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Muon Neutrino and Antineutrino Cross Sections & Neutrino Detector Readout

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Abstract

The Micro-scale Booster Neutrino Experiment is a ground-level Liquid Argon Time Projection Chamber neutrino detector, which collected data from the Booster Neutrino Beam and coincidentally, the Neutrinos at the Main Injector accelerator neutrino beam at Fermilab. The Deep Underground Neutrino Experiment is a next generation neutrino detector experiment that aims to provide answers to several critical questions posed by the current Standard Model of particle physics. This thesis will explore the use of Machine Learning techniques to extract interesting physics events from Liquid Argon Time Projection Chambers. It presents an investigation into the online triggering of data readout, using a prototype DUNE far detector, based at CERN. An attempt to separate an admixture of muon neutrinos and antineutrinos arriving at the MicroBooNE detector from the NuMI flux is also presented. The analysis then proceeds to extract charged current cross sections for the separated neutrino and antineutrino charged current interactions on argon nucleons. An understanding of these interactions is critical to a successful DUNE physics campaign.

Lay Summary

Neutrinos are tiny, nearly invisible particles that travel through space and matter at speeds which are extremely close to the speed of light. They are studied to investigate some of the biggest mysteries about the universe, such as why there is more matter than antimatter and how fundamental forces work. This research focuses on improving how neutrinos are detected and analysed using advanced particle detection technologies and machine learning techniques.

At Fermilab, two major neutrino experiments, MicroBooNE and DUNE, aim to improve our understanding of these elusive particles. MicroBooNE is a state-of-the-art neutrino detector that collects data from two different particle beams. DUNE, a very large detector which is under construction in an underground mine in South Dakota, hopes to answer fundamental physics questions about neutrinos and the universe.

This thesis explores how machine learning can be used to identify interesting neutrino events within large amounts of detector data. It also investigates a new method for separating a mixture of matter and antimatter neutrinos that arrive at the MicroBooNE detector. Finally, the work contains a measurement for how neutrinos interact with argon atoms. This is an essential step in preparing for future discoveries at DUNE. These improvements in data analysis will help future precision measurements and reveal new insights into the nature of neutrinos and the biggest open questions in physics.

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Chapter 1

Introduction

The last 150 years have brought us much in terms of our understanding of nature. At its core, we have what is known as the Standard Model of particle physics, which is a theory that attempts to describe the most fundamental building blocks of nature, and the interactions between them that govern their dynamical collective behaviour. The interactions themselves are mediated by the four observed forces of nature. These are the **electromagnetic**, **strong**, **weak** and **gravitational** forces. The Standard Model (SM), with its remarkable experimental successes, has given us profound insights into the subtleties of the natural laws and how they operate on the smallest scales. It is a theory based on the symmetries of an expression for the energy of a particular system, the particle interactions in our Universe.

The SM predicts a set of particles called neutrinos, and has, in the past, assumed them to be both massless and only of the left-handed type. Their antiparticle equivalent similarly existing only in the right-handed state. In fact, this is now known not to be the case. The experimental observation of neutrino flavour oscillations implies that the differences in mass between the different freely travelling neutrinos are necessarily non-zero [1]. That is to say, the neutrino's mass is also necessarily non-zero, albeit possibly very small [2][3]. This also implies that the neutrinos cannot travel at the speed of light, and so it is possible to shift to an inertial frame via a boost, such that the neutrino handedness is correspondingly transformed to the right-handed state.

According to limits determined by the LEP collider experiments [4][5], investigating the invisible decay width of the Z^0 boson [6], a mediator of the weak

interaction, there exist three types of neutrino that are each associated with one of the 3 charged leptons via the weak interaction. It is the oscillation between these three different neutrinos that is the subject of much current experimental effort. The distinct possibility for a difference in oscillation probability between matter and antimatter neutrinos is of particular interest, as it could resolve one of the observed SM discrepancies.

One of the current outstanding questions in physics stems from the apparent abundance of matter over antimatter in our universe. Particle physicists have been studying the SM for decades in search of parts that violate a once-supposed symmetry of the SM called Charge Parity (CP). The violation of this symmetry transformation is required for a possible explanation of the observed matter-antimatter imbalance, hence the efforts to use the SM to find elements of CP Violation (CPV) in nature. Although the weak interaction in the lepton sector *does not* violate CP, the existence of neutrino oscillations could lead to a different oscillation probability between neutrinos and antineutrinos. This difference in oscillation probability would, in fact, constitute a measurement of CPV since the action of CP on a left-handed neutrino is to transform it into a right-handed antineutrino state, and we would expect their observed physical behaviour to be identical if CP was indeed a good symmetry of the SM. It is the next generation of neutrino oscillation experiments that will answer these questions, and the work presented in this thesis contributes to our understanding of neutrino and antineutrino interactions, which are crucial to those future physics endeavours.

This thesis will start by reviewing the theoretical framework surrounding neutrinos and their interactions in Chapter 2. The Deep Underground Neutrino Experiment (DUNE) and MicroBooNE detector technology is then described in Chapter 3, along with the NuMI neutrino beam in the context of its exposure to the MicroBooNE detector. In Chapter 4, the triggering mechanism of the current DUNE Data Acquisition system (DAQ) is detailed. A detailed breakdown of a prototype detector used in this work, with an investigation into the use of traditional recursive algorithms designed to identify specific physics event topologies is presented. Artificial Intelligence (AI) and in particular, Machine Learning (ML) techniques are then described in general, leading onto how they have been used in neutrino experiments and in this thesis in Chapter 5. The remaining portion of the thesis is the data analysis performed during my PhD: an extraction of muon neutrino and antineutrino cross sections from the current MicroBooNE data. Chapter 6 details the event selection chain using ML models

which aim to distinguish muon neutrino and antineutrino interactions in liquid argon. Chapter 7 completes the analysis with two cross section measurements using the data selected with those algorithms. The thesis concludes with some comments on the work in general, the use of ML techniques for neutrino analyses in LArTPCs and some suggested further work.

Chapter 2

Particle Physics and Neutrinos

The history and relevant theory of the Standard Model (SM) weak interactions will be reviewed. Following that, a focused discussion on neutrinos, which includes their theory, specific interaction regimes and current status of oscillation parameter measurements. The chapter concludes with a review of some recent cross section measurements, relevant to the main analysis of this thesis.

2.1 The Standard Model

The SM is a theoretical framework which describes the fundamental particles and their interactions via specific symmetries. One formalism through which these symmetries can be described is via an expression for the energy of a system, called the Lagrangian density $\mathcal{L}$. It is given by the difference between the total kinetic and total potential energies constituting that system. It describes how the known elementary particles can communicate with one another, i.e. how they can interact [7][8]. The interactions themselves are mediated by the four observed forces of nature: the **electromagnetic**, **strong**, **weak**, and **gravitational** forces.

However, the SM specifically accounts for only three of these forces, the electromagnetic, strong, and weak interactions. The electromagnetic force is responsible for the interactions between electrically charged particles and is mediated by massless photons. The strong force, which holds the atomic nuclei together, is mediated by the massless gluons. The weak force, responsible

for processes like beta decay, is mediated by *massive* W and Z bosons. The gravitational force, on the other hand, which governs the attraction between masses, is not included in the SM. A theory that incorporates all four forces, including gravity, is yet to be found *and* tested. Such a theory is commonly referred to as a Grand Unified Theory (GUT), whereby all four observed forces are expected to come together to form one fundamental force, presumably at energies determined by the Planck length [9]. Reaching energies of this scale is far outside the bounds of current technological capability, and so the discussion that follows is based on the SM that excludes gravity.

It is therefore in other areas where the SM fails to explain observed behaviour that current experimental efforts are focused. These, among a long list of observations, include the matter and antimatter asymmetry and massive neutrinos. Physicists have been searching the SM for sources of CP Violation (CPV) for decades, and where some has been found [10], it is not enough to explain the observed abundance of matter over antimatter in our universe. Neutrinos are a curious set of fundamental particles that are often assumed to be massless in the SM. This is now known *not* to be the case [11][3][12]. The discovery of neutrino oscillations as a solution to the solar neutrino problem implies that they necessarily travel at speeds less than the speed of light, and therefore cannot be massless. Although experiments have been done to place upper bounds on the neutrino masses [13], the absolute mass scale is yet to be determined. It is actually thought that with a good understanding of neutrino oscillations and their masses via experiment, the above mentioned CPV could be explained.

2.1.1 A Recent History of The Standard Model

By 1914, a fairly satisfactory picture of the fundamental constituents of matter had been put together. The electron, e , had been identified as a key ingredient of the atom by Thomson in 1891, where very small, very dense, positively charged nuclei were surmised via the famous alpha particle scattering experiments. The name for this nucleus, for a hydrogen atom, was given by Bohr in 1914, the proton, p . Additionally, through the efforts of Planck and Einstein in 1900 and 1905, the massless photon, γ , had been discovered as a particle of the electromagnetic field, light. This set of three particles appeared to be all that was required for the makeup of all known elements and observed interactions and behaviours, gravity aside. However, an issue with this picture presented itself. The nucleus of the

next heaviest atom from hydrogen was not roughly double the mass, as was to be expected from Bohr's proton model, but *quadruple*.

In 1932, Chadwick's discovery of the neutron, n , had resolved this issue, indicating that the nucleus of an atom was in fact made up of protons and neutrons, in such a way that the number of protons matches the number of electrons resulting in a net zero electric charge for the atom, since the neutrons are themselves electrically neutral also. The exact number of neutrons in a nucleus turned out to be variable, whereby atoms of particular elements can take a variable number of neutrons in its nucleus, being called an isotope of that element.

Unfortunately, this more complete and satisfactory picture of fundamental particles had already been suggested to be incorrect, since in 1927, Paul Dirac had constructed the first relativistic quantum theory of particles which predicted particle states of negative energies, the *antiparticles*. Dirac had intended to describe the motion of electrons in a relativistic and quantum way. In doing so, his factorisation of the energy-momentum relation permitted negative energy states in addition to the positive ones. Dirac surmised that there exists a *sea* of states of negative energy already filled, where an empty negative electron state would be observed as a positively charged electron. Just five years later in 1932, Anderson made the discovery of this anti-electron, the *positron*, e^+ [14]. He took a photograph of a cosmic ray crossing a 6 mm lead plate, losing energy and increasing its curvature in the magnetic field it was exposed to. Figure 2.1 shows one of the 15 photographs that were taken clearly showing a positively charged particle passing through the lead plate. In similar experiments, Anderson also discovered the muon μ in 1936, a heavier version of the electron [15].

Introduction of The Neutrino

Around the same time, in 1930, another problem with the description of fundamental particles came to light. At the time, it was thought that β -decay was a simple two-body decay process, $X \rightarrow Y + e^-$. In this process, the energies of the produced particles are fixed by kinematics. However, the expected energy of the electron corresponded only to the *maximum* possible energy, when compared against the continuous spectrum of energies actually observed. It was this observation that lead Pauli to the conclusion that there must exist a neutral particle involved in this decay, carrying away the energy that is unaccounted for in the above mentioned spectrum. Electrons were observed to reach energies very

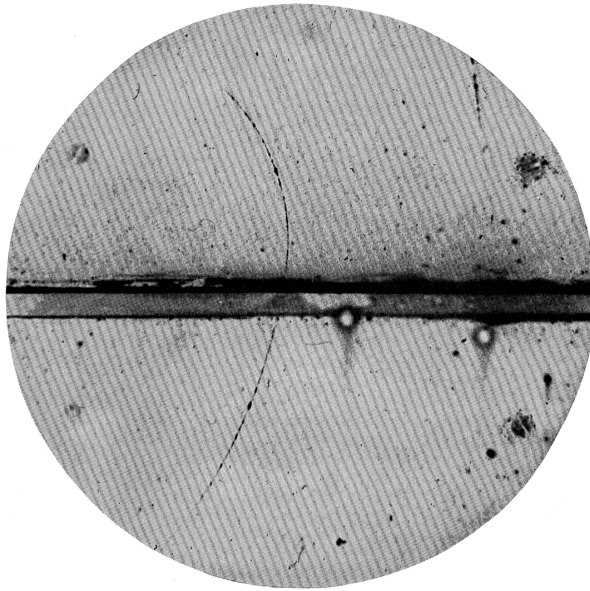


Figure 2.1 *One of fifteen photographs of positively charged particles passing through a 6 mm thick lead plate (horizontal dark band), leading to the discovery of the positron by Anderson in 1932 [14].*

close to the top end of the observed spectrum, and so it was known that this neutral particle had to be of low mass. For this reason, it has been given the name *neutrino* by Fermi, ν , meaning *little neutral one*. The neutrino interacts so weakly with matter, that it took over 20 years for the free particle to be detected by Reines and Cowan in 1953 [16].

Quark Models

Whilst experimental techniques were - and still are - being developed for neutrino detection, the quark model for baryons was initiated by Yukawa in 1935 when he suggested the exchange of a massive charged meson between protons and neutrons. It was this interaction that he hypothesised held the nuclei together despite the electromagnetic repulsion of the protons [17]. In fact, in December of 1947, another photograph of cosmic rays indicated a new type of particle decaying into two oppositely charged pions. The neutral parent particle was called a kaon, K^0 . Many more particles were discovered over the subsequent years, and it lead Murray Gell-Mann to the concept of *the Eightfold Way*. He arranged particles into geometrical shapes that aligned the various properties of strangeness and electrical charge for example. It was in fact the Eightfold Way that lead Gell-Mann to predict the existence of the Ω^- particle of strangeness -3. It was discovered in 1964. The growing confidence in the Eightfold Way actually

lead Gell-Mann and Zweig that same year to propose that all of these particles were in fact composed of yet smaller fundamental constituents, which came to be known as quarks.

In much the same way, the Eightfold Way placed the quarks into patterns that aligned their strangeness and charge properties. The 1974 discovery of the J/ψ meson expanded this model with a new quark called charm c . The quark composition of the J/ψ meson is a charm-anticharm ($c\bar{c}$). This was confirmed when the mesons with naked charmness were discovered in 1976, the D^0 ($c\bar{u}$) and D^+ ($c\bar{d}$) mesons. During this period, 1975 brought the discovery of the third lepton, the tau τ , giving three generations of leptons in total: (e, ν_e) , (μ, ν_μ) and (τ, ν_τ) where the subscripts on the neutrinos were used in anticipation of lepton flavour conservation in particle decays. With three generations of leptons, and only two for quarks, it was natural to seek a third. Just another two years on, the upsilon meson, Υ , was discovered at Fermilab in 1977 [18]. This was again via a meson, consisting of a quark-antiquark pair with a new property called bottomness, ($b\bar{b}$). Similarly, naked bottomness was observed via the B mesons where a bottom quark combines with either an u, d, s or c quark. Finally, after almost another 20 years, in 1995 the top quark t was detected at the Tevatron experiment [19]. In the year 2000, the DONUT experiment discovered the tau neutrino, ν_τ [20]. The three generation picture of quarks and leptons was complete.

