This paper presents a study on the implementation of nuclear effects on neutrino generators, specifically GENIE. The expected theoretical kinematics of a neutrino interaction given a free nucleon are compared to true-CCQE events in the MicroBooNE detector produced by GENIE in the presence of various nuclear effects, including binding energy, Fermi motion, and final state interactions. Additionally, this paper examines the potential of using single transverse variables to distinguish true CCQE-events from single pion absorption events. A better understanding of event generator kinematics and the ability to identify single pion absorption events could improve kinematic reconstruction and neutrino energy determination.

I. INTRODUCTION

A. Standard Model

The fundamental particles and three of the four fundamental forces that shape our universe and how they relate to one another are concisely described in the Standard Model of particle physics. While still not a truly complete theory of physical phenomena, the standard model included the prediction of the Higgs boson and tau neutrino, which have since both been experimentally confirmed, adding to the credibility of the model.

In the standard model, there are twelve elementary particles of spin-$\frac{1}{2}$ split into two groups of six, known as quarks and leptons.

Quarks are defined by the intrinsic properties mass, electric charge, spin, and color charge and combine to form colorless composite particles in groups of two (mesons) or three (baryons). They are self-interactive via the strong force, mediated by gluon, and can also interact with other fermions via the electromagnetic and weak forces. Quarks are further split into three generations (or flavors), each consisting of an up-type quark (up, charm, top) of spin-$\frac{2}{3}$ and a down-type quark (down, strange, bottom) of spin-$\frac{1}{2}$, increasing in mass with each flavor.

Leptons are split into charged leptons (electrons $e^-$, muons $\mu^-$, and taus $\tau^-$) and massless, neutral leptons (electron neutrinos $\nu_e$, muon neutrinos $\nu_\mu$, and tau neutrinos $\nu_\tau$). Leptons interact via the electromagnetic and weak forces, mediated by the photon and $W^\pm$ or $Z^0$, but not the strong force. Leptons are also split into three flavors consisting of a charged lepton and its’ neutrino pair (e.g. electron $e^-$ and electron neutrino $\nu_e$) [1].

B. MicroBooNE

MicroBooNE is a liquid argon time projection chamber (LArTPC) located on-axis of the booster neutrino beam line at Fermilab. The experiment was designed to measure low energy neutrino cross-sections in order to look for the low energy excess events (dubbed the sterile neutrino) originally observed by the MiniBooNE experiment. Unlike its’ predecessor, MicroBooNE’s LArTPC is able to identify photon from electron signals and has higher resolution capabilities at low energies [2].

The LArTPC detects and measures both the trails of ionization electrons and the scintillation light created by the particles traveling through the liquid argon. An electric field, created by a cathode plane on one side, drifts the ionization electrons into the three wire planes, two induction – offset at ±60 degrees from vertical – and one, vertical collection plane (Fig. 2) in order to create a two-dimensional reconstruction in the y-z plane. The x-
component is determined by the time it takes for the ionization electrons to drift to the wire planes, allowing for a full three-dimensional reconstruction of the event. The scintillation light is observed by 32 photomultiplier tubes (PMTs), allowing the exact timing an event occurred to be matched with the 3D interaction reconstruction [3].

Originally proposed in October 2007, MicroBooNE began collecting data eight years later, in October 2015. In addition to searching for the low energy excess, the MicroBooNE detector is set to look for cosmic neutrinos from astronomical events like Super Novae. MicroBooNE also plays an important role in the future of LArTPC technology and long baseline neutrino experiments like the Deep Underground Neutrino Experiment (DUNE).

II. NEUTRINO PHYSICS

A. History of Neutrino Physics

The neutrino was originally proposed by Pauli as the “neutron” or “little neutral one” in 1930 in an effort to explain the supposed lack of conservation of momentum, angular spin, and energy in beta decay. Pauli’s constraints were that it would be a particle of spin-\(\frac{1}{2}\) and electrically neutral, only interacting via the weak force. The first electron antineutrino \(\bar{\nu}_e\) was detected in 1956 in Cowan-Reines neutrino experiment. The two additional flavors of neutrinos were discovered later, the muon neutrino \(\nu_\mu\) in 1962 and the tau neutrino \(\nu_\tau\) in 2000.

