Charged Current Anti-Neutrino Interactions in the ND280 Detector

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CHARGED CURRENT ANTI-NEUTRINO INTERACTIONS IN THE ND280 DETECTOR

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ABSTRACT. For the neutrino beamline oscillation experiment Tokai to Kamioka, the beam is classified before oscillation by the near detector complex. The detector is used to measure the flux of different particles through the detector, and compare them to Monte Carlo Simulations. For this work, the $\bar{\nu}_\mu$ background of the detector was isolated by examining the Monte Carlo simulation and determining cuts which removed unwanted particles. Then, a selection of the data from the near detector complex underwent the same cuts, and compared to the Monte Carlo to determine if the Monte Carlo represented the data distribution accurately. The data was found to be consistent with the Monte Carlo Simulation.

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1. The Standard Model and Neutrinos

The Standard Model is the current, incomplete model which describes the interactions of the known fundamental particles which constitute the universe and dictate the rules of their interactions. The standard model consists of 61 particles that, when not counting multiplicities due to color and anti-particles, can be represented in the chart of 17 particles seen in Figure 1. These particles can be split into two different groups of particles: bosons and fermions[1, 2].

1.1. Bosons. Bosons (excluding the Higgs boson) are spin-1 particles that mediate interactions between the other particles. The three forces described by the standard model—the weak, electromagnetic, and strong force—are all encoded in the interactions of the spin-1 bosons.

There are 12 different spin-1 bosons: the W and Z ($W^\pm$, $Z^0$) bosons, the photon ($\gamma$), and the 8 gluons ($g$). The $W^\pm$ and $Z^0$ bosons mediate interactions of the weak force. Photons mediate electromagnetic interactions. The gluons mediate interactions of the strong force.

The remaining boson, the Higgs boson, is a spin-0 particle. It’s a representative of the Higgs field, which is responsible for imparting mass onto particles[1, 2].

![Figure 1. This is a chart of the currently known particles, not accounting for anti-particles and color](image-url)
1.2. Fermions. The remaining 48 (12 base particles ignoring color and anti-particles) particles are spin-1/2 particles, also known as fermions. Fermions form the basis of matter—their combinations through the strong and electromagnetic forces forming the macrostructures that are normally dealt with.

Fermions are described by the Dirac equation,

\[ i\hbar \gamma^\mu \partial_\mu \Psi - mc\Psi = 0 \]

where \( \gamma^\mu \) is the set of 4x4 matrices

\[
\gamma^0 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \quad \gamma^i = \begin{bmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{bmatrix},
\]

where \( \sigma^i \) are the Pauli matrices

\[
\begin{align*}
[0 1], & \quad [0 -i], & \quad [1 0], & \quad [1 0 -i 0].
\end{align*}
\]

and \( \Psi \) is the bi-spinor

\[
\Psi = \begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{bmatrix}
\]

The four functions \( \psi_1 - \psi_4 \) form a complete space of independent solutions, describing spin±1/2 particle states and their spin±1/2 anti-particle states[1].

Fermions are sorted into generations, based on their mass and charge with respect to the three forces. For each fermion, there are two other fermions with identical charges, but different masses. In general, for particles which the absolute mass scale is known, the first generation particle is the lightest of the three, the second generation the second lightest, and the third generation the third heaviest. The exception to this are the neutrinos, for which the absolute mass-scale is not known. Therefore, they are organized based on their corresponding lepton, which will be explained later[1].

1.3. Quarks and the Strong Force. Quarks are fermions which interact with the strong force. Quarks can be split into two groups: charge 2/3 and charge -1/3. The charge 2/3 quarks are referred to, in order of increasing generation, as the up (2.3 MeV), charm (1.275 GeV) and top (173 GeV) quarks. The charge -1/3 quarks are referred to as the down (4.8 MeV), strange (95 MeV), and bottom (4.18 GeV) quarks[2].

Quarks contain a value referred to as color, which acts as the charge for the strong force. Unlike the electric force, however, there are three different types of charges—red, green, and blue. Regular quarks have one of these three colors, and anti-quarks have negative color. Note that when accounting for separate types of quarks for each color and anti-color, there are a total of 36 different quarks. Additionally, gluons carry a unit of color and a unit of anti-color. The gluons are superpositions of color combinations, resulting in the eight possible states below[1]:

\[
\begin{align*}
(r\bar{b} + b\bar{r})/\sqrt{2} & \quad -i(r\bar{b} - b\bar{r})/\sqrt{2} \\
(r\bar{g} + g\bar{r})/\sqrt{2} & \quad -i(r\bar{g} - g\bar{r})/\sqrt{2} \\
(g\bar{b} + b\bar{g})/\sqrt{2} & \quad -i(b\bar{g} - g\bar{b})/\sqrt{2} \\
(r\bar{r} + b\bar{b})/\sqrt{2} & \quad (r\bar{r} + b\bar{b} - 2g\bar{g})/\sqrt{2}
\end{align*}
\]
The strong force, unlike other forces, is mediated by a particle which contains a strong charge. Therefore, gluons will interact strongly with other gluons, resulting in extraordinarily complex interactions. Color, like electromagnetic charge, is conserved in interactions.

Strong force systems are neutral when either all three colors are present or a color and its negative are present. This enables two possible macrostates of quarks held together by the strong force: 3-quark systems known as baryons, or two quark systems known as mesons. Baryons contain three quarks or three anti-quarks. Because quark charges come in units of 2/3rds or -1/3rds, any combination of three quarks leads to whole charge systems. Similarly, two quark systems have three possible charge combinations, as represented by the following particles known as pions. There is the $ud$ ($\pi^+$), the $d\bar{u}$ ($\pi^-$), and the $(u\bar{u} + d\bar{d})/\sqrt{2}$ ($\pi^0$). Each of these possible charge combinations, again, results in whole charges.

The strong force is the strongest of the known forces, and as such dominates in interactions where it is allowed. It’s 3 orders of magnitude stronger than the electromagnetic force, 14 orders of magnitude stronger than the weak force, and 43 orders of magnitude stronger than gravity [1]. Therefore, when considering, for example, interactions between high energy baryons (such as protons and neutrons), the dominant process will be the strong force, and other interaction contributions can effectively be ignored.

1.4. Leptons and the Weak Force. The remaining 12 particles are the leptons and their antiparticles. Leptons do not interact through the strong force, having no color. The regular leptons can be split into two groups: charge -1 and charge 0. The charge -1 particles are, in order of generation, the electron ($e^-$, .511 MeV), the muon ($\mu^-$, 105.7 MeV), and the tau ($\tau^-$, 1.78 GeV). Each one of these has an associated neutrino, referred to as the electron-neutrino ($\nu_e$), muon-neutrino ($\nu_\mu$), and the tau-neutrino ($\nu_\tau$)[1, 2].

The neutrinos, having no color and no charge, only interact through the weak force. Each neutrino is named after the lepton by which it is coupled by the $W^\pm$ bosons.

![Figure 2. The primitive vertices of the $W^-$ boson](image)

The $W^\pm$ vertices preserve lepton generation (otherwise referred to as flavor), and mediate the transfer of a charge. They do not conserve quark flavor. $W^\pm$ interactions primarily allow for the decays of charged meson systems, such as the $\pi^\pm$, resulting in the generation of leptons. The $Z^0$ boson, on the other hand, contains no charge. It conserves quark flavor, and mediates neutrino scattering interaction for which charged muons are not produced.
One of the properties that arises from the above is conservation of lepton number. Regular leptons are given a value of 1, and anti-leptons are given a value of -1. Interactions that produce leptons, such as pion decay, produce a lepton and anti-lepton pair, and leptons are only removed in interactions involving an anti-lepton\cite{1}.

