or 0); an electron has charge −1 while neutrinos are taken to have zero charge and mass [3].

In the Standard Model the recently discovered Higgs boson is responsible for giving masses to these fundamental particles, however gravity is still not well accounted for. The Standard Model also does not explain why neutrinos have very small but non-zero masses. Despite some residual unresolved questions from the Standard Model it has proven to be a robust model of the elementary particles and their behaviors in both experimental and theoretical investigations.

1.2 Neutrino Oscillations

Neutrinos are created and annihilated as three flavor eigenstates, $\nu_e, \nu_\mu, \text{and } \nu_\tau$, but propagate through space according to their mass eigenstates, $\nu_1, \nu_2, \text{and } \nu_3$, with each flavor eigenstate being a certain linear combination of the three mass eigenstates:

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

Where $U_{\alpha i}$ is the unitary matrix:

$$U_{\alpha i} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$$

This matrix can be further decomposed into mixing matrices:

$$U_{\alpha i} = [A][B][C]$$

such that:

$$A = \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$B = \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ e^{-i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix}$$

$$C = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix}$$

Where $\theta_{ij}$ is the mixing angle between two mass eigenstates and $\delta_{CP}$ is the charge-parity violation phase which has yet to be experimentally determined but predicted to be non-zero. If this is the case it would indicate that neutrinos and anti-neutrinos oscillate differently, a violation of CP symmetry [3].

For a given pair of neutrino flavors the probability that a neutrino with flavor $\alpha$ will be observed at a later time as a neutrino with flavor $\beta$ is given by (see Fig. 2):

$$P_{\alpha \rightarrow \beta} = |\langle \nu_\beta | \nu_\alpha \rangle|^2 = |\sum_i U_{\alpha i}^* U_{\beta i} e^{-im_i^2 L/E} |^2$$

such that $m_i$ is the mass of a given mass eigenstate, $L$ is the distance traveled, and $E$ is the energy. For two neutrino case this simplifies to:

$$P_{\alpha \rightarrow \beta, \alpha \neq \beta} = \sin^2(2\theta) \sin^2(1.27\Delta m^2 L/E)$$

Because of this $\Delta m^2$ term, only the difference between the masses of any two mass states can be observed experimentally. Also, because of the $\sin^2(1.27\Delta m^2 L/E)$ term current observations are insensitive to whether $\Delta m^2$ is positive or negative,

|Figure 2: [2] Probability of an electron neutrino oscillation as a function of distance per energy. The black curve shows the probability of observing an electron neutrino, red a tau neutrino, and blue a muon neutrino. Here it is clear that at short distances the probability of observing an electron neutrino remains close to 1, but at certain greater distances the probabilities of observing a muon or tau neutrino dominate. |
The two possible neutrino mass hierarchies, referred to as normal(left) and inverted(right). Because the masses are only known relative to each other it is currently unclear which version correctly describes their absolute ranking.

which leads to an uncertainty in the mass hierarchy [4] (see Fig. 3).

1.3 MicroBooNE

MicroBooNE is a liquid argon time projection chamber (LArTPC) neutrino oscillation experiment located at the Fermi National Accelerator Laboratory (FNAL). It is installed colinear with Booster beam line, downstream of the beryllium target at a distance of 469m (see Fig. 4). With a total volume of approximately 170 tons of liquid argon and a 2.4 x 2.4 x 2.4 m$^3$ drift region, it is the largest liquid argon neutrino experiment operating in the U.S.

Neutrinos in the detector interact with the liquid argon via both neutral and charged current interactions (see Fig. 7), ionizing the argon atoms and generating a trail of electrons (see Fig. 6). The information about the position and timing of these interactions is available thanks to the two primary components of the time projection chamber: the photomultiplier tubes (PMTs) and the three wire planes.

When ionization occurs in the liquid argon, the resulting electrons drift towards the wire recording planes at a speed of 1.6 cm/ms thanks to a 500V/cm electric field generated by a negatively charged cathode plate on the opposite side. The three wire planes are each offset by 60 degrees from each other, and each has wires spaced a distance of 3 mm apart. As the electrons drift past the negatively charged U and V planes they produce a signal via induction are attracted towards the Y plane that collects the electrons. 36 PMTs are installed behind the wire planes to detect the light emitted from liquid argon scintillation, each of which is covered by a light shifter to increase the wavelength of the 128nm light to around 430nm. Position and charge information from the wire planes can be used in conjunction with timing information from the PMTs to reconstruct a 3D event in the detector [7] (see Fig. 5).