Interaction Mediators - Bosons

All of the above particles, γ aside, are called *fermions* in the SM. All fundamental particles have an intrinsic property called spin, s , for which the fermions take an absolute value of $n/2$, where n is an integer, $n = 1$ for the fermions summarised above. There do exist another essential set of particles commonly referred to as the interaction gauge *bosons*. These have integer spin, $s = n$, and are commonly described as the *mediators* of the fundamental forces. The electromagnetic interaction is mediated by the photon, γ , the strong interaction by the massless gluons g , and the weak interaction by the three massive bosons, $W^\pm$ and Z^0 . These all have $s = 1$. The gravitational force is hypothesised to be mediated by the graviton, though that will not be considered here.

The current dictionary of particles will be completed here with the most recently discovered boson in 2012 [21], the scalar spin zero Higgs Boson, H . The EM and

weak interactions are in a sense fragments of a higher unified electroweak force. The underlying symmetry for the electroweak force is spontaneously broken below a certain energy, leaving the EM and weak interactions as measurable observables at everyday accessible energies. Spontaneous symmetry breaking paves the way for the famous Higgs mechanism, by which all particles acquire their mass, except perhaps the neutrinos. Since the neutrinos only interact via the weak force, the core details of electroweak theory will be reviewed below. This reveals the origin of the weak interaction in the context of the SM, along with the masses of the weakly interacting bosons.

A complete picture of the presently known fundamental particles of nature have been presented. The fermions and the interactions they each participate in are summarised in Table 2.1. The bosons are similarly summarised with their masses and interaction mediated in Table 2.2.

Table 2.1 *The presently known fundamental fermions, with ticks indicating their participation in the interaction types of the standard model [2].*

Particle Name	Symbol	Electromagnetic	Strong	Weak
Electron	e^-	✓	×	✓
Muon	μ^-	✓	×	✓
Tau	τ^-	✓	×	✓
Electron Neutrino	ν_e	×	×	✓
Muon Neutrino	ν_μ	×	×	✓
Tau Neutrino	ν_τ	×	×	✓
Up Quark	u	✓	✓	✓
Down Quark	d	✓	✓	✓
Charm Quark	c	✓	✓	✓
Strange Quark	s	✓	✓	✓
Top Quark	t	✓	✓	✓
Bottom Quark	b	✓	✓	✓

Table 2.2 *The interaction-mediating bosons, including their masses [2].*

Boson Name	Symbol	Interaction	Mass (GeV/c^2)
Photon	γ	Electromagnetic	0
Gluon	g	Strong	0
W Bosons	$W^\pm$	Charged Weak	80.433 ± 0.009
Z Boson	Z^0	Neutral Weak	91.1876 ± 0.0021
Higgs Boson	H	Mass	125.18 ± 0.16

2.1.2 Electroweak Theory

The SM unifies the EM and the weak interactions into one electroweak force. The underlying symmetry group for this interaction is $SU(2)_L \times U(1)_Y$. The subscript L on the $SU(2)$ group serves as a reminder that the SM only predicts couplings to left handed doublet particle states,

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L, \begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L, \begin{pmatrix} s \\ b' \end{pmatrix}_L, \quad (2.1)$$

and their right handed singlet states,

$$e_R, \mu_R, \tau_R, u_R, d'_R, c_R, s'_R, t_R, b'_R \quad (2.2)$$

where a dash ' indicates a rotated state, corresponding to the weak interaction eigenstate transformed from the free *mass* eigenstates via the CKM (Cabibbo-Kobayashi-Maskawa) matrix, V_{CKM} . The CKM matrix was originally formulated to describe the mixing of quark flavours in the context of weak interactions. More specifically, the development started when Cabibbo was investigating the weak decays of strange particles in 1963 [22], and was later refined for the three-generation model of quarks by Kobayashi and Maskawa to describe CP violation in 1973 [23]. It is defined as

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}, \quad (2.3)$$

where the elements V_{ij} can be interpreted as a transition amplitude from quark j into i . Just as V_{CKM} describes the mixing between freely travelling and weakly interacting quark states, a similar matrix exists describing the rotated lepton doublet and singlet states above.

Note the lack of right handed neutrino states in the standard formulation. The subscript L indicates a projection of a doublet onto the left handed states only. The Y subscript on the $U(1)$ subgroup is called the weak hypercharge, related to the electric charge Q and the third component of weak isospin I_3 via $Q = I_3 + \frac{1}{2}Y$. By making the requirement of local gauge invariance under this symmetry group, three massless vector gauge bosons are introduced, denoted W_μ^1, W_μ^2 and

W_μ^3 , with an interaction coupling strength, g . These are associated with the $SU(2)_L$ subgroup. There is one other massless vector gauge boson, B_μ , introduced which is similarly associated with the $U(1)_Y$ subgroup and this has an interaction coupling strength denoted by g' . In this scheme, the gauge bosons introduced are required to be massless in order to preserve Lorentz invariance of the Lagrangian density, $\mathcal{L}$. Nevertheless, the weakly interacting bosons that are observed in experiments have relatively large masses as described above, and this is attributed to the spontaneous mass generation via the change from zero to non-zero vacuum expectation value (VEV) of the Higgs field.

Spontaneous Symmetry Breaking and The Higgs Mechanism

The $SU(2)_L \times U(1)_Y$ symmetry is in fact spontaneously broken via the non-zero expectation value for the ground state of a newly introduced doublet complex scalar field. This is the Higgs field and it was observed in 2012 by ATLAS and CMS experiments at CERN [21][24]. A simple model is considered here, of spontaneous symmetry breaking under local $U(1)$ gauge invariance to illustrate how mass is generated by the Higgs mechanism. The Higgs field is scalar ($s = 0$) and will be represented by a Lagrangian density given in Equation 2.4,

$$\mathcal{L} = \partial_\mu \phi_1 \partial^\mu \phi_1 + \partial_\mu \phi_2 \partial^\mu \phi_2 + \frac{1}{2} \mu^2 (\phi_1^2 + \phi_2^2) - \frac{1}{4} \lambda^2 (\phi_1^2 + \phi_2^2)^2, \quad (2.4)$$

where $\phi(x) = \phi_1(x) + i\phi_2(x)$ is a complex scalar field representing the Higgs field. Notice that a $\mu^2 < 0$ would be required to denote the mass of this field which is the general approach for the coefficient of the term quadratic in the relevant field. A real valued $\lambda \neq 0$ allows for a quartic self-interaction. Note that with $\lambda = 0$, this is simply the Klein-Gordon Lagrangian for two scalar fields ϕ_1 and ϕ_2 , each with mass $\sqrt{-\mu^2}$. The demonstration begins by interpreting this system as such. In this scheme, $\mathcal{L} = \mathcal{K} - \mathcal{V}$ where $\mathcal{K}$ represents the total kinetic energy and $\mathcal{V}$ the total potential energy, the field potential $V(\phi)$ is given by Equation 2.5. For a $\mu^2 < 0$, the minimum of this potential is unique and occurs at $\phi(x) = \phi_1 = \phi_2 = 0$. However, if $\mu^2 > 0$, the ground state is infinitely degenerate and a circle of minima occur at $|\phi(x)|^2 = \phi^*(x)\phi(x) = \phi_1^2 + \phi_2^2 = \mu^2/\lambda^2$. Figure 2.2 illustrates the two cases graphically.

$$V(\phi) = -\frac{1}{2}\mu^2(\phi_1^2 + \phi_2^2) + \frac{1}{4}\lambda^2(\phi_1^2 + \phi_2^2)^2 \quad (2.5)$$

In a proper field-theoretic treatment for particle physics, it is required to choose a specific ground state around which oscillations represent a particle of the relevant field. Making an appropriate choice of point on the above mentioned circle of minima leads to a redefinition of the complex scalar field components: $\phi_1 \rightarrow \eta = \phi_1 - \mu/\lambda$ and $\phi_2 \rightarrow \theta = \phi_2$ remaining unchanged. The resulting Lagrangian in terms of these new field definitions is given by Equation 2.6.

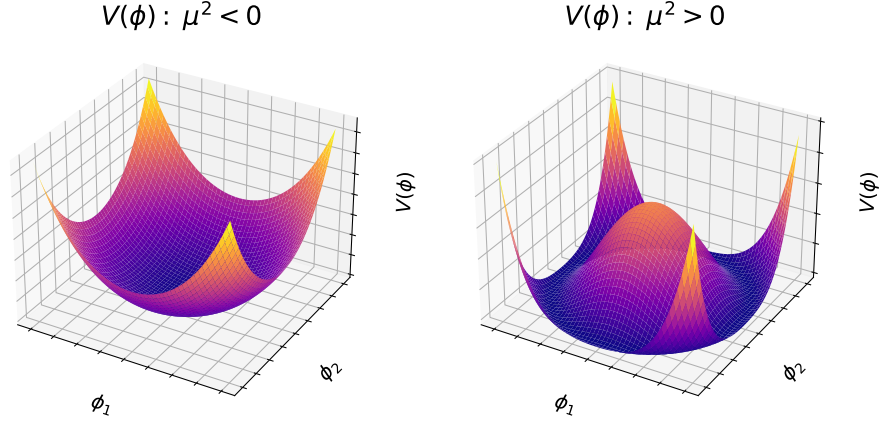


Figure 2.2 *Two cases for the Higgs potential in Equation 2.5, describing a simple spontaneous symmetry breaking model. The left surface represents the case for $\mu^2 < 0$, where a unique vacuum expectation value exists at $\phi(x) = \phi_1 = \phi_2 = 0$. The shift to $\mu^2 > 0$ leads to an infinitely degenerate ground state, shown on the right. Particles are necessarily described as oscillations around a specific value for the vacuum energy, and this choice of field components is said to spontaneously break the symmetry.*

$$\begin{aligned} \mathcal{L} = & \partial_\mu \eta \partial^\mu \eta + \partial_\mu \theta \partial^\mu \theta - \mu^2 \eta^2 - \mu \lambda \eta^3 - \mu \lambda \eta \theta^2 \\ & + \frac{\lambda^2}{4}(\eta^4 + \theta^4 + 2\eta^2 \theta^2) + \frac{\mu^4}{4\lambda^2} \end{aligned} \quad (2.6)$$

It is seen that an appropriate redefinition of the field in the case of $\mu^2 > 0$ has resulted in a Lagrangian with the expected sign on the mass term for η whilst rendering the θ field *massless*. Additional third and fourth order couplings of the new field components represent the various self-interactions that might

occur. The last term is a constant and therefore irrelevant to physical applications since the Euler-Lagrange equations will not be affected by the transition to field equations of motion.

Recast the interpretation of the field back from the two real scalar fields ϕ_1 and ϕ_2 , to the single complex field $\phi(x) = \phi_1 + i\phi_2$ that was started with. This interpretation can be represented with a simple change of notation, transforming Equation 2.4 into Equation 2.7. Imposing local $U(1)$ gauge invariance, the Higgs mechanism is discovered, the process by which the gauge bosons can acquire a mass term in the Lagrangian.

$$\mathcal{L} = (\partial_\mu \phi)^* (\partial^\mu \phi) + \frac{1}{2} \mu^2 \phi^* \phi - \frac{1}{4} \lambda^2 (\phi^* \phi)^2 \quad (2.7)$$

The local $U(1)$ gauge transformation acts on the field via $\phi \rightarrow \phi' = e^{i\alpha(x)} \phi$, by which the second and last terms in Equation 2.7 are manifestly locally $U(1)$ gauge invariant. The focus then shifts to the first term, where the standard procedure is followed, of introducing a covariant derivative to restore gauge invariance to $\mathcal{L}$ as a whole. The covariant derivative is given by $D_\mu = \partial_\mu + iqA_\mu$. The newly introduced massless vector gauge field A_μ is required to transform as $A_\mu \rightarrow A'_\mu = A_\mu + \partial_\mu \alpha(x)$ simultaneously with $\phi \rightarrow \phi'$. Including the free Lagrangian for the A_μ field via the Proca equation, the result is Equation 2.8,

$$\mathcal{L} = (D_\mu \phi)^* (D^\mu \phi) + \frac{1}{2} \mu^2 \phi^* \phi - \frac{1}{4} \lambda^2 (\phi^* \phi)^2 - \frac{1}{16\pi} F^{\mu\nu} F_{\mu\nu}. \quad (2.8)$$

The field strength variable is given by $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$ and encodes the curvature of the gauge field A^μ .

The same prescription is now followed for spontaneous symmetry breaking, where $\mu^2 > 0$ in Equation 2.8 and the components of the complex scalar field are redefined. That is, the components ϕ are defined to correspond to a minimum of the potential, i.e. $\eta = \phi_1 - \mu/\lambda$ and $\theta = \phi_2$, and re-express the Lagrangian, Equation 2.8, in terms of these new fields. The result is Equation 2.9,

$$\begin{aligned}
\mathcal{L} = & \partial_\mu \eta \partial^\mu \eta - \mu^2 \eta^2 + \partial_\mu \theta \partial^\mu \theta - \frac{1}{16\pi} F^{\mu\nu} F_{\mu\nu} \\
& + \frac{q^2 \mu^2}{2\lambda^2} A_\mu A^\mu + q(\eta \partial_\mu \theta - \theta \partial_\mu \eta) A^\mu + \frac{\mu q^2}{\lambda} \eta A_\mu A^\mu \\
& + \frac{q^2}{2} (\theta^2 + \eta^2) A_\mu A^\mu - \lambda \mu (\eta^3 - \eta \theta^2) - \frac{\lambda^2}{4} (\eta^4 2\eta^2 \theta^2 + \theta^4) \\
& + \frac{\mu q}{\lambda} \partial \theta A^\mu + \frac{\mu^4}{4\lambda^2}.
\end{aligned} \tag{2.9}$$

The combination of spontaneous symmetry breaking and imposing local gauge invariance under a continuous symmetry transformation has resulted in the previously massless vector gauge field picking up a mass term with $m_A \propto q\mu/\lambda$. This all happened due to the non-zero expectation value of the vacuum of the field in question, resulting in the redefined fields picking up a constant, thereby generating a non-zero coefficient for the $A_\mu A^\mu$ term in the Lagrangian. The gauge freedom can be exploited to remove the massless Goldstone boson, along with the associated interaction terms. This is done by making an appropriate choice of gauge transformation, $\phi \rightarrow \phi'$ and $A_\mu \rightarrow A'_\mu$. Thus, the Higgs mechanism for spontaneous mass generation of gauge bosons has been demonstrated for continuous $U(1)$ symmetry transformations on a complex scalar field.

