Constraining Of The Minerva Medium Energy Neutrino Flux Using Neutrino-Electron Scattering

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Constraining the MINERνA Medium Energy Neutrino Flux Using Neutrino-Electron Scattering

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Doctor of Philosophy

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ABSTRACT

Long baseline neutrino oscillation experiments rely on the flux from accelerator-based neutrino beams. As experimental neutrino physics moves to the next generation of experiments a precise characterization of the neutrino flux on a given experiment becomes crucial to the goals of the experiments: to precisely determine the neutrino oscillation parameters. This work takes advantage of neutrino-electron scattering processes for their precisely predicted cross section. The observed number of scattering events can be used as a benchmark to constrain the neutrino flux. A measurement was made of the energy spectrum of neutrino-electron elastic scattering ($\nu e^- \rightarrow \nu e^-$), using data from the antineutrino-enhanced run period of the NuMI beam line with an energy peak at 6 GeV. These new data were combined with previous measurements of neutrino-electron elastic scattering and inverse muon decay ($\nu_\mu e^- \rightarrow \mu^- \nu_e$). A Bayesian probability technique was applied to constrain the multi-simulation prediction of the neutrino flux. A constraint was set on the normalization and uncertainty of the NuMI neutrino flux at the MINERvA detector. The fractional uncertainty on the integrated neutrino flux was reduced from 7.6% to 3.3% for the muon neutrino beam and from 7.8% to 4.7% for the muon antineutrino beam. The reduced flux uncertainty will improve the precision of MINERvA cross sections measurements. Additionally, the technique demonstrated in this work can be applied to other accelerator-based neutrino experiments as tool to characterize the neutrino flux.
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A mi madre, Claudia.
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CONSTRAINING THE MINERνA MEDIUM ENERGY NEUTRINO FLUX USING NEUTRINO-ELECTRON SCATTERING
CHAPTER 1

Introduction

The Standard Model of particle physics is a model that attempts to describe all the fundamen-
tal particles that exist in the universe and the interactions that occur between them. It is
arguably the most successful physical model to date. It describes three of the four fundamental
interactions of nature: electromagnetic, strong nuclear, and weak nuclear interaction, but it
excludes gravity. It also describes how these forces interact with the fundamental particles of
matter.

The fundamental particles that make up conventional matter are the electron, the up and
down quarks that compose protons and neutrons, and the electron neutrino present in great
quantities coming from the Sun as a result of the nuclear reactions at its core. Additionally,
there are more fundamental particles that share the same properties as the particles previously
mentioned except for their mass. These second and third generation particles are more massive
than their first generation counterparts.

In the Standard Model, there are three types (also called “flavors”) of neutrinos: electron
neutrino, muon neutrino, and tau neutrino ($\nu_e$, $\nu_\mu$ and $\nu_\tau$ respectively), the flavor indicates
which of the charged leptons it interacts with.
FIG. 1.1: The particles and force carriers of the Standard Model of elementary particles [1].

Neutrinos are fermions with no electric charge; the only way they interact with other matter is through the weak nuclear force. Neutrino interactions are categorized as charged current, neutral current, or a combination of both. Focusing on scattering by neutrinos, in a charged current interaction the result is a charged lepton in the final state. For example, in the process known as neutrino capture

\[ \nu_e n \rightarrow e^- p , \]  

an electron neutrino interacts with a neutron (usually inside an atomic nucleus) and the reaction produces an electron and a proton in the final state. In a neutral current interaction, the neutrino remains in the final state and no new charged lepton is produced, for example in neutrino-electron elastic scattering;

\[ \nu_\mu e^- \rightarrow \nu_\mu e^- . \]  

3
Although previously believed to be massless, experiments in recent decades have confirmed that neutrinos have non-zero masses, by observing the phenomenon of neutrino oscillations; neutrinos change their flavor as they propagate through space, where the change happens in a periodic way.

The first evidence of neutrino oscillations came from the observation of a deficit of neutrinos coming from the Sun [2]. At the time it was unclear if the deficit was due to oscillations or an incorrect understanding of the physics at the Sun’s core. Oscillations were later observed from atmospheric neutrinos by the Super-Kamiokande experiment [3], and the oscillation hypothesis for solar neutrinos was confirmed by the Sudbury Neutrino Observatory (SNO) [4, 5]. The observation of oscillation of neutrinos coming from nuclear reactors came shortly after by the KamLAND collaboration [6].

The discovery of the neutrino non-zero masses is one of the most promising pieces of evidence of physics beyond the Standard Model from recent years and opens the door to Charge-Parity violation in the lepton sector, that is, the possibility that matter and anti-matter are not treated equally by the weak interaction. This could potentially lead to an explanation of why the observable universe is dominated by matter. Moreover, neutrino masses are much smaller than those of any other massive particle, which could point to a different mechanism for them acquiring their mass, and thus to additional physics beyond the Standard Model.

1.1 Neutrino Oscillations

Neutrino masses are so much smaller than the masses of other particles that they are practically zero compared to any other massive particle. Still, the masses not being exactly zero gives rise to the oscillation of their flavor as they propagate.

The three Standard Model neutrinos can be described using two different bases. One is the interaction basis, where the states are labeled by their flavor ($\nu_e$, $\nu_\mu$, and $\nu_\tau$). In
this basis the interactions that can be observed are well-defined. For example, an electron neutrino interacting through a W boson exchange will include an electron. On the other hand, propagating neutrinos can be described using the mass basis \((\nu_1, \nu_2, \nu_3)\), with defined mass \(m_i\), for \(i = 1, 2, 3\). The two bases are related to each other by a complex unitary matrix, known as the Pontecorvo–Maki-Nakagawa-Sakata (PMNS) matrix

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}.
\tag{1.3}
\]

The PMNS matrix can be parameterized by three two-flavor mixing rotations. There are four parameters: three mixing angles \(\theta_{12}, \theta_{23}, \theta_{13}\), and a phase \(\delta_{CP}\). Using the shorthand \(c_{ij} = \cos \theta_{ij}\) and \(s_{ij} = \sin \theta_{ij}\), the PMNS matrix is in this parameterization

\[
U_{\text{PMNS}} =
\begin{pmatrix}
   c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\
-s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\
   s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & -c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}c_{23}
\end{pmatrix}.
\tag{1.4}
\]

The PMNS matrix is analogous to the Cabibbo–Kobayashi–Maskawa matrix from the quark sector. However, neutrino mixing is quantitatively different from quark mixing in that, where the CKM matrix is approximately diagonal, the elements of the PMNS matrix are almost all on the order of unity.

\[
|U_{\text{PMNS}}| \sim
\begin{pmatrix}
   0.8 & 0.5 & 0.1 \\
   0.5 & 0.6 & 0.7 \\
   0.3 & 0.6 & 0.7
\end{pmatrix}.
\tag{1.5}
\]

With the PMNS matrix, one can write the interaction basis in terms of a linear combination
of the mass states with masses \(m_i\) as

\[
|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle, \quad \text{for } \alpha = e, \mu, \tau. \tag{1.6}
\]

Then, the probability of observing a neutrino of flavor \(\beta\) when originally it was of flavor \(\alpha\) is given by

\[
P_{\nu_\alpha \rightarrow \nu_\beta} = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = |\sum_{i=1}^{3} \sum_{j=1}^{3} U_{\alpha i}^* U_{\beta j} \langle \nu_j | \nu_i(t) \rangle|^2. \tag{1.7}
\]

The propagating neutrino state is, using natural units \(|\nu_i(t)\rangle = e^{-iE_i t} |\nu(0)\rangle\). For ultrarelativistic neutrinos one can make the approximation \(E_i = \sqrt{p_i^2 + m_i^2} \approx p_i^2/2E_\nu\), where \(p_i \approx p_j \equiv p \approx E_\nu\), that is, the different mass states have the same momentum, and thus their time dependence is \(|\nu_i(t)\rangle = e^{-im_i^2 L t/2E_\nu} |\nu(0)\rangle\). With this the transition probability from Eq. 1.7 becomes

\[
P_{\nu_\alpha \rightarrow \nu_\beta}(L) = \delta_{\alpha\beta} - 4 \sum_{i<j}^{3} \text{Re}[U_{\alpha i}^* U_{\beta i} U_{\alpha j}^* U_{\beta j}] \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E_\nu}\right) + 2 \sum_{i<j}^{3} \text{Im}[U_{\alpha i}^* U_{\beta i} U_{\alpha j}^* U_{\beta j}] \sin \left(\frac{\Delta m_{ij}^2 L}{2E_\nu}\right) \tag{1.8}
\]

where \(\Delta m_{ij}^2 = m_i^2 - m_j^2\) and \(L\) is the distance between the point where the \(\nu_\alpha\) neutrino is produced and the \(\nu_\beta\) is observed. The substitution \(t = L\) was made in Eq. 1.8 due to the neutrinos traveling practically at the speed of light.

Six unknown parameters describe the oscillation probability for three neutrino flavors: two mass splittings \(\Delta m_{ij}^2\) and the four parameters of the PMNS matrix: \(\theta_{12}, \theta_{23}, \theta_{13},\) and \(\delta_{CP}\). These six parameters must be determined experimentally.

In order to observe the effects of the flavor oscillation for a given mass splitting \(\Delta m^2\), experiments must choose the neutrino energy and the baseline distance such that \(E_\nu/L \approx \Delta m^2\). 

\(c = h = 1\)
The mass splittings present in two different regimes: $\Delta m_{21}^2$, also known as the solar splitting, is two orders of magnitude smaller than $|\Delta m_{32}^2|$, also known as the atmospheric splitting. The remaining mass difference can be written in terms of the other two as $\Delta m_{31}^2 = \Delta m_{32}^2 + \Delta m_{21}^2$.

In practice, one can take advantage of the relative sizes of the mass splittings and the mixing angle to simplify the transition probability. In those cases, a two-flavor oscillation model is a good approximation. For two flavors, the mixing matrix depends only on one mixing angle, and there is only one frequency determined by the relevant mass splitting for the experiment oscillation length $L_{\text{osc}}$

$$L_{\text{osc}} = \frac{4\pi E_\nu}{\Delta m_{ij}^2}.$$  \hfill (1.9)

The transition probability for two-flavor mixing is

$$P_{\alpha \rightarrow \beta} = \delta_{\alpha \beta} - (2\delta_{\alpha \beta} - 1) \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{E_\nu} \right).$$  \hfill (1.10)

The simplified transition probability presents two ambiguities; changing the sign of $\Delta m^2$ or changing the octant of the mixing angle as $\theta \rightarrow \pi/2 - \theta$ both leave Eq. 1.10 unchanged. This ambiguity is broken in two possible ways: by taking into account the three flavors in the oscillation, or by the effect of neutrinos traveling through regions of dense matter while they propagate.

The sign of $\Delta m_{31}^2$ is currently unknown, that is, it is unknown if $m_3$ is the smallest or largest of the masses. This opens the possibility of two different ordering for the neutrino masses (sometimes called the neutrino mass hierarchy). One can write the mass states in terms of the flavor states using the inverse of the mixing matrix in a similar way to Eq. 1.6. This leads to the state with mass $m_1$ being mainly electron neutrino, the state with $m_2$ about even proportion three flavors, and $m_3$ having very little $\nu_e$ contribution. If the masses of the
neutrinos are ordered the same way as their partner leptons one would assume that the state that is the most $\nu_e$-like is the lightest, and the one that is the least $\nu_e$-like is the heaviest. If that were the case, then $\Delta m_{31}^2 > 0$. This is called normal ordering (NO). However, it is still possible that $\Delta m_{31}^2 < 0$, which means that the state with $m_3$ is the lightest, this case is called inverted ordering (IO). The two possible orders are pictured in Fig. 1.2. Table 1.1 displays the current best global fit values \[7\] for the three neutrino oscillations for normal and inverted mass orderings assumptions.

One of the more interesting features of neutrino oscillation is that it might not treat neutrinos and antineutrinos the same way. This is known as Charge-Parity (CP) violation. CP violation is quantified by the value of the phase $\delta_{CP}$. A value of zero or $\pi$ means no CP violation; a value of $\frac{\pi}{2}$ or $\frac{3\pi}{2}$ means the maximum amount of CP violation.

The transition probabilities $P_{\nu_\alpha \rightarrow \nu_\beta}$ and $P_{\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta}$ are functionally the same except for the sign of the term that contains $\delta_{CP}$. One would see different rates from $\nu$ and $\bar{\nu}$ at the oscillation peak purely from oscillation effects.
### TABLE 1.1: Neutrino oscillation parameter from a global fit. From [7].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal Ordering</th>
<th>Inverted Ordering</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{12}$ [10$^{-5}$ eV$^2$]</td>
<td>7.50$^{+0.22}_{-0.20}$</td>
<td>7.50$^{+0.22}_{-0.20}$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2_{31}</td>
<td>$ [10$^{-3}$ eV$^2$]</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12} / 10^{-1}$</td>
<td>3.18$^{+0.16}_{-0.16}$</td>
<td>3.18$^{+0.16}_{-0.16}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23} / 10^{-1}$</td>
<td>5.74$^{+0.14}_{-0.14}$</td>
<td>5.78$^{+0.10}_{-0.17}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13} / 10^{-2}$</td>
<td>2.200$^{+0.069}_{-0.069}$</td>
<td>2.225$^{+0.064}_{-0.070}$</td>
</tr>
<tr>
<td>$\delta_{CP} / \pi$</td>
<td>1.08$^{+0.13}_{-0.12}$</td>
<td>1.58$^{+0.15}_{-0.16}$</td>
</tr>
</tbody>
</table>

1.2 Neutrino Oscillation Experiments

In neutrino oscillation experiments, the goal is to observe the effect of flavor oscillation by seeing a discrepancy between the observed neutrino flux, and that expected in the absence of oscillations. Experiments that study neutrinos produced on Earth do this by having two detectors: one near the source where the oscillation effects are not present ($L \ll L_{osc}$), and one far detector at $L \approx L_{osc}$. The oscillation is observed by comparing the number of neutrino events observed in the near and far detectors. Due to the difference in sizes of the solar and atmospheric mass splittings, oscillation experiments are categorized into two types: short and long baseline. Short baseline experiments can use neutrinos from nuclear reactors as well as accelerator facilities and have the distance between the near and far detector on the order of $\sim 100$ meters. Long Baseline experiments rely on getting neutrinos from accelerators and have a baseline on the order of $\sim 1000$ kilometers. The next generation of long baseline neutrino oscillation experiments like DUNE [8] and T2HK [9] look to achieve precision measurements of the oscillation parameters, including a measurement of the CP violating phase and the answer to the mass hierarchy problem.

The rate seen on the near detector is determined by three ingredients: the reaction cross section of the neutrino with the target nuclei, $\sigma$; the incoming neutrino flux $\Phi$; and a detector
response term $f$ that encapsulates the resolution and efficiency of the detector technology. Thus, the rate at the near detector is

$$N_{ND}(E_{\nu}) = \int \sigma_{ND}(E'_{\nu}) \Phi_{ND}(E'_{\nu}) f_{ND}(E_{\nu}, E'_{\nu}) dE'_{\nu} \quad (1.11)$$

where $E'_{\nu}$ and $E_{\nu}$ are the true and reconstructed neutrino energies.

Similarly on the far detector, assuming neutrino oscillation, the rate is

$$N_{FD}(E_{\nu}) = \int \sigma_{FD}(E'_{\nu}) \Phi_{FD}(E'_{\nu}) P(E'_{\nu}) f_{FD}(E_{\nu}, E'_{\nu}) dE'_{\nu}. \quad (1.12)$$

The average transition probability is

$$\langle P \rangle = \frac{N_{FD}}{N_{ND}} \quad (1.13)$$

Precise knowledge of the three terms not coming from the oscillation is crucial for the success of neutrino oscillation experiments. It becomes necessary to use every possible handle to improve the knowledge of these components. Uncertainties can be mitigated on the ratio by similarities on the near and far detector, on the cross section by having the same target nuclei and similar overall composition, and on the detector response by having the same technology.

