

Reconstruction and Selection of Michel Electrons from Muon Decay in SBND

REU Program at Columbia University - Nevis Labs

by Nicolaus A. Chlanda

December 12, 2024

Contents

1	Background	1
1.1	The Standard Model	1
1.2	Neutrino Oscillations	2
1.3	The Booster Neutrino Beam at Fermilab	2
1.4	How a LArTPC works	3
1.5	The SBND Experiment	3
2	Michel Electrons as a calibration tool	4
2.1	Characteristics of Michel Electrons	4
2.2	Michel Electrons in SBND	5
3	Updating Selection	6
3.1	Distance Selection	6
3.2	Pixel Selection	6
3.3	Results	6
4	Boosted Decision Tree	7
4.1	BDT Input	7
4.2	Results	7
5	Conclusion	8
6	Acknowledgments	8

Abstract

This paper describes the selection process that can be applied to cosmic muon data in SBND to reconstruct the Michel electron energy spectrum using a Boosted Decision Tree. This BDT takes into account muon and michel information to accurately separate signal and background events. In which precisely maps the Michel electron energy spectrum. The Michel energy spectrum will be useful as a calibration method to test detector response to low energy particles.

1 Background

1.1 The Standard Model

The Standard Model is a fundamental theory in physics that explains the elementary particles and the forces acting upon them, which constitute all visible matter in the universe. It identifies twelve elementary particles known as fermions, each having a corresponding antiparticle. These fermions

are divided into two main types, quarks (up, down, charm, strange, top, bottom) and leptons (electron, electron neutrino, muon, muon neutrino, tau, tau neutrino). Both quarks and leptons are further grouped into three generations.

The Standard Model also includes particles that act as force carriers: gluons, $W^\pm$ and Z_0 bosons, and photons, which mediate the strong, weak, and electromagnetic forces, respectively. Quarks carry fractional electric charges ($+2/3$ or

-1/3) and are organized by their flavors. They combine to form hadrons, which are subdivided into baryons (made up of three quarks) and mesons (consisting of a quark and an antiquark). Examples of hadrons are protons and neutrons (baryons) and pions (mesons).

Leptons have integer electric charges, either -1 or 0. For example, electrons have a charge of -1, while neutrinos are considered to have zero charge and very small masses. The recently discovered Higgs boson plays a crucial role in the Standard Model by providing mass to these fundamental particles. However, the model does not fully explain gravity or the small but non-zero masses of neutrinos.

Despite these gaps, the Standard Model has been remarkably successful in explaining a wide range of phenomena and remains a cornerstone of modern physics, validated by numerous experimental and theoretical studies.

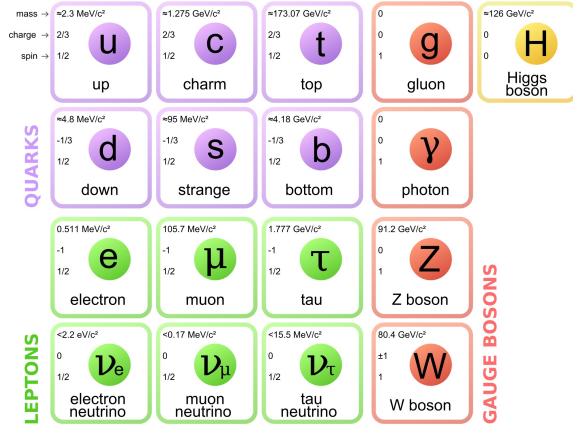


Figure 1: The Standard Model of Particle Physics. Increasing generations of fermions (from left to right) correspond to increasing masses. [4]

1.2 Neutrino Oscillations

Neutrino oscillations describe a quantum mechanical phenomenon where neutrinos, which are fundamental particles with very small masses, change their type or "flavor" as they travel through space. Neutrinos come in three flavors, electron neutrinos, muon neutrinos, and tau neutrinos. Unlike other particles, neutrinos can transform from one flavor to another, a process known as oscillation.