Glashow Weinberg Salam (GWS) Model for Electroweak Unification

The SM Higgs is actually described by a complex doublet, H . The electroweak symmetry group is then $SU(2)_L \times U(1)_Y$ as described above, which is broken into $U(1)_{EM}$ at low energies. The Higgs field has a hypercharge $Y = 1/2$, associated with the $U(1)_Y$. The corresponding hypercharge gauge boson is B_μ . Similarly, the gauge bosons of the $SU(2)_L$ group are W_μ^1 , W_μ^2 and W_μ^3 . When a non-zero VEV is chosen for the field, the symmetry is broken and it is observed that the weak interaction bosons, $W_\mu^\pm$ and Z_μ^0 and the electromagnetic boson, the photon, A_μ are each linear combinations of the aforementioned electroweak gauge bosons, given by Equations 2.10 to 2.12:

$$Z_\mu^0 = \cos \theta_w W_\mu^3 - \sin \theta_w B_\mu, \tag{2.10}$$

$$A_\mu = \sin \theta_w W_\mu^3 + \cos \theta_w B_\mu, \tag{2.11}$$

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2). \quad (2.12)$$

The parameter θ_w is called the Weinberg mixing angle, and is defined by the ratio of the coupling strengths $\tan \theta_w = g/g'$.

The unification of the weak and EM interactions was achieved by resolving several discrepancies between the two:

1. The weak interaction mediators are massive, whereas the EM interaction mediator is massless. This is resolved by the use of the Higgs mechanism with local gauge symmetry under the $SU(2)_L \times U(1)_Y$ group described above.
2. The weak interactions only couple to the left handed fermions, whereas the EM couples to both the left and right handed. This is resolved by treating the two chiral states as separate particles, the EM interacting with both right and left chiral particles, and the weak interaction only interacting with left chiral particles, and right chiral antiparticles.

This summarises the Glashow Weinberg Salam (GWS) model of electroweak unification under the lens of continuous local gauge symmetry of a Lagrangian exhibiting spontaneous symmetry breaking. Next discussed are the weak interactions of the standard model.

2.1.3 Standard Model Weak Interactions

This section will outline the important peculiarities of the weak interaction, before moving onto the neutrinos, wholesale. The weak interactions are what enable cross-generational flavour changing in the SM, and are responsible for some particle decays, including the neutron β -decay. One of the most notable features of them is the vector minus axial-vector, $(V - A)$ structure of the theory. The linear combination of both vector and axial-vector bispinors (with opposite parity) is guaranteed to introduce parity symmetry violation to some degree. This has, in fact, turned out to be maximal.

Propagator

One of the major differences in the weak interactions, compared to the electromagnetic and strong, is that the mediators are massive. Their masses are so large, that at everyday energies, the interactions have often been successfully approximated to point interactions of the particles. However, the full propagator takes the form of Equation 2.13,

$$\frac{-i(g_{\mu\nu} - q_\mu q_\nu / M^2 c^2)}{q^2 - M^2}, \quad (2.13)$$

and when interaction energies become comparable to M , the full form must be used in thorough calculations. Here, M is the mass of the spin one vector boson, the mediator. The 4-momentum transfer vector between the interacting particles is represented by q_μ and $g_{\mu\nu}$ is the metric tensor of the surrounding space-time. At everyday energies, the effects of the mass of the mediator boson can be safely approximated with the expression $-ig_{\mu\nu}/M^2 c^2$ for the propagator.

Vertex Factors

Another surprising feature of the weak interactions is the vector minus axial-vector structure of the interaction vertices. The vertex factor is given by Equation 2.14,

$$-i\frac{g_W}{\sqrt{2}}\gamma^\mu(1 - \gamma^5), \quad (2.14)$$

where g_W is the weak coupling constant, and the γ^μ are as usual, the Dirac gamma matrices. The $(1 - \gamma^5)$ factor brings about two interaction terms, proportional to the vector γ^μ and the axial-vector $\gamma^\mu\gamma^5$ bispinors, which each have parity +1 and -1, respectively.

The above linear combination of both vector and axial-vector bispinors in the interaction guarantees an element of parity violation in the weak interactions. Experimentally, these were shown to be maximal, when a new parameter, ϵ , was introduced into the $V - A$ factor $(1 + \epsilon\gamma^5)$ to quantify the contributions from each. The experiments that followed in the 1950s soon found $\epsilon = -1$, confirming a contribution of equal magnitude from both V and A bispinors in the interaction:

maximal parity violation. Parity symmetry violation itself was first demonstrated via the weak interactions by the famous experiment using polarised ^{60}Co nuclei by C.S Wu [25].

2.2 Neutrinos

A description of the SM, with the weak interaction that the neutrinos participate in has been provided. What follows is a discussion of neutrinos in more detail. The neutrino was first proposed by W. Pauli, in 1930 as a *desperate remedy*, an attempt to combat the apparent violation of conservation of energy in β decay [3]. So far, light neutrinos have been discovered and this is confirmed by the Large Electron-Positron collider (LEP) and cosmological constraints [4]. This section will detail the neutrinos, including the history, theory of oscillations and interactions, detection mechanisms with current experiments and then leading up to the current status. That includes mass measurements, mixing angles and the charge parity (CP) violating phase δ_{CP} . The mass hierarchy problem and the potential for CP violation in the lepton sector are also outlined.

2.2.1 History & Discovery

Once the neutrino was proposed as a solution to the continuous energy spectrum of β -decay, it was also realised that this particle, if it existed, had to be of low mass. Indeed, it was confidently suggested that the technological capability to detect such a particle would never be achieved. It took over 20 years to disprove this statement, and in 1956, Reines and Cowan discovered the neutrino using the large antineutrino flux that originates from a nuclear reactor to do so [26].

1956 - The Electron (Anti)Neutrino: $\bar{\nu}_e$

It was in 1956 that Cowan and Reines used the large number of β -decay events produced by Savannah River Plant's nuclear reactor as a source of antineutrinos. The detection medium used was Cd-doped water, where in the event of a $\bar{\nu}_e$ interacting via inverse β -decay with a proton in the water, a positron e^+ and a neutron n would be produced, see Equation 2.15,

$$\bar{\nu}_e + p \rightarrow e^+ + n. \quad (2.15)$$

The positron almost immediately annihilates, and the neutron captures on the Cd,

$$n + {}^{108}\text{Cd} \rightarrow {}^{109}\text{Cd} + \gamma, \quad (2.16)$$

around $10\,\mu\text{s}$ later. The scintillation light from these two interactions determined the reaction signature, and a direct comparison of the observed rate, whilst the reactor was both operational and not, provided clear evidence of antineutrino interactions present in the detector [26].

1962 - The Muon Neutrino: ν_μ

In 1959, it was unknown if the electron neutrino was identical to the muon neutrino ($\nu_e \stackrel{?}{=} \nu_\mu$), and Schwartz proposed a method to determine if this was the case. This used decaying high energy pions and kaons in flight, which were produced by colliding 15 GeV protons onto a beryllium target at CERN in 1962 [27]. The main products of these collisions (the pions), centered on 7° solid angle, were aimed at the detector. The decaying mesons would primarily produce muons and muon neutrinos, where, if $\nu_e \neq \nu_\mu$, the detection of a charged current muon neutrino interaction should only produce a muon with a characteristic long track, in comparison to a shower produced by an electron. Most of the other hadrons and muons were absorbed by a 13.5 m long iron shield, constructed from pieces of an old ship [3]. This provided a test to confirm whether ν_μ and ν_e were truly distinct particles.

In total, the spark chamber [28] used as a detector observed 34 independent muon events, whereby the muons characteristically manifested themselves as long tracks passing through the 2.5 cm thick plates of the spark chamber. Given that no electron shower events were observed, it was concluded that the neutrino produced alongside a μ from a π decay, also produced only muons when they interact via charged current with the detection medium. This was the pivotal confirmation that ν_μ and ν_e are each themselves, distinct particles in the SM.

2000 - The Tau Neutrino: ν_τ

It would take until 2000 to discover the tau neutrino, ν_τ , at the DONUT experiment [20]. The primary reason for this being that the τ particle produced by the charged current interaction of a ν_τ has a rest mass of 1.77 GeV, meaning that it also decays extraordinarily fast, with a lifetime of only 2.9×10^{-13} s. Much higher energy protons, up to 800 GeV, from the accelerator were used to produce charged D_s mesons via a tungsten target. The mesons subsequently decay and have a 5.3% branching ratio to tau neutrinos, $D_s^+ \rightarrow \tau^+ + \nu_\tau$ [2]. The observation of 4 independent events confirmed the third generation flavour of neutrino.

Solar Neutrinos & The Solar Neutrino Problem

At the time of the Cowan and Reines experiment, it was assumed that nuclear reactions were the source of the Sun's energy. Neutrinos produced in the Sun primarily result from nuclear fusion reactions, such as the proton-proton (pp) chain and the carbon-nitrogen-oxygen (CNO) cycle. In the pp chain, which dominates in the Sun, the principal reactions are:

1. $p + p \rightarrow d + e^+ + \nu_e$
 2. $p + e^- + p \rightarrow d + \nu_e$
 3. ${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2p$
 4. ${}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$
 5. ${}^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$
 6. ${}^8\text{B} \rightarrow {}^8\text{Be}^* + e^+ + \nu_e$
- (2.17)

The estimated flux of solar neutrinos at Earth is approximately $6 \times 10^{14} \text{ m}^{-2}\text{s}^{-1}$. By 1964, two key works were in place to make the detection of solar neutrinos feasible. First, John Bahcall had been working on a complete model of solar neutrinos and had calculated the estimated flux of them according to this latest solar model. The realisation in 1963 that the relatively large energies (≈ 10 MeV) of boron B neutrinos made experimental detection feasible, by exceeding the interaction detection energy threshold of 814 keV [3].

Second, in 1964, Raymond Davis had finished the experimental design. The key detector concept was to use a large tank of chlorine (C_2Cl_4), such that the

neutrino capture reaction,

$$\nu_e + {}^{37}\text{Cl} \rightarrow e^- + {}^{37}\text{Ar}, \quad (2.18)$$

would produce ${}^{37}\text{Ar}$ nuclei. From the predicted flux, Davis should have expected approximately one ${}^{37}\text{Ar}$ nucleus (atom) to be formed per day, which were extracted via a helium stream. He then monitored the number of ${}^{37}\text{Ar}$ β -decays from them, in order to provide a count for the total number of interactions observed.

Davis placed his detector in an old gold mine, 1480 m deep, in South Dakota, such that it would be heavily shielded from the constant bombardment of cosmic rays. The estimated flux of solar neutrinos at Earth is approximately $6 \times 10^{14} \text{ m}^{-2}\text{s}^{-1}$, much smaller than that from a reactor, hence the requirement for such extreme background shielding efforts. The first published results were in 1968 [29], but it took a further 3 decades to confirm the signal and surprise the physics community when it was found that approximately two thirds of the expected flux was *missing*. The boron neutrino deficit was later confirmed by the Kamiokande experiment in 1987 [30], and again by its successor Super-Kamiokande (SK) [31]. This became known as the solar neutrino problem.

Coincidentally, it was Pontecorvo who had hypothesised the neutrino oscillations between both flavour and particle-antiparticle mass states in 1967, just two weeks before the first ${}^{37}\text{Ar}$ extraction took place. In fact, the boron neutrino deficit, which were the only neutrinos Davis' detector was sensitive to, was due to the Mikheyev-Smirnov-Wolfenstein (MSW) matter effect, described below, which is specifically a manifestation of neutrino oscillations in matter *and* vacuum neutrino oscillations. Between the dense core of the Sun to the vacuum in which they travel to Earth, the neutrinos travelling through a slowly varying density of mass experience flavour oscillations with 100% probability.

To continue this account of neutrino physics, the theoretical framework that allows neutrinos to change flavor is now discussed. This phenomenon, known as neutrino oscillations, is purely quantum mechanical and played a crucial role in resolving the solar neutrino problem.

2.2.2 Neutrino Oscillations

The formalism for neutrino oscillations are now described, following with the MSW matter effect which includes the resonant flavour oscillation behaviour. The first thing to note is that at the point of creation via weak interaction, the weak eigenstate neutrino is either of the electron, muon or tau flavours, where $\alpha, \beta = \{e, \mu, \tau\}$ is used in the following. Each of the weak eigenstates can be written as a linear combination of the mass eigenstates, represented here with Latin characters, $i, j = \{1, 2, 3\}$ in Equation 2.19,

$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i}^* |\nu_i\rangle, \quad \text{where} \quad \begin{cases} \alpha = e, \mu, \tau & (\text{flavour}) \\ i = 1, 2, 3 & (\text{mass}) \end{cases} \quad (2.19)$$

Here, $U_{\alpha i}$ is a value used to describe the mixing between the neutrino mass state i and weak interaction state α . For example, in the case of an electron neutrino, U_{e1}, U_{e2} and U_{e3} represent the probability amplitudes that an electron neutrino is in the ν_1, ν_2 or ν_3 mass states, respectively. The bra-ket notation has been introduced for clarity in calculating probabilities.

PMNS Matrix

In the more extended parameterisation formalism, the above description of mixing takes the form of Equation 2.20. It is called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, U_{PMNS} . It is often written in a matrix-factorised fashion, which makes it easier to interpret in terms of specific mixing pairs. This is shown in the second equality of Equation 2.20,

$$\begin{aligned} U_{PMNS} &= \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}. \end{aligned} \quad (2.20)$$

Here,

$$c_{ij} = \cos \theta_{ij}, \quad s_{ij} = \sin \theta_{ij}$$

and δ_{CP} is the CP-violating phase.

