Examining the Feasibility of Identifying Tau Neutrino Charged Current Events in the DUNE Far Detector

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ABSTRACT

EXAMINING THE FEASIBILITY OF IDENTIFYING TAU NEUTRINO CHARGED CURRENT EVENTS IN THE DUNE FAR DETECTOR

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Department of Physics
Northern Illinois University, 2023
Michael Eads, PhD, Director

Neutrinos began as theoretical, massless particles, and since their first detection they have continued to be the subject of various experiments. One such experiment is DUNE, which is a long baseline neutrino experiment with the goal of studying neutrino properties, such as neutrino oscillation parameters. In this work, two projects were completed, one dealing with the hardware of DUNE and the other dealing with neutrino simulations. For the hardware project, we designed a quality control method for testing adaptor boards which make up part of the Far Detector circuit boards. This method was completed and prototyped, however was not implemented as planned due to funding changes. For the simulation project, we simulated $\nu_\tau$, $\nu_\mu$, and $\nu_e$ CC interactions using two simulation methods (stand alone GENIE and a full detector simulation) in order to begin to understand what a $\nu_\tau$ CC event would look like in the Far Detector and create an initial list of kinematic properties that can be used for this purpose. We found that there is not a complete understanding of what is occurring in the full detector simulation. We also found that there is promise in using kinematic properties to be able to differentiate $\nu_\tau$ CC events, however properties beyond those covered here, as well as a more accurate simulation, will be required for any definitive statistical statements.
EXAMINING THE FEASIBILITY OF IDENTIFYING TAU NEUTRINO CHARGED CURRENT EVENTS IN THE DUNE FAR DETECTOR

BY

SARAH CHOATE
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A THESIS SUBMITTED TO THE GRADUATE SCHOOL IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE MASTER OF SCIENCE

DEPARTMENT OF PHYSICS

Thesis Director:
Michael Eads, PhD
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CHAPTER 1
INTRODUCTION

1.1 The Standard Model

As it stands, all matter can be broken down into three types of fundamental particles which are leptons, quarks, and gauge bosons. A lepton is an elementary particle with half integer spin that is not affected by strong interactions. There are six leptons and six antileptons, which have the same properties as their corresponding lepton but with a charge reversal. The leptons can be categorized by their charge and lepton number resulting in three generations of leptons. The first generation is the electron ($e$) and electron neutrino ($\nu_e$), the second generation is the muon ($\mu$) and the muon neutrino ($\nu_\mu$), and the third generation is the tau ($\tau$) and the tau neutrino ($\nu_\tau$). There are also six flavors of quarks and six antiquarks which are categorized by their charge and quark number and also fall into three generations. The first generation is the up ($u$) and down ($d$), the second generation is the strange ($s$) and charm ($c$), and the third generation is the bottom ($b$) and top ($t$). Each quark and antiquark can be one of three colors resulting in thirty six total quarks. The leptons and quarks make up the classification of fermions, which are defined by the property of having half integer spin. Finally, there are the gauge bosons or mediators. These are integer spin particles which act as force carriers to mediate the interaction of particles with different forces. These include the gluon ($g$), the photon ($\gamma$), the W ($W^\pm$) and Z ($Z^0$) bosons, and the Higgs ($H^0$). These fermions and bosons make up the current Standard Model (SM) picture [1].
Table 1.1: Table of leptons (spin = 1/2), pulled from [1] with neutrino masses from [2].

<table>
<thead>
<tr>
<th>Generation</th>
<th>Flavor</th>
<th>Charge</th>
<th>Mass (MeV/c$^2$)</th>
<th>Lifetime (s)</th>
<th>Principle Decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>$e$</td>
<td>-1</td>
<td>0.510999</td>
<td>$\infty$</td>
<td>$e\nu_e$</td>
</tr>
<tr>
<td></td>
<td>$\nu_e$</td>
<td>0</td>
<td>$&lt;1.1 \times 10^{-6}$</td>
<td>$\infty$</td>
<td>-</td>
</tr>
<tr>
<td>Second</td>
<td>$\mu$</td>
<td>-1</td>
<td>105.956</td>
<td>$2.19703 \times 10^{-6}$</td>
<td>$e\nu_\mu \bar{\nu}_e$</td>
</tr>
<tr>
<td></td>
<td>$\nu_\mu$</td>
<td>0</td>
<td>$&lt;0.19$</td>
<td>$\infty$</td>
<td>-</td>
</tr>
<tr>
<td>Third</td>
<td>$\tau$</td>
<td>-1</td>
<td>1776.99</td>
<td>$2.19 \times 10^{-13}$</td>
<td>$e\nu_\tau \bar{\nu}<em>e$, $\mu\nu</em>\tau \bar{\nu}<em>\mu$, $\pi^- \nu</em>\tau$</td>
</tr>
<tr>
<td></td>
<td>$\nu_\tau$</td>
<td>0</td>
<td>$&lt;18.2$</td>
<td>$\infty$</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1.2: Table of quarks (spin = 1/2), pulled from [1] with masses from [2].

<table>
<thead>
<tr>
<th>Generation</th>
<th>Flavor</th>
<th>Charge</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>$d$</td>
<td>-1/3</td>
<td>4.67$^{+0.48}_{-0.17}$ (MeV/c$^2$)</td>
</tr>
<tr>
<td></td>
<td>$u$</td>
<td>2/3</td>
<td>2.16$^{+0.49}_{-0.26}$ (MeV/c$^2$)</td>
</tr>
<tr>
<td>Second</td>
<td>$s$</td>
<td>-1/3</td>
<td>93.4$^{+8.6}_{-3.4}$ (MeV/c$^2$)</td>
</tr>
<tr>
<td></td>
<td>$c$</td>
<td>2/3</td>
<td>1.27 $\pm$ 0.02 (GeV/c$^2$)</td>
</tr>
<tr>
<td>Third</td>
<td>$t$</td>
<td>-1/3</td>
<td>172.69 $\pm$ 0.3 (GeV/c$^2$)</td>
</tr>
<tr>
<td></td>
<td>$b$</td>
<td>2/3</td>
<td>4.18$^{+0.03}_{-0.02}$ (GeV/c$^2$)</td>
</tr>
</tbody>
</table>

Table 1.3: Table of vector bosons (spin = 1), pulled from [1] with masses from [2].

<table>
<thead>
<tr>
<th>Force</th>
<th>Mediator</th>
<th>Charge</th>
<th>Mass</th>
<th>Lifetime (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>$g$ (8 gluons)</td>
<td>0</td>
<td>Theoretical, may be as large as a few MeV/c$^2$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>$\gamma$</td>
<td>0</td>
<td>$&lt;1 \times 10^{-18}$ (eV/c$^2$)</td>
<td>$\infty$</td>
</tr>
<tr>
<td>Weak</td>
<td>$W^\pm$</td>
<td>$\pm1$</td>
<td>$80.377 \pm 0.012$ (GeV/c$^2$)</td>
<td>$3.11 \times 10^{-25}$</td>
</tr>
<tr>
<td></td>
<td>$Z^0$</td>
<td>0</td>
<td>$91.1876 \pm 0.0023$ (GeV/c$^2$)</td>
<td>$2.64 \times 10^{-25}$</td>
</tr>
</tbody>
</table>

Table 1.4: Table of scalar boson (spin = 0) with values from [2] and lifetime from [3].

<table>
<thead>
<tr>
<th>Mediator</th>
<th>Charge</th>
<th>Mass (GeV/c$^2$)</th>
<th>Lifetime (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H^0$</td>
<td>0</td>
<td>125.25 $\pm$ 0.17</td>
<td>$&lt; 1.9 \times 10^{-13}$</td>
</tr>
</tbody>
</table>

Notice that of the six leptons, three of them were neutrinos, the $\nu_\mu$, $\nu_e$, and $\nu_\tau$. Neutrinos are neutral, weakly interacting fermions, initially thought to be massless, and each of the three types of neutrino is described as a flavor. The necessity for a light, neutral particle came about in the 1930s as a result of nuclear beta decay. The general process for beta decay
is $A \rightarrow B + e^-$, where $A$ is a radioactive nucleus which transforms into a slightly lighter nucleus $B$ and, from that transformation, an electron is emitted. The problem arose as a result of conservation of energy. Conservation of energy through this reaction says that the electron energy, in the center of mass frame (such that the parent nucleus, $A$, is at rest with $B$ and $e^-$ having equal and opposite momenta), must be given by

$$E = \left(\frac{m_A^2 - m_B^2 + m_e^2}{2m_A}\right)c^2.$$  \hspace{1cm} (1.1)

Therefore, $E$ is fixed if $m_A$, $m_B$, and $m_e$ are specified. However, experiments found that emitted electrons had varying energies. In fact, Equation (1.1) only gives the maximum electron energy for the specific reaction between $A$ and $B$ and otherwise the energy varied dramatically. It was suggested by Pauli that another particle was carrying off the missing energy. In order for conservation of charge to hold, it must be neutral and extremely light making it difficult to track, which would explain why it was not seen in the reaction. As a result, the theory that neutrinos existed came about [1]. Neutrinos were first directly detected by the Cowan-Reines neutrino experiment, which involved measuring ‘inverse’ beta decay such that a neutrino was produced. Initial results for this experiment were obtained in 1953 using a reactor at the Hanford Site in Washington utilizing the reaction $\bar{\nu} + p \rightarrow \beta^+ + n^0$ [4]. The experiment was repeated and results were confirmed in 1956 at the Savannah River plant in South Carolina, which had better shielding from cosmic rays than was available at Hanford and thus a lower background than the previous data had allowing for increased certainty in the results of a positive neutrino detection [5].

Neutrinos interact through the weak force (and extremely minimally through gravitational forces, which will be seen later), making them difficult to detect and track. Because of this, they are the subject of various experiments. It was initially predicted by the SM that neutrinos were massless. However, it was discovered that neutrinos can oscillate between
flavors [6], meaning that they can start as one flavor and transform into a different flavor at a later time. If neutrinos were massless, there could not be flavor differentiation in experiment as they are electrically neutral, so there would be no distinguishing factor to tell the flavors apart. As a result, there are now questions about the nature of neutrino mass, such as the ordering of neutrinos masses, which will be discussed in section 1.2. There are also questions about whether neutrinos are their own antiparticle. If they were massless, again it would not matter since each neutrino type would be experimentally indistinguishable. Since neutrinos do have mass, this question requires an answer. If there are separate neutrinos and antineutrinos, they would be classified as Dirac fermions, but if each flavor of neutrino is its own antiparticle then they would be classified as Majorana fermions. This will be discussed further in Section 1.3. One of the many experiments dedicated to investigating answers to neutrino questions is the Deep Underground Neutrino Experiment (DUNE), which will consist of two detectors, a Near Detector (ND) and Far Detector (FD), and a neutrino beamline [7]. The goals and broad configuration of DUNE will be discussed in Section 1.4 and the setup of DUNE specific to this work will be discussed in Chapter 2. A final introductory note for completeness is that throughout this discussion, it is assumed that there are three active neutrino flavors ($\nu_e$, $\nu_\mu$, and $\nu_\tau$, as previously mentioned). There is the possibility of a fourth sterile neutrino state which only interacts gravitationally and not through a SM gauge interaction, however these types of neutrinos are beyond the scope of this discussion and therefore will be omitted for the duration of this work.

