Evaluating the ProtoDUNE-SP Detector Performance to Measure a 6 GeV/c Positive Kaon Inelastic Cross Section on Argon

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Abstract

The ProtoDUNE Single-Phase Liquid Argon Time Projection Chamber (ProtoDUNE-SP LArTPC) is a prototype for the Deep Underground Neutrino Experiment (DUNE), a future long-baseline neutrino oscillation experiment. Based at the CERN Neutrino Platform, ProtoDUNE-SP LArTPC collected data from a charged test beam in the fall of 2018. It then took data of cosmic-ray muons from November 2018 to the summer of 2020. The main goals of the prototype were to measure parameters related to charged particle passage in argon and evaluate the performance of the detector to inform future DUNE Far Detector development. The test beam provided kaons, pions, muons, protons, and electrons to the detector. These particles represent common final state particles in neutrino interactions, therefore providing information to DUNE on modeling charged particles in argon for its neutrino physics program. In addition to neutrino physics, DUNE has proposed an analysis using the DUNE Far Detector module to set limits for proton decay through the decay channel $p \; ! \; K^{+} + \;$. This measurement would require information on kaons in argon, providing ProtoDUNE-SP LArTPC another opportunity to aid DUNE.

This thesis describes the calibration of ProtoDUNE-SP and its detector performance, which serves as a benchmark for the performance of the DUNE Far Detector modules. A specific calibration highlighted is the evaluation of the liquid argon purity in the detector. These measurements use cosmic-ray muons reconstructed in the detector that are calibrated and matched to data from scintillator strips external to the TPC, known as the Cosmic Ray Tagger (CRT). The thesis will discuss the algorithms to match the data between the ProtoDUNE-SP LArTPC and the CRT and discuss the liquid argon pu-

rity measurements using one of the algorithms. Data sets of calibrated tracks measured the liquid argon contamination as consistently below 100 ppt oxygen equivalent. After these discussions on the ProtoDUNE-SP LArTPC detector, the thesis will present an evaluation of the inclusive inelastic, sometimes referred to as a reactive, cross section on argon of kaons from the ProtoDUNE-SP test beam with an average momentum of 6 GeV/c.

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Chapter 1

Introduction to Neutrino Physics

1.1 History of Neutrino Physics

The discovery of neutrinos originates from an anomaly in the observed physics of radioactive decay events. In studies done in the early 1900s, three separate common channels of radioactive decay were observed. These decay channels include the emission of a helium atom from the nucleus (alpha decay), the emission of a photon (gamma decay), and beta decay. The third of these was originally classi ed as the conversion of a neutron into a proton and electron. However, the nal state electron had a smooth continuous energy spectrum that contradicted the monoenergetic peak that should occur for the hypothesized two-body decay. The violation of this hypothesis led to a myriad of ideas on the data-to-theory di erences in the energies of beta decay products [1]. In 1930, Wolfgang Pauli provided a desperate remedy to the anomaly by proposing a neutral particle that carries the missing energy. This little neutral particle, referred to as a neutrino (little neutral one in Italian), would make the beta decay a three-body decay and explain the results [2]. Pauli's remedy

was proven to be correct through the Reines and Cowan experiment. Operating near the Savannah River nuclear power plant in South Carolina during the 1950s, the experiment observed an inverse beta decay ($\bar{\nu}_e + p \rightarrow n + e^+$) only possible through a neutrino interaction on a proton [3, 4]. Other avors of the neutrino were found in subsequent experiments over the next fty years. Muon neutrinos were discovered in 1962 at the Brookhaven National Laboratory, and tau neutrinos were discovered in 2000 at the Fermi National Accelerator Laboratory (Fermilab) [5, 6]. These neutrinos are the three weak avors of neutrinos. They are called the weak avor states of the neutrino as they represent the states that interact with the weak force.

Neutrinos come from a wide variety of sources ranging from outside the Milky Way galaxy to inside the Earth. The most common neutrino sources used for neutrino experiments are of solar, atmospheric, or arti cial origins [1]. Solar neutrinos arise from the nuclear fusion process that fuels a star, while atmospheric neutrinos represent the decay products of particles colliding with Earth's atmosphere. Arti cial neutrino sources typically include either neutrinos from nuclear power plants or neutrinos from beams of decayed particles. In the case of the muon neutrino and tau neutrino discoveries, both used beams of neutrinos [5, 6]. These beams commonly use protons colliding with a target to produce large amounts of charged pions and kaons. As these mesons travel, a magnetic horn directs them in the direction of the neutrino detector and serves as a veto for mesons of the wrong charge. The neutrinos from the decays then travel towards the detector for observation, where they will hopefully interact with the material in the detector. Figure I shows a diagram of generating a neutrino beam [7]. Experiments use beamline monitoring detectors to understand the energy spectrum and intensity of the neutrino beam to a degree of

Figure I: Diagram from [7] of a neutrino beam being generated from decaying pions.

precision not possible in experiments using natural sources.

Even though the discovery of the electron neutrino solved an anomaly, new issues soon arose. Experiments throughout the 20th century measured the ux of solar and atmospheric neutrinos. The most notable of these experiments was the Ray Davis solar neutrino experiment using a 615-ton container of dry cleaning uid (C_2Cl_4) in the Homestake Gold Mine in South Dakota. This experiment, led by chemist Ray Davis, intended to measure the ux of solar neutrinos using the neutrino interaction of electron neutrinos on chlorine, which has a nal state of an electron and the conversion of chlorine to argon ($_e + {}^{37}_{16}\mathrm{Cl} \; ! \; {}^{37}_{18}\mathrm{Ar} + e$) [7, 8]. Interestingly, the detector measured only 0.48 0.04 solar electron neutrinos per day, less than a third of the expected rate of 1.7 solar electron neutrinos a day. With that discrepancy, the solar neutrino problem was born as it appeared the sun was producing fewer neutrinos than it should [7]. It was hypothesized the problem came from either issues in modeling the sun or that solar electron neutrinos were transitioning to di erent neutrino avors. The latter is commonly called neutrino oscillation and refers to neutrinos oscillating between weak avor states. This theory of neutrino oscillation is attributed initially to Italian physicist Bruno Pontecorvo [9, 10]. Later Ziro Maki, Masami Nakagawa, and Shoichi Sakata then created a matrix for neutrino oscillations in 1962 referred to now as the PMNS

(Pontecorvo Maki Nakagawa Sakata) matrix [10, 11]. The PMNS mixing matrix allows for the parameterization of neutrino oscillations with measurable parameters that will be discussed in the following sections.

Neutrinos of another origin showed similar issues. High-energy particles can collide with the atmosphere, generating kaons and pions showering the Earth's surface. Many typically decay before reaching the Earth's surface. A typical decay leads to a muon and a muon antineutrino or an antimuon and a muon neutrino. These muons then commonly decay again into an electron, an electron antineutrino, and a muon neutrino [12]. Counting the number of neutrinos from a single atmospheric pion or kaon, two muon neutrinos and one electron neutrino should exist in the nal state, as is demonstrated for a positive pion in Equation 1.1 and a negative pion in Equation 1.2. Experiments tried to con rm this atmospheric neutrino ratio between muon neutrinos and electron neutrinos.

$$^{+} \; ! \quad ^{+} + \quad ! \quad + \quad + \; e^{+} + \; _{e} \tag{1.1}$$

$$! \quad + \quad ! \quad + \quad + \; e \; + \; _{e} \tag{1.2}$$

However, they consistently found fewer muon neutrinos than expected. Experiment after experiment failed to nd the measured ratio between atmospheric muon neutrinos to atmospheric electron neutrinos that matched expectation [13]. Figure II shows a myriad of experiments in the late 1900s and the ratio measured between data and the expectations at the time [13]. Most saw a discrepancy that hinted at new physics, but they did not have the precision to con rm it. Nevertheless, the de ciency in atmospheric muon

Figure II: Ratio of muon-like to electron-like neutrino events between data and simulation taken from [13].

neutrinos led to more hints that neutrinos are possibly transitioning from one avor to another along their travels, and plots such as in Figure II were packaged in publications surveying the eld [13].

These problems were solved in two neutrino experiments using water Cherenkov detectors, the Sudbury Neutrino Observatory (SNO) in Canada and Super-Kamiokande in Japan. These experiments, similar to Ray Davis' experiment, intended to search for solar electron neutrinos. As water Cherenkov experiments, they used photomultiplier tubes (PMTs) surrounding water to detect Cherenkov light from particles traversing the water to identify the nal state particles of neutrinos scattering o the water [7]. Super-Kamiokande also attempted to solve the atmospheric neutrino anomaly, allowing for a probe of neutrino oscillations from two distinct sources with two di erent energy ranges. For the solar neutrino sector, a clear di erence was observed as the solar electron neutrino ux was measured to be 45.1% of its expected value [7, 14].

For Super-Kamiokande's atmospheric neutrino measurements, a de cit

again appeared. The event rate for muon-like events decreased as a function of distance traveled. Therefore, muon neutrinos that went through the core of the Earth to arrive at Kamioka traveled further, leading to an increased probability in muon neutrinos transitioning to other neutrino avors [15]. Figure III shows the ratio of data to the expectation of muon-like and electron-like events. It shows the decrease in the number of muon neutrinos measured as a function of the distance traveled (L) and neutrino energy (E) as they disappear to other weak avors.

Figure III: Plot of the data to Monte Carlo ratio of muon-like and electron-like events as a function of the measured distance the atmospheric neutrino traveled divided by the reconstructed neutrino energy. Originally found in [15].

SNO used a water Cherenkov detector that was lled with heavy water [16]. The heavy water target gave SNO another data set for veri cation. It enabled SNO to have sensitivity to measure neutral current interactions, providing a data set of scatters with all three neutrino avors. If neutrino oscillations exist,

SNO should measure a de cit of solar electron neutrinos. The de cit should be recouped by neutral current interactions and interactions with atomic electrons from solar neutrinos that transitioned to other weak avors. It expected a solar electron neutrino ux ($_{e\ \mathrm{expected}}$) of (5:1 0:9) 10 ^{6} cm ^{2} s ^{1}; however, it instead measured a ux ($_{e;\mathrm{SNO}}$) of (1:76 0:10) 10 ^{6} cm ^{2} s ^{1} with the di erence being compensated with an additional ux from muon neutrinos and tau neutrinos ($_{;\ \mathrm{SNO}}$ + $_{;\ \mathrm{SNO}}$) of (3:41 0:63) 10 ^{6} cm ^{2} s ^{1} [7, 17]. The ux of muon neutrinos and tau neutrinos were measured to compensate the de cit in solar electron neutrinos observed between data and simulation. Figure IV plots the ux measurements of solar neutrinos taken at SNO, specifically the non-zero ux from muon and tau neutrinos [7, 17]. Both SNO and Super-Kamiokande revealed proof that neutrinos mix between avor states on their travels to the detectors. They answered Ray Davis' solar neutrino problem and the atmospheric neutrino anomaly by discovering they were due to neutrinos transitioning between avors. SNO and Super-Kamiokande's measurements showing mixing between neutrino avors earned Arthur McDonald of SNO and Takaaki Kajita of Super-Kamiokande the Nobel Prize in Physics in 2015.