θ_{ij} are referred to as the mixing angles between the different eigenstates. U_{PMNS} is unitary, and therefore has 9 independent parameters from the $U^\dagger U = \hat{\mathbb{1}}$ condition. In the neutrino oscillation formalism, these are further reduced as follows:

- **Neutrino Phase Redefinitions:** One is always free to redefine the phase of the three independent neutrino particles, and this makes three of the parameters redundant. Six free parameters remain.
- **Overall Phase:** Similarly, there is also freedom to remove an overall phase on the entire matrix, which applies to every element, wholesale. This reduces the total number of parameters to describe oscillations to 5.
- **Unitary Constraints:** One more number can be removed in the description of U_{PMNS} , which also comes from the unitary constraint. It defines a relationship between the three mixing angles $\theta_{\alpha i}$ and the CP violating phase δ_{CP} . These relationships allow the removal of one more redundant parameter from the description and so just 4 numbers remain to describe the PMNS matrix.

In order to see how neutrino oscillations can arise, the time evolution of the state can be traced, which is given by acting on it with the Hamiltonian of the system. From there, the probability of oscillation from one flavour α to another β is determined by acting on it with the Hermitian conjugate state of $\nu_\beta(t)$. These steps are demonstrated in Equations 2.21 and 2.22,

$$|\nu_\alpha(t)\rangle = e^{-iHt}|\nu_\alpha(t=0)\rangle = \sum_{i=1}^3 U_{\alpha i}^* |\nu_i(t)\rangle = \sum_{i=1}^3 U_{\alpha i}^* e^{-iE_i t} |\nu_i\rangle \quad (2.21)$$

$$\begin{aligned}
P(\nu_\alpha \rightarrow \nu_\beta) &= |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 \\
&= \left| \sum_{i=1}^3 U_{\alpha i}^* e^{-iE_i t} \langle \nu_\beta | \nu_i \rangle \right|^2 \\
&= \left| \sum_{i=1}^3 \sum_{j=1}^3 U_{\alpha i}^* U_{\beta j} e^{-iE_i t} \langle \nu_j | \nu_i \rangle \right|^2 \\
&= \left| \sum_{i=1}^3 U_{\alpha i}^* U_{\beta i} e^{-iE_i t} \right|^2 \\
&= \sum_{i=1}^3 \sum_{j=1}^3 U_{\alpha i}^* U_{\beta i} U_{\beta j}^* U_{\alpha j} e^{-i(E_i - E_j)t}.
\end{aligned} \tag{2.22}$$

Here, the energies of the free Hamiltonian eigenstates can be approximated by the use of a Taylor expansion on the relativistic energy-momentum relation,

$$E_i = \sqrt{p_i^2 + m_i^2} \approx p_i + m_i^2/2p_i \approx E_i + m_i^2/2E_i, \tag{2.23}$$

since neutrinos are light, and essentially always exist in the ultra-relativistic regime $p_i \gg m_i$. This means the relation $E_i = p_i c = p_i L/t$ also holds, where L is the distance travelled in time t . In that case, the energy difference in the last line of Equation 2.22 can be written as

$$E_i - E_j = \frac{E_i^2 - E_j^2}{E_i + E_j} = \frac{m_i^2 - m_j^2}{E_i + E_j} \approx \frac{m_i^2 - m_j^2}{2E} \equiv \frac{\Delta m_{ij}^2}{2E}, \tag{2.24}$$

since $E_i \approx E_j \approx p \approx E$. The mass splittings have been defined, i.e. $m_i^2 - m_j^2 \equiv \Delta m_{ij}^2$. The probability can be written as Equation 2.25,

$$\begin{aligned}
P(\nu_\alpha \rightarrow \nu_\beta) &= \delta_{\alpha\beta} - 4 \sum_{i < j} \text{Re} \left(U_{\beta j}^* U_{\alpha j} U_{\beta i} U_{\alpha i}^* \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E} \right) \right) \\
&\quad + 2 \sum_{i < j} \text{Im} \left(U_{\beta j}^* U_{\alpha j} U_{\beta i} U_{\alpha i}^* \sin \left(\frac{2\Delta m_{ij}^2 L}{4E} \right) \right) \\
&= \sin^2(2\theta_{ij}) \sin^2 \left(1.27 \Delta m_{ij}^2 \frac{L}{E} \frac{[\text{eV}][\text{km}]}{[\text{GeV}]} \right) \quad (\text{two neutrinos}).
\end{aligned} \tag{2.25}$$

For antineutrinos, a change of sign on the imaginary term in the first equality is required. The second equality describes the oscillation probability for a simpler model considering just two neutrinos.

The change of units in the final line provides a more convenient and intuitive expression for practical calculations in neutrino oscillation experiments. The neutrinos used typically travel distances on the order of kilometres and have energies measured in GeV. It is now seen that an important parameter for neutrino oscillation experiments is the L/E value, which can be determined from the distance to the detector the accelerator produced neutrinos must travel, and the energy spectrum into which they are produced.

Physics Consequences in the PMNS Formalism

From the formalism described above, there are some important observations which should be noted before proceeding:

- **Possibility of Oscillations:** In order for neutrino oscillations to be possible, the masses of the free Hamiltonian states must be non-degenerate. That is, $\Delta m_{ij}^2 \neq 0$. This is immediately apparent from Equation 2.25.
- **CP Violation:** If just one of the mixing angles $\theta_{ij} = 0$, then the possibility of CP Violation in the lepton sector is extinguished. This is encapsulated in the Jarlskog invariant, J_{CP} , which is given (in the standard parameterisation, as above) as [32]

$$J_{CP} = s_{12}s_{23}s_{13}c_{12}c_{23}c_{13}^2s\delta_{CP}. \quad (2.26)$$

The Jarlskog invariant quantifies the amount of CP violation possible due to the neutrino oscillations. The maximum value of $J_{CP}^{max} = 1/(6\sqrt{3})$ is obtained when $\theta_{12} = \theta_{23} = \pi/4$, $\sin \theta_{13} = 1/\sqrt{3}$ and $\delta_{CP} = \pi/2$.

- **Detector Parameter L/E:** As remarked above, this quantity is the key parameter for experimentalists to design oscillation experiments, since it characterises the wavelength of the oscillations themselves, as seen from Equations 2.25 and 2.28. It can be tuned by varying the distance of the detector to the neutrino source, and adjusting the neutrino energies directed at the detector.

2.2.3 The Mikheyev-Smirnov-Wolfenstein (Matter) Effect

The above discussion reveals how the purely quantum phenomenon of neutrino flavour oscillations can arise in the vacuum. The section now concerns the oscillation effects of neutrinos travelling in matter, leading to a concept known as the Mikheyev-Smirnov-Wolfenstein (MSW) effect. This will be done in the context of ν_e produced in the middle of the Sun, travelling outwards through the solar radius of slowly varying density, through the vacuum of space to Earth, where they might be detected by our experiments. The discussion is based on the two neutrino model, say $\alpha = \{e, \mu\}$ and $i = \{1, 2\}$ in the following.

The mass states are eigenstates of the free Hamiltonian in the vacuum. If one considers the neutrinos travelling through matter, the Hamiltonian must first be amended by adding an interaction potential. This can be done by adding an interaction potential to the free Hamiltonian. This interaction potential need not be the same for each flavour, indeed, one can add an associated V_α for each flavour. However, for electron neutrinos travelling radially outwards in the Sun, the charged current interactions are the only modes available to provide a relative difference with respect to the other flavour, since the energy thresholds for muon or tau production are not reached here. In the flavour basis then, the time evolution would look as follows,

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \left[H_0 + \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + V_e & -\frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} \right] \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \quad (2.27)$$

where H_0 is a part of the free Hamiltonian in the flavour basis.

The consequence of this alteration is that the relative mass states have been changed in the presence of the matter interaction potential. The added potential, V_e , itself takes the form $2\sqrt{2}G_F E_\nu N_e$, where G_F is the Fermi constant, and N_e is the electron number density in matter. This makes sense, since it is only the electron neutrinos that are affected by the possibility to interact via charged current with the electrons in matter.

The key take-away here is that an *effective* mass difference Δm_m^2 and mixing angle θ_m are derived from the adjusted Hamiltonian, to describe the behaviour of oscillations in matter. For the two flavour model, the resulting flavour transition probability for distance travelled by an initially created ν_e , L and energy E is,

$$P_m(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta_m) \sin^2(1.27\Delta m_m^2 \frac{L}{E}), \quad (2.28)$$

and

$$\sin(2\theta_m) = \frac{\sin 2\theta}{\sqrt{(\Delta V/\Delta m^2 - \cos 2\theta)^2 + \sin^2 2\theta}} \quad (2.29)$$

From here, it is plain to see that if $\Delta V/\Delta m^2 = \cos 2\theta$, then $\sin 2\theta_m = 1$, i.e. the mixing is maximal. In this case, there may exist an electron density N_e^* such that the flavour oscillation probability is 100%. Between the centre of the Sun, and the vacuum of space, the produced ν_e will likely encounter the N_e^* , and experience a flavour transition to the muon flavour. This effect is known as MSW resonance, and contributed to the resolution of the solar neutrino problem.

The final confirmation for the neutrino oscillations solution to the solar neutrino problem, via the vacuum oscillations and MSW matter effect contribution to the boron neutrino deficit, came from the Sudbury Neutrino Observatory (SNO) in 2002 [33]. SNO used a heavy water Cherenkov light detector, which was independently sensitive to both charged current (CC) electron neutrino events and neutral current (NC) (all flavours) elastic scattering events. SNO's measurements showed that the total number of observed neutrinos, via CC, NC, and elastic scattering interactions, matched the predictions of the standard solar model. However, the number of observed electron neutrinos, via CC interactions alone, was significantly lower than expected. Neutrino oscillations were changing the flavour of ν_e produced in the Sun.

The Super-Kamiokande experiment also provided strong evidence for neutrino oscillations by observing a deficit of muon neutrinos [31]. This deficit was identified by comparing the detected neutrino interactions originating from directly above and below the Cherenkov detector. Muon neutrinos travelling upward through the Earth—having traversed a much longer distance—had sufficient time to oscillate into other flavours, resulting in a reduced flux. In contrast, the downward-going flux, consisting of neutrinos that travelled only a short distance through the atmosphere, showed no significant deficit.

2.2.4 Oscillation Parameters: Current Status

The current status of the oscillation parameters measurements will now be reviewed, before moving onto the interactions of neutrinos themselves. For reasons that will be described below, the mixing parameters are often described in terms of Solar, Atmospheric and Reactor regimes. These are described in turn, before summarising the latest measurements. All values are taken from [2]. Measured values are all given in terms of the normal hierarchy of neutrino masses before the discussion on the mass hierarchy problem.

Solar Mixing Parameters: Δm_{21}^2 and θ_{12}

Solar neutrinos are produced as ν_e , and the probability for them to transition as they propagate to ν_μ or even ν_τ types are largely characterised by θ_{12} . For this reason, the 1-2 sector is commonly referred to as the Solar mixing parameters. The current best fit for this mixing angle is $\theta_{12} = 33.82^{+0.78}_{-0.76}$ degrees [34], where for the mass splitting, it is $\Delta m_{21}^2 = 7.39^{+0.21}_{-0.20} \times 10^{-5} \text{eV}^2$ [35][2].

Atmospheric Mixing Parameters: Δm_{32}^2 and θ_{23}

Cosmic rays are primarily made up of protons and helium, striking the particles in Earth's atmosphere, producing pions and kaons. The decay of these mesons produce the atmospheric neutrinos, and they have an extremely wide energy range, from O(100) MeV all the way up to PeV. They reach neutrino detectors, such as Super-Kamiokande from distances of approximately 10 km (directly above) to 10^4 km (directly below, travelling through the Earth). The θ_{23} mixing angle characterises the probability for ν_μ to transition to ν_τ as they propagate. Given the long distances and higher energies associated with these physical processes, it enables the searches for higher mass states parameters. It is commonly referred to as the atmospheric mixing angle, due to the origin of those processes. The current best fit value is $\theta_{23} = 48.3^{+1.2}_{-1.9}$ degrees [36], implying close to maximal mixing. In particular, it is not yet known with confidence whether this parameter lies in the lower octant ($\theta_{23} < 45^\circ$) or the higher octant ($\theta_{23} > 45^\circ$), and independent measurements favour different regimes. Maximal mixing ($\theta_{23} = 45^\circ$) is also a possibility, whereby the muon and tau neutrinos contribute equally to the mass state. This open question is critical to

experiments that aim to make precision measurements of δ_{CP} , since they typically use transitions such as $\nu_\mu \rightarrow \nu_e$, whose probability amplitudes include terms which are proportional to $\sin^2(\theta_{23})$. The mass splitting Δm_{32}^2 is two orders of magnitude larger than the solar mass splitting, and has a current best fit value of $|\Delta m_{32}^2| = 2.449_{-0.030}^{+0.032} \times 10^{-3} \text{ eV}^2$ [36][2].

Reactor Mixing Parameter: θ_{13}

The neutrinos produced in nuclear reactors are from the β -decay of neutrons, and provide a pure sample of $\bar{\nu}_e$. The primary mixing parameters here come from the first and third mass states, m_1 and m_3 . The reactor mixing angle is therefore θ_{13} , and characterises the probability amplitude for electron anti-neutrinos to transition to other flavour states $\bar{\nu}_e \rightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$, as they propagate. The current best fit value for the reactor mixing angle is $\theta_{13} = 8.61_{-0.13}^{+0.13}$ degrees [36][2].

Mass Hierarchy Problem

Oscillation experiments so far have only been able to provide measurements of mass-squared differences, since it is those values, Δm_{ij}^2 , that oscillations are functions of, as in Equation 2.25. This leaves an open question in neutrino physics: What is the absolute mass scale of neutrinos? Given the measured values of Δm_{32}^2 and Δm_{21}^2 above, there are two possible orderings of the ν mass eigenstates:

1. **Normal Mass Hierarchy (NMH):** The size of the masses are ordered according to $m_1 < m_2 < m_3$.
2. **Inverted Mass Hierarchy (IMH):** The size of the masses are ordered as $m_3 < m_1 < m_2$.

The two options are illustrated graphically according to the mass splitting measurements in Figure 2.3.