The weak force propagators, unlike the other known force propagators, have mass. The $W^\pm$ bosons have a mass of 80.4 GeV, and the $Z^0$ bosons have a mass of 91.2 GeV\cite{2}. This causes weak force interactions to be repressed relative to the other forces. The weak force propagator is

\begin{equation}
\frac{-i(g_{\mu\nu} - q_\mu q_\nu / M^2 c^2)}{q^2 - M^2 c^2}
\end{equation}

where $g_{\mu\nu}$ is the Minkowski metric, $q$ is the momenta of the propagator, and $M$ is the mass of the $W^\pm$ or $Z^0$ boson. Because $M$ is large, the propagator’s value is strongly reduced for most interactions, where $q^2 << (Mc)^2$.

In addition to this is the weak force vertex factor,

\begin{equation}
\frac{-ig_w}{2\sqrt{2}} \gamma^\mu (1 - \gamma^5)
\end{equation}

where $g_w$ is the weak force coupling constant, and $\gamma^5 = i \gamma^0 \gamma^1 \gamma^2 \gamma^3$. The factor $\gamma^\mu (1 - \gamma^5)$ encodes a maximal parity violation. Therefore, in the example of a massless particle moving at the speed of light, the weak force would only interact with regular particles with left-handed helicity or anti-particles with right-handed helicity\cite{1, 2}.

1.5. Neutrino Oscillations. When neutrinos interact with the weak force, they interact in one of three flavor eigenstates: electron, muon, or tau neutrino. However, when traveling through space, they travel in a set of mass eigenstates which are not equal to their flavor eigenstates. These mass eigenstates are referred to as $\nu_1$, $\nu_2$, and $\nu_3$. These eigenstates are linearly related, such that

\begin{equation}
|\nu_\alpha\rangle = U_{\alpha i} |\nu_i\rangle
\end{equation}

where $\nu_\alpha$ are the flavor eigenstates, $\nu_i$ are the mass eigenstates, and $U_{\alpha i}$ is the mixing matrix between the two bases\cite{3, 2}.

The neutrino mixing matrix is can be written as the product of three unitary matrices as follows:

\begin{equation}
U^*_{\alpha i} = \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}\cr
0 & 1 & 0\cr
-s_{13} e^{i\delta}\cr
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\end{equation}

where $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, and $\delta$ is a complex phase which encodes charge-parity violation. $\theta_{ij}$ is referred to as the mixing angle, and encodes the size of the mixing between the two neutrino modes\cite{3, 2}.

We can write $|\nu_\alpha\rangle = \sum U^*_{\alpha i} e^{-iE_i t/\hbar} |\nu_i\rangle$ which gives the probability that a flavor state $\alpha$ transitions to a flavor state $\beta$ as follows:

\begin{equation}
P(\nu_\alpha \rightarrow \nu_\beta) = \sum U^*_{\alpha i} U_{\beta i} e^{-iE_i t/\hbar} = \sum U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} e^{-iE_j t/2E_i}
\end{equation}
where $\delta m^2_{ij}$ is the mass difference between the two mass eigenvalues, $E$ is the total energy, and $t$ is the travel time. Exchanging travel distance for time, this allows simple calculations of $\nu_\alpha$ disappearance (from $P(\nu_\alpha \rightarrow \nu_\alpha)$), and $\nu_\alpha$ appearance (from $P(\nu_\beta \rightarrow \nu_\alpha)$)[3].

The experiment Tokai to Kamioka (T2K), among others, recently reported its mixing angle results for the $\theta_{23}$ measurement. T2K, being a long baseline neutrino experiment, measured $\nu_\mu$ disappearance and $\nu_\mu$ appearance into $\nu_e$,

\begin{align}
  P(\nu_\mu \rightarrow \nu_\mu) &= 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} [1 - \cos^2 \theta_{13} \sin^2 \theta_{23}] \sin^2 \left(\frac{\Delta m^2_{32} L}{4E}\right) \\
  P(\nu_\mu \rightarrow \nu_e) &\approx \sin^2 (\theta_{23}) \sin^2 2\theta_{13} + .03 \sin \delta \cos \theta_{13} \sin^2 2\theta_{12} \sin^2 2\theta_{13} \sin 2\theta_{23} + ...
\end{align}

They measured $\sin^2 \theta_{23} = .514 \pm 0.082 (\theta_{23} \approx 45^\circ)$, with $\theta_{13} = 9.12$. The previous value for $\theta_{13}$ is a best-fit value between three experiments, T2K, RENO, and Daya Bay, which establish $\theta_{13} > 0$ with a 99.73% confidence level [3, 2]. Additionally, current calculations put $\theta_{12} \approx 33^\circ$[3, 4, 5, 6, 7].

1.6. The Relative Neutrino Mass Scale. Because of the presence of $\Delta m^2_{ij}$ in the mixing equations, the confirmation of neutrino oscillations demonstrated that neutrinos do in fact contain mass. However, because the only mass difference term available for standard oscillation experiments is this squared term, only the relative neutrino mass scale can be determined. This provides only a lower bound on the possible neutrino masses, and results in two different mass hierarchies for the neutrino masses since the sign of the $\Delta m^2$ values is currently unknown. These two hierarchies are the normal hierarchy ($m_{\nu_1} < m_{\nu_2} < m_{\nu_3}$ and the inverted neutrino hierarchy ($m_{\nu_3} < m_{\nu_1} < m_{\nu_2}$)[5, 6]

![Figure 3. The regular mass hierarchy (left) versus the inverted hierarchy (right)](image)

Currently, measurements yield the following for the neutrino mass scale:

\begin{align}
  (13) & \quad \Delta m^2_{12} \approx 7.6 \times 10^{-5} \text{ eV}^2 \\
  (14) & \quad \Delta m^2_{23} \approx 2.4 \times 10^{-3} \text{ eV}^2 \\
  (15) & \quad \Delta m^2_{13} \approx \Delta m^2_{23}
\end{align}
1.7. Neutrino Helicity and Anti-Neutrinos. Due to the $\gamma^\mu(1 - \gamma^5)$ term in the weak force vertex factor, all neutrinos which have been measured have been shown to be left-handed (helicity $= -1$). Similarly, all anti-neutrinos which have been measured have been shown to be right-handed. This is due to them having such low mass that measurable neutrinos are traveling near the speed of light, resulting in strong coupling of the weak force to the helicity of the particle.

Several possibilities arise from this dichotomy between neutrino and anti-neutrino spin, the two most prominent being the following: the existence of “sterile” neutrinos, or that $\bar{\nu} \equiv \nu$.

Sterile neutrinos, in the context of the helicity problem, would be neutrinos and anti-neutrinos of opposite spin relative to what has been observed. Under this approach, right-handed neutrinos and left-handed anti-neutrinos would exist. However, because of the coupling of helicity to the weak force, these particles would essentially be unable to interact—hence the term, sterile.