The contemporary age of neutrino physics aims at measuring neutrino oscillations and the characteristics of neutrino interactions. These experiments include long-baseline experiments like NOvA and Tokai-to-Kamiokande (T2K) that measure neutrino oscillation parameters primarily through a beam of neutrinos traveling hundreds of kilometers to a large detector [18, 19]. Smaller experiments exist measuring neutrino oscillations from a beam traveling a few hundred meters like ICARUS and MicroBooNE [20]. Experiments not using a neutrino beam for neutrino oscillation measurements include the nu-

Figure IV: Flux of solar neutrinos measured using SNO data. Figure from [17].

clear reactor experiment Daya Bay and the atmospheric and cosmic neutrino experiment IceCube [21, 22]. The largest future experiments for neutrino physics are Hyper-Kamiokande and the Deep Underground Neutrino Experiment (DUNE), both of which hope to have high precision measurements of as many neutrino oscillation parameters as possible [23, 24].

1.2 The Standard Model

Neutrinos are known to transition to di erent weak avors thanks to experimental evidence from SNO and Super-Kamiokande. Neutrinos are leptons in the Standard Model. This section and the following section will explain the physics and mathematics that serve as the foundation of the Standard Model of particle physics and neutrino oscillation physics.

The Standard Model is a Lagrangian that forms the basis for particle

physics. The Standard Model Lagrangian forms a local symmetry group of $SU(3)_C x SU(2)_L x U(1)_Y$, where S represents the group being special with its determinant of one and U represents the unitarity of the group. As an example of how to interpret these terms,$SU(3)_C$ means that it is a Lie group with a determinant of one with 3 by 3 dimensions characterized by the variable C [1, 25]. The variables (C, L, Y) in these equations relate to speci c characteristics of the symmetry group terms. The parameter C represents the color of the elements in the group.$SU(3)_C$ represents quantum chromodynamics (QCD), which the massless gluon gauge boson mediates [25]. Gluons ultimately tie quarks together through the strong force. Leptons, such as neutrinos, do not interact with QCD. Therefore, the digression on QCD ends here. The $SU(2)_L x U(1)_Y$ group represents the electroweak sector, with L representing left-handed chirality and Y representing hypercharge [25].

The Standard Model has three generations of leptons and quarks. These particles are fermions. Quarks couple to the weak, electromagnetic, gravitational, and strong forces. Charged leptons experience the weak, electromagnetic, and gravitational forces. Neutrinos, which are neutral leptons, only experience the weak and gravitational forces. Table I shows an outline of the quarks and leptons known in the Standard Model [7].

Type	Leptons	Quarks
1st Generation	e (electron), $_e$ (electron neutrino)	u $^{2=3}$ (up), d $^{1=3}$ (down)
2nd Generation	(muon), (muon neutrino)	c $^{2=3}$ (charm), s $^{1=3}$ (strange)
3rd Generation	(tau), (tau neutrino)	t $^{2=3}$ (top), b $^{1=3}$ (bottom)

Table I: Table of elementary leptons and quarks with their charges sorted by generation [7]. The bottom superscript represents the antimatter equivalent of the charged fermions. Antineutrinos () exist in three identical avors as the antimatter equivalent of neutrinos.

The four gauge bosons considered part of the Standard Model are the pho-

ton, W , Z^0, and gluon. Quarks can couple to any of these bosons. Charged leptons can interact with the photon, W , and Z^0 bosons. Neutrinos, being electromagnetically neutral leptons, only couple to the weak bosons. The weak force gauge bosons are the W and Z^0 bosons. Table II shows the four forces in the Standard Model organized by their respective gauge bosons [7].

Force	Electromagnetic	Weak	Strong
W boson		X	
Z^0 boson		X	
(photon)	X		
gluon			X

Table II: Outline of the forces with the bosons that mediate them [7].

The Higgs mechanism leads to the division of the electroweak sector into the weak force and the electromagnetic force. This mechanism divides the $SU(2)_L xU(1)_L$ portion of the Standard Model through Spontaneous Symmetry Breaking (SSB) [1]. The end result provides the evaluations of the masses for the Higgs boson, the W bosons, and the Z boson.

The Higgs boson can be expressed as a Higgs scalar doublet (t) that is a part of the Lagrangian density (L) with a Higgs potential (V( )) and fermion gauge (D) [25]. Equation 1.3 shows the Lagrangian density for the Higgs mechanism.

$$L = (D \quad)^{y} D \qquad V( ) \tag{1.3}$$

The Higgs doublet consists of a charged vector eld ( ) and a neutral scalar eld (^{0}) [25].

The constraints of being a part of the $SU(2)_L xU(1)_Y$ group ensure that V( ) can only exist as:

$$V(\ ) = \quad {}^{2} \quad {}^{y} + \qquad {}^{y} \quad {}^{2} \tag{1.4}$$

The parameter ^{2} is presumed to be negative, which leads to the $SU(2)_L xU(1)_Y$ group to have an $U(1)_Q$ group emerge. The $U(1)_Q$ group represents the electromagnetic force mediated by the photon [1]. The subscript Q represents electromagnetic charge. The variable can be established as a relationship between and (= $\sqrt{\ ^{2}=\ }$). Substituting this into Equation 1.4 allows one to take a derivative of the Higgs potential expressed in. is found from the minimum of the potential and shown in Equation 1.5 [1].

$$^{y} = \frac{^{2}}{2} \tag{1.5}$$

Making this substitution leads to the solution of the vacuum expectation value of the Higgs eld that the potential is minimized when is at $\frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \end{pmatrix}$ [1]. This doublet represents the vacuum expectation value for the potential in the Lagrangian density in Equation 1.3 with the bottom component representing the neutral scalar eld of the doublet. The vacuum is electrically neutral; therefore, only the neutral scalar eld can gain this vacuum expectation value from the potential [1]. The quanti cation of the physical Higgs boson (H(x)) and its impact on the rest of the Standard Model comes from adding H(x) to the neutral component:

$$= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ {}_{H} + H(x) \end{pmatrix} \tag{1.6}$$

This doublet is placed into Equation 1.3. The doublet with the physical

Higgs bosons (H(x)) allows for the extraction of a mass term of the Higgs through the Lagrangian density:

$$L_{\text{Higgs mass}} = \quad {}^2H^2 = \quad {}^2H^2 \tag{1.7}$$

Equation 1.7 gives the solution that the Higgs mass is $\sqrt{2\ ^2}$. The mass generation of the W and Z bosons also arises from looking at their mass terms when substituting the Higgs doublet with the physical Higgs boson in Equation 1.3. The mass of the W bosons are $\frac{g}{2}$ and the mass of the Z boson is $\frac{g}{2\cos(\ _W)}$, where g is a coupling constant in the electroweak terms of the Lagrangian density and $_W$ is the Weinberg angle [1].

For neutrinos, the generation of their masses depends on if the neutrino is Dirac or Majorana. Being electrically neutral and colorless, neutrinos could theoretically be their own antiparticle, known as a Majorana neutrino. If a neutrino is not its own antiparticle, then the neutrino is considered a Dirac neutrino [25]. There is no experimental con rmation of either and experiments currently are looking for neutrinoless double-beta decay to solve the issue. In a neutrinoless double-beta decay, a nucleus could undergo two beta decays that produce two neutrinos. However, if neutrinos are their own antiparticles they would annihilate one another, leading to no neutrinos in the nal state. The result leads to a speci c energy spectrum for the nal state particles that can be experimentally observed [25]. Current and future experiments continue to look for this signature and, in the meantime, set limits on the frequency of neutrinoless double-beta decay occurring.

The neutrino does not share the same mass eigenstates as the avor eigenstates in Table I. As an example, assuming the neutrino is a Dirac particle, the

Lagrangian density for mass is the following for a triplet of left-handed and right-handed neutrinos ($^{0}_{L;R}$) with a mass matrix (M_D) as seen in Equation 1.8 [25].

$$L = \quad {}^{0}_{L} M_D \; {}^{0}_{R} + \; {}^{0}_{R} M_D^{y} \; {}^{0}_{L} \tag{1.8}$$

The term M_D can be turned into a diagonal matrix using unitary matrices ($A_L{}^{y} M_D A_R$) [25]. The diagonal terms are referred to as m_1, m_2, and m_3. The mass generation of charged leptons is near identical but has a di erent unitary matrix (A^{L}_{R}) to form the diagonal charged lepton mass matrix. As these two matrices are di erent, it allows for neutrinos to mix between mass and weak avor states. These avor state transitions are detected in weak interactions as neutrinos and charged leptons are connected through the weak charged current [1].

Both the neutrino avor state masses and the mass ordering of m_1, m_2, and m_3 are not theoretically ascertained. The mass ordering, sometimes referred to as the neutrino mass hierarchy, is of particular interest for neutrino oscillation experiments. Using neutrino oscillation experiments, it is known that m_2^2 is larger than m_1^2. That leaves two possibilities of the mass ordering of neutrinos that Figure V demonstrates [7]. These possibilities are called the normal hierarchy ($m_1 < m_2 < m_3$) and the inverted hierarchy ($m_3 < m_1 < m_2$). Experiments addressing the masses of neutrinos intend to directly measure the electron neutrino mass, like KATRIN, or use neutrino oscillation measurements to determine the mass ordering [26, 27].

The scalar Higgs boson, vector gauge bosons in Table II, and quarks and leptons in Table I constitute the current understanding of the particles in the

Figure V: Diagram from [7] for the normal mass ordering (left) and inverted mass ordering (right).

Standard Model. Research is ongoing and additions are possible. The most notable potential addition is gravity, which is the missing fundamental force observed but not included currently in the Standard Model [25].

1.3 Basics of Neutrino Oscillations

Because neutrinos have masses, they are allowed to transition to other weak states. The mass states and weak avor states are quanti ed in the PMNS matrix [12]. It is a 3 by 3 matrix that transforms from the neutrino mass states to the neutrino weak avor states. The translation between the two is de ned as such:

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e;1} & U_{e;2} & U_{e;3} \\ U_{\mu;1} & U_{\mu;2} & U_{\mu;3} \\ U_{\tau;1} & U_{\tau;2} & U_{\tau;3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \tag{1.9}$$

The simplest example of neutrino oscillation is the example of neutrino oscillation with only two generations. The derivation comes from constructing a similar unitary mixing matrix. Allowing the ket representing the neutrino to evolve in time leads to possible transitions from one avor state to another [28]. Equation 1.10 shows the mixing matrix for neutrino oscillation limited to two neutrinos. The example has avor states corresponding to the electron

neutrino ($_e$) and muon neutrino ( ) and mass states corresponding to the rst neutrino mass state ($_1$) and second neutrino mass state ($_2$) [28].

$$\begin{bmatrix} U_{1e} & U_{2e} \\ U_1 & U_2 \end{bmatrix} = \begin{bmatrix} \cos(\ ) & \sin(\ ) \\ \sin(\ ) & \cos(\ ) \end{bmatrix} \tag{1.10}$$