For accelerator-based neutrino experiments, the neutrino flux is known \textit{a priori} from the simulation of the beamline. The flux is produced by colliding protons into a target and focusing the produced mesons using magnetic horns, selecting a specific sign for their charge, and reducing their transverse momentum. The neutrinos are produced when the mesons decay. Each stage of the chain of events that produces a neutrino is simulated to predict the flux as a function of neutrino energy.

The flux simulation is often based on micro-physical models that simulate the interaction and propagation of particles in the target and other beamline components. In practice, this is
a hard endeavor because a precise prediction is complicated by the limited knowledge of the hadron production cross section at the kinematic phase space relevant to neutrino beams and by the multiple possible chains of interactions that can eventually produce a neutrino. Historically, neutrino flux uncertainty started around 30%, but the development of better technology and techniques has lowered that number. For example, as dedicated hadron production measurements become available (same target nuclei, similar phase-space, replica targets), the flux simulation can be re-scaled to better match the new data. External hadron production has been used on several beamlines to constrain the flux uncertainty to about $\sim 8\%$ [10, 11].

Neutrino-nucleus cross sections lack a single precise model at the energy ranges of few GeV where oscillation experiments operate. At this energy, there is an overlap of different channels that contribute to the total cross section, but there is not a single model that incorporates all of them. This is due to the non-perturbative nature of the Strong interaction in this energy range. The use of nuclei with large atomic numbers helps to increase the rate of neutrino interactions by having a larger cross section, with the trade-off of the nuclear effects that add to the uncertainty of the interaction. Oscillation experiments can use the near detector to measure the relevant cross section, but the uncertainty on the flux contributes to the uncertainty of the measurement. That means that the near detector data can only be used to constrain the product of the flux and the cross section.

A way to separate the characterization of the neutrino-nucleus cross sections and the flux is to measure the scattering of neutrinos with atomic electrons in the near detector. Since the cross section of neutrino electron scattering is well predicted by the Standard Model, a precise measurement of the rate of electron scattering events can be used as a “standard candle”, a process with a known cross section, for the normalization of the neutrino flux.

The work of this dissertation focuses on a new measurement of the number of antineutrino-electron elastic scattering events in the MINERνA detector as a means to constrain the neutrino flux. The new $\bar{\nu}$ measurement is used in conjunction with two previous measurements: one
using neutrino-electron elastic scattering and one using the inverse muon decay reaction $\nu_\mu e^- \rightarrow \mu^- \nu_e$. The number of events is compared with the simulated prediction, and this is used to apply a constraint on the normalization of the neutrino flux. By using the technique outlined in this work, the normalization of the predicted neutrino flux at MINER$\nu$A is reduced by 10% from the \textit{a priori} simulation and the flux uncertainty is reduced to 3-5%. The details and discussion on this can be found in Chap. 7.

The document is structured as follows. The theoretical framework of neutrino interactions is visited in Chap. 2. A more complete description of accelerator-based neutrino beams and a description of the NuMI beamline that is the source of neutrinos of the MINER$\nu$A experiment are provided in Chap. 3. The MINER$\nu$A detector and its simulation are described in Chap. 4. A description of the reconstruction and selection procedure for the antineutrino-electron scattering events is in Chap. 5 and the procedure followed to constraint the background and evaluate the uncertainties are in Chap. 6. Once there is a measurement of the electron energy spectrum from the elastic scattering events, it is used to constrain the flux following the procedure in Chap. 7. The conclusions are in Chap. 8.
CHAPTER 2

Neutrino Interactions

Neutrinos are a great probe of the weak interaction. In contrast with other particles like quarks and the charged leptons, neutrinos only interact through the weak force. This allows experiments to isolate and study the weak interaction processes. Historically, the study of neutrino interactions has helped to test the validity of the Standard Model of particle physics by observing both charged and neutral current interactions. The Standard Model was the main interest of most of the neutrino experiments done in the 70s, which were made at the neutrino energy range of dozens to hundreds of GeV. Modern studies of neutrino physics focus on neutrino masses and flavor oscillation, where the experiments operate at the neutrino energy range of hundreds of MeV to about 20 GeV, with the neutrino energy spectrum usually peaking between 1-6 GeV. Thus the present interest is in the knowledge of neutrino cross sections at few-GeV energies, with the goal of reducing the systematic uncertainties on the oscillation measurements.

Both current and future oscillation experiments use a range of nuclei as targets, from hydrogen, through carbon, all the way to lead. Liquid argon time projection chambers are a promising technology that is planned to be used in the DUNE experiment \[8\], as well as in the
Short Baseline program at Fermilab with SBND \cite{12}, ICARUS \cite{13}, and which is currently being used by the MicroBoone detector \cite{14}. Heavy nuclei have the advantage of being a “bigger” target, increasing the cross section and thus the rate of neutrino events. On the downside, the nuclear effects on the neutrino-nucleon cross sections are not well understood at the energy range of a few GeV or less. The theoretical prediction of this energy range is limited by the non-perturbative nature of Quantum Chromodynamics (QCD) and depends on several models for the different interaction channels that can occur in this energy range.

This work focuses on neutrino-electron scattering. This channel is precisely predicted by theory since they are lepton-lepton interactions, and no other models are needed besides the Standard Model. Using processes with well-known cross sections it is possible to measure the neutrino flux without having to worry about attributing neutrino-nucleus cross sections effects to the neutrino flux.

This chapter will focus first on neutrino-electron scattering, allowing it to also cover the description of the weak interaction on the Standard Model. In the subsequent sections, there is a brief description of neutrino-nucleus interactions and the different interaction channels possible, which are all backgrounds to the processes of interest. Only Standard Model interactions are considered in the analysis and a short discussion of non-Standard Model interactions is in Chap. 8.

\section{2.1 Neutrino Interactions in the Standard Model}

The weak interaction is described in the Standard Model by the exchange of the $W^\pm$ and $Z^0$ vector bosons. The possible neutrino interaction can be divided into three categories: charged current (CC), neutral current (NC), or a combination of both. The charge current
interactions are mediated by the $W^+$ or $W^-$ bosons. The interaction Lagrangian here is

$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}}(J^\mu_W W^-_\mu + J^\dagger_W W^+_\mu)$$

(2.1)

where $g$ is the coupling constant, $W^\pm_\mu$ are the gauge boson fields and $J^\mu_W$ is the (leptonic) charged weak current:

$$J^\mu_W = 2 \sum_{i=e,\mu,\tau} \bar{\nu}_{L,i} \gamma^\mu \nu_{L,i}.$$  

(2.2)

This means that for neutrino scattering, there is a charged lepton in the final state with the same flavor as the incoming neutrino.

Neutral current interactions are mediated by the exchange of a $Z^0$ boson. This interaction has the particularity of coupling with different strengths to the left and right chiral projections of fermion fields with couplings $g_L, g_R$. It is also written as the V-A form with couplings $g_V$ and $g_A$ for the vector and axial vector components. The weak neutral current is

$$J^\mu_Z = 2 \sum_{i=e,\mu,\tau} \left[ g_{L,i} \bar{\nu}_{i,L} \gamma^\mu \nu_{i,L} + g_{R,i} \bar{l}_{i,L} \gamma^\mu l_{i,L} \right]$$

(2.3)

$$= \sum_{i=e,\mu,\tau} \left[ \bar{\nu}_i \gamma^\mu (g_V - g_A^5) \nu_i + \bar{l}_i \gamma^\mu (g_V - g_A^5) l_i \right]$$

(2.4)

where the two sets of coupling are related to each other as $g_V = g_L + g_R, g_A = g_L - g_R$. Their values at tree-level are shown in Tab. 2.1. The neutral current interaction Lagrangian is

$$\mathcal{L}_{NC} = -\frac{g}{2 \cos \theta_W} J^\mu_Z Z^-_\mu$$

(2.5)

here $\theta_W$ is the weak mixing angle.

Focusing on the energy range of modern neutrino experiments (hundreds of MeV to about
TABLE 2.1: Values of couplings $g_L$ and $g_R$ for leptons in the Standard Model.

<table>
<thead>
<tr>
<th>fermion</th>
<th>$g_L$</th>
<th>$g_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$, $\nu_\mu$, $\nu_\tau$</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
</tr>
<tr>
<td>$e$, $\mu$, $\tau$</td>
<td>$-\frac{1}{2} + \sin^2 \theta_W$</td>
<td>$\sin^2 \theta_W$</td>
</tr>
</tbody>
</table>

$20 \text{ GeV}$ one can assume that the four-momentum transfer squared $q^2$ is much smaller than $M^2_{W,Z}$, the mass of the $W$ and $Z$ bosons, thus one can take the propagator to be constant when calculating the matrix element. In this case, the Standard Model description of the weak interaction reduces to the Fermi effective theory by recognizing

$$G_F = \frac{g^2}{4\sqrt{2}M^2_W} = 1.1663788(7) \times 10^{-5} \text{ GeV}^{-2}$$

and then the effective Lagrangians are

$$\mathcal{L}_{CC} = -\frac{G_F}{\sqrt{2}} j^\dagger_{W\mu} j^\mu_W$$

$$\mathcal{L}_{NC} = -\frac{G_F}{\sqrt{2}} j^\dagger_{Z\mu} j^\mu_Z.$$  

2.2 Neutrino-Electron Scattering

2.2.1 Neutrino-electron elastic Scattering

In the process of neutrino-electron elastic scattering, the neutrino interacts with an electron and both remain in the final state. No other particle is produced, i.e.

$$\nu_x e^- \to \nu_x e^- \text{ and } \bar{\nu}_x e^- \to \bar{\nu}_x e^-,$$
where $x = e, \mu$. For a muon neutrino, this is a pure NC interaction\footnote{This is also true for tau neutrinos, but they are omitted from this discussion for simplicity. Tau neutrinos are not produced in conventional neutrino beams and will only appear as a consequence of oscillations.} (see Fig. 2.1). For electron neutrinos, there is a charged current component as well. Neither the incoming nor outgoing neutrinos can be directly observed in experiments. This process is instead studied by reconstructing the scattered electron’s energy and scattering angle. The differential cross section for this process is often expressed as a function of the kinematic variable $y$, known as inelasticity, defined from the initial four-momenta of the incoming neutrino $p_\nu$ and the electron $p_e$ as

$$y = \frac{p_e \cdot q_{\text{Lab}}}{p_e \cdot p_\nu} \frac{E_e - m_e}{E_\nu}$$

(2.10)

Here $y$ spans $0 \leq y \leq y_{\text{max}}$ where $y_{\text{max}} = (1 + m_e/2E_\nu)^{-1} \approx 1$.

The differential cross section is

$$\frac{d\sigma(\nu_\mu e^- \rightarrow \nu_\mu e^-)}{dy} = \frac{2m_e G_F^2 E_\nu}{\pi} \left( g_L^2 + g_R^2 (1 - y)^2 - g_L g_R \frac{m_e y}{E_\nu} \right)$$

(2.11)

$$\frac{d\sigma(\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-)}{dy} = \frac{2m_e G_F^2 E_\nu}{\pi} \left( g_R^2 + g_L^2 (1 - y)^2 - g_L g_R \frac{m_e y}{E_\nu} \right)$$

(2.12)

Here the couplings $g$ are for the charged leptons, those for the neutrino have been substituted by their numerical value. Notice how the neutrino and antineutrino cross sections are related by the interchange between $g_L$ and $g_R$. The term containing $g_L g_R$ becomes very small at $E_\nu \approx 1$ GeV, the energies relevant for accelerator neutrinos, and can be neglected. The integrated cross sections are then

$$\sigma(\nu_\mu e \rightarrow \nu_\mu e) = \frac{m_e G_F^2 E_\nu}{2\pi} \left( 1 - 4 \sin^2 \theta_W + \frac{16}{3} \sin^4 \theta_W \right)$$

(2.13)
For electron neutrinos (see Figs. 2.2, 2.3), the elastic scattering of electrons has both a neutral and charged current components. The electron neutrino cross sections are related to the muon by the replacement $g_L \rightarrow g_L + 1$. Again neglecting the $m_e/E$ term the cross sections are

$$\sigma(\bar{\nu}_e e \rightarrow \nu_e e) = \frac{G_F^2 m_e E}{2\pi} \left( \frac{1}{3} + \frac{4}{3} \sin^2 \theta_W + \frac{16}{3} \sin^4 \theta_W \right)$$

(2.15)

$$\sigma(\bar{\nu}_e e \rightarrow \bar{\nu}_e e) = \frac{G_F^2 m_e E}{2\pi} \left( \frac{1}{3} + \frac{4}{3} \sin^2 \theta_W + \frac{16}{3} \sin^4 \theta_W \right)$$

(2.16)

Fun fact: The s-channel process that happens only for $\bar{\nu}_e$ has a resonance on the cross section at $E_{\text{res}} = M_W^2/2m_e = 6.3$ PeV, which makes electron elastic scattering the largest cross section at that energy.
2.2.2 Inverse muon decay

The remaining neutrino-electron processes are $\nu_l e^- \rightarrow l^- \nu_e$ and $\nu_e e^- \rightarrow l^- \nu_l$ for $l = \mu, \tau$. They are purely charged current processes and are kinetically constrained by the mass of the final state lepton as

$$E_\nu \geq \frac{m_l^2 - m_e^2}{2m_e}.$$  \hspace{1cm} (2.17)

For the muon, the threshold is about 10.8 GeV.

The cross sections after averaging over all polarization and spin states and integrating over all unobserved momenta are

$$\frac{d\sigma(\nu_\mu e^- \rightarrow \mu^- \nu_e)}{dy} = \frac{2m_e G_F^2 E_\nu}{\pi} \left(1 - \frac{m_\mu^2 - m_e^2}{2m_e E_\nu}\right)$$  \hspace{1cm} (2.18)

$$\frac{d\sigma(\bar{\nu}_e e^- \rightarrow \mu^- \bar{\nu}_\mu)}{dy} = \frac{2m_e G_F^2 E_\nu}{\pi} \left(1 - y\right)^2 - \frac{(m_\mu^2 - m_e^2)(1 - y)}{2m_e E_\nu}.$$  \hspace{1cm} (2.19)

Integrating over $y$ in the limit where $E_\nu \gg E_{\text{thresh}}$

$$\sigma(\nu_\mu e^- \rightarrow \mu^- \nu_e) \simeq 3\sigma(\bar{\nu}_e e \rightarrow \mu \bar{\nu}_\mu) \simeq \frac{2G_F^2 m_e E_\nu}{\pi}$$  \hspace{1cm} (2.20)

A comparison of the magnitudes of the cross sections of all the neutrino-electron scattering
\[
\sigma / (G_F^2 m_e E_\nu / 2\pi) \\
\begin{array}{ll}
\nu_\mu e^- \rightarrow \nu_\mu e^- & 1 - 4 \sin^2 \theta_W + 16/3 \sin^4 \theta_W = 0.326 \\
\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^- & 1/3 - 4/3 \sin^2 \theta_W + 16/3 \sin^4 \theta_W = 0.309 \\
\nu_e e^- \rightarrow \nu_e e^- & 1 + 4 \sin^2 \theta_W + 16/3 \sin^4 \theta_W = 2.2 \\
\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^- & 1/3 + 4/3 \sin^2 \theta_W + 16/3 \sin^4 \theta_W = 0.922 \\
\nu_\mu e^- \rightarrow \mu^- \nu_e & 4 \\
\bar{\nu}_e e^- \rightarrow \mu^- \bar{\nu}_\mu & 4/3 \\
\end{array}
\]

TABLE 2.2: Summary of the relative size of neutrino-electron cross sections in the limit \( E_\nu \gg m_\mu^2 / 2m_e \) and \(-q^2 \ll M_W^2\). The numerical values use the approximate value \( \sin^2 \theta_W = 0.23 \).

The very directional nature of neutrino-electron elastic scattering is used in solar neutrino oscillation experiments to confirm that the neutrinos come from the sun.

### 2.2.3 Kinematic Constraint for Elastic Scattering

These neutrino-electron scattering processes have the remarkable characteristic that the final state particles are scattered in the forward direction, with minimal angles. This is very useful for isolating these processes from a background with a much larger cross section\(^3\).