CP Violating Phase δ_{CP}

The CP violating phase of the neutrino oscillation parameters is yet to be determined. Experiments are ongoing to measure the value of δ_{CP} , where the

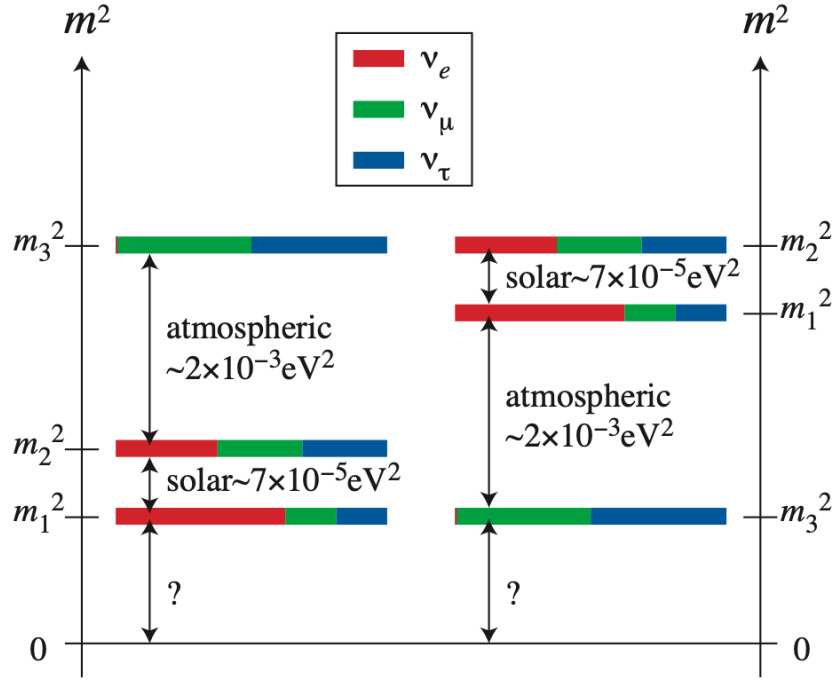


Figure 2.3 *A graphical illustration of the neutrino mass states and the mass hierarchy problem in neutrino physics. The left scenario describes Normal Mass Hierarchy (NMH), where $m_1 < m_2 < m_3$. The right describes Inverted Mass Hierarchy (IMH), where $m_3 < m_1 < m_2$. The solar and atmospheric mass splitting measurements are also labelled, corresponding to those described in the main text [37].*

T2K (Tokai to Kamioka) experiment in Japan has reported a non-zero value (or π) [38]. The DUNE physics programme includes a 5σ precision measurement of δ_{CP} , in addition to determining the ordering of the neutrino mass hierarchy. Hyper-Kamiokande aims for the same 5σ confidence for a measurement of δ_{CP} . A non-zero (or π) value of this parameter could contribute to our understanding of the matter-antimatter asymmetry observed in our universe.

Current Best Fit Measurements

The current best fit measurements are summarised in Table 2.3 below. The values reported are for the NMH scenario.

Table 2.3 *Neutrino mixing parameters for normal mass hierarchy (NMH) [2].*

Oscillation Parameter	NMH Value
Solar Angle ($\theta_{12}/^\circ$)	$33.82^{+0.78}_{-0.76}$
Atmospheric Angle ($\theta_{23}/^\circ$)	$48.3^{+1.2}_{-1.9}$
Reactor Angle ($\theta_{13}/^\circ$)	$8.61^{+0.13}_{-0.13}$
Solar Mass ($\Delta m_{21}^2/\text{eV}^2$)	$7.39^{+0.21}_{-0.20} \times 10^{-5}$
Atmospheric Mass ($ \Delta m_{32}^2 /\text{eV}^2$)	$2.449^{+0.032}_{-0.030} \times 10^{-3}$

2.3 Neutrino Interactions and Cross Sections

The physics to understand how neutrinos interact with matter has now been discussed. This has included an overview of neutrino physics with the theory of oscillations, along with a review of the current status of the oscillation parameter measurements. This section describes the neutrino interactions themselves, and goes on to describe the various types of cross section measurements one can make in accelerator-based neutrino oscillation experiments such as MicroBooNE and DUNE. This is all done in the context of muon neutrinos ν_μ , which are the dominant constituent of accelerator-produced neutrino beams. A review of the latest relevant measurements for muon neutrinos on argon is also given.

Neutrino cross sections are essential for long baseline oscillation experiments. They are used for event rate predictions, background modelling and perhaps most importantly, the probability of oscillation calculations. In addition to their use in neutrino oscillation experiments, they improve our understanding of neutrino interactions as a whole, reduce systematic uncertainties which improves the confidence in future results and allow the probing of nuclear effects. As shall be seen in Chapter 7, the uncertainty from cross section predictions is still large, and dominates some of the simulation to data comparisons. Hence the tremendous ongoing effort to precisely measure them for the next generation of oscillation experiments. In particular, this thesis will attempt the first measurement of the CC $\bar{\nu}_\mu$ on argon cross section using the MicroBooNE experiment data from the NuMI neutrino beam.

2.3.1 Neutrino Interactions

The flavour of a neutrino that has undergone an interaction in particle detectors can only be determined by identifying the charged lepton that emerges from a charged current (CC) weak interaction. In LArTPCs, an electron will produce an electromagnetic shower, whilst a muon will produce a characteristic long track. If the energy of the muon is low enough, the high stopping power of liquid argon can be sufficient to bring it to a halt, where it will decay $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$, after roughly $2.2\,\mu\text{s}$, the lifetime of the muon, τ_μ . The products of that decay will include a Michel electron, which has well-understood energies up to 53 MeV. These types of electrons can provide additional selection criteria for muon events in LArTPCs, and have even been used for studying the low energy response of this detector type [39][40]. This work is incredibly important for the next generation neutrino experiments, such as DUNE, which will potentially make a supernova neutrino measurement. The spectrum of these neutrino energies is concentrated in the $O(10\text{s})$ MeV region. It is also possible to detect neutral current (NC) neutrino interactions in particle detectors, though the flavour will remain undetermined. This is entirely due to the lack of a charged lepton that tags the flavour in the final interaction state.

This thesis is concerned with neutrino interactions with nuclei, and will present two cross section measurements per nucleon. The nuclear model of those interactions is now outlined, followed by an explanation of the several energy regimes they are often categorised into in the literature.

1. Before the interaction occurs, the motion of nucleons is described by Fermi motion, typically of momenta around 200 MeV. This is a result of their confinement via the nuclear potential.
2. Neutrino-nucleus interactions occur via the weak force with some subset of nucleons. The neutrino can interact with single nucleons in the Quasi-Elastic (QE) regime. It is also possible to interact with two nucleons, or, two-particle-two-hole (2p2h), whereby energy is transferred to this nucleon-pair system as a whole. The result is that two nucleons can be kicked out of the nucleus. A description of the 2p2h interaction is called the meson-exchange-current (MEC) [41], whereby a virtual meson is exchanged, allowing energy transfer to a correlated nucleon pair. MEC interactions alter the observed cross section shape with respect to energy, and in

particular, make a significant contribution to the QE-like signal region.

3. Finally, the final state interactions (FSI) can alter the kinematics and even identities of the daughter particles inside the nucleus. Additionally, secondary particles such as pions can be produced and leave the nucleus. The particles that emerge can be detected and widen the spectrum of energies observed, other than those predicted by the Quasi-Elastic and 2p2h models alone.

The initial neutrino interaction with a nucleus can be entirely shielded from the view of the detector, and it is only the final state particles that emerge after traversing the intranuclear medium that can be detected. It is the cumulation of the above interaction steps which are observed by neutrino detectors, and hence the requirement for a layered interaction framework for well-considered event reconstruction and cross section analyses. In the case of neutrino-nucleus interactions, rather than classifying them as CCQE, or NCDIS directly, it can be more appropriate to classify based on the set of final state particles and their multiplicities observed, $(1\mu^-, 0p, 1\pi^+)$, for example. This has the advantage of mitigating uncertainties in the nuclear interaction models.

Quasi-Elastic (QE) Interactions

Quasi-Elastic (QE) interactions are the dominant contribution to the total neutrino cross section at a low energy range (0.1 - 1 GeV). The charged current QE (CCQE) interactions proceed as follows, where $l = e, \mu, \tau$:

$$\nu_l + n \rightarrow l^- + p \quad (2.30)$$

$$\bar{\nu}_l + p \rightarrow l^+ + n. \quad (2.31)$$

CCQE interactions are of particular interest to neutrino experiments, since they provide a clean signal definition compared to inelastic processes, such that they are easier to detect and obtain reconstructed neutrino energies with relatively high precision. The QE regime also has a relatively high cross section at energies where accelerator experiments are concerned. Coupled together, this means that oscillation parameters can be extracted with good precision.

Resonant (RES) Pion Production Interactions

Resonant pion production reactions occur at slightly higher energies are interactions in which a neutrino inelastically interacts with a nucleon and produces pions, $\pi^\pm$ or π^0 , as one of the primary final-state particles. These reactions are characterised by the excitation of a nucleon (proton or neutron) to a higher energy resonance state, i.e. a Delta resonance, before pion production occurs. Resonant pion production reactions are an important part of neutrino-nucleus interactions, and they play a significant role in neutrino experiments. As an example, consider the following muon neutrino CC resonant (CCRES) interaction with a proton,

$$\nu_\mu + p \rightarrow \mu^- + \Delta^{++} \rightarrow \mu^- + p + \pi^+ \quad (2.32)$$

and a neutral current resonant example,

$$\nu_\mu + n \rightarrow \nu_\mu + n + \pi^0. \quad (2.33)$$

As shall be seen, the NC interactions such as this can produce a background for CC event searches. The neutral pion very quickly decays to two photons which are close together. From a wide range of perspectives, this can appear as one electromagnetic shower, a signature of a CC ν_e event.

Coherent (COH) Pion Production

In the case of coherent scattering, the neutrino momentum transfer is low $Q \sim O(10)$ MeV and interacts with the entire nucleus N , and so the term coherent refers to the nucleus responding collectively as a whole. For accelerator-based neutrino beam experiments, the transfer can be large enough to produce a pion. The result is minimal disturbance to the nucleic medium and a pion in the final state of the interaction. See both CC and NC examples below.

$$CC : \nu_l + N \rightarrow l^- + N + \pi^+ \quad (2.34)$$

$$CC : \bar{\nu}_l + N \rightarrow l^+ + N + \pi^- \quad (2.35)$$

$$NC : \nu_l + N \rightarrow \nu_l + N + \pi^0 \quad (2.36)$$

$$NC : \bar{\nu}_l + N \rightarrow \bar{\nu}_l + N + \pi^0 \quad (2.37)$$

Again, the pions can form a significant background in neutrino experiments, when trying to identify electrons and muons in our detectors, to tag the flavour of a CC interacting neutrino.

Deep Inelastic Scattering (DIS)

At higher energies still, starting around 1-2 GeV, the deep inelastic scattering (DIS) processes start to have a significant contribution to the total neutrino cross section. Here, the neutrino has enough energy to resolve the structure of the intranuclear medium. It can therefore interact with the point-like quarks directly, and breaks apart the nucleus. This type of interaction includes many nuclear effects, where understanding and well-modelled simulations are lacking.

2.3.2 Total Neutrino Cross Section

A summary of the above discussed interaction types in terms of the total neutrino cross section is now presented. Figure 2.4 shows the cross sections for each of the interaction types, and the total summed cross section for them, for both neutrino and antineutrino interactions. Note that antineutrinos have a reduced cross section with respect to the neutrinos by around $\sigma_{\bar{\nu}} \approx \frac{1}{3}\sigma_{\nu}$. This is in fact due to the helicity suppression in the weak interaction of the neutrinos. The affect arises from the $V - A$ structure of the weak interaction, whereby only interactions with left-handed (LH) chiral particles and right-handed (RH) chiral anti-particles are permitted. Whilst the LH interactions have a total spin change of 0, the RH have $\Delta J_z = 1$, which contributes an angular dependence to the cross section. This leads to backward scattering being suppressed, where more forward scattering $\theta \approx 0$ is favoured. Here, θ represents the polar angle of the outgoing lepton. Indeed, integrating the cross sections over all solid angles leads to $\sigma(J_z = 1) = \frac{1}{3}\sigma(J_z = 0)$.

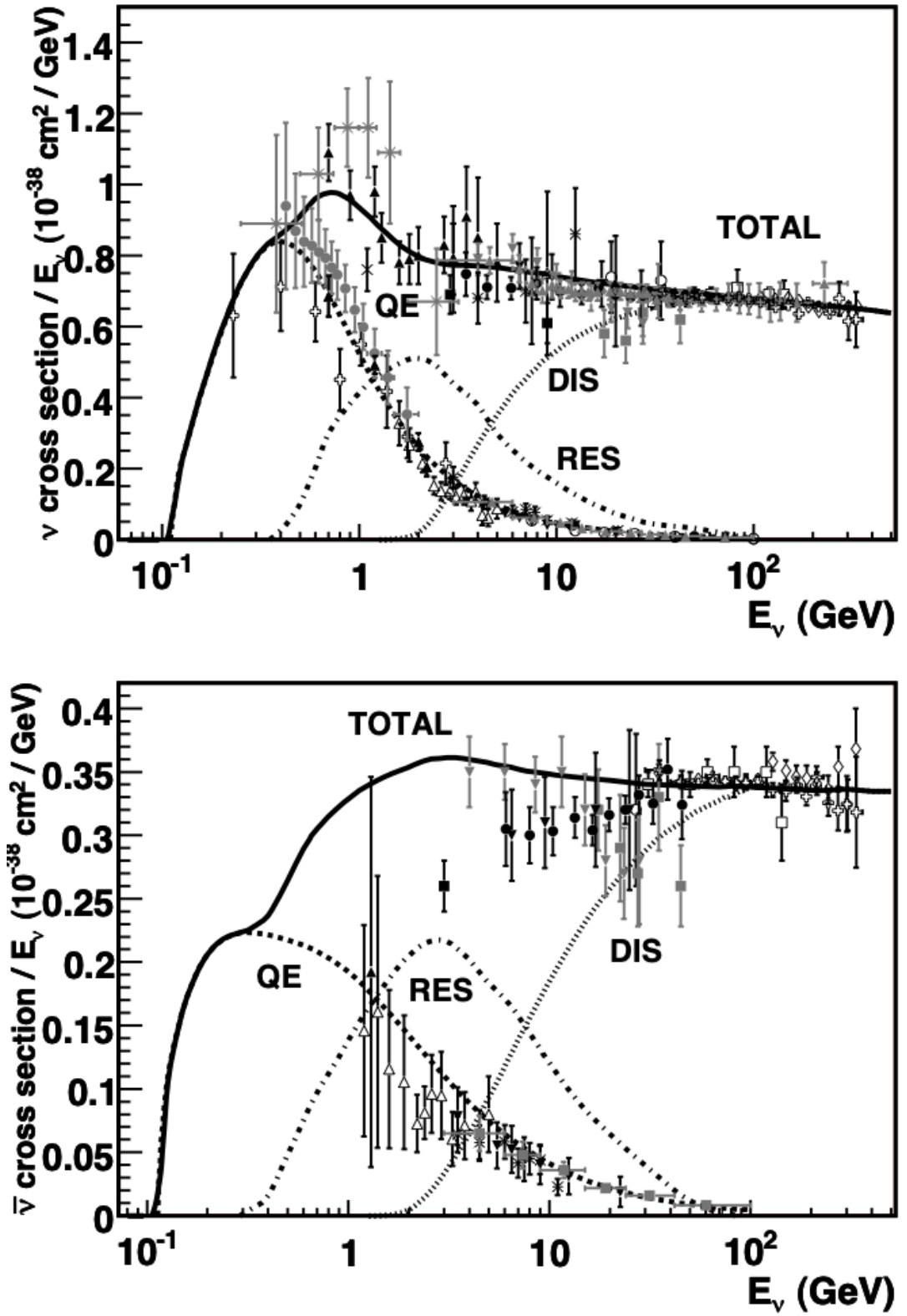


Figure 2.4 Total neutrino cross section plots as a function of neutrino energy E_ν , for both ν (top) and $\bar{\nu}$ (bottom). Values are divided by the neutrino energy to hide the linear dependence in the plot. The figure also shows independent cross section curves for the CC, RES and DIS interaction types as described in the main text, further illustrating their dominant energy regions [42].