With the mixing matrix, the following parameterization of the neutrino mass states of two neutrinos can be made as such:

$$|\ _e\rangle = \cos(\ )|\ _1\rangle + \sin(\ )|\ _2\rangle \tag{1.11}$$

$$|\ \rangle = \sin(\ )|\ _1\rangle \quad \cos(\ )|\ _2\rangle \tag{1.12}$$

After time evolving (t) the neutrino state ($|\ (t)\rangle$), the probability that a neutrino initially in the electron avor ($|\ (0)\rangle = |\ _e\rangle$) remains an electron avored neutrino upon detection can be obtained. The rst step uses the mixing matrix and nds the initial vector in terms of the mass states and neutrino avor states. Assuming the mass of the neutrino (m) is much smaller than the energy of the neutrino (E), it travels near the speed of light (c) and a Taylor approximation is made using the neutrino momentum (p) derived in Equation 1.13. Another approximation made is that because the neutrino travels near the speed of light (c), then the time evolution can be evaluated as the distance traveled by the neutrino $t(= L = c)$ [7].

$$E = \sqrt{m^2c^4 + p^2c^2} \quad pc \quad 1 + \frac{m^2c^2}{2p^2} \tag{1.13}$$

The time-evolved state is:

$$j\ \ (E;t)\,i = \cos(\ )e^{\ \ iE_1t=\sim}j\ _1i + \sin(\ \ )e^{\ \ iE_2t=\sim}j\ _2i \tag{1.14}$$

Substituting the mass states gives:

$$\begin{aligned} j\ \ (E;t)\,i = {} & \cos(\ )e^{\ \ iE_1t=\sim}(\cos(\ )j\ _ei \quad \sin(\ )j\ \ \ i)+ \\ & \sin(\ )e^{\ \ iE_2t=\sim}(\sin(\ )j\ _ei + \cos(\ )j\ \ \ i) \end{aligned} \tag{1.15}$$

The algebra simpli es to the following:

$$\begin{aligned} j\ \ (E;t)\,i = {} & (\cos^2(\ )e^{\ \ iE_1t=\sim} + \sin^2(\ )e^{\ \ iE_2t=\sim})j\ _ei + \\ & \cos(\ )\sin(\ )(e^{\ \ iE_2t=\sim} \quad e^{\ \ iE_1t=\sim})j\ \ \ i \end{aligned} \tag{1.16}$$

The variables for the neutrino's distance traveled and neutrino's energy are substituted into Equation 1.16. As the mass is much smaller than its energy, the momentum (p) is also approximately equivalent to the neutrino energy (E). Multiplying the corresponding $h\ _ej$ bra to the ket leads to the probability as:

$$P\ _{e!\ \ e}(L;E) = 1 \quad P\ _{e!\ \ \ \ } = 1 \quad \sin^2(2\ \ )\sin^2\ \frac{Lc^3(m_2^2 \quad m_1^2)}{4E\sim} \tag{1.17}$$

If neutrinos were massless, then neutrino oscillation would not be possible. The probability of observing a neutrino as a di erent avor would be zero as the mass squared di erence would be zero. With only two generations of neutrinos, the probability that the neutrino is now in the muon weak state is the complement of Equation 1.17 $P\ _{e!\ \ \ \ } = 1 \quad P\ _{e!\ \ e} = \sin^2(2\ \ )\sin^2\ \frac{Lc^3(m_2^2 \quad m_1^2)}{4E\sim}$.

The PMNS matrix, in its current form, uses all three known generations

of neutrinos and merely expands from a 2 by 2 mixing matrix to a 3 by 3 mixing matrix. A few interesting concepts come out of the derivation of the mixing matrix. First, there are now three mixing angles between the various generations ($_{12}$, $_{13}$, and $_{23}$), three mass states, and an interesting property of a CP-violating phase ($_{CP}$). A CP-violating phase adds a complex phase to the mixing. The addition of two new angles and a new mass state appears logical as each of the three generations of active neutrinos can mix with one another [25]. The less obvious CP-violating phase comes from the parameter requirements placed on the 3 by 3 unitary mixing matrix. These parameters have similar equivalents in the Cabibbo -Kobayashi Maskawa (CKM) matrix for quark mixing. The CKM matrix, because it has similar constraints to its 3 by 3 mixing matrix, also contains a CP-violating phase [25].

Equation 1.18 shows the PMNS matrix derived for three generations of neutrino states. In the full PMNS matrix, the symbols labeled such as c_{xy} and s_{xy} correspond to the cosine and sine of the mixing angle $_{xy}$, respectively [1].

$$\begin{bmatrix} U_{e;1} & U_{e;2} & U_{e;3} \\ U_{;1} & U_{;2} & U_{;3} \\ U_{;1} & U_{;2} & U_{;3} \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\ _{CP}} \\ (s_{12}c_{23} + c_{12}s_{13}s_{23}e^{i\ _{CP}}) & c_{12}c_{23} & s_{12}s_{13}s_{23}e^{i\ _{CP}} \quad c_{13}s_{23} \\ s_{12}s_{23} & c_{12}s_{13}c_{23}e^{i\ _{CP}} & (c_{12}s_{23} + s_{12}s_{13}c_{23}e^{i\ _{CP}}) \quad c_{13}c_{23} \end{bmatrix} \tag{1.18}$$

The PMNS matrix in Equation 1.18 assumes the neutrino is Dirac. An additional two phases are added if the neutrino is found to be Majorana [25]. These new parameters are called $_1$ and $_2$. The PMNS matrix would then have the following matrix multiplied on its diagonal:

$$\begin{bmatrix} e^{i\ 1} & 0 & 0 \\ 0 & e^{i\ 2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1.19}$$

The neutrino oscillation probabilities for three generations of neutrinos use the PMNS matrix and time evolve similarly to the much more simplistic example of neutrino oscillation with two avors (Equation 1.16) [1, 12]. The resulting probability is shown below.

$$P_{\ !\ }(L;E) = \begin{array}{l} 4\sum_{j>i}^{n} R\ U_{\ j}U_{\ j}U_{\ i}U_{\ i}\ \sin^2\left[\frac{m_j^2\ \ m_i^2\ \ Lc^3}{4E\sim}\right] \\ 2\sum_{j>i}^{n} I\ \ U_{\ j}U_{\ j}U_{\ i}U_{\ i}\ \sin\left[\frac{m_j^2\ \ m_i^2\ \ Lc^3}{2E\sim}\right] \end{array} \tag{1.20}$$

The third term is positive for neutrinos and negative for antineutrinos [1]. Neutrino experiments measure neutrino oscillation by counting the neutrino avor at the detector and comparing it to the expectation as a function of the distance traveled divided by the neutrino energy (L/E) [7]. Fitting the data provides information on the mixing angles and squared di erences of the mass states. With the wide variety of parameters in neutrino oscillation probabilities (Equation 1.20), experiments can have low precision or only probe speci c parameters. Experiments consider this and use their expected L/E to formulate constrained measurements of parameters. For example, the former experiment MINOS used a beam from Fermilab that traveled to a far detector site at the Soudan Iron Mine in Minnesota to measure neutrino oscillation parameters. MINOS measured $P_{\ !\ }$, amongst other analyses. Given the

neutrino energy provided by the beam at Fermilab (1-5 GeV) and the baseline from Fermilab in Batavia, Illinois to the mine (735 km), MINOS was able to measure the di erence betweem_2 and m_3 ($j\ m\ {}^{2}_{23}j = 2{:}3 \quad 0{:}1 \quad 10\ {}^{3}\ eV^2$) and provided a constraint that $\sin^2(2\ {}_{23}) \ \&\ 0{:}9$ [7, 29].

1.4 Neutrino Cross Sections

Experiments measure neutrino oscillation parameters by detecting the rate and spectrum of neutrinos that scatter o a detector's target material and comparing that rate to the expectation of the rate from the source of neutrinos [1]. The neutrino rarely interacts through the weak force, via the W or Z bosons, with leptons and nucleons. Neutrino cross section measurements seek to clarify the rate of neutrinos scattering o a target. Interactions mediated with a W boson are considered charged current (CC) interactions and those mediated with the Z boson are considered neutral current (NC) interactions. The Lagrangian densities for neutrinos undergoing weak interactions are shown in Equation 1.21 and Equation 1.22 [1].

$$L^{CC}_{l;L} = \frac{g}{2\sqrt{2}}\ j_{W;L}W \ + j^{y}_{W;L}W^{y} \tag{1.21}$$

$$L^{NC}_{l;} = \frac{g}{2\cos(\ {}_{W})}\ j_{Z;}\ Z \tag{1.22}$$

The charged and neutral currents (j) are de ned in Equation 1.23 and Equation 1.24, respectively.

$$j_{W;L} = \sum_{=e;;} \quad 1 \quad {}^{5} \; l \tag{1.23}$$

$$j_{Z;} = 0:5 \sum_{=e;;} \quad 1 \quad {}^{5} \tag{1.24}$$

Neutrinos cross sections are divided into various interaction types. The simplest classi cation method identi es a neutrino interaction based on their mediating boson and the other initial state particle in the interaction. There are four general types of interactions of a neutrino on a target. Figure VI shows the four possible interactions [7].

Figure VI: Feynman diagrams for four common neutrino interactions mediated by the W and Z bosons. From [7].

Identifying the neutrino avor state in the interaction enables neutrino oscillations to count the avor and spectrum of neutrinos that reach the detector. Therefore, CC interactions represent the most important type of interaction for neutrino oscillation experiments as the nal state lepton (l) can identify the initial neutrino's avor ($_{l}$) [1]. These predominantly are interactions o atomic electrons or nucleons. A CC interaction with an electron is shown in the leftmost diagram and a CC interaction with a nucleon is displayed in the second leftmost diagram in Figure VI.

To reconstruct the neutrino energy of an interaction, every nal state particle needs to be identi ed and have its energy measured. Neutrinos are elec-

tromagnetically neutral; therefore, they make no direct signal indicating their travel in the detector. Only the nal state particles from a weak interaction can provide information on an initial state neutrino. A myriad of di erent nal state particles then could arise from the basic diagrams in Figure VI.

Figure VII shows the distribution of the cross section of CC interactions on nucleons with the exclusive cross sections relative to the total CC cross section. The most common CC interaction o a nucleon at neutrino energy approximately 1 GeV and lower is the quasi-elastic interaction (QE) [30]. It is also represented in the second leftmost diagram in Figure VI. A CCQE interaction comes from a neutrino scattering o a neutron with a proton and charged lepton in the nal state. The more complex channels represented in Figure VII are the deep inelastic (DIS) and resonant (RES) interactions, which typically lead to multiple hadrons in the nal state of the interaction. Figure VIII shows the nal state particles across 0-5 GeV. Ostensibly, most of the particles in the nal state are pions and nucleons. A small portion of interactions with neutrino energies near 5 GeV will have a kaon in the nal state [30].

Modern neutrino experiments typically use carbon or argon as targets for neutrino scattering events [18, 24, 31]. These nuclei add complexity to the observed nal state particles from the interaction because the nal state particles of the interaction need to escape the target nucleus. The interaction of an outgoing particle with the nucleus is considered an intranuclear interaction or a nal state interaction. It is typically quanti ed with an intranuclear reactive cross section [32]. Some common in-depth descriptors for inelastic intranuclear interactions are those of absorption, production, and charge exchange. Absorption interactions lead to the potential nal state particle being lost in

Figure VII: CC cross section on nucleons as a function of energy with both inclusive and exclusive channels plotted from [30].

Figure VIII: Fraction of events divided amongst the particles in the nal state. The separation between the lines represents the fraction of events. Figure from [30].

the intranuclear interactions. Production interactions lead to new nal state particles appearing from intermediary particles interacting with the nucleus. A charge exchange interaction changes the charge of the outgoing nal state particle. For example, it can turn a charged pion into a neutral pion or a proton into a neutron.