The latter option—that $\nu_R \equiv \bar{\nu}_R$ and $\bar{\nu}_L \equiv \nu_L$—is true if the neutrino is a Majorana fermion rather than a Dirac fermion. A Majorana fermion is one where the following holds:

\begin{equation}
\Psi = \Psi_c
\end{equation}

where $\Psi$ is the Bi-spinor

\begin{equation}
\Psi = \begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{bmatrix} = \begin{bmatrix} \psi_A \\ \psi_B \end{bmatrix}
\end{equation}

and $\Psi_c$ is the charge conjugate $\Psi_c = i\gamma^2\Psi^*$. Plugging this into the Dirac equation, we find the following:

\begin{equation}
-\text{i}\sigma_2\psi_B = \psi_A
\end{equation}

indicating that if the bi-spinor is equal to its charge conjugate, then it can be represented by a pair of independent equations rather than a quartet. Because the weak force is coupled to the helicity of the particle, the neutrino has the possibility of meeting this requirement, and therefore being Majorana rather than Dirac in nature[1, 8, 9].

2. The Tokai to Kamioka Experiment

The Tokai to Kamioka (T2K) experiment is a long baseline neutrino oscillation experiment located in Japan. The physical goals of the T2K experiment are to be sensitive to the values of $\sin^22\theta_{13}$ down to .006 and to measure the neutrino oscillation parameters with precision of $\delta(\Delta m^2_{32}) 10^{-4}$eV$^2$ and $\delta(\sin^22\theta_{23}) .01$ [10, 11].

The T2K experiment consists of three main parts: the Japan Proton Accelerator Research Complex, which creates the neutrino beam for the experiment; the near detector complex, which classifies the beam prior to neutrino oscillation; and the Super-Kamiokande detector, which measures the neutrino beam at the muon neutrino oscillation maximum.
2.1. Japan Proton Accelerator Research Complex. The Japan Proton Accelerator Research Complex (J-PARC) is responsible for the creation of the neutrino beam for T2K. The sections used to create the neutrino beam consist of three proton accelerators and the target used to create the neutrino beamline.

The first accelerator is a linear accelerator which accelerates bunches of $H^−$ atoms to approximately 400 MeV. These atoms then have their electrons stripped—converting the beam to a $H^+$ beam—as they enter the second accelerator. This second accelerator—a rapid-cycling synchrotron—accelerates the protons up to 3 GeV. These protons are then fed into the third accelerator, which accelerates the bunches of protons to 30 GeV, at which point they are diverted down towards the target to create the neutrino beam[10, 11]. The 30 GeV acceleration is specific for the T2K experiment: other experiments at J-PARC use higher momentum beams.
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Figure 6. The Preparatory and decay pipe regions of the beamline creation[10, 11]

When the protons are diverted towards the start of the neutrino beamline, they first enter the preparatory and arc regions before encountering the target. The preparatory region is designed to receive an accurate measurement of the proton beam flux and flux loss. Figure 6 lists the position of the primary detectors used to qualify the beamline. Specifically, there are 5 current transformers used to track beam intensity, 21 electrostatic monitors which determine the exact beam position, 19 segment secondary emission monitors which track the beam profile, and 50 beam loss monitors, which tracks the loss in the beam.

The preparatory and arc region ends with the graphite target. The target is a 91.4 centimeter long by 2.6 centimeter diameter rod. Graphite, being a carbon lattice, is densely packed with baryons that the incoming protons, now at roughly 30 GeV, collide with. At this energy level, the baryon-baryon interactions that occur are dominated by the strong force, leading to the production of a shower of mesons and baryons[10, 11].

Figure 7. This diagram is of the target, located in the center of the first magnetic horn[10]

The beam post collision with the target consists primarily of pions and kaons, which are sent through a series of three magnetic horns to focus the beam. The magnetic horns create a toroidal magnetic field designed to focus positive particles. This focuses the positively charged particles produced by the interaction with the target, primarily $\pi^+$ and $K^+$, and diverts negatively charged particles, such as $\pi^-$. Since the magnetic horns are powered by a 250 kA source, the polarity can be reversed such that negative particles are focused rather than positive particles[10, 11].

The Beam then enters the decay pipe. The decay pipe is a 96 m long, 1500 m$^3$ box filled with helium gas (to reduce pion absorption and tritium production). The pipe undergoes water-cooling to keep the temperature below 100°C. In this region, the particles created by the proton collisions with the graphite decay, producing the neutrino beam[10, 11].
The pions and kaons decay through weak force processes, producing leptons, primarily muons and muon neutrinos. Additionally, some of the muons decay again, producing electrons, electron neutrinos, and muon neutrinos. Tables 1, 2 depicts the decay paths and neutrino product ratios of these decays, as predicted by simulation[11].

<table>
<thead>
<tr>
<th>Particle Decay Products</th>
<th>Branching Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+ \rightarrow \mu^+ \nu_\mu$</td>
<td>99.9877</td>
</tr>
<tr>
<td>$\pi^+ \rightarrow e^+ \nu_e$</td>
<td>$1.23 \times 10^{-4}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu_\mu$</td>
<td>63.55</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$</td>
<td>3.353</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0 e^+ \nu_e$</td>
<td>5.07</td>
</tr>
<tr>
<td>$K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$</td>
<td>27.04</td>
</tr>
<tr>
<td>$K_L^0 \rightarrow \pi^- e^+ \nu_e$</td>
<td>40.55</td>
</tr>
<tr>
<td>$\mu^+ \rightarrow e^+ \bar{\nu}<em>\mu \nu</em>\mu$</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 1. This table details the decay ratio of common particles in the beam that result in neutrinos[11]

immediately after the end of the decay pipe lies the beam dump, which consists of 75 tons of graphite, surrounded by iron plates that add up to a total of 2.4 meters of iron. This stops all incoming muons with energy less than approximately 5.0 GeV. This is followed by a muon monitor. this makes a measurement of the positions of the muons which pass through the beam dump. The centered of the position of these muon detections is compared to the position of the beam as it enters the target, giving the beam direction[11, 10].

2.2. The Near Detector Complex. After the beamline is created, the next target along its path is the near detector complex. The near detector complex is located 280 meters after the end of the beam dump, and contains two main detectors; the INGRID detector and the ND280. The on-axis detector INGRID is located at a zero degree angle with the neutrino beam. The off-axis detector is at a 2.5° degree angle with the neutrino beam, matching the angle of the far detector with the neutrino beam[12, 13, 10].