This oscillation occurs because the flavor states of neutrinos are not the same as their mass states. Instead, each flavor state is an independent admixture of three different mass states. As neutrinos propagate, the differences in their masses cause the probability of detecting a specific flavor

to change periodically.

The discovery of neutrino oscillations has massive implications for our understanding of particle physics. It provides strong evidence that neutrinos have non-zero masses, a fact that is not accounted for in the original formulation of the Standard Model. This discovery has prompted revisions to the model and has opened up new areas of research in both theoretical and experimental physics.

Neutrino oscillations are typically studied through experiments involving neutrino sources such as the Sun, nuclear reactors, or particle accelerators. Detectors placed at various distances from these sources measure the changing proportions of neutrino flavors, providing data that can be used to calculate the differences in mass between the neutrino mass states and the mixing angles that describe how flavor states combine to form mass states.

Understanding neutrino oscillations is crucial for answering fundamental questions about the nature of neutrinos, the asymmetry between matter and antimatter in the universe, and the overall structure of the Standard Model. Despite many advances, the precise values of neutrino masses and the full implications of neutrino oscillations remain active areas of research.

1.3 The Booster Neutrino Beam at Fermilab

For the short base-line experiment at Fermilab which includes the SBND detector the source for these neutrinos is The Booster Neutrino Beam (BNB). Rather than waiting for neutrinos from the sun, we create a neutrino beam which we can control in many ways. The process begins with the Booster synchrotron, which accelerates protons to an energy of approximately 8 GeV. These high energy protons are then directed towards a beryllium target, where they collide and produce a variety of secondary particles, including pions and kaons. These secondary particles are unstable and quickly decay into neutrinos and other particles.

Specifically, the pions and kaons produced in the target decay primarily into muon neutrinos. To focus these secondary particles and direct them towards the detectors, a system of magnetic horns is used. These horns are large, current-carrying devices that generate strong magnetic fields to focus the charged pions and kaons, guiding them down a decay pipe. As these particles travel through the decay pipe, they decay into muons and neutrinos.

The resulting neutrino beam is composed pre-

dominantly of muon neutrinos, which are then directed towards various detectors positioned along the beamline. The three detectors MicroBooNE, ICARUS and SBND, are located at different distances from the source to study the oscillations of the neutrinos over varying baselines.

1.4 How a LArTPC works

All of the three detectors mentioned previously are LArTPC's (Liquid Argon Time Projection Chamber). A Liquid Argon Time Projection Chamber is an advanced particle detector technology used extensively in experimental particle physics. It is particularly crucial for the study of neutrino interactions, which are elusive and require highly sensitive and precise detection methods. The LArTPC technology has the ability to provide high-resolution, three-dimensional imaging of particle trajectories, offering amazing insight into particle interactions.

The operation of an LArTPC is based on several fundamental principles. When a charged particle traverses the liquid argon, it ionizes the argon atoms along its path. This ionization process results in the production of free electrons and positively charged argon ions. The number of ionization electrons generated is proportional to the energy deposited by the particle, making it possible to infer the particle's energy from the ionization signal.

A uniform electric field is applied across the liquid argon volume, typically generated by applying a high voltage to a cathode placed at one end of the chamber. This electric field causes the free electrons, produced by the ionization process, to drift towards a collection plane. The direction and magnitude of the electric field are carefully controlled to ensure consistent and predictable electron movement.

The collection plane consists of an array of wires or other types of sensors arranged in multiple layers. As the electrons reach the collection plane, they induce signals on the wires, which are then read out and recorded. The time it takes for the electrons to travel from their point of origin to the collection plane, combined with the known drift velocity of electrons in liquid argon, allows for precise determination of the original ionization location. This process effectively translates the ionization pattern into a three-dimensional image of the particle's path through the detector.

One of the significant advantages of LArTPCs is their ability to provide detailed spatial resolution and excellent particle identification. The liquid argon medium is dense, offering a high probability of interaction for passing particles, particu-

larly neutrinos. The high granularity of the detection system allows for the reconstruction of complex interaction topologies, such as those involving multiple particles and intricate decay chains.

