MicroBooNE investigations on the photon interpretation of the MiniBooNE low energy excess

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Abstract

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The MicroBooNE experiment is a liquid argon time projection chamber with 85-ton active volume at Fermilab, operated from 2015 to 2020 to collect neutrino data from Fermilab's Booster Neutrino Beam. One of MicroBooNE's physics goals is to investigate possible explanations of the low-energy excess observed by the MiniBooNE experiment in $\ !\ _e$ neutrino oscillation measurements. MicroBooNE has performed searches to test hypothetical interpretations of the MiniBooNE low-energy excess, including the underestimation of the photon background or instrinic $_e$ background. This thesis presents MicroBooNE's searches for two neutral current (NC) single-photon production processes that contribute to the photon background of the MiniBooNE measurement: NC resonance production followed by radiative decay: $\ !\ N$, and NC coherent single-photon production. Both searches take advantage of boosted decision trees to yield efficient background rejection, and a high-statistic NC ^{0} measurement to constrain dominant background, and make use of MicroBooNE's first three years of data. The NC $\ !\ N$ measurement yielded a bound on the radiative decay process at 2.3 times the predicted nominal rate at 90% confidence level (C.L.), disfavoring a candidate photon interpretation of the MiniBooNE low-energy excess as a factor of 3.18 times the nominal NC radiative decay rate at the 94.8% C.L. The NC coherent single photon measurement leads to the world's first experimental limit on the cross-section of this process below 1 GeV, of $1.49\ \ 10^{\ 41}$cm^2 at 90% C.L., corresponding to 24.0 times the nominal

prediction.

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To my parents, sis, and grandma.

To my dear grandpa, in loving memory.

Introduction

The eld of neutrino physics has evolved signi cantly in the recent decades in both experimental and theoretical fronts, and has witnessed several milestones over the past century: postulation of neutrino, integration of neutrino in the Standard Model (SM), experimental discovery of neutrinos, and the con rmation of neutrino oscillation. While the neutrinos are massless in the SM theory, experimental observation of neutrino oscillation implies non-zero neutrino mass therefore physics Beyond the Standard Model (BSM). Besides the origin of neutrino mass, there are other remaining questions such as, what is the mass hierarchy of neutrinos, do neutrinos and anti-neutrinos behave the same or differently (CP conservation or CP violation), why is our universe dominated with matter, and do neutrinos have something to do with this? etc. Answering these questions requires precise measurements of neutrino interaction cross-sections and neutrino oscillation parameters.

For muon neutrino ( ) to electron neutrino ($_e$) oscillation measurements, neutral current single photon (NC1) events have been an important background, especially for experiments with dif culty in distinguishing electrons from photons. One such example is the MiniBooNE experiment using a Cherenkov detector, which was designed to measure $_e$ appearance at $\mathcal{O}(1)$ eV^2 neutrino mass-squared difference with a neutrino beam in $\mathcal{O}(1)$ GeV energy regime. MiniBooNE observed an excess above the predicted background in the low energy region, and suffered from large contributions of NC1 backgrounds due to the similarity in Cherenkov rings from electrons and photons.

The NC radiative decay (! N) process dominates NC1 production in the sub-GeV energy regime. This process is a very important background to the MiniBooNE $_e$ measurement

and has not been directly measured in MiniBooNE. With liquid argon time projection chamber (LArTPC) technology, which offers excellent calorimetric and spatial resolution and enables electron versus photon separation, MicroBooNE is well suited to investigate whether the MiniBooNE excess is truly a photon excess or electron excess. MicroBooNE performed a search for NC ! N events, and I was involved in the validation of background modeling and signal ts for the nal result. The result of this search with MicroBooNE's rst three years of data has been published in Physical Review Letters and selected as editors' suggestion.

The NC coherent 1 process is a sub-dominant contribution for NC production, with predicted rate at one tenth of that of NC radiative decay, but understanding the rate of NC coherent 1 is important for future precise neutrino measurements. This process has never been measured experimentally, and I have been leading the search for it in MicroBooNE. As of this writing, this analysis has been unblinded with MicroBooNE's rst three years of data and is in the stage of preparing a paper for submission to Physical Review D.

The operation of the MicroBooNE detector has facilitated exploring the LArTPC technology and R&D studies that are critical for future experiments, such as the upcoming Short-Baseline Near Detector (SBND) as part of the Short-Baseline Neutrino (SBN) program at Fermilab, and the future Deep Underground Neutrino Experiment (DUNE). As part of the Columbia neutrino group at Nevis Labs, I participated in the production test of the TPC readout front-end modules (FEMs) for SBND. I have also studied the sensitivity of the SBN program to neutrino oscillation due to eV-scale sterile neutrinos, and currently been involved with the development of new-generation tting software for this purpose [1]. For the DUNE experiment, I was involved in TPC self-trigggering studies for detecting neutrinos from supernova bursts, based on convolutional neural networks.

This thesis focuses on MicroBooNE's searches for the NC incoherent production, more speci cally NC resonance production followed by radiative decay, and NC coherent. Chapter 1 overviews the history of neutrinos, neutrino oscillation and the MiniBooNE excess. Chapter 2 introduces the MicroBooNE experiment, including neutrino beam and the MicroBooNE detector, followed by a description of the modelling and event reconstruction in MicroBooNE in

Ch. 3. Chapter 4 describes the search for NC π^0 radiative decay. Chapter 5 discusses the NC coherent π^0 process and its simulation in MicroBooNE, and Ch. 6 describes the NC coherent π^0 search in MicroBooNE.

Chapter 1: Neutrinos and Neutrino Oscillation

Neutrinos are one of the elementary matter particles and are known as the most “elusive” ones because they are extremely hard to detect.[1] They are believed to have been generated in abundance in the early universe, and studying the properties of neutrinos would help us probe one of the most fundamental questions: “How did our universe evolve?” This chapter first gives a brief overview of the history of neutrino theory and experimental discovery in Sec. 1.1, then introduces neutrino oscillation and its empirical formalism in Sec. 1.2, 1.3 and 1.4, as well as recent experimental neutrino oscillation anomalies in Sec. 1.5.

1.1 Neutrinos in the Standard Model

1.1.1 Evolution of Neutrino Theory

Neutrino was first postulated in 1930 by W. Pauli as an electrically neutral particle with $\frac{1}{2}$ spin to explain the continuous energy spectrum of electrons emitted from nuclear beta decay,

$$n \rightarrow p + e^- + \bar{\nu}_e \tag{1.1}$$

in an “desperate” attempt to rescue energy conservation law [2]. Later, in 1934, Fermi published his theory of beta decay in conformity with Pauli's proposal and named this new, neutral charge and lightweight particle “neutrino”.[2]

Fermi proposed that the electron and neutrino are emitted during beta decay similarly to photon emission from radioactive nucleus. He assumed that electrons and neutrinos can be created or annihilated and all four particles of the decay interact at the same vertex, and developed the

[1] For 1GeV neutrinos, interaction cross section is 10^{-38} cm^2 per nucleon.

[2] Though Fermi named this neutral particle as “neutrino”, now we know it is actually an antineutrino because of conservation of lepton number.

theory for beta decay [3, 4] in complete analogy with radiation theory [5]. The Lagrangian for the interaction part of four particles is [6]:

$$L_{int} = G_F(\overline{u_p} \quad u_n)(\overline{u_e} \quad u \ ) \tag{1.2}$$

Where G_F is the Fermi coupling constant, u_x is the Dirac spinor of particle x, $\overline{u_x} = u_x^y \ ^0$ is the conjugate Dirac spinor and = are Dirac gamma matrices. Fermi concluded that neutrino has a mass of either zero or very small in comparison to the mass of the electron. Fermi theory is not only useful for the description of the beta decay but also applies to other processes, for example, ! e + + $\overline{\ }_e$ and $^+$! $^+$ + [3].

While many processes can be understood within Fermi's framework, this theory faced several challenges[4], one of which is the violation of parity conservation observed experimentally. Parity transformation (P) is a mirror re ection:

$$P' \ (t; \ x)P \ ^1 = \ _a \ ^{0'} \ (t; \ -x) \tag{1.3}$$

where' is Dirac spinor and $_a$ is a phase term. Parity is a multiplicative quantum number, and particles have intrinsic parity. $\overline{\ }$ ' transforms like a vector under Parity transformation [7], so Fermi's theory conserves parity. However, experimental ndings on K mesons in the 1950s presented a very puzzling situation: two charged mesons $^+$ and $^+$ with different decay modes ($^+$! $^+$ + ^{0} and $^+$! $^+$ + $^+$ + respectively) were found to have nearly identical mass [8, 9] and lifetime [10, 11]. This indicated that $^+$ and $^+$ are the same particle[5], while parity conservation would suggest otherwise: with the intrinsic parity of pion being -1, the parity of $^+$ is thought to be +1, and -1 for $^+$.

[3]For these interactions, the same strength constant G_F applies, hence this class of interactions are also called as "universal Fermi interactions" [7].

[4]In Fermi's theory, only charge-current neutrino interaction was accommodated, not neutral current neutrino scattering. There are also other dif culties such as violation of unitarity for cross section of rst-order scattering process, and divergence of higher-order processes, please see Ref. [7] for more detailed overview.

[5] $^+$ and $^+$ are the same particles, now referred to as K^+.

In 1956, T. D. Lee and C. N. Yang pointed out that while parity conservation is tested to be experimentally true for strong and electromagnetic interactions, it remains a hypothesis for the weak interaction and is not yet backed up by experimental evidence, and proposed several experiments to test parity conservation [12]. A few months after Lee and Yang's paper, C. S. Wu and her collaborators showed that the angular distribution of emitted electron from the beta decay of polarized Co^{60} nuclei is asymmetric [13], evidence that parity conservation is violated in beta decays. Soon after Wu's nding, parity violation was con rmed in muon decay too [14].

In light of the parity non-conservation, in 1957, Lee and Yang proposed a possible two-component theory of neutrinos, where the state of neutrino can be described by a wave function with only two components instead of the usual four [15]. This theory requires the neutrino mass to be zero, and shows that the neutrino always enters the beta-decay interaction in a polarized state (the spin of neutrino will always be parallel to its momentum while vice-versa for the antineutrino)[6]. One limitation of the proposed theory is that it can not explain weak decays that do not involve neutrinos (for example the puzzle). This is acknowledged at the end of their paper: “Perhaps this means that a more fundamental theoretical question should be investigated: the origin of all weak interactions. ”

The 1950's witnessed a signi cant breakthrough in the theoretical development of weak interactions. In 1958, R. P. Feynman and M. Gell-mann went further and suggested a universal (V, A) interaction [18]. Universal (V, A) theory was also independently postulated by E. C. G. Sudarshan and R. E. Marshak [19, 20] in the same year; here we will brie y discuss Feynman and Gell-mann's model following the same notation.

In general, the Lagrangian for the four-particle interaction can be described by:

$$L_{int} = \sum_i C_i (\overline{\psi}_n O_i \psi_p)(\overline{\psi}_\nu O_i \psi_e) \tag{1.4}$$

where ψ_x is the four-component Dirac spinor of particle x, $\overline{\psi}_x$ is the conjugate Dirac spinor, and

[6] At the same year, A. Salam [16] and L. Landau [17] both also proposed theory that violates parity conservation and requires zero neutrino mass.

O_i represents appropriate operators characterizing the decay and weighted by constant C_i. Table 1.1 shows all the possible forms of O_i such that $(\bar{\psi} O_i \psi)$ transforms correctly under Lorentz transformation and $(\bar{\psi}_n O_i \psi_p)(\bar{\psi}_e O_i \psi_e)$ is Lorentz scalar.