Some of the primary research goals for the MicroBooNE experiment are to study neutrino cross-sections in liquid argon and to probe the region of low energy neutrino events seen in excess in MiniBooNE [6] at greater resolution than prior experiments (see Fig. 8). MicroBooNE will have double the sensi-
Figure 6: Example of neutrino event tracks in liquid argon taken in the ArgoNeuT experiment. Regions in red indicate a higher charge deposition [9].

Figure 7: Neutrino Scattering Feynman diagrams. In the case of neutral current the neutrino "bounces off" of another particle (shown in the left diagram), exchanging a neutral Z boson. In a charged current interaction the neutrino interacts via an exchange of a W boson (shown in the center and right diagrams [3].

Figure 8: The signal seen in the MiniBooNE experiment in the low energy region (200-475 MeV) could not be accounted for by current models [15].

is conserved, one neutrino must be muon-type neutrino, the other an electron-type anti-neutrino. For charge conservation, the electron must have the same charge as the muon. This decay mode is also called a Michel decay after French physicist Louis Michel and a Michel electron is emitted isotropically from a decay probability given by:

\[
\frac{dP}{dx}(x; \rho, \eta) = \frac{1}{N} x^2 (3(1 - x) + \frac{2}{3} \rho(4x - 3) + 3\eta \frac{m_e}{E_{\max}} \frac{1 - x}{x} + \frac{1}{2} f(x) + O(\frac{m_e^2}{E_{\max}^2}) \quad (5)
\]

Where \( N \) is a normalization factor, \( x = \frac{E_e}{E_{\max}} \) is the reduced energy that ranges from \( \frac{E_e}{E_{\max}} \) to 1, \( E_e \) is the energy of the Michel electron, \( m_e \) is its mass, \( E_{\max} = \frac{m_\mu}{2} \) is the endpoint of the spectrum, \( f(x) \) is the term accounting for first order radiative corrections assuming local V-A (weak) interaction, and \( \rho \) and \( \eta \) are the Michel parameters. In a Standard Model V-A interaction these parameters are \( \rho_{SM} = 0.75 \) and \( \eta_{SM} = 0 \), and the V-A assumption has been well confirmed through prior measurements of these parameters.

The energy probability spectrum including radiative correction for muon decay in liquid argon is shown in Fig. 11. It is important to note that while the theoretical drops off sharply around 52MeV, in matter this endpoint is extended and the peak shifted slightly towards lower energies [10].

2 Why the Michel Energy Spectrum?

2.1 The Michel Electron

Muons decay via the weak interaction, whereby the dominant decay mode yields an electron and two neutrinos (See Fig. 9). To ensure the lepton number...
2.2 Michels in MicroBooNE

Successfully reconstructing an energy spectrum for Michel electrons in MicroBooNE would provide a good benchmark for low energy detector calibration since they occur in approximately a 0-60 MeV range. The signal is initially analog pulses which go through an analog to digital converter (ADC) and so all measurements will be taken in ADC units. Thus for meaningful results it is critical to properly calibrate the energy conversion from ADC to MeV. A charge in ADC is directly proportional to an energy in MeV, however ADC units are determined by the electronics configuration and therefore unique to the detector.

Another compelling reason to look into Michel electrons for calibration is the high statistics data that will be available from the cosmic data samples taken during commissioning.

Doing so would give MicroBooNE a basis for comparison with many other prior neutrino experiments like MiniBooNE, Minerva, ICARUS, and TWIST [10] that have all reconstructed the Michel spectrum for calibration and to demonstrate a good understanding of the detector output (see Fig. 10).

3 Reconstructing the Michel Energy Spectrum

All of the analyses to be discussed in the upcoming sections were conducted using LArLite, a C++ and ROOT based code development toolkit that can be used to perform analysis on LArSoft equivalent data products. LArSoft is a software data package for simulation, analysis, and reconstruction with liquid argon time projection chambers. LArLite allows for flexibility in a user’s coding in a simple code development environment with a fast build process. The advantages of using LArLite include avoiding extra software dependencies, fast data processing, compatibility with python and CINT, and not having to work directly with LArSoft [12].