1.2 Neutrino Oscillations

According to the current SM, neutrinos are neutral, left-handed fermions which can only interact through the weak force. Initially, neutrinos were predicted to be massless because it
fit well with what was expected of them, since they were so difficult to detect. Once the SM came into existence as a theory, neutrinos continued to be predicted as massless because only left handed neutrinos were ever observed since only left handed particles can couple to the weak force, the only force that neutrinos are predicted to interact with. In order to interact with the Higgs mechanism, both left handed and right handed particles must exist as an interaction with the Higgs mechanism alternates the helicity of the interacting particle. Since it is believed that only left handed neutrinos exist, it follows that they must not participate in the SM Higgs mechanism to acquire mass as, if they did, right handed neutrinos would have to be observed. However, it has been shown that neutrinos do, in fact, have mass through the observation of neutrino oscillations. If neutrinos were massless, there could be no experimental flavor differentiation, so the ability to observe neutrinos oscillating between flavors shows there must be some mass. Neutrinos then additionally interact gravitationally, although extremely minimally. The concept of neutrino oscillations was initially predicted by Pontecorvo in 1957 but lacked experimental evidence until 1998 when the Super-Kamiokande (SK) Collaboration published results regarding atmospheric neutrinos [8]. While measuring the ratio of neutrinos detected, $\nu_\mu/\nu_e$, produced through charged current (CC) interactions using the observation of final state leptons, it was found that the ratio was much smaller than predicted through SM calculations. However, the data was consistent with a two flavor oscillation paradigm, $\nu_\mu \rightarrow \nu_e$, such that the $\nu_\mu$ were transforming to $\nu_e$, to a 90% confidence level [9]. There was also a problem in the solar neutrino sector, where there was a deficit in $\nu_e$ as compared with Solar Standard Model (SSM) calculations. The Sudbury Neutrino Observatory (SNO) measured fewer $\nu_e$ than expected and published these results in 2001 and 2002. In the 2002 publication, the results were presented at 5.3$\sigma$ and provided strong evidence that the $\nu_e$ were transforming flavors [6]. In 2010, The Oscillation Project with Emulsion-tRacking Apparatus (OPERA) Experiment observed a $\nu_\tau$ candidate from a $\nu_\mu$ beam, meaning that there were $\nu_\tau$ observed from a beamline that should only produce $\nu_\mu$. 
These results were published in 2018 with 6.1σ significance and ruled out the null hypothesis that oscillations to $\nu_\tau$ did not occur [10]. Then, in 2019, the IceCube Collaboration published their measurement of $\nu_\tau$ appearance, placing further constraints on mixing parameters [11].

Neutrino flavor oscillation is a quantum mechanical phenomenon. Neutrino do not have a single mass eigenstate, instead neutrinos exist as a coherent superposition of mass eigenstates [12]. In quantum mechanics, coherent states are linear combinations that minimize the uncertainty product such that, for a superposition of these states, it is possible to move between observables that are present in the superposition [13]. For neutrinos, this coherence is what allows neutrino oscillations to occur, since they exist as a superposition of all three mass eigenstates and can move between them. This is also why, despite what is predicted in the SM, neutrinos must have mass. If they did not, there would be no distinguishable mass eigenstates for them to move between [12].

There exists a transformation matrix which relates neutrino flavor to mass eigenstate called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix [12]. Assuming a three-flavor oscillation paradigm, the PMNS mixing matrix is written as

$$
\begin{pmatrix}
  U_\ell_1 & U_\ell_2 & U_\ell_3 \\
  U_\mu_1 & U_\mu_2 & U_\mu_3 \\
  U_\tau_1 & U_\tau_2 & U_\tau_3
\end{pmatrix},
$$

where

$$
\begin{pmatrix}
  U_\ell_1 & U_\ell_2 & U_\ell_3 \\
  U_\mu_1 & U_\mu_2 & U_\mu_3 \\
  U_\tau_1 & U_\tau_2 & U_\tau_3
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\
0 & 1 & 0 \\
-s_{13}e^{-i\delta_{CP}} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\quad \text{(1.2)}
$$
is the standard parametrization of the PMNS mixing matrix assuming unity. Here, $s_{ij} = \sin \theta_{ij}$, $c_{ij} = \cos \theta_{ij}$, and each $U$ has two subscripts to specify both flavor and mass state. $	heta_{ij}$ are the angles which rotation occurs and determine the amplitude of mixing, while $\delta_{\text{CP}}$ is the charge-parity (CP) violating phase [11]. CP violation will be discussed further in Section 1.3. There is the possibility of an additional diagonal matrix of phases denoted as $P$ (not included in Equation (1.2) as written), however its existence in Equation (1.2) is dependent on if neutrinos are Dirac or Majorana fermions. For Dirac fermions, $P_{\text{Dirac}} = 1$ is a unitary matrix and for Majorana fermions, $P_{\text{Majorana}}$ is a diagonal matrix involving two phases. Notation for $P_{\text{Majorana}}$ can vary but one representation for it is

$$P_{\text{Majorana}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & e^{i(\phi_3 - \delta_{\text{CP}})} \end{pmatrix},$$

where $\phi_2$ and $\phi_3 - \delta_{\text{CP}}$ are called Majorana phases and can range from $[0, \pi]$. The difference between Dirac and Majorana fermions will be discussed in Section 1.3 but for this section $P$ will be omitted for the discussion of Equation (1.2) as $P$ only affects probability for processes which violate lepton number [12].

One important question regarding the PMNS mixing matrix is whether or not it is in fact unitary. For a matrix to be unitary, the rows and columns must maintain rational probabilities such that the probability amplitude of each element in a row or column must add to one. This condition states that

$$|U_{i1}|^2 + |U_{i2}|^2 + |U_{i3}|^2 = 1 \text{ with } i = e^-, \mu^-, \tau^- \quad (1.3)$$

$$|U_{ej}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1 \text{ with } j = 1, 2, 3.$$
Unitarity matters for any theory as a fundamental property that ensures the theoretical framework is consistent. Non-unitarity implies a violation of probability \[14\]. It has been established that \(|U_{e3}|^2 + |U_{\mu 3}|^2 \simeq 0.5\) so one check of unitarity requires \(|U_{r3}|^2 \simeq 0.5\) \[11\].

The probability that a neutrino of flavor \(\alpha\) will oscillate to a different flavor \(\beta\) at some time \(t\) is given by

\[
P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu(t) \rangle|^2 = \left| \sum_i U_{\beta i} U_{\alpha i}^* e^{-i E_i t} \right|^2 \quad (1.4)
\]

[12]. For example, the probability for \(\nu_\mu \rightarrow \nu_\tau\) for neutrinos propagating through matter is

\[
P_{\nu_\mu \rightarrow \nu_\tau} = \sum_{j,k} U_{\mu j}^* U_{\tau j} U_{\mu k}^* U_{\tau k} \exp \left( -i \frac{\Delta m_{jk}^2 L}{2 E_\nu} \right) \approx \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4 E_\nu} \right)
\]

where \(L\) is the path length, \(E_\nu\) is the neutrino energy, and \(\Delta m_{jk}^2 = m_j^2 - m_k^2\) is the mass-squared splittings \[11\].

The sign of \(\Delta m_{jk}^2\) is still unknown and leads to the question of mass hierarchy. When discussing flavors, the neutrinos can be denoted as \(\nu_\mu, \nu_e,\) and \(\nu_\tau\). But, when we talk about mass, the neutrinos can be denoted as \(\nu_1, \nu_2,\) and \(\nu_3\). To entirely describe a neutrino, both flavor and mass number need to be specified. Due to neutrinos being a superposition of mass eigenstates, there is not a clear definition of which mass number corresponds to which flavor, as each mass number can act as any of the three flavors, just with varying levels of probability, such that each flavor can be written as

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\cdot
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix} \quad (1.5)
\]
There are two possible ways to order neutrino masses: normal or inverted hierarchy. Normal hierarchy states that $m_1 < m_2 < m_3$, whereas inverted hierarchy states that $m_3 < m_1 < m_2$. These options come from measurements of $\Delta m^2_{21}$ and $\Delta m^2_{31}$. From the Kamioka Liquid-Scintillator Anti-Neutrino Detector (KamLAND), $\Delta m^2_{21} = 7.9^{+0.6}_{-0.5} \times 10^{-5}$ eV$^2$/c$^4$ [16] and from the Main Injector Neutrino Oscillation Search (MINOS) Collaboration, $\Delta m^2_{31} = 2.32^{+0.12}_{-0.08} \times 10^{-3}$ eV$^2$/c$^4$ [17]. Since $\Delta m^2_{21}$ is small and $\Delta m^2_{31}$ is relatively large, the difference between $m_1$ and $m_2$ is smaller than the difference between $m_1$ and $m_3$, giving the two mass hierarchy options. Current data from various experiments is more favorable towards normal hierarchy, although inverted hierarchy also provides a reasonable fit for data [7]. Recent results from the NO$\nu$A experiment and the Tokai to Kamioka (T2K) experiment have placed further constraints on neutrino oscillation parameters, including on values for the mass-squared splittings. In 2021 NO$\nu$A published results showing that $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}$ eV$^2$/c$^4$ indicating normal hierarchy [18]. Prior to these results in 2021, T2K published results stating that $\Delta m^2_{32} = (2.45 \pm 0.07) \times 10^{-3}$ eV$^2$/c$^4$, also indicating normal hierarchy [19]. Propagation of oscillating neutrinos through matter results in the sensitivity for experiments to be able to measure the neutrino mass spectrum. Since neutrinos do not have a small amount of mass, as path length increases, matter effects increase and, in turn, sensitivity to mass ordering also increases, which can be seen by the dependency on $L$ in the expansion of Equation (1.4). For normal mass ordering, the oscillation probabilities are enhanced for neutrinos, while the oscillation probabilities are suppressed for inverted mass ordering [20].