O_i	Transformation property of $(\bar{\psi} O_i \psi)$
$O_S = 1$	Scalar (S)
$O_V =$	Vector (V)
$O_T = \quad = \frac{i}{2}[\quad ; \quad]$	Tensor (T)
$O_A = \quad {}_5$	Axial Vector (A)
$O_P = \quad {}_5$	Pseudoscalar (P)

Table 1.1: Five possible transition operators O_i where $\quad$ are Dirac matrices, and ${}_5 \quad i \quad {}_0 \; {}_1 \; {}_2 \; {}_3$. Taken from Tab. 1.2 from Ref. [7] with modi cation.

Instead of replacing only ψ_e by $\frac{1}{2}(1 \quad {}_5)\psi_e$, Feynman and Gell-mann supposed that all particles entering the interaction should be treated in the same way. Projection operator a is defined[7]:

$$a = \frac{1}{2}(1 \quad {}_5) \tag{1.5}$$

${}_5$, the chirality operator has eigenvalues ± 1 corresponding to particles' chirality: left-handed (-1) or right-handed (+1). Operator $\frac{1}{2}(1 \quad {}_5)$ would project Dirac eld' to its left-hand component, and $\frac{1}{2}(1 + \quad {}_5)$ leads to particles' right-hand component.

In this case, the Lagrangian takes the form of

$$L_{int} = \sum_i C_i (\bar{a}_n O_i a_p)(\bar{a}_e O_i a_e) \tag{1.6}$$

Because operators O_S, O_T, and O_P all commute with ${}_5$, only contributions with O_A and O_V coupling remain. Furthermore, since ${}_5^2 = I$ and ${}_5 a = \quad a$ (depending on the sign in a), this

[7] The sign of `+' or `-' for the projection operator was not determined yet when the theory was proposed. Note also that in the original paper, operator a was de ned as $a = \frac{1}{2}(1 \quad i \quad {}_5)$; this was due to a slight change in the de nition of ${}_5$ matrix. Here we are following modern notation of Gamma matrices.

leads to the same coupling for O_A and O_V and the Lagrangian becomes:

$$L_{int} \quad (\overleftarrow{\ }_n \quad a' \ _p)(\overleftarrow{\ } \quad a' \ _e) \tag{1.7}$$

$$(\overleftarrow{\ }_n \quad (1 \quad _5)' \ _p)(\overleftarrow{\ } \quad (1 \quad _5)' \ _e) \tag{1.8}$$

Further applying this rule universally to other weak decays, such as decay, yields the conclusion that the neutrino only enters the interaction in state, i.e. only neutrinos in polarized spin can exist.

This theory yields a two-component neutrino with polarized spin and, due to the mixture of vector and axial vector contribution, gives a violation of the parity conservation. The helicity of neutrinos[8] was reported to be negative in 1958 [21], i.e. the neutrino is a left-handed particle, and its spin is antiparallel to its momentum, consistent with V-A (vector “minus” axial) theory. Neutrinos have been assumed to be massless, spin $\frac{1}{2}$, “left-handed” particles in the theory development since.

The (V-A) theory is a starting point for the formulation of the uni ed electroweak gauge theory. J. Schwinger rst suggested that there could be a synthesis between electromagnetism and weak interactions by introducing an "isotopic" triplet of vector elds, which comprise two electrically-charged massive particle elds mediating the weak interaction – now known as the W^+ and W boson – and a neutral massless photon eld [22]. Extending Schwinger's work, later, S. L. Glashow showed that, with the requirement of “partially-symmetric”[9] Lagrangian and experimental consideration, at least one neutral vector boson Z^0 is needed besides the three elds (including photon) [24], though the masses of W and Z^0 remain arbitrary.

A. Salam and J. C. Ward shared the same idea as Glashow and pointed out that the mass of the neutral vector boson Z^0 should not be massless, and might be at least as massive as the charged vector bosons W [25]. In 1967 S. Weinberg proposed a theory that unites the electromagnetism

[8] For massless particles, helicity and chirality are the same.

[9] Partial symmetry refers to the invariance of only part of the Lagrangian under a group of in nitesimal transformations in Ref. [23].

and weak interaction but spontaneously breaks the symmetry between the two and gives masses to intermediate boson elds (W, Z) [26], by incorporating Brout-Englert-Higgs mechanism [27, 28, 29]. This is now known as electroweak theory, or Glashow-Salam-Weinberg theory, which is an important part of the Standard Model (SM) of particle physics.

1.1.2 Neutrinos in the Standard Model

The SM is a gauge theory developed in the 1950 - 1970s describing electromagnetic, weak and strong interactions. Here we will limit our discussion to electroweak theory related to neutrinos following Ref. [7].

In the SM, neutrinos are assumed to be massless “left-handed” particles, and there are three generations of neutrinos (, and), which together with charged leptons (,) form three generations of lepton families. The left-handed neutrino eld forms an “isospin” doublet with the left-handed component of the charged lepton eld, and the right-handed component of the charged lepton eld by itself forms a singlet:

$$L_l = \frac{1 \quad {}^5}{2} \begin{pmatrix} \quad \\ \quad \end{pmatrix}; \quad R_l = \frac{1+ \quad {}^5}{2} \quad ; \quad l = (e; \; ; \quad)$$ (1.9)

The W and Z boson elds are mixtures of vector elds $\vec{A} = (A^1; A^2; A^3)$ and singlet B with respective coupling constants g and g^0:

$$\text{photon eld: } A \quad = \cos \quad B \quad + \sin \quad A^3$$ (1.10)

$$Z^0 \text{ eld: } Z \quad = \quad \sin \quad B \quad + \cos \quad A^3$$ (1.11)

$$W \text{ elds: } W \quad = \frac{1}{\sqrt{2}}(A^1 \quad iA^2)$$ (1.12)

where mixing angle is the Weinberg angle, and de ned as:

$$\sin \quad = \frac{g^0}{\sqrt{g^2 + g^{02}}}; \quad \cos \quad = \frac{g}{\sqrt{g^2 + g^{02}}}$$ (1.13)

The Lagrangian for lepton-boson interaction writes as:

$$
\begin{aligned}
L^{int} = & \frac{g}{2}\frac{v}{\sqrt{2}}[\bar{\nu}_l (1 \quad {}_5)\gamma^{\mu} {}_l W^{(\ )}_{\mu} + \bar{\nu}_l (1 \quad {}_5)\gamma^{\mu} {}_l W^{(+)}_{\mu}] \\
& + \frac{g}{4\cos}[\bar{\nu}_l (1 \quad {}_5)\gamma^{\mu} {}_l \quad \bar{\nu}_l (1 \quad 4\sin^2 \quad {}_5)\gamma^{\mu} {}_l]Z_{\mu} \\
& e\bar{\nu}_l \quad \gamma^{\mu} {}_l A_{\mu}
\end{aligned}
\tag{1.14}
$$

The Lagrangian prescribes two types of weak interactions neutrinos can participate in:

- Charged current (CC) interaction, mediated by either charged $W^{\pm}$ or charged W^{1} boson as indicated by the rst and second terms in the Lagrangian.
- Neutral current (NC) interaction, mediated by neutral Z^{0} boson, presented by the third term.

The fourth term in the Lagrangian represents the NC interaction of leptons through the Z boson, and the last term corresponds to charged lepton scattering through photon exchange. Figure 1.1 shows the Feynman diagrams of these interactions.

Figure 1.1: Feynman diagrams correponding to Eq. 1.14. Direction of time in the Feynman histogram is from left to right.

Physical W and Z elds gain masses through symmetry-breaking by the Higgs mechanism:

$$
M_W = \frac{g}{2}; \; M_Z = \frac{g}{2\cos} = \frac{M_W}{\cos}
\tag{1.15}
$$

where $\frac{v}{2}$ is vacuum expectation of the Higgs eld. The Lagrangian Eq. 1.14 also indicates some

decay modes of W and Z bosons[10]:

$$W^+ \to l^+ + \bar{\nu}_l; \quad W^+ \to l^+ + \bar{\nu}_l; \quad Z^0 \to l^+ l^- ; \quad Z^0 \to \nu_l \bar{\nu}_l \tag{1.16}$$

Especially for $Z^0 \to \nu_l \bar{\nu}_l$ decay, since neutrinos are hard to detect, this is an "invisible" decay mode. By theoretically calculating the decay width of Z^0 into neutrinos, and experimentally measuring the overall decay width of Z^0 boson and the decay width of Z^0 in other visible decay channels, the number of neutrino avors that interact with Z^0 (with mass $< \frac{M_Z}{2}$) can be determined. This is measured to be $N_\nu = 2.9963 \pm 0.0074$ by the Large Electron Position experiments [30], and agrees with three lepton families.

1.1.3 Experimental Discovery of Neutrinos

After the postulation of the neutrino, it took more than 20 years before it was experimentally observed. The rst electron antineutrino was observed by F. Reines and C. Cowan in 1956 through inverse beta-decay [31]. They made use of two 200-liter water targets located near a ssion reactor with a large ux of electron antineutrinos and observed the signal from positron annihilation and neutron capture, both of which are products of the inverse beta decay:

$$\bar{\nu}_e + p \to e^+ + n \tag{1.17}$$

The second neutrino species was discovered by L. Lederman, M. Schwartz and J. Steinberger [32] in 1962 in an experiment at Brookhaven Alternating Gradient Synchrotron accelerator. The neutrino beam was created by the decay-in- ight of pions produced by bombarding 15 GeV protons on the Beryllium target. Muon tracks produced by the neutrino interactions were observed instead of electrons expected from electron neutrino interactions, thus showing that there are at least two types of neutrinos distinct from each other: electron neutrino and muon neutrino.

[10] W and Z bosons also couple to quarks, and can decay to hadrons as well, which in fact has overall larger branching ratio than decay into leptons.

Tau neutrino, the third species, was not experimentally found until 2000 by the DONUT experiment [33] at Fermilab, though its existence was implied by the discovery of tau lepton in 1975 [34], both of which form the third-generation lepton family. Tau neutrino interaction was identi ed by the tau lepton from the neutrino interaction vertex. Because the tau lepton is very heavy with a rest mass of 1.8GeV, the DONUT experiment made use of a proton beam with energy as high as 800 GeV colliding with a tungsten target, producing charged mesons, which subsequently decay and generate high-energy neutrinos. Four tau neutrino interactions were observed by DONUT, with an estimated background of 0.34 events, establishing the evidence of the existence of tau neutrino.

1.2 Evidence of Non-zero Neutrino Mass

While it was widely believed that neutrinos were massless particles through the 1970s, the rst hint of non-zero neutrino mass came from a series of solar neutrino measurements starting in the late 1960s, which led to the so-called “solar neutrino problem” [35].

The rst solar neutrino measurement was made by the Homestake experiment of R. Davis and his collaborators [36]. They utilized a cylindrical tank of 520 tones of chlorine to detect neutrinos from the Sun through CC interaction $^{37}Cl + {}_e \; ! \; {}^{37}Ar + e$. A total of 108 solar neutrinos were observed during 25 years (1970 - 1994), and the combined result yielded a reaction rate of neutrinos from B^8 decay in the Sun at $2:56 \quad 0:16$(statistical) $\quad 0:16$(systematic) solar neutrino units (SNU, de ned as one interaction per 10^{36} atoms per second) [37]. This was much lower than the standard solar model prediction of $8:5 \quad 1:8$ SNU [38].