For this project we developed a framework within LArLite, “MichelReco”, and the stages explained in the energy reconstruction algorithm describe an analysis unit in this framework.
Figure 12: The figure on the left shows an example of the raw signal on the U plane including the induced signal, while the figure on the right shows the same signal after deconvolution.

3.1 The Y Plane

For this reconstruction of the Michel energy spectrum, we chose to use exclusively hits on the Y plane (collection plane). In doing so, we avoid dependence firstly on matching between the three planes and secondly on the deconvolution of the signal on the U and V planes (see Fig. 12(a)). By doing so, we limit the dependency of this analysis on other detector functions and mean that it can be run at the earliest stages of data collection.

3.2 Input

As a first step, it was important to ensure that the clusters of Michel electrons could be identified and that this correct identification would yield a recognizable energy spectrum. In order to do so, this portion of analysis was conducted using only muons known to stop in the detector and decay into Michel electrons. Further constraints were placed on the energy containment of the Michel electron (a deposited energy of at least 95% of the true energy) to ensure that the energy spectrum would not be biased towards the lower energy Michel electrons by virtue of them exiting the detector. Information about whether a given event contained a Michel electron shower and whether the energy of that shower was sufficiently contained was taken from the truth information to filter through a sample of single muon files and select the ones of interest to use in the Michel spectrum analysis, which was approximately 5% of the initial sample.

3.3 Merging Clusters to Create a Trajectory

From this sample of events, clusters were then reconstructed from the Reco 2D hits using the fuzzycell algorithm, which was applied to only the hits on the collection plane (see Fig. 13).

The first algorithm applied to these clusters of hits generates an ordered list of Reco hits that forms a trajectory across the plane from a given start point. Two potential start points are considered for each trajectory; the lowest and highest wire number (position in Z).

From each of these two possible start points, the algorithm looks for the next closest hit in the cluster according to its X and Z positions and chooses that to be the second. This process continues by comparing the second ordered hit to all of the remaining unordered hits in the cluster and choosing the closest. A maximum distance cutoff of 5 cm is in place to ensure that the distance between any consecutive hits along the trajectory are at most 5 cm, and any farther hits are not added to the ordered hits. The key reasons for this measure are delta rays and photons, which have a radiation length 14 cm in liquid argon, which may be included in the cluster but are of low enough energy to not be of interest for the further steps in the Michel charge identification (see Fig. 14).

Once the algorithm has created trajectories for both start points, it chooses the one that is longer to pass on to the next step. After this initial clustering, a merging algorithm joins neighboring clusters in the case where the start or end of one cluster is close to the start or end point of another (see Fig. 15).

3.4 Identifying a Boundary

Continuing with this ordered trajectory that contains hits produced by both the muon and Michel, the next step in the process is to determine a boundary point.
Figure 13: This diagram shows two 2D clusters in the Y plane that are inputted to the algorithm, one in blue and one in red. Although a muon and a Michel are contained in these clusters, the contents of either cluster does not accurately reflect the true clustering of either particle.

Figure 14: Here the algorithm creates a trajectory using the nearest hit in the cluster. The green hits indicate points that will be removed thanks to the distance cutoff.

Figure 15: In the last stage the algorithm merges the two clusters in the trajectory and this is output to the next step.

Figure 16: $\frac{dE}{dx}$ versus residual range for various stopping particles in liquid argon where residual range is defined as the distance remaining to the end of the track [11].

Figure 17: Example of $Q$ versus $s$, distance along the track, for a stopping muon.

at which the muon decays and the Michel cluster begins.

One useful property of a stopping muon which helps to identify this boundary is the rise in the charge deposited per distance ($\frac{dQ}{ds}$) along the muon’s trajectory as it approaches the end and decays (See Fig. 16). Thus a large peak in the charge per hit ($Q$) along the trajectory should indicate the end of the muon track and a dip afterwards the start of the Michel. Finding this large peak in the $Q$ should indicate the boundary between the two. However, this peak is difficult to isolate for a given stopping-muon track because of the “noise” in the $Q$ versus $s$ distribution (see Fig. 17).