The mixing angles, $\theta_{12}$, $\theta_{13}$, and $\theta_{23}$ determine what the flavor content of the mass eigenstate will be and can be measured through different neutrino experiments [21]. Solar neutrino experiments, such as SNO, are sensitive to measure $\theta_{12}$. According to the Particle Data Group (PDG), which gives an average of results for values across multiple experiments, $\sin^2(\theta_{12}) = 0.307 \pm 0.013$. Atmospheric neutrino experiments, such as SK, are sensitive to
\( \theta_{23} \) and according to the PDG, \( \sin^2(\theta_{23}) = 0.546 \pm 0.021 \) indicating that \( \theta_{23} \approx 45^\circ \) [2]. The sign of \( \theta_{23} \) is not currently known meaning there is question as to whether \( \theta_{23} > \pi/4 \), which is referred to as the higher octant, or \( \theta_{23} < \pi/4 \), which is referred to as the lower octant [22]. This question is known as the octant degeneracy. Long baseline neutrino experiments, such as DUNE, are sensitive to \( \theta_{13} \) and according to the PDG, \( \sin^2(\theta_{13}) = 0.0220 \pm 0.0007 \) [2]. Knowledge of these values is critical in determining whether or not the PMNS mixing matrix is unitary. Values that result in a deviation from unitarity indicate the possibility of physics beyond the SM such as non-standard interactions between the three active neutrino flavors or the existence of a fourth sterile neutrino. Values that result in a matrix that is unitary or approximately unitary would place further constraints on any experimental oscillation anomalies [11].

1.3 CP Violation

CP symmetry is a fundamental symmetry between matter and antimatter. Charge symmetry states that if a particle is exchanged with its antiparticle, such that the charge is mirrored, then the laws of physics will still apply. Similarly, parity symmetry states that if the spatial coordinates of a particle are inverted then the laws of physics will still hold. CP symmetry is the combination of both of these symmetries. It has been found that CP symmetry is violated, although the source of violation is unknown. This violation was first observed in 1964 in neutral kaon decay where the existence of a two pion decay mode for neutral kaons was confirmed, indicating a violation of CP symmetry [23]. Violation of CP symmetry was then observed in the decay of \( B \) mesons by the BaBar Collaboration in 2004 [24]. In 2019, the Large Hadron Collider beauty (LHCb) Experiment observed CP violation in charm decays using the decay of the \( D^0 \) meson [25]. These results indicate that CP is
violated at least in neutral kaon decays, as well as in quarks. The concept of CP violation was proposed out of necessity for the universe to exist in the state that it does, since matter dominates antimatter. If CP symmetry held, then the amount of matter in the universe should be equivalent to the amount of antimatter. However, the amount of CP violation that occurs in quarks is not large enough to account for the matter-antimatter imbalance of the universe. CP violation has not been observed in any other fundamental particles, however it is possible that if it is violated in other leptons that this could result in the disparity between matter and antimatter. A possible source of CP violation is leptonic mixing, which results in a CP violating phase, $\delta_{CP}$. Since neutrinos oscillate, and thus mix, they provide a possible mechanism through which CP violation can be measured using $\delta_{CP}$, which shows up in the PMNS mixing matrix, Equation (1.2) [26].

The debate between if neutrinos are Dirac or Majorana fermions is important for the discussion of the CP violating phase. The only measurable difference between a particle and its corresponding antiparticle is the inversion of the charge. Since neutrinos are electrically neutral, it is uncertain whether or not they are their own antiparticle, meaning that a $\nu_\tau$ and antitau neutrino ($\bar{\nu}_\tau$) could be the same particle and similarly for the other two flavors. In the event that each flavor of neutrino is its own antiparticle, they would be classified as Majorana fermions. If neutrinos and antineutrinos are distinct particles, then they are classified as Dirac fermions [27]. The necessity of the $\delta_{CP}$ term in the PMNS mixing matrix as well as the existence of the P matrix in Equation (1.2) depends on if neutrinos are Dirac or Majorana fermions, making it an important distinction to determine. Dirac fermions have a Lagrangian that is invariant under a U(1) global transformation, meaning that the multiplication by a factor of $e^{i\phi}$, where $\phi$ is arbitrary and independent of position in spacetime, does not result in a change in theory. Because of this, the phase $\delta_{CP}$ can be removed from Equation (1.2). The Lagrangian for Majorana fermions, on the other hand, is not invariant under a U(1) global transformation, therefore requiring the presence of the $\delta_{CP}$.
factor in Equation (1.2). In terms of measurements, it is only possible to measure $\delta_{CP}$ for neutrinos that propagate through matter because this CP violating phase does not affect the oscillation formula for neutrinos that propagate through a vacuum [28].

### 1.4 Deep Underground Neutrino Experiment

DUNE is an experiment dedicated to answering various questions about the nature of neutrinos. The primary goals of DUNE are: (1) to explore why matter dominates over antimatter through CP violation and obtain a measurement of the CP violating phase, $\delta_{CP}$, (2) determine neutrino mass ordering, specifically the sign of $\Delta m_{13}^2$, and (3) acquire precise measurements of neutrino mixing parameters and improve the precision of the $\theta_{13}$ measurement [7]. The first goal is achievable, as the neutrinos measured by the DUNE detectors will have propagated through matter and, from Section 1.3, it is required that to measure $\delta_{CP}$ the neutrinos travel through matter. The second goal is achievable because, as seen in Section 1.2, sensitivity to mass ordering increases as length increases and DUNE will have a far detector such that the neutrinos produced by the beamline will travel through many kilometers of matter before they are measured by the far detector. The third goal is achievable because, as seen in Section 1.2, long-baseline experiments are sensitive to the measurement of $\theta_{13}$.

There are three main components that make up DUNE. First is a high-intensity neutrino source which is generated from a proton accelerator. The beam is produced by the Long-Baseline Neutrino Facility (LBNF) at Fermilab, which collides with a production target and creates a secondary beam. The secondary beam results in an intense neutrino flux traveling in the direction of two detectors. The second component is a ND, located downstream of the neutrino source close enough to the source that neutrinos produced will not oscillate by
the time they reach the ND. The third component is a FD, located 1300 km from the near detector and 1.5 km underground at the Sanford Underground Research Facility (SURF), in South Dakota and will be the main focus of this discussion. This separation between the ND and FD is optimized for determining mass hierarchy and measuring the CP violating phase as the optimal baseline to determine these quantities is between 1000 and 2000 km [7].

![Figure 1.1: Cartoon schematic of the configuration of DUNE. [7]](image)

The main purpose of the ND is that it will serve as a control for the experiment, particularly with respect to measuring neutrino oscillations. Since the ND will measure neutrinos produced from the beamline in their initial state, it will allow for comparisons to be made to the final state of the neutrinos as measured later by the FD. The ND will also function to constrain systematic uncertainties. This is the extent that the two detectors will work in tandem, as the ND has its own physics program and goals [29]. The FD will be discussed in further detail in Chapter 2.
CHAPTER 2
FAR DETECTOR

2.1 Background

The FD is a modular liquid Argon time-projection chamber (LArTPC) with the ability to reconstruct neutrino interactions with high resolution and precision. It will be situated 1300 km from the ND and 1.5 km underground at SURF, which allows for a long enough baseline to measure mass hierarchy and $\delta_{CP}$, as mentioned in Section 1.4. The FD will also be on-axis, which differs from many current long-baseline neutrino experiments. Other experiments, such as NO$\nu$A, utilize an off-axis configuration. For an off-axis beam configuration, the beam is shifted from the detector direction by a few degrees. The amount that the beam is shifted corresponds to the peak neutrino energy. For example, T2K is an off-axis detector with an angle that can vary from 2.5° to 3.0° which equates to the mean energy of the neutrinos ranging from 0.5 GeV to 0.9 GeV [30]. Off-axis detectors offer low background for $\nu_e$ appearance and $\nu_\mu$ disappearance channels, but this comes with reduced flux and spectral information, meaning that DUNE will not suffer from the reduction of this information but will have to contend with higher $\nu_e$ appearance and $\nu_\mu$ disappearance backgrounds which begins to hint at the idea that it will be necessary to be able to separate these background from signals of interest, for example $\nu_\tau$ CC interactions. The detector modules making up the FD are called LArTPC modules and there are two types. One is the single-phase (SP), which will be discussed further in Chapter 3, and is where all the detector elements are submerged in liquid Argon and the ionized charge drifts horizontally. This module is also
referred to as the horizontal drift detector. The other module was originally the dual-phase (DP) which had some components that operate in gaseous Argon above the liquid Argon and the ionized charge would drift vertically, allowing for a different maximum drift length than in the SP module [7]. The DP module has since been replaced with a vertical drift design which is more similar to the horizontal SP module. It is also a SP module meaning that all components will be submerged in liquid Argon but rather than the charges drifting horizontally, they drift vertically [31]. However, the vertical drift module will not be the focus of this discussion as this work was only done for the horizontal drift detector.

2.2 Liquid Argon

Liquid Argon has been chosen as a neutrino target in various experiments before DUNE such as MicroBooNE. There are several advantages to using liquid Argon as a neutrino target. First, it is dense, which is advantageous because detectors can be smaller but still have a reasonable probability of neutrino detection occurring. Argon is also inert meaning that it does not react with other chemical substances, so there is no risk of the argon reacting with anything making up the submerged electronic components [32]. Additionally, compared to other noble liquids, Argon is a fairly inexpensive option and a large volume of liquid argon is required for the detector as the DUNE FD has a fiducial mass of 40 kt [7].

2.3 Time Projection Chamber

There are various way to design a detector in order to detect high energy particles. Early methods of tracking particles included bubble chambers and spark chambers, however these methods have the disadvantage that the events must be photographed and then analyzed
at a later time, which is not ideal for large quantities of data. In the 1960s, Charpak developed multi-wire proportional chambers (MWPC), or wire chambers, which no longer require events to be photographed. Wire chambers are self-triggering with very good time resolution and position accuracy. The setup involves wires stretched in one direction across a frame with a voltage applied, creating a cathode surfaces with anode wires. The chamber is filled with a gas such as Argon. When an ionizing particle passes through the gas, an ion pair is created and electrons produced near the wire and accelerates towards it. These electrons have enough energy to produce additional pairs, resulting in a negative pulse in the wire. The resulting output includes the position and time of the particle that traveled through the chamber [33].