The discovery of neutrino oscillations began with the solar neutrino problem of Ray Davis’ Homestake experiment in the 1960s. The Homestake experiment was designed to detect solar neutrinos in order to verify John Bachall’s theoretical calculations. The experiment operated for over 40 years and consistently found only a third of Bachall’s prediction. In the late 1950s, Pontecorvo began developing the theory of neutrino oscillations, where electron neutrinos would turn into muon neutrinos (\(\nu_e \rightarrow \nu_\mu\)). The existence of neutrino oscillations implies that neutrinos must have a nonzero mass, contradicting the current Standard Model. Neutrino oscillations were first observed starting in 1998 by Super-Kamiokande and Sudbury Neutrino Observatory (SNO). Since Davis’ experiment was only sensitive to one flavor of neutrino (\(\nu_e\)), this discovery solved the solar neutrino problem and verified both Davis’ experiment and Bachall’s calculations [4].

Today, there are many ongoing and future neutrino experiments along with MicroBooNE to search for new physics as well as validate and expand upon previous studies. Experiments like T2K, NOvA, and the future DUNE aim to further investigate neutrino oscillations, looking for charge-parity (CP) violation and determining the neutrino mass hierarchy. Other types of experiments such as IceCube and the future KM3NeT look to use neutrinos to determined point sources of high-energy astrophysical phenomenon.

B. Neutrino Oscillations and the Mass Hierarchy Problem

When Bruno Pontecorvo first proposed the theory of neutrino oscillations in 1957, it implied that neutrinos must be massive and that the Standard Model was not a complete picture. The three neutrino flavor eigenstates \((\nu_e, \nu_\mu, \nu_\tau)\) can be expressed as superpositions of the neutrino mass eigenstates \((|\nu_1\rangle, |\nu_2\rangle, |\nu_3\rangle)\) and vice-versa. A neutrino propagates through space according to it’s mass eigenstate \(|\nu_i\rangle\) and interacts according to it’s flavor eigenstate \(|\nu_\alpha\rangle\), which are both written as linear combinations of the other:

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

\[
|\nu_i\rangle = \sum_\alpha U_{i \alpha} |\nu_\alpha\rangle
\]

where \(i = 1, 2, 3\), \(\alpha = e, \mu, \tau\), and \(U_{\alpha i}\) is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix or the lepton mixing matrix. If the neutrino flavor eigenstates were equal to the mass eigenstates, \(U_{\alpha i}\) would be the identity matrix, but experimental evidence has shown this not to be the case [5].

In the case of three neutrino states, \(U_{\alpha i}\) is a 3x3 unitary matrix:

\[
U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\]

Which is generally factorized into three matrices of four free parameters, the three mixing angles between the
mass eigenstates \((\theta_{12}, \theta_{23}, \theta_{13})\) and a CP violating phase \(\delta\), so that \(U\) can be written as:

\[
U = XYZ
\]

where \(X, Y,\) and \(Z\) are:

\[
X = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos(\theta_{23}) & \sin(\theta_{23}) \\
0 & -\sin(\theta_{23}) & \cos(\theta_{23})
\end{bmatrix}
\]

\[
Y = \begin{bmatrix}
\cos(\theta_{13}) & 0 & \sin(\theta_{13})e^{-i\delta} \\
0 & 1 & 0 \\
-\sin(\theta_{13})e^{-i\delta} & 0 & \cos(\theta_{13})
\end{bmatrix}
\]

\[
Z = \begin{bmatrix}
\cos(\theta_{12}) & \sin(\theta_{12}) & 0 \\
-\sin(\theta_{12}) & \cos(\theta_{12}) & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