The scattering angle of the charged lepton \( \theta \) can be uniquely determined by its energy and the energy of the neutrino as

\[
1 - \cos \theta = \frac{2m_e(1 - y)}{E_e},
\]

and since \( y \) is bounded between 0 and 1, the product of the energy and the angle is bounded as

\[
0 \leq E_e(1 - \cos \theta) \leq 2m_e.
\]

Making a small-angle approximation, this kinematic constraint can be simplified to

\[
E_e \theta^2 \leq 2m_e.
\]

\(^3\)The very directional nature of neutrino-electron elastic scattering is used in solar neutrino oscillation experiments to confirm that the neutrinos come from the sun.
2.2.4 Radiative Corrections

Although by itself the predicted cross section to leading order is well known from theory especially as compared to poorly known neutrino-nucleus cross sections, it is possible to go further and take into account the next-to-leading order corrections.

The next-to-leading order corrections to neutrino electron elastic scattering are calculated in Ref. [15]. This calculation includes two final states: with one electron ($\nu e^- \to \nu e^-$) and with an electron, and a photon ($\nu e^- \to \nu e^- \gamma$). These two final states are experimentally indistinguishable in most neutrino experiments and it is necessary to add the second process to correctly predict the observed cross section.

These radiative corrections are incorporated into the analysis by reweighting the simulated number of $\nu e^- \to \nu e^-$ events as a function of neutrino energy. This is further discussed in Sec. 4.3.

2.3 Neutrino-Nucleus Scattering

Interactions of neutrinos with atomic nuclei make the bulk of neutrino interactions seen in cross section and oscillation experiments, as they are three orders of magnitude bigger than neutrino-electron cross sections. Over the MeV to few GeV range, several channels overlap to contribute to the total cross section (see Fig. 2.4). One of the challenges of modern neutrino physics is to find a model that predicts correctly the cross section over the wide energy range relevant for oscillation experiments. The important channels are outlined next.

Quasi-Elastic Scattering (QE). In this process, neutrinos elastically scatter off a nucleon, liberating one or more nucleons from the target nucleus. In the simplest case this happens as $\nu_\mu n \to \mu^- p$ and $\bar{\nu}_\mu p \to \mu^+ n$ for muon neutrinos, and $\nu_e n \to e^- p$ and $\bar{\nu}_e p \to e^+ n$ for electron neutrinos. The latter will be the largest source of background to the neutrino-electron
FIG. 2.4: Total charged current total cross section for neutrino and antineutrino. Shows contributions from quasi-elastic (QE), resonant (RES), and deep inelastic scattering (DIS). MINERνA flux used in this analysis spans a broadband neutrino energy spectrum, with a peak around 6 GeV, thus the three channels will contribute. At 5 GeV the cross section is $3.8 \times 10^{-38}$ ($1.8 \times 10^{-38}$) cm$^2$ for neutrino (antineutrino). From [16].

scattering analysis. Due to the effect of the correlations between different nucleons in the same nucleus, scattering from multiple nucleons can also happen. This process is referred to as 2p2h (from two particles, two holes).

**Resonant Pion Production (RES).** In resonant pion production, the nucleus is excited into a resonance that decays shortly after into one of the multiple final states containing mesons, most often to a nucleon and a single pion$^4$. The most relevant final states for this analysis are the ones that produce neutral pions, which quickly decay into two photons. There are both charged-current and neutral-current resonance processes with a pion final state. For muon neutrinos these are

$$\nu_\mu n \rightarrow \mu^- p \pi^0, \quad \bar{\nu}_\mu p \rightarrow \mu^+ n \pi^0$$

(2.24)

$$\nu_\mu p \rightarrow \nu_\mu p \pi^0, \quad \bar{\nu}_\mu p \rightarrow \bar{\nu}_\mu p \pi^0$$

(2.25)

$^4$There are non-resonant processes that can also produce a single pion. These are simulated as an extension of the DIS model.
\[ \nu_\mu n \rightarrow \nu_\mu n \pi^0, \quad \bar{\nu}_\mu n \rightarrow \bar{\nu}_\mu n \pi^0. \] (2.26)

**Coherent Pion Production.** Neutrinos can also produce a single pion by interacting coherently with the entire nucleus. The nucleus is transferred a negligible amount of energy and produces a single forward-scattered pion. This channel has both CC and NC processes; particularly, the NC neutral pion production is a significant background for the electron elastic scattering analysis because of the forward nature of the \( \pi^0 \) and the photons from its subsequent decay.

**Deep Inelastic Scattering (DIS).** In deep inelastic scattering the neutrino has enough energy that it can probe the constituent quarks inside a nucleon, scattering off of one of them and producing a hadronic shower. This channel would have only a small contribution to the background of the present analysis.
CHAPTER 3

Neutrino Flux

3.1 Neutrino sources

Neutrino experiments can get neutrinos from several different sources. Although neutrinos are the second most common particle in the universe (after the photon which is the particle of light) the majority of these neutrinos will rarely interact with matter, passing through it without leaving a trace, and even if there is an interaction, the lack of information on its incoming direction makes it difficult to infer the kinematics of the neutrino.

The most common source of neutrinos in everyday experience is radioactive decay. Some radioactive isotopes like Potassium emit radiation by emitting electrons (also called beta rays). In the process of beta decay a neutron inside an atomic nucleus decays via the weak interaction $n \rightarrow p e^- \bar{\nu}_e$. The energy of a beta decay neutrino is on the order of MeV. Another common source of neutrinos in nature is cosmic rays. Highly energetic particles that travel through space coming from unknown sources reach Earth and interact with the atmosphere. Because of their high energy, of the order of hundreds of GeV, they produce a cascade of hadrons. Charged pions produced in the interaction decay on their way down to Earth to a muon and a muon
neutrino.

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \]  
\[ (3.1) \]
\[ \pi^- \rightarrow \mu^- \bar{\nu}_\mu. \]  
\[ (3.2) \]

Muons can also decay to produce a muon neutrino, an electron, and an electron antineutrino,

\[ \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \]  
\[ (3.3) \]
\[ \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu. \]  
\[ (3.4) \]

Neutrino experiments need to have a controlled source of neutrinos while also having a way to remove background from external sources. For low-energy neutrinos, nuclear reactors are a common tool. Similarly, nuclear reactions at the core of the Sun produce neutrinos of energy on the order of MeV that can reach the Earth.

Particle accelerators provide a way to reproduce the hadronic showers from cosmic rays in a controlled manner. Neutrino beams are made by colliding high-energy protons coming from an accelerator into a stationary target, producing a hadron shower as a result. Downstream the target are the focusing magnetic horns. The job of the horns is to produce a magnetic field that deflects the particles into the center of the beam. Modern neutrino beams use more than one magnetic horn. Once focused, mesons are given enough distance to decay. The decay length of a 10 GeV pion is about 700 m. Due to the conservation of momentum, the neutrinos that are produced in the decays will be going in the desired direction.

The MINER\(\nu\)A experiment source is the NuMI neutrino beam \[17\]. NuMI is also the source for the NOvA experiment and acts as a secondary source for the MicroBoone experiment. The most relevant components of the NuMI beamline are described in the following sections.
3.2 The NuMI Beamline

3.2.1 Proton Beam

The NuMI beam starts with a proton beam using the Fermilab accelerator complex. The protons start as H⁻ ions that accelerated to 400 MeV kinetic energy in the LINAC. The protons are extracted when the ions pass through a carbon foil and are stripped of their electron, then are subsequently injected into the Booster synchrotron where they are accelerated to 8 GeV kinetic energy. After that, the protons go to the Main Injector. The Main Injector is a synchrotron accelerator of 3.3 km in circumference. Here the protons reach a kinetic energy of 120 GeV (the main injector provided protons for the Tevatron accelerator). Finally, protons are extracted in 6 batches, on a beam spill that lasts approximately 10 µs using the single turn technique. The beam is bent 58 mrad downward towards the cave that houses the MINERνA detector (The original design was to send the neutrinos to the MINOS near detector). A schematic of the beamline is shown in Fig. 3.1.
3.2.2 Target

The target is a graphite rod of 1.2 m long (approximately 2.5 interaction lengths) made of segmented rectangular pieces (called fins) with a density of 1.78 g/cm$^3$. The fins are stacked along the beam direction with a 0.5 mm separation between each fin. The goal of having a long segmented target is to have a target that is several interaction lengths long while allowing the particles produced in the interaction to exit the target medium with a low probability of rescattering.

The target is cooled by a pipe that circulated water. The pipe is attached to the upper and lower edges of the fins. The whole target is enclosed in a helium-filled container.

Budal monitors\footnote{Budal Monitors measure the signal from particles that are kicked off when the proton beam interacts within a fin. They provide a position-dependent signal proportional to the beam intensity \cite{18, 19}.} are placed to check the position of the target. The target is 48 vertical...
fins along with two additional horizontal fins with Budal monitors. Each fin is 24 mm long, 63 mm tall, and 7.4 mm wide.

A 1.5 m long baffle is placed to protect the target and the magnetic horns from any mis-steering in the proton beam and it also helps to monitor the beam. The baffle consists of a 57 mm diameter graphite core with an 11 mm diameter hole, all encased in an aluminum tube and two 0.5 mm thickness beryllium windows. A diagram of the target/baffle system is shown in Fig. 3.2.

The position of the target can be changed to change the mean neutrino energy of the beam. For all the measurements presented in this thesis, the NuMI beam was in the medium-energy (ME) configuration, with a mean neutrino energy of 6 GeV.

### 3.2.3 Magnetic Horns

NuMI uses two parabolic magnetic horns, each 3 m long. Current circulates along the inner conductor and returns through the outer conductor creating a toroidal magnetic field on the inside of the horns. The region inside the horns is filled with Argon gas to reduce corrosion and to remove oxygen and hydrogen from the dissociation of water by ionizing particles. A picture of one of the horns is shown in Fig. 3.3.

A current is pulsed in a half-sine wave with a peak at 200 kA for ME configuration. The pulse has a duration of 2.3 ms which provides a stable magnetic field during the 10 µs spill of the proton beam. To keep the magnetic horns cool, the exterior is continuously sprayed with water. According to Ampere’s law, the field decreases as $1/R$ from the center. The relative distances between horns 1 and 2 and the target are crucial for the focusing process. Horn 2 is located approximately 16 m downstream of horn 1.

The direction of the current on the magnetic horns determines which particles are focused (see Fig. 3.4). In the forward horn current (FHC) configuration positively charged particles are
focused, producing a beam of predominately muon neutrinos. On reverse horn current (RHC) configuration the beam is made of predominately anti muon neutrinos.

### 3.2.4 Decay Pipe and Absorbers

Once the secondary hadrons have been focused by the horns they will encounter the decay pipe which is a steel pipe of 2 m in diameter and 675 m long, surrounded by concrete. Here the secondary hadrons decay into neutrinos, muons, and tertiary hadrons. The interior of the decay pipe is filled with helium to prevent corrosion.

The absorber is essentially a box made of aluminum, steel, and concrete, located just downstream of the decay pipe, whose function is to absorb the residual beam. It is 5.5 wide, 5.6 m tall, and 8.5 m long. At its core, it has a block of aluminum on the upstream side and a core of steel on the downstream side, all surrounded by steel and concrete.
A more detailed description of the components described here and those not relevant to this thesis are described in Ref. [17].

### 3.3 NuMI Simulations

Neutrino fluxes can be predicted by simulation. NuMI is simulated by an implementation of GEANT-4 [21] called *g4numi*. The Monte Carlo simulation starts with the 120 GeV proton beam with a Gaussian transverse profile. The geometry of the beamline components discussed before is considered. The *g4numi* simulation ends when the neutrino is produced. After that, the GENIE neutrino generator [22] is used to simulate the neutrino interactions. The decay points and momenta of the mesons of the *g4numi* simulation are used as input for the neutrino events simulation discussed in Chap. 4.

The challenge with the prediction of neutrino fluxes is that the physics of hadron production is not precisely understood. This leads to producing simulations with imprecise models, from which the uncertainty propagates to the simulated neutrino event rate. This can be alleviated
by hadron production measurements that are incorporated into the simulation prediction.

The sources of uncertainty of the predicted neutrino flux can be organized into two categories: hadron production and focusing.

### 3.3.1 Hadron Production

When the 120 GeV protons interact with the carbon target, the collision typically produces a shower of hadrons: mainly protons, neutrons, pions, and kaons. The kinematics of the particles that make up the hadronic shower need to be well known for a precise prediction of the flux by the simulations. Also, the interactions of the secondary particles with carbon, and the rest of the components of the beam need to be well understood.

The simulation of hadron production relies on models that have been seen to disagree with data at the energy ranges of interest for neutrino production. It is possible to directly measure the produced flux of mesons at the beamline, but this would require measuring the energy and multiplicity of roughly $10^6$ particles / cm$^2$ in each beam pulse, which happens about every 10 µs. These measurements have been done in the past but tend to suffer from poorly constrained backgrounds and from detector uncertainties.

Improvement to the original simulation can be achieved by using external hadron production data. MINER$\nu$A uses results mainly from two hadron production experiments: NA49 and MIPP. The NA49 experiment [23], a hadron production experiment at CERN that studied proton-on-carbon interaction at 158 GeV/c, uses a thin target of a few percentages of an interaction length. MIPP [24] used a spare NuMI target of 2.5 interactions length and 120 GeV/c protons. Two flux predictions were made: a “thin-target” flux mainly using NA49 as the hadron production data, and a “thick-target” flux prediction mainly using MIPP. Both fluxes were compared to a sample of low-energy transfer to the nucleon at MINER$\nu$A, which is predicted to have a very flat cross section against the neutrino energy. It was found that the
thin-target flux agrees with the data better [18, 10]. Furthermore, the thin-target flux is used for all MINERνA analysis and it is the *a priori* flux that is further constrained by the analysis of this thesis. The details of the procedure of incorporating the hadron production measurements and the estimation of their uncertainties are explained in full in [18].

The thin target flux uses the NA49 measurement of the invariant cross section of pion production [25] to compute the yield of charged pions per inelastic interaction

\[
    f_{\text{data}} = \frac{1}{\sigma_{\text{inel}}} E_\pi \frac{d^3\sigma}{dp^3}
\]

where \(E_\pi\) is the energy of the pion, \(\sigma_{\text{inel}}\) is the inelastic cross section for meson and heavy baryon production. A set of weights is produced by comparing the hadron production data to the Monte Carlo prediction,

\[
    w(x_F, p_T, p_0) = \frac{f_{\text{data}}(x_F, p_T, p_0 = 158 \text{ GeV/c})}{f_{\text{MC}}(x_F, p_T, p_0 = 158 \text{ GeV/c})} \times s(x_F, p_T, p)
\]

Here \(p_T\) and \(p\) are the transverse and total momentum of the proton, and \(x_F\) is the Feynman scaling variable

\[
    x_F \equiv \frac{2p_{CM}^\parallel}{E_{CM}},
\]

where \(p_{CM}^\parallel\) and \(E_{CM}\) are the parallel momentum and total energy in the center-of-mass frame. The scale \(s((x_F, p_T, p))\) translates the proton momenta from 158 GeV/c between 12 and 120 GeV/c using FLUKA

\[
    s(x_F, p_T, p) = \frac{\sigma_{\text{FLUKA}}(x_F, p_T, p)}{\sigma_{\text{FLUKA}}(x_F, p_T, p_0 = 158\text{GeV/c})}
\]

The systematic uncertainty of the NA49 measurement is 3.8%, but since a covariance matrix is not reported a conservative 100% bin-to-bin correlation is assumed when propagating the
FIG. 3.5: Hadron production weights from NA49 for the determination of the thin target flux. The markers show the location of the NA49 data. The contours indicate the percentage of $pC \rightarrow \pi^+X$ interactions that lead to $\nu_\mu$ in MINER$\nu$A in the low energy flux. From the inner one to the outer they represent 75%, 50%, 25%, 10%, and 2.5% from the peak value. From [10].

errors. The NA49 weights are applied for $x_F < 0.5$ and data from Barton et al. [26] is used for $0.5 < x_F < 0.88$ and $0.3 < p_T < 0.5$ GeV/c. Several other data sets are used in the thin target flux prediction. The weights obtained from the data/MC ratio are displayed in Fig. 3.5.