Other experiments also observed a reduced neutrino ux from the Sun: radiochemical gallium-based experiments (GALLEX [39] and SAGE [40]) that measure neutrinos through gallium interaction $^{71}Ga + {}_e \; ! \; {}^{71}Ge + e$, and water-based experiments (Kamiokande [41] and Super-Kamiokande [42]) that measure neutrino-electron scattering. While these experiments differ in detector material and technologies as well as the neutrino energy they are sensitive to, all reported that the measured neutrino ux to be one-half or a third of the standard solar model prediction.

While many explanations were raised to explain the observed de cit (such as errors in the solar

model assumption or unknown experimental error), a lot was ruled out. One plausible explanation was neutrino oscillation, an idea rst proposed by B. Pontecorvo [43] in 1957, where he pointed out that like the K^0 meson, a neutrino could be a mixed particle with the possibility of neutrino oscillation. In 1985 S. P. Mikheyev and A. Yu. Smirnov discovered that in the matter of the Sun, the mixing of neutrinos could be resonantly enhanced and thus could explain the measured de cit even with a very small mixing angle [44].

The solar neutrino problem was nally resolved in 2002 when Sudbury Neutrino Observatory (SNO) published result of measured solar neutrino ux using the NC interaction [45]:

$$_x + d \,!\; p + n + \;_x$$

where x could be any type of neutrinos. The total ux measured with NC interaction was found to be consistent with the solar model prediction. This, together with different levels of de cits observed in the CC and elastic-scattering channels, provided strong evidence that solar electron neutrinos experience avor transitions between their generation in the core of the Sun and their arrival on Earth[11].

The rst rm evidence of neutrino oscillation came from the Super-Kamiokande (Super-K) experiment in 1998 [47]. Super-K measured atmospheric muon neutrinos and observed a de cit in the number of muon neutrinos with zenith angle dependence – the number of upward-going neutrinos (which arrive at the detector after traveling through the earth) was half of the number of downward-going neutrinos, while assuming no neutrino oscillation the prediction is at over the zenith angle.

The experimental observations of the SNO and Super-K experiments established neutrino a-vor transformation – electron neutrino disappearance by the SNO experiment and muon neutrino disappearance by the Super-K experiment, respectively – and de nitively con rmed that neutrinos have non-zero mass; these pioneering observations were recognized with the 2015 Nobel Prize in

[11]The oscillation of electron neutrinos is enhanced by the Mikheyev–Smirnov–Wolfenstein (MSW) effect in the medium of the Sun [46].

Physics [48].

1.3 Introducing Non-zero Neutrino Mass in Minimal Extension to the Standard Model

This section brie y describes how the SM can be extended to accommodate neutrinos with masses. Two possible mass terms could be constructed for neutrinos: Dirac mass term or Majorana mass term, where neutrinos are treated either as Dirac particles or Majorana particles[12].

1.3.1 Dirac Neutrino Mass

In the SM electroweak theory, all quarks and charged fermions get their masses through the Yukawa couplings with the Higgs eld, and the mass term connects the left-handed eld with the right-handed eld. The most straightforward way to add neutrino mass in the theory is to introduce a right-handed neutrino, in the same way as other fermions gain mass from Yukawa coupling. The right-handed neutrino would be an SU(2) singlet, $_{iR}$, and couple to the Higgs boson through Yukawa coupling. We can add a Dirac mass term to the Lagrangian [52]:

$$L_{Yukawa} = \frac{p}{2}\,' _L Y^i \,_{iR}\,\tilde{} + h:c: \tag{1.18}$$

where runs through e; ; and i = 1; 2; ::n where n is the number of singlet fermion elds; ' $_L$ is the left-handed lepton doublet, Y^i are Yukawa couplings and is the conjugated Higgs doublet. This, after spontaneous symmetry breaking and diagonalization of the Y matrix, would give a neutrino mass term:

$$L = \sum m \,\overline{\ }_L \,_R + h:c: = \sum m \,\overline{\ } \tag{1.19}$$

This is called the Dirac mass term. Here, the left-handed and right-handed neutrino elds combine to form the four-component neutrino eld = $_L$ + $_R$ with mass of m = y , where y is Yukawa coupling and $\frac{p}{2}$ is the vacuum expectation of the Higgs eld [7].

[12] Please refer to [49, 50, 51, 52] for more detailed overview.

While this mechanism allows incorporating neutrino mass, it does not explain why neutrinos are much lighter than the charged leptons, since y_ν are input parameters. Moreover, to accommodate small neutrino mass consistent with experimental limits, coupling y_ν has to be at least ten orders of magnitude smaller than Yukawa couplings of other fermions, which seems unnatural.

1.3.2 Majorana Neutrino Mass

Instead of introducing a right-handed neutrino, which is experimentally not observed, it's possible to introduce neutrino mass with only left-handed neutrino fields, provided that lepton number conservation is violated [43, 53]. This could be done by realizing that the particle-antiparticle conjugation operation $\hat{C}$ defined as:

$$\hat{C} : \psi \to \psi^c = C\bar{\psi}^T; \quad C = i\gamma_2\gamma_0 \tag{1.20}$$

flips the chirality of particles [54]:

$$\hat{C} : \psi_L \to (\psi_L)^c = (\psi^c)_R; \quad \psi_R \to (\psi_R)^c = (\psi^c)_L \tag{1.21}$$

Thus, a Majorana mass term can be added to the Lagrangian [52]:

$$\mathcal{L}^M = \frac{1}{2}\bar{\psi}_L M (\psi_L)^c + h.c. \tag{1.22}$$

where $\psi = \psi_e, \psi_\mu, \psi_\tau$ and ψ_L represents the left-handed neutrino field, and M is complex, symmetric 3×3 matrix[13]. Since M is symmetric, it can be diagonalized by a unitary matrix

$$M = U M^{diag} U^T; \quad M^{diag} = diag(m_1, m_2, m_3)$$

[13] If there are n different flavors of neutrinos, M will be $n \times n$ matrix.

and the Lagrangian takes the form of:

$$L^M = \frac{1}{2}\sum_{i=1}^{3} m_i \bar{\ }_i \ _i \tag{1.23}$$

$$_i = \sum U_i^y \ _L + \sum (U_i^y \ _L)^c; \quad = e; \ ; \tag{1.24}$$

Here $_i$ $(i = 1; 2; 3)$ is the mass eigenstate and is a Majorana field $_i = \ _i^c$.

The avor neutrino elds can thus be derived as a mixture of different mass elds:

$$_L(x) = \sum_i U_i \ _{iL}(x) \tag{1.25}$$

U is the mixing matrix, also called Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix [55]. In this approach, the lepton number is broken by $y = 2$ units, and the neutrino masses are also free parameters, meaning this also does not explain neutrinos' lightness.

1.3.3 See-saw Mechanism

The see-saw mechanism offers a very simple and satisfactory explanation of the lightness of neutrinos by introducing right-handed neutrinos with large mass. In type-I seesaw mechanism [56, 57, 58, 59, 60, 61], a right-handed SU(2) singlet $_{iR}$ is introduced and the Lagrangian has a Yukawa coupling term of the right-handed neutrino with the Higgs boson and lepton doublet $_L$ (first term), and a Majorana mass term for the right-handed neutrino (second term):

$$L^M = \frac{p}{2}\bar{\ }_L D^i \ _{iR} \sim \frac{1}{2}\bar{\ }_{iR} M_R^{ij} (\ _{jR})^c + h:c: \tag{1.26}$$

Here D^i and M_R^{ij} are complex Dirac and Majorana mass matrices. The Lagrangian can be reorganized into:

$$L^M = \frac{1}{2} n_L^T C M \ n_L + h:c: \tag{1.27}$$

where $n_L = (\ _L ; (\ _R)^c)$ and matrix M has the form of

$$M = \begin{pmatrix} 0 & D \\ D^T & M \end{pmatrix} \tag{1.28}$$

and can be diagonalized by a unitary matrix U to give mass eigenvalues m_i and corresponding mass-eigenstates $_i$. Again the mass-eigenstates $_i$ are Majorana elds, and the avor neutrino elds (as well as right-handed neutrino elds) can be written as:

$$(x) = \sum_i U_i \ _i(x) \tag{1.29}$$

In the simple one- avor case $D; M$ are numbers and the mass eigenvalues are:

$$m_{1;2} = \frac{M}{2} \quad \sqrt{(\frac{M}{2})^2 + D^2} \tag{1.30}$$

In the case of $M \quad D$, $m_1 \quad \frac{D^2}{M}$ and $m_2 \quad M$. The small neutrino mass is thus achieved.

Note that Eq. 1.29 implies that for three light Majorana neutrinos, the PMNS matrix is not a $3 \quad 3$ matrix, and its top-left $3 \quad 3$ submatrix will not be unitary. However the violation of unitarity is very small, on the order of $O(D=M)$ [49], so for the three neutrino case, the PMNS matrix is treated unitary.

The PMNS matrix can be parametrized as the product of three rotations through mixing angles

$_{23}$, $_{13}$ and $_{12}$ with phase $_{CP}$ and a diagonal phase matrix:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{1} & U_{2} & U_{3} \\ U_{1} & U_{2} & U_{3} \end{pmatrix} \tag{1.31}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\ _{CP}} \\ 0 & 1 & 0 \\ s_{13}e^{i\ _{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\ _{1}} & 0 & 0 \\ 0 & e^{i\ _{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{1.32}$$

where $c_{ij} = \cos\ _{ij}$ and $s_{ij} = \sin\ _{ij}$. The two phases $_1$ and $_2$ are associated with the Majorana neutrinos and are zero for the case of Dirac neutrino.

1.4 Neutrino Oscillation in Vacuum

With the mixing PMNS matrix relating neutrino avor eigenstates with mass eigenstates, neutrino oscillation can be formalized. Neutrinos are produced in pure avor eigenstates from a weak interaction, which can be written as a superposition of the mass eigenstates[14]

$$j\ (t = 0)i = j\ \ i = U_i\ j\ _i i \tag{1.33}$$

When a neutrino travels, the mass eigenstates evolve with time:

$$j\ (t)i = U_i\ j\ _i(t)i = U_i\ e^{iE_i t} j\ _i i \tag{1.34}$$

[14] Note complex conjugate of PMNS matrix is used here different from Eq. 1.29, this is because the neutrino eld annihilates neutrino state, while creation operator is needed to act on the vacuum to create neutrino state [62]

After time t, the probability of detecting a neutrino in avor j i is:

$$P = |\langle j | (t)\rangle i|^2 \tag{1.35}$$

$$= \sum_{i;j} U_i U_j e^{-iE_i t} \langle j | i\rangle|^2 \tag{1.36}$$

$$= \sum_{i} U_i U_i e^{-iE_i t} |^2 \tag{1.37}$$

$$= \sum_{i;j} U_i U_i U_j U_j e^{-i(E_j - E_i)t} \tag{1.38}$$

We treat mass eigenstates as plane waves with well-de ned momenta[15], and because neutrinos are ultra-relativistic, the energy of the neutrino can be expanded: $E_i = \sqrt{p^2 + m_i^2} \simeq p + \frac{m_i^2}{2p} \simeq p + \frac{m_i^2}{2E}$ (using $E \simeq p$) and time $t \simeq L/c$, with L being the distance the neutrino travels. The oscillation probability takes the form of:

$$P = -4\sum_{i<j} \mathrm{Re}(U_i U_i U_j U_j) \sin^2\left(\frac{m_{ji}^2 L}{4E}\right) + 2\sum_{i<j} \mathrm{Im}(U_i U_i U_j U_j) \sin\left(\frac{m_{ji}^2 L}{2E}\right) \tag{1.39}$$

where E is the energy of the neutrino and $m_{ji}^2 = m_j^2 - m_i^2$ is the mass-squared difference between the ith and j^{th} mass eigenstates. Note that this probability formula also applies to n neutrino scenarios.