The propagation of \(|\nu_i\rangle\) can be described as a plane wave with the solutions of the form:

\[
|\nu_i(t)\rangle = e^{-i(E_i t - \vec{p} \cdot \vec{x})} |\nu_i(0)\rangle
\]

where \(E_i = \sqrt{p_i^2 + m_i^2}\). Then the probability that a neutrino will oscillate from the flavor \(\alpha \to \beta\) is:

\[
P_{\alpha \to \beta} = |\langle \nu_\beta(t) | \nu_\alpha \rangle|^2 = \sum_i U_{\alpha i}^* U_{\beta i} e^{-i m_i^2 L/2E}^2
\]

This holds true for any number of neutrino generations, but in the case of two neutrino oscillation this formula becomes:

\[
P_{\alpha \to \beta, \alpha \neq \beta} = \sin^2(2\theta)\sin^2\left(1.27 \frac{\Delta m^2 L}{E} \frac{[eV^2][km]}{[GeV]} \right)
\]

While the actual masses of these mass eigenstates are unmeasured, the mass-squared splitting difference between them has been measured:

\[
\Delta m_{1,i,j}^2 = m_j^2 - m_i^2
\]

As only the difference, and not the direction, is known, this allows for two possible neutrino mass orderings: a “normal” hierarchy where \(m_1 < m_2 < m_3\) and an “inverted” hierarchy where \(m_3 < m_1 < m_2\) (Fig. 3).

The results of the LSND and MiniBooNE experiments showed evidence for the existence of one or more “sterile” neutrinos. The low energy excess measured by MicroBooNE disagreed with the known measurements of the mixing angles and \(\Delta m^2\) when using the three-neutrino oscillation model. In fact, \(\Delta m^2_{1,2}\) and \(\Delta m^2_{2,3}\) were several orders of magnitude lower than the value found from the MicroBooNE data. The addition of a massive sterile neutrino that does not interact via the weak force could explain that measured difference. Ultimately, this would changes neutrino oscillation probabilities and each sterile neutrino adds to the lepton mixing matrix, with a new sterile mass eigenstate being defined as:

\[
|\nu_s\rangle = \sum_{\alpha} U_{\alpha s} |\nu_\alpha\rangle
\]

where \(N\) is the number of new sterile neutrinos. The addition of the sterile neutrino to the mass hierarchy can be seen at the bottom of figure 3.
C. Theoretical Relativistic Kinematics

Under the simplest charged current quasi-elastic neutrino interaction conditions – a neutrino incident on a free nucleon:

$$\nu + n \longrightarrow l^- + p$$

– the outgoing particles’ scattering angle and energy in the lab frame are found using relativistic kinematics. In short, this is found by calculating the 4-momentum of the exiting lepton and proton in the interaction’s center of mass frame and then boosting them into the lab frame. In all of these interactions, the z-axis is defined to be along the direction of motion of the neutrino. Figure 4 shows the expected kinematic plots for both $\nu_e$ and $\nu_\mu$ incident on a free neutron at various incoming neutrino energy $E_\nu$ levels. At low energy levels, the plot for the exiting proton turns over and quickly tails to zero, while the exiting lepton makes a full range of angles. This is due to the size of the proton relative to the energy exiting the interaction. With a mass of 938.3 MeV, the proton will never go backwards, thus the scattering angle will never go above $\frac{\pi}{2}$.

It is important to note that the low energy side of the exiting lepton plot corresponds to the high energy side of the proton plot and vice-versa. At the extreme, as show in Figure 5 by the green line, the proton receives all of the energy from the interaction and moves along the $+z$-direction, while the lepton goes backwards (in the $-z$-direction).

D. Nuclear Effects

In a true neutrino interaction, the kinematics of the outgoing particles are heavily affected by the nuclear effects within the nucleus both during and after the initial interaction. The effects examined in this study are binding energy, Fermi motion, and final state interactions, but there are additional factors such as Pauli blocking and generator specific settings, such as the chosen nuclear model, that influence the final state kinematics as well.