While the wire chamber does address some of the disadvantages of the bubble and spark chambers, the wire chamber does have its own problems. The largest disadvantage is that wire chambers only give information about one spatial direction, meaning that in order to determine a coordinate, two wire chambers are required, thus increasing the complexity of detector arrangement and reducing the solid angle spanned by the detector. In order to negate this disadvantage, time projection chambers (TPCs) are used. TPCs are nearly identical to wire chambers, but have large solid angles with spatial resolution in three dimensions. They include a drift chamber which uses a small electric field to make electrons drift to an anode wire. For a TPC, the drift chamber is filled with gas, like Argon, and a uniform electric and magnetic field is applied. As a charged particle passes through the drift chamber, ion pairs are produced and then accelerated by the applied electric field. The endcaps of the TPC contain a MWPC arrangement. The $z$ coordinate for the event is determined by measuring drift time from the event to the endcap where drift velocity is given by

$$v_D = \frac{e \tau E}{2m},$$

(2.1)
where \( e \) is the charge of the particle, \( \tau \) is the mean collection time, \( E \) is the electric field intensity, and \( m \) is the mass of the particle. The radial coordinate, \( r \), is measured by the MWPC arrangement using anode wires in the azimuthal direction, \( \theta \). Energy loss per unit length, \(-\frac{dE}{dx}\), is determined by the total charge deposited at the endcaps which gives total ionization. This measurement allows the calculation of particle speed, \( v \), using the Bethe-Bloch equation

\[
-\frac{dE}{dx} = \frac{4\pi n_z^2 Z e^4}{m_e v^2} \left( \ln \frac{2m_e v^2}{I[1-(v/c)^2]} - \left( \frac{v}{c} \right)^2 \right),
\]

where \( n \) is number of electrons per cm\(^3\) in the medium, \( Z \) is the atomic number, \( ze \) is charge, \( I \) is mean excitation potential of the atoms in the medium, and \( m_e \) is the mass of the electron. The curvature of the particle’s path due to the applied electric and magnetic fields can be found using the particle’s coordinates and the momentum can be found from the total scattering cross section, \( \sigma_{\text{tot}} \), which is given by the equation

\[
\sigma_{\text{tot}} = \int \sigma(\theta) d\Omega,
\]

where \( \sigma(\theta) \) is the differential scattering cross section, \( \sigma(\theta)d\Omega = d\sigma(\theta) \). Once the momentum and velocity are determined, the particle can be identified [33]. This is generically how TPCs work, the specifics of the DUNE SP module are discussed in Chapter 3.
CHAPTER 3
FAR DETECTOR SINGLE PHASE MODULE

3.1 Anode Plane Assembly System

In order to detect ionized particles traversing through the fiducial volume of the FD, DUNE uses an anode plane assembly (APA) system as a SP module element. These are modular elements such that 150 APAs can be tiled together to form the readout system for one 10 kt detector module. The anode planes are used to sense the signals that are created as a result of ionization drifting in the TPC volume which, in turn, is the result of a charged particle traveling through the liquid Argon in the SP module. When the anode planes are tiled together, they form the APA. A single APA is 6.3 m high by 2.3 m wide such that, when tiled together, the readout plane is 12 m high by 58 m long. This size was chosen in order to have an integer number of electronic readout channels and boards.

Figure 3.1: Visual of one FD SP module where the regions labeled “A” represent anode planes and the regions labeled “C” represent cathode planes. This image is from [7].
The APA frames are made of stainless steel tubes and are covered by 2500 wires. The wires are oriented at angles in three planes such that the readout plane spans almost the entirety of the APA. The vertical collection plane is defined by $X$ and two induction planes are defined by $U$ and $V$. Additional wires which are not read create an outer shielding plane, $G$, which runs parallel to $X$, and is meant for pulse shaping to improve the signal shape on $U$ by shielding it from the drifting charge. $U$ and $V$ are angled at $\pm 35.7^\circ$ to the vertical in order to ensure that each induction wire crosses any given collection wire once. This reduces ambiguities in the reconstructed data and results in an integer multiple of electronics boards needed to read out one APA. $G$, $U$, and $V$ are completely transparent to drifting ionization while $X$ is completely opaque [34]. The wiring method can be seen in Figure 3.2.

Figure 3.2: Schematic of the APA wire wrapping method. The top portion of the image shows the dimensions of the APA and the direction of each of the wires making up the three signal planes ($X$, $U$, and $V$) as well as the fourth shielding plane, $G$. When looking at the APA from outside in, the order of the layers is $G$, $U$, $V$, $X$, followed by a grounding mesh. The bottom portion of the image shows the board in a horizontal orientation [34].
3.2 TPC Electronics

Mounted on the APAs and submerged in the liquid Argon are TPC readout electronics which are referred to as cold electronics (CE). The motivation for submerging the CE system is driven mainly by noise reduction as a result of minimizing the input capacitance, as well as a reduction in the number of cables required to come out of the cryostat. By decreasing the noise, smaller charge deposits can be detected allowing for low-energy physics measurements such as $^{39}$Ar beta decay, which is used to calibrate the DUNE SP module [34]. The CE are connected to the $X$, $U$, and $V$ layers on the APA. $V$ is connected directly to the CE and $X$ and $U$ are connected through DC-blocking capacitors [35]. The CE are continuously read out while sampling at a rate of 2 MHz. This means that a digitized analog-to-digital converter (ADC) sample from each APA wire occurs every 500 ns. The CE signal processing itself is implemented with application-specific integrated circuits (ASICs) and utilizes complementary metal-oxide-semiconductor (CMOS) electronics. Utilizing CMOS electronics results in higher gain and lower noise when submerged in the liquid Argon than would exist at room temperature. Overall, the CE system is made up of various components. There are the front-end mother boards (FEMBs) where the ASICs are mounted and installed on the APAs. Then there are the cold cables which consist of the cables for data, clock and control signals, low voltage power, and wire bias voltages. Next there are signal flanges which pass the data, clock and control signals, low voltage power, and wire bias voltages between the inside and outside of the cryostat. From there, the warm interface electronics crates (WIECs) are mounted on the signal flanges which further process and distribute the signals entering and exiting the cryostat. Finally, there are the cables for the low voltage power and wire bias voltages as well as the low voltage power supplies for the CE and bias-voltage
power supplies for the APAs. In total, a CE module consists of all these CE components associated with 128 channels of digitized readout from the APAs [34].

Figure 3.3: Layout of the connections between the signal flanges of the CE modules and the upper APA [34].

3.3 Capacitive-Resistive Boards and Adaptor Boards

In principle, a majority of the capacitors and resistors for the system could be attached to the CE module submerged in the liquid Argon. Instead, they are attached to the capacitive-resistive (CR) board outside of the cryostat for easy access in the event of component failure. The attached resistors are bias resistors, while the capacitors are DC blocking capacitors corresponding to each wire in the $X$ and $U$ planes of the APAs. Additionally, the CR boards contain two R-C filters which are used for the bias voltages [34]. In order to connect the
CR boards to the CE mounted on the APAs through a capacitor-resistor chain on the CR boards, an adaptor board is utilized [35]. This adaptor board will be the focus of Chapter 4.

Figure 3.4: Schematic of the cross sectional view of an APA frame end connecting to the CE box. The adaptor board is shown by the blue box connecting to the CE box [35].

Figure 3.5: Zoomed in image of Figure 3.4 in order to see the adaptor board more clearly [35].
CHAPTER 4
ADAPTOR BOARD TEST

4.1 Motivation

The goal of this portion of the project was to design a method of quality control for the adaptor boards. According to the technical design report, there will be 150 APAs with 20 adaptor boards per SP module, resulting in a total of 3000 adaptor boards that would need to be tested [35]. Because of the amount of adaptor boards that would need to be tested, the quality control process was required to be as automated as possible. The necessity for testing the boards came from the soldering connections on the board. The schematics for the adaptor board as well as images of a prototype of the adaptor board are seen in Figures 4.1 and 4.2.

(a) Schematic for the top layer wiring of the adaptor board
(b) Schematic for the bottom layer wiring of the adaptor board

Figure 4.1: Schematic for the wiring of the adaptor boards [36].
Looking at one pin, there should be one other pin connected to it while all other pins should not be connected to it. Because the pins are very close together, it is possible the soldering for a pin leaks over to an adjacent pin causing an additional pin, and in turn its partner, to also be connected when they should not be. It is also possible for connections to be broken such that pins are not connected when they should be. So, the goal of testing was to make sure each pin was only connected to the pin it should be connected to and no others.

4.2 Hardware Method

As mentioned in Section 4.1, there would be about 3000 boards to test so the testing process would need to be as automated as possible for efficiency. In order to do this, we utilized a Raspberry Pi with expanders as well as a Python script. Additionally, a custom board with the expanders and Raspberry Pi built in was designed and made in collaboration with Todd Fletcher from Northern Illinois University’s electronics shop for the adaptor boards to be plugged into. There needed to be a one-to-one connection between the Raspberry Pi and the adaptor board. The adaptor board has 128 pins on the top layer and the Raspberry Pi only had twenty eight pins that could lead directly to the adaptor board. In order to
account for the rest of the pins, eight MCP23017 I/O (input/output) expanders were used which give an additional sixteen pins. So, in total, there was access to 144 usable pins. In addition to the 128 adaptor board pins, there was also a middle row of grounding pins that were all connected to each other and sixteen pins on the bottom of the adaptor board that were also grounding pins which needed to be tested, so any extra pins on the expanders that were not used for the top of the adaptor board were used for testing the grounding pins. The bottom layer pins of the adaptor board that were not ground pins were connected to the top layer, so the layers did not need to be tested separately. The custom board allowed for each adaptor board to simply be plugged in without having to connect individual wires for each test. The schematic for the custom board is shown in Figure 4.3.

4.3 Software Method

In order to test the pins, pairs of pins were first defined which are two pins that should be connected to each other. The pairs of pins were such that the first pin from the top on J4 on the left side was paired with the first pin from the bottom on J5 on the left side and were defined as pair 1, then the second pin from the top on J4 on the left side was paired with the second pin from the bottom on J5 on the left and defined as pair 2, and so on for the rest of the left side of the board. The right side of the board has the same pattern such that the first pin from the top on J4 on the right side was paired with the first pin from the bottom on J5 on the right side and were defined as pair 3. Each pin on the adaptor board is only associated with one pair since each pin only has one other pin that should be
Figure 4.3: Schematic of the custom board used. On the left, J1 represents the Raspberry Pi header. J2, J3, J4, and J5 represent where the adaptor board will plug in, it will be connected to J2 and J3 through ribbon cables and will be directly plugged into J4 and J5. U1-U8 represent the eight Raspberry Pi expanders used.
(a) Top view of the adaptor board plugged into the custom board oriented in the same direction as Figure 4.3. The ribbon cable for the Raspberry Pi header connects to a computer.