To give the large peak in the $Q$ a smoother rise and thereby make it easier to isolate with the first derivative ($\frac{dQ}{ds}$), a truncated mean is applied to the $Q$ spectrum. The truncated mean algorithm works by sliding along the length of the track and calculating
Figure 18: The same $Q$ spectrum as in Fig. 17 with a truncated mean.

Figure 19: The first derivative of the truncated $Q$ taken with the Lanczos differentiator.

a local mean $Q$ for all the points in a given window of 15 points and then removing all of the points that are above or below the mean by a given percent, 20% in this analysis. Because a larger window is necessary for a robust calculation of the truncated mean, the first and last three points in the truncated charge are disregarded.

The resulting truncated charge (see Fig. 18) yields a large positive peak in $Q$ and a corresponding large negative peak in $\frac{dQ}{ds}$ with the use of a Lanczos differentiator for increased noise suppression (see Fig. 19). The differentiator works by using a smoothing least squares polynomial approximation [14].

Next, the location in $s$ of all of the local maximums in the truncated $Q$ and minimums in the truncated $\frac{dQ}{ds}$ are found using a peak finding algorithm. For the $Q$ spectrum, a pedestal estimator finds a mean value for the baseline by looking for a window along the track with a low RMS (less than 0.5). With this pedestal mean, the algorithm then looks along the entire track for regions where the values rise above the baseline by a certain factor, 5 times the pedestal RMS, and then fall back to a given value above the baseline, 6 times the pedestal RMS. All of the points that fall between these thresholds are then considered to be part of a peak, the maximum $Q$ in the peak being a local maximum in the spectrum. The same process is repeated for the local minimums in the $\frac{dQ}{ds}$.

To make an educated guess about which of these local maximums and minimums corresponds to the peak in $Q$ at the end of the muon track a matching algorithm pairs a peak in the truncated $Q$ to a dip in the truncated $\frac{dQ}{ds}$ based on the strength of the peak and its position relative to its counterpart. First the algorithm finds the largest local maximum in the truncated $Q$, and then looks in a region of 20 points to either side around this peak in the truncated $\frac{dQ}{ds}$ for any local minimums. From there:

- If there is one minimum in this region, the maximum and the minimum are then “matched”
- If there are multiple minimums the algorithm matches the maximum with the lowest minimum
- If there are no local minimums in the truncated $\frac{dQ}{ds}$ in this region around the highest maximum in the truncated $Q$, the algorithm next considers any the remaining local maximums
- If there is at least one more local maximum in truncated $Q$ the algorithm chooses the highest local maximum remaining and repeats the procedure to find a matched local minimum

The process is complete when a match has been made or there are no more local maximums in the truncated $Q$. In the advent of there not being a matched pair of peaks in the event in question, this event is excluded from remainder of the analysis.

### 3.5 Identifying the Muon and Michel Electron Clusters

As the start of the trajectory does not necessarily correspond to the start of the muon track and could instead be the end of the Michel track, the following algorithm takes only an ordered trajectory of hits and a boundary in order to determine which portion of the track is the Michel.
There are four stages of checks used to determine whether the Michel electron track occurs “forward” or “behind” the boundary, meaning to the right or left of the boundary in the positive Z direction.

- The first takes into account the amount of charge contained by the hits on either side of the boundary; if either of the sides has 15% or more charge than the other, the side with lower charge is taken to be that of the Michel electron.

- If this is not the case, the second stage considers the lengths of the trajectories in number of hits; if either side of the track is double the other then the one with fewer hits is taken to be the Michel electron.

- If the conditions for using the first and second stages were unfulfilled, the third stage looks at the total charge in a window of 10 hits to either side of the boundary, the side with higher charge being taken to be that of the muon. If there are fewer than 10 hits on either side of the boundary and the first two stages were unsuccessful the event is discarded from the next steps in the analysis.

- The fourth and final step is to crosscheck the result of “forward” using a linear fit chi-square algorithm, regardless of which of the previous three steps was used in the decision.

The chi-square algorithm uses a sliding window of 15 hits to perform a linear fit for small regions of a track, the chi-square value of which is assigned to the central point in that window (see Fig. 20). The resulting plot of chi-square versus distance along the track shows peaks in the chi-square value at bends in the track. The same local maximum peak finder as was used for the truncated Q peaks is applied to the chi-square plot, resulting in a set of local maximums in chi-square and their corresponding distances along the track.