Kaon production is constrained by a NA49 measurement of $pC \rightarrow K^\pm X$ for $0 \leq x_F \leq 0.2$, $0.1 \leq p_T \leq 0.9$ [27]. Nucleon production is constrained in $pC$ collisions by using data from NA49 [28]. These data covers $-0.8 \leq x_F \leq 0.95$, $0.05 \leq p_T \leq 1.9$ GeV/c for produced protons. For neutrons, the data are integrated over $p_T$ and cover $0.1 \leq x_F \leq 0.9$.

Neutron-induced pion production on carbon is constrained by the isoscalar nature of $^{12}C$. The isospin symmetry for deuterium establishes that $\sigma(pd \rightarrow \pi^+nd) = \sigma(nd \rightarrow \pi^-pd)$. Then,
it was inferred that $\sigma(pC \rightarrow \pi^{\pm}X) = \sigma(nC \rightarrow \pi^{\pm}X)$.

To extend the NA49 data to target nuclei other than carbon (Helium, Iron and Aluminum) the invariant cross section is scaled by the number of nucleons $A$ as $f(A, x_F, p_T) = \sigma_0 A^\alpha(x_F, p_T)$, with $\alpha = 0.569 \pm 0.0216$ obtained by a fit from Ref. [18] based on data from Ref. [29]. The uncertainties range from 5% to 30% depending on $x_F, p_T$, and the produced meson.

There was no relevant data that cover incident meson interaction on beamline elements nuclei other than Carbon. Different GEANT-4 simulation models were compared with existing hadron production data and it was found that they agree when a 40% fractional uncertainty is assumed. The size of the uncertainty comes from the spread between the different models on GEANT-4. Then, GEANT-4 is used to predict the meson interactions with elements other than Carbon, and a 40% uncertainty is assigned. This same procedure and uncertainty are assigned to interactions that fall outside the kinematic space covered.

The absorption cross sections are also important since the secondary particles have to travel through a significant amount of material while getting out of the target or passing through other components such as the magnetic horns or the decay pipe. A correction is applied to the absorption cross section which is defined as $\sigma_{abs} = \sigma_{total} - \sigma_{elastic}$. The probability that a particle will survive after traversing a distance $r$ in a material with nuclear density $\rho$ is $P(r) = \exp(-rN_A\rho\sigma_{abs})$. The ratio of the probabilities is calculated for each relevant nucleus for both the data and the simulation and the ratio is applied as a weight.

### 3.3.2 Focusing uncertainties

The neutrino flux is very sensitive to the geometrical details of the beamline. The relevant sources of uncertainty due to the geometry are the following: The relative position of the target and the magnetic horns. In particular, the position of the upstream horn has the greatest effect on the uncertainty of the neutrino flux. X (left-right) and Y (vertical) positions of the target
and horn are known up to ± 1 mm. The magnetic field is determined by the horn current (for medium energy it is 200 ± 1 kA ) and by the Inner conductor shape which is modeled using GEANT-4. Additionally, there is a residual water layer from the cooling system that can absorb some of the particles that go through the horns. The water layer is measured to be 1 ± 0.5 mm thick.

The radial profile of the beam has non-gaussian tails that can hit the baffle which protects the horns from mis-steered protons. By temperature measurements, the beam deposits 0.25% of its power on the baffle. Additionally, there is a flat 2% uncertainty coming from the total number of protons that hit the target. The beam spot position and the beam spot size also affect the flux uncertainty.

Although tolerances for the relevant parameters are well understood, it is not feasible to do regular measurements due to the high levels of radiation in the target hall. Studies on the possible effects of mismodeling the focusing parameters have been made by the MINERνA
collaboration. The shape of the flux can be constrained by using a sample of events with low hadronic recoil (low-\(\nu\) method), where the cross section is approximately flat with neutrino energy. A fit was done where the focusing parameters were varied around their nominal values. The goal was to find a culprit for the data-Monte Carlo discrepancy on inclusive analyses at the time. It was found by the fit that the focusing parameters are consistent with their 1 \(\sigma\) uncertainties and the disagreement seen was instead attributed to a mismodeling of the muon energy scale at the MINOS near detector. The effects of shifting the focusing parameters from their nominal value by 1 standard deviation are shown in Fig. 3.6.

3.3.3 Multi-Universe Methods

There are many sources of uncertainty that need to be propagated to the neutrino flux. The way this is accomplished is by the multiple universes or multiple simulation methods. For example, let’s imagine a toy model with one parameter where the uncertainty of this parameter is known. A set of alternative simulations can be produced by randomly shifting the parameter’s value around its nominal value within its standard deviation. The shifted parameter can be expressed as \(\mu_i = \mu + \sigma r_i\) where \(\mu\) is the central value of the parameter, \(\sigma\) is its uncertainty, and \(r_i\) is randomly distributed around zero with unit standard deviation. For each variation of the parameter, the toy model would have a different prediction for a quantity \(f\) that depends on the parameter. For example, the function \(f\) can be the rate of neutrinos as a function of neutrino energy, and the parameter being shifted can be the z-position of the target. The value of \(f(\mu_i)\) is called a “universe” of the quantity \(f\). When calculating a prediction based on the toy model, it is calculated using its central value prediction and also all the other universes. The error in the prediction of \(f\) due to the uncertainty of the parameter with central value \(\mu\)
is given by the standard deviation of the universe predictions for that bin:

$$\sigma(f) = \sqrt{\frac{1}{N} \sum_{i}^{N} (f(\mu) - f(\mu_i))^2},$$  \hspace{1cm} (3.9)

where the sum is over $N$ universes. In a similar way, the covariance matrix can be calculated as

$$\text{cov}(f_j, f_k) = \frac{1}{N} \sum_{i}^{N} [(f_j(\mu) - f_j(\mu_i))(f_k(\mu) - f_k(\mu_i))].$$ \hspace{1cm} (3.10)

where the subindices $j$ and $k$ label the bins of the histogram.

For a realistic model with several parameters, the correlation between the bins is also important. The set of shifted parameters can be expressed in vector form

$$\vec{x} = \vec{\mu} + \vec{R} \vec{L}$$ \hspace{1cm} (3.11)

where $\vec{\mu}$ is the vector with the nominal values, $\vec{R}$ is a vector of random Gaussian numbers with mean zero and unit standard deviation, and $\vec{L}$ is the Cholesky decomposition of the covariance matrix.\footnote{For a matrix $M$, a triangular matrix $L$ such that $M = L \cdot L^T$.} Along with the flux simulation, a set of 1000 flux universes are created by randomly sampling all the uncertain parameters (most of them coming from hadron production data points) within their uncertainties while considering the correlations between them. The ratio of a given universe prediction and the nominal flux is taken to get a weight. Predicted events that use the model are weighted using these weights. These weights can be stored with the events and carried through the analysis.

The simulated neutrino flux and its universes are one of the inputs for the constraint procedure that is the deliverable of this thesis. The procedure is explained in Chap. \hspace{1cm} 4.

The multi-universe method is also used to estimate the uncertainty coming from the interaction models and detector response of the MINER$\nu$A detector. In those cases, there are
usually only two universes where the shift is by ± one standard deviation of the parameter, not a random distribution around it. The MINERνA simulation is described in Sec. 4.3.

3.4 NuMI Fluxes

A neutrino beam is made of predominately muon neutrinos or muon antineutrinos depending on the direction of the current in the magnetic horns. There are also electron neutrinos in the beam coming mainly from muon and $K_L^0$ decays. The wrong sign component comes from muon decay and from the mesons that are produced in the forward direction of the target which do not pass through the magnetic field.

The fluxes for the medium energy FHC NuMI beam at MINERνA are shown in Fig. 3.7. The fluxes for medium energy RHC NuMI beam at MINERνA are in Fig. 3.8. These fluxes are the a priori fluxes that are input for the analysis of this thesis.
FIG. 3.7: Simulation of medium-energy FHC fluxes at MINERνA. Figure from [31].
FIG. 3.8: Simulation of medium-energy RHC fluxes at MINER\(\nu\)A.
CHAPTER 4

MINER$\nu$A Detector

The MINER$\nu$A detector (Main INjector ExpeRiment $\nu$-A) is a fixed target neutrino experiment with the main goal of measuring the cross section of neutrinos with several atomic nuclei [32]. It is located at Fermi National Laboratory in Batavia, IL. It sits on the axis of the NuMI neutrino beam on a cavern 100 meters underground. It is capable of three-dimensional reconstruction of particle scattering in the few GeV range. The presence of passive material embedded in the active plastic scintillator tracker allows measurements of the cross sections of different atomic nuclei. The components of the detector are described in the following section. Figure 4.1 provides a schematic of the detector.

4.1 Scintillator Modules

The detector consists of a plastic scintillator tracker, built of triangular scintillator strips. A wavelength-shifting optical fiber runs through the middle of each strip and collects the scintillation light produced by a passing ionizing particle. The collected light is guided to photomultiplier tubes (PMTs) that convert the light into an electrical signal that can be read
and recorded. The amount of light produced directly correlates to the amount of energy ionizing particles deposit in the detector.

The strips are arranged to form hexagonal planes made out of 127 strips; each plane is 1.7 cm thick. The planes are stacked along the beam direction (defined as the z-direction) in three different orientations. The first of these three orientations is one that is aligned to the vertical (defining the y-direction); this way, the position of a lighted-up strip yields the position of the passing particle in the x-direction. To remove degeneracy in the reconstruction, the other two orientations used are at ±60° angle with respect to the vertical. The orientations are labeled as X (0°), U (+60°), and V (-60°).

The detector is organized into modules, each containing two planes. A tracker module can be in a XU or a XV configuration. A 2 mm-thick lead collar covers the outer 15 cm of each scintillator plane, acting as an electromagnetic calorimeter at the sides of the detector. The tracking modules are the basic component of the detector since they act as the active detection component. The rest of the detector components are described in the following sections, starting from the most upstream relative to the beam.
4.2 Components of the Detector

4.2.1 Veto Wall

The veto wall is a structure made of alternating steel and scintillator planes that sits between the beam and the detector. Its purpose is to identify muons produced in the rock that is in between the neutrino beam and the detector and tag them. That way, it is avoided to mistake a rock muon track for a track coming from an interaction that occurred inside the detector.

4.2.2 Nuclear Targets

Embedded between scintillator modules there are modules with passive material used as targets for the incoming neutrino beam to interact with. The nuclear targets consist of five regions containing liquid helium, carbon, lead, iron, and water (see Fig. 4.2). Interactions with a reconstructed vertex in the nuclear targets are not used in this analysis.

4.2.3 Tracker

The main tracker region of the detector consists of 54 scintillator modules which act as both trackers for charged particles with a vertex in the nuclear targets and as a hydrocarbon target. The main tracker amounts to 8.3 tons.

4.2.4 Electromagnetic Calorimeter

The electromagnetic calorimetry is achieved by a system of 2 mm thick lead planes interleaved with scintillator planes. The 10 modules downstream of the tracker have lead planes that cover the full span of the inner detector, acting as containment for forward electromagnetic showers. Additionally, the outermost 15 cm of each plane in the tracker has a lead collar that
FIG. 4.2: Side view of the nuclear targets region. In this view, the beam comes from the right and the main tracker (not shown) is on the right.

acts as containment for electromagnetic showers on the sides of the detector. The ECAL is represented in yellow in Fig. 4.1.

4.2.5 Hadronic Calorimeter

The hadronic calorimeter (HCAL) consists of the last 20 modules of the detector each with 25 mm thick steel plates between planes. This provides containment for hadronic showers reaching the back of the detector. The hadronic calorimeter on the outer detector is achieved by a solid steel frame that surrounds all models. The frame is instrumented with four scintillator strips interleaved with steel on each side of the hexagon. The HCAL is shown in blue in Fig. 4.1.
4.2.6 MINOS Near Detector

The MINER$\nu$A detector is installed two meters upstream of the MINOS experiment near detector. The near detector is used as a muon magnetic spectrometer for muons that exit the back of the MINER$\nu$A detector. MINOS is not used in this analysis since any event containing a muon would be a background, and thus it is not necessary to reconstruct the muon’s momentum.

4.2.7 Optical system

The signal chain in the MINER$\nu$A detector is as follows. A charged particle passes through the doped plastic scintillator which by the ionization from the particle emits ultraviolet light. This light is collected by an optic fiber at the center of each scintillator strip (see Fig. 4.3). The optic fiber directs the light to a photomultiplier tube that collects the light. The signal of the photomultiplier tube is read by electronics that are mounted on the detector. The light signal for a single scintillator strip is called a “hit.”
4.2.8 Scintillator

The plastic scintillator strips are made of polystyrene pellets (Dow Styron 663 W) doped with 1% (by weight) 2,5-diphenyloxazole (PPO) and 0.03% (by weight) 1,4-bis(5-phenyloxazol-2-yl)benzene (POPOP). This scintillator composition was previously tested and used by the MINOS experiment scintillator strips. PPO acts as the primary scintillator, absorbing the energy of an ionizing particle and emitting ultraviolet light with a wavelength of 357 nm. POPOP absorbs the ultraviolet light and re-emits it as violet light with a wavelength of 410 nm.

The ID strips have a triangular cross section with a height of 17 ± 0.5 mm and a width of 33 ± 0.5 mm. Each strip has a hole in the middle of 2.6 ± 0.5 mm diameter centered at 8.5 ± 0.25 mm above the base of the triangle. The ends of the strips are coated with titanium dioxide white paint (TiO$_2$) for optical isolation. The light emitted by the strip is collected by a 175 ppm $^{11}$Y doped, $^{35}$S, wavelength shifting (WLS) optical fiber of 1.2 mm diameter, produced by the Kuraray corporation. One of the ends of the optic fiber is mirrored to maximize light collection. The other end of the fibers goes into optical connectors that connect to cables that contain clear optical fibers.

4.2.9 Photomultiplier Tube

The light coming from the optical fibers is routed to the multi-anode photomultiplier tube, model number H8804MOD-2. The PMT has an array of 8 × 8 pixels on a 2 cm × 2 cm grid, that is 64 pixels per PMT with each pixel having a size of 2 × 2 mm$^2$. The PMTs are housed in a light-tight, cylindrical case made of 2.36 mm thick steel. The case provides mechanical protection and shielding from the magnetic field from MINOS. A total of 507 PMTs are used in the instrumentation of the detector. The light signal from physically adjacent strips is woven so is not read by adjacent PMT pixels. This is to avoid cross-talk of the signal between neighboring pixels.
4.2.10 Readout Electronics

The analog signal from the PMTs is fed into the front-end board electronics that record the signal over a 16 µs gate. The timing is not based on a trigger from hits on the detector, but rather on synchronization with of the NuMI beam timing signal. The NuMI beam spills the last 10 µs each, and the extra 6 µs allow for the detection of delayed activity, such as electrons coming from muon decays (Michel electrons).

4.3 MINERνA Simulation

Neutrino events on MINERνA are simulated by the GENIE event generator. GENIE uses a random number generator to simulate events on MINERνA based on the expected neutrino energy spectrum. A description of the detector geometry based on GEANT4 tells GENIE what materials are where in the detector. GENIE produces neutrino events based on the probability of different processes that can occur. The uncertainties in the simulation originating from the models in GENIE are estimated using the multiple universe method (as for the flux in Sec. 3.3.3). For the case of GENIE, the underlying uncertain parameters are not correlated the way those for the neutrino flux are. Thus instead of sampling randomly, only two universes are used which there are calculated by shifting the parameters by +1 and -1 standard deviation from their central value. The spread in the predictions is used to evaluate the uncertainties in the predicted distributions. Additions and modifications to the GENIE models are described later in this section.