Furthermore, LArTPCs are equipped to handle large volumes of data, which is essential for capturing rare events like neutrino interactions. The detectors can be scaled to substantial sizes, making them good for experiments requiring large detection volumes to increase interaction rates. Additionally, the cryogenic technology used to maintain argon in its liquid state is well-developed, it uses a process of filtration, recirculation, and a purification system to ensure the stable operation of these detectors over extended periods.

In summary, the Liquid Argon Time Projection Chamber is a powerful and sophisticated tool in particle physics. Its ability to provide high-resolution, three-dimensional imaging of particle interactions, coupled with its excellent particle identification capabilities, makes it invaluable for studying neutrino interactions. The detailed understanding gained from LArTPCs continues to advance our knowledge of fundamental particles and their behaviors. An example of a LArTPC can be seen in Figure 2.

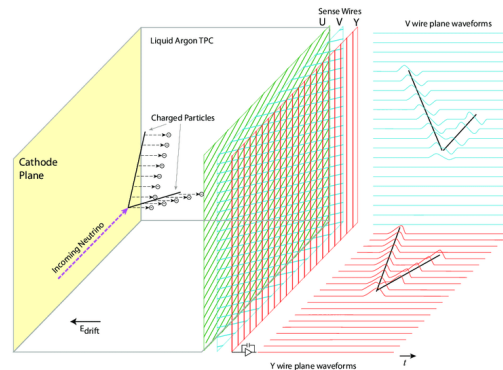


Figure 2: An example event for an LArTPC. A neutrino interacting with argon nucleus and ionizing. [3]

1.5 The SBND Experiment

The Short-Baseline Near Detector (SBND) is a crucial component of the Short-Baseline Neutrino (SBN) program at Fermilab, aimed at investigating the properties of neutrinos. As one of the three detectors in the SBN program, SBND plays a pivotal role in understanding neutrino oscillations and addressing fundamental questions in particle physics.

SBND is the first detector in the line of three and is the closest to the neutrino source at Fermilab and is designed to measure the neutrino flux and interactions with high precision before any significant oscillation can occur. This near detector is positioned just 110 meters from the target where neutrinos are produced, providing a critical baseline measurement for comparing with the far detectors, MicroBooNE and ICARUS, which are located further away.

One of the primary scientific goals of SBND is to search for evidence of sterile neutrinos, hypothetical particles that do not interact via the weak force like regular neutrinos. The existence of sterile neutrinos could provide explanations for several anomalies observed in previous neutrino experiments. By precisely measuring the neutrino flux and interaction rates at the near detector, SBND helps identify any deviations from expected behavior that could signal the presence of sterile neutrinos.

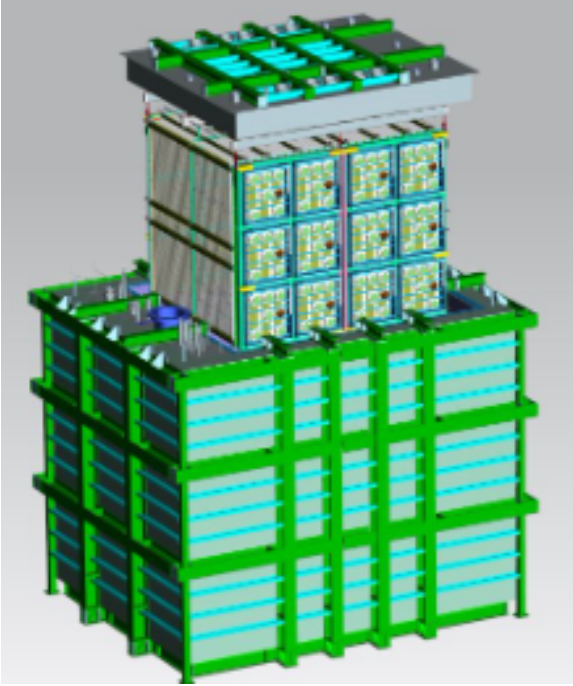


Figure 3: A diagram of the SBND detector.[2]

SBND has just starting taking data in July 2024 so, it will provide essential data that will inform and refine our understanding of neutrino properties. The insights gained from SBND will contribute to resolving outstanding questions about neutrino masses, mixing angles, and the potential existence of sterile neutrinos. Additionally, the technology and methodologies developed for SBND will benefit future neutrino experiments,

paving the way for further discoveries in particle physics.