The far detector and the near detector are located off-axis in order to increase the statistics of the oscillation measurement. By having the neutrino beam in-line, the average energy peaks at higher

<table>
<thead>
<tr>
<th>Parent</th>
<th>$\nu_\mu$</th>
<th>$\bar{\nu}_\mu$</th>
<th>$\nu_e$</th>
<th>$\bar{\nu}_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>secondary</td>
<td>$\pi^\pm$</td>
<td>60.0(55.6)%</td>
<td>41.8(2.5)%</td>
<td>31.9(0.4)%</td>
</tr>
<tr>
<td></td>
<td>$K^\pm$</td>
<td>4.0(3.7)%</td>
<td>4.3(0.3)%</td>
<td>26.9(0.3)%</td>
</tr>
<tr>
<td></td>
<td>$K_L^0$</td>
<td>0.1(0.1)%</td>
<td>0.9(0.1)%</td>
<td>7.6(0.1)%</td>
</tr>
<tr>
<td>tertiary</td>
<td>$\pi^\pm$</td>
<td>34.4(31.9)%</td>
<td>50.0(3.0)%</td>
<td>20.4(0.2)%</td>
</tr>
<tr>
<td></td>
<td>$K^\pm$</td>
<td>1.4(1.3)%</td>
<td>2.6(0.2)%</td>
<td>10.0(0.1)%</td>
</tr>
<tr>
<td></td>
<td>$K_L^0$</td>
<td>0.0(0.0)%</td>
<td>0.4(0.1)%</td>
<td>3.2(0.0)%</td>
</tr>
<tr>
<td>total (all)</td>
<td>(92.6)%</td>
<td>(6.2)%</td>
<td>(1.1)%</td>
<td>(0.1)%</td>
</tr>
</tbody>
</table>

Table 2. This table details the percentage of each type of neutrino produced by a particular parent, and their percentage relative to other neutrinos in the beam[11].
value, but contains a longer tail. By making an off-axis measurement, the peak energy of the beam is lowered, and the long tail is removed, creating a narrow-band neutrino distribution.

Figure 8 demonstrates this change. By placing the detector 2.5° off axis from the generated neutrino beam, the measured energy range peaks at .6 GeV. This peak is aligned with the energy where neutrino oscillations for $\nu_\mu$ are maximal to other flavors[10].

2.2.1. The INGRID Detector. INGRID is a on-axis detector which measures neutrino interactions with Iron. The detector consists of 17 modules, arranged in the shape of a cross, with two modules overlapping in the center. The center of this cross is situated with the center of the neutrino beam. Additionally, there are two additional modules located off axis, as depicted in Figure 9, in order to check axial symmetry of the beam[10, 13].

Each module consists of nine iron plates intermixed with 11 scintillator planes, with a veto surrounding them. They make a measurement of the center of the neutrino beam, and the intensity of the neutrino beam.

2.2.2. The ND280. The ND280 detector is the off-axis detector at the near detector complex. It’s angular position with respect to the neutrino beam is designed to be identical to T2K detector. The purpose of the ND280 is to precisely quantify the neutrino beam prior to neutrino oscillation to achieve an experimental measurement of the pre-oscillated beam, which will provide more accurate statistics than a purely theoretical measurement.

More specifically, Three of the main backgrounds that need classification for accurate measurements at the far detector are the ones that follow. The First of these three is the $\nu_e$ component of the
Figure 9. The on-axis detector, INGRID[10]

beam. This is a non-removable background, which can only be accurately measured before neutrino oscillation becomes a significant factor in the result. The second is the $\nu_\mu$ measurement, which must provide information such that the $\nu_\mu$ flux can be determined at Super-Kamiokande [10]. The third of these three primary measurements is a measurement of the primary background to the $\nu_e$ measurement. This is the neutral current interaction component $\nu_\mu + N \rightarrow \nu_\mu + \pi^0 + X [12]$.

The ND280 consists of the following major parts: The Pi-Zero Detector (P0D), the time projection chambers (TPCs), the fine-grain detectors (FGDs), the surrounding electronic calorimeters, the UA1 magnetic yoke, and the side muon range detector (SMRD). The layout is shown in Figure 10.

2.2.3. The magnetic yoke and Side Muon Range Detector. The magnetic yoke provides a magnetic field that the P0D, TPCs, and FGDs are situated in. The field is a .2 Tesla field, and allows the charge sign of detected particles to be determined.

The body of the magnet is also used as a mass for the SMRD. The SMRD has 440 scintillator modules made of polystyrene which are inserted into gaps in the UA1 magnet. The SMRD measures the flux of muons traveling with a significant angle relative to the direction of the neutrino beam. Secondly, it detects cosmic muons which travel into the detector. Finally, it detects beam interactions which occur outside the detector. This allows it to act as a veto for the ND280 detector, assisting in the removal of external events[10].

2.2.4. The Pi-Zero Detector. The P0D is a high mass detector module which is located upstream of the TPCs and FGDs. The P0D consists of three section; the upstream ECal, the water/air target,
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Figure 10. This diagram contains the major parts of the ND280 detector, and indicates the direction of the neutrino beam relative to the detector[10]

and the downstream ECAL. The upstream and downstream ECAls consist of mixed layers of lead and scintillator (polystyrene) sheets. The P0D uses these as bookends to constrict electromagnetic showers and veto interactions which occur outside the P0D. Both the upstream and downstream ECAls contain 8 layers of scintillator intermixed with 8 layers of lead.

The center section of the P0D consists of a repeating pattern of scintillator, brass, and water. The water layers have the ability to be drained and emptied, so that the P0D can take data with air gaps rather than water. There are a total of 25 water bags, as well as 25 scintillator and 25 brass layers in this section.

The P0D contains a water volume because the neutrino interaction cross sections must correctly quantify the background for the same cross-section as the far detector, which is a large tank of water. However, the interactions at the far detector occur in liquid water, while the P0D is primarily made up of solid carbon and oxygen. To account for this, the P0D takes measurements with the water bags full, which are then compared to measurements taken while the water bags are filled with air. The difference between these two sets is a measurement of the interactions which occurred in the water portion of the P0D[10, 12].

2.2.5. TPCs and FGDs. Downstream of the P0D are 3 (time projection chambers) TPCs intermixed with 2 fine grain detectors (FGDs). The TPCs and FGDs measure 2.3 meters x 2.4 meters x 1.0 meters and 2.3 meters x 2.4 meters x .365 meters respectively, and provide precision data on the path and energy loss of charged particles which they interact with.

The TPCs are filled with an argon gas, inside an electric field. When charged particles travel through the detector, they interact with the argon electromagnetically, transferring energy and
Figure 11. The P0D detector and its layout. The above image details the lead, polystyrene, brass, and water layer locations in the P0D. The Z axis is towards the right of the page, the Y axis is to the top of the page, and the X axis is into the page[10]

Figure 12. Diagram of a TPC. The Cathode provides an electric field, which causes the electrons to drift to the micrometer gas detectors on the sides of the detector[10]

freeing electrons. The electrons created by this interaction drift through the TPC, and collide with detectors placed along its side, causing a voltage which is read out. By comparing the drift time
of the ionized gas, the position of the particle can be determined in the detector. By comparing the relative number of electrons, the energy of the particle traveling through the detector can be determined. This returns a measurement of energy loss per distance, which can be compared to the Bethe-Bloch equation to determine the type of particle which streamed through the detector[10].

![Figure 13. The fine grain detector.](image)

The two FGDs provide an additional mass of 1.1 tons each for neutrino interaction, in addition to tracking charged particles. The two FGDs do this differently, with the first consisting of bars of scintillator isolated from each other by a coating of titanium oxide. The second FGD consists of scintillator alternating with 2.5 centimeter thick layers of water. By comparing the two FGD’s, separate cross sections can be calculated on carbon and water [10].

2.3. The Super-Kamiokande Detector. Super-KamiokaNDE is the largest water Čerenkov detector to have been built. It is the far detector for the T2K neutrino oscillation experiment. Operation began in April of 1996, and took a brief break for repairs in 2001. Located in the Mozumi mine, the detector is located under the peak of Mt. Ikenoyama, with roughly 1,000 meters of rock (equivalent to 2,700 meters of water when considering density) as shielding from above. This layer of material can successfully block muons of a cosmic origin with energies up to about 1.3 TeV, significantly reducing the number of expected background events.