To model the initial momentum of a stuck nucleon, GENIE uses the Relativistic Fermi Gas model [33] (RFG) with a Fermi momentum of \( k_F = 0.221 \) GeV/c. The RFG model is improved by adding a high momentum tail that incorporates short-range nucleon-nucleon correlations [34].
As discussed in Chap. 2 at the energy range of a few GeV where neutrino experiments are, there are three main channels of interaction, each is simulated independently in GENIE and are described as follows:

**Quasi-elastic interactions:** The model follows the Llewellyn-Smith prescription \[35\]. This parameterizes the cross section as a function of \(Q^2\). The form factor follows the BBBA05 model \[36\].

**Resonance interactions:** Resonance interactions are modeled by the Rein-Sehgal model \[37\] with an axial mass of \(M_A^{\text{RES}} = 1.12\) GeV/c\(^2\).

**Deep inelastic scattering:** follows the Bodek-Yang model \[38\], the hadronic showers are modeled with AGKY model \[39\].

More nuclear effects appear as final state interactions (FSI). These effects occur due to the products of the interaction having to travel through the nucleus environment, leading to changes in the kinematics of the interaction product by modifying the kinematics expected from a nucleon on a small nucleus or even by completely absorbing a meson. The re-scattering inside the nucleus is simulated with the GENIE INTRANUK\(E-hA\) hadron cascade package.

MINER\(\nu\)A makes several modifications to the GENIE predictions to better describe the data. Multi-nucleon scattering (also referred to as “two particles, two holes” or 2p2h for short) is simulated using the Valencia model \[40\]. The cross section of 2p2h events is increased in specific regions of energy and three momentum transfer \[41\]. The increase in the integrated phase space of 2p2h events is about 50% of the nominal prediction. The effects of screening the weak charge of a nucleon by the nuclear environment are modeled by a random phase approximation (RPA) \[42, 43\], this effectively suppresses quasi-elastic events at low four-momentum transfer. Other MINER\(\nu\)A analyses make further modifications to the interaction models, but only those relevant to the type of events that end up in the selection of this analysis are used here to simplify the analysis flow.

The neutrino-electron elastic scattering in GENIE is the leading-order cross section. For
this analysis, a modification is made to take into account radiative corrections to the electron elastic cross section. Several calculations of the radiative correction to the cross section exist. Particularly, the calculation from [15] includes the effect of producing a real photon on the final state, which is particularly relevant to experimental measurements due to the fact that electrons are observed in the detector as electromagnetic showers. The results from the radiative correction from [15] are compared to the cross section in GENIE. The ratio between the GENIE cross section and the radiative correction prediction is applied as a weight to the simulated electron elastic scattering events as a function of true neutrino energy. The ratio between the updated cross section and the GENIE cross section is shown in Fig. 4.4.

Once the simulation of the neutrino interaction is generated GEANT-4 is used to propagate the final state particles through the detector. GEANT-4 has a detailed model of the detector geometry and simulates energy loss, production and decay of new particles, as well as the ionization of the passage of these particles through the detector materials. In this way, the effect of the passage of the particles through the detector, the generation and propagation of optical photons, and the electronics response are simulated. Once the neutrino interactions are simulated they are randomly overlaid with actual data to simulate accidental activity not coming from neutrino interactions in the detector. At the end of the simulation chain, the simulation produces a collection of hits that looks the same way as the actual data does.

The number of events simulated corresponds to four times the actual beam exposure that the detector received. Additionally, special samples are simulated. For this analysis, a special sample is made of only neutrino-electron scattering events corresponding to an exposure of $2.5 \times 10^{23}$ proton on target, 300 times the actual exposure. Also, a sample is made of diffractive neutral current $\pi^0$ production events off hydrogen based on the model from [44], with a simulated exposure of $9.5 \times 10^{21}$. This process is a background to the presented analysis but ends up not being a significant one.
FIG. 4.4: Ratio between the cross section predicted by the calculation in [15] and GENIE neutrino-electron elastic scattering cross sections is used as a correction on the simulation as a function of the true neutrino energy.
CHAPTER 5

Reconstruction And Signal Definition

5.1 Reconstruction

A physics event in MINERνA consists of an incoming neutrino that interacts with one of the subatomic particles that make up the detector. The neutrino itself doesn’t leave a track on the scintillator due to its lack of electric charge. What we observe are the tracks left by charged particles that are scattered and produced by the incoming neutrino. By measuring the amount of light that a charged particle produces on a scintillator strip it is possible to calculate how much energy the particle deposited in it. By using contiguous hits, one can reconstruct the path of charged particles.

For this analysis, the process of interest is the scattering of neutrinos off electrons, where the final state is a single electron track. The main goal is to measure the scattering electron total energy $E_e$ and its scattering angle $\theta$. 
5.1.1 Time Slicing

The NuMI beamline provides the MINERνA detector with a beam spill of 10 μsec in duration. A typical neutrino interaction spans a couple of hundreds of nanoseconds. All hits are stored during a spill. To separate the multiple independent interactions that occurred in a single spill an algorithm is used to create “time slices”. The algorithm looks for a peak in the amount of light in the detector, if it exceeds the 10 photo-electrons threshold within an 80 ns window a time slice is created. The time window is extended forward until the criteria of 10 photo-electrons is no longer met. The algorithm continues to scan until the criteria are met again and a new time slice is created. A single beam spill can contain around a dozen of time slices. An example of a set of time slices from a single beam spill is shown in Fig. 5.1.

5.1.2 Clustering

After the hits are grouped in time, the next step is to use their spacial information to create “clusters”. A cluster is a group of adjacent strips belonging to a single plane that contains activity. Once grouped, time is assigned to the cluster by the time stamp of the highest energy hit on it, and its position is determined as the energy-weighted average position of the hits.

Clusters are organized into the following categories:

- Low energy: Clusters with total energy less than 1 MeV
- Trackable: Clusters with total energy between 1-12 MeV, with four or fewer hits and at
least one hit with more than 0.5 MeV. Typically from minimum ionizing particles, such as muons.

- **Heavily ionizing**: Total energy over 1 MeV and one to three hits with energy greater than 0.5 MeV that are required to be adjacent to each other.

- **Supercluster**: Total energy higher than 1 MeV and 5 hits or more.

- **Cross-talk**: If hits within a cluster are coming from a PMT pixel that is right next to a pixel associated with a particle interaction, the cluster is most likely coming from optical leakage rather than an actual particle interaction, and the cluster is categorized as cross-talk.

### 5.1.3 Tracks

The next step is to use clusters to form tracks. Three trackable or heavily ionizing clusters that are found in consecutive planes are grouped to form track “seeds”. These seeds are required to be on consecutive planes of the same orientation (X, U, or V) and fit into a straight two-dimensional line.

Seeds that share orientation and fit into a straight line are combined to make track candidates if they share a common cluster and do not include more than one cluster in the same plane. Then, track candidates are combined following similar rules to seeds. Track candidates are not required to share clusters, which allows tracks to have gaps.

Finally, to create 3-dimensional tracks, candidates are combined with one of two methods: By merging candidates from the three different orientations or by merging candidates from pairs of plane orientations (XU, XV, or UV).

Once tracks are formed they are fitted by a Kalman filter routine. The fit is required to converge but does place a maximum requirement on the $\chi^2$/dof. The fit is later used to add any additional unused clusters to the track by searching adjacent planes from which the track
does not contain a cluster, allowing the use of superclusters allows the track to be projected in regions of high activity like hadronic showers from a DIS event.

If a track is found that has 25 clusters or more, it is designated as an anchor track, and its starting point is used to set the primary vertex of the interaction.

### 5.2 Electromagnetic Shower Reconstruction

A neutrino-electron elastic scattering analysis has been done by the collaboration in the past. The first time, it was done for the low-energy run of the NuMI beam with an energy peak of around 3 GeV. The reconstruction algorithm for the electromagnetic showers and the signal selection was originally designed at that time [45]. The low-energy analysis had an exposure of $3.43 \times 10^{20}$ protons on target. Using both FHC and RHC a sample of 135 events was used to constrain the fractional uncertainty of the integrated flux between 2 and 10 GeV from 9% to 6% [46]. This was also the first time that the flux was constrained using the Bayesian probability procedure followed in Chap. 7.

Later, a medium-energy version of the analysis was performed using the FHC beam polarity. The medium-energy beam with an energy peak at 6 GeV yielded a greater number of events due to higher intensity and a larger cross section. The medium-energy FHC analysis found 810 events for a beam exposure of $1.16 \times 10^{21}$ proton on target and reduced the fractional uncertainty of the integrated flux from 2 to 20 GeV from 7.6% to 3.9% [31]. The FHC medium-energy analysis used a different background constraint procedure than did the low-energy analysis.

The analysis presented in this thesis is based on the two previous analyses, this time using data from the medium-energy RHC NuMI flux. The reconstruction and selection mostly follow the low-energy analysis, except for small details. The background constraint is based on the ME FHC analysis but with a smaller number of fit parameters and a small change in the
distributions that are fitted in the background constraint procedure (more in Chp. 6).

This analysis uses data taken on the medium-energy RHC configuration of the NuMI beam between June 2016 and February 2019 making up the complete RHC beam data set from MINERνA, corresponding to a total exposure of $1.12 \times 10^{21}$ protons on target. The novelty of this analysis, besides the new data, is using the new measurement in combination with the medium-energy FHC result which results in a stronger constraint of the flux for both FHC and RHC operation modes. Additionally, a measurement of inverse muon decay is also added to the combined constraint.

5.2.1 Shower Cone and Calorimetry

Electrons propagating through the scintillator leave a special kind of track called an electromagnetic shower (EM shower). When a high-energy electron propagates through a dense material it generates photons by the process of bremsstrahlung. Photons in a dense material then can pair produce an electron-position pair, which can have enough energy to themselves produce photons that then can continue this process chain until the energy of the particles created falls below the energy threshold which stops the cascade. This process produces a track that is narrow but widens as it develops. It is important to note that an EM shower can also begin with a high-energy photon instead of an electron. The way that the photon background is removed is described in Section 5.4. The radiation length of an electron in the scintillator is about 42 cm, which corresponds to 25 scintillation planes for an electron traveling perpendicular to the planes.

To reconstruct the energy of an EM shower, a cone of fixed opening angle is fit to the track using its reconstructed vertex and the direction of the track. The cone has an opening angle of $10^\circ$ with respect to the track direction, the cone offset is 50 mm and the opening width is 80 mm; an illustration is shown in Fig. 5.2. If there is no reconstructed vertex, the
The algorithm will group clusters, starting from the most upstream one, to form the track. Once a cone has been fitted to the track, all hits in each view are added together to estimate the energy of the EM shower. All the events are selected to start in the main tracker section of the detector, and most of them will go into the ECAL and a few will go all the way into the HCAL. Since each section has different calorimetric responses, the energy deposition in each one is calibrated individually and the total reconstructed energy of the shower is

\[ E_{\text{Reco}} = \alpha (E_{\text{tracker}} + k_e E_{\text{ECAL}} + k_h E_{\text{HCAL}}), \]  

(5.1)

where \( E_{\text{Reco}} \) is the total visible energy of the event, \( E_{\text{tracker}} \) and \( E_{\text{ECAL}} \) is the energy deposited in the tracker, ECAL and HCAL sections respectively. The calibration constants \( k_e \) and \( k_h \) are calculated using a particle cannon simulation [45] and are displayed in Table 5.1. The calibration constants obtained were also corroborated by test beam data and a sample of Michel electrons from muon decays in the detector [32, 47]. The overall calibration constant \( \alpha \) is estimated using a special MC sample of only \( \nu + e \) elastic scatterings. The constant is estimated by comparing the reconstructed energy as in Eq 5.1 with \( \alpha = 1 \) against the true energy of the simulated event, so then \( \alpha = E_{\text{True}} / E_{\text{Reco}} \). This compensates for energy loss in non-tracking material. For this calculation, reconstruction cuts are applied to the events, which include selecting events with energy above 0.8 GeV. At lower energy, the relation of the
true and reconstructed electron energy is no longer linear. The histogram of the ratio between the true electron energy divided by the reconstructed is fit to a Gaussian function. The mean of the Gaussian is taken as $\alpha$. The result from the procedure is shown in Fig. 5.3.

5.2.2 Angle Correction

The neutrino beam from NuMI is designed with long baseline experiments in mind, so it is aimed downward such that the beam reaches the far detectors located in Minnesota. The
TABLE 5.1: Calorimetric constants.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>1.320</td>
</tr>
<tr>
<td>$k_E$</td>
<td>2.341</td>
</tr>
<tr>
<td>$k_H$</td>
<td>9.540</td>
</tr>
</tbody>
</table>

FIG. 5.4: Average beam angle deviation in the x- and y-axis for different values of neutrino recoil energy for data and simulation. Figure from [48].

The angle between the beam and the detector z-axis is 58.87 mrad.

The angle between the beam and the detector’s z-axis can be corroborated by using a sample of inclusive charged-current muon neutrino events. The events are divided into samples of neutrino recoil energy $\nu = E_\nu - E_\mu$ in bins 100 MeV wide. For each bin of $\nu$, the mean deviation from the nominal angle is calculated by a Gaussian fit for both data and simulation. The results are shown in Fig. 5.4. The difference between the average deviation from data and simulation is -1.32 mrad for the x-axis and -0.77 mrad for the y-axis. This shift is applied to the data before going through the event selection.

5.3 Background Rejection

A selection is made using several properties of the tracks to reject events that come from a different channel other than neutrino-electron elastic scattering. Some of the selection cuts
that are used to isolate this channel were designed for the low-energy analysis \cite{45}, where the
statistics were very limited and it was necessary to make a lot of very specific cuts to remove
very specific kinds of events. These analysis cuts survive to the medium-energy versions of the
analysis, but their effect on the overall selection is minor. The cuts that have the most impact
on the selection are described in this section, while the minor cuts are described in Appx. A.
This distinction is made for the sake of making this section more readable.

The Monte Carlo simulation is grouped into different categories of signal and background.
The signal groups are:

- $\nu_\mu e$: Neutrino-electron elastic scattering from $\nu_\mu$.
- $\nu_e e$: Neutrino-electron elastic scattering from $\nu_e$.

The backgrounds are:

- $\nu_e$ CCQE: Charged-current quasi-elastic events from $\nu_e$.
- 2p2h: Charged-current 2p2h interaction from $\nu_e$.
- $\nu_e$ other: Remaining $\nu_e$ interactions not included in the other categories. Includes both NC
  and CC, resonant and DIS interactions.
- $\nu_\mu$ CC: Charged-current interaction from $\nu_\mu$. This category is populated by stopping muon
  tracks, and also by resonant and DIS events where the muon rejection cuts failed.
- $\nu_\mu$ Other: Neutral-current interaction from $\nu_\mu$ excluding the signal and coherent pion pro-
  duction. Populated by resonance pion production.
- NC Coherent: Coherent $\pi^0$ production from $\nu_\mu$.
- DRF: Diffractive $\pi^0$ production on hydrogen.
5.3.1 Reconstruction Quality Cuts

Fiducial Volume Cut

Events are required to have their interaction vertex inside the fiducial volume. The fiducial volume is defined for this analysis to be the hexagon of apothem $188.125 \text{ cm}$ centered on the detector. The outer boundary of the fiducial volume is 4 cm away from the inner boundary of the side ECAL. The first two modules downstream of the nuclear targets are excluded so as to remove interactions that originate in the nuclear targets. The four most downstream modules of the tracker are excluded so as to have the track travel at least four modules on the tracker; this improves the angular resolution.

\footnote{The apothem of a regular polygon is the line segment from the center to the middle of the sides, akin to the radius of a circle.}
Minimum Energy Cut

The reconstructed energy of the electron candidate is required to be greater than 0.8 GeV; at lower energies, there is a significant amount of background coming from $\pi^0$ decaying to photons. Event reconstruction also becomes difficult at low energies since the electron might not have enough energy for bremsstrahlung and therefore does not create an EM shower in the detector.

Shower End Position

Events that reach the back of the detector have to travel through the whole ECAL and HCAL. If a track reaches the back or sides of the detector are almost always background events containing a muon. The end position of a track is used to discriminate this type of background.

A track end position is defined with the most downstream hits in a triplet of planes, one in each view, that do not extend longer than five modules. Defined in this way, the track end is required to be between module 70 in the tracker, and module 112, near the upstream end of the HCAL. To remove tracks that end on the sides of the detector, events are required to be inside of a hexagon with an apothem of 100 cm. In contrast, the detector apothem is 107 cm.