The Short-Baseline Near Detector is a important aspect of the SBN program, playing a vital role in advancing our knowledge of neutrino physics. Through its precise measurements and advanced detection capabilities, SBND is poised to address fundamental questions about neutrino oscillations and the possible existence of sterile neutrinos.

2 Michel Electrons as a calibration tool

2.1 Characteristics of Michel Electrons

When a muon decays at rest via the weak interaction, the most dominant decay mode leads to an electron and two neutrinos. Seen in Figure 4.

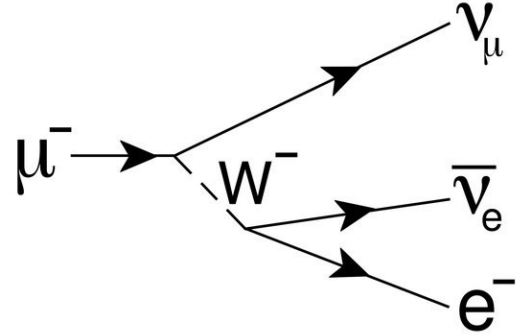


Figure 4: The Muon decay into an Michel electron, muon neutrino and electron anti-neutrino via the weak force (W boson).

Similarly to conservation of energy, a particle decay must conserve its lepton number as well as charge conservation. To guarantee lepton number conservation, one neutrino must be a muon-type neutrino, the other, an electron-type anti-neutrino. For charge conservation, the electron will have the same charge as the muon since neutrinos do not have charge. The Michel energy spectrum is understood extremely well due to its purely weak decay process.

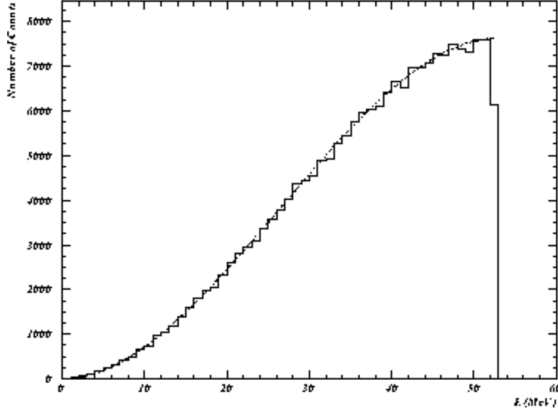


Figure 5: The theoretical Michel energy spectrum.

The energy spectrum of the Michel electron as what we would measure in a LArTPC is shown in figure 6. The red spectrum includes radiative photons due to the fact when Michel electron interacts with Argon nucleus it goes through a process called Bremsstrahlung which releases a photon, contributing to the overall energy. The grey spectrum is strictly the Michel electron spectrum. It is important to notice that this spectrum drops off around 52 MeV.

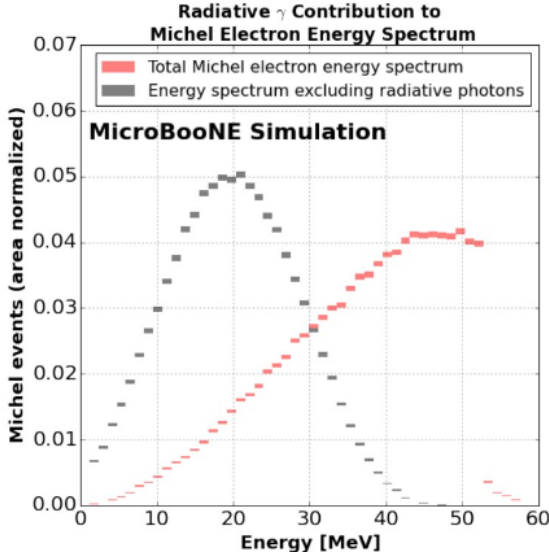


Figure 6: The Michel energy spectrum taken by MicroBooNE simulation. The grey curve is the Michel energy excluding the radiative photon energy, while the red is including both Michel and photon energy from Bremsstrahlung. [3]