(b) Side view of the adaptor board plugged into the custom board. Oriented 180° from Figure 4.3.

Figure 4.4: Images of the prototype adaptor board plugged into the custom board.
connected to it. The middle row was grounding pins which were all chained together. The pins on the J4 side of the board were always set as input pins and the pins on the J5 side of the board were always set as output pins in the code.

As previously mentioned, the code to test the adaptor boards was written in Python. Overall, the method was to have one pin in the pair be an input pin and the other be an output pin, which is why pins on J4 were always set to be inputs and pins on J5 were always set to be outputs. The input pin would initially be set to a low voltage (defined as 0 V and read on the Raspberry Pi as 0) and then would be set to a high voltage (defined as about 3.3 V and read on the Raspberry Pi as 1). Once the voltage on the input pin changes to high, the output pin should read the same high voltage if it is connected to the input pin. If it is not connected then it would still read a low voltage. For pins that should be connected, this is a simple test, as only the one input and one output pin need to be tested. In order to test pins that should not be connected, only the output side of the board needed to be tested rather than going through every single pin on both the J4 and J5 side. This is because every pin on J4 has a pin it is connected to on J5 and so if two adjacent pins are connected on J4 when they should not be, a connection would be read on J5. Additionally, there is no concern about missing an adjacent connection due to faulty connections between pairs, since in the test for connected pairs, any pins that should be connected but are not would be noted and looked at further.

The first step in writing this test was to define individual pin numbers for the Python code. The individual pin numbers were defined based on their connection to the Raspberry Pi or expander. Every pin on the Raspberry Pi or expander has an associated number. However, in order to be able to define pins in the way required for the Python code, the WiringPi library was utilized, which is a GPIO (general purpose input/output) access library for the Raspberry Pi that can be used with Python. WiringPi uses a different numbering scheme than the default Raspberry Pi numbering scheme, so a conversion was done between
the default numbers to the WiringPi numbers and the individual pins were defined from that within the code.

The structure of the Python code begins with a reset function such that all voltages are set to zero in order to reduce the possibility of a floating voltage giving an improper readout. Then the code goes pin by pin on the J4 side of the board setting each pin, one by one, to a high voltage and first reading the output of the pin on the J5 side of the board that should be connected then reading the output of the rest of the pins on the J5 side of the board that should not be connected. The output pin is then set to a low voltage and the reset function is run again to ensure no pins are still floating high. The middle rail of grounding pins is tested in a similar fashion where the ground pin is set high and tested with every expander on the J5 side of the test board to see if anything is connected. The additional sixteen ground pins are just tested against the pins in the surrounding area, but the method is similar. At the end, the results are output to three separate text files. The first text file represents the output of the pairs of pins that should be connected. The readout of this file is of the form “Pair {} is Connected/Not Connected” where {} represents the pair number. For an adaptor board with all pairs connected as expected, all pairs should read as connected meaning a high voltage was read on each appropriate output pin. If a pair reads as not connected then there is a problem that needs to be further examined on the adaptor board and it would be known exactly which pair is the issue since each pair is numbered.

The next text file represents the output of the pins that should not be connected to each pair. There is a header stating which input pin is set to high and then the readout is of the form “Pin {} is Connected/Not Connected” where {} is the pin number of the output pin being tested. For a working adaptor board, all pins in this file should be read as not connected. If a pin reads as connected then it is most likely that some soldering leaked to an adjacent pin resulting in an extra connection. The final output file represents the ground pins, both the middle ground rail and sixteen additional ground pins. The output are of
the same format as the other two output files and the readout should again indicate that there are no connected pins. If any pins read as connected there is an issue with the adaptor board.

An additional Python script was made for troubleshooting purposes. This is a simpler version of the main Python script, relying on user input rather than running through every possible pin combination. The user inputs a specific pair of pins to read, one on J4 and one on J5 with the same format where J4 will be the input pin and J5 will be the output pin. The output will be either 1 or 0, with 1 indicating that the pins that were input are connected and 0 indicating that the pins that were input are not connected. This can be used to double check unexpected readouts or if changes are made to specific connections on the adaptor board, those can be checked prior to running through the main test code. The main code, troubleshooting code, and further documentation can be found at [37].

4.4 Results and Future Use

The code was tested using the prototype adaptor board until it appeared that all bugs had been removed and every situation was accounted for. However, soon after the code and custom board were complete, the grant for fabricating and testing adaptor boards was denied. As a result, no formal tests were done on the effectiveness of the code for this application, as it would not be utilized for testing the adaptor boards. Even though the code was not able to be used for its original purpose, it has been given to another group to be slightly adapted in order to test cable harnesses. These harnesses will be used to connect power supplies for the ATLAS project at CERN.
CHAPTER 5
SIMULATIONS

5.1 Background and Motivation

The current status of constraints on neutrino properties come predominantly from studies of $\nu_\mu$ and $\nu_e$ disappearance as well as $\nu_\mu \rightarrow \nu_e$ appearance. This means that data associated with $\nu_\tau$ appearance is minimal and much less robust, which is why DUNE seeks to observe a far greater number of $\nu_\tau$ reconstructed beam events than previous experiments [38]. The challenge with this goal, however, is being able to determine $\nu_\tau$ events in the detector. The two types of interactions are CC and neutral current (NC) interactions. The distinguishing factor for the products of a CC interaction is the existence of a charged lepton. This means that for a $\nu_\tau$ CC interaction, a $\tau^-$ would exist as a product, for a $\nu_\mu$ CC interaction, a $\mu^-$ would exist as a product, and for an $\nu_e$ CC interaction, an $e^-$ would exist as a product.

![Tree level diagrams](image)

Figure 5.1: Tree level diagrams for the t-channel process of each neutrino flavor interacting via NC with a particle ($q$) where the incoming neutrino simply continues along its path.
This makes distinguishing CC interactions from NC interactions as well as distinguishing
the CC interaction for different flavors of neutrinos fairly straightforward, given the resulting
products. It does become more complicated to differentiate between the CC interaction for
different flavors of neutrinos when further decay products are taken into consideration. For
DUNE specifically when looking at $\nu_\tau$ CC interactions, the decay products of the $\tau^-$ must be
considered since the $\tau^-$ is heavy and therefore unstable with a short lifetime. This means the
decay products of the $\tau^-$ will be seen in the detector as opposed to the $\tau^-$ itself. There are
multiple possible decay channels for the $\tau^-$, with both hadronic and leptonic possibilities,
and all channels with their associated probabilities can be found in the PDG. Two leptonic
decay modes of particular interest are

$$
\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau,
$$

$$
\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau,
$$

each with $\sim 17\%$ probability of occurring [2].
The reason that these two channels are of interest is because each contains a charged lepton that could be associated with a $\nu_\mu$ or $\nu_e$ CC interaction. In order to be able to effectively determine the source of the charged lepton in the far detector, there must be a way to distinguish between $\mu^-$ that come from $\nu_\mu$ CC interactions versus the decay of the $\tau^-$, and similarly for $e^-$. As a result, the goal of this portion of the project was to come up with a set of kinematic properties of resulting $\mu^-$ and $e^-$ in order to try to be able to determine if they came from the decay of a $\tau^-$, meaning they can be traced back to a $\nu_\tau$ CC interaction, or if they came from a $\nu_\mu$ or $\nu_e$ CC interaction. The motivation for this study came from [39], which discussed possible kinematic properties that could be used to tag $\nu_\tau$ events using a different simulation method than used for this work, and from [38] which provided theoretical backing that the pursuit of identifying $\nu_\tau$ events in the FD is a reasonable and worthwhile endeavour.

We used simulations to study and compare the various properties for resulting leptons. The two simulation methods that were used were a stand alone GENIE simulation to provide a baseline of expected results as well as a full simulation including detector effects for a more complete analysis. For both simulation methods, the results of the charged lepton from the $\tau^-$ decay are treated as the signal, while results of the charged lepton from the $\nu_\mu$ or $\nu_e$ simulation are treated as the background. The overall goal was to analyze various kinematic properties for each interaction and compare resulting histogram shapes and correlation plots between the signal and background in order to see if any of the properties chosen have reasonable potential to be used to tag $\nu_\tau$ events, indicated by differences in shape of the signal and background histograms. In the results sections, Section 5.4 and 5.5, it will be seen that the number of events generated for the $\nu_\mu$ and $\nu_e$ simulations were based on the number of $\mu^-$ and $e^-$ resulting from $\tau^-$ in the $\nu_\tau$ simulation. This was the case for both the GENIE and full detector simulations, and was decided due to the ability to conduct a one-to-one comparison between histogram shapes. In order to make any solid statistical
conclusions, the plots would need to be normalized based on expected number of events in the
detector. Since this work is looking to gauge the feasibility of various kinematic properties
to be used to identify $\nu_\tau$ CC events, normalizing based on number of expected events would
be the next step but was not conducted here. In order to get the best idea of histogram
shape and aid in visual comparison, however, the histograms will be normalized such that
the area under the curve is one, making it a probability distribution function (PDF).

5.2 GENIE Simulation Background

GENIE stands for Generates Events for Neutrino Interaction Experiments and is a ROOT
based Monte Carlo neutrino generator. ROOT is a framework used for data processing [40].
GENIE simulates the initial interaction between the neutrino and detector medium, which
would be Argon for the DUNE detector, as well as the first decay of the particles produced as
a result of that interaction. The output is a ROOT file containing the information for these
initial interactions and decays. A stand alone GENIE simulation is initiated interactively
through the command line such that it is straightforward to specify the parameters which
will be used to generate the simulation, including the interaction type. The general format
for running stand alone GENIE is:

```
gevgen -n {number of events} -p {pdg of incoming neutrino} -t {pdg of target nucleus} -
e {neutrino energy} -f {flux file with path} --cross-sections {cross section file with path}
--event-generator-list {“type of events to generate”}
```

[41]. The pdg of a particle is defined by the Monte Carlo Particle Numbering Scheme
in order to classify each particle based on a number. This is done in order to allow for the
interface between event generators, detector simulators, and analysis packages for particle physics. Particles are classified by positive numbers and antiparticles are classified by negative numbers. The codes are based on and contain information about each particle’s spin, internal quantum number, and flavor content [42].