Final state interactions of hadrons within the nucleus are near impossible to measure. Modeling remains the primary method for neutrino experiments to understand how these interactions impact neutrino oscillation and cross section measurements. These models use reactive cross section measurements of hadrons at well-understood energies traversing through a target, such as carbon. The measurements are then interpreted to handle the complexities of traveling through the nucleus for simulations of neutrino interactions [32].

A Monte Carlo event generator uses models of cross section data, neutrino interaction theory, and reactive hadron cross sections to generate simulations of neutrino interactions. The following section will discuss how an experiment can leverage an event generator to engender Monte Carlo data sets that better resemble cross section measurements from experiments like T2K and MiniBooNE.

1.5 Case Study of a Cross Section Tune for MicroBooNE

Cross sections of neutrinos will determine the rate of certain events observed by the neutrino detector. Therefore, neutrino cross section measurements are necessary for oscillation experiments to understand how many ob-

served events to predict and the neutrino energy distribution of the events. However, robust simulations need to be developed to understand the modeling of nal state particles that emerge from neutrino events. Neutrino interaction event generators exist to inform these predictions, including simulation packages such as GENIE, NuWro, and NEUT [33, 34, 35]. Despite the numerous empirical and theoretical inputs to the simulation software, gaps exist between data and Monte Carlo simulations. These gaps can cause signi cant discrepancies between the data of an experiment and its simulation that can reduce the accuracy and precision of a neutrino oscillation or neutrino cross section measurement. Experiments can tune the event generator of the experiment to alter the shape and normalization of neutrino interactions to adjudicate modeling choices and discrepancies. The tune establishes a new central-value set of inputs for the simulation. The new parameter values alter the nominal Monte Carlo neutrino data set to form an improved Monte Carlo data set of neutrino events.

As a case study, the thesis will explain the MicroBooNE tune done on the GENIE event generator using cross section data sets for muon neutrinos. MicroBooNE is a short-baseline neutrino experiment hundreds of meters away from a neutrino beam at Fermilab that consists primarily of muon neutrinos [36]. It intends to prototype the liquid argon detector technology, measure neutrino cross sections, and investigate the low-energy excess of electron neutrinos reported by LSND and MiniBooNE [36, 37]. The event generator for simulating neutrino interactions impacts the latter two goals of MicroBooNE. This case study comes from personal work done on a forthcoming MicroBooNE publication written with a small group of colleagues, speci cally Kirsty Du y, Steve Dytman, and Steven Gardiner. A paper based on the work below will be

submitted to Physical Review Dand the arxiv as a MicroBooNE collaboration paper entitled New Theory-driven GENIE Tune for MicroBooNE. It is also an update of the event generator tune and event reweighting scheme included in a previous MicroBooNE public technical note [38].

GENIE is a widely used neutrino event generator used by experiments like DUNE, MicroBooNE, and NOvA [33]. MicroBooNE more speci cally utilizes the GENIE v3.0.6 G18_10a_02_11a simulation [39, 40]. MicroBooNE uses the Fermilab Booster Neutrino Beam (BNB), which has an energy range of 0-2 GeV with 93.6% of neutrinos being muon neutrinos [31]. With that energy range, the Fermilab BNB roughly covers the CCQE peak of the neutrino cross section distribution (Figure VII) [30]. CCQE events eject a single nucleon from the target nucleus and dominate the charge current events measured with MicroBooNE's beam.

In addition to quasi-elastic events, CC two particle-two hole (CC2p2h) events may appear at the beam energy range. For these CC2p2h interactions, a second nucleon leaves the target nucleus leading to two nal state nucleons with two corresponding holes in the target nucleus. Therefore, most events in MicroBooNE with zero pions are CC interactions that have either one or two nucleons in the nal state. GENIE v3.0.6G18_10a_02_11a simulates both processes through the Valencia model of quasi-elastic and 2p2h events [41, 42, 43, 44]. The Valencia modeling was chosen, in particular, as its implementation in GENIE is speci cally designed to simulate CC2p2h and CCQE events near 1 GeV.

After choosing an event generator, the next step in establishing an event generator tune involves selecting relevant data sets to tune. Little data exists on argon; therefore, MicroBooNE decided to use a di erent target nucleus to

understand its cross section modeling. Because of this, the 2016 T2K Analysis 1 near detector data set of muon neutrinos with zero pions in the nal state was chosen [45]. This data set uses a hydrocarbon target from ND280, T2K's near detector 280 m away from the target of the experiment's neutrino beam. The 2016 T2K charged current data contains CCQE and CC2p2h events with minimum background from other event types such as CC1 events. The data published by T2K produced a double-di erential cross section as a function of the outgoing muon's momentum and angle relative to the T2K beam [45]. Table III shows the global binning of the double-di erential cross section. Distributions of truth-level variables from out-of-the-box GENIE simulated events were generated for GENIE v3.06 618_10a_02_11a and GENIE v2.12.2. Figure IX compares those two Monte Carlo data sets to the T2K data set. Unfortunately, apparent normalization issues appear evident as neither out-of-the-box simulation could obtain a match to the T2K data.

cos	p (GeV/c)	Global bin numbers
-1.00, 0.00	0, 0.3, 0.4, 30	1 3
0.00, 0.60	0, 0.3, 0.4, 0.5, 0.6, 30	4 8
0.60, 0.70	0, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 30	9 15
0.70, 0.80	0, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 30	16 22
0.80, 0.85	0, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 1, 30	23 30
0.85, 0.90	0, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 1, 1.5, 30	31 39
0.90, 0.94	0, 0.4, 0.5, 0.6, 0.7, 0.8, 1.25, 2, 30	40 47
0.94, 0.98	0, 0.4, 0.5, 0.6, 0.7, 0.8, 1, 1.25, 1.5, 2, 3, 30	48 58
0.98, 1.00	0, 0.5, 0.6, 0.7, 0.8, 1.25, 2, 3, 5, 30	59 67

Table III: Table of bin edges for the ux-averaged T2K CC0 data set in terms of cos and p [45].

Figure IX: Comparison of the ux-averaged T2K CC0 data and two versions of the GENIE neutrino event generator [45]. The shading represents di erent slices of the cross section in terms of the cos( ) as described in Table III. Only errors on the data from the diagonal of the covariance matrix are used for the ^{2} calculation.

Modeling gaps ostensibly exist given the large ^{2} values in Figure IX. Looking individually at slices of the double-di erential cross section in Figure X, the discrepancies appear regardless of the outgoing muon cos( ). Both Figure IX and Figure X show clear tension in normalization between the simulation and data and between the two di erent versions of GENIE.

To reduce the discrepancies between simulation and data, the simulation is tuned for a variety of parameters. MicroBooNE opted for a theory-driven tune that selects parameters that answer outlying questions on the normalization

Figure X: Plot of ux-averaged T2K CC0 cross section for two slices of cos( ) from 0.8 to 0.85 (top) and 0.98 to 1.00 (bottom) [45].

of neutrino events and the shape of their nal state particle kinematics. These parameters modify the existing simulation into a new prediction with di erent kinematic distributions and normalizations of cross section channels. The creation of altered data sets comes from GENIE Reweight, a reweighting package for GENIE [33, 39, 46]. The emphasis for a theory-driven tune of CCQE and CC2p2h events led MicroBooNE to select the following parameters to tune:

- Axial mass of CCQE interactions: The axial mass in the form factor of CCQE interactions is altered. The modulation is related to the overall normalization of CCQE events. Increasing the axial mass, therefore, increases the normalization of CCQE events in the prediction.

- Norm. of CC2p2h events : As the name implies, the parameter increases or decreases the normalization of CC2p2h events. It will be interesting to monitor the nal result of tuning CC2p2h events as they are a non-negligible portion for data sets taken at energies around 1 GeV. For example, Figure XI shows the distribution of true neutrino energy for a simulation of CC events at MicroBooNE with GENIE v3.0.6 G18_10a_02_11a Roughly, the simulation predicts approximately 20% of all CC interactions will be CC2p2h events.

- CCQE Random Phase Approximation (RPA): The Valencia CCQE model corrects for long-range correlations in the nucleus using the RPA for the neutrino interaction. The parameter takes into account the uncertainty on the Valencia CCQE RPA corrections strength, which directly impacts the suppression of low Q^2 events. Q^2 is the square of the four-momentum transfer. The nominal value of 100% sets the RPA correction at its nominal Valencia model strength. The parameter as

Figure XI: Energy distribution of CC events sorted by inclusive and 2p2h events.

implemented can also increase the correction strength by 100% or turn o the Valencia CCQE RPA correction entirely. Figure XII shows the overall e ect this parameter has on CCQE events on argon with the Fermilab BNB ux at MicroBooNE. As the RPA correction increases strength, low Q^2 events are suppressed. The opposite occurs with the reduction of the Valencia CCQE RPA correction. Figure XIII shows the overall e ect this has on the slices of the T2K CC0 ux-averaged cross section. Bins with shallow angled muons (cos 1) of the cross section contain more low Q^2 events. Therefore, the absence of the correction increases the amount of forward-going events by eliminating low Q^2 suppression.

Figure XII: Distributions of Q^2 for simulated CCQE events with varying degrees of the Valencia CCQE RPA correction strength. Figure by Steven Gardiner.

Figure XIII: The most forwards-going slice of T2K CC0 data compared to GENIE v3.0.6 G18_10a_02_11a with the CCQE RPA correction and without the CCQE RPA correction [45].

- Cross section shape of CC2p2h events: The tune uses a specific knob made for MicroBooNE that tunes CC2p2h events between the Valencia model used in GENIE v3.0.6 G18_10a_02_11a and the GENIE Empirical cross section model used in GENIE v2.12.2 [47]. It uses a parameter (k) with a range from zero to one. The Valencia model distribution is declared the nominal distribution (k=0). The GENIE Empirical distribution is considered the fully reweighted distribution (k=1). Figure XIV shows the impact the parameter has on the GENIE simulation. Changes are noticeable for the most forward-going bin.

Figure XIV: Flux-averaged cross section at two di erent bins of T2K data compared to GENIE v3.0.6G18_10a_02_11awith the nominal Valencia CC2p2h shape and the GENIE Empirical shape. The bins chosen have cos( ) from 0.60 to 0.70 (top) and 0.98 to 1.00 (bottom) [45].

The parameter creates a noticeable di erence in the three-momentum transfer and energy transfer of the CC2p2h events. The parameter reweighting was tested by taking the expected Fermilab BNB ux used by MicroBooNE and generating inclusive charged current neutrino events (Figure XV). When the CC2p2h components of the sample are separated, a clear di erence exists between the GENIE Empirical implementation of CC2p2h in GENIE v2.12.2 and the Valencia model used in GENIE v3.0.6 G18_10a_02_11a [47]. The distribution is a function of energy transfer (q^0) and three-momentum transfer (q^3). The Valencia model has two peaks in the distribution, while the GENIE Empirical model has a distribution with a single peak. The reweighting attempts to go between these signi cantly di erent model distributions to cover model di erences between the older GENIE v2.12.2 and the newer GENIE v3.0.6 with the Valencia CC2p2h modeling [41, 47].