2.2 Michel Electrons in SBND

Muons from cosmic rays are a significant source of background in the Short-Baseline Near Detector (SBND) experiment. Cosmic rays, which are high-energy particles originating from outer space, continuously bombard the Earth's atmosphere. Once inside SBND, they ionize the liquid argon, creating ionization tracks that can mimic the signals produced by neutrino interactions. Being able to successfully reconstruct the Michel electron energy spectrum in SBND would be a great benchmark for low energy detector calibration since the Michel spectrum is roughly 0-60 MeV range. This calibration will also be good for comparing cosmic data samples which can be compared to prior neutrino experiments like (MiniBooNE, Minerva, ICARUS, and TWIST) that have already completed the reconstruction of the Michel spectrum to show a good understanding of the detector's detection process. Figure 7 is an example of a muon event inside MicroBooNE.

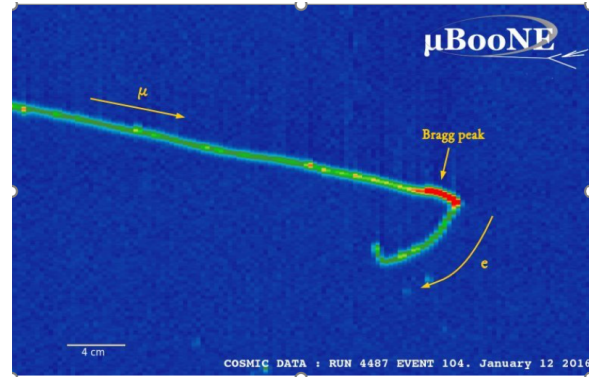


Figure 7: An example of a muon event inside the MicroBooNE detector. The coloring spectrum shows the muon ionizing through the detector and stopping creating a Bragg peak and decaying releasing a Michel. The Michel has a distinct curl due to the electron interacting with the argon nucleus and scattering. [3]

3 Updating Selection

3.1 Distance Selection

Physically in the process of a muon stopping inside our detector and decaying, the Michel electron will start exactly where the muon decays, so there is no displacement between the two. However, since the reconstruction process is not perfect, there is going to be a displacement between the Muon end point and where the Michel electron starts. Since the displacement is not uniform, we need to find a proper cut to place on all events to eliminate background events. If the cut is too small, we might eliminate true events, and if it is too big, we might include things other than just the Michel. To do so, we plot the efficiency and purity at each cut value along the entire data set as seen in Figure 8. To pick a cut value, we look at where the two lines intersect. However since the two ranges are so drastically different, we can choose to prioritize efficiency and set the cut at 2 cm. Choosing a cut value past 2 cm would result in an increase in Miss ID'd events.

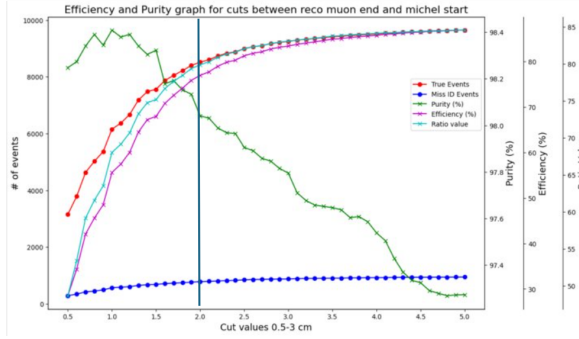


Figure 8: The Purity and Efficiency graph for each cut value over all data.