The term

$$\frac{m_{ji}^2 L}{4E} = 1.267 \frac{m_{ji}^2}{\mathrm{eV}^2} \frac{L/E}{\mathrm{m/MeV}}$$

in Eq. 1.39 controls the oscillation frequency of probability. Moreover, to enable avor oscillation, elements of the mixing matrix shall not be zero, and there should be at least two non-zero, different masses (for the 3×3 neutrino case) such that $m_{ji}^2 \neq 0$ for any $i < j; i; j \in [1; 2; 3]$. By experimentally controlling neutrinos' energy and travel distance, and observing the oscillation effect, oscillation amplitude and mass square difference m^2 can be measured. Table 1.2 shows

[15] Please see Ref. [63] for a detailed review of quantum mechanical aspects in the theory of neutrino oscillations.

the range of L and E of different experiments with different neutrino sources and the corresponding $|m^2|$ they are sensitive to.

Experiment		L (m)	E (MeV)	$\lvert m^2\rvert$ (eV^2)
Solar		10^{10}	1	10^{-10}
Atmospheric		10^4 - 10^7	10^2 - 10^5	10^{-1} - 10^{-4}
Reactor	SBL	10^2 - 10^3	1	10^{-2} - 10^{-3}
	LBL	10^4 - 10^5	1	10^{-4} - 10^{-5}
Accelerator	SBL	10^2	10^3 - 10^4	> 0.1
	LBL	10^5 - 10^6	10^3 - 10^4	10^{-2} - 10^{-3}

Table 1.2: Characteristic values of L and E for experiments performed using various neutrino sources and the corresponding ranges of $|m^2|$ to which they can be most sensitive for α vor oscillations in vacuum. SBL stands for Short Baseline, which is used to indicate that experiments are located close to the site of neutrino production, and LBL for Long Baseline. It should be noted that the solar neutrino measurements are probing the MSW matter effect inside the Sun rather than neutrino oscillation occurring during travel through the vaccum. Taken from Tab. 14.1 from Ref. [49].

1.5 Short-Baseline Neutrino Anomalies

"If there's one thing you can count on physicists for, it's to keep an eye out for an anomaly".[16]

As highlighted in Tab. 1.2, in general, experiments at shorter baselines are sensitive to larger mass-squared differences. Anomalies have been observed in both solar neutrino experiments employing calibration sources of neutrinos, for example the GALLEX experiment [64, 65, 66] and the SAGE experiment [67, 68], and experiments using neutrino beams. In this section, we review two experimental anomalies observed in accelerator-based short-baseline experiments: the LSND anomaly and the MiniBooNE anomaly. The MiniBooNE anomaly motivated the proposal for the MicroBooNE experiment [69], on which the searches presented in this thesis are performed.

1.5.1 Liquid Scintillator Neutrino Detector Experiment

The Liquid Scintillator Neutrino Detector (LSND) was a short-baseline experiment located at Los Alamos National Laboratory, constructed in the 1990s to search for $\bar{\nu}_e$ oscillation in the

[16] quoted from E. Siegel's article at https://www.forbes.com/

m^2_{21} 1eV^2 region. The LSND detector was located about 30m from the neutrino source, and saw a neutrino beam dominated by $\bar{\ }$ and $_e$ produced with a proton beam of 798 MeV kinetic energy (KE) producing pions and muons decaying at rest. The $\bar{\ }_e$ ux was only 8 10^{4} as large as the $\bar{\ }$ ux in the neutrino energy range of [20., 52.8] MeV [70].

The detection of $\bar{\ }_e$ in LSND is through inverse beta decay:

$$\bar{\ }_e + p \,!\, e^+ + n$$

which could be identi ed by detecting the Cherenkov light of the prompt e^+ and a correlated 2.2 MeV from neutron capture. LSND took data from 1993-1998 and a $\bar{\ }$ $\bar{\ }_e$ oscillation search was performed with the combined dataset. A total excess of 87.9 22.4 6.0 events with positron energy between 20 and 60 MeV was observed above the expected background as highlighted in Fig. 1.2. An oscillation t with the entire sample (events with 20 < E$_e$ < 200MeV) including both $\bar{\ }$! $\bar{\ }_e$ and ! $_e$ oscillation yields a best t at $m^2 = 1.2$eV^2. This is much higher than the mass-squared differences between the three mass eigenstates ν_1, ν_2, ν_3, which give magnitudes of mass splittings of m^2_{21} 10^{5}eV^2 and m^2_{32} 10^{3}eV^2 [49], and seems to suggest additional, heavier "sterile" neutrino states.[17]

1.5.2 The MiniBooNE Experiment

The MiniBooNE experiment is a Cherenkov detector at the Fermi National Accelerator Laboratory (Fermilab). MiniBooNE was proposed to follow up on the signal observed by LSND with similar L=E, while utilizing different detector technology and being exposed to a different neutrino ux.

MiniBooNE makes use of the Booster Neutrino Beam (BNB) at Fermilab, which is produced from 8 GeV protons incident on a beryllium target. The secondary mesons produced in the process decay in ight (instead of at rest) and produce (anti)neutrino beam. When running in neutrino

[17] The additional neutrinos should not couple to W and Z bosons, as limited by the number of active neutrino avors allowed by Z boson decay width. Thus they don't interact weakly, thus are called "sterile" neutrinos.

Figure 1.2: Distribution of reconstructed positron energy for selected oscillated candidate events. The top shaded region shows the expectation from neutrino oscillation at low m^2. Bottom two shared histograms represent the expected neutrino backgrounds. Taken from Fig. 16 of Ref. [71]

(antineutrino) mode, MiniBooNE received an intense beam of highly pure muon neutrinos (anti-neutrinos). The and $^{-}$ ux peak at 600 and 400 MeV respectively and extend to 3000 MeV [72]. The MiniBooNE detector is located 541m from the beryllium target, thus satisfying L=E 1m=MeV. It's a 12.2 m in diameter spherical tank lled with pure mineral oil (CH_2) and records neutrino interactions by detecting primarily the directional Cherenkov light, and isotropic scintillation light generated by charged particles from the neutrino interaction.

To measure neutrino oscillation, MiniBooNE searches for charge-current quasi-elastic (CCQE) scattering of $_e$ and $^{-}_e$:

$$^{-}_e + p \,!\, e^+ + n; \quad _e + n \,!\, e \; + p$$

While the KE of heavy nucleons usually is not enough to pass the Cherenkov threshold in mineral oil (350 MeV KE threshold for protons) and thus can't be observed via Cherenkov radiation, light particles such as e and can usually produce Cherenkov rings, thus be distinguished by

the distinct pattern of the ring, and classi ed as electron- or muon-like.

MiniBooNE collected data between 2002 and 2019 [73]. Combining the data collected in both neutrino mode and antineutrino mode, an excess in data of 4.8 signi cance was observed in the observed electron-like events [74]. While the excess in antineutrino mode is consistent with $\bar{\ } \to \bar{\ }_e$ oscillation with $0.01 < \ m^2 < 1.0\,\mathrm{eV}^2$ and overlaps with what's observed in LSND [73], the excess in neutrino mode is marginally compatible with such neutrino oscillation assumption (assuming two neutrinos).

Figure 1.3 shows the comparison between data collected during neutrino mode and Monte Carlo (MC) prediction as a function of reconstructed neutrino energy, E^{QE}, assuming CCQE kinematics, in Fig. 1.3a and the cosine of the angle of reconstructed lepton in Fig. 1.3b, highlighting a data excess focused in the low energy region and relatively forward direction. Figure 1.4 shows the excess in data over the predicted background, with predictions of oscillated spectra with different oscillation parameters assuming two-neutrino oscillations overlaid. The data excess in the low energy region ($200 < E^{QE} < 475\,\mathrm{MeV}$) can not be explained by two-neutrino oscillation with $m^2 \quad O(1)\,\mathrm{eV}^2$. This anomaly in the low energy region is referred to as the “MiniBooNE Low Energy Excess” (LEE).

Due to the identical Cherenkov signatures of electrons and photons in the detector, MiniBooNE is not able to distinguish electrons from photons, as highlighted by the photon contributions in Fig. 1.3. A plethora of interpretations have been proposed to explain the LEE [75], such as misestimated SM background in the selection, beyond-SM interpretations like more complex scenarios with sterile neutrinos, or more exotic explanations that would generate a similar Cherenkov ring signatures in the MiniBooNE detector.

The MicroBooNE experiment was proposed to investigate the true nature of the MiniBooNE LEE [69]. With exceptional performance offered by liquid argon time projection chamber technology, MicroBooNE has the ability to unambiguously differentiate electrons from photons. Some proposed LEE interpretations have been investigated or are currently being pursued with MicroBooNE. One of the proposed interpretations is that of anomalously large rate of the SM process

NC ! N [74]. This has been investigated with MicroBooNE's rst three years of data [76] and is described in more detail in Ch. 4 due to its close relation with the main thesis work. More discussions on the MiniBooNE LEE interpretations can be found in the App. A.

(a) Data-MC comparison in E^{QE} (b) Data-MC comparison in cos

Figure 1.3: Distribution of MiniBooNE data collected in neutrino mode with reconstructed energy $150 < E^{QE} < 1250$ MeV. The stacked color histograms represent the MC prediction, with green histograms represent contributions from intrinsic $_e$s in the beam and belgian and red histograms denotes the dominant photon contribution from radiative decay and ^{0} background. Fig. 1.3a shows the comparison between data and MC simulation as a function of reconstructed neutrino energy E^{QE}. Fig. 1.3b shows the comparison in the cosine of the measured angle of outgoing reconstructed candidate electron. The dashed line represents the best- t two-neutrino oscillation to neutrino-mode data. Taken from Figs. 17 and 18 from Ref. [74].

Figure 1.4: Distribution of the MiniBooNE event excess in reconstructed neutrino energy E^{QE}_{ν} in neutrino mode data. The solid red line shows prediction at best-fit to neutrino-mode and antineutrino-mode data assuming two-neutrino oscillation. Taken from Fig. 19 from Ref. [74].

Chapter 2: The MicroBooNE Experiment

The Micro Booster Neutrino Experiment (MicroBooNE) is an experiment located at Fermilab with the primary physics goal of investigating the MiniBooNE LEE. The MicroBooNE experiment is exposed to the same on-axis Booster Neutrino Beam (BNB) as MiniBooNE at a slightly different baseline, and makes use of the state-of-the-art liquid argon time projection chamber (LArTPC) technology for its superior spatial and calorimetric resolution. This chapter gives an overview of the MicroBooNE experiment, covering the BNB in Sec. 2.1, the MicroBooNE LArTPC detector in Sec. 2.2 and at last MicroBooNE readout and triggering system in Sec. 2.3.

2.1 The Neutrino Beam

2.1.1 The Booster Neutrino Beam Line

MicroBooNE is exposed to two independent neutrino beams at different energies: on-axis neutrino ux from the BNB and off-axis neutrino ux from Neutrinos at the Main Injector (NuMI) beam. Since analysis in this thesis uses only data collected with the BNB, we will only discuss the BNB beam here.

The neutrino beam is produced by the decay of secondary mesons from bombarding high-energy protons onto a beryllium target. It comprises predominantly ν_μ with an average energy of 800MeV [72]. The protons are produced by the Fermilab accelerator complex [77]. First, H^- hydrogen ions are accelerated in the linear accelerator (Linac) to energy up to 400 MeV and then pass through a carbon foil, which removes electrons from the ions, producing a beam of protons. Then protons are injected into the Booster, which is a 474-meter circumference synchrotron, travel around the Booster about 20,000 times and get accelerated to a momentum of 8.9 GeV/c before they are extracted to the BNB.