The experiment contains two sets of detectors made from photo multiplier tubes, which are referred to as the inner and outer detectors. The inner detector consists of 11,146 PMTs, while the outer detector consists of 1,885 PMTs. The inner detector contains a mass of 50 kilotons of water and is surrounded by the outer detector. The water is ultra-purified, and is used as the interaction medium[14].

The outer detector works as a veto, detecting charged particles which enter the experiment from outside the detector. Neutrino interactions are the interactions which occur within the main volume of the detector, as detected by the inner detector, with no inbound track linked to it from the outer detector.
When charged particles enter the detector, due to their energy their interactions with the water result in Cherenkov radiation being produced. The light of the Cherenkov radiation is then detected by the PMTs. The intensity of the light, as well as the distribution over the array of PMTs in the inner detector, allows the momentum and position of interacting particles to be pinned down. Additionally, the direction of the Cherenkov ring produced can be used to determine the direction of the interacting particle[14].

Muon and electron rings are separated by measuring how “fuzzy” the rings are. When muons interact in the detector, they create a single ring of Cherenkov radiation while traveling through the water. Electron’s lower mass, however, means that the water acts strongly like an electronic calorimeter, create an electron shower. Each of these particles, in turn, also produce rings of Cherenkov radiation in the same direction as the original. The ring detected by the PMTs is a
combination of these rings. Due to this nature, the Cherenkov rings created by electrons are not quite as well defined as the rings created by muon events.

3. Isolation of the Anti-Neutrino Component of Neutrino Beam

The remainder of this document focuses on original work done analyzing data in the near detector at T2K. As stated previously, the purpose of the near detector is to measure the unoscillated neutrino fluxes, neutrino interaction cross sections, and general backgrounds. These values are compared with the Monte Carlo in order to determine the makeup of the neutrino beam.

Currently, only a theoretical calculation of the anti muon-neutrino component of the T2K neutrino beam exists. The purpose of this research is to isolate a selection of $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ events from the data in the near detector using Monte Carlo, and compare that to the selection run on data to determine if the predicted interaction rate and the experimental interaction rate are consistent.

To do this, several large backgrounds need to be dealt with. The data analyzed was gathered when the neutrino beam was running in $\nu_\mu$ mode. The magnetic horns focus the positively charged particles which decay to $\nu_\mu$ and divert the negatively charged mesons which produce an abundance of $\bar{\nu}_\mu$. Therefore, when searching for the products of $\bar{\nu}_\mu$ interactions, a large background of of the products of $\nu_\mu$ interactions must be dealt with.

The primary $\nu_\mu$ interactions, whose products cause problems, are as follows [11]:

\begin{align*}
(19) & \quad \nu_\mu + n \rightarrow \mu^- + p \\
(20) & \quad \nu_\mu + n \rightarrow \mu^- + n + \pi^+ \\
(21) & \quad \nu_\mu + p \rightarrow \mu^- + p + \pi^+
\end{align*}

All three charged products of these interactions ($\mu^-$, $p$, and $\pi^+$) provide large backgrounds that must be removed. The following analysis details the process used to remove these particles from the selection, and the comparison between the remaining particles in data versus Monte Carlo.

3.1. Experiment details. The detector used for this analysis was the near detector at the T2K experiment.

The Monte Carlo simulation used was the production 5F GENIE magnet air simulation. Production 5F indicates the current iteration of the detector simulation currently being used. The simulation is specific to run 3c of the data. GENIE is a neutrino interaction generator, which generates neutrino interactions given the set of all nuclear targets and a energy range from a few MeV to a few hundred GeV [10]. These predictions are passed to Geant4, which simulates the interactions. Magnet indicates that events were simulated as possibly occurring throughout the entire detector, rather than in a select region such as the P0D. air indicates the simulation assumed the water section of the P0D contained air rather than water. Monte Carlo analysis was done of a set of $2.5 \times 10^{20}$ protons on target.

This was combined with a set of production 5F NEUT air sand muon simulation. NEUT is another neutrino interaction generator, like GENIE. It produces neutrino interactions–and their products–based on a a set of energy points and neutrino flux. For anti-neutrinos, the error on this flux at low energies is currently relatively unknown. Like GENIE, these are fed to Geant4, which simulates interactions[10]. The sand muon Monte Carlo was created by simulating particle interactions in a region of sand matching the makeup of the sand surrounding the near detector complex, and feeding
the output of that simulation into the simulation of the near detector. Sand muon simulation for $3 \times 10^{20}$ protons on target were used.

The data used was the the run3c air data. This data was gathered while the P0D water sections were drained during run three, which was gathered between March and June 2012. A total of $1.35 \times 10^{20}$ protons on target were analyzed.

For each cut, the resulting initial momentum (otherwise referred to as front momentum) and muon PID cuts were compared to ensure that the data and Monte Carlo distributions resulted in similar results. The front momentum plot demonstrates that particles of the roughly same energies are streaming into the detector. The muon PID plot demonstrates that the makeup of these particles is similar between the two sets of data.

In the following sections, the tables, unless specified, contain no scaling based on protons on target. The plots, however, are scaled based on protons on target. The Protons on target provide a value which is based on the number of interactions in the target—this is directly proportional to the number of particles produced in the beam. Scaling based on protons on target should produce nearly identical distributions between the data and Monte Carlo. Any significant difference after proton on target scaling would indicate distribution problems between the simulation and data.

3.2. **Selection Cuts**. TheFollowing cuts were used to isolate the $\bar{\nu}_\mu + p \rightarrow n + \mu^+$ events.

1. Beam Data Quality – remove bad events due to detector or beamline condition
2. Bunch Timing Cut – removes events not in time with proton pulses from neutrino beamline creation.
3. Single Track Cut – removes bunches that have multiple particle tracks.
4. P0D Track Cut – removes particles that do not travel through P0D.
5. TPC Track Cut – removes particles that do not travel through TPCs.
6. Fiducial Volume Cut – removes particles not originating in P0D.
7. Charge Particle Cut – removes negatively charged particles.

These cuts will be detailed in the following section.

4. **Cut Descriptions**

4.1. **Beam Data Quality**. Events pass the beam data quality based on the condition of the detector and the beamline. If either is not fully functional, then events in that time are reported as bad events and removed from the sample.

4.2. **Bunch Timing Cut**. Due to the method by which protons are accelerated, the neutrino beam comes in pulses. Each spill contains eight pulses, as depicted in the plot below. The Monte Carlo events have a different time offset than the data events.

Data and Monte Carlo particle tracks were organized into one of eight bins depending on their front momentum time. Events not occurring within 80 micro-seconds of the center of a bin were removed from the set. Analysis following this point was done on bunches, rather than entire spills.
4.3. Single Track Cut. The single track cut removes timing bunches which contain multiple charged particle tracks in the P0D. The event being searched for, $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$, contains only a single charged particle, compared to the events trying to be removed, $\nu_\mu + N \rightarrow \mu^- + N + \pi^+$, which contains two. Therefore, events with multiple charged particle tracks were removed.

72.1% of particles from the Monte Carlo and 66.8% remained after this selection.