3.2 Pixel Selection

The Pixel selection is very similar to the distance selection. Once the muon stops and decays in the detector, the Michel electron ionizes the surrounding liquid argon, creating a trail of ionization electrons. These ionization electrons drift under an electric field toward the readout planes. The TPC captures the 3D image of the resulting electron track. We call these pixels, every single Michel electron hit, is a pixel. These pixels directly correlate to electrons energy. We need to place on a cut how many pixels we receive in the Michel cluster to try and eliminate any background events, if our cut is too low, we may include background events, if our cut is too high, we may eliminate some true events. Similarly to how we find the

distance selection, we calculate the efficiency and purity at each cut value and find where they intersect as seen in Figure 9. Commonly to find a proper cut value, we plot the Signal divided by the square root of background and see where it peaks. When doing so, we see that the optimal cut value is at 7 pixels.

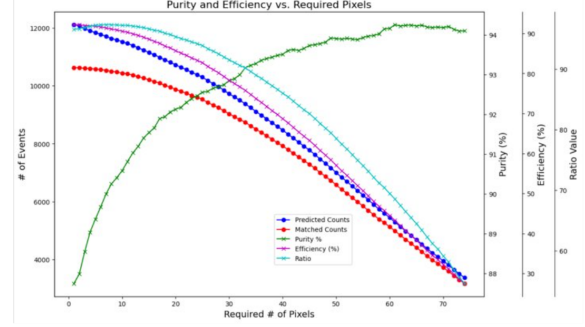


Figure 9: The Purity and Efficiency graph for each cut value over all data.

3.3 Results

When applying these cuts, we are looking for a better representation of the reconstructed Michel energy spectrum. Figure 10 is the resulting spectrum with these selections. We can see that we are including Miss ID'd events as well as eliminating some events from 30-50 MeV range. The resulting efficiency and purity is 72.25% and 97.19%. While the purity is very good, there is room for improvement with efficiency. An efficiency at 72.25% means we are eliminating some true events. Considering only two different cuts does not adequately represent the Michel energy spectrum, so we need to find a better way to do so.

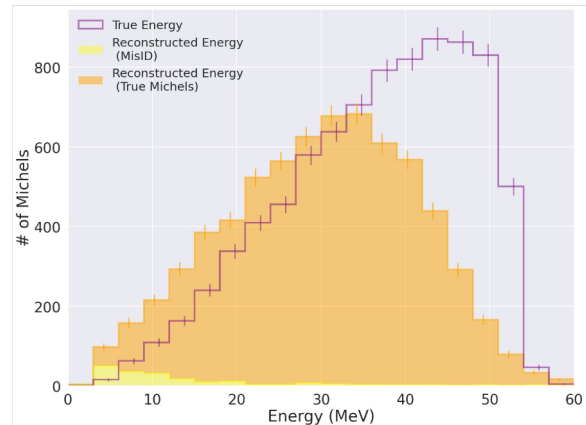


Figure 10: The Michel energy spectrum after applying updated cuts.

4 Boosted Decision Tree

Instead of optimizing each cut value by hand, we use machine learning to do so, specifically a Boosted Decision Tree. A Boosted Decision Tree using XGBoost (Extreme Gradient Boosting) is an advanced implementation of gradient boosting designed for high efficiency, speed, and performance.

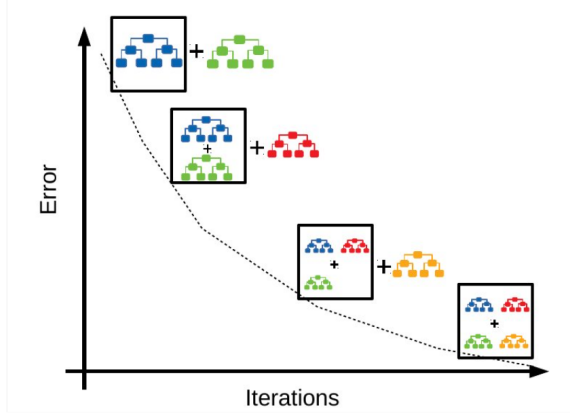


Figure 11: The process the BDT takes to achieve a proper prediction.