2.3.3 Existing Muon Neutrino Cross Section Measurements

This section will review some of the limited number of existing measurements for muon (anti)neutrinos on argon. To date, only a few $\nu_\mu, \bar{\nu}_\mu$ cross section measurements have been made, whereas this thesis will attempt the first measurement using MicroBooNE off-axis beam data from the NuMI neutrino beam by separating a mixed sample of neutrino and antineutrino interactions. Charged current muon (anti)neutrino cross sections in the energy range of approximately $0.5 \rightarrow 2.0$ GeV, where QE scattering transitions into 2p2h interactions, are crucial for precise neutrino energy reconstruction and oscillation studies in current and future experiments. While the QE interaction mechanism is relatively well understood, the overlapping 2p2h processes in this energy region remain less so. This overlap has contributed to discrepancies in cross section measurements across experiments. Further measurements in this region will aid our understanding and improve modelling, reducing systematic uncertainties and enabling more accurate interpretations of neutrino oscillation data.

T2K Flux Integrated Muon (Anti)Neutrino Cross Sections

The data collected during 2010 and 2011 by the T2K experiment were used to measure the inclusive charged current muon neutrino interaction cross section per nucleon, using an estimated number of Protons On Target (POT) of 10.8×10^{19} [43]. The total flux-averaged cross section measured was

$$\sigma = 0.691 \pm 0.013(\text{stat}) \pm 0.084(\text{syst}) \times 10^{-38} \text{ cm}^2/\text{nucleon}, \quad (2.38)$$

for a selected sample of 4485 candidate signal interaction events. The results reported were for a mean incoming neutrino energy of 0.85 GeV. The neutrino interactions were detected in a near detector, ND280, which is situated off-axis to the neutrino beam.

A measurement for the flux-integrated muon antineutrino cross section per nucleon was also later published, and made using the off-axis near detector [44]. Measurements on water (H₂O) and hydrocarbon (HC) targets were reported. The mean incoming antineutrino energy for this analysis was 0.86 GeV. It used a restricted phase space where the momentum of the muon was required to be > 400 MeV and the outgoing muon angle to be $< 30^\circ$. The values reported were,

$$\sigma_{\bar{\nu}_\mu}^{\text{H}_2\text{O}} = (1.082 \pm 0.068 \text{ (stat.) } {}^{+0.145}_{-0.128} \text{ (syst.)}) \times 10^{-39} \text{ cm}^2/\text{nucleon} \quad (2.39)$$

$$\sigma_{\bar{\nu}_\mu}^{\text{CH}} = (1.096 \pm 0.054 \text{ (stat.) } {}^{+0.132}_{-0.128} \text{ (syst.)}) \times 10^{-39} \text{ cm}^2/\text{nucleon}. \quad (2.40)$$

MicroBooNE Inclusive Muon Neutrino Cross Section

In 2019, MicroBooNE published a measurement of the inclusive muon neutrino cross section on argon [45]. The MicroBooNE detector is described in Chapter 3. The neutrinos were provided by the Fermilab Booster Neutrino Beam (BNB) which consisted of 93.6% muon neutrinos within the energy range of tens of MeV $\rightarrow$ 2 GeV. The total four-month exposure corresponds to 1.6×10^{20} protons on target (POT). Event selection included selecting the longest reconstructed track, in addition to using a measurement of the deposited charge per unit length, dQ/dx , to identify potential muons. A coincident photon detection system (PDS) signal was also required to assist in cosmic rejection. In all, a selected sample of 27200 events lead to a flux integrated cross section $\sigma(\nu_\mu + Ar \rightarrow \mu^- + X)$ of

$$\sigma = 0.693 \pm 0.010(\text{stat}) \pm 0.165(\text{syst}) \times 10^{-38} \text{ cm}^2/\text{nucleon}, \quad (2.41)$$

where the dominant contributions to the relatively large systematic uncertainty came from the beam flux predictions, detector response and the dirt background. “Dirt” events are those where a neutrino interacts outside of the detector cryostat, but the final state muon, or lepton, continues through into the TPC and survives the reconstruction and selection criteria.

The work also compared the double differential cross section, with respect to muon momentum, p_μ and angle, θ_μ for various ranges of the polar muon angle θ_μ with respect to the beam neutrino direction. The data were compared to various simulation frameworks, most notably the **GENIE v2** with empirical Meson Exchange Current (MEC) modelling, and **GENIE v3 G1810a0211a** versions. The results are shown in Figure 2.5. The strongest discrepancy between simulation and data comes from the forward-going muons, for which the cross section values are highest, where the **GENIE** with MEC modelling falls outside of the error calculated on the data.

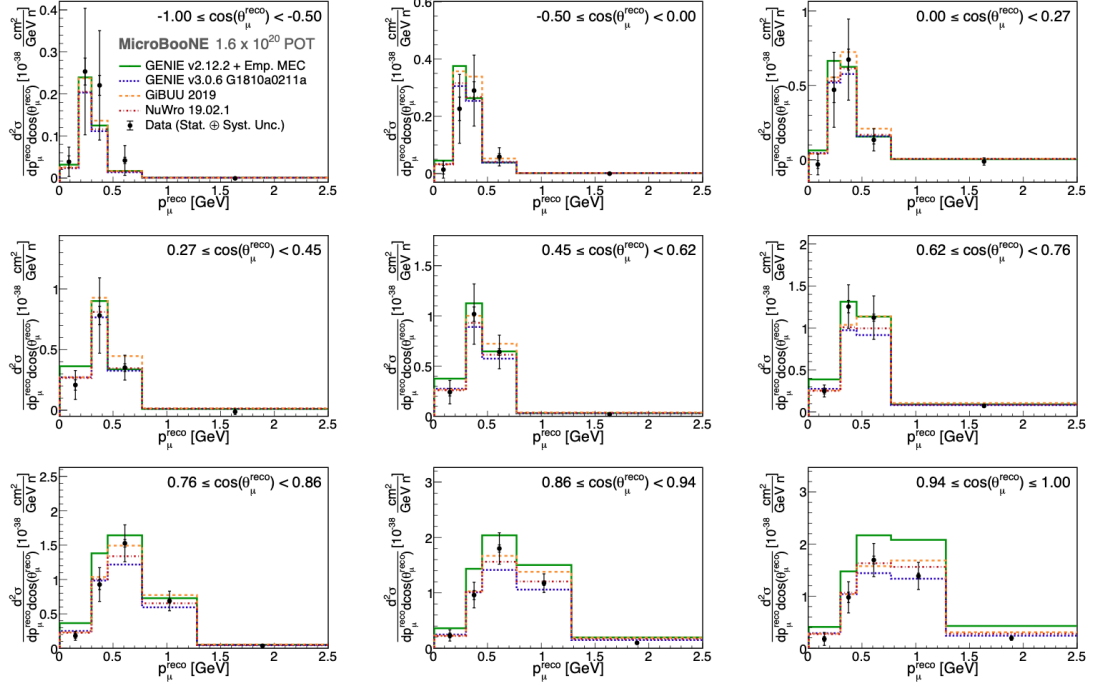


Figure 2.5 *Double differential ν_μ cross section results from MicroBooNE. Each subplot represents a portion of the full range of outgoing muon polar angles θ_μ^{reco} , and gives the muon neutrino cross section as a function of reconstructed muon momentum, p_μ^{reco} . Data is compared to the GENIE simulation framework (and others), where the largest discrepancy is given in the most forward-going muon (bottom-middle and bottom-right plots) [45].*

MicroBooNE Inclusive Muon Neutrino Energy Differential Cross Section

In 2022, MicroBooNE published another result for an energy-dependent cross section of CC ν_μ interactions on argon [46]. The neutrino source was the same, coming from the Booster Neutrino Beam (BNB), with a total exposure of 5.3×10^{19} POT. The selection criteria required the neutrino interaction vertex to be at least 3 cm inside the fiducial volume of LAr. Cosmic activity was similarly tagged with a background tagger to reduce background from the signal selection, and the NC background interactions were largely reduced by requiring that the primary muon track in the final state be longer than 5 cm.

The results are summarised in Figure 2.6, where the left plot (a) shows the cross section per nucleon, divided by the mean neutrino energy per bin, as a function of neutrino energy E_ν . The middle plot (b) shows the cross section as a function of the primary outgoing muon energy, E_μ . The right plot (c) shows the cross section as a function of the energy transferred to the argon nucleus $\nu = E_\nu - E_\mu$. The

plotted results are also directly compared to the simulation frameworks, GENIE, NEUT, MicroBooNE MC, GiBUU and NuWro. Overall, the best agreement is with the GiBUU predictions, where significant disagreement is shown with the other frameworks, particularly GENIE v3 at lower energies.

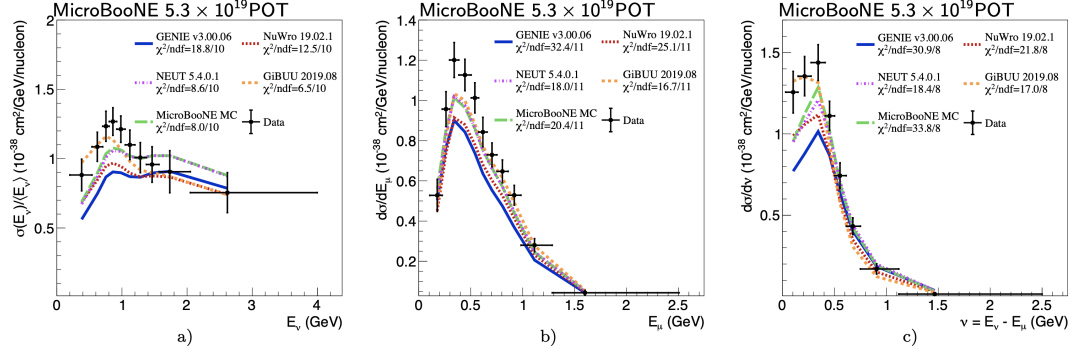


Figure 2.6 *MicroBooNE CC ν_μ cross section on argon measurements as a function of (a) the neutrino energy E_ν (b) the primary outgoing muon energy E_μ and (c) the energy transferred to the argon nucleus $\nu = E_\nu - E_\mu$. [46].*

Chapter 3

LArTPC Detectors: DUNE and MicroBooNE

Liquid Argon (LAr) has emerged as a useful medium for the detection of neutrinos. It has well-suited properties including its high density, electron-ion pair creation capabilities and scalability, making it an ideal candidate for building large scale, sensitive detectors [47][3]. The DUNE and MicroBooNE detectors both implement Liquid Argon Time Projection Chamber (LArTPC) technology to detect neutrino interactions [48][49]. This chapter will first review the working principle of a LArTPC. It then moves on to the specifics of particle physics behaviour within liquid argon which is relied upon to inform the development of triggering algorithms and event reconstruction for liquid argon detectors. This includes the ionisation and scintillation induced by charged particles traversing a LArTPC. The remaining portion of the chapter describes each experiment's detector implementation in further detail.

3.1 Liquid Argon Time Projection Chambers

This section will describe the operating principles of a LArTPC detector. A generic LArTPC geometry is described for illustrative purposes, explaining the choice of detection medium, energy loss in liquid argon, ionisation charge, scintillation mechanisms and the electronic readout of the associated signals, with a view toward their use in triggering event readout for DUNE prototype

detectors, which is the topic of the following chapter.

3.1.1 Overview

The LArTPC essentially consists of a large container, filled with LAr. A strong, uniform electric field, on the order of a few 100 Vcm^{-1} , is applied between the cathode and the anode, located at opposite sides of the LAr container. Charged particles traversing the LArTPC active volume will ionise the Ar atoms, producing ionisation electrons that will drift toward the anode, where they can be detected. Figure 3.1 illustrates the working principle of a LArTPC. By reading out the signals induced at the anode plane, the trajectory and calorimetry details of particles crossing the LAr can be reconstructed. Further, this information can be combined with the prompt emission of scintillation photons from the LAr, detected with a dedicated Photon Detector System (PDS), to provide an initial timestamp t_0 of the event. A generic LArTPC diagram is shown in Figure 3.1, where the left-most yellow plane corresponds to the cathode and the three layers of sense wires, U, V and Y correspond to the anode plane. The signals produced by the ionisation charge of an interaction are visualised on the right half of this image. This figure will be used as a reference for LArTPCs henceforth.

Liquid Argon as a Detection Medium

LAr has several outstanding physics properties which make it an excellent candidate for a TPC detection medium. These are listed below, before continuing to its specific use in TPC detectors.