Neighbourhood Energy Cut

Sometimes an event can have a very forward EM shower and a separate track also coming from the same vertex. While the cone algorithm would capture the hits coming from the EM shower, some of the hits from the secondary track can be outside the cone. To reject these types of events, a “neighborhood” energy cut is applied, where the neighborhood is defined to be the region within 5 cm from the outer boundary of the shower cone.

Since high-energy electrons can produce a wide shower that can sometimes be slightly wider than the cone, the cut is loosened for energy above 7 GeV. The selected region is shown
FIG. 5.6: Neighborhood energy cut. The selected region is below the red line. Figure from [45].

in Fig. 5.6. The selection requires

$$\text{Neighborhood energy} \begin{cases} < 120 \text{ MeV} & \text{if } E_{\text{reco}} < 7 \text{ GeV} \\ < 7.8 E_{\text{reco}} + 65.2 & \text{if } E_{\text{reco}} > 7 \text{ GeV} \end{cases}$$  \quad (5.2)

Maximum Transverse Energy Spread

Once the track is formed from a shower cone, one can estimate how wide the track gets as it propagates. One way to estimate this is the energy-weighted mean residual distance of clusters from the shower axis, that is

$$R = \left[ \frac{1}{E_e} \sum_i (\Delta t_i)^2 e_i \right]^{1/2},$$  \quad (5.3)
where \( e_i \) is the energy of the \( i \)-th cluster in a given view, \( \Delta t_i \) is its distance to the shower’s axis, and \( E_e = \sum e_i \). The sums are done over individual views, so for a given event there are three \( R \), but only the largest of the three is used to discriminate the event. Overlapping tracks, especially an EM shower track that also has a hadron track coming from the vertex would have a larger \( R \) in a particular view. This quantity is required to be less than 65 mm so as to reject events with two or more overlapping tracks in the shower cone.

**Shower Transverse RMS at First 1/3 of Shower**

Another useful quantity is a similar energy-weighted RMS but instead of using only a single view over the whole track, one can use only the beginning of the shower, averaging over the three views. Since an electron typically travels through the detector as a single particle through several modules before it starts to shower, there is not a very significant transverse spread on the deposited energy compared to the rest of the shower. But background events with multiple particles near the vertex would have a more significant transverse energy spread. The transverse residual energy in the first third of the shower in the tracker region is required to be less than 20 mm.

**ECAL-HCAL Visible Energy Asymmetry**

In the case that an EM shower reaches the HCAL from an event originating in the tracker, it has to go through the whole ECAL. While an EM shower would be stopped at the ECAL, a muon or other minimum-ionizing particle can pass through the ECAL and reach the HCAL. For an EM shower, a greater fraction of the energy would be deposited in the ECAL compared to the HCAL. To remove tracks that go into the HCAL but do not reach the back end of the detector it is required that 80% of the total energy in the ECAL and the HCAL is seen in the ECAL.
Upstream Interaction Veto

A neutrino interaction that happens upstream of the fiducial volume can produce a background event if the vertex is misreconstructed. As an example, a neutral current interaction in the nuclear targets creates a $\pi^0$, which later decays into two photons that can travel about one radiation length without making a track and which can later produce an EM shower in the fiducial volume. It is possible to look for energy upstream from a track candidate in order to look for hits that can tag this event, in the case of a misreconstructed vertex. A cylinder of radius 30 cm is extrapolated upstream, where the axis is the reconstructed track axis. If there is localized activity that overlaps in all three views within the cylinder, the event is rejected if the upstream energy is greater than 300 MeV.

5.4 Photon Rejection: $dE/dx$ Cut

An important background for the analysis is electromagnetic showers produced by high-energy photons. These photons come from the decay of neutral pions that come from resonant, coherent and DIS interactions. Several cuts are applied to reject these events.

There are cases where the $\pi^0$ decay photons can look like a single EM shower, either by one of the photons having very little energy, leading to not being observed or if the $\pi^0$ was highly relativistic and the decay photons are produced with a small opening angle, producing two overlapping showers that cannot be distinguished from a single shower by previous methods.

However, it is still possible to separate electron and photon showers using the deposited energy per unit of length ($dE/dx$) of the start of a track. Since a photon starts an EM shower by $e^+e^-$ pair production, the start of a photon shower would have about two times the deposited energy than would a shower started by an electron. This difference is only valid near the start of a shower because the shower would develop stochastically as it propagates, thus
making the selection less reliable.

The average $dE/dx$ in the first four scintillator planes at the start of the EM shower is found to be a good discriminant. This is defined as

$$\langle \frac{dE}{dx} \rangle_4 = \frac{1}{4} \sum_{i=1}^{4} dE_i \cos \theta$$

(5.4)

where $dE_i$ is the energy deposited in the $i$th plane and $\theta$ is the angle of the track in the detector coordinates. The average $dE/dx$ on the first four planes of a track is required to be less than 4.5 MeV/1.7cm, \footnote{A MINER$\nu$A plane is 1.7 cm thick.} consistent with a single minimum ionizing particle. Events with higher $dE/dx$ are used for constraining the background as is explained in Chap. 6. The distributions of $dE/dx$ on the first four planes for data and simulation are shown in Fig. 5.7.

### 5.5 $\nu_e$ Event Rejection: $E_e \theta^2$

The predominant background channel in the analysis is charged-current quasi-elastic events of $\bar{\nu}_e$ or $\nu_e$ neutrinos that have an energetic positron or electron in the final state. These events have a cross section three orders of magnitude larger than the neutrino-electron elastic scattering events. The topology of these events is an electron-like EM shower and nucleon that often deposits little energy on the detector. although a subset of these events ends up being an irreducible background, the bulk of the events can be rejected by an angular cut.

The final state electrons coming from the neutrino-electron elastic scattering are kinematically constrained to have a very small scattering angle. The constraint can be expressed as

$$E_e \theta^2 < 2m_e$$

(5.5)

where $E_e$ is the energy of the final state electron and $\theta$ is its scattering angle with respect to
FIG. 5.7: Distribution of $dE/dx$ of events that pass all other cuts for data and simulation, bin width normalized. The error bars in the data points are statistical only. Simulation is normalized to data exposure. The simulation by category and stacked. The legend shows the total number of events per category.
the incoming neutrino beam. The MC simulations show that the CCQE background is mostly flat in this quantity, while the elastic scattering events peak near zero. The event selection requires that events to satisfy $E_e\theta^2 < 0.0032 \text{ GeV radian}^2$. Notice how this is much higher than $2m_e \approx 0.001 \text{ GeV}$. This is to take into account the smearing due to the angular resolution of the reconstruction. The distributions of $E\theta^2$ from data and simulation are shown in Fig. 5.8.

**Quasi-Elastic $Q^2$ Cut**

Some high-energy CCQE events will still pass the angular cut. In order to reduce the amount of those events in the final selection a cut is applied to the four-momentum transfer $Q^2$ reconstructed under the assumption that the event was a CCQE event. Under that assumption the neutrino energy $E_\nu$ and the four-momentum transfer are

$$E_\nu = \frac{m_p E_e - m_e^2/2}{m_p - E_e + p_e \cos \theta} \quad (5.6)$$

$$Q^2 = 2m_p (E_\nu - E_e) \quad (5.7)$$

where $m_p$ is the proton mass and $m_e$, $E_e$ and $p_e$ are the electron’s mass, energy and momentum. To reject high-energy electrons coming from the CCQE channel it is required that the events satisfy $Q^2 < 0.02 \text{ GeV}^2$.

**5.5.1 Electron candidate sample**

The result is a sample of mostly neutrino electron elastic scattering events for the RHC medium-energy beam with an exposure of $1.12 \times 10^{21}$ protons on target. After all the cuts are applied, the selected sample is $898 \pm 49.3$ (statistical) $\nu + e$ elastic scattering candidates in data. The simulation predicts 921 events, from which 601 are signal events and 320 are background events. Neutral current interaction from $\nu_\mu$ amounts to 38% of the background,
concentrated in the lowest energy bin, except for coherent $\pi^0$ which is spread across several bins.

Another 28% of the background comes from quasi-elastic events from $\nu_e$ with a forward-going shower corresponding to a positron track and a non-visible final-state neutron.

The distribution of the energy and angle of the electron candidates are shown in Figs. 5.9, 5.10.
FIG. 5.8: Distribution of $E\theta^2$ for data and simulation. All cuts are applied except the $E\theta^2$ cut and the $Q^2$ cut, bin width normalized. The error bars in the data points are statistical only. Simulation is normalized to data exposure. The simulation by category and stacked. The legend shows the total number of events per category.
FIG. 5.9: Histogram of electron energy after all cuts for data and simulation, bin width normalized. The error bars in the data points are statistical only. Simulation is normalized to data exposure. The simulation by category and stacked. The legend shows the total number of events per category.
FIG. 5.10: Angle of the scattered electron with respect to the beam after all cuts for data and simulation, bin width normalized. The error bars in the data points are statistical only. Simulation is normalized to data exposure. The simulation by category and stacked. The legend shows the total number of events per category.
CHAPTER 6

Background Subtraction

6.1 Background Constraint

The systematic uncertainties enter the measurement of the electron energy spectrum when subtracting the background and correcting for the selection efficiency.

The backgrounds predicted by the GENIE simulation are constrained using four kinematic sidebands. The sidebands are defined by the quantities $E_e \theta^2$ and $dE/dx_{(4)}$. As stated in the previous chapter, the signal region is defined to satisfy $E_e \theta^2 < 0.0032 \text{ GeV rad}^2$ and $dE/dx_{(4)} < 4.5 \text{ MeV/1.7cm}$. Events with greater $dE/dx_{(4)}$ predominately are photon-induced electromagnetic showers, and events with larger $E_e \theta^2$ have a larger scattering angle than what is expected from electron elastic scattering.

Sidebands 1-3 have $0.005 < E_e \theta^2 < 0.112 \text{ GeV rad}^2$ and $dE/dx_{(4)} < 20 \text{ MeV/1.7cm}$. Two cuts are omitted from the sidebands to increase statistics: the cut on $Q^2$ and the cut on the transverse energy spread of the first third of the shower. Sideband 1 requires events in which the single plane minimum energy deposition between the second and sixth plane of the track $(\text{Min}(dE/dx_{2-6}))$ is greater than 3 MeV. Sideband 2 and 3 have $\text{Min}(dE/dx_{2-6}) < 3 \text{ MeV}$,
and are further divided by requiring that reconstructed energy is $E_e < 1.2$ GeV for sidebands 2 and $E_e > 1.2$ GeV for sideband 3. The $\text{Min}(dE/dx_{2-6})$ condition separates events that are more likely to be a track from a single particle and tracks that have two or more particle tracks overlapping. Events with higher $\text{Min}(dE/dx_{2-6})$ are more likely to have another track overlapping with the EM shower, such as a proton or a charged pion. Sideband 4 is defined at the region of $dE/dx$ where the peak of the photo-like track is located. This sideband has all the same cuts that the signal region except that events must fall into $4.5 < dE/dx_{(4)} < 10$ MeV/1.7cm. A diagram of the sidebands is shown in Fig. 6.1.

A $\chi^2$ fit is done simultaneously for the four sideband distributions between data and simulation, where the normalization of the different background components is allowed to float. The fit has 8 parameters: the normalization of the background from $\nu_e$, from the $\nu_\mu$ background except for coherent $\pi^0$ events, which are fit separately in six bins of electron energy. Sidebands 1-3 are fitted to the distribution of the transverse end position of the tracks. Sideband 4 is fitted in six bins of reconstructed energy to allow an energy dependence in the region of $dE/dx_{(4)}$ above 4.5 MeV/1.7cm where the rate is under-predicted. By fitting the normalization of the background templates, these are tuned to agree with the data on the sideband region. The tuned normalization is later applied to the background in the signal region.

The fit is done independently for the central value prediction and each of the systematic
FIG. 6.2: Simulation of the electron energy spectrum with 20 flux universes.

universes of the analysis. The systematic uncertainties from the GENIE simulation are evaluated using the multi-universe method (as in Sec. 3.3.3). Doing the fit on the systematic universes helps constraint their associated uncertainty by comparing them with data in the sidebands. The fit yields the scale by which to change the normalization of the backgrounds. The resulting scale factors from the fit are shown in Table 6.1. The scaled background is shown in the reconstructed distributions in Figs. 6.5, 6.6, 6.7, 6.8.

6.2 Efficiency Correction

It is expected that not all neutrino-electron elastic scattering events are recognized as such in the reconstruction. A fraction of true electron elastic scattering events would be rejected by the selection cuts. In order to correct the energy spectrum, the efficiency of the selection is calculated using a special simulation sample that has only neutrino-electron elastic scattering
FIG. 6.3: Sidebands before background fit.
FIG. 6.4: Sidebands after background fit.
FIG. 6.5: Distribution of $dE/dx$ of events that pass all other cuts. The backgrounds are tuned according to the sideband fit. The error bars in the data are statistical only.
FIG. 6.6: Distribution of $E\theta^2$ of events that pass all other cuts except the $Q^2$ cut. The backgrounds are tuned according to the sidebands fit. The error bars in the data are statistical only.
FIG. 6.7: Distribution of the electron energy of events that pass all cuts. The backgrounds are tuned according to the sideband fit. The error bars in the data are statistical only.
FIG. 6.8: Distribution of the scattering angle $\theta$ with respect to the beam of events that pass all cuts. The backgrounds are tuned according to the sideband fit. The error bars in the data are statistical only.
Process | Scale factor
--- | ---
$\nu_e$ | $1.03 \pm 0.02$
$\nu_\mu$ (excluding NC COH) | $0.94 \pm 0.03$
NC COH $0.8 < E_e < 2.0$ GeV | $1.5 \pm 0.2$
NC COH $2.0 < E_e < 3.0$ GeV | $2.0 \pm 0.3$
NC COH $3.0 < E_e < 5.0$ GeV | $1.6 \pm 0.2$
NC COH $5.0 < E_e < 7.0$ GeV | $2.1 \pm 0.4$
NC COH $7.0 < E_e < 9.0$ GeV | $1.3 \pm 1.0$
NC COH $9.0 < E_e$ | $0.8 \pm 0.8$

TABLE 6.1: Background normalization scale factors extracted from the fits to the kinematic sidebands, with statistical uncertainties.

The efficiency is defined as the ratio of the true signal events that pass the analysis cuts described in Chap. 5 and the number of those same events that have true electron energy higher than 800 MeV and have a true simulated vertex within the fiducial volume. The efficiency is shown in Fig. 6.9. The efficiency calculation is also done in universes that represent lateral systematic uncertainties, that is, those where the uncertainty affects the migration between bins. The electron energy spectrum is divided by the efficiency and by doing so the estimated systematic uncertainties on the signal enter the measurement.

The background-subtracted and efficiency-corrected electron energy spectrum is the final product of the physics analysis, shown in Fig. 6.10. The systematic error on the electron energy is shown in Fig. 6.11. This is one of the inputs to the flux constraint procedure described in Chap. 7. A summary of the systematic uncertainties is shown in Fig. 6.11. The sources of systematic uncertainty are described in the following section.
FIG. 6.9: Efficiency of the neutrino-electron elastic scattering selection (top) and its systematic uncertainties (bottom).
FIG. 6.10: Electron energy spectrum after background subtraction and efficiency correction. Errors are statistical and systematic for data and simulation.
FIG. 6.11: Fractional uncertainty on the electron energy spectrum. The individual components are described in section 6.3.
6.3 Systematic Uncertainties

6.3.1 Interaction Model

The uncertainties of the GENIE models are estimated by using the multi-universe method. In this case, the underlying uncertain parameters in the models used to produce the simulations are shifted by ±1 sigma, resulting in two alternative simulations. The standard deviation of the different predictions for each bin on any reconstructed distribution is the systematic uncertainty due to that parameter.