Boosting is a machine learning technique that improves prediction accuracy by combining the outputs of several weak learners. The process is sequential, with each model in the series working to correct the errors made by the previous ones. By building on the shortcomings of earlier models, boosting creates a strong, highly accurate predictive model.

In XGBoost, decision trees are used as weak learners. However, unlike traditional decision trees that are grown until they can perfectly classify training data, the trees in XGBoost are usually shallow, with limited depth. This approach helps prevent overfitting and ensures that each tree contributes just enough to improve the overall model's performance.

The gradient boosting process starts with an initial simple prediction, often the mean of the target variable. In each subsequent iteration, the model calculates residuals, which are essentially the errors of the current predictions. A new decision tree is then trained to predict these residuals. The model is updated by adding the predictions of this new tree to the ensemble, adjusted by a learning rate. This iterative process is designed to minimize a loss function, gradually improving the accuracy of the predictions.

XGBoost builds on the basic gradient boosting framework with several advanced features. It includes L1 and L2 regularization to reduce the risk

of overfitting, handles sparse and missing data efficiently, and uses techniques like weighted quantile sketching to optimize tree construction.

4.1 BDT Input

We provide the BDT with all relevant variables to achieve the best possible classification performance. We split the data into a test and training set, 80% of the events are used to train the model, while the remaining 20% are for testing its performance. The training set had 8000 events to train on, 7209 of those events being signal and 791 being background. Then the BDT had 204 background events and 2158 signal events to test on to determine its efficiency. Figure 12 shows the importance of each variable at determining if the event is an background or signal.

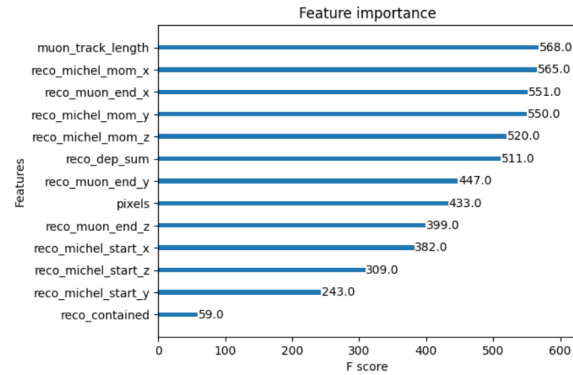


Figure 12: The Featured Importance Graph for the variables given to the BDT

4.2 Results

When looking at the BDT score predictions for each event in figure 13, we can see that the BDT did an excellent job at labeling each event as either background or signal, we know this by events being strongly near 1 or 0. By plotting the signal over the square root of the background graph, we observe a peak at a BDT score of 0.97. This peak allows us to assign each event its BDT score and place a cut at 0.97, effectively eliminating the background events from our data. Consequently, we plot our energy spectrum in figure 14.

The previously misidentified events are now removed, and many events in the 30-52 MeV range are now correctly filled in. The significant gap at higher energy is due to the reconstruction process missing many radiative photons. Many events would have been shifted to higher energy if their radiative photons had been included in the Michel energy calculation.

As a result, we find a purity of 99.76% and an efficiency of 82.20%. With our new cuts, there is an increase of 2.3% in purity and a decrease of 2.73% in efficiency, which is a small price to pay for achieving a very pure result.

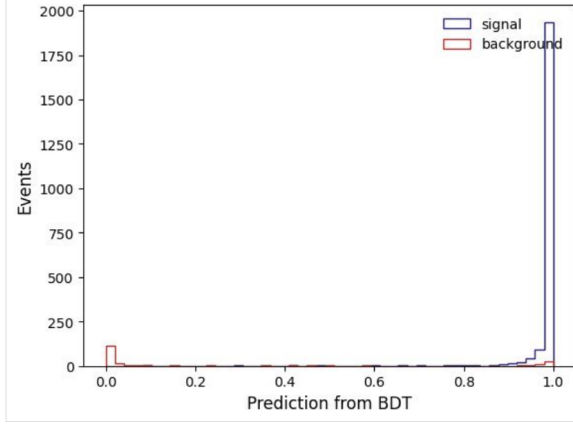


Figure 13: The resulting prediction from BDT. This shows that the BDT did a good job separating signal and background events.