Figure 2.1: Overall layout of the BNB. The proton beam extracted from the booster enters the target hall from the left. After leaving the target hall, particles enter a 50-meter-long decay region which terminates on the right at the beam stop. Taken from Fig. 1 in Ref. [72].

Figure 2.1 shows the layout of the BNB. The 8.9 GeV/c momentum protons strike the beryllium target embedded within a “horn” electromagnet. The monitoring systems located upstream of the target monitor the time and intensity of the proton beam before they are incident on the target. The delivery rate of proton pulses to the BNB is 5 Hz, and approximately 4×10^{12} protons-per-pulse. Each pulse is called a beam-spill, and lasts 1.6 s with 82 bunches of protons each 2 ns wide and 19 ns apart [72, 78].

The horn receives a pulsed current coinciding with the arrival of the proton beam at the target, producing a magnetic eld inside. When running in neutrino mode, the primary particles from p-Be interaction and secondary particles further produced from the interaction of primary particles with the surrounding materials such as, K and K^0 are then (de)focused by the magnetic eld. The ow of the current can be changed such that charged particles with different signs can be focused in neutrino versus antineutrino mode.

After the target-horn assembly is a concrete collimator followed by the decay pipe. The collimator is 214 cm long with an aperture of increasing radius from upstream to downstream. It

reduces radiation elsewhere in the beamline by absorbing particles that would not contribute to the neutrino ux. The decay region extends for 45 meters, inside which the secondary mesons decay to produce an intense (anti)neutrino beam. The beam stop sits 50 meters downstream from the upstream end of the beryllium target and absorbs particles apart from the neutrinos. There is another set of absorbing plates located above the decay pipe at 25 meters. This absorber is only used to study systematic uncertainty and was not deployed during MicroBooNE neutrino running.

2.1.2 The Neutrino Flux Prediction

MicroBooNE has only taken data during neutrino mode, when positively charged particles are focused and eventually produce a neutrino-enhanced beam. In neutrino mode, the neutrino beam is predominantly produced by pion decay $^{+} \; ! \; ^{+} + \;$ and kaon decay $K^{+} \; ! \; ^{+} + \;$; the later becomes the main mechanism to generate neutrinos with energy higher than 2.3 GeV [78]. The contamination from wrong-sign $\bar{n}$ neutrino and electron neutrino originates from the decay of $^{+}$ produced in meson two-body decay, $^{+} \; ! \; e^{+} + \; _{e} + \bar{}$, and from kaon decay, $K^{+} \; ! \; e^{+} + \; _{e} + \; ^{0}$. The simulation of the MicroBooNE neutrino ux is based on the GEANT4 framework [79], adapted from earlier work by the MiniBooNE Collaboration [72, 80]. Figure 2.2 shows the composition of the beam in neutrino mode as a function of neutrino energy; 93.6% of the beam is made up of ν with 5.8% $\bar{}$ and $< 0.6\%$ $_{e} = \bar{}_{e}$ contamination [80].

2.2 The Detector

The MicroBooNE detector is situated on-axis in the BNB 468.5 meters downstream from the target and consists mainly of the LArTPC, the light collection system and the cryogenic system [81]. The LArTPC is a rectangular eld cage of dimension 10.6 meters long, 2.6 meters wide, and 2.3 meters high, lled with about 85 metric tons of highly puri ed liquid argon. Inside the LArTPC are the cathod plane and anode wire planes connected to different voltages, creating an electric eld inside the detector. The light-collection system comprises 32 photomultiplier tubes (PMTs) located behind the LArTPC for the scintillation light collection. The LArTPC and

Figure 2.2: The simulated neutrino ux prediction at the MicroBooNE detector. Fluxes shown averaged through the TPC detector volume. Taken from Fig. 1 in Ref. [78].

the light-collection system are both housed inside a foam-insulated cryostat vessel containing 170 tons of liquid argon, as depicted in Fig 2.3a.

2.2.1 The LArTPC

The MicroBooNE LArTPC is situated along the neutrino beam direction, with the cathode and anode planes sitting at the beam-left and beam-right sides of the detector, parallel to the beam direction. Figure 2.4 shows the arrangement of the LArTPC.

The cathode plane is assembled by nine individual stainless steel sheets and kept at a high negative voltage of -70kV during normal operation. A uniform electric eld of strength 273 V/cm is established by a series of eld rings enclosing the volume between the cathode and anode planes. The eld rings are connected by a voltage divider chain such that each ring is kept at a different electrical potential, which maintains a uniform electric eld between the cathode and anode planes. A picture of the eld rings and the cathode plane is shown in Fig. 2.3b.

At the anode, there are three sense wire planes: two induction planes with wires oriented at 60 from vertical (also called “U” and “V” plane, or plane 0 and plane 1), and one collection plane with vertically oriented wires (referred to as “Y” plane, or plane 2). The U, V, and Y wire

(a) (b)

Figure 2.3: (a): Diagram of the MicroBooNE rectangular LArTPC, housed inside the cylindrical cryostat. (b) interior view of the cathode plane (the shiny wall on the left) as viewed from the upstream end of the LArTPC. Also visible are the eld rings on the top, bottom and downstream end. Taken from Figs. 9 and 10 in Ref. [81].

planes are spaced 3 mm apart and have 2368, 2368, and 3456 wires respectively, each with a wire pitch of 3 mm. The bias voltages set on the U, V and Y planes are 110 V, 0 V and 230 V.

Figure 2.4: Cartoon of the MicroBooNE LArTPC showing arrangement of the anode and cathode planes, and the detector's working principle. Taken from Fig. 2 in Ref. [81].

Figure 2.5: The electron drift paths in the applied electric eld (in yellow) for a 2D model of a portion of MicroBooNE LArTPC near a subset of wires, simulated with the Gar eld software [82]. The x-axis is the direction of the drifting electric eld, and the z-axis is in the beam direction. Taken from Fig. 2 in Ref. [83].

Figure 2.4 shows the working principle of the LArTPC. When charged particles from a neutrino interaction traverse through liquid argon, they ionize argon atoms along their path, leaving free ionization electrons and creating prompt scintillation photons. Under the uniform electric eld, the ionization electrons drift toward the anode planes. Thanks to the highly-puri ed liquid argon, the ionization electrons can drift over distances of O(m) with minimal attenuation until they reach the anode planes. Under 273 V/cm electric eld in the detector, electrons drift at a velocity of 1.1 mm= s [84] leading to a maximum drift time of 2.3 ms from the cathode plane to the anode plane. As shown in Fig. 2.5, due to different bias voltages on three planes, the drifting electrons pass by the two induction planes and eventually get collected by wires on the collection plane. This creates “bipolar” induced signals on the induction planes and “unipolar” signals on the collection plane.

2.2.2 Light Detection System

Besides the ionization electrons, light is also produced in this process. Liquid argon is an excellent scintillator and is transparent to its own scintillation light. When excited argon atoms

decay, they emit vacuum ultraviolet (VUV) scintillation light with a wavelength of 128 nm isotropically [81]. The emitted scintillation photons have a fast component of 6.8 ns, thus, once detected in coincidence with a BNB beam spill, they serve as a neutrino interaction candidate trigger, and they are also used to determine the time of neutrino interaction t_0. This is needed to determine the location of the interaction in the drifting direction, in combination with the measured arrival time of corresponding ionization charge on the anode plane.

Figure 2.6: Diagram of one optical unit: a PMT situated behind a TPB-plate and surrounded by a mu-metal shield. Taken from Fig. 29 in Ref. [81].

The light-collection system is situated behind the anode plane facing into the detector volume and primarily comprises 32 cryogenic R5912-02MOD Hamamatsu PMTs. The placement of the PMTs are shown in Fig. 2.7a, yielding 0.9% photocathode coverage. As highlighted in Fig. 2.7b, the MicroBooNE PMTs are sensitive to photons with wavelengths of 300–600 nm. Thus, in order to detect the scintillation light, tetraphenyl-butadiene (TPB) is used to convert the VUV light to visible wavelengths peaking at 425 detectable by the PMTs. Figure 2.6 shows one unit of the PMT placed behind an acrylic plate coated with a TPB-rich layer.

(a) Sketch of MicroBooNE light-collection system

(b) Scintillation light emission and detection spectrum

Figure 2.7: (a): Diagram showing the orientation of the 32 PMTs (labeled as “optical units”) in MicroBooNE detector. (b): This gure highlights the challenge in detecting the scintillation light from argon. The red dashed curve shows the spectrum of scintillation light emitted by argon; the solid blue curve represents the ef ciency of the R5912-02MOD PMT employed by MicroBooNE; the dashed green curve represents the re-emission spectrum of the TPB. Taken from Figs. 26 and 28 in Ref. [81].

2.3 Detector Readout and Triggering

The signals from the LArTPC and light collection system need to be ampli ed, digitized, and organized by the Data Acquisition (DAQ) systems before being written to disk for analysis. The LArTPC and PMT readout systems use a different designs for analog front-end and digitization

and share the same back-end design for organizing and packaging data[1] before sending them to the DAQ system [81], as shown in Fig. 2.8. This section will brie y describe the readout system for the LArTPC and PMT, as well as the trigger system employed in MicroBooNE.

2.3.1 TPC Readout System

To minimize the electronics noise, MicroBooNE uses cryogenic front-end electronics situated inside the Cryostat to read out the LArTPC. For this purpose, the analog front-end application-speci c integrated circuits (ASICs) are integrated on a cold motherboard directly attached to wire carrier boards on the LArTPC. The signals from 8256 LArTPC wires are independently pre-ampli ed and shaped by the front-end ASICs before being transmitted to the warm interface electronics through cold cables. The warm interface electronics are installed on top of signal-feedthrough ange onto the Cryostat. Here, the signals are further ampli ed by intermediate ampli ers shielded in a Faraday cage in order to prepare for 20 meter-long transmission to the warm digitizing and processing readout electronics in the detector hall.

The readout of 8256 LArTPC wires is distributed among 9 readout crates, each consisting of 16 18 Front End readout Modules (FEMs) and connected to a dedicated DAQ server. A custom, BNL-designed analog-to-digital conversion (ADC) module on the FEM handles signals from 64 wires through 8 octal-channel 12-bit ADCs and digitizes the signals continuously at a frequency of 16 MHz. The digitized data then get downsampled to 2 MHz by the eld-programmable gate array (FPGA) on the FEM. The FPGA is responsible for processing the signals, reducing the data rate, and preparing the data for readout by the DAQ system.

MicroBooNE has two separate data streams for readout for different purposes: one stream contains losslessly compressed LArTPC data recorded in coincidence with the event Level-1 trigger (discussed in Sec. 2.3.3), which is referred to as the “NU” data stream; the second stream is a continuous, lossily compressed readout of the LArTPC data. The continuous data is used for beam-unrelated physics analysis, such as the detection of potential supernova bursts, and is referred to as

[1]The Columbia neutrino group at Nevis Labs led the design and construction of the warm readout electronics for the MicroBooNE detector.

Figure 2.8: Scheme for MicroBooNE's LArTPC and PMT signal processing and readout. Taken from Fig. 45 in Ref. [81].

the ”SN” stream.

In MicroBooNE, the frame size for readout is set to 1.6 ms. For the NU stream, when an event trigger is received, 4.8 ms of data spanning three or four frames are trimmed, as shown in Fig. 2.9. Then, the trimmed data is run through the Huffman encoding [85], which losslessly reduces the data rate by a factor of 5. For the continuous SN stream, further reduction is required. The FPGA applies two sequential data reduction algorithms to the SN data [86]. Zero suppression is applied rst, where the ADC samples not meeting a con gurable threshold (for each channel) with reference to a con gured baseline are discarded, followed by the Huffman compression, yielding an overall compression factor of 20 80.