**Figure 16.** This plot illustrates the distance, in time, between each particle bunch and the start of each spill.

**Figure 17.** The image on the left gives an example of a typical pion event in comparison to the desired anti-muon event. The image on the right gives examples of events removed by the TPC and P0d track cuts.
4.4. **P0D Track Cut.** The P0D track cut removed events detected which did not contain a P0D portion of the track. Since all the particles produced by the interaction could not be verified in these events, they are removed from the sample. This cut reduced the total Monte Carlo events to 11.5% the previous amount and the total data events to 13.1% the previous amount.

4.5. **TPC Track Cut.** This cut removes events from the selection which did not contain a track through the TPC. The TPC was necessary to correctly reconstruct the momentum of particles passing through the detector, which allowed identification of a muon PID value. Additionally, the TPCs measure the curvature of the trap, allowing the particle charge to be identified. After the application of this cut, 25.2% of particles from Monte Carlo and 27.1% from data remained.

All the cuts up to this point were necessary in the pre-selection process. After these selections, the particles had the following breakdown:

<table>
<thead>
<tr>
<th>Particle</th>
<th>Number</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+$ (Monte Carlo)</td>
<td>1553</td>
<td>4.12%</td>
</tr>
<tr>
<td>$\mu^-$ (Monte Carlo)</td>
<td>34316</td>
<td>90.82%</td>
</tr>
<tr>
<td>Proton (Monte Carlo)</td>
<td>1587</td>
<td>4.20%</td>
</tr>
<tr>
<td>$\pi^+$ (Monte Carlo)</td>
<td>330</td>
<td>0.87%</td>
</tr>
<tr>
<td>Total (Monte Carlo)</td>
<td>37786</td>
<td>—</td>
</tr>
<tr>
<td>Sand (Monte Carlo)</td>
<td>177252</td>
<td>—</td>
</tr>
<tr>
<td>Data</td>
<td>81036</td>
<td>—</td>
</tr>
</tbody>
</table>

**Table 3. Breakdown of initial selection of particles**

The selection to remove pions has successfully eliminated most pions–only 0.87% of the makeup after this selection consists of pion particles. The size of this selection is roughly 21% of the total number of positive muons.

Prior to this cut, an approximately 5.56% selection of pions, slightly larger than the number of antimuons, was found in this sample. Therefore, this single track selection cut was deemed successful.

4.6. **Fiducial Volume Cut.** This cut removes particle events which are reconstructed to occur in the P0D, but have a significant possibility of occurring elsewhere. Primarily, this is focused on removing sand muons, cosmic muons, and magnet events. Sand muons are muons produced by neutrino interactions in the sand surrounding the detector. Cosmic muons are charged muons occurring outside the detector at energies high enough to not be blocked by the earth surrounding the detector. Magnet muons are muons produced in interactions in the UA1 magnet, where enough information is not generated to reconstruct a complete picture of the interaction. Figure 18 is an example of a sand muon track through the detector, which would be removed by the fiducial volume cut.

In either case, a track is made through the P0D. The reconstruction software finds the charged particle track and places an event at the perceived origin, where it entered the P0D. Therefore, by removing the outer few layers of the P0D from consideration, these events can almost completely be removed.

The P0D measures a volume of 2103 mm x 2239 mm x 2400 mm. The Fiducial Volume of the P0D is given as the following coordinates[15]:

\[ 1030 > x > -970 \text{mm} \]
This event image shows a sand muon entering the detector and streaming through all three TPCs. This event was reconstructed in the first layer of the P0D, which is removed by the fiducial volume cut

\[ 850 > y > -950 \text{mm} \]

\[ -1010 > z > -3175 \text{mm} \]

This cut removes between 200 and 300 mm from each axis in the P0D. This cut removes all but 18.57% percent of the Monte Carlo (combining magnet Monte Carlo and sand Monte Carlo) and all but 9.19% percent of the remaining data. After this cut, we have the following breakdown of the remaining selection:

![Fiducial/TPC Track Cut](image)

**Figure 19.** Distributions for fiducial, single P0D and TPC track events. The distribution for muon PID exhibits such a sharp peak next to a flattened zone due to similar energy-loss per distance of pions.

4.7. **Muon Particle Identification Cut.** To remove the protons, a cut on the muon particle identification (PID or likelihood) is enacted. The muon PID cut is based on a comparison of the energy lost per distance as measured by the detector to the theoretical energy-loss per distance of each particle. The particles being searched for are the anti-muons generated from the anti muon neutrinos. Therefore, a cut on the muon likelihood is done to remove the particles which can possibly be confused with the muons, specifically protons and pions.
Table 4. Particle Breakdown for combined fiducial, single P0D and TPC track events

<table>
<thead>
<tr>
<th>Particle</th>
<th>Percent Remaining</th>
<th>Number Remaining</th>
<th>Percentage of Remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+$ (Monte Carlo)</td>
<td>41.92%</td>
<td>652</td>
<td>4.23%</td>
</tr>
<tr>
<td>$\mu^-$ (Monte Carlo)</td>
<td>39.86%</td>
<td>13679</td>
<td>88.88%</td>
</tr>
<tr>
<td>Proton (Monte Carlo)</td>
<td>57.40%</td>
<td>911</td>
<td>5.91%</td>
</tr>
<tr>
<td>$\pi^+$ (Monte Carlo)</td>
<td>53.33%</td>
<td>176</td>
<td>1.14%</td>
</tr>
<tr>
<td>Total (Monte Carlo)</td>
<td>40.78%</td>
<td>15409</td>
<td>—</td>
</tr>
<tr>
<td>Sand (Monte Carlo)</td>
<td>0.06%</td>
<td>115</td>
<td>—</td>
</tr>
<tr>
<td>Data</td>
<td>9.19%</td>
<td>7448</td>
<td>—</td>
</tr>
</tbody>
</table>

$L_{MIP} > .05$

where $L_{MIP}$ is the muon likelihood. Normally, the muon likelihood cut also includes a cut to remove electrons at initial momenta less than 500 MeV, but due to later cuts this part of the cut was not necessary to include.

The muon likelihood is calculated from the pull values, which are calculated from the energy-loss per distance measurements of the TPC in comparison with the expected energy-loss per distance for which ever particle type is being discussed, as seen in the following equation:

$$Pull_i = \frac{dE/dx_m - dE/dx_{e,i}}{\sigma(dE/dx_m - dE/dx_{e,i})}$$

where $dE/dx_m$ is the measured energy-loss per distance, $dE/dx_{e,i}$ is the expected energy loss per distance for particle $i$, and $\sigma$ is the error in the difference. Using these pull values, the likelihood is calculated from the following equation:

$$L_{MIP} = \sum_{Pull_i} \frac{e^{-Pull_i^2}}{e^{-Pull_i^2}}$$

which compares how well the energy-loss per distance matches any of the particles expected to be seen in the detector, and returns a fraction which represents how well the detected particle matches the theoretical particles in question. The expected energy-loss per distance is given by figure 20.

This cut’s focus was the removal of particles with low probability of being a muon. Before the cut at .05 muons, the majority of the particles present which were not muons were located below .05 muon likelihood, as seen in table 5.

By applying this cut, the number of protons in the final result were reduced to 6.3% of the remaining anti-muons, compared to the previous 140% of the remaining anti-muons, reducing their presence significantly. Additionally, the number of positive pions were reduce to 11.31% of the remaining anti-muons compared to a previous 27% of the anti-muon component.