The leading systematics from GENIE is the normalization of the charged-current quasi-elastic cross section. The fractional uncertainty on the total number of events is 1.60%. After that, the closest contribution on this category comes from the uncertainty on the axial mass parameter in the resonance cross section. The fractional uncertainty from this source is 1.41%.

As mentioned in Sec. 4.3, the default GENIE simulation is modified to achieve better agreement with MINERνA data. The quasi-elastic cross section is modified using the RPA correction based on the Nieves model [42] and the uncertainties associated with the modification come from [43] and are assigned to events based on their true values of the four-momentum transfer components \( q_0 \) and \( q_3 \). The RPA correction reduces the predicted number of quasi-elastic events and the uncertainty on the total number of neutrino-electron elastic scattering events is 1.5% after background subtraction and efficiency correction. Similarly, the uncertainty on the number of events coming from the tune to 2p2h interactions is estimated by comparing the effect on the simulation with and without the tune, and was found to be 1.52%.

A summary of the fractional uncertainty from different models is shown in Fig. 6.12. Figures for the complete breakdown of the systematics are in Appx. C.
FIG. 6.12: Fractional uncertainties on the electron energy spectrum due to the interaction model.
6.3.2 Electron Reconstruction Uncertainties

The uncertainty on the electromagnetic energy scale was studied by comparing the reconstructed invariant mass of $\pi^0$ candidates in charged-current $\nu_\mu$ events between data and simulations [49]. The $\pi^0$ sample indicated a 5.8% mismodeling of the energy scale of the electromagnetic calorimeter. The energy deposition in the ECAL is adjusted by 5.8% and an overall uncertainty in the electromagnetic response of 1.5% is applied based on the precision of the $\pi^0$ sample, which results in a 0.2% uncertainty on the total number of events.
6.3.3 Beam Uncertainties

Only a small fraction of the total uncertainties in the energy spectrum come from the beam. The uncertainty on the neutrino-electron scattering rate due to uncertainties in the flux model is 0.2%.

The uncertainty in the beam angle is estimated by looking at the angular spectra of muons from charged-current $\nu_\mu$ candidates with low hadron recoil in data and simulation [50]. The uncertainty in the beam angle is 0.5 mrad, which gives an uncertainty in the neutrino-electron elastic scattering rate of 0.09%.
TABLE 6.2: Uncertainties on the total number of neutrinos elastic scattering off electrons in MINERνA, after background subtraction and efficiency correction.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>0.22</td>
</tr>
<tr>
<td>Electron Reconstruction</td>
<td>0.20</td>
</tr>
<tr>
<td>Interaction Model</td>
<td>3.74</td>
</tr>
<tr>
<td>Detector Mass</td>
<td>1.40</td>
</tr>
<tr>
<td>Total Systematic</td>
<td>4.06</td>
</tr>
<tr>
<td>Statistical</td>
<td>5.49</td>
</tr>
<tr>
<td>Total</td>
<td>6.83</td>
</tr>
</tbody>
</table>

### 6.3.4 Detector Mass Uncertainty

The mass uncertainty on the total mass of the tracker from the detector assay is 1.4% \[51\]. Technically, this is an uncertainty on the prediction of the number of neutrino-electron scattering events in MINERνA rather than an uncertainty in the measurement but is added to the uncertainty of the data spectrum to facilitate the flux constraint procedure.
In section 3.3.3 we described how the uncertainty on the flux comes from the spread of multiple simulations. At that stage, all those flux universes represent equally valid estimations of the flux. The flux constraint procedure in this chapter works by presenting a procedure for selecting those flux universes that have good agreement with the measurement.

The procedure to constrain the flux uses the electron energy spectrum from the last section as an experimental benchmark. The prediction of each flux universe’s number of neutrino-electron scattering events is compared to the measurement. A $\chi^2$-based likelihood is calculated for each flux universe. The flux uncertainty is then recalculated using the likelihood as a weight. In this way, the flux universes that have a poor agreement with the data would contribute less to the flux uncertainty, effectively reducing it. The central value of the flux is also modified. The new central value is given by the new mean of the flux universes.

This procedure has been used before by MINER$\nu$A to constrain the flux [46 31]. During the ME FHC beam, the flux uncertainty on the $\nu_\mu$ flux was reduced from 7.6% to 3.9% using this technique and the energy spectrum of neutrino-electron elastic scattering. In principle, the measurement could be used to constrain the RHC flux since it is correlated with the FHC flux.
because they both come from the same beamline, with the only differences being the polarity of the magnetic horns and the intensity of the beam. Additionally, the production of positive and negative pions is correlated through the systematic errors of the NA49 experiment (the main data set used on the constraint from external hadron production) effectively correlating the production of neutrinos and antineutrinos.

The initial work of this thesis carries out the analysis of the ME RHC beam. As it will be shown later in this chapter, using the electron elastic measurement from RHC reduces the uncertainty further than what could have been accomplished by using the FHC measurement on the RHC flux. Taking the analysis even further, since both fluxes (FHC and RHC) are correlated, the results from both neutrino-electron elastic scattering measurements are used together for a combined constraint that can be applied to both flux periods.

Lastly, an analysis based on the same procedure was done using inverse muon decay (IMD) events \( \nu_\mu e^- \rightarrow \mu^- \nu_e \) \(^{52}\). These events’ final state has only a negatively charged muon going in the forward direction. This process has an energy threshold of about 11 GeV and it is only induced by a \( \nu_\mu \), greatly limiting the statistics achievable\(^{[1]}\). Both flux polarities are used in the IMD analysis. In the case of the RHC beam, the \( \nu_\mu \) comes from the wrong-sign contamination of the beam.

Due to the low statistics, the result is not reported as an energy spectrum but as the total number of events for each beam polarity. After subtracting the constrained background the IMD analysis found 127±20.4 events for the FHC beam and 56±11.4 for the RHC beam. For the purpose of the combined constraint, the IMD events are added into a single number. The mathematical basis behind the technique is Bayes’ theorem, which relates the conditional

\(^{[1]}\)The process \( \nu_\mu e^- \rightarrow \mu^- \bar{\nu}_e \) has a final state that is practically indistinguishable from the \( \nu_\mu \)-induced inverse muon decay but is limited by the small flux of \( \nu_\mu \) which is only a few percent compared to the \( \nu_\mu \) flux above the energy threshold. The simulation predicts 0.5% (half an event) and 2% (one event) of the signal rate for FHC and RHC respectively and thus it is treated as a background in the analysis.
probabilities of events $A$ and $B$ as:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

(7.1)

where $P(A)$ ($P(B)$) is the probability that event $A$ ($B$) happens and $P(A|B)$ ($P(B|A)$) is the conditional probability that $A$ ($B$) happens given that $B$ ($A$) happened. The term $P(A—B)$ is also called the posterior probability. The idea behind Bayes statistics is that one starts with a prior probability which is later updated by new information. In that vein, this technique is updating the a priori knowledge of the flux.

In the case of the present study, we can see the different universes as random rolls with probability; it is possible to create a probability distribution for the value of the integrated flux $P(M)$. $P(N)$ is the probability of observing the number of neutrino-electron scattering events in MINER$\nu$A that are seen by doing the measurement. Then, $P(N—M)$ is the probability of observing that number of events given the assumption of the flux. The goal is to get $P(M—N)$, the flux’s posterior probability, given that a fixed number of neutrino-electron scattering events were observed. Mathematically:

$$P(M_i|N_{\nu e\rightarrow \nu e}) \propto P(M_i) P(N_{\nu e\rightarrow \nu e}|M_i).$$

(7.2)

The proportionality sign is removed by normalizing over all the $P(N|M_i)P(M_i)$.

In practice, the constraint can be seen as applying a weight to each flux universe. Each flux universe $M_i$ is weighted by a factor $P(N|M_i)/\sum_i P(N|M_i)$. The way $P(N|M)$ is calculated is based on a chi-squared likelihood

$$P(N_{\nu e\rightarrow \nu e}|M_i) = \frac{1}{(2\pi)^{K/2} |\Sigma_N|^{1/2}} e^{-\frac{1}{2}(N-M_i)^T \Sigma_N^{-1}(N-M_i)},$$

(7.3)

where $N$ is a vector of the bin content of the measured data, $M_i$ is a vector of the bin
content for the simulated prediction for the \(i\)th flux universe, \(\Sigma_N\) is the covariance matrix of the measurements in \(N\), and \(K\) is the number of bins for the measurement.

To obtain the constraint based on the RHC neutrino-electron elastic scattering measurement \(N\) and \(M\) will contain the six bins of the electron energy spectrum from the RHC beam data set. To make a constraint that includes both electron elastic scattering measurements the vector \(N\) is made of the six bins of electron energy from the FHC beam and the six bins from the RHC beam, for a total of 12 bins. Finally, to add the IMD measurement another bin is added that has the total number of IMD events. For each case, an equivalent vector \(M\) is formed from the Monte Carlo simulations. The electron energy spectrum from FHC flux is shown in Fig. 7.1 and the selected events from the inverse muon decay measurement are shown in Fig. 7.2.

The covariance matrix \(\Sigma_N\) is constructed by calculating the covariance between all the elements of \(N\). The result is a \(13 \times 13\) matrix that contains the covariance matrices of both electron elastic scattering measurements and the correlation of these measurements with each other and their correlation for each bin to the IMD results. The tabulated values of the covariance matrix can be found in appendix D. The correlation matrix is shown in Fig. 7.4 with and without statistical uncertainty.

When calculating the covariance matrix, systematic errors are assumed 100% correlated when coming from the same source. For example, the uncertainties from the models in the GENIE simulation that are common between the three measurements are correlated in this way. Uncertainties that are specific to the electron elastic scattering analysis such as the one on the electron reconstruction are correlated between just the two elastic scattering measurements. Uncertainties that only appear in the IMD analysis like muon reconstruction efficiencies are not correlated with the other bins. The fractional uncertainty of the 13 bins of the combined

\[\text{Since the expression of the likelihood is an exponential function, this is equivalent to calculating the chi-squared for each data set and multiplying the probabilities for the case were there is no correlation between the different measurements; which is approximately the case here, as will be apparent from the correlation matrix.}\]

93
FIG. 7.1: Electron energy spectrum from neutrino-electron elastic scattering using the FHC neutrino flux at MINERνA. Taken from [31].

The probability distributions of the integrated flux at MINERνA are constructed by filling a histogram with the integrated flux for each universe before and after applying the constraint. They are shown in Figs. 7.6, 7.7, 7.12, and 7.13. The neutrino flux exposure is measured as protons on target (POT).

These distributions show the effect of the constraint on the predicted flux. The shift of the mean of the distributions represents a reduction in the normalization and the reduction in the RMS shows the uncertainty reduction on the predicted flux. The flux and its fractional uncertainty are shown before and after the constraint for the RHC flux in Figs. 7.8, 7.9, 7.10, and 7.11 and for the FHC flux on Figs. 7.14, 7.15, 7.16, and 7.17.

The normalization is reduced for about 10% for all the fluxes compared to the a priori flux simulation. This is not a new result, because it agrees with both the low-energy and the
FIG. 7.2: Spectrum of inverse muon decay events observed for the MINERνA detector for FHC (left) and RHC (right). Taken from [52].

medium-energy ν + e elastic analysis that has been used to constrain the flux in the past.

One way to visualize the effect of the constraint is to make a new prediction for the total number of neutrino-electron elastic scattering events. Each point in Fig. 7.5 shows a flux universe, and the value on each axis indicates the total number of events predicted for the FHC beam and the RHC beam. The distribution for the a priori flux is shown in the left panel. The distribution after applying the constraint is on the right panel. The constraint reduces the spread of the predictions, thus reducing the uncertainty on the total number of events.

The effect on the flux uncertainty after applying the constraint is summarized in Table 7.1. One can see that even only using data from one flux mode still reduces the error of the other mode. The reason is that the uncertainties of pion production for both positive and negative pions are constrained by the external data coming from NA49 (as described in Sec. 3.3.1). The production cross sections coming from NA49 are dominated by the uncertainty on the normalization, effectively correlating the pion production measurements and therefore making the two beam polarities correlated. In a similar way, the ν_e flux is directly correlated with the ν_μ flux due to the decay chain π^+ → μ^+ν_μ, μ^+ → e^+ν_e, and additionally by the use of kaon-pion cross section ratios as the hadron production data that informs the kaon production. This argument can also be used to extend the validity of the IMD constraint to energies lower...
FIG. 7.3: Histogram of the bin content of the different measurements. Bins 0-5 are FHC $\nu_e$, 6-11 are RHC $\nu_e$ and bin 12 is the total number of IMD events in both beam polarities.
FIG. 7.4: Combined covariance matrix of the $\nu e$ and IMD measurements. Bins 0-5 are FHC $\nu e$, 6-11 are RHC $\nu e$ and bin 12 is the total number of IMD events in both beam polarities. The top panel has statistical and systematic uncertainties. The bottom has only systematic uncertainty.
FIG. 7.5: Comparison of the distribution of the number of neutrino electron elastic scattering events for \( \nu_\mu \) and \( \bar{\nu}_\mu \) beams. Each point represents the prediction from a flux universe. The left panel is the \textit{a priori} flux and the right panel is the constrained flux.

than the energy threshold of the process and to the other components of the flux that are not \( \nu_\mu \).

Several observations can be made by looking at Table 7.1. The flux constraint coming from neutrino electron elastic scattering has a greater effect on reducing the uncertainty when applied to the flux that it comes from. That is, the FHC measurement has a greater effect on the uncertainty of the FHC flux and the same for the RHC flux measurement. There is an effect of improving the uncertainty of the other flux period anyway since the sources of uncertainty that affect the number of events are very similar for both beam periods. The combination of the elastic scattering measurements makes the biggest improvement to the flux uncertainty for all the fluxes, justifying the combination of the measurements. The effect of adding the IMD
TABLE 7.1: Resulting estimated fractional uncertainties of the neutrino flux for each flavor and polarity of the beam. Each row represents the measurement from which the constraint was calculated.

<table>
<thead>
<tr>
<th></th>
<th>RHC (%)</th>
<th>FHC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\bar{\nu}_\mu$ $\bar{\nu}<em>e$ $\nu</em>\mu$ $\nu_e$</td>
<td>$\nu_\mu$ $\nu_e$ $\bar{\nu}_\mu$ $\bar{\nu}_e$</td>
</tr>
<tr>
<td>A priori</td>
<td>7.76</td>
<td>7.81</td>
</tr>
<tr>
<td>FHC $\nu e^-$</td>
<td>6.11</td>
<td>5.81</td>
</tr>
<tr>
<td>RHC $\nu e^-$</td>
<td>4.92</td>
<td>4.98</td>
</tr>
<tr>
<td>combined $\nu e^-$</td>
<td>4.68</td>
<td>4.62</td>
</tr>
<tr>
<td>combined $\nu e^- +$ IMD</td>
<td>4.66</td>
<td>4.56</td>
</tr>
</tbody>
</table>

measurement is minor overall but provides improvement for some of the fluxes, particularly to the wrong sign contamination during both flux periods. This is because the effect of the IMD measurement is stronger on the high-energy tail since the process only will occur with high-energy neutrinos, and the high-energy tail of the beam is populated predominantly by the wrong-sign contamination coming from neutrinos whose meson parent were produced in the beam direction already and were not deflected by the magnetic horns.
FIG. 7.6: Integrated flux probability distribution for the $\bar{\nu}_\mu$ (top) and $\nu_\mu$ (bottom) fluxes in the RHC beam.
FIG. 7.7: Integrated flux probability distribution for the $\bar{\nu}_e$ (top) and $\nu_e$ (bottom) fluxes in the RHC beam.
FIG. 7.8: Top: $\bar{\nu}_\mu$ flux before and after the constraint for the RHC beam. Bottom: Fractional uncertainty before and after the constraint.
FIG. 7.9: Top: $\nu_\mu$ flux before and after the constraint for the RHC beam. Bottom: Fractional uncertainty before and after the constraint.
FIG. 7.10: Top: $\bar{\nu}_e$ flux before and after the constraint for the RHC beam. Bottom: Fractional uncertainty before and after the constraint.
FIG. 7.11: Top: $\nu_e$ flux before and after the constraint for the RHC beam. Bottom: Fractional uncertainty before and after the constraint.
FIG. 7.12: Integrated flux probability distribution for the $\nu_\mu$ (top) and $\bar{\nu}_\mu$ (bottom) fluxes in the FHC beam.
FIG. 7.13: Integrated flux probability distribution for the $\nu_e$ (top) and $\bar{\nu}_e$ (bottom) fluxes in the FHC beam.
FIG. 7.14: Top: $\nu_\mu$ flux before and after the constraint for the FHC beam. Bottom: Fractional uncertainty before and after the constraint.
FIG. 7.15: Top: $\bar{\nu}_\mu$ flux before and after the constraint for the FHC beam. Bottom: Fractional uncertainty before and after the constraint.
FIG. 7.16: Top: $\nu_e$ flux before and after the constraint for the FHC beam. Bottom: Fractional uncertainty before and after the constraint.
FIG. 7.17: Top: $\bar{\nu}_e$ flux before and after the constraint for the FHC beam. Bottom: Fractional uncertainty before and after the constraint.
CHAPTER 8

Conclusion and Outlook

In Chapter 1, we introduced the phenomena of neutrino flavor oscillations, the relation between it and the neutrino masses, and their relevance in the current particle physics landscape as fundamental missing pieces in the Standard Model. The procedure for measuring the oscillation probability was also introduced, with emphasis on the necessary inputs: the neutrino flux, neutrino-nucleus cross sections, and the reconstruction capabilities of the detector. The work presented in this thesis offers a procedure to constrain the normalization and the uncertainty of the flux from a neutrino beam. The technique relies on measuring the number of neutrino-electron elastic scattering events and using it as a benchmark for the flux.