The target nucleus will always be Argon for the DUNE far detector, which has a pdg code of 1000180400, the cross sections file can remain consistent, and the neutrino energy is always set to be 0,100, meaning that the maximum neutrino energy possibly simulated is 100 GeV, however the actual energies that end up being simulated will follow the input flux files. The pdg code for the incoming neutrino will vary depending on flavor. \( \nu_\tau \) have a pdg code of 16, \( \nu_\mu \) have a pdg code of 14, and \( \nu_e \) have a pdg code of 12. For these simulations, only CC interactions were required to be generated, so the event-generator-list parameter would specify “CC”. The flux file input will vary depending on neutrino flavor as well as detector type (FD or ND). Flux files were found from the ancillary files attached to [43] which were released by the DUNE Collaboration in order to be able to match neutrino flux conditions that the DUNE Technical Design Report ([7]) simulations utilized. Specifically the file ‘flux_dune_neutrino_FD.root’ was used. From this file, the flux for \( \nu_\tau \), \( \nu_\mu \), and \( \nu_e \) are seen in Figure 5.3.
Figure 5.3: Histograms from flux file used for stand-alone Genie simulation. These histograms were pulled from [43]. Note the limits on the $x$-axis of Figure 5.3a are smaller than the limits for 5.3b or 5.3c.

The important features of the histograms is the general shape of the flux for each neutrino flavor. From these, it is expected that plots of the energy will result in a similar shape, an immediate spike with a long tail. For the $\nu_\tau$ flux, the tail extends to $\sim 14$ GeV, for the $\nu_\mu$ flux, the tail extends to $\sim 40$ GeV, and for the $\nu_e$ flux, the tail extends to $\sim 35$ GeV. Plots of energy for each neutrino flavor should therefore not have tails that extend beyond the length of the tail in the corresponding flux file. Because of the simplicity and certainty of the parameters applied when using stand alone GENIE, the results were used as a comparison for the full simulation in order to ensure that things worked as expected and that the desired type of interaction, CC, is actually occurring. It will become clear in Section 5.3 that the requirements and parameters for running a full detector simulation were much more involved and ambiguous than those required to run the GENIE simulation. The output products from the full detector simulation were also less clear than the results from the GENIE simulation.
Because we were somewhat uncertain that the full detector simulation was applying the required parameters to produce a CC interaction, but we were certain that GENIE was producing CC interactions, the main motivation for including the GENIE results was to compare general histogram trends. If the full detector simulation produced results that vary drastically from the stand alone GENIE results, it would be an indicator that something went wrong, most likely with the simulation.

5.3 Full Simulation Background

The full simulation takes place in four steps and all utilize the Liquid Argon Software (LArSoft) [44] which is built on the art analysis framework [45]. The base file type required for running simulations this way are called Fermilab Hierarchical Configuration Language (FHiCL) files. There are various FHiCL files available for use however, for this application, edits were required to be made in order to ensure only CC events were being produced. Although it would be possible to run an unedited FHiCL file for the required neutrino flavor and get CC events in addition to NC events, for $\nu_\tau$, the probability of getting a CC event is very small because the $\tau^-$ is so heavy. Because of this, it would require an extremely large amount of events to get a usable quantity of CC events which would be computationally intensive. It was much more reasonable to take an already existing FHiCL file that would generate a simulation for a specific flavor of neutrino and then edit it to change the event generation to just CC events rather than both NC and CC events.

This edited FHiCL file was the base for running the first step of the full simulation, which is the Genie step. This is identical in concept to running stand alone Genie however it is different in process. While this version of Genie is still run interactively, it utilizes LArSoft, so the basic command is of the form:
A ROOT file with the initial neutrino interactions is still produced, as with stand alone Genie.

Each step in the full detector simulation builds off the previous step, so the ROOT file from the prior steps becomes an input in the command for the next step. After Genie is run, the next step is to run Geant4. This is a software which uses Monte Carlo methods to simulate particles propagating through matter and generate further decays beyond the initial interaction and decay [46]. Like Genie, Geant4 utilizes LArSoft and is run interactively so the basic command is of the form:

\texttt{lar -n \{number of events\} -c \{FHiCL\_file\_name\_fcl\}.}

In this case, the file “standard\_g4\_dune10kt.fcl” was used because the basic dune10kt detector (DUNE 10 kt FD) geometry was utilized. If a different geometry was used, a different FHiCL file would be needed. The next step is to run Detsim which adds detector effects as well as noise to the simulation. Again, LArSoft is used and this step is run interactively with the basic command being of the form:

\texttt{lar -n \{number of events\} -c \{standard\_detsim\_dune10kt.fcl\} \{name of root file from Geant4 step\}}

where if a different geometry is used then a different FHiCL file is required. The final step is the reconstruction step. The previous three steps all used Monte Carlo methods to generate particles, so the reconstruction step provides a visualization for how the particles
moved through the detector as well as data for resulting jets. The process for running the
reconstruction step follows similarly to the Geant4 and detsim steps, with the process being
run interactively using LArSoft and the command being of the format:

\[ \text{lar -n \{number of events\} -c \{standard reco dune10kt.fcl\} \{name of root file from detsim step\}} \]

with a different FHiCL file used if a different geometry is needed.

### 5.4 Stand Alone GENIE Results

For stand alone GENIE, three CC simulations were run, one for each neutrino flavor. 100,000 events were generated for $\nu_\tau$ CC interactions and then the number of $\nu_\mu$ and $\nu_e$ events generated were dependent on how many $\mu^-$ and $e^-$ resulted from the $\tau^-$ decay from the $\nu_\tau$ simulation. Initially, two properties were studied for the resulting leading leptons ($\mu^-$ or $e^-$). The first property was the energy of the leading lepton, $E_{\text{lepton flavor}}$. The energy was a built in attribute for the resulting ROOT file, so no calculations were required for this property. The second property was the angle of the leading lepton with respect to the beam, $\theta_{\text{lepton flavor}}$. The angle did need to be calculated, as it was not a built in attribute of the file. This was done first by defining a momentum three vector consisting of $(p_x, p_y, p_z)$, which were attributes of the file. The beam was defined to be on the $z$-axis, $(0,0,1)$. The angle between the beam and the momentum three vector was then calculated using a PyROOT function, which is the Python interface for ROOT. Independent histograms of $E_{\text{lepton flavor}}$ and $\theta_{\text{lepton flavor}}$ were produced for each of the three simulations resulting in histograms for $E_{\mu^-}$ and $\theta_{\mu^-}$ for both the $\nu_\tau$ and $\nu_\mu$ simulation as well as histograms for $E_{e^-}$ and $\theta_{e^-}$ for
both the $\nu_\tau$ and $\nu_e$ simulation. However, because a comparison of the shape of each property between the $\nu_\tau$ and the $\nu_\mu$ or $\nu_e$ simulation was required, only the stacked histograms are included to allow for clearer visual comparison. Here, both the original histograms as well as the PDF are included.

First, the results of the leading $\mu^-$ from the $\nu_\tau$ simulation and the leading $\mu^-$ from the $\nu_\mu$ simulation were compared. For the $\nu_\mu$ simulation, every event should have a resulting $\mu^-$ since only CC events were being generated. For the $\nu_\tau$ simulation, every event would have a resulting $\tau^-$, but not all of those $\tau^-$ would decay to a $\mu^-$, so only the events that had a $\tau^-$ decaying to a $\mu^-$ were included in the comparison. From the decay of the $\tau^-$ in the $\nu_\tau$ simulation, there were 17,259 resulting $\mu^-$ so this is how many $\nu_\mu$ CC events were generated. According to the PDG, the decay channel $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ has about a 17.32% probability of occurring [2]. With 100,000 $\nu_\tau$ events generated and 17,259 resulting $\mu^-$, this gives a probability of about 17.259%, which agrees well with the predicted probability showing that GENIE is generating events as expected. The results for $E_{\mu^-}$ and $\theta_{\mu^-}$ are shown in Figure 5.4 and Figure 5.5.
(a) $E_{\mu^-}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_\mu$ in red.

(b) PDF of $E_{\mu^-}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_\mu$ in red.

(c) $\theta_{\mu^-}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_\mu$ in red.

(d) PDF of $\theta_{\mu^-}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_\mu$ in red.

Figure 5.4: Histograms for $E_{\mu^-}$ and $\theta_{\mu^-}$ from the stand alone GENIE simulation.

Figure 5.5: Correlation plot for leading $\mu^-$ properties.
Looking at Figure 5.4b, it is clear that the shape of the signal is either essentially the same or lies under the background. This is also the case for the normalized plot of $\theta_{\mu^-}$. This becomes even more clear when looking at Figure 5.5. Although data for both the $\nu_\tau$ and $\nu_\mu$ simulations are included on this correlation plot, the data for $\nu_\mu$ entirely takes over and the signal very clearly lies entirely within the background.

For this reason, additional kinematic properties have been included. These are $E_{\text{other}}$, $\theta_{\text{other}}$, $E_{\pi^\pm}$, and $\theta_{\pi^\pm}$. “Other” represents other visible particles in the event besides the leading lepton. For this case, this only includes charged pions and protons. The motivation for choosing these additional parameters as well as the decision for the definition of a visible particle came from [39] as well as [47]. In theory there will be other visible particles beyond just charged pions and protons, neutrons for example, however due to limitations on the completeness and accuracy of the simulation, the uncertainty in those products was too high to reasonably include them in the list of visible particles. Additionally when considering $E_{\text{other}}$, the total energy of the charged pions is used but only the kinetic energy of the proton is taken into account since protons are not being created in the detector, rather they already exist and are simply ejected from the Argon nucleus. To calculate the kinetic energy of the proton, the equation

$$T_{\text{proton}} = E_{\text{proton}} - m_{\text{proton}}$$

was used with $c = 1$ where $E_{\text{proton}}$ is an attribute of the ROOT file and $m_{\text{proton}} = 0.938$ GeV/$c^2$.

Continuing with the plots associated with events containing a leading $\mu^-$, next are the stacked histograms for $E_{\text{other}}$ and $\theta_{\text{other}}$. The same event numbers are used for these plots as for the histograms in Figure 5.4, however the number of entries will differ between the $\nu_\tau$ results and the $\nu_\mu$ results. This is because different particles are produced in each simulation so there are a different number of particles interacting and decaying. This is also why the
PDF is a valuable plot since the entries can no longer be equal, but the area under the curve can at least be normalized for a more accurate visual comparison. The results for $E_{other}$ and $\theta_{other}$ are shown in Figure 5.6, Figure 5.7, and Figure 5.8.