From the readout electronics, the compressed data is then sent to a dedicated sub-event buffer (SEB) DAQ server, which creates sub-event fragments. For the NU stream, these fragments are sent to an event-building machine (EVB) for full-event building, and an additional high-level soft-

Figure 2.9: MicroBooNE readout for NU stream. Taken from Fig. 56 in Ref. [81].

ware trigger utilizing light information is applied to further reduce the event rate before the events are written to the local disk on the EVB and later sent of ine for further processing. For the SN stream, data sits on the SEB, and is not transferred to of ine storage unless a SuperNova Early Warning System (SNEWS) [87] alert is received. If no SNEWS alert is issued and disk occupancy reaches 80%, the oldest SN data is permanently deleted until the occupancy falls below 70% [86].

2.3.2 Light Readout System

Light produced by neutrino interactions in the detector is an important complement of the charge information and provides critical information for neutrino event selection and reconstruction. For NU stream, requiring light collected to be in coincidence with the beam spill can help reject cosmic-ray background signi cantly; for SN stream, the light information can provide event time t_0 when matched correctly to corresponding ionization activity in the TPC.

The PMT readout system processes signals from the PMTs and identi es light coincident with the beam spills for triggering. Figure 2.10 shows the stages of PMT signal processing. The signal from each PMT is split into two different gains: the high-gain (HG) channel carries 18% of the signal, and the low-gain (LG) channel carries 1.8% of the signal [81]. Each gain channel is split again into HG1, HG2, and LG1 and LG2. These separate copies allow the PMT readout system to separately process beam-related and beam-unrelated PMT signals with ease.

After the HV/signal splitter, the PMT signals are pre-ampli ed and shaped into unipolar signals by preamp/shaper boards and then passed to PMT readout modules, which digitize the signals at 64 MHz and further process them. In the case of a BNB or other external trigger, PMT signals

Figure 2.10: Cartoon illustrating the processing of PMT signal in MicroBooNE. Taken from Fig. 58 in Ref. [81].

spanning four 1.6 ms frames (frame containing the trigger, one/two frames preceding/following the trigger frame) are recorded for the NU stream. Zero suppression is applied after the digitization in order to reduce the data rate except for data surrounding the beam spill. When a BNB-coincident beam-gate signal is received, 4 earlier than the expected arrival of neutrinos, 1500 consecutive PMT samples (corresponding to 23.4) surrounding and including the beam-spill period are read out continuously with no compression. After signal processing, PMT data is sent to the designated DAQ in the same way as for LArTPC data.

While processing the PMT signals, the PMT readout module can also generate two different PMT-based triggers when certain criteria are met: a cosmic PMT trigger or a beam-gate-coincident PMT trigger [81]. The formation of the cosmic PMT trigger makes use of PMT signals outside the beam-spill-surrounding period, while the beam-gate-coincident PMT trigger requires PMT signals inside the beam spill period, and the construction of these two triggers has different requirements on the PMT hit amplitude and hit multiplicity. The PMT trigger information is available for the events in the NU stream at the event-building stage and of ine for future analysis.

2.3.3 MicroBooNE Trigger System

MicroBooNE employs two-level triggering to control the data rate to a maintainable level. The first trigger is the *hardware trigger*, or "Level-1" trigger. The MicroBooNE Trigger Board (TB) takes charge of issuing the "Level-1" trigger. The TB takes input from the BNB, NUMI, a configurable fake beam (strobe) trigger, and two calibration signals as trigger inputs. These trigger inputs can be independently pre-scaled, masked, and mixed together to generate a Level-1 trigger. Once a hardware trigger is received, the readout of the NU data stream from both the LArTPC and the PMT systems is recorded.

If every triggered event were to be recorded, running with a 5 Hz beam trigger rate would lead to a data volume of 13 TB per day with Huffman compression. Since, on average, MicroBooNE expects to see one neutrino interaction inside the detector active volume per 600 beam-spills, to reduce the data rate further, MicroBooNE applies a high-level *software trigger*, run within the DAQ in the event-building stage. For all Level-1 triggered events, the software trigger looks at the PMT signal during the beam-spill, and if there is a significant amount of PMT light coincident with the arrival of the neutrino beam, the event will be saved. This software trigger reduces the data rate by a factor of 22 to 500 GB per day with negligible efficiency loss for the neutrino interactions [78]. This is lower than the factor of 600 because of random coincident cosmics since MicroBooNE detector operates on-surface.

2.4 Detector Operations

MicroBooNE ran for 5 years between 2015 and 2020, with a total exposure of 1.3×10^{21} protons-on-target (POT). Data collected each year marks an individual run, starting with first-year data considered as "Run 1", etc. Figure 2.11 shows the accumulated POT delivered to MicroBooNE during Runs 1-5 data taking. The analysis presented in this thesis utilizes 6.368×10^{20} POT of data collected during the first three years of running (referred to as "Runs 123").

Figure 2.11: POT delivered to MicroBooNE over ve-year data-taking period.

Chapter 3: Simulation and Reconstruction in MicroBooNE

This chapter discusses the simulation and reconstruction of events in MicroBooNE. Section 3.1 describes general event simulation and background modeling in MicroBooNE, followed by Sec. 3.2 where the signal processing and pattern-recognition reconstruction are brie y discussed, and Sec. 3.3 focusing on high-level reconstruction speci c to the analyses presented in this thesis.

3.1 Neutrino Interaction Simulation and Cosmic Modeling

Any new process search or precise cross-section measurement typically requires an accurate MC simulation of the experiment for a reliable estimate of the contribution from different types of backgrounds. MicroBooNE uses both MC simulation and data-driven techniques for background evaluation.

3.1.1 Cosmic Modeling

As a detector operating on the Earth's surface, without signi cant overburden, the MicroBooNE LArTPC sees a high rate of cosmic-ray muons at 5 kHz; this leads to $O(10)$ cosmic muons entering the detector volume during each 2.3 ms drift time window [88]. Thus, it is crucial to have a precise model of the cosmic ray activity in the detector. MicroBooNE utilizes recorded data collected when the neutrino beam is turned off to estimate the cosmic activity in the detector. Two sets of beam-off data are recorded for different purposes. One data stream records cosmic activity without any optical requirements, and is overlaid with simulated neutrino activity to account for cosmic activity in the detector during the TPC readout window. The other data stream contains events that are triggered by the optical signals from cosmic activity during the fake beam spill window and saved in the same manner as the NU stream. This data stream is used to estimate recorded

events that are triggered by cosmic activity when no neutrino interacts in the detector during the BNB beam-spill.

In MicroBooNE, the cosmic-ray rate can also be simulated using CORSIKA v7.4003 [89]. CORSIKA simulates a ux of the cosmic nuclei and the hadronic interactions in the air showers initiated by the cosmic nuclei [88]; then the primary particles from the interaction and their interaction/decay products are propagated through the MicroBooNE LArTPC using GEANT4 and subsequent simulation tools in MicroBooNE.

3.1.2 Neutrino Interaction Simulation

In general simulation of neutrino interactions in MicroBooNE can be broken down into four steps. First, the ux of the neutrino beam is simulated, as described in Sec. 2.1.2. Then, the simulated neutrino ux pro le is fed into the GENIE [90] neutrino event generator. MicroBooNE adopted GENIE v3.0.6 as the core event generator with a customized tune [91] of the CCQE and CC two-particle two-hole (CC2p2h) models to T2K ν_μCC data [92]. The GENIE simulation takes into account the energy of the neutrino sampled, the materials the neutrino encounters, and the cross-section of the interaction, and simulates neutrino interactions inside and outside the MicroBooNE cryostat.

The nal state particles from GENIE interactions are passed to LArSoft [93] framework, which is a toolkit for the full simulation in the detector, reconstruction as well as analysis of the LArTPC events. The propagation of the nal state particles in the detector is simulated by the GEANT4 [79] toolkit v4_10_3_03c implemented in LArSoft. This includes the energy deposition, ionization electrons, and optical photons produced along the path of the particle trajectory. LArSoft simulates the propagation of scintillation light in the detector medium to the PMTs and the drift of the ionization charge to the wires while taking into account different detector effects, such as Rayleigh scattering, re ection, and partial absorption of the light in the medium, electron recombination with argon ions [94], and space charge effects [95, 96, 97, 98].

Then, a dedicated detector simulation is used to simulate the electric field response[1] and electronics response of the detector [83], while taking into account the diffusion [99] and absorption of the ionization charge during the drift. The field response functions of wires are calculated based on the electron drift paths (example shown in Fig. 2.5) and the weighting fields of wires simulated with the Garfield program [82]. The electronics response includes two parts and models the behavior of the pre-amplifier that amplifies and shapes the analog signals from the TPC, and the behavior of resistor-capacitor (RC) circuits employed to remove the baseline from the pre-amplifier and the intermediate amplifier [100].

Eventually, the TPC signal for each channel is simulated as [83]:

$$M = (I^{depo} \quad T^{drift} \quad R^{duct} + N) \quad R^{digit} \tag{3.1}$$

where

- I^{depo} represents the initial distribution of the ionization electrons due to energy deposition of charged particles.
- T^{drift} represents a function that transforms initial ionization charges to distributions of electrons arriving at the wires, which includes various detector effects.
- R^{duct} represents the response of the wires, which is the convolution of field response and electronics response.
- N represents simulated inherent electronics noise [83].
- R^{digit} models the waveform digitization process.

Figure 3.1 shows the simulated waveform for a 5-GeV muon.

As discussed in Sec. 3.1.1, the MicroBooNE detector is exposed to a constant cosmic-ray rate. Thus, to account for cosmic activities during the readout window, at last, the simulated waveforms

[1] Field response function is defined by the induced current on one wire due to a single electron charge [83].

are overlaid with the data waveform collected for beam-off events; the resulting simulation sample is referred to as Monte Carlo “overlay”. It's worth-noting that the NC coherent π^0 events, signal targeted by one of the two analyses presented in this thesis, is simulated in a standalone GENIE, not the default MicroBooNE GENIE tune. Therefore all steps remain the same for the simulation of NC coherent π^0 events, except the GENIE simulation step. This is discussed in more details in Ch. 5.

Figure 3.1: Simulated waveforms from a GEANT4-based 5-GeV muon track in liquid argon. The x-axis represents the channel (wire) of the three wire planes, the y-axis represents the sampled time tick, and the z-axis shows the ADC value of the simulated waveform proportional to the energy deposition per unit length. Taken from Fig. 22 in Ref. [83].

3.2 Event Reconstruction

Event reconstruction is a sequential process, which includes processing of the TPC signals and PMT light signals applied to all recorded data events, and high-level reconstructions leading to reconstructed particle tracks and showers. Section 3.2.1 and 3.2.2 describes the TPC and optical reconstruction respectively, and Sec. 3.2.3 brie y describes the Pandora [101] event reconstruction used in the analyses presented in this thesis.

3.2.1 Light Signal Reconstruction

The optical reconstruction processes the raw waveform from all PMTs, and identi es PMT signals close in time to form " ashes" which are usually caused by the neutrino or cosmic-ray interactions in the detector. First, a baseline is estimated for the PMT ADC waveform, and PMT pulses are formed from the waveform above a threshold relative to the baseline [102, 103]. Then, a ash is formed if a group of pulses across several PMTs within the same time interval are identi ed. The starting time of the ash is de ned as the time of the maximal summed photoelectrons (PEs) from all PMTs, and each ash window is 7.8 s long, in order to collect the slow component of the scintillation light and exclude noise. Each ash is characterized by the time of ash with respect to the trigger and the total PEs of the ash which are integrated across all PMTs over the entire window. Flashes are used in charge-light matching later in the reconstruction chain to identify neutrino interactions.

3.2.2 TPC Signal Reconstruction

The TPC signal processing starts with the removal of inherent noise from electronics, which includes inherent noise from the cold ASICs, the intermediate ampli er, and the ADC. During the initial operation of the detector from October 2015 through July 2016, excess noise was identi ed in the TPC readout, and of ine noise ltering was developed, which removes most of the excess noise while preserving the signal [100]. Hardware upgrades were performed in the summer of

2016, after which the noise level was suppressed by a factor of 3 for the induction planes and a factor of 2 for the collection plane. The of ine noise lter further suppresses the noise by an additional 10 20%.

The second step of TPC signal processing is to reconstruct the ionization charge distribution. As shown in Eq. 3.1, the raw wire signal is a result of convolution between the ionization electron distribution and the detector response. MicroBooNE employs two-dimensional (2D) deconvolution [83, 104] to deconvolve the detector response and recover the ionization distribution. Unlike traditional 1D deconvolution [105], which considers current induced by ionization electrons when passing by the sense wire, 2D deconvolution also takes into account the contribution from ionization electrons drifting in neighboring wire regions and thus involves both time and wire dimensions. During the deconvolution, an additional software lter inspired by the Wiener lter [106] is applied to attenuate high-frequency noise while excluding the suppression at low-frequency in the Wiener lter. The 2D deconvolution method yields a more accurate recovery of the ionization charge distribution, as highlighted in Fig. 3.2.

In order to reduce the data size, the region-of-interest (ROIs) technique [105] is applied on the deconvolved signal distribution. For each channel, the root mean square (RMS) noise is calculated from the deconvolved signal over the entire readout window (4.8 ms) and used to set the threshold for ROI identi cation. Once ROIs are identi ed on the deconvolved signals, the entire TPC readout is replaced by a set of ROIs[2] Each ROI can contain more than one (typically less than ve) Gaussian pulses (referred to as “hits”), and a hit- nding algorithm [107] is utilized to identify these Gaussian hits with associated hit time, width and peak amplitude information. These reconstructed Gaussian hits serve as inputs to high-level reconstruction algorithms later in the reconstruction chain.

[2]For the induction plane, additional linear baseline subtraction is performed in the ROI window, in order to suppress the low-frequency noise arising from 2D deconvolution [83]. The baseline is calculated as the interpolation of baselines at the start and end of the ROI window.

Figure 3.2: The U plane waveforms for a recorded neutrino candidate in MicroBooNE: the x-axis represents the wire and the y-axis represents the time in units of 3 (corresponding to 6 sampling ticks). (a) Raw waveform after noise filtering, shown in unit of baseline subtracted ADC scaled by 250. (b) Charge spectrum in units of electrons after 1D deconvolution. (c) Charge spectrum in units of electrons after 2D deconvolution. Taken from Fig. 11 in Ref. [83].

3.2.3 Pandora High-level Reconstruction

MicroBooNE has explored multiple high-level reconstruction paradigms, including Pandora reconstruction [101], Wire-Cell tomographic reconstruction [108], and Deep-learning based reconstruction [109]. The wire cell reconstruction leverages the sparsity of neutrino interaction and utilizes the charge, light, and time information to identify energy deposition in 3D first, prior to forming particle trajectories. The deep-learning based reconstruction takes advantage of MicroBooNE's 2D readout from each plane and uses convolutional neural networks to associate pixels with different particle activities. The Pandora reconstruction technique is used by the analyses discussed in this thesis and is discussed in more detail below.

The Pandora reconstruction is integrated into the LArSoft framework, and it takes a multi-

algorithm approach to pattern recognition. Given reconstructed hits with wire number and waveform information as inputs, Pandora runs two reconstruction paths on them: “PandoraCosmic” and “PandoraNu”, each involving multiple algorithms.

“PandoraCosmic” is run first, aiming to reconstruct cosmic-ray particles and associated delta rays. The clustering algorithms are run on hits to identify 2D clusters, which are groups of continuous hits on each plane. Then, all combinations of clusters from three planes (one from each plane) are examined, and the time and consistency of each group are checked to identify track-like trajectories in 3D. The clustering algorithms and 3D track reconstruction algorithms are run back and forth until there is no ambiguity in the clusters formed, and the final 3D tracks are taken as the reconstructed cosmic-ray muons. After the track reconstruction, any hits that are not associated with reconstructed tracks are regrouped in 2D and matched in 3D to reconstruct the delta rays and associate them with parent muon tracks. For any reconstructed particle, 3D hits (called “spacepoints”) are created from the 2D hits across planes.

“PandoraNu” then takes hits that are not reconstructed as cosmic activity by “PandoraCosmic” and reconstructs neutrino interactions out of them. The same algorithms are run as in “PandoraCosmic”, and the original 2D input hits are split into different groups (called “slices”) based on the geometric information of associated 3D hits [101]. The 2D Gaussian hits in each slice are then processed individually to reconstruct neutrino interactions.

In neutrino interaction reconstruction, a 3D vertex that defines the interaction point or the first energy deposit is first identified. Vertex candidates are formed from pairs of 2D clusters across different planes, scored based on cluster energy, distribution of hits, and the position of the candidate vertex, and the vertex candidate with the highest score is picked.

Following the identification of interaction vertex, shower and track reconstruction starts. 2D clusters are classified as shower-like or track-like based on the linearity, hit dispersion, and cluster extent. On each plane, a long shower-like cluster that typically points back to the vertex is identified and represents the shower spine, and small shower-like clusters are then added recursively to the shower spine, eventually yielding a large, complete 2D shower cluster. The 2D shower clusters

Conversion Constant	Plane 0	Plane 1	Plane 2
Monte Carlo Overlay	235.5	249.7	237.6
Data	230.3	237.6	243.7

Table 3.1: The ADC-charge conversion constants measured for each plane for data and MC, in units of e^-/ADC.

on three planes are matched to form 3D shower particles. Like the track reconstruction case, 2D clustering and 3D matching processes are run recursively until unambiguous shower particles can be formed. Track-like clusters are examined to form 3D track reconstruction in the same way as discussed for "PandoraCosmic" path.

3.3 High-Level Energy Reconstruction

The output from Pandora is processed further to extract additional high-level information for physics analysis. This section focuses on the two main calorimetric quantities associated with reconstructed showers most relevant to analyses in this thesis: the total shower energy, and energy loss per unit length (dE/dx) at the shower start.

3.3.1 Shower Energy Reconstruction

The energy of the reconstructed shower starts with the energy reconstruction of the hits making up the shower, and involves two steps: 1) translating the integral of hit ADC waveforms to ionization charge; and 2) using the charge to recover the deposited energy of the particle. To convert from the hit integral (in ADC) to the charge (Q in e^-), the conversion constant is calculated for MC simulation, and extracted for data using the dE/dx profile of stopping muons in the detector [97, 110]. The conversion constants measured for data and MC for each readout plane are summarized in Tab. 3.1 [111].

Then to convert from charge to the energy of the particle, a simplified conversion is applied:

$$E = \frac{W_f}{R_C} \quad Q \tag{3.2}$$

where $W_f = 23.6\,\mathrm{eV}/e$ is the ionization work function of argon, and $R_C = 0.62$ is the recombination factor, accounting for the fact that the dispersed drift electrons may quickly thermalize and recombine with nearby ions. Using a fixed recombination factor is a simplification because the recombination factor is a function of energy deposition. Larger energy deposition leads to a higher density of positive ions, thus the probability that one of the liberated electrons can recombine with an ion is higher and the recombination factor R_C decreases. Here a simplified assumption of fixed R_C is adopted, and its value is calculated using the so-called modified box model with parameter values measured by the ArgoNeuT experiment [112] at MicroBooNE's electric field strength of 273 V/cm.

The reconstructed energy of the entire shower is found by summing up the energy E of all hits on a plane-by-plane basis, and taking the max of all planes. This is due to the fact that clumps of energy are often not associated to the shower on all planes, due to dead wires or incorrect clustering, and choosing the maximum provides the most reliable information.

The shower dE/dx at the shower start is a powerful tool for distinguishing showers originating from photons from those originating from electrons. A photon doesn't ionize the argon until it pair-produces an e^+ and e^- and the electromagnetic shower cascade happens. So while the initial dE/dx of electron showers corresponds to the dE/dx of minimum ionizing particle (MIP), showers induced from photons will have higher initial dE/dx corresponding to twice that of MIPs. To evaluate the dE/dx at the shower start, a Kalman filter [113] based procedure is applied to the reconstructed shower to identify the main trunk of the shower and reject transversely or longitudinally displaced hits. The values of dE/dx measured for the first 4-cm of the shower are extracted, and the median dE/dx is used as the reconstructed dE/dx at the shower start.

3.3.2 Shower Energy Correction

As highlighted in Fig. 3.3a, the resulting reconstructed shower energy turns out to be systematically below the true shower energy. This is due to lossy effects such as thresholding, where small local energy depositions created during the shower cascade may go undetected because they fall

below the detection threshold, and mis-clustering, which refers to hits being missed during clustering in the reconstruction leading to a partially reconstructed shower. On average, there is 20% energy loss due to these effects [114].

(a) Uncorrected (b) Corrected

Figure 3.3: (a) 2D distribution of reconstructed shower energy (y-axis) v.s. true energy (x-axis) for reconstructed showers with at least 30 MeV, evaluated with 100,000 simulated NC^0 events. The points represent the most probable value in each true energy bin. (b) 2D distribution of corrected shower energy (y-axis) v.s. true shower. Taken from Fig. 10 in Ref. [115]

To account for reconstructed energy bias, a shower energy correction factor is extracted using simulated NC^0 sample with Run 1 overlay. Reconstructed shower energy is plotted against the true photon energy for all showers with at least 30 MeV of simulated and reconstructed energy, as shown in Fig. 3.3a. Then a linear t is performed to the most probable value (MPV) in bins of true shower energy. The various-sized bins are hand-tuned to account for lower statistics at high energies and to provide a reasonable t to the underlying 2D distribution. The correction equation derived from linear t result is:

$$E_{corr} = (1.21 \pm 0.03)E_{reco} + (9.88 \pm 4.86)\ \text{MeV} \tag{3.3}$$

where E_{reco} and E_{corr} correspond to the reconstructed shower energy before and after correction, respectively. This represents an approximately 20% correction, consistent with a previous MicroBooNE study [114]. Figure 3.3b shows the 2D distribution of the corrected shower energy and true photon energy which are much closer after the correction. The validity of the reconstruction en-

ergy correction for Runs 2 and 3 is cross-checked through the reconstructed π^0 mass distributions across different runs. Good data-MC agreements are seen, and fitting the π^0 mass distributions with Gaussian-plus-linear functions yields consistent mass and width parameters across runs that are consistent to the expected values [115].

Chapter 4: MicroBooNE Neutral Current Delta Radiative Decay Measurement

Single photons from NC radiative decay is the second largest contribution to the photon background at low energy in MiniBooNE's ν_e measurement, as shown in Fig. 1.3a. NC radiative decay becomes a background because, while the nucleon from decay is too heavy to generate Cherenkov light in the MiniBooNE detector, the decay photon creates Cherenkov light which cannot be separated from Cherenkov rings produced by electrons in MiniBooNE. On the other hand, the extraordinary spatial and energy resolution offered by the MicroBooNE LArTPC enables MicroBooNE to distinguish photons from electrons, making it ideal for investigating the root cause of the MiniBooNE LEE.

This chapter gives a summary of the investigation of one of the leading interpretations of the MiniBooNE LEE by MicroBooNE: an anomalous rate of neutrino-induced NC radiative decay, targeting speci cally a 3.18 times enhancement of the process. The NC radiative decay search is the rst search performed by MicroBooNE under the photon hypothesis of the MiniBooNE LEE. Section 4.1 brie y discusses the motivation and analysis overview, Secs. 4.2, 4.3, 4.4 and 4.5 describe different parts of the analysis in more detail. The full details of the analysis can be found in Ref. [76, 115, 116].

4.1 Analysis Motivation and Overview

NC radiative decay has never been directly measured in MiniBooNE; it was only indirectly constrained through in-situ NC ^{0} measurements [117]. MiniBooNE's latest data release shows that a normalization scaling of 3.18 of the predicted NC N + background provides the best t to the observed excess [74]. More speci cally, different processes are tested through a shape-

only t to the vertex radial distribution of the excess with only statistical uncertainty, where each process is normalized to explain the size of the excess. It was found that an enhancement of the NC ! N process (as predicted by the NEUANCE [118] neutrino generator used by MiniBooNE) by a factor of 3.18 ts the radial distribution the best, as highlighted in Fig. 4.1.

Figure 4.1: The vertex radial distribution of the excess in neutrino-mode data in MiniBooNE's ! $_e$ oscillation measurement, overlaid with the prediction for NC radiative decay in MiniBooNE scaled to explain the excess. This distribution shows the good shape agreement between the observed excess and scaled NC radiative decay prediction. Taken from Fig. 23 in Ref. [74].

A previous search of neutrino-induced NC processes in the O(1) GeV neutrino energy regime was performed by the T2K experiment [119], using a neutrino beam with E 0.6 GeV. The search had limited sensitivity and no positive evidence of NC was observed by T2K. If all NC 1 are assumed to be solely from NC radiative decay, T2K's result leads to an upper limit on the NC radiative decay rate at 100 times the SM predicted rate at 90% con dence level (CL). Thus in order to test whether there was a factor of 3.18 enhancement of the radiative decay process with respect to the SM prediction suf cient to explain the MiniBooNE LEE, a highly sensitive research for this process was warranted.

MicroBooNE tested the hypothesis of a factor of 3.18 enhancement of the radiative decay rate using the rst three years of data (referred to as “Runs 1-3”) through four exclusive, independent selections. First, in order to yield a pure and ef cient selection of the NC radiative decay

events, two selections targeting exclusive topologies were developed to select events that have the same topologies as and similar kinematics with the NC radiative decay event in MicroBooNE detector. Second, the NC ^{0}1 process was anticipated to be a dominant background for the NC radiative decay search. Thus, in order to ensure the correct modeling of this important background, two mutually exclusive, high-statistic NC ^{0}1 selections were developed. Moreover, due to the high correlation of the NC 1^0 selection with both the NC 1^0 background in the NC single photon selections and the NC radiative decay signal, the high-statistic NC ^{0}1 selections can constrain the background prediction and systematic uncertainty in the single photon selections. This was achieved through a combined t performed with four selections simultaneously and was critical in yielding a sensitive search of NC single photon events. The result came out in 2021 and was published in Physical Review Letters with editors' suggestion [76]. My direct contributions to this analysis are the rate validation of NC ^{0}1 background, and the exploration of methods and tool development for the nal combined t, which extracts an ultimate limit on the NC radiative decay process; these are discussed in Sec. 4.4 and 4.5.

4.2 NC Radiative Decay Targeted Selections

NC ! N + creates two different topologies in the MicroBooNE detector, depending on the type of the nucleon that excites:

1. If nucleon is proton, the corresponding resonance decay is $^+$! p + . Since the proton is a charged particle, it will ionize the argon atoms along its path, leading to an identi able "track" in the detector. The photon from the decay will cascade and create "shower" some distance away from the proton. An example of such topology is shown in Fig. 4.2a.

2. If nucleon is neutron, the corresponding resonance decay is ^{0} ! n + . Being a charge-neutral particle, neutrons will not ionize argon atoms and will be invisible in the detector. So in this case, only one "shower" from the decay photon is expected in the detector, with no other associated vertex acitivities. An example of such topology is shown in Fig. 4.2b.

(a) Candidate data event in 1p selection (b) Candidate data event in 0p selection

Figure 4.2: Event displays of selected candidate NC radiative decay event in 1p selection (left) and 0p selection (right). The horizontal axis represents wires on a plane while the vertical axis represents the time of the induced wire signal. Colored pixel represents the deposited energy in each hit; the red pixels indicate higher energy deposition than the green pixels. In the selected 1p event, we can see clean proton and photon candidates: the reconstructed track shows calorimetry in good agreement with a proton-like Bragg peak, and the shower is displaced from the track start. In the selected 0p event, we see a single shower, and a track nearby. The track has an energy deposition pro le of a MIP, which is correctly identi ed to be cosmic-ray and not associated with the reconstructed neutrino interaction.

Thus, two selections targeting different and exclusive topologies are developed (1p and 0p), selecting events with a single shower and exactly one (zero) protons exiting the nucleus with no charged leptons in the nal states. Note that particles from the interaction might experience nal state interactions on their way out of the nucleus. Thus, the actual particles exiting the nucleus might be different from daughter particles from the decay. Hence the 1p and 0p selections will end up with events from both decay modes.

With the speci c topologies in mind, the selections require events to have exactly one reconstructed shower and one (or zero) reconstructed tracks, depending on whether it is the 1p or the 0p selection. Preselection quality cuts are subsequently applied to the reconstructed objects, to reject obvious muon background and ensure good reconstruction of the shower, and that the events are well contained within the TPC active volume. Machine learning methods, speci cally boosted decision trees (BDTs) using the XGBoost library [120], are then used and optimized to separate the NC radiative decay signals from various neutrino-induced and cosmic backgrounds. There

are ve BDTs developed for the selection:

- Cosmic BDT rejects cosmogenic backgrounds and is trained on cosmic ray data events collected when no neutrino beam was present. Track calorimetry is used to reject cosmic muons, with track and shower directionality-based variables proving powerful discriminators.

- NC ^{0} BDT compares the relationship of the reconstructed shower and track to those expected from ^{0} decay kinematics to separate true single-photon events from ^{0} background where a second photon from ^{0} decay is not reconstructed.

- CC $_e$ BDT targets the intrinsic $_e$ background events, which leverages the power of the photon conversion distance and shower calorimetry variables.

- A dedicated "second-shower" BDT vetos events in which a second shower from ^{0} decay deposits some charge in the detector, but fails 3D shower reconstruction. Such events can result in 2D charge hits near the neutrino interaction that are not associated with a 3D object. A plane-by-plane clustering algorithm, DBSCAN [121], is used to group these unassociated hits, and properties including direction, shape and energy of the cluster are used to determine consistency with a second shower from ^{0} decay. The clustering procedure for the second shower clusters is described in more detail in Sec. 6.4.1.

- CC -focused BDT removes any remaining backgrounds, primarily targeting the muon track through track calorimetry variables.

The 1 0p sample is limited to shower-only variables due to the absence of a track. As such, it uses variations of the cosmic and NC ^{0} BDTs, and a third BDT merging the functionality of the CC $_e$ and CC -focused BDTs, targeting all remaining backgrounds. The BDTs for the 1 1p and 1 0p selections are trained and optimized independently for each selection towards the highest statistical signi cance of the NC ! N signal over background in each sample. The topological, pre-selection, BDT selection, and combined signal ef ciencies are summarized in Table 4.1.

Selection Efficiencies of NC 1 1p and 1 0p selections		
Selection Stage	1 1p eff.	1 0p eff.
Topological	19.4%	13.5%
Pre-selection	63.9%	98.4 %
BDT Selection	32.1%	39.8%
Combined	3.99%	5.29%

Table 4.1: Signal efficiencies for the 1 1p and 1 0p selections. The topological and combined efficiencies are evaluated relative to all true NC ! N events inside the active TPC in the simulation (124.1 events expected for 6.30 10^{20} POT). The pre-selection and BDT selection efficiencies are evaluated relative to their respective preceding selection stage. Taken from Tab. I in Ref. [76].

	1 1p	1 0p
Unconstr. bkgd.	27.0 8.1	165.4 31.7
Constr. bkgd.	20.5 3.6	145.1 13.8
NC ! N	4.88	6.55
LEE (x_{MB} = 3:18)	15.5	20.1
Data	16	153

Table 4.2: Number of predicted background, predicted signal, and observed data events for the 1 1p and 1 0p samples, with background systematic uncertainties. “Unconstr. bkgd.” represents the nominal MC prediction for the backgrounds, while “Constr. bkgd.” represents the prediction for background after constraint from the NC^0 selections is applied. The constraint is discussed later in Sec. 4.5. The table is taken from Tab. IV in Ref. [76].

For MicroBooNE's Runs 1-3 data, with an exposure equivalent to 6.8 10^{20} POT, a total of 16 data events are selected in the 1 1p channel and 153 in the 1 0p channel [76], compared to an expected constrained[1] background of 20.5 3:6(sys.) 4:5(stat.) events in the 1 1p sample and of 145.1 13:8(sys.) 12:0(stat.) events in the 1 0p sample. The expected signal, overall background predictions, and observed data in both selections are summarized in Tab. 4.2. The small number of events selected arises from the fact that strict cuts on the BDTs are required to improve the signal-to-background ratio due to the sheer amount of (cosmic-ray) background present and the difficulty of cleanly separating signals from background events thanks to the overlapping kinematic phase space.

The distribution of the final selected events in the 1 1p and 1 0p samples with MicroBooNE

[1] Constraint is discussed later in Sec. 4.5.

Runs 1-3 data are shown in Fig. 4.3. Compared to the $0p$ channel, the $1p$ selection leverages the presence of the reconstructed track to aid in the rejection of CC background and yield higher purity and less diverse backgrounds. In both $1p$ and $0p$ selections, the observed data agree better with the central value prediction than the prediction with enhanced NC radiative decay rate.

Figure 4.3: Distribution of reconstructed shower energy of the final selected sample in $1p$ (left) and $0p$ (right) analysis. The upper panel of both plots show the observed data overlaid on top of the MC prediction before any constraint. Prediction of only backgrounds is shown as the stacked histogram beneath the predicted signal in yellow; central value spectrum including the background and nominal NC radiative decay prediction is shown as the stack of all colored histograms; overall prediction with enhanced NC radiative decay rate at a factor of 3.18 is highlighted in yellow dashed line. The error band represents the systematic uncertainty evaluated on the predicted background only. The bottom panel shows the comparison between data and overall predictions before (dashed line) and after (solid line) the constraint from 2ν selection is applied. Taken from Fig. 2 in Ref. [76]

4.3 NC $1\pi^0$ Targeted Selection

As shown in Fig. 4.3, NC π^0 by far dominates the background in the $1p$ selections. This occurs when one of the decay photons from π^0 is missed by the reconstruction either due to the low photon energy below the detection threshold, or because the photon pair produces outside the detector active volume. For BNB with $\langle E_\nu \rangle = 0.8$ GeV, NC π^0 events are mainly from the NC resonance production followed by $\Delta \to N + \pi^0$ decay. The Δ resonance decay to π^0 has a branching ratio of 99.4%, compared to the radiative decay branching ratio of $0.55 - 0.65\%$ [35]. Thus NC π^0 events are much more abundant than NC radiative decay events in MicroBooNE. Moreover, a