Working under the assumption that the muon track should be straighter and thus have fewer peaks in chi-square than the Michel electron track, the number of peaks in chi-square, their distances from the
Figure 22: This diagram illustrates how the charge integral is determined using a circle algorithm. The dotted arrow indicates the radius of the circle as determined by the length of the Michel track. The green shaded circle indicates the region of interest, any hits in which will be counted towards the Michel charge, excluding the blue hits in the muon cluster.

boundary, and the side of the boundary they fall on are useful in verifying that the choice of whether the Michel electron was “forward” or “behind” the boundary (see Fig. 21). If there are several peaks in the chi-square that are relatively close to the position of the boundary on one of the sides but that side was not chosen to be the Michel electron the event is disregarded.

3.6 Charge Spectrum of the Michel Electron

The next algorithm applied to the events in the sample returns a charge of the Michel electron, accounting for the hits which were included in the cluster but not in the ordered trajectory. It first determines a radius from the length of the Michel track and then draws a circular region of interest centered at the end of the Michel track. Any hits that fall in this region and that are not in the muon trajectory as determined in the previous step are counted towards the charge of the Michel.

From our sample this yields a charge distribution as seen in Fig. 22. For a sample of approximately 2700 stopping muons with Michels this yielded the charge spectrum shown in Fig. 23.

3.7 Energy Spectrum with Lifetime Correction

3.7.1 Lifetime Correction

One correction that must be applied to the obtained charge spectrum is a lifetime correction, which takes into account the absorption of the drifting electrons by impurities in the liquid argon as they move towards the wire planes. For electrons that are initially further away from the wire planes there will be fewer than reach the collection plane. Thus a correction is applied:

\[ Q_{\text{corr}} = Q_{\text{raw}} \frac{e^t}{\tau} \]

Where \( Q_{\text{raw}} \) is the charge collected on the wire planes and \( \tau = 3 \text{ms} \) is an experimentally determined constant. \( t \) refers to the time it took for the electrons to drift from their initial location to the wire planes given by:

\[ t_{\text{drift}} = \frac{X}{v} \]

Where \( v \) is the drift velocity in liquid argon given the electric field strength and temperature, in this case 160 cm/ms.

The resulting correction applied to the reconstructed Michel charge spectrum can be seen in Fig. 24 and Fig. 25.

3.7.2 Energy Conversion

The final stage of the process is to convert the spectrum from an ADC unit of charge to energy in units
Figure 24: The lifetime correction scaling as a function of time.

Figure 25: Here the reconstructed charge spectrum cuts in blue is overlayed with the lifetime-corrected charge spectrum.

Figure 26: Energy in MeV vs Charge in ADC for single electrons.

Figure 27: The reconstructed Michel spectrum including the lifetime correction and MeV conversion factor obtained from Fig. 26.

of MeV in order to check the accuracy of the reconstructed spectrum as compared to the true spectrum and thereby look at the efficacy of the algorithm as a whole. To verify that the conversion is a linear one and obtain a rough conversion constant, the true energy in MeV was plotted against the reconstructed charge in ADC units for a sample of MC single electrons (see Fig. 26). The slope of a linear fit yields a conversion factor of approximately 0.008219 ADC per MeV.

Multiplying the reconstructed charge spectrum including the lifetime correction by this conversion factor yields the energy spectrum seen in Fig. 27. This reconstructed energy spectrum is overlaid with the true energy spectrum for the Michels in the sample in Fig. 28.

4 Filtering Signal and Background

Having verified that the algorithm described in the previous sections can generate a Michel energy spectrum from a sample of stopping muons which are known to decay into a Michel, the next step is to remove the filter and apply cuts to a sample that contains muons both with and without Michels. The output of the algorithm without any selection cuts
on a sample of approximately 60,000 such events is shown in Fig. 29.

The primary criteria available as a cut parameter is the chi-square from the chi-square algorithm, although the number of hits in a cluster and the number of clusters in an event also provide useful information. The chi-square is a powerful tool to filter Michel-containing and non-Michel-containing muon events because a track for a muon which either does not stop in the detector or stops but does not decay into a Michel is expected to be much straighter than one that does, which is reflected in the chi-square value.