(a) $E_{other}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_\mu$ in red.

(b) PDF of $E_{other}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_\mu$ in red.

(c) $\theta_{other}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_\mu$ in red.

(d) PDF of $\theta_{other}$ histogram for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_\mu$ in red.

Figure 5.6: Histograms for $E_{other}$ and $\theta_{other}$ from the stand alone GENIE simulation.
Figure 5.7: Histograms for $E_{\text{other}}$ with the $x$-axis bounds changed from $[0,80]$ to $[0,8]$ so details can be more clearly seen. In Figures 5.6a and 5.6b the bounds were set to $[0,80]$ in order to have a better visual comparison to Figures 5.4a and 5.4b.

Figure 5.8: Correlation plot for properties of other visible particles coming from events containing a leading $\mu^-$. 

Looking at Figure 5.7a, $E_{\text{other}}$ for the signal shape is still almost identical to the background. But, looking at Figure 5.6d, $\theta_{\text{other}}$ has a signal with a slightly different shape at the peak than the background, which shows some promise. However, looking at the correlation
plot the signal is still almost entirely obscured by the background. So, we move on finally to the results for $E_{\pi^\pm}$ and $\theta_{\pi^\pm}$, shown in Figure 5.9, Figure 5.10, and Figure 5.11.

Figure 5.9: Histograms for $E_{\pi^\pm}$ and $\theta_{\pi^\pm}$ from the stand alone GENIE simulation.
Figure 5.10: Histograms for $E_{\pi^\pm}$ with the $x$-axis bounds changed from $[0,80]$ to $[0,15]$ so details can be more clearly seen. In Figures 5.9a and 5.9b the bounds were set to $[0,80]$ in order to have a better visual comparison to Figures 5.4a and 5.4b.

Figure 5.11: Correlation plot for properties of $\pi^\pm$ coming from events containing a leading $\mu^-$. The general consensus for the plots for $E_{\pi^\pm}$ and $\theta_{\pi^\pm}$ shown in Figure 5.10b and Figure 5.9d is the same as for the previous plots. The shapes of the signal and background in Figure 5.10b are extremely similar and, in this case, the signal and background in Figure 5.9d are also extremely similar. The background also continues to dominate the correlation plot.
Figure 5.11. Overall, although $\theta_{other}$ shows some promise, $\mu^-$ seem like they will be difficult to differentiate and will most likely require additional variables to be considered beyond the additional kinematic properties already included here.

Moving on to the comparison between the results of the leading $e^-$ from the $\nu_\tau$ simulation and the leading $e^-$ from the $\nu_e$ simulation. Again, every $\nu_\tau$ event will have a $\tau^-$ but not every $\tau^-$ will decay to an $e^-$. For the $\nu_e$ simulation, every event should have a resulting $e^-$ since only CC events were being generated. Only the events from the $\nu_\tau$ simulation that result in an $e^-$ were included in this comparison. From the decay of the $\tau^-$ in the $\nu_\tau$ simulation, there were 18,578 resulting $e^-$ so this is how many $\nu_e$ CC events were generated. According to the PDG, the decay channel $\tau \rightarrow e^- \bar{\nu}_e \nu_\tau$ has about a 17.82% probability of occurring [2]. With 100,000 $\nu_\tau$ events generated and 18,578 resulting $e^-$, this gives a probability of about 18.578%. This is higher than predicted by the PDG, however multiple $\nu_\tau$ GENIE simulations were generated and the percentage that an $e^-$ was produced was consistently $\sim$18%. Because of the consistency, we accepted this value and noted that any future work will have to involve looking deeper into how GENIE is simulation $\nu_e$ CC interactions and if $e^-$ are perhaps being over-counted due to the way GENIE decays certain particles despite efforts to only count leading $e^-$. The histograms for $E_{e^-}$ and $\theta_{e^-}$ are shown in Figure 5.12 and Figure 5.13.
Figure 5.12: Histograms for $E_{e^-}$ and $\theta_{e^-}$ from the stand alone GENIE simulation.

(a) $E_{e^-}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_e$ in green.

(b) PDF of $E_{e^-}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_e$ in green.

(c) $\theta_{e^-}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_e$ in green.

(d) PDF of $\theta_{e^-}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_e$ in green.
Figure 5.13: Correlation plot for properties of leading $e^\gamma$.

Looking at Figure 5.12b, the signal and the background have essentially the same shape. It is the same situation with Figure 5.12d. This is confirmed looking at the correlation plot in Figure 5.13. This further indicated a necessity for properties beyond the leading lepton. As a result, we move on to $E_{\text{other}}$ and $\theta_{\text{other}}$, where the definition of “other” particles remains as other visible particles in events that contain an $e^\gamma$. Visible particles still include charged pions and protons, as was the case for the $\mu^-$. The results for $E_{\text{other}}$ and $\theta_{\text{other}}$ can be seen in Figure 5.14, Figure 5.15, and Figure 5.16.
Figure 5.14: Histograms for $E_{other}$ and $\theta_{other}$ from the stand alone GENIE simulation.
Figure 5.15: Histograms for $E_{\text{other}}$ with the $x$-axis bounds changed from [0,80] to [0,8] so details can be more clearly seen. In Figures 5.14a and 5.14b the bounds were set to [0,80] in order to have a better visual comparison to Figures 5.4a and 5.4b.

Figure 5.16: Correlation plot for properties of other visible particles coming from events containing a leading $e^-$. The results for $E_{\text{other}}$ in Figure 5.15b show a very similar shape for the signal as the background. However, looking at Figure 5.14d, there is a shape difference between the signal and the background. This is confirmed from figure 5.16 where the signal is beginning to emerge out of the background, although with the shapes for $E_{\text{other}}$ being so similar, the
signal is still not entirely separated from the background. But, the fact that we are beginning to see some differences in shape is promising. Finally, we look at \( E_{\pi^\pm} \) and \( \theta_{\pi^\pm} \). The results can be seen in Figure 5.17, Figure 5.18, and Figure 5.19.

(a) \( E_{\pi^\pm} \) for the decay of the \( \tau^- \) in blue and the CC interaction of \( \nu_e \) in green.

(b) PDF of \( E_{\pi^\pm} \) for the decay of the \( \tau^- \) in blue and the CC interaction of \( \nu_e \) in green.

(c) \( \theta_{\pi^\pm} \) for the decay of the \( \tau^- \) in blue and the CC interaction of \( \nu_e \) in green.

(d) PDF of \( \theta_{\pi^\pm} \) for the decay of the \( \tau^- \) in blue and the CC interaction of \( \nu_e \) in green.

Figure 5.17: Histograms for \( E_{\pi^\pm} \) and \( \theta_{\pi^\pm} \) from the stand alone GENIE simulation.
(a) $E_{\pi^\pm}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_e$ in green with new $x$-axis bounds.

(b) PDF of $E_{\pi^\pm}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_e$ in green with new $x$-axis bounds.

Figure 5.18: Histograms for $E_{\pi^\pm}$ with the $x$-axis bounds changed from [0,80] to [0,8] so details can be more clearly seen. In Figures 5.17a and 5.17b the bounds were set to [0,80] in order to have a better visual comparison to Figures 5.4a and 5.4b.

Figure 5.19: Correlation plot for properties of $\pi^\pm$ coming from events containing a leading $e^-$. As seen with $E_{\text{other}}$ and $\theta_{\text{other}}$, in Figures 5.15b and 5.14d, Figure 5.18b shows a signal and background with very similar shapes. But, once again, the shape between the signal and background has some difference in Figure 5.17d. Figure 5.19 reflected this deviation at high energies and low angles.
From these initial GENIE results, we confirm that it is necessary to have kinematic properties beyond $E_{\text{lepton flavor}}$ and $\theta_{\text{lepton flavor}}$, as the signal had a very similar shape to the background in both $E_{\text{lepton flavor}}$ and $\theta_{\text{lepton flavor}}$. We did begin to see some deviation in $\theta_{\text{other}}$ and $\theta^\pm_\pi$, particularly for the $e^-$ channel. The GENIE results also give a baseline for general shapes to expect from the full detector simulation. In principle, the plots for the leading leptons should look extremely similar, as the first step in the full simulation is GENIE and every step beyond that is mainly dealing with additional particle interactions and decays. So, the $E_{\text{lepton flavor}}$ and $\theta_{\text{lepton flavor}}$ plots for the full simulation will be of particular interest to compare to the corresponding stand alone GENIE plots.

### 5.5 Full Simulation Results

For the full detector simulation results, only the PDF plots will be included unless the shape varies drastically from what is predicted by the histograms in section 5.4. In general, the histograms in section 5.4 will be used as the expected shape for the full detector results to ensure that the simulation ran as it should, which was discussed in section 5.2. As was done before, first are the results for the $\mu^-$ channel from both the $\nu_\tau$ and $\nu_\mu$ simulations. For the full detector simulation, the final step included was the Detsim step (from section 5.3). The $\nu_\tau$ simulation produced 17,320 events where the resulting $\tau^-$ decayed to a $\mu^-$. This gives a decay rate of 17.32% which agrees exactly with the predicted decay rate of 17.32% given in the PDG. Given this, 17,320 $\nu_\mu$ CC events were generated. The results for the leading $\mu^-$ are seen in Figure 5.20 and Figure 5.21.
(a) PDF of $E_\mu^-$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_\mu$ in red.

(b) PDF of $\theta_\mu^-$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_\mu$ in red.

Figure 5.20: PDF for $E_\mu^-$ and $\theta_\mu^-$ from the full detector simulation.

Figure 5.21: Correlation plot for properties of leading $\mu^-$.  

From Figure 5.20a, the shape of the signal is slightly different from the background beginning at around 8 GeV. However, from Figure 5.20b, the shape of the signal almost exactly matches the background. Figure 5.21 also indicates the background dominating. We should note that Figures 5.20a and 5.20b do differ in general shape and trend to their stand alone GENIE counterparts shown in Figures 5.4b and 5.4d. Recall it was stated in Section 5.4 that the leading lepton plots should be generally the same for the full simulation as with stand alone GENIE, so the fact that they differ is cause for some concern as to whether the
full simulation is behaving in the way we believe it is. Keeping this in mind, we move to the same additional kinematic properties discussed in Section 5.4 beginning with the $E_{\text{other}}$ and $\theta_{\text{other}}$ where the definition of other visible particles remains the same as in Section 5.4. The results are seen in Figure 5.22 and Figure 5.23.