- **Chemically Inert:** Argon is a noble gas, and so chemically inert. This means the electronegativity is small, and ionisation charge can easily traverse large distances at the scale of meters through it. However, LAr generally contains electronegative impurities, which can attach themselves to the drift electrons. Some common impurity examples are oxygen, nitrogen and water.
- **Prolific Scintillator:** LAr is a high-yield scintillator, emitting around 24000 photons per MeV of energy deposited into the medium. The spectrum of the photons emitted peaks strongly at 128 nm wavelength, with a width of approximately 10 nm. For detection, these photons typically need to be

shifted in wavelength in order for photon detectors, such as Photo-Multiplier Tubes (PMTs) to be able to detect them. LAr is also transparent to its own scintillation light, meaning the photons can travel far through the medium to reach the PMTs.

- **Low Ionisation Energy:** For a Minimum Ionising Particle (MIP), the energy required to form a (Ar^+, e^-) pair, W_{ion} , is 23.6 eV [47]. This is a relatively low value, and results in lots of ionisation charge which can provide calorimetric and tracking information about the observed particle activity.
- **High Density:** With a density of approximately 1.4 gcm^{-3} , LAr offers a large mass target. It is even higher than water, which directly increases the chance of neutrino interactions for a given volume.
- **Scalable:** Argon is the third most abundant gas in the Earth's atmosphere, making up approximately 1% of it. In comparison, xenon has a larger density, approximately 3 gcm^{-3} , and produces more scintillation light. In this respect, xenon would be the better choice for a detection medium. However, xenon makes up only a very small amount of the atmosphere, $9.7 \times 10^{-6}\%$ and so it is the relatively large availability of argon which makes it an attractive, cheaper option for large scale experiments.

3.1.2 Energy Loss In Liquid Argon

LArTPCs can detect traversing charged particles via the ionisation charge and scintillation photons they produce via Coulomb scattering with atomic electrons. These processes are more generally described by the mean energy lost per unit distance $\langle -\frac{dE}{dx} \rangle$, which is very well described by the Bethe-Bloch equation [47][28]. It is given by

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right], \quad (3.1)$$

where the negative sign on $\frac{dE}{dx}$ indicates energy *lost*. Here, z is the charge of the incident particle, e.g. -1 for a muon, μ^- . Z and A are the atomic number and atomic mass of the detector medium, β is the velocity of the incident particle as a fraction of the speed of light c . γ is the Lorentz factor, m_e is the electron rest mass

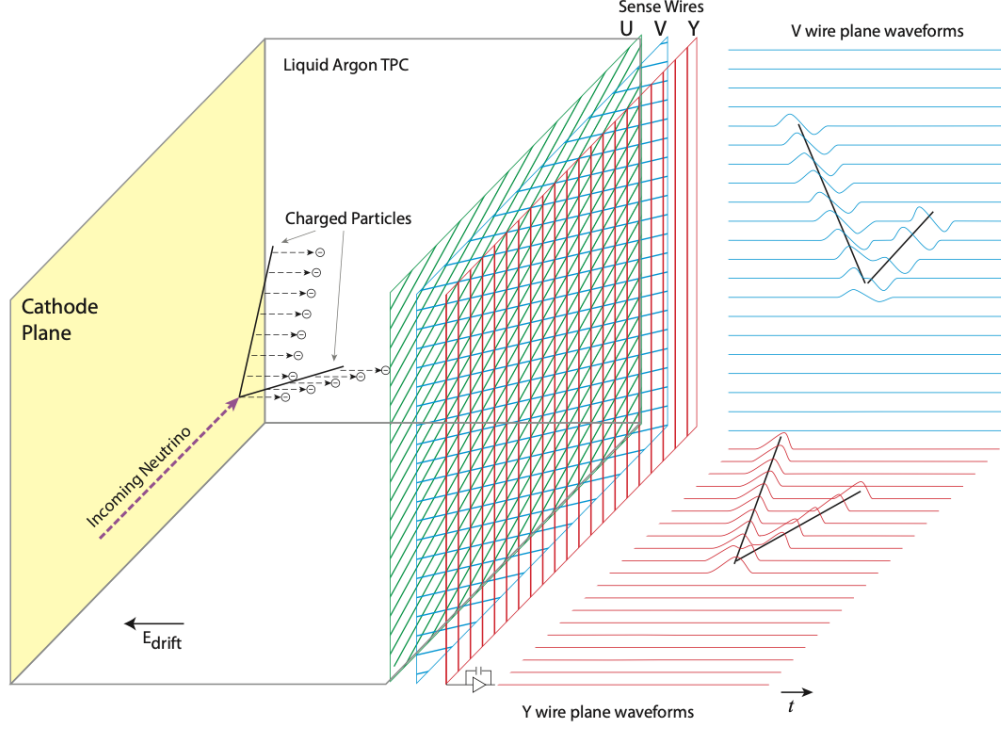


Figure 3.1 Working principle diagram of a LArTPC. Charged particles traversing the active liquid argon medium ionise the Ar atoms. A uniform electric field E_{drift} , is applied between the cathode plane (yellow) and anode plane (U V & Y wires). The ionisation electrons quickly reach terminal velocity and drift to the anode plane sense wires, inducing bipolar (unipolar) waveforms on the induction, U, V (collection, Y) wires [48].

($\approx 0.511 \text{ MeV}/c^2$). T_{max} is the maximum kinetic energy that can be transferred to an atomic electron of the detector medium. I is the mean excitation energy of the medium. The $\delta(\beta\gamma)$ factor is a density correction term. It attempts to describe the limit on how much energy can be lost for a fast-moving charged particle. Finally, $K = 4\pi N_A r_e^2 m_e c^2 = 0.307075 \text{ MeV cm}^2 \text{ mol}^{-1}$ is a constant, where N_A is Avogadro's number and r_e is the classical radius of an electron.

The shape of this curve is graphically illustrated in Figure 3.2. It shows the mean energy loss per unit distance as a function of particle velocity, for various mediums. Also shown is an x -axis which allows one to see the dE/dx as a function of muon *momentum*, below the main x -axis. There are a few general things to note about this curve, that are true for most detector mediums and ionising radiation. First, there is a characteristic minimum ionising energy range, for each particle and medium type, at $\beta\gamma \approx 3 - 4$. For the *muon momentum*, this corresponds to around 0.1-1 GeV/c range. Particles around this region are

referred to as minimum ionising particles (MIPs). As particles continue to lose energy by traversing the medium, the mean $-dE/dx$ very quickly rises. For a stopping muon, just before decaying to an electron and two neutrinos, this is what is referred to as the Bragg peak of an observed track. For increasingly higher momentum particles, the curve slowly rises due to the logarithmic factor. This is commonly referred to as the *relativistic rise*. The levelling off of this region, out to the right of the curve is due to the density correction term $\delta(\beta\gamma)/2$.

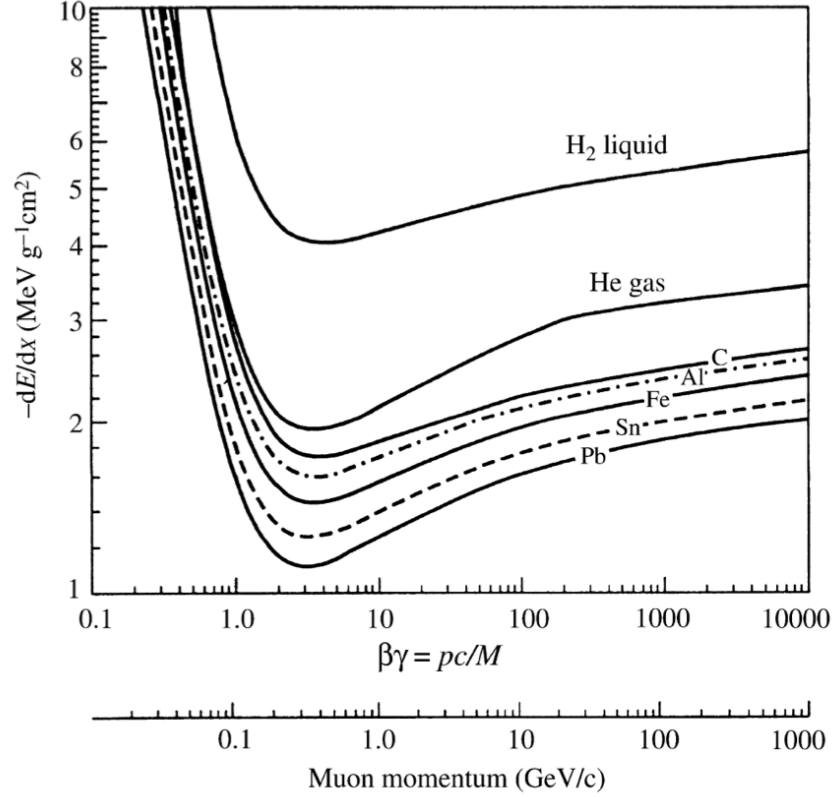


Figure 3.2 Mean energy loss per unit distance in various mediums, as a function of particle momentum. The specific x -axis for a passing muon is given below the main axis [50].

Neutral Particles in Liquid Argon

Neutrino interactions can also produce neutral particles such as neutrons and pions in their final state. Neutral pions rapidly decay into two photons, which produce electromagnetic (EM) showers. This makes them detectable but can sometimes form a background for electrons from CC ν_e event searches if the two showers are very close together, and viewed from an appropriate angle. The main interactions for photons are Coulomb scattering (lower energies), photoelectric

effect (above 1 MeV) and pair production (higher energies). For the energy ranges considered here, the dominant interaction for neutrons is (in)elastic scattering. Therefore, neutrons are effectively invisible to the detector, and may only be indirectly detected by small blips of photons produced in inelastic collisions, starting above 1.5 MeV [51].

3.1.3 Ionisation Charge

As stated above, charged particles traversing LAr produce ionisation charge, specifically Ar^+, e^- pairs. Approximately 10^5 electrons per MeV deposited are liberated along a charged particle's path. With a strong enough drift field, they can be separated permanently so that the electrons may induce signals on the sense wires for readout. The electrons are chosen for readout since they are orders of magnitude lighter than the Ar^+ ions, and so travel with much higher drift velocity v_{drift} than the ions. This speed of the moving charge is described by short periods of acceleration, interrupted by collisions with the LAr. For a nominal electric field of 500 V/cm, the average drift velocity of an electron is approximately $v_e = 1.60 \text{ mm}/\mu\text{s}$. For the same field strength, the drift velocity of an Ar^+ ion is around $8.0 \times 10^{-6} \text{ mm}/\mu\text{s}$ [47].

It is the high uniformity of the electric field between the cathode and anode in the LArTPC that allows the reconstruction of high resolution, photographic-like images of particle trajectories. Using a readout of the charge-induced signals on the planes of sense wires, a raw Analogue to Digital Conversion (ADC) two dimensional (2D) image of the interaction can be formed. As an example, see Figure 3.3, which is a 2D representation from the collection plane channels, of a candidate Michel electron (stopping muon) event. The specific detector is a DUNE prototype called the vertical drift cold box, based at the Neutrino Platform at CERN, EHN1. This detector will be described in Chapter 4. The event in particular was captured using the trigger algorithms developed in this thesis, which themselves will also be further discussed in the following chapter.

The colour in this image corresponds to the raw ADC values that are read out from the collection channels. That is, the ionisation charge from the track event is streamed across a maximum of 21 cm (LAr depth in the detector) to the collection plane. The unipolar signals are integrated to obtain a total measure of the charge collected. The channel signals are readout at a rate of 2 MHz, and so each unit in the time direction measures $0.5 \mu\text{s}$. Therefore, the approximate 350 units of

time the track crosses in the y -axis correspond to 0.175 ms of detector readout.

This event shows a cosmic ray entering from the top left of the display, travelling nearly horizontally, across approximately 365 wires. The wires are pitched at 4.3 mm apart, so the track length in the collection direction corresponds to about 157 cm. As the particle travels through to the right, $\langle -dE/dx \rangle$ clearly increases and the red colour intensifies. This is the characteristic Bragg peak of a slowing charged particle described above. There is a very short gap in the time direction, before decaying to a lighter, low energy charged particle, possibly an electron. This is a candidate stopping muon event, emitting a Michel electron.

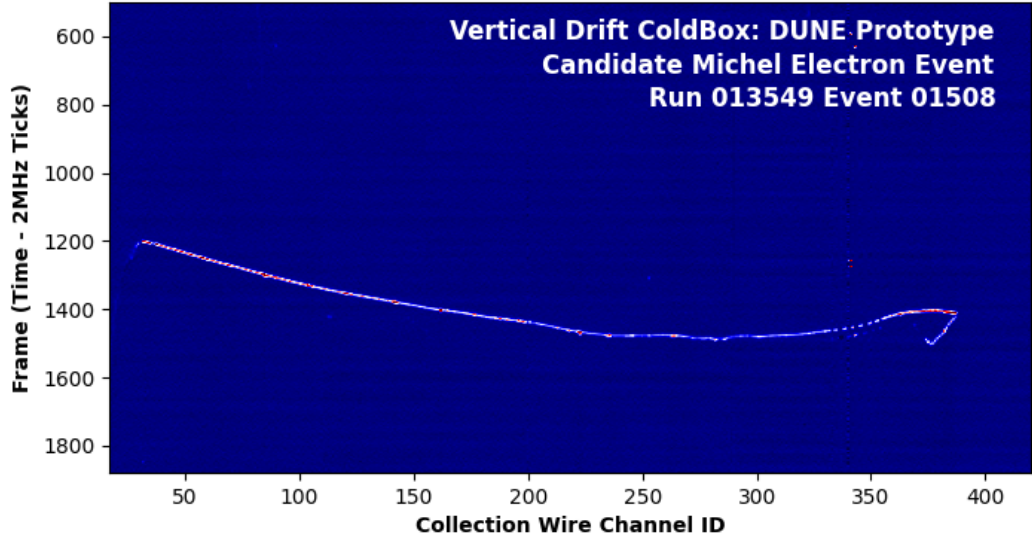


Figure 3.3 *Example LArTPC event display, captured using a DUNE prototype, the vertical drift cold box. The image shows the ionisation charge observed (represented by colour) by TPC collection channels (x -axis) vs. time (y -axis). Time is given in 2 MHz hardware clock cycles, so one unit measures 0.5 μ s. The collection channels are pitched at 4.3 mm. Thus, the track has a length of roughly 157 cm in the collection view, and the 1200 - 1550 time frames it fills correspond to approximately 0.175 ms of detector readout.*

There are several general LArTPC detector effects which can distort the quality of these photographic-like representations of the data, and they are outlined next. These include the space charge effect, diffusion, and recombination.