Neutrino-electron elastic scattering can be used in this way because of its well-predicted cross section, as illustrated in Chapter 2. Chapter 3 describes the NuMI beamline as the neutrino source for our measurement, and serves as an example of how conventional neutrino beams are produced and what are the main challenges when trying to predict them through simulation.

Chapters 4 and 5 described the MINERνA detector and how the neutrino-electron elastic scattering events are reconstructed as electromagnetic showers. The event selection for the
see events relied on the separation of electron and photon EM shower by using the energy loss per unit of length $dE/dx$, and the discrimination of $\nu_e$ CCQE events by the cut on the quantity $E_e\theta^2$. After all cuts are applied the result is a sample of mostly neutrino-electron elastic scattering events presented as an electron energy spectrum. In Chapter 6, background constraint was determined by fitting the normalization of the background to the data in the control samples (sidebands). The post-fit background was subtracted from the data and in this way, the systematic uncertainties entered the measured electron energy spectrum. An efficiency correction was calculated using simulation and applied to the electron energy spectrum.

Once the background-subtracted efficiency-corrected electron energy spectrum is obtained for the RHC beam, it is used in conjunction with an equivalent measurement done during the FHC beam period, and also a measurement of inverse muon decay. The combination is used to constrain the flux by comparing the Monte Carlo prediction of the multiple flux universes to the measurements. The combination of $\nu + e^-$ elastic scattering from both NuMI medium energy FHC and RHC fluxes with the addition of the inverse muon decay measurement yields a reduction in the fractional uncertainty of the flux from 7.6% to 3.3% for the FHC $\nu_\mu$ flux and from 7.8% to 4.7% to the RHC $\bar{\nu}_\mu$ flux. Although the technique of using $\nu + e$ elastic scattering has been used by the MINER$\nu$A collaboration before, this is the first time it is used by treating FHC and RHC $\nu + e$ samples as separate samples. Additionally, it is the first time that the samples for two different channels are used in combination, those channels being $\nu + e$ elastic and inverse muon decay.

The new constrained flux will improve the precision of current and future cross sections measurements made by the MINER$\nu$A collaboration by reducing the flux uncertainty, which can often be a dominant source. In what follows we present two examples of MINER$\nu$A analyses that use the constrained flux from this thesis.

The cross section of muon antineutrinos on hydrogen was measured as a function of $Q^2$ with the goal of extracting the axial vector form factor $F_A$ \cite{53}. This allows MINER$\nu$A to
access the form factor without the need for nuclear theory correction because the proton is not bound to other nucleons. The uncertainty on the measurement is predominantly statistical. For the systematic uncertainties, the flux uncertainty is under 4%, below the dominant sources from different nuclear interaction models. The event selection for the antineutrino-hydrogen analysis is displayed in Fig. 8.1.

Another result was a high-statistics measurement of the muon neutrino charged-current cross section on hydrocarbon with no pions on the final state [54], also called CCQE-like because the signal has the topology of a CCQE interaction with a free nucleon. This signal definition includes other channels like 2p2h or resonant processes where the pion is reabsorbed in the nucleus. A double-differential cross section of the muon transverse and longitudinal momentum $p_T$ and $p_\parallel$ is shown in Fig. 8.2 and a summary of the systematic uncertainties are shown in Fig. 8.3. This analysis greatly benefits from the flux constraint since the flux is the leading uncertainty on the more populated bins of $p_\parallel$. The flux constraint from the work reported here reduces the fractional uncertainty on the cross section to 5%.

The MINER$\nu$A collaboration has many other cross section analyses that are in progress. Those analyses will also use the flux constraint reported here. The result also works as a proof of concept for other experiments that rely on a neutrino beam. A study has been made for DUNE [55] on the use of neutrino electron elastic scattering for event-by-event neutrino energy reconstruction, that would allow the direct reconstruction of the flux. Based on the assumption of a 30 ton liquid argon detector, it was found that the absolute flux uncertainty can be reduced from 8% to 2%, and the shape uncertainty by 20%-30%. They also conclude that the detector mass is the most important factor for making a $\nu + e$ flux constraint. Reducing the statistical uncertainty improves the analysis greatly. In the case of MINER$\nu$A, we determined that the ability to do the direct flux determination using event-by-event neutrino energy reconstruction was limited by the angular resolution.

Very forward photon-like EM shower events are also of interest for physics searches for
FIG. 8.1: Event rate of charged-current elastic (CCE) scattering of $\bar{\nu}_\mu$ with hydrogen (top) and ratio to the simulation (bottom). From [53].
FIG. 8.2: Double differential antineutrino CCQE-like cross section on hydrocarbon as a function of muon momentum $p_T$ and $p_\parallel$. Multipliers are used to scale the histograms in individual panels. From [54].

FIG. 8.3: Summary of the systematic uncertainties on the $p_T$, $p_\parallel$ CCQE-like cross section. From [54].
particles beyond the Standard Model, such as heavy neutral lepton production \cite{56}. This is an active area of research that may be fruitful. It is a priority for DUNE and other experiments that are being planned, such as the SHIP experiment at CERN.
APPENDIX A

Minor selection cuts

Cut that have a very small effect on the analysis are described in this appendix.

Plausibility

Since data-overlay (see Sec. 4.3) is used in the MC simulation to mimic the overlap of multiple events and dead time of electronics, it is possible that a neutrino-electron scattering event from the overlaid data is reconstructed as a MC event, even if the true MC interaction is some other reaction that happens outside the fiducial volume. An event is not treated as a genuine MC event if the fraction of energy coming from the overlay data is greater than 50%. This practically never happens in the medium energy.

Reduced $\chi^2$ Cut

The Kalman filter is used to get the direction of the electron shower candidate. The filter produces a $\chi^2$ statistic describing the fit to the single particle model. The resulting reduced $\chi^2$ per degree of freedom does not follow the expected $\chi^2$ distribution because the single particle hypothesis is not correct. However, high values of the reduced $\chi^2$ are correlated with events
where the fit direction is misreconstructed. Events are required to have a $\chi^2$/NDF < 100.

**Bending Angle Cut**

While electromagnetic showers travel on a straight line that gets wider at the end, and pion or proton tracks might bend from hadronic interactions. To prevent the small background coming from misidentifying short hadronic tracks with electromagnetic showers a cut is applied to how much a track can bend. The bending angle is measured by dividing the track in half and creating two line segments, one going from start to middle, and the other from the middle to end. The angle between the two segments is required to be less than 9 degrees.

**Dead Time**

The data acquisition has a period of "dead time" after hits of 188 ns. To avoid incorrect reconstruction of the vertex position, channels upstream of the start of the reconstructed cone are checked for dead time. An electron candidate track is extrapolated from four upstream planes to find the central strip in each plane. The total number of dead channels on these strips and the adjacent strips in each of the four planes is required to be no more than one.

**Energy Balance Between Views**

The visible energy is spread into the three views of the detector. Since the scintillator plane follows the XUXV pattern, on average, the EM shower will deposit 50% of its energy on the X-view and 25% on the U and V views. One can expect that the true visible energy would behave like $E_x - E_u - E_v \approx 0$ and $E_u - E_v \approx 0$. This is not exactly true on an event-to-event basis, but still, it is possible to apply some constraints to reject events that contain overlapping
tracks from multiple hadrons. The requirement is

\[
\frac{|E_x - E_u - E_v|}{E_x + E_u + E_v} < 0.2, \quad (A.1)
\]

\[
\frac{|E_u - E_v|}{E_u + E_v} < 0.5. \quad (A.2)
\]

**Non-trackable Cluster Fraction in the Tracker**

For an EM shower with energy below 2 GeV that has its vertex upstream of module 65 (but still in the fiducial volume), the fraction of non-trackable clusters is required to be less than 0.05.

**Number of Transverse Energy Peaks in ECAL**

A common background event that can mimic the signal is π^0 decay events where one of the two photons in the decay is not observed. Either the energy of one of the photons is very small, or the π^0 was energetic and the two photons are nearly colinear and might get reconstructed as a single shower. The second case is complicated further by the fact that the photons could travel a significant distance without starting to shower in the tracker, but would start a shower a short distance into the ECAL.

In the case when the two photons from a π^0 decay are colinear with each other, it is sometimes possible to distinguish two separate peaks in the energy peaks in the transverse profile. A histogram of the hits is constructed using their locations and their energy, then an algorithm looks for local maximums of the histogram that are about the same size. Events are required to have only one peak.
APPENDIX B

List of GENIE sources of systematic uncertainty
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NormCCQE</td>
<td>Adjust overall CCQE normalization</td>
</tr>
<tr>
<td>VecFFCCQEShape</td>
<td>Adjust the elastic nucleon form factors. Shape-only effect of $d\sigma_{\text{CCQE}}/dQ^2$</td>
</tr>
<tr>
<td>CCQEPauliSupViaKF</td>
<td>Adjust Pauli Blocking by the parameter $\kappa$</td>
</tr>
<tr>
<td>MaNCEL</td>
<td>Adjust the neutral current elastic $M_A$, affects $d\sigma_{\text{NC}}/dQ^2$</td>
</tr>
<tr>
<td>EtaNCEL</td>
<td>Adjust the $\eta$ parameter in elastic neutral current. Affects both the shape and normalization of $d\sigma_{\text{NCEL}}/dQ^2$</td>
</tr>
<tr>
<td>NormCCRES</td>
<td>Adjust the normalization of charge current resonant production</td>
</tr>
<tr>
<td>NormNCRES</td>
<td>Adjust the normalization of neutral current resonant production</td>
</tr>
<tr>
<td>MaRES</td>
<td>Adjust the $M_A$ parameter of $d\sigma_{\text{CCRES}}/dQ^2$</td>
</tr>
<tr>
<td>MvRES</td>
<td>Adjust the $M_V$ parameter of $d\sigma_{\text{CCRES}}/dQ^2$</td>
</tr>
<tr>
<td>Rvn1pi</td>
<td>Adjust the NC and CC 1 pion final states off neutrons from the Bodek-Yang model</td>
</tr>
<tr>
<td>Rvn2pi</td>
<td>Adjust the NC and CC 2 pion final states off neutrons from the Bodek-Yang model</td>
</tr>
<tr>
<td>Rvp1pi</td>
<td>Adjust the NC and CC 1 pion final states off protons from the Bodek-Yang model</td>
</tr>
<tr>
<td>Rvp2pi</td>
<td>Adjust the NC and CC 2 pion final states off protons from the Bodek-Yang model</td>
</tr>
<tr>
<td>AhtBY</td>
<td>Adjust the $A_{ht}$ parameter on the Bodek-Yang model</td>
</tr>
<tr>
<td>BhtBY</td>
<td>Adjust the $B_{ht}$ parameter on the Bodek-Yang model</td>
</tr>
<tr>
<td>CV1uBY</td>
<td>Adjust the $C_{v1u}$ parameter on the Bodek-Yang model</td>
</tr>
<tr>
<td>CV2uBY</td>
<td>Adjust the $C_{v2u}$ parameter on the Bodek-Yang model</td>
</tr>
<tr>
<td>FrAbs_N</td>
<td>Adjust the absorption probability for nucleons</td>
</tr>
<tr>
<td>FrAbs_pi</td>
<td>Adjust the absorption probability for pions</td>
</tr>
<tr>
<td>FrCEx_N</td>
<td>Adjust the exchange probability for nucleons</td>
</tr>
<tr>
<td>FrCEx_pi</td>
<td>Adjust the exchange probability for nucleons</td>
</tr>
<tr>
<td>FrElas_N</td>
<td>Adjust the elastic probability for nucleons</td>
</tr>
<tr>
<td>FrElas_pi</td>
<td>Adjust the elastic probability for pions</td>
</tr>
<tr>
<td>FrInel_N</td>
<td>Adjust the inelastic probability for nucleons</td>
</tr>
<tr>
<td>FrInel_pi</td>
<td>Adjust the inelastic probability for pions</td>
</tr>
<tr>
<td>FrPiProd_N</td>
<td>Adjust the pion production probability for nucleons</td>
</tr>
<tr>
<td>FrPiProd_pi</td>
<td>Adjust the pion production probability for pions</td>
</tr>
<tr>
<td>MFP_N</td>
<td>Adjust the mean free path for nucleons</td>
</tr>
<tr>
<td>MFP_pi</td>
<td>Adjust the mean free path for pions</td>
</tr>
<tr>
<td>AGKYxf1pi</td>
<td>Adjust the $xF$ distribution for low multiplicity states in the AGKY model</td>
</tr>
<tr>
<td>RDecBR1gamma</td>
<td>Adjust resonance of $\rightarrow X + \gamma$ branching ratio</td>
</tr>
<tr>
<td>Theta_Delta2Npi</td>
<td>Distorts the pion angular distribution in $\Delta \rightarrow X + \eta$ branching ratio</td>
</tr>
</tbody>
</table>

**TABLE B.1: GENIE model uncertainties.**
APPENDIX C

Figures for the Interaction Model

Uncertainties on the Electron Energy Spectrum
FIG. C.1: Fractional uncertainty on the electron energy spectrum due to the signal elastic scattering models.
FIG. C.2: Fractional uncertainty from nucleon final state interactions.
FIG. C.3: Fractional uncertainty from interaction model others.
FIG. C.4: Fractional uncertainty from pion final state interactions.
FIG. C.5: Fractional uncertainty from the interaction model. All sources are presented individually.
The covariance matrix of the measurements used in the calculation of the combined constraint. The bin range of each bin is shown for the electron elastic scattering results. The error for the inverse muon decay is the error on the total number of events. The covariance from the FHC is from [31], and for IMD it is from the results of [52]. The covariance from RHC and that between the different measurements is a result of this analysis.
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[43] R. Gran (2017), 1705.02932


[54] A. Bashyal et al., High-statistics measurement of antineutrino quasielastic-like scattering at $e_\nu \sim 6$ gev on a hydrocarbon target (2022), 2211.10402.

VITA

Luis Alberto Zazueta Reyes

Luis Zazueta Reyes was born in Hermosillo, Sonora, Mexico on May 27th 1992. Growing up in Santa Ana, Sonora, he became interested in science and especially particle physics. In 2010 he began his undergrad education at the Universidad de Sonora culminating in a Bachelor’s degree in physics in 2015. In 2016 he started the Ph.D. program at William and Mary working on experimental neutrino physics with the MINERvA collaboration under the supervision of Dr. Michael Kordosky. After graduation, he aspires to continue working toward the future of neutrino physics experiments.