4.8. Charge Particle Cut. The charged particle cut aims to remove the $\mu^-$ events from the selection. These are particles produced by the overwhelming number of $\nu_\mu$ interactions, and need to be removed to select the $\bar{\nu}_\mu$ events.
Charged Current Anti-Neutrino Interactions in the ND280 Detector

Figure 20. Monte Carlo simulation of energy lost per distance traveled of particles. The best-fit for each particle is given.[10]

Figure 21. Distributions after muon PID, fiducial, and P0D/TPC track cuts

<table>
<thead>
<tr>
<th>Particle</th>
<th>Percentage Remaining</th>
<th>Number Remaining</th>
<th>Percentage of Remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+$ (Monte Carlo)</td>
<td>75.92%</td>
<td>495</td>
<td>5.48%</td>
</tr>
<tr>
<td>$\mu^-$ (Monte Carlo)</td>
<td>61.75%</td>
<td>8447</td>
<td>93.55%</td>
</tr>
<tr>
<td>Proton (Monte Carlo)</td>
<td>3.40%</td>
<td>31</td>
<td>0.34%</td>
</tr>
<tr>
<td>$\pi^+$ (Monte Carlo)</td>
<td>31.82%</td>
<td>56</td>
<td>0.62%</td>
</tr>
<tr>
<td>Total (Monte Carlo)</td>
<td>58.56%</td>
<td>9029</td>
<td>—</td>
</tr>
<tr>
<td>Sand (Monte Carlo)</td>
<td>14.78%</td>
<td>17</td>
<td>—</td>
</tr>
<tr>
<td>Data</td>
<td>58.62%</td>
<td>4366</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 5. Particle breakdown after muon PID, fiducial, and P0D/TPC track cuts

The charge is determined by the curvature of the particles as they travel through the detector. The overall curvature is analyzed through all sections of the detector and returned as the global charge.
This cut successfully removes most of the negative muons, leaving 1.41% of the original number of muons. However, this remaining percentage still makes up 17.10% percentage of the current final result.

4.9. Initial Momentum Cut. This leads into the initial momentum cut. An analysis of the remaining particles reveals that a significant number of the remaining muons are particles traveling backwards through the detector. Therefore, these $\mu^-$ particles appear to have positive curvature.

These backwards traveling particles are gathered in a spike just below 500 MeV, as shown in Figure 23. These particles cannot be removed with a fiducial volume cut, since 500 MeV is roughly the energy required to make it through the P0D. Therefore, a cut a 500 MeV was applied, completing the set of cuts used to isolate the anti-neutrino component of the beam. This results in the following data.

4.10. Proton on Target Scaling and Final Cut Statistical Errors. The final result is an 80% pure selection of anti-muons, with nearly equal contamination from muons, protons, and positive pions.

The final sand muon sample consists of $8 \pm 2.8$ particles. This value is scaled down to match the muon sample using the proton on target values. The ratio of protons of targets of data to sand is .45, which indicates that the expected number of sand muons in the data is $3.60 \pm 1.26$.

The final number of magnet Monte Carlo particles, including statistical error, is $559 \pm 24$ events. Like the sand muons, this needs to be scaled by protons on target to compare to the data. The ratio of protons on target between data and Monte Carlo is $302 \pm 13$ events. Combining with the sand
Figure 23. A Comparison of the momentum of particles traveling forward in the detector to particles traveling backwards in the detector

Figure 24. Distribution following momentum, muon PID, charge, fiducial, and P0D/TPC track cuts

<table>
<thead>
<tr>
<th>Particle</th>
<th>Percentage Remaining</th>
<th>Number Remaining</th>
<th>Percentage of Remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+$</td>
<td>94.92%</td>
<td>468</td>
<td>83.72%</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>26.89%</td>
<td>32</td>
<td>5.72%</td>
</tr>
<tr>
<td>Proton</td>
<td>93.55%</td>
<td>29</td>
<td>5.19%</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>56.60%</td>
<td>30</td>
<td>5.37%</td>
</tr>
<tr>
<td>Total</td>
<td>80.31%</td>
<td>559</td>
<td>—</td>
</tr>
<tr>
<td>Sand</td>
<td>88.89%</td>
<td>8</td>
<td>—</td>
</tr>
<tr>
<td>Data</td>
<td>82.10%</td>
<td>321</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 7. Particle breakdown of momentum, muon PID, charge, fiducial, and P0D/TPC track cuts

muons gives a total expected number of particles in this cut of 305 ± 13. The final data selection after the cuts are applied contains 321 ± 18 particles.
5. **Systematic Errors**

Each of these cuts contributes a systematic error. The following sections cover the calculation of the systematic error based on the calculation.

5.1. **TPC Track Finding Efficiency.** The TPC track finding efficiency is a measure of how successful the reconstruction software is at determining that a track occurred in the TPCs in comparison between the Monte Carlo and the data.

The TPC track finding efficiency error was taken to be .5%, as stated in [16].

5.2. **Reconstruction Efficiencies.** The reconstruction efficiency is a measure of the accuracy of matching P0D tracks to TPC tracks. This measurement was made by analyzing cosmic muon tracks which intersected with the front of the first TPC, and determining whether it was reconstructed with a P0D track.

For Monte Carlo, the P0D track was always found. For data, however, a track was found only 99.5% of the time. Therefore, the reconstruction efficiency adds a 0.5% systematic uncertainty to the results [17].

5.3. **Fiducial Volume Systematic.** The fiducial volume systematic is calculated based on the difference between the reconstructed front position of Monte Carlo particles versus the true front position of these particles. Due to the low density of scintillator in the P0D, the reconstructed starting position can vary significantly from the true start position.

![Figure 25](image)

**Figure 25.** The above diagram demonstrates the source of the fiducial volume offset. In the Z direction, there is the potential for great difference between the position of the particle interaction and reconstructed position, since events are reconstructed as occurring in the first layer of scintillator they are detected in.

This mean distance between the reconstructed and true initial position can be used to calculate the systematic error associated with the fiducial volume cuts. Particles at the edge of the fiducial volume could have a initial position that on average would be this mean distance away. Therefore, by varying the fiducial volume by this mean distance, the change in the number of particles can be taken as the fiducial volume error.

The Z position shows an indication of a directional bias in its initial positions, yet the mean deviation remains relatively small. The Z direction has this bias due to the makeup of the P0D. Specifically, the scintillator layers in the Z direction are separated by water and brass layers. Since most events are single particle events, they get recreated as occurring in the scintillator, rather than their actual position in the P0D, as depicted in figure 25.
Charged Current Anti-Neutrino Interactions in the ND280 Detector

<table>
<thead>
<tr>
<th>Coordinate</th>
<th>Mean (True - Reco) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>−0.03 ± 1.81</td>
</tr>
<tr>
<td>Y</td>
<td>1.24 ± 2.07</td>
</tr>
<tr>
<td>Z</td>
<td>−12.8 ± 3.84</td>
</tr>
</tbody>
</table>

Table 8. Fiducial volume Error

By varying the fiducial volume cut in and out by the above amount, the error was found to be ±0.91%.

5.4. **Charge Cut Systematic.** The systematic on the charge cut was retrieved by calculating the percentage of the time that a TPC measurement disagreed with the global charge. To do this, events in which a charged particle traveled through all three TPCs was examined. The events where all three TPCs agreed with global were compared to the events where a TPC disagreed with global.