(a) PDF of $E_{\text{other}}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_\mu$ in red.

(b) PDF of $E_{\text{other}}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_\mu$ in red with limited range on the $x$-axis.

(c) PDF of $\theta_{\text{other}}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_\mu$ in red.

Figure 5.22: PDF for $E_{\text{other}}$ and $\theta_{\text{other}}$ from the full detector simulation.
Figure 5.23: Correlation plot for properties of other visible particles associated with events that have the $\tau^-$ decaying to a $\mu^-$.

The values for the $x$-axis in Figure 5.22a were chosen to provide a one-to-one visual comparison to the plot from Figure 5.20a, however the data falls in a much more narrow range so, in Figure 5.22b, the $x$-axis was limited to $[0,12]$ in order to be able to see the details of the data better. Looking at Figure 5.22b, the shape of the signal is very similar to the background. It is the same situation with figure 5.22c. This, however, is not as clear from Figure 5.23 as previous correlation plots. The signal can clearly be seen at lower angles with higher energies. However, there is still background data dispersed throughout the entirety of the signal with enough density to make it impossible to say with any certainty that there is a region where every point would most likely be signal data. The shape of Figure 5.22c is also concerning, as none of the stand alone GENIE results displayed angle data with such a shape. With this information, we move to the results for $E_{\pi^\pm}$ and $\theta_{\pi^\pm}$ seen in Figure 5.24 and Figure 5.25.
(a) PDF of $E_{\pi^\pm}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_\mu$ in red.

(b) PDF of $E_{\pi^\pm}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_\mu$ in red with limited range on the $x$-axis.

(c) PDF of $\theta_{\pi^\pm}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_\mu$ in red.

Figure 5.24: PDF for $E_{\pi^\pm}$ and $\theta_{\pi^\pm}$ from the full detector simulation.
Again, the values for the $x$-axis in Figure 5.24a were chosen to be able to easily visually compare to Figure 5.20a, but since the data falls in a narrow range the $x$-axis values were limited in Figure 5.24b to [0,12]. Looking at Figure 5.24b, the shape of the signal and background remain very similar. This is the same with Figure 5.24c. Similar to Figure 5.23, the signal appears to be separate from the background at low angles and high energies in Figure 5.25, however the background data is still too densely intermixed with that part of the signal. As expected given the results for the $\mu^{-}$ channel from Section 5.4, the $\mu^{-}$ channel is going to be particularly difficult to discern the signal from the background as they continue to be extremely similar for every kinematic property tested.

We now move to the comparison between the results of the $e^{-}$ channel. With the Detsim step as the final step included in the simulation, there were 18,642 $e^{-}$ resulting from the $\tau^{-}$ decay in the $\nu_{\tau}$ simulation giving a decay rate of 18.842%. According to the PDG, the decay rate for $\tau^{-}$ to $e^{-}$ is 17.82% which is lower than the simulation results. However, as stated in Section 5.4, the rate of $e^{-}$ was consistently high in every simulation produced, whether it was a GENIE simulation or a full simulation, with a decay rate always of $\sim$18%. Since this

![Correlation plot for properties of charged pions associated with events that have the $\tau^{-}$ decaying to a $\mu^{-}$.](image)
was a consistent situation, we accepted the simulation results and produced plots as before. The leading electron results can be seen in Figure 5.26 and Figure 5.27.

![Graph](image1)

(a) PDF of $E_{e^-}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_e$ in green.

![Graph](image2)

(b) PDF of $\theta_{e^-}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_e$ in green.

Figure 5.26: PDF for $E_{e^-}$ and $\theta_{e^-}$ from the full detector simulation.

![Graph](image3)

Figure 5.27: Correlation plot for properties of leading $e^-$. 

In Figure 5.26a, the signal has a slightly different shape than the background with the signal generally having a steeper slope and the background having a more gradual slope. However, in Figure 5.26b, the shapes, once again, are essentially the same. Figure 5.27 confirms this, as the background dominates the correlation plot. We once again note the
differences in shape for Figure 5.26a compared to the GENIE result in Figure 5.12b, but the general trend for $\theta_{e^-}$ match what was expected from the GENIE simulation. We now move on to $E_{other}$ and $\theta_{other}$ for the $e^-$ channel. These results can be seen in Figure 5.28 and Figure 5.29.

(a) PDF of $E_{other}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_e$ in green.

(b) PDF of $E_{other}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_e$ in green with limited range on the $x$-axis.

(c) PDF of $\theta_{other}$ for the decay of the $\tau^-$ in blue and the CC interaction of $\nu_e$ in green.

Figure 5.28: PDF for $E_{other}$ and $\theta_{other}$ from the full detector simulation.
Figure 5.29: Correlation plot for properties of other visible particles associated with events that have the $\tau^-$ decaying to a $e^-$. 

The $x$-axis limits for Figure 5.28a were set, once again, to be consistent with Figure 5.20a (and now additionally to be consistent with Figure 5.26a). But, since the range was much more narrow than for the leading leptons, the $x$-axis was limited to $[0,12]$ in Figure 5.28b in order to see detail of the data shapes better. Looking at Figure 5.28b, the signal and the background have very similar shapes. This is, once again, the same with Figure 5.28c. In Figure 5.29, like in Figure 5.23, the background cannot be clearly separated from the signal since there are so many background data points scattered throughout the signal, even in regions where the signal seems clearer like at low angles ad high energies. We also note once again that the shape of Figure 5.28c is unlike any plot produced in Section 5.4. Finally, we move to the results for $E_{\pi^\pm}$ and $\theta_{\pi^\pm}$ which can be see in Figure 5.30 and Figure 5.31.
Figure 5.30: PDF for $E_{\pi^\pm}$ and $\theta_{\pi^\pm}$ from the full detector simulation.
As before, the $x$-axis in Figure 5.30a was set for visual comparison with Figure 5.20a and Figure 5.26a, but the data had a much more narrow range so Figure 5.30b has the $x$-axis limited to [0,20]. These results match with what was said about the results for $E_{other}$ and $\theta_{other}$, the background and signal have very similar shapes in Figure 5.30b and Figure 5.30c and Figure 5.31 confirms that there is no clear way to separate the signal from the background.

As seen with the results throughout this section, a perfectly certain parameter for differentiating between signal and background cannot be identified using these properties. However, the signal can be seen beginning to emerge out of the background especially in the correlation plots for $E_{other}$ vs $\theta_{other}$ and $E_{\pi\pm}$ vs $\theta_{\pi\pm}$. Because, in general, the differences between the signal and the background were always going to be extremely small, it was predicted from the beginning that multiple kinematic properties would be required to make any definitive statements. This is confirmed with these results and shows that, although some of these plots show promise, more kinematic properties need to be taken into consideration in order to begin to make any statements about how to determine which data belongs to $\tau^-$ decay and which data belongs to $\nu_\mu$ or $\nu_e$ CC interactions. That being said, since there are plots
showing shape difference between the signal and background, it can be reasonably said that it is feasible to use kinematic properties to identify $\nu_\tau$ CC interactions, there just were not enough properties examined in this work. We do have to also note that there were differences in the general shape and trends for some of the GENIE plots as compared to their full simulation counterparts. This indicates that there are also unknowns in the full detector simulation. This was predicted to be the case from the beginning, which is why the GENIE simulations were completed and included at all.

### 5.6 Conclusions and Future Work

The goal of the simulations included in this work was to determine the feasibility of identifying and tagging $\nu_\tau$ CC events in the DUNE far detector. This was motivated first by the work in [38] and additionally by the methods discussed in [39]. [38] discussed the necessity for detecting $\nu_\tau$ events in the DUNE detector, which can be summarized by the fact that there is a lack of $\nu_\tau$ events detected and the majority of neutrino research relying on $\nu_\mu$ and $\nu_e$ oscillations. In order to constrain neutrino properties, further measurements are required and that includes collecting data from $\nu_\tau$ events, which DUNE is set up to be able to do assuming that those events can be tagged in the detector. Inspiration for the method was derived from [39], which included looking at kinematic properties to determine differences in both the leptonic and hadronic decay channels of the $\tau^-$ produced from $\nu_\tau$ CC events. This work, however, deviated from the results presented here as different simulation methods were used as well as different methods of analyzing the results.

Initially, only $E_{\text{leading lepton}}$ and $\theta_{\text{leading lepton}}$ were utilized as kinematic properties however, from the stand alone GENIE results, these were not going to be enough to differentiate leading leptons from $\tau^-$ decay and $\nu_\mu$ or $\nu_e$ CC events. Because of this, $E_{\text{other}}, \theta_{\text{other}}, E_{\pi\pm}$,
and $\theta_{\pi^\pm}$ were chosen as additional kinematic properties to look at. From the stand alone GENIE results, in Section 5.4, it was predicted that this would be a bit more sufficient for $e^-$ but $\mu^-$ would still result in excessive ambiguities, even with these additional parameters. This was confirmed from the full detector simulation results in Section 5.5. There were plots that showed promise in being able to separate the signal from the background showing that this is a feasible endeavour, however additional kinematic properties will be needed to make any definitive statements or place any definitive constraints on the signal and background.

There is ample opportunity for further work based on these initial results. The next step is to discern how the full simulation is actually running and gaining a clearer understanding of how neutrinos are interacting and how products are decaying. It is imperative to understand this fully before continuing with any further work. Once this is complete further work can be done to try to determine a more complete set of kinematic properties. First, rather than normalizing the histograms such that the area under the curve is one, the results can be normalized based on the expected number of results in the far detector. This would give a more accurate picture of what the kinematic properties would look like in the detector since it is not realistic to expect as many events as were produced with a one-to-one ratio of $\mu^-$ or $e^-$ produced from $\nu_\mu$ or $\nu_e$ CC events to those leptons produced by $\nu_\tau$ CC events to be seen in the detector. Another important aspect that was not included in these simulations is the inclusion of the spin of the $\tau^-$, which can drastically effect the energy of resulting decay products. In order to more accurately model what the energies would look like, this needs to be taken into account which can be done using the TAUOLA library [48]. Finally, note how in section 5.3 there was an additional step included in the full simulation background which was not utilized in the full detector simulation. This was the reconstruction step and was not included due to time constraints. However, in order to utilize other kinematic properties, specifically properties involving jets, as was included in [39], this step would be needed. Finally, once a cohesive list of kinematic properties and valid constraints on those
properties is created, there is the possibility of being able to use machine learning techniques to train a neural network to identify events within these constraining values and tag them as possible $\nu_r$ CC events.
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