These parameters alter the simulation by reweighting individual events in the data set using GENIE Reweight [39, 40, 46]. The CC2p2h shape and RPA CCQE parameters are custom made for GENIE Reweight by MicroBooNE collaborators.

The MicroBooNE GENIE tune was created by reweighting a data set generated by GENIE and optimizing the reweighting parameters through a t to data using a software package called NUISANCE [48]. To operate, NUISANCE also uses ROOT and MINUIT for its tting calculations and plot generation [49, 50]. The tting mechanism with MINUIT in NUISANCE will increment the reweighting parameters until the di erence between the data and simulation is minimized as calculated by a ^{2} metric. Figure XVI shows

Figure XV: GENIE truth-level distributions of the energy transfer and three-momentum transfer for CC2p2h events generated on argon with the MicroBooNE simulated ux. The Valencia model is the top plot and the reweighted simulation to the GENIE Empirical model is the bottom plot [41, 47]. Figure by Steven Gardiner.

the nal performance of the measured MicroBooNE tune on the T2K CC0 data using the four parameters chosen. Table IV reveals the evolution of the t as each parameter is added.

Figure XVI: Flux-averaged T2K CC0 cross section data compared to GENIE v3.0.6 G18_10a_02_11a and the MicroBooNE tune [45]. Only errors on the data from the diagonal of the covariance matrix are used for the ^{2} calculation.

The MicroBooNE tune signi cantly improves the agreement between the simulation and data. It nearly eliminates the normalization di erences from out-of-the-box GENIE simulations and has a ^{2}=d:o:f: of approximately 1.

	$M_{A;CCQE}$ value	Norm. CC2p2h value	CCQE RPA value	CC2p2h shape value	T2K ^{2}=N_{bins}
Nominal	0.961242 GeV	1	100%	0	106.7/58
CCQE Axial Mass + Norm. CC2p2h	1.14 0.07 GeV	1.61 0.19	100% (xed)	0 (xed)	71.8/58
CCQE Axial Mass + CC2p2h Norm. + CCQE RPA	1.18 0.08 GeV	1.12 0.38	(64 23)%	0 (xed)	69.7/58
MicroBooNE Tune	1.10 0.07 GeV	1.66 0.19	(85 32)%	$1^{+0}_{0:74}$	52.5/58

Table IV: Parameter values for the MicroBooNE tune using ux-averaged CC0 T2K data. The last bin in each slice of cos( ) is considered part of the over ow and is omitted from the t, reducing the total bins of the t to 58 bins. Table by Kirsty Du y.

The preferred parameter values of the MicroBooNE tune to T2K data lead to the following interpretations:

- Tuned CCQE axial mass : The tune preferred an increase of 0.138 GeV of the axial mass of CCQE. The measured increase leads to a higher normalization of CCQE events. Every iteration of the tune desired a higher axial mass than the nominal Valencia CCQE modeling of GENIE v3.0.6 intended.

- Tuned 2p2h Normalization : The tune also reported an increase in the normalization of CC2p2h events to reduce. The tune increases the parameter by 66% of the nominal CC2p2h normalization of GENIE v3.0.6 G18_10a_02_11a

- Tuned 2p2h shape parameter : Although the default simulation used the Valencia 2p2h cross section modeling, the t showed that the data had less tension with the simulation when the simulation was reweighted to the GENIE Empirical CC2p2h cross section shape.

- Tune Valencia CCQE RPA correction : The tune preferred a slight reduction of 15% of the RPA CCQE correction, which leads to more events with low Q^2.

A correlation matrix was created for the tting of the tune parameters as shown in Figure XVII. Some acceptable correlations exist for o -diagonal elements in the matrix. For example, the normalization parameters have a slight anti-correlation. There is an observed anti-correlation between the CCQE RPA and CC2p2h normalization parameters. However, these were not considered abnormal enough to warrant concern.

Figure XVII: Correlation matrix from t to T2K CC0 data.

Comparisons of the MicroBooNE tune to MiniBooNE data show more encouraging signs of the MicroBooNE tune's performance. MiniBooNE, which used a mineral oil target, uniquely uses the same beam as MicroBooNE. Therefore, MiniBooNE data should have similarities with MicroBooNE data and is a reasonable test for the MicroBooNE GENIE tune. The data set used for comparison was the MiniBooNE CCQE-like double-di erential cross section measurement [51]. Its events are sorted into the kinetic energy of the nal state muon and the cosine of the nal state muon angle. The publication itself merely reports the CCQE cross section. Therefore, to form the CCQE-like cross section, the nal state pion absorption correction in the CCQE analysis is removed [51]. This was done to reduce the nal state interaction model dependency of the cross section data in MiniBooNE. Table V shows the rel-

ative binning of the MiniBooNE double-di erential CCQE-like analysis. Figure XVIII displays the MicroBooNE tune applied to simulated MiniBooNE events with their comparison to the published CCQE-like data [51].

T (GeV)	cos( )	Global bin numbers
0.2 0.3	-1.0 1.0	1 20
0.3 0.4	-1.0 1.0	21 40
0.4 0.5	-0.7 1.0	41 57
0.5 0.6	-0.3 1.0	58-70
0.6 0.7	-0.2 1.0	71-82
0.7 0.8	0.1 1.0	82 91
0.8 0.9	0.2 1.0	92 99
0.9 1.0	0.4 1.0	100 105
1.0 1.1	0.4 1.0	106 111
1.1 1.2	0.5 1.0	112 116
1.2 1.3	0.5 1.0	117 121
1.3 1.4	0.6 1.0	122 125
1.4 1.5	0.7 1.0	126 128
1.5 1.6	0.7 1.0	129 131
1.6 1.7	0.8 1.0	132 133
1.7 1.8	0.8 1.0	134 135
1.8 1.9	0.9 1.0	136
1.9 2.0	0.9 1.0	137

Table V: MiniBooNE ux-averaged double-di erential CCQE-like cross section bin edges and their global bin numbers. The binning of the cross section is of equal slices of 0.1 GeV in muon kinetic energy and 0.1 in the cosine of the muon angle [51]. The binning means there are 20 bins of cos( ) for T from 0.2 to 0.3 GeV.

The MicroBooNE tune far exceeds the performance of GENIE v3.0.6 G18_10a_02_11a; however, some signi cant discrepancies between the MicroBooNE tune and MiniBooNE data still exist. These mainly occur at low muon kinetic energy as seen in Figure XIX, where there appears a shape difference as a function of muon angle. As the MicroBooNE tune is not tted to MiniBooNE data, these di erences were considered tolerable.

When the events have nal state muons near parallel to the beam, the

Figure XVIII: Comparison of MiniBooNE CCQE-like data with GENIE v3.0.6 G18_10a_02_11a and the MicroBooNE tune [51]. Shaded regions are slices of the cross section in terms of the outgoing muon's kinetic energy. Only errors on the diagonal of a covariance matrix were published.

MicroBooNE tune agrees reasonably well with the MiniBooNE data as shown in Figure XX. It encouragingly suggests that the tune robustly adjusts the normalization and can match the forward outgoing muon bins reported in the cross section data despite being tuned to data from a di erent experiment.

Figure XIX: Comparisons between the MicroBooNE tune and MiniBooNE CCQE-like ux-averaged data for the lowest kinetic energy bin (top) and second lowest kinetic energy bin (bottom) [51].

Figure XX: Comparisons between the MicroBooNE tune and MiniBooNE CCQE-like ux-averaged data for the second most forwards-going muon angle bin (top) and the most forwards-going muon angle bin (bottom) [51].

The nal validation of the MicroBooNE tune investigated its performance on MicroBooNE data itself. The MicroBooNE tune of simulated events was plotted against data from a generic neutrino interaction selection [52]. The

GENIE v3.0.6 G18_10a_02_11a simulation underestimates the normalization of MicroBooNE events. The MicroBooNE tune, even though tted to T2K data, xes that discrepancy and increases the overall normalization of the simulation. The MicroBooNE collaboration considers the comparison in Figure XXI as a sign that the MicroBooNE tune decreases data-to-simulation discrepancies. The MicroBooNE collaboration has adopted this GENIE tune as its baseline neutrino interaction simulation since the fall of 2020 and, as of September 2021, continues to use it.

Figure XXI: MicroBooNE WireCell generic event selection data compared with GENIE v3.0.6 G18_10a_02_11a out-of-the-box (top) and with the MicroBooNE tune (bottom). Adapted gures from [52].

The development of event generator tunes requires further investigation to bene t current and future measurements of neutrino oscillation experiments. Future versions plan to add other exclusive event channels to the tune and

generate tunes that experiments with higher neutrino energies can employ. Neutrino oscillation experiments will continue to use central-value tunes to understand modeling uncertainties. In the future, these tunes will likely be more descriptive as event generators improve in their modeling and computational exibility. Therefore, in-depth investigations of the MicroBooNE tune and tuning event generators will be necessary to provide consummate event generators for the DUNE and Hyper-K generation of experiments. A tune of an event generator is already used for simulations evaluating DUNE's sensitivities in measuring various neutrino oscillation parameters [27].

Chapter 2

Basics of DUNE and its Physics Program

This chapter delineates the DUNE program, its detectors, and the prospects of meeting its physics goals. The focus will be on highlighting potential problems. Ideally, prototypes of the detector and measurements of the passage and interaction of particles in argon will forestall any possible obstacles.

2.1 Motivation for DUNE

If simpli ed to its highest priority measurements, DUNE is a long-baseline neutrino experiment with a Near Detector complex in Fermilab and a Far Detector complex in the Sanford Underground Research Facility near Lead, South Dakota. Figure XXII shows a conceptual diagram of the detector complexes with the neutrino beam traveling from right-to-left to the Far Detector site in South Dakota [24]. As the beam travels to South Dakota, the weak avor of

the neutrino may change in a process referred to as neutrino oscillation. The beam will be a 1.2 MW neutrino beam with1:1 10^{21} protons on target per year. Plans exist to upgrade the beam to 2.4 MW at a later date [24]. DUNE can measure neutrino oscillation parameters by measuring the weak avor and energy of neutrinos measured at the Near Detector and Far Detector sites [24]. The Far Detector site aims to have four 10 kT liquid argon detector modules underground. These four modules will be approximately 1.5 km underground, with the earth providing signi cant shielding from cosmic-ray muons. Due to the low cosmic-ray background and the capabilities of a liquid argon detector, DUNE can thoroughly search for proton decay, detect neutrinos from a supernova, and explore physics beyond the Standard Model (BSM) [24].

Figure XXII: Diagram of DUNE baseline with the DUNE neutrino beam traveling to the Far Detector site (right to left). Cartoon from [24].

The Near Detector (ND) site will measure neutrino interactions at a distance of 0.575 km from the neutrino beam. It contains a liquid argon detector (ND-LAr), a gaseous argon detector (ND-GAr), and a System for on-Axis Neutrino Detection (SAND) [53]. ND-LAr and ND-GAr will be able to move 30 m o -axis from the beam to enable the Near Detector to probe speci c energy regions of the beam and understand the ux o -axis. SAND intends

Figure XXIII: DUNE Near Detector conceptual diagram with the three systems. These system are, from left to right, SAND, ND-GAr, and ND-LAr. The neutrino beam enters from the right of the image taken from [53].

to have the required statistics to monitor the DUNE neutrino beam on the timescale of a week. Figure XXIII has a diagram of the Near Detector taken from the DUNE Near Detector Conceptual Design Review [53].