The specific parameters considered related to the chi-square were lowest chi-square value, mean chi-square value, chi-square value at the boundary between the muon and the Michel. In order to determine whether these would be meaningful cuts, and if so which cut value that would be optimal, sensitivity plots showing the significance of different cut parameter values were made for these three parameters. Significance is defined as:

$$\text{Sig.} = \sum_{\text{bins}} \frac{S_i}{\sqrt{S_i + B_i}}$$

Where \( \text{bins} \) is the number of bins in the histogram, \( S_i \) is the number of signal events per bin and \( B_i \) is the number of background events per bin [16].

Thus for each cut, the significance is determined by the number of signal events that are lost as compared to the reductions in both signal and background. A lower significance means that there are fewer cut signal events as compared to the overall reduction in the number of events.

Beginning with a significance of 515, we then make various cut on the pairs of chi-square parameter values. The loss in significance as a function of these two-parameter cuts is plotted for all cut values, as seen in Fig. 30(a), 31(a), and 32(a). Regions of low loss significance are shown in red and high loss of significance in blue. These same plots are shown with more detail in these regions of low significance in Fig. 30(b), 31(b), and 32(b). The optimized cut is the one which minimizes the loss of significance.

From these plots cut values of a lowest chi-square value of 0.28 or less, a mean chi of 0.98 or more, and a chi at the boundary of less than 0.68 where chosen to apply to the energy spectrum, resulting in a new spectrum as seen in Fig. 33.

This new energy spectrum has a signal purity of 81%, where the purity is defined as the number of events in the spectrum that contained a Michel out of all of the events in the spectrum.

The signal efficiency, defined as the number of events with Michels in the spectrum out of all of the events with Michels in the sample, was 3.8%.
Figure 30: Significance of the chi-square at the boundary vs. the lowest chi-square.

Figure 31: Significance of the chi-square at the boundary vs. the mean chi-square.

Figure 32: Significance of the mean chi-square vs. the lowest chi-square. An island of high significance is observed for certain cuts in this parameter space, this island corresponds to the chosen optimized cut.
Figure 33: The energy spectrum reconstructed from the algorithm with cuts. Events in red did not actually contain a Michel, the ones in blue did.

The mis-ID efficiency, defined as the number of events without Michels in the spectrum as compared to all of the events in the sample with only a muon, was 0.07

5 Side Project with Clock Oscillators

This portion of the paper is unrelated to the Michel energy reconstruction project and instead details another brief project: replacing a crystal on a MicroBooNE controller board and verifying that it performed both as expected as according to the manufacturer’s specifications as well as at the same frequency as the previous crystal.

Crystal oscillators are used in digital circuits to provide a stable clock signal using the mechanical resonance of a piezoelectric material with a precise frequency. The crystal that was previously in use was a Pletronics LV77 quartz crystal, the replacement was an SiLabs 591. Both produce low-voltage differential signal outputs but the SiLabs crystal has a range of frequencies whereas the Pletronics crystal only oscillates at one set frequency, 156.25 MHz. Thus the goal was to compare the frequencies and verify that the new crystal could really be set to oscillate at the same frequency as the old one.

Results of the frequency comparison between the two crystals can be seen in Fig. 34. Their frequencies are in good agreement although the amplitude of the voltage output from the Pletronics crystal was much larger than that of the SiLabs. The difference in the shape of the waveform is due to the two different probes which were used.

6 Conclusion

In this 2D Michel energy reconstruction project we have created an algorithm which merges muon and Michel clusters together, creates an ordered trajectory of hits, determines a boundary point, chooses a Michel track, and then creates a charge spectrum for the Michel electrons which can be converted to an energy spectrum using a lifetime correction and an ADC to MeV scaling constant.

This algorithm has been tested on a sample of events which contained muons both with and without Michels. By optimizing cuts on chi-square and other parameters we were able to isolate to a good degree of purity and a low mis-ID efficiency the Michel energy spectrum from a background of muons. Moving forward with this algorithm, the next necessary step is to refine the cuts with the goal of improving signal efficiency and purity. Once this is done it should be tested on a cosmic sample and further tuned. The final goal of the project is to apply the algorithm to the cosmic data taken in the detector.
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