Within the nucleus, Fermi motion gives each nucleon a random momentum that changes an individual neutrino interaction event away from the expected theoretical kinematics given a free nucleon. If this random momentum was known at the time of the interaction, the resultant kinematics could be calculated. Since we are unable to make intranuclear measurements beyond probing, this can only be accounted for experimentally within a range for a given atom.

Final state interactions add an additional degree of randomness that is harder to predict or estimate. After the initial interaction occurs, there are many paths the exiting lepton and nucleon can take, the most basic being both the lepton and nucleon exit the nucleus with no further interactions to the most complicated, where the entire nucleus is “busted” up and all of the nucleons wind up exiting the system. Most often, several final state interactions will occur, making it impossible to track the “initial” proton and, even if it was, it would disagree with the expected kinematics.
III. GENIE ANALYSIS

A. GENIE

GENIE is a ROOT-based Neutrino Monte Carlo Generator designed to work with all nuclear targets over a wide range of energies. It allows for a wide variety of inputs, including neutrino flux spectrum and cross-sections. Additionally, a wide variety of physics parameters can be altered, like various nuclear effects, hadronization and nuclear gas models, and form factor types. GENIE is currently being used by a large number of neutrino experiments, including MicroBooNE, MINERvA, T2K, and IceCUBE. [6]

B. Analysis

For the purpose of this analysis, we will take an in-depth look at the resultant kinematics for one interaction type\(^1\). The interaction is a true-charged current quasi-elastic event from an 800 MeV $\nu_\mu$ incident on a neutron in liquid argon. When present, the Bodek-Ritchie relativistic fermi gas model and the HAIntranuke cascade model for final state interactions was used.

a. No Nuclear Effects Figure 7 shows the kinematics produced by GENIE with no nuclear effects compared to the expected theoretical relativistic kinematic plots for $\nu_\mu$ at 0.8 GeV. The agreement in these plots show that under the simplest neutrino interaction, GENIE behaves as expected.

b. With Binding Energy Recreating these plots with binding energy turned on, both the exiting lepton and proton curves keep the expected shape, as shown in the top of figure 8. Including the binding energy shifts the proton plot to the left at a constant amount of 29.5 MeV. While this amount is considerably higher than the nucleon separation energy for a neutron in \(^{40}\)Ar [7], GENIE defaults to an average nucleon removal energy over the entire nucleus to account for interactions that occur towards the center of the nucleus.

The concentration in these density plots show that low energy interactions are more likely to produce a higher energy lepton and a lower energy proton exiting the hadronic system.

c. With Fermi Motion and Binding Energy The kinematic plots at the bottom of figure 8 include both the binding energy and Fermi motion, with final state interactions turned off. The initial motion of the nucleon target given by the Fermi motion causes an even banding around the expected theoretical plots. The density plots show a heavier concentration around the center of the bands that becomes lighter as the distance from the expected plots increase. Additionally, the highest concentrations are at the higher energy leptons and lower energy protons, which is consistent with the previous plots.

---

\(^1\) Additional interactions, including those for $\nu_e$, $\bar{\nu}_e$, and $\bar{\nu}_\mu$ as well as varying energy levels are included in Appendix.
d. With Final State Interactions and Binding Energy

With just the final state interactions and binding energy enabled (Fig. 9), the exiting lepton matches with the expected plot exactly as if all nuclear effects were turned off. The exiting proton, however, exhibits a few noticeable changes. First, the scattering angle of the proton now ranges from 0 to π at low energies rather than from 0 to π/2. This is directly caused by any final state interactions the proton experiences before exiting the nucleus, completely altering the original path of the proton. The density plot shows the majority of protons exit with low energy regardless of the scattering angle. Second, there are more single outliers away from the heavy concentration, because of the randomness of the interactions. And third, there is a much tighter concentration along the tail at higher energy protons than the interaction with Fermi motion present, as protons that do not experience FSI will fall along the expected path.