DUNE's four topics of investigation that serve as their objectives include the following below [54].

- Neutrino oscillation physics: DUNE hopes to have the sensitivity to detect neutrino interactions from beam, atmospheric, solar, and possibly cosmic sources [54]. With the high-intensity beam from Fermilab, the goal of the beam neutrino analyses would be to attempt to measure mixing angles in the PMNS matrix, the mass hierarchy, and the Dirac CP-violating phase (Equation 1.18).

- Baryon number violation searches: DUNE plans to look for instances in which the baryon number of an event is not conserved. The most fruitful proposals at the moment are looking for neutron-antineutron oscillation

and proton decay [55].

- BSM searches: The topic here is a catch-all term for all ancillary searches for BSM not included in the previous two programs. They could rely on the neutrino beam to search for exotic nal states that involve coupling to unknown bosons. These searches could also look for abnormal events in the DUNE Far Detector, such as remnants of dark matter annihilation from the Sun [54].

- Supernova neutrinos: It has been decades since a supernova close to Earth has been observed. If one were to be observed, the neutrinos from the event would provide de nitive evidence of which mass hierarchy of neutrinos is preferred [54]. Figure XXIV shows an example event rate of a supernova event. It shows that the mass hierarchy of the neutrino mass states can be determined from the event rate over time.

Figure XXIV: Evolution of the event rate during a supernova with 40 kT of argon in the DUNE Far Detector cavern at a distance of 10 kpc away from the supernova. Time-dependent plot from [54].

The highest priority for DUNE is to measure neutrino oscillation param-

eters from the beam at Fermilab to the Far Detector site in South Dakota. If an asymmetry between the measurements for neutrinos and antineutrinos exists greater than the expectation, DUNE will have measured CP-violation in the lepton sector [24]. Theories propose that CP-violation in the lepton sector could explain the matter-to-antimatter asymmetry in the early universe.

2.2 Liquid Argon Time Projection Chamber Technology

To achieve the lofty goals of measuring the neutrino mass hierarchy and $_{CP}$ in the lepton sector, DUNE will use liquid argon time projection chambers (LArTPCs) to measure the tracking and calorimetry of leptons and hadrons that arise as the nal state particles from neutrinos scattering on argon nuclei. As a noble atom, argon does not recapture ionized electrons, leading to a pure signal of ionization electrons and scintillation light in the argon [24]. A time projection chamber drifts these ionized electrons from their ionization deposit location to the detector's sensors for measurement. The time it takes the signal to reach the sensors and the location of the sensors allow the detector to nd the ionization deposit's original location [24]. By measuring the position of ionization deposits and the number of ionized electrons in the deposits, a TPC can reconstruct the tracking and calorimetry of a charged particle that ionized the electrons. Algorithms can then further identify the charged particle and its origin. The combination of tracking and calorimetry information allows o ine imaging of events as continuous tracks and showers in the detector.

For a TPC with readout wires, wires on a detector wall detect ionized

electrons as they drift in an electric eld inside the TPC to the wires. In total, DUNE plans to use four 10 kT detectors at a Far Detector site in Lead, South Dakota [24]. At the time of writing, all of these detectors are assumed to be liquid argon TPCs. DUNE is prototyping its detector module designs with the ProtoDUNE Single-Phase (ProtoDUNE-SP) program. ProtoDUNE-SP's rst detector ran from 2018 to 2020 at the CERN Neutrino Platform. It was a LArTPC that contained 419 tons of instrumented liquid argon [56].

The readout wires are placed on what is referred to as the Anode Plane Array (APA). Both DUNE and ProtoDUNE use three separate planes of wires on their APAs that run at di erent angles up and down the height of the detector. Only two planes of wires are necessary to measure a position in three dimensions. The usage of three planes provides redundancy. This redundancy is a widely used aspect of liquid argon detectors. For example, MicroBooNE and ICARUS also use three separate wire planes to measure ionized electrons in their liquid argon TPCs [36, 57].

The wire planes are labeled as the U, V, and W planes. The U and V wire planes lie at an angle of 35.7 degrees relative to the height of DUNE and ProtoDUNE-SP. The third wire plane runs parallel to the height of the detector and will be labeled the W plane in this thesis. A fourth plane not involved in readout is also on the APA, referred to as the grid plane (G plane). It protects the detector from electrostatic discharge and is behind the readout wires [56]. Figure XXV is a diagram of these four wire planes that constitute the APA. The APA in Figure XXV is instrumented with the longer side installed vertically in the cryostat [58]. Most experiments using this technology employ a wire pitch near 5 mm from wire-to-wire. ProtoDUNE-SP has a wire pitch of 4.67 mm for induction wires and 4.79 mm for collection wires [56].

Figure XXV: Diagram from [58] of ProtoDUNE Single-Phase module wire planes.

The U and V wires detect drifting electrons via induction. Therefore, they have a bipolar signal that is positive as the drifting electrons come towards the wires and then negative as they pass the wires. They nish their drift on the W wire plane, also known as the collection plane [58]. As the name suggests, the collection plane collects the drifting electrons in a single unipolar pulse. Each signal on a wire undergoes digitization via an analog-to-digital converter (ADC), which for DUNE will operate within parts of the detector kept at cryogenic temperatures [58].

The U, V, and W wire planes provide a two-dimensional location of the track, typically referred to as the height (Y) and length (Z) location for the ionized electron deposit. The time it takes for the ionized electrons to drift to the wire planes allows the wires to reconstruct the track in three-dimensional space by giving the position of the track along the drift distance or width of the detector (X).

Altogether, the size of the hit signals on the wire enables the TPC to measure the dE/dx of the particle track. Figure XXVI shows an example

Figure XXVI: Example diagram of a single-phase liquid argon TPC detecting the travel of charged particles from a neutrino interaction through the readout of ionized electrons that drifted to the readout wires. Figure from [36].

of a particle track that ionizes electrons that drift to the wire plane and the resulting signals on each wire plane with the lines laid on top of the signals representing the tracking and the magnitudes of the signals providing the calorimetry [36].

The electric eld is generated by a Cathode Plane Assembly (CPA) [58]. ProtoDUNE-SP had an electric eld of 500 V/cm, accomplished through -180 kV being placed on the CPA. The CPA is made of various individual panels of the berglass-epoxy composite material FR4 [56]. The electric eld drifts the ionized electrons at a rate referred to as the drift velocity. With a similar detector to that in Figure XXVI, the electric eld of 500 V/cm should provide a drift velocity of approximately 1.6 mm/ s [56]. Knowledge of the drift velocity

determines the position of an ionization deposit in terms of its drift distance.

The detector technology for LArTPCs is susceptible to multiple detector e ects despite its theoretical ability to measure each ionized electron engendered from a charged particle. Proceeding sections will cover possible issues with LArTPCs and the methods of ProtoDUNE-SP to calibrate for these effects. As a preamble to these discussions, a list of detector e ects for a LArTPC includes:

- Electronegative Impurities: Molecules like oxygen and water may contaminate the TPC's liquid argon and capture ionized electrons. Systems for argon recirculation and ltration intend to eliminate impurities out of the liquid argon [59, 60]. However, this process is not perfect and some impurities could still exist in the TPC. Ionized electrons that drift through more liquid argon are more susceptible to capture from these electronegative impurities. Therefore, this detector e ect is quanti ed by measuring the attenuation as a function of the drift distance traveled by an ionization deposit, known as a drift electron lifetime [59]. With that measurement, the e ect is then calibrated. The process of measuring the drift electron lifetime and its calibration is covered in Section 3.8.

- Drift electron di usion: Ionized electrons drift in an electric eld to the readout wire planes after they separate from their parent liquid argon atoms. However, these free electrons may undergo random walks that lead to a di usion of the electrons as they drift. This di usion could occur either transversely or longitudinally to the drift direction. Readout signals of the detector may experience attenuation and increase in their width due to the di usion of drift electrons [60]. Similar to the drift

electron lifetime, the severity of this e ect is quanti ed as a function of drift distance [58]. This e ect is not typically directly calibrated, but instead quanti ed to improve the accuracy of the detector simulation.

- Electronics and Field Response of Readout Wires: Readout wires of the single-phase TPC are connected to ADCs that digitize the amount of charge detected on the wires. Issues with broken or dead wires may arise that would cause a loss of signal. Other detector issues could appear. For example, the wires may be unable to reconstruct tracks because of the tracks' angle relative to the readout wires. The ADC could have nonlinearity e ects and electronics noise that lead to distorted digitized signals [58]. Furthermore, the ionized electrons may induce charge on not only the wire it drifts to, but also on nearby wires [61]. The induced charge on nearby wires can extend the tracks even in ideal TPCs. Modeling and calibrating wire response discrepancies between data and simulation can control for these potential issues.

- Space charge e ect and electric eld distortions: Some liquid argon TPCs sit on the Earth's surface, such as ProtoDUNE-SP and MicroBooNE. Unfortunately, this leads to a high ux of cosmic-ray muons. ProtoDUNE-SP, for example, experiences an approximately 20 kHz ux of cosmic muons that creates an excess of ionized electrons and positive argon ions [56]. Those positive argon ions build in the bulk of the detector and cause distortions of the electric eld, referred to as the space charge e ect. Furthermore, misalignment of the CPA, misalignment of the APA, and distortions of the high voltage on the CPA could also cause discrepancies between the global electric eld and the local electric eld

inside the TPC [58]. Since the magnitude and direction of the electric eld impact the drift velocity of drift electrons, the calibration of the electric eld is necessary for precise calorimetry and tracking.

2.3 Neutrino Oscillation Measurements at DUNE

DUNE aims to measure neutrino mixing angles, the relative order of the neutrino masses, and the CP-violating phase. To solve the mass hierarchy problem and measure the CP-violating phase in particular, DUNE will analyze both disappearance and $_e$ appearance [27]. The two analyses will then be repeated to instead look for disappearance and $_e$ appearance. The term disappearance refers to the fact that the DUNE neutrino beam is predominantly a muon neutrino beam, as seen in Figure XXVII [54]. Therefore, the rate of muon neutrinos reaching the Far Detector should be lower than at the Near Detector due to neutrino oscillations [27]. Appearance analyses look for an excess of a neutrino avor. DUNE measures the appearance of electron neutrinos and tau neutrinos from its primarily muon neutrino beam.

Figure XXVII: Planned neutrino beam ux as observed at the DUNE Far Detector running in neutrino mode (left) and antineutrino mode (right). Plot from [54].

The probability of a muon neutrino being detected as an electron neutrino at the Far Detector site is shown in Figure XXVIII. In addition, Figure XXIX reveals the same information for antineutrinos. Both distributions assume the normal ordering of the mass hierarchy ($m_1 < m_2 < m_3$) [27].

Figure XXVIII: Probability of a muon neutrino from the DUNE neutrino beam being detected as an electron neutrino at the Far Detector site. Plot from [27].

Figure XXIX: Probability of a muon antineutrino from the DUNE neutrino beam being detected as an electron antineutrino at the Far Detector site. Plot from [27].