This percentage was taken for both the Monte Carlo and the data. Then, these percentages were compared, and the difference between the data and Monte Carlo wrong sign percentage was calculated. To account for the difference between the Monte Carlo and the data, the Monte Carlo was then scaled up and down by the difference, and the percent difference due to this shift returned as the systematic error.

<table>
<thead>
<tr>
<th>Match</th>
<th>Differ</th>
<th>Total</th>
<th>Percent Differ</th>
<th>Statistical Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monte Carlo</td>
<td>3947</td>
<td>312</td>
<td>4259</td>
<td>7.32%</td>
</tr>
<tr>
<td>Data</td>
<td>1860</td>
<td>160</td>
<td>2020</td>
<td>7.92%</td>
</tr>
</tbody>
</table>

Table 9. Charge Cut Error

7.32% of Monte Carlo and 7.92% of data have a disagreement between a TPC charge and the global charge. These percentages differ by .6. Therefore, the wrong sign percentage of the Monte Carlo was scaled by a factor of 1.08, and a systematic error of 7.5% included in the results. Therefore, when including statistical error for this cut, this cut provides 9.72%(stat) ± 7.5%(sys) error.

5.5. **Muon PID Systematic.** The muon PID systematic was created by comparing the muon particle ID for the $\mu^-$ events in the Monte Carlo to the $\mu^-$ events in the data.

The method for calculating the PID systematic mirrors the method for calculating the charge misidentification systematic. The mean PID for the data and the Monte Carlo was found. Then, the means were compared and the difference between them found. Then the events were shifted by the difference, and the error calculated from the number of particles gained or lost from the shift.

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Mean PID</th>
<th>Mean Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monte Carlo</td>
<td>6922</td>
<td>.411</td>
<td>.161%</td>
</tr>
<tr>
<td>Data</td>
<td>3766</td>
<td>.415</td>
<td>.226%</td>
</tr>
</tbody>
</table>

Table 10. This table contains the differences between the Monte Carlo and data muon PID means

The difference between Monte Carlo PID mean and the data PID mean is .0039. This results in a scalar factor for the Monte Carlo PID of 1.01 and a systematic error of .945%. Therefore, the total error for this calculation is ±2.77%±.945%.
Figure 26. The diagram on the left illustrates the measurement being made, which is the difference between the Monte Carlo mean and the data mean. The plot on the right contains the plot of the Monte Carlo $\mu^-$ mean compared to the the data $\mu^-$ mean.

5.6. Initial Momentum Systematic. According to [16], there is a 5% uncertainty in the initial momentum. To calculate the uncertainty for the initial momentum cut, the initial momentum was varied up and down by 5%, and its observed effects on the result calculated.

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>+5%</th>
<th>-5%</th>
<th>mom. error</th>
<th>stat error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monte Carlo</td>
<td>7862</td>
<td>8083</td>
<td>7594</td>
<td>3.5%</td>
<td>1.1%</td>
</tr>
<tr>
<td>Data</td>
<td>3771</td>
<td>3873</td>
<td>3658</td>
<td>3.0%</td>
<td>1.6%</td>
</tr>
</tbody>
</table>

Table 11. This table contains the difference between the momentum error in the data and the Monte Carlo.

The difference between the Monte Carlo and data error was added in as additional error, resulting in the error due to this cut being 3.5% ± 1.9%.

6. Results

For Monte Carlo, a final selection of 305 particles was found, of which 83% consisted of anti-muons. This resulted in the Monte Carlo selection, after proton on target scaling, consisting of 305±12±40 particles. This systematically agrees with the number of particles remaining in the data selection, which consists of 321 ± 18 events. Therefore, the assumption that the number of anti-neutrinos in the simulation due to $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ events agrees with the number of such events in the data is valid.

The three largest sources of error are the charge misidentification error, the statistical error due to the low number of events, and the momentum measurement error. This measurement has room for improvement by increasing the statistics in the data sample. Much of the limits on the error in the charge misidentification were due to the low statistics of the data sample, which prevented a much further in-depth analysis of the TPC-global charge misidentification rate.
Charged Current Anti-Neutrino Interactions in the ND280 Detector

<table>
<thead>
<tr>
<th>Error</th>
<th>Monte Carlo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>559</td>
</tr>
<tr>
<td>Statistical</td>
<td>6.6%</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>0.5%</td>
</tr>
<tr>
<td>TPC Track Finding</td>
<td>0.5%</td>
</tr>
<tr>
<td>Fiducial Vol.</td>
<td>0.91%</td>
</tr>
<tr>
<td>Charge ID</td>
<td>12.23%</td>
</tr>
<tr>
<td>Particle ID</td>
<td>0.98%</td>
</tr>
<tr>
<td>Momentum</td>
<td>4.0%</td>
</tr>
<tr>
<td>Total Systematic</td>
<td>13%</td>
</tr>
</tbody>
</table>

Table 12. The resulting error due to each cut

The 4% error due to the momentum measurement, however, will not be reduced with increased statistics, making this the most likely lower limit to the error present in the measurement.

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5 The J-PARC layout

6 The Preparatory and decay pipe regions of the beamline creation[10, 11]

7 This diagram is of the target, located in the center of the first magnetic horn[10]


9 The on-axis detector, INGRID[10]

10 This diagram contains the major parts of the ND280 detector, and indicates the direction of the neutrino beam relative to the detector[10]

11 The P0D detector and its layout. The above image details the lead, polystyrene, brass, and water layer locations in the P0D. The Z axis is towards the right of the page, the Y axis is to the top of the page, and the X axis is into the page[10]

12 Diagram of a TPC. The Cathode provides an electric field, which causes the electrons to drift to the micrometer gas detectors on the sides of the detector[10]

13 The fine grain detector. The fine grain detector consists of layers of tightly packed scintillator. Light is read out from optical fibres located in the polystyrene.[10]

14 The Super-Kamiokande detector[10]

15 This figure shows the difference between muon Cherenkov rings (left) and electron Cherenkov rings (right)[10]

16 This plot illustrates the distance, in time, between each particle bunch and the start of each spill

17 The image on the left gives an example of a typical pion event in comparison to the desired anti-muon event. The image on the right gives examples of events removed by the TPC and P0D track cuts

18 This event image shows a sand muon entering the detector and streaming through all three TPCs. This event was reconstructed in the first layer of the P0D, which is removed by the fiducial volume cut

19 Distributions for fiducial, single P0D and TPC track events The distribution for muon PID exhibits such a sharp peak next to a flattened zone due to similar energy-loss per distance of pions.

20 Monte Carlo simulation of energy lost per distance traveled of particles. The best-fit for each particle is given.[10]

21 Distributions after muon PID, fiducial, and P0D/TPC track cuts

22 Distributions after charge, PID, fiducial, and P0D/TPC track cuts

23 A Comparison of the momentum of particles traveling forward in the detector to particles traveling backwards in the detector
24 Distribution following momentum, muon PID, charge, fiducial, and P0D/TPC track cuts

25 The above diagram demonstrates the source of the fiducial volume offset. In the Z direction, there is the potential for great difference between the position of the particle interaction and reconstructed position, since events are reconstructed as occurring in the first layer of scintillator they are detected in.

26 The diagram on the left illustrates the measurement being made, which is the difference between the Monte Carlo mean and the data mean. The plot on the right contains the plot of the Monte Carlo $\mu^-$ mean compared to the data $\mu^-$ mean

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