FIG. 9. With binding energy and final state interactions

IV. ISOLATING SINGLE PION ABSORPTION EVENTS

A. True-CCQE vs. Pion Absorption

The study of true-CCQE events plays an important role in neutrino physics. The two body interaction allows for kinematic reconstruction, leading to the initial incoming neutrino energy being determined, which is necessary for the precision study of neutrino oscillation parameters, like mass splitting and mixing angles [8]. But is it possible to be certain that an event is true-CCQE? In a CCQE-like event, a pion is produced via a two particle two hole (2p2h) multi-nucleon effect and then absorbed before exiting the nucleus (Fig. 11). This interaction produces the same final state particles as a true-CCQE event. By identifying pion absorption events, we might be able to improve kinematic reconstruction and improve neutrino energy determination.

FIG. 11. Example of a CCQE-like event

e. Default Settings

Using GENIE default settings, which includes final state interactions, Fermi motion, and binding energy, figure 10 shows a combination of features from the previous plots. There is a wider banding around the line of the expected plot, similar to the plot without final state interactions, and the proton has a full range of scattering angles, like the plot without Fermi motion. The density plot of the exiting proton can be misleading as it appears less of the protons exit at higher energies than in figure 9. This is due to the concentration along low energy protons combined with the wider banding around the expected plot at higher energies. Although the band is less noticeable, it tapers off considerably slower, containing more scattering angles, than figure 9.

FIG. 10. Default GENIE settings
B. Single-Transverse Variables

Within the last year, there have been several transverse kinematic studies looking at nuclear effects and momentum conservation in the transverse plane. The three single-transverse variables (STV) looked at are $\delta \vec{p}_T$, $\delta \phi_T$, and $\delta \alpha_T$, defined in the plane that is transverse to the incoming neutrino.

\begin{align*}
\delta \vec{p}_T &= \vec{p}_{T}^{\nu} + \vec{p}_{T}^{\nu'} \\
\delta \phi_T &= \arccos \frac{-\vec{p}_{T}^{\nu} \cdot \vec{p}_{T}^{\nu'}}{p_{T}^{\nu} p_{T}^{\nu'}} \\
\delta \alpha_T &= \arccos \frac{-\vec{p}_{T}^{\nu} \cdot \delta \vec{p}_T}{p_{T}^{\nu} \delta p_T}
\end{align*}

1. $\delta \vec{p}_T$ is the overall 3-momentum imbalance in the transverse plane and is generated by nuclear effects.

2. $\delta \phi_T$ is the angular difference between the measured final state particles and if the particles were back-to-back in the transverse plane.

3. $\delta \alpha_T$ is the accelerating or decelerating effect on the hadronic system and is defined by the direction of the transverse momentum imbalance in relation to the axis defined by the charged lepton [9].

A major benefit of STVs for neutrino interaction studies is that these variables are less dependent on the incoming neutrino energy. As a result, the distributions for $\delta \vec{p}_T$, $\delta \phi_T$, and $\delta \alpha_T$ are largely consistent across varying $E_\nu$ and the differences become insignificant at higher energy levels (Fig. 13).

![Fig. 12. Cartoon depicting the transverse variables [10].](image)

![Fig. 13. The distributions for all three defined STVs for true-CCQE $\nu_\mu$ events in GENIE using default settings and the MicroBooNE flux.](image)
C. STVs and Nuclear Effects

In the absence of nuclear effects, $\delta \vec{p}_T$ and $\delta \phi_T$ would be zero, while $\delta \alpha_T$ would be undefined. Figure 14 shows distributions for all three STVs in the presence of various nuclear effects. Final state interactions play more of a role in causing $\delta \vec{p}_T$ and $\delta \phi_T$ to deviate from zero than Fermi motion. All three distributions agree with the expected result in the presence of no nuclear effects.