These predicted probabilities in Figure XXVIII and Figure XXIX will then be compared to the spectrum and rate of neutrinos detected at the DUNE Far Detector and DUNE Near Detector. Sensitivity curves have been constructed by tting the predicted distributions. Figure XXX displays the sensitivity of the DUNE program to measure and reach a conclusion on the mass hierarchy of neutrinos [27]. It should be noted that the beam operates at 1.2 MW and at least one 10 kT detector will operate at the Far Detector site. With that beam and only a single Far Detector module, Figure XXX shows that the mass ordering problem can be solved by DUNE for all values of the CP-violating phase in less than ten years [27].

A similar curve can be made with the CP-violating phase as seen in Figure XXXI [27]. Both Figure XXX and Figure XXXI come from full mock-up simulations of both the Near Detector and Far Detector. The systematic uncertainties applied to evaluate the sensitivities come from the neutrino interaction modeling and expected detector resolution given detector speci cations and calibration plans [27].

Figure XXX: Plot of the exposure to the beam required to determine the mass hierarchy of the neutrino mass states. Image from [27].

Figure XXXI: Plot from [27] of the exposure to the beam required to reach a discovery on the CP-violating phase.

Suppose the CP-violating phase is at $= 2$. In that case, DUNE has a strong chance of measuring it to ve standard deviations in approximately a decade of operation, given the beam upgrade to 2.4 MW and the construction of all four Far Detector modules [27]. Issues may still arise, which is why ProtoDUNE-SP proactively tries to understand liquid argon detectors and charged particle passage in argon.

2.4 Proton Decay Searches at DUNE

The theoretical success of the Standard Model led to further ventures by theorists. A natural idea was to formulate a uni cation of everything into a Grand Uni ed Theory (GUT). A GUT would emerge from a SU(5) Lie group or a SO(10) symmetry group [25]. Baryon number violation is predicted by some GUT models. Baryons include neutrons and protons, which have baryon numbers of 1. Proton decay is then predicted by GUTs and large detectors could probe for it. Famously, proton decay searches were main drivers for detectors that would become well known for neutrino oscillation measurements like Super-Kamiokande [62, 63].

The two most popular decay channels for nucleon decay searches are $p^+ \; ! \quad {}^0 + l^+$ and $p^+ \; ! \quad K^+ + \quad$. However, a channel of interest for DUNE is the decay channel of a proton to a kaon and a neutrino [55]. The focus is due to Super-Kamiokande already setting strong limits on the decay channel to a neutral pion and a charged lepton. Currently, Super-Kamiokande has a limit at the 90% level of $7.7*10^{33}$ years for the $p^+ \; ! \quad {}^0 + \quad {}^+$ decay channel and $1.6*10^{34}$ years for the $p^+ \; ! \quad {}^0 + e^+$ decay channel [63].

DUNE has several advantages over the Super-Kamiokande detector that enable it to probe deeper into the search for proton decay to a kaon in the nal state. The most notable comes from its ability to detect low momentum charged particles traveling in liquid argon. Experiments, such as ArgoNeuT, have found an ability to measure charged particles at the MeV-scale using liquid argon detectors [64]. While Super-Kamiokande has searched for this decay channel, the water Cherenkov detector cannot directly measure the monoenergetic kaons from the decay process. Instead, the detector looks for the

detectable decay products of the kaon, such as an isolated muon with a discrete momentum at 231 MeV/c or a positive pion with a neutral pion [62]. DUNE eliminates the need for an indirect search for proton decay by allowing for the direct identi cation of an isolated kaon with a momentum of 339 MeV/c [55]. Ideally, a proton decay event display would reveal a kaon traveling several centimeters in the detector, stopping in the detector, and then decaying. Figure XXXII shows a simulated event display of a kaon appearing in the detector and then decaying to a muon [55].

To measure proton decay or at least set competitive limits, DUNE needs to understand kaons in argon and investigate potential background events. Identifying kaons is accomplished by measuring the unique Bragg peak of dE/dx that kaons exhibit as they stop in argon. Unfortunately, kaons have a very similar dE/dx to protons at high residual range; therefore, the kaon needs to stop to allow for particle identi cation. The kaon can undergo intranuclear scattering while leaving the nucleus or scatter o the liquid argon while traversing the detector, sometimes referred to as hadronic rescattering [55]. Both types of interactions reduce the ability of reconstruction methods to identify the original kaon and determine the kaon's initial momentum.

However, atmospheric neutrinos can interact with the liquid argon and produce kaons in the nal state [30]. These atmospheric neutrino interactions can also have protons in their nal states that appear kaon-like given a myriad of e ects. Constraining kaon production and understanding atmospheric neutrino uxes increases the ability for DUNE to handle these possible issues. An example of a proton imitating the signal of a kaon in a proton decay event is shown in Figure XXXIII [55].

The priority of DUNE's proton decay program, until the DUNE Far De-

Figure XXXII: A simulated event display of a proton decay with a kaon (green) and the resulting muon from its decay (red). The muon then stops in the detector and emits a Michel electron. The displays are of each wire plane with the x-axis being the wire number and the y-axis being the time of the readout. The rst two images at the top are of the induction planes and the third is of the collection plane. Image from [55].

Figure XXXIII: Simulated event display from [55] of + n ! p^+ + from an atmospheric neutrino interaction. The proton (green) and muon (red) tracks look nearly identical to Figure XXXII despite being a simulation of an entirely di erent physics process.

Figure XXXIV: Reactive (red) and elastic (blue) cross sections for K^+ on argon in Geant4 [65, 68].

tector modules are constructed, lies in simulating the reconstruction of such a decay and understanding the calorimetry and cross section of kaons in argon. Figure XXXIV shows the inelastic and elastic cross sections of a positively charged kaon as a function of momentum using Geant4 [65, 66, 67]. Calculations were aided by code from Geant4Reweight [68]. The approximately 300 MeV/c kaon that is predicted will have a cross section that is a part of the sharp rise at low kinetic energy. ProtoDUNE-SP has analyses studying the particle passage of kaons. One such analysis is the kaon total inelastic cross section that will be discussed in Chapter 4.

Chapter 3

Overview of the ProtoDUNE-SP Detector

This chapter speci cally highlights the ProtoDUNE-SP LArTPC detector and calibration. The ProtoDUNE-SP program ran its rst single-phase detector from 2018 to 2020. Speci c highlights in this chapter are the measurements of low electronegative impurities in the argon for an extended period of time using cosmic-ray muons and a purity monitoring system. The liquid argon impurity was measured consistently lower than 30 ppt oxygen equivalent using cosmic-ray muons, which exceeds the technical design requirements of the DUNE Far Detector modules [56].

3.1 Detector Dimensions

The ProtoDUNE-SP detector contains six APAs, three attached to each sidewall of the detector. Each drift volume has a drift distance of 3.597 m. The drift length gives a total drift volume, otherwise known as the width of

Figure XXXV: Diagram of the ProtoDUNE-SP cryostat from [56].

the detector, of approximately 7.2 m. The sidewalls have TPCs that are 6.086 m high. The total length of the active detector is 7.045 m. ProtoDUNE-SP has in total 15,360 instrumented wires [56]. Figure XXXV displays the ProtoDUNE-SP cryostat. There are three APAs on the visible side in the diagram and three APAs on the other side of the detector.

In addition to the six modular TPCs from the six APAs, ProtoDUNE-SP also includes three subsystems. They are a beamline monitoring system for the test beam, an array of scintillator strips placed outside the cryostat known

as the Cosmic Ray Tagger (CRT), and arrays of photodetectors placed behind the APAs known as the Photon Detection System (PDS) [69].

3.2 Motivation of ProtoDUNE

The DUNE Far Detector will measure charged particles and use the tracking and calorimetry of the charged particles to reconstruct neutrino interactions or potential nucleon decay events. Since neither nucleon decay events nor neutrino interactions reveal their initial states, charged particle reconstruction remains the only way for DUNE to measure physics related to its objectives. Two challenges then arise. The rst involves demonstrating a detector's ability to track particles in the detector and measure their energies. The second involves using information about particle passage in argon to better model physics in simulation [56]. The ProtoDUNE program was developed to empower the DUNE Far Detector to tackle these issues. To do so, it will evaluate its detector performance and also measure parameters related to charged particles in argon that can improve the simulation of events in the Far Detector modules.

The ProtoDUNE prototype program operates single-phase and dual-phase liquid argon TPC detectors. The single-phase and dual-phase detectors were based at the CERN Neutrino Platform in Neutrino Platform 4 and Neutrino Platform 2, respectively. This thesis will focus on the physics of the single-phase prototype, referred to as ProtoDUNE-SP. The initial focus for members of ProtoDUNE-SP from 2018 to 2019 was in evaluating the detector performance and comparing the results to the DUNE Far Detector technical speci- cations [56]. Some results, such as tests of the liquid argon impurity, will be

included in the proceeding sections. Characterization of the whole TPC performance has been published and represents the rst data analysis publication from ProtoDUNE-SP [56].

In terms of providing real-world physics output to the DUNE Far Detector analyses, ProtoDUNE-SP also serves as a test beam experiment that can measure the energy deposited for charged particles as a function of kinetic energy and cross sections of hadrons on argon [56]. The latter is the most important for DUNE as elastic and inelastic scatters o liquid argon can prevent an accurate identi cation of a particle and measurement of its total energy. These issues can then impact neutrino physics analyses and baron number violation searches by potentially causing the topology of the event to be misidenti ed and by biasing the total reconstructed energy of the event. ProtoDUNE-SP intends to use a test beam of charged hadrons, muons, and electrons to investigate the properties of particles in liquid argon and ensure that the issues above do not impact the eventual physics analyses of DUNE.

Pions are potential nal state particles of interest for DUNE. The DUNE PIP-II neutrino beam will reach the Far Detector complex with a ux observed in Figure XXVII [54]. The neutrino ux has many neutrinos that will reach the DUNE Far Detector with energies above 1 GeV. Above these energies, resonant and deep inelastic scattering events become much more common (Figure VII) [30]. These events will produce pions that may scatter before stopping in the detector. Understanding how often they scatter o the argon through ProtoDUNE-SP can improve the precision in event reconstruction. The same is true for protons and kaons when they emerge as the nal state particles of a physics processes. The focus on ProtoDUNE-SP, in particular, is on pions due to their prominence in predicted neutrino interaction events (Figure VIII)

[30].

The simulation of charged particles in liquid argon is modeled by DUNE and ProtoDUNE-SP through Geant4, a software package that simulates particle passage in matter [65, 66, 67]. There are two main scattering types for hadrons in liquid argon as classi ed by Geant4, elastic and reactive scattering. Reactive scattering will be referred to as inelastic scattering throughout this work. Figure XXXVI and Figure XXXVII show the inelastic and elastic cross sections for pions and protons as simulated by Geant4. ProtoDUNE-SP intends to measure these cross sections using the test beam and enable DUNE to tune its simulation to better account for nal state hadrons scattering o of argon in the TPC. Geant4 v4.10.6 will be used throughout this work with calculations aided by code from Geant4Reweight [65, 66, 67, 68].

Figure XXXVI: Inelastic (red) and elastic (blue) cross sections for pions on argon in Geant4 [65, 68].

Figure XXXVII: Inelastic (red) and elastic (blue) cross sections for protons on argon in Geant4 [65, 68].