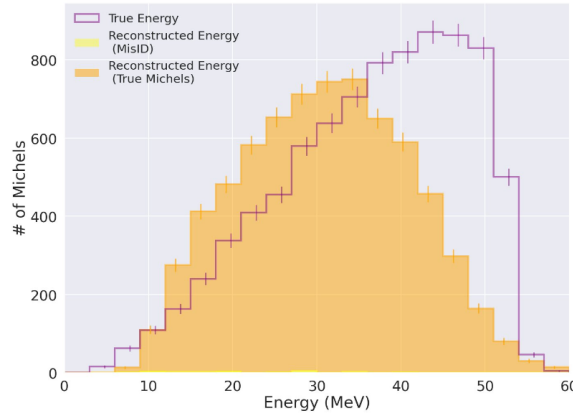


Figure 14: The resulting Michel energy spectrum with updated cuts from BDT.

5 Conclusion

For this Michel electron energy reconstruction and selection project we have built a machine learning process which creates the well defined energy spectrum. This algorithm was tested on both muons passing through our detector and stopping muons decaying in our detector. By improving the selection process we were able to produce a high purity and also a high efficiency for eliminating a large majority of miss ID'd Michels.

For the future, we should look at further increasing the efficiency of this data, by improving the reconstruction process to include radiative photons. Once we have improved and have a well matched energy spectrum then it can be compared to real data taken by SBND.

6 Acknowledgments

I would like to thank Georgia Karagiorgi for giving me the opportunity to tackle such an amazing project, and also for supporting me throughout the entire summer, this process has been extremely rewarding. Thank you as well to everyone in the SBND collaboration, which helped me through difficult parts of my project. Thank you to Nupur Oza for helping me through the theory of the project, and taking your time to guide me through many stages. Thank you to Karan Kumar for giving me advice throughout the summer and helping troubleshoot whenever I needed help.

Finally, thank you to all of the other REU students who were always there with another set of eyes when something wasn't working, but also for being a pleasure to hang out with this summer.

This material is based upon work supported by the National Science Foundation under Grant No. PHY-2349438.53

References

- [1] R. Acciarri et al. *A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam*. 2015. arXiv: [1503.01520](https://arxiv.org/abs/1503.01520) [physics.ins-det]. URL: <https://arxiv.org/abs/1503.01520>.
- [2] R. Acciarri et al. "Cosmic Ray Background Removal With Deep Neural Networks in SBND". In: *Frontiers in Artificial Intelligence* 4 (2021). ISSN: 2624-8212. DOI: [10.3389/frai.2021.649917](https://doi.org/10.3389/frai.2021.649917). URL: <https://www.frontiersin.org/journals/artificial-intelligence/articles/10.3389/frai.2021.649917>.
- [3] R. Acciarri et al. "Michel electron reconstruction using cosmic-ray data from the MicroBooNE LArTPC". In: *Journal of Instrumentation* 12.09 (Sept. 2017), P09014–P09014. ISSN: 1748-0221.

DOI: [10.1088/1748-0221/12/09/p09014](https://doi.org/10.1088/1748-0221/12/09/p09014). URL: <http://dx.doi.org/10.1088/1748-0221/12/09/P09014>.

- [4] Mary K. Gaillard, Paul D. Grannis, and Frank J. Sciulli. “The standard model of particle physics”. In: *Reviews of Modern Physics* 71.2 (Mar. 1999), S96–S111. ISSN: 1539-0756. DOI: [10.1103/revmodphys.71.s96](https://doi.org/10.1103/revmodphys.71.s96). URL: <http://dx.doi.org/10.1103/RevModPhys.71.S96>.