![Graphs showing distributions for all three STVs with and without nuclear effects.]

FIG. 14. The distributions for all three defined STVs in the presence of various nuclear effects.

D. Identifying Single Pion Absorption Events

The top of figure 15 shows the kinematic plots for a GENIE run containing both true-CCQE (in black) and single pion absorption events (in red). The single pion absorption events do not line up with theoretical kinematic plots, particularly for the lepton.

The bottom of figure 15 shows a comparison of the STV distributions for true-CCQE and single pion absorption events. Using these distributions, a series of cuts were applied to the data in an effort to remove CCQE-like events. Most noticeably, in the distribution for $\delta \phi_T$, the true-CCQE events fall off fairly quickly above an angle of 100°, while the pion absorption events stay fairly level. Applying the cut $\delta \phi_T < 100$ removes 37% of the pion absorption events, while only removing 13% of the true-CCQE events. The kinematic plot for this cut is shown in figure 16.

![Kinematic plots and STV distributions for true-CCQE and pion absorption events.]

FIG. 15. (top) The kinematic plots for a GENIE run containing both true-CCQE (black) and single pion absorption events (red). (bottom) A comparison of the STV distributions for true-CCQE (orange) and pion absorption (blue).
FIG. 16. Kinematic plots for CCQE-like events with the cut $\delta\phi_T < 100$ applied.

A secondary cut was made based off the distribution for $\delta\alpha_T$ with the reverse of the first cut applied ($\delta\phi_T > 100$), shown at the top of figure 17. This plot shows hardly any true-CCQE events below 140° and a cut there should eliminate a large portion of the pion absorption events. Applying this secondary cut $\delta\phi_T < 100$ and $\delta\alpha_T > 140$ removes 71.1% of the pion absorption events, but also removes 39.4% of the true-CCQE events. The kinematic plots for this additional cut shows that it is a little heavy handed, resulting in too much of a loss in true-CCQE events.

V. FUTURE WORK

Future work on this project includes looking into energy reconstruction under these various nuclear effects to account for missing energy in the final state. Also looking into improving these simple cuts for better rejection and efficiency. This might mean developing a likelihood cut variable or using Monte Carlo Expectation Maximization. Additionally, expand this study to further investigate using longitudinal variables [11]. Finally, quantifying how well these cuts might improve the reconstructed neutrino energy.

VI. ACKNOWLEDGEMENTS

First, thanks to Mike Shaevitz, who continually showed interest in the progress of this project and consistently offered me invaluable direction and advice. Also for being patient with me while I figured out how to make GENIE turn off Fermi motion.

Thanks to Georgia Karagiorgi for her feedback, interest, and engagement in my progress, along with Jose Crespo-Anadon and the entire neutrino group at Nevis.

I am especially grateful to Bill Seligman for getting GENIE to run at Nevis and getting me excited about plots.

John Parsons, Amy Garwood, and Georgia have put together an incredible and welcoming experience here with this Nevis Laboratories REU, and I am incredibly thankful to them for allowing me to be a part of it.

Lastly, I’d like to thank the National Science Foundation for funding this and all REU programs. It is an invaluable experience that should not and cannot be replaced.


Appendix A: Reading GENIE Event Display

There can be a lot of information to process in one individual event displayed by GENIE. The information is displayed in two tables, the GENIE GHEP Event Record and the GENIE Interaction Summary.

First, the GENIE GHEP Event Record contains all of the particles present (or really anything that added or removed energy from the interaction), those particles mothers and daughters, momentum, and mass. It also displays the cross-section size and number of final state interactions.