3.3 Simulation and Reconstruction Software

ProtoDUNE-SP is simulated using the LArSoft software package [70]. LArSoft software simulates events from the generator stage to reconstruction and is also the software framework that operates the data reconstruction. LArSoft uses ROOT to process, save, and store information from data and simulation [50, 71]. The simulated events start at a generator stage that models events with test beam particles only, cosmic-ray muons only, or events with both cosmic-ray muons and test beam particles. The proton-on-beryllium interaction that produces the ProtoDUNE-SP test beam particle is fully simulated. The next step in the simulation uses Geant4 to create ionization deposits and scintillation light of the generated particles traversing the LArTPC and its subsystems [65]. The drifting of ionized electrons and detector readout are then simulated, including the readout of the CRT and PDS. The CRT, in par-

ticular, contains a CRT module trigger simulation that creates mock triggers when Geant4 leaves a su cient deposit of energy in a single CRT scintillator strip. This simulation of the CRT was implemented with code from myself, Hans Wenzel, and Andrew Olivier [72, 73].

ProtoDUNE-SP LArTPC reconstructs data and simulation in two steps. The rst step is hit reconstruction, which takes signals on the induction and collection wires. The corresponding signals read from the LArTPC's ADCs are noise ltered and deconvolved. The deconvolved signals are then tted to Gaussian functions to form Gaussian hits with peaks, integrals, and standard deviations associated with all tted hits [56].

The next process in event reconstruction is the de nition of tracks and showers in the detector. ProtoDUNE-SP uses the Pandora software package to reconstruct tracks and showers in the detector [74, 75]. It uses pattern recognition algorithms to nd 2D clusters generated from the results of the TPC hit reconstruction. Algorithms match two-dimensional clusters across all three wire planes and then create three-dimensional space points based on the algorithms' ndings.

Pandora then sorts information in the detector. The most critical designations for ProtoDUNE-SP are if signals constitute a track or shower and if the tracks or showers are cosmic-ray particles or test beam particles [56, 75]. The former decision on if signals constitute a track or shower comes about from Pandora's algorithms looking for straight lines (tracks from muons or charged hadrons) or wide cones (electromagnetic showers from electrons or photons) from the information in the hit reconstruction. The decision on if a particle is cosmic or from the test beam starts with cutting out tracks that enter the top or bottom of the detector and eliminating tracks out-of-time with the beam-

line trigger. At the nal step, Pandora runs the particle through a boosted decision tree to decide if it meets the criteria for a test beam particle candidate [56].

After classifying associated 2D clusters, Pandora and the ProtoDUNE-SP LArTPC reconstruction will then associate tracking and calorimetry variables with the tracks and showers identi ed. This step includes saving the endpoints of the track or shower, saving the track length, and calculating the energy deposited per unit length (dE/dx) [56, 70]. Variables such as these are then compiled into a data product for storage in ROOT. The resulting les in data and simulation have the same detector readout and reconstruction products, except that the TPC triggering information exists only in data. The simulation les include backtracking information from LArSoft and Geant4 to better understand distortions from the detector and quantify the e ciency and purity of the event selections of analyses.

3.4 Test Beam of ProtoDUNE-SP

The almost two years of operation included two months of data-taking from a test beam that originated from the CERN Super Proton Synchrotron (SPS) [56]. The beam particles that reach ProtoDUNE-SP come from a tertiary beamline. The primary beam from the CERN SPS travels to a beryllium target, where a secondary beam emerges. The secondary beam consists of an array of hadrons at around 80 GeV/c that hit another target, either tungsten or copper, that creates a single test beam particle that spans 0.3-7 GeV/c in momentum. The tertiary test beam particle runs through beamline monitors that measure the particle momentum and identi es the particle using a time-

of- ight system and Cherenkov detectors [56]. The tertiary beam is the test beam for ProtoDUNE-SP and can produce muons, electrons, pions, protons, and kaons at di erent momenta. These test beam particles are red one at a time per beam trigger and travel through a beam pipe into the LArTPC. The beam pipe directs the beam into the TPC and attempts to reduce the chance the beam particle will scatter before reaching the TPC. The test beam was in operation from late September 2018 to early November 2018 with Table VI showing the number of beamline triggers of speci c particles [56].

Momentum (GeV/c)	Pion-like (k)	Proton-like (k)	Electron-like (k)	Kaon-like (k)
0.3	0	0	242.5	0
0.5	1.5	1.5	296.3	0
1	381.8	420.8	262.7	0
2	333.0	128.1	173.5	5.4
3	284.1	107.5	113.2	15.6
6	394.5	70.1	197.0	27.9
7	343.7	58.4	112.9	28.2

Table VI: Total number of cumulative triggers for speci c beam momentum settings as a function of candidate particle as reported from the beamline monitoring system.

Figure XXXVIII represents a diagram of the beamline monitoring system, otherwise known as the beamline instrumentation, and Figure XXXIX diagrams the physics of measuring the momentum while directing the beam into the detector [56, 76]. Fibers measure the time-of- ight and tracking of the particle (XBTF and XBPF). The Cherenkov detectors aid in particle identi- cation based on if the detectors read high or low during a trigger (XCET) [56].

Figure XXXVIII: Symbolic representation of the beamline monitoring system from [56].

Figure XXXIX: Schematic of the system that bends and directs the beam towards the ProtoDUNE-SP detector and provides momentum measurements based on the position points (P) and angle ϕ. From [56, 76].

The selection process utilizes the Cherenkov detectors and the time-of- ight measurements shown in Figure XXXVIII. Table VII shows the relevant cuts necessary to select particle candidates given the beamline monitoring system data. Figure XL displays the time-of- ight measurements for various particles at di erent momentum ranges. At high momentum, the Cherenkov detectors

must be relied upon to label candidate beam particles as the time-of- ight measurements between all possible test beam particle types are near identical [56].

		Momentum (GeV/ c)			
Par.	Beam Inst.	1	2	3	6 - 7
e	TOF (ns)	0, 105	0, 105		
	Low Pressure Cherenkov	1	1	1	1
	High Pressure Cherenkov			1	1
=	TOF (ns)	0, 110	0, 103		
	Low Pressure Cherenkov	0	0	0	1
	High Pressure Cherenkov			1	1
K	TOF (ns)				
	Low Pressure Cherenkov			0	0
	High Pressure Cherenkov			0	1
p	TOF (ns)	110, 160	103, 160		
	Low Pressure Cherenkov	0	0	0	0
	High Pressure Cherenkov			0	0

Table VII: Beamline particle identi cation provided by the time-of- ight measurement and readings from the Cherenkov detectors of the beamline monitoring system. Table from [56].

Figure XL: Time-of- ight measurements of candidate particles as identi ed by the beamline monitors. Plot from [56].

The bers provide tracking information that can be corroborated with the

TPC track information provided by Pandora. The combined information can enable better precision of tracking beam particles and help eliminate erroneous events. The latter is accomplished by looking at the distribution between the angular and spatial displacements between the beamline monitoring system track and the TPC track. The cuts vary between the momentum settings of the beam and, to a certain extent, between data and simulation; therefore, this will be revisited during the discussion of the 6 GeV/c positive kaon inelastic cross section on argon analysis (Chapter 4).

Of importance for physics measurements, the beamline monitors provide a momentum measurement of the test beam candidate particle. Simulations have shown that the measurements of the momenta have a resolution of 2.5% [76, 77].

3.5 Detector Triggering

The ProtoDUNE-SP detector saves information by creating events of compiled data from the TPC, CRT, beamline monitors, and photon detectors within a time window. Typically, an event contains a readout window of 3 ms with possibly 5 ms of data from the TPC. The Central Trigger Board (CTB) triggers data collection and represents the data acquisition system [56]. The CTB can be instructed to trigger given the conditions from a system. During operation, only one type of CTB trigger is active at a time typically. Included below are the three most common CTB triggers used during the nearly two years of operation:

- Beam trigger : The beamline monitoring system will report a test beam particle event. The report will tell the CTB to trigger an event.

- Cosmic trigger : If CRT modules upstream and downstream of the TPC report a trigger within a coincidence window, then the CTB will trigger the event when set to a cosmic trigger setting.

- Random trigger : As the name suggests, the CTB will randomly trigger an event at a set frequency. This frequency is typically set to what the computing and data acquisition systems can handle. During runs taken in late 2019, a randomly triggered event was set to occur at a rate of 2 Hz.

3.6 ProtoDUNE-SP Cosmic Ray Tagger

The CRT is a subsystem of refurbished modules of scintillator strips from the Double Chooz experiment's outer veto [78, 79]. It consists of 32 modules that each contain 64 scintillator strips. These strips are approximately 3.2 meters long and 5 cm wide, but the CRT strips are overlaid in a way that the resolution of each CRT module is 2.5 cm for a given direction. That means that a CRT module has dimensions of approximately 3.2 m by 1.6 m. These CRT modules are assembled so they sit either ahead of or behind a CRT module in a perpendicular direction [56]. These orientations translate to one CRT module measuring one direction and the other CRT module measuring the perpendicular direction (Figure XLI). In conjunction with the position of the CRT modules relative to the TPC, the CRT can reconstruct a hit in three dimensions. The proceeding sections will cover more discussions on the reconstruction of the CRT and its ability to aid the TPC.

The CRT only covers the front and back faces of the TPC. Figure XLII

shows the CRT modules relative to the cryostat and the test beam. The CRT modules placed upstream of the TPC are o set relative to the length of the detector [56]. This o set was chosen in order for the pipe that the beam travels through to enter the front face of the TPC without obstruction. Because of the o set placement of the upstream CRT modules, cosmic-ray muons that hit both the TPC and the upstream CRT modules are typically on the upstream CRT modules on the left side of the beam (Figure XLII). The upstream beam left CRT modules are approximately 2.5 m upstream of the TPC and the upstream beam right CRT modules are approximately 9.5 m upstream of the TPC. The downstream CRT modules are roughly 3 m downstream of the end of the TPC [56].

Reconstructing charged particles in ProtoDUNE-SP requires numerous calibration steps to eliminate detector e ects. The initial time the track enters the TPC needs to be well-understood since a TPC measures the x-position based on the time it takes to drift to the readout wires. Unfortunately, the time the detector triggers an event and the time a track travels through the TPC might not be simultaneous. The readout window of an event is 3 ms. However, it takes roughly 100 ns for a track to pass through the entire detector, an order of magnitude of di erence compared to the readout window [56]. The CRT intends to provide timestamps to calibrate timing o sets and externally reconstruct muons entering and exiting the TPC. The following subsections outline CRT reconstruction from creating a three-dimensional hit to matching a CRT track to its counterpart in the TPC.

Figure XLI: Drawing from [56] of downstream CRT modules with them overlaid on top of each other. For the 16 downstream CRT modules, eight CRT modules measure the x-coordinate (long side vertical) and eight CRT modules measure the y-coordinate (long side horizontal).

Figure XLII: Placement of the CRT modules relative to CERN Neutrino Platform 4. Shown are views in front of the cryostat (top) and from above the cryostat (bottom). Beamline travels from left to right from the beamline instrumentation to the cryostat through the beam pipe. Diagrams from [56].

3.6.1 CRT Hit Reconstruction

A CRT module triggers when any strip in the module is above an ADC threshold. Once a CRT module is triggered, the CRT module directly in front or behind it is also triggered. Saved within a single CRT module trigger are the CRT strip ADC values for all 64 strips within a CRT module with one