Space Charge Effect

Over time, LArTPCs exposed to ionising radiation build up an increasingly large portion of Ar^+ ions. The argon ions slowly drift at speeds of $O(10^{-6})$ mm/ μs toward the cathode of the detector, and this collection of charge distorts the otherwise uniform drift field. This is known as the Space Charge Effect (SCE) [52], and it distorts the reconstruction of detected events, *displacing* portions of the tracks and showers. The more exposure a detector has to ionising radiation, the more problematic the SCE becomes. This is an even more significant problem for ground-based detectors such as MicroBooNE and the DUNE prototype, ProtoDUNE which are subject to a large flux of cosmic ray activity. That is in comparison to the DUNE Far Detectors (FDs), which will be 1480 m underground, heavily shielded from a constant bombardment of cosmic rays [49].

Figure 3.4 illustrates the impact of the SCE on the MicroBooNE detector. The plot represents a cross section of the LArTPC, with the Booster Neutrino Beam (BNB) beam direction perpendicular to the page. The y -axis represents the vertical direction, whereas the x -axis is the horizontal (drift) direction. The cathode of this LArTPC is located on the right at $x = 256$ cm, and the anode on the left at $x = 0$ cm. The blue data points mark the start/end (entry/exit) locations of reconstructed cosmic ray tracks, taken during periods whilst the beam was off. It is seen that at the cathode, where the build up of Ar^+ is expected to occur, there is a distorted drift field, attracting ionisation electrons toward the vertical centre of the plot. This has the effect of displacing the reconstructed trajectory of tracks within the LArTPC. The effect is stronger for larger x values, and weaker when closer to the anode, as might be expected.

Diffusion

When ionisation electrons are produced in the LArTPC, they travel variable distances to the anode. Over that travel time, the electrons diffuse, which smears the spatial distribution of charge. This can therefore affect the spatial resolution of reconstructed events. There are two components to this diffusion, *transverse* and *longitudinal* with respect to the drift field. They are each characterised by a diffusion coefficient D_T and D_L , respectively. The transverse diffusion widens the signal in the spatial (wire) direction, and the coefficient is described by,

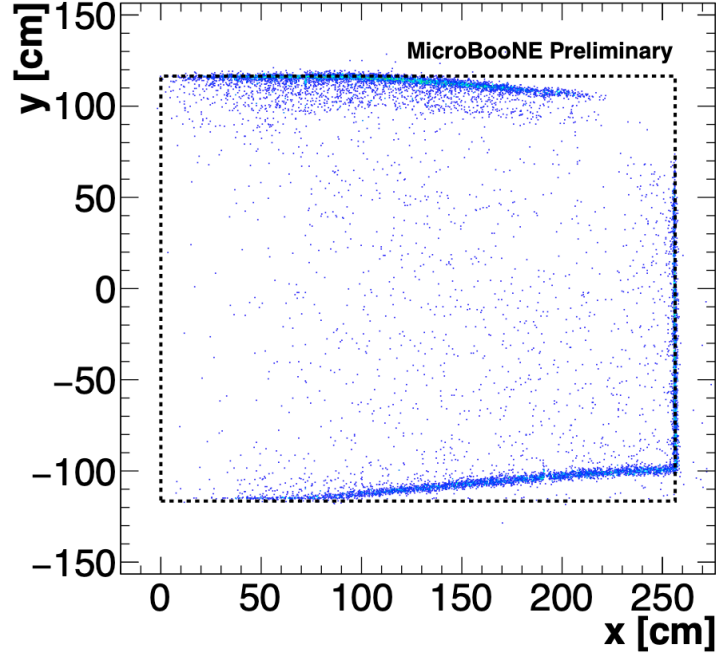


Figure 3.4 *Occupancy of the entry and exit coordinate points of many reconstructed cosmic tracks, in the MicroBooNE LArTPC, showing the impact of the Space Charge Effect (SCE). Shown in the x (drift) and y (zenith/vertical) directions. The beam is in the z direction, normal to the $x - y$ plane. The cathode is positioned at $x = 256$ cm and the anode at $x = 0$ cm. The blue data points represent the start/end (entry/exit) points of reconstructed tracks, from data that was taken during beam-off time. The distorted drift field draws ionisation charge toward the Ar^+ ion build-up near the cathode, hence the increasing distortion with an increase in x value. In the absence of any SCE, the data points should largely be concentrated at the TPC boundaries, represented by the dashed box, as they are in the leftmost part of the plot [52].*

$$D_T = \frac{\mu_e \epsilon_e}{q_e}, \quad (3.2)$$

where μ_e , ϵ_e and q_e are the electron mobility, energy and charge, respectively. The electron mobility in liquid argon, at 500 V/cm drift field is approximately 518 cm^2/Vs [47].

The longitudinal diffusion stretches out the signal pulse in the drift time direction. A study with the MicroBooNE LArTPC produced the plot in Figure 3.5, showing clearly the increase in time-width σ_t of the signal pulse, with an increase in drift time. The total σ_t as a function of drift time t , for particles with drift velocity ν_t

is described by

$$\sigma_t(t) \approx \sqrt{\sigma_t^2(0) + \left(\frac{2D_L}{v_d^2}\right) t}, \quad (3.3)$$

where the $\sigma_t(0)$ contribution describes the minimum pulse width, for ionisation produced at the plane of the anode and accounts for the Gaussian noise filter used in the waveform deconvolution [53]. This is approximately $1.96 \mu\text{s}^2$.

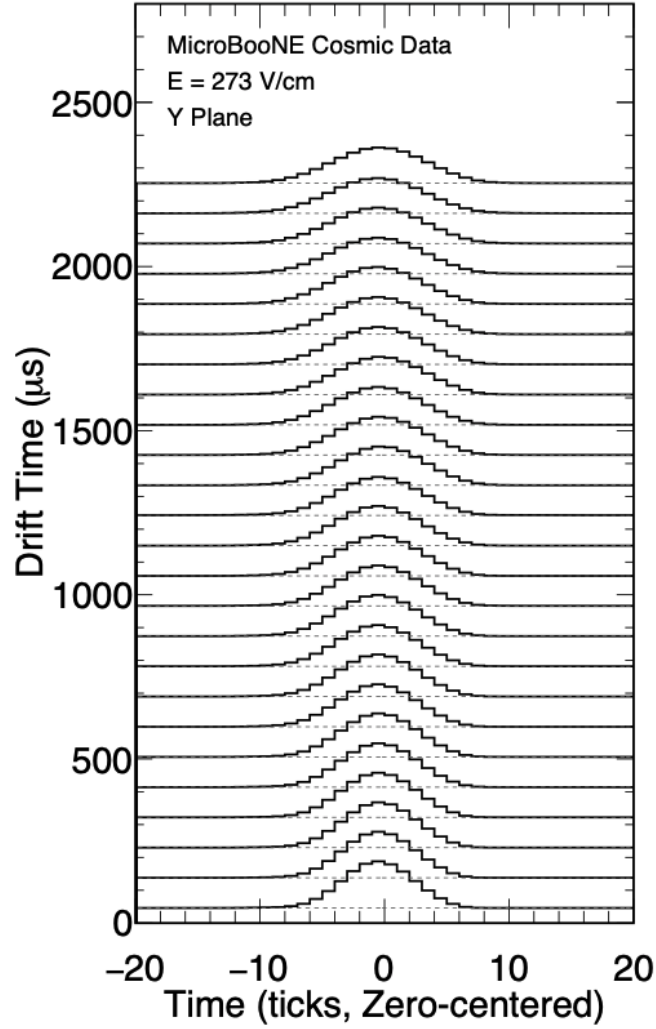


Figure 3.5 *Graphical demonstration of the effect of longitudinal diffusion on the width of the ionisation signal observed by TPC channels. Time ticks on the x-axis correspond to $0.5 \mu\text{s}$. Drift time on the y-axis provides a measure of the distance the ionisation charge has travelled to the TPC sense channels. A clear increase in pulse width can be seen with increasing drift time [53].*

Recombination & Electron Attachment Losses

The ionisation electrons themselves can fail to reach the sense wires, due to either Ar^+ , e^- recombination, or attachment to electronegative impurities present in the LAr. Examples of electronegative impurities in LAr commonly include water, H_2O , oxygen, O_2 and carbon dioxide, CO_2 . Their tendency to attach to drifting electrons to form ions leads to a reduction in the observed energy deposits, in otherwise pure LAr. The attachment of drifting electrons via impurities and Ar ions reduces the total charge that can be readout, and so decreases the signal to background ratio of the detector.

Alternatively, the Ar^+ , e^- can fail to be separated quickly enough by the drift field, leading to recombination. The main idea here is that the drifting electron quickly thermalises with the surrounding medium within $\text{O}(1)$ ns, and so may be close enough to an Ar^+ ion to recombine with it. There exist many models to describe this behaviour, but the most relevant here is the Modified Box Model (MBM) by ArgoNEUT [54]. It is a *columnar* model and models the probability of recombination based on local ion-electron density within a cylindrical volume. The model assumes a normal distribution of that ionisation around the drift path, and so the portion of drift charge that *escapes* recombination R , reaching the anode for readout, is given by

$$R = \frac{1}{\beta(dE/dx)} \log(\alpha + \beta(dE/dx)), \quad (3.4)$$

where dE/dx is the energy loss per unit distance, as above. The parameters α and β are to be fit to data, but β is generally proportional to the electric field strength of the TPC. Once R is known, it is then possible to correctly obtain the dE/dx of the particle, for Particle Identification (PID) by Equation 3.5.

$$\frac{dE}{dx} = \frac{(dQ/dx)}{RW_i}, \quad (3.5)$$

where again, W_i is the energy required to ionise an argon atom, 23.6 eV.

3.1.4 Liquid Argon Scintillation

The scintillation light produced by LAr has the capability to provide high resolution timing information on the events observed, at the ns scale. For an applied electric field of 500 V/cm, which is the nominal drift field for DUNE, LAr emits approximately 24000 photons per MeV of deposited energy. This Scintillation Yield (SY) is provided by the emission of photons from two excited states of argon, the singlet, $^1\Sigma_u$, and triplet, $^3\Sigma_u$, *excimer* states. The word excimer is derived from “excited” and “dimer”, and so describes an excited state of two argon atoms. The decay back to their ground state with the emission of photons then proceeds as follows,

$$Ar_2^* \rightarrow 2Ar + \gamma, \quad (3.6)$$

where the singlet state $2Ar^*(^1\Sigma_u)$ decays very quickly, in approximately $\tau_s \approx 6$ ns. However, the triplet state $2Ar^*(^3\Sigma_u)$ has a much longer lifetime of $\tau_t \approx 1500$ ns. These states can be produced via two chains of events, known as *Self-trapped exciton luminescence* and *Recombination luminescence*. Both chains are illustrated in the top and bottom chains of Figure 3.6, respectively.

Self-Trapped Exciton Luminescence

Charged particles traversing the LAr can leave Ar atoms in a higher energy electronic state, which form the dimers described above with other argon atoms. For self-trapped luminescence, 65% of these excimers are in the singlet state, and 35% are in the triplet state. This process is shown as the top chain in Figure 3.6.

Recombination Luminescence

When the charged particles produce Ar^+, e^- pairs, they can recombine, where some of the excess energy leads to the creation of excimers. The singlet and triplet states are created in equal proportions here. This process is proportional to the local density of ionised argon, i.e. the more Ar^+, e^- pairs available in a given region, the more chances there are for recombination to occur.

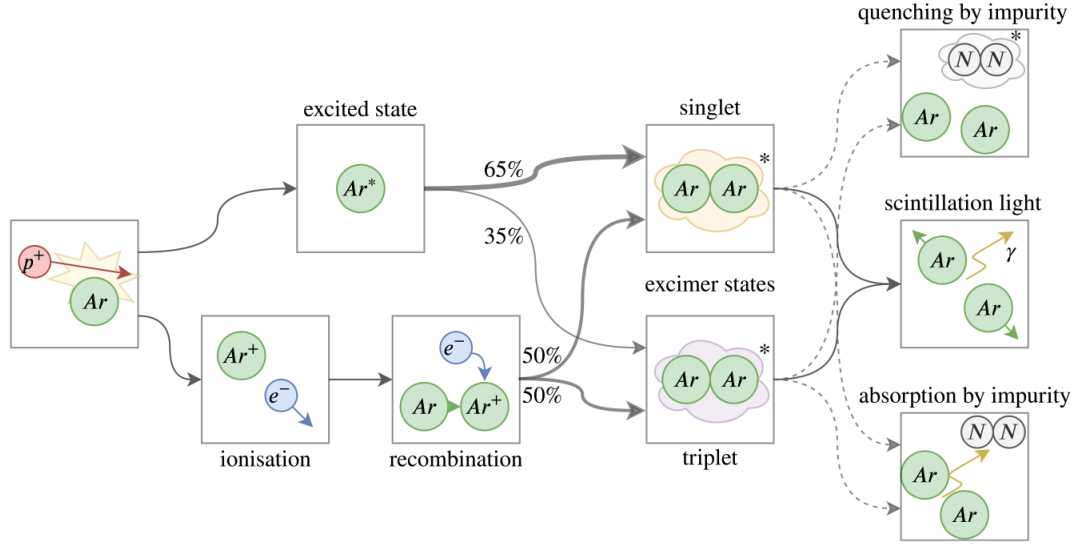


Figure 3.6 *The scintillation mechanisms of liquid argon. Charged particles traversing the argon can either excite (upper thread) or ionise (lower thread) the Ar atoms. Both threads lead to the production of short lived excimers, in either the singlet $^1\Sigma_u$ or triplet $^3\Sigma_u$ states as labelled. The scintillation photons produced by these excimers (represented by a wiggly yellow arrow here) can be absorbed by impurities, reducing the light available for detection. This mechanism is known as quenching, and one of the reasons to monitor and maintain an extremely high argon purity throughout LArTPC detectors [55].*

Quenching & Absorption

Quenching and absorption are the two main processes which reduce the total amount of scintillation light that can be detected in