<table>
<thead>
<tr>
<th>GENIE GHEP Event Record [print level: 3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idx</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
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<tr>
<td>8</td>
</tr>
<tr>
<td>9</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>12</td>
</tr>
</tbody>
</table>

The first thing to do is look at the status code (Ist) of each particle to see which particles were involved in the initial interaction (initial state, 0 or nucleon target, 1), the particles that don’t make it out of the system (hadron in the nucleus, 14), and the final state particles (stable final state,1). In this example, there are 7 final state particles (1 μ, 2 p, and 4 n).
Then using the mother/daughter codes, you can follow where each particle comes from (to a degree). If it says daughter codes “7 : 12”, then it is the parent of particles 7 through 12. The diagram below shows the interaction with the final state particles in red.

<table>
<thead>
<tr>
<th>Index</th>
<th>Mother</th>
<th>Daughter</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>1 4 4</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
<td>2 3</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>- 5 5</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>- 13 13</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>- 11 -1</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>6 6</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>1 7 12</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>-1 -1 -1</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>-1 -1 -1</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>-1 -1 -1</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>-1 -1 -1</td>
</tr>
<tr>
<td>11</td>
<td>6</td>
<td>-1 -1 -1</td>
</tr>
<tr>
<td>12</td>
<td>6</td>
<td>-1 -1 -1</td>
</tr>
<tr>
<td>13</td>
<td>3</td>
<td>-1 -1 -1</td>
</tr>
</tbody>
</table>

Second, the GENIE Interaction Summary which contains information about the initial interaction, the particles involved and the type of interaction.

Appendix B: Altering Nuclear Effects in GENIE

There are several ways to alter parameters within GENIE, some of them easier than others. The easiest (and suggested) parameters to play with are located within $GENIE/config/UserPhysicsOptions.xml. Here you can alter a variety of physics options like the nuclear model, hadronization model and FSI, and binding energy.

Nuclear Model (around line 430):
- Bodek-Ritchie relativistic Fermi gas model
- Local Fermi gas model
- 1D Spectral Function
- Effective Spectral Function

Hadronization Model and FSI (around line 670):
- Turn FSI off by switching "HadronTransp-Enable" to false
• Alter the model being used
• Change various parameters within the model (including whether or not there is Fermi motion in the FSI)

Binding Energy (around line 450):
• GENIE defaults to an average binding energy, you can explicitly specify a binding energy
• Turn binding energy off by setting the "NucRemovalE@Pdg" for the given nucleus to zero

While there are many other settings in this file, these are the main ones that I changed in this file, but I encourage you to look around. Additionally, there are many other alterable files in $GENIE/config/ to look through, but a lot of it is covered in the UserPhysicsOptions. Note that if you change anything that influences the cross-section, a new spline must be generated. When in doubt, I’d always recommend regenerating the cross-section spline.

Turning off the Fermi motion was a bit more challenging. The first thing to note is that altering the Fermi-Mover.xml file does not seem to change anything with the initial movement of the target nucleon. To change this, you have to go into the source files, in this case $GENIE/src/Nuclear/FGMBodekRitchie.cxx, or which ever nuclear model is being used, and alter GenerateNucleon to force p3 = (0, 0, 0). Alternatively, you could do this in $GENIE/src/Nuclear/NuclearModelMap.cxx or $GENIE/src/EVGModules/FermiMover.cxx by forcing p4 to (0, 0, 0, nucleonmass) and not have to worry about which nuclear model is used. However, I’m unsure of any additional repercussions this might have and setting it at the source seems much safer. On that note, keep in mind that changing the source files may have unintended effects on the interactions!

There are a few things I’ve learned along the way that others may find useful, though they may seem obvious. Despite having been told this many times already in life, print statements are your friend. If you’re running GENIE through Fermilab, make sure your path leads to your own library. And don’t generate cross-section splines for things you don’t intend to run. If you decide to expand your study, you can always use your old cross-section file to generate a new one.
Appendix C: Additional Plots

FIG. 18. 800 MeV $\nu_e$: with binding energy (top) and with binding energy and final state interactions (bottom)
FIG. 19. 800 MeV $\nu_e$: with binding energy and fermi motion (top) and with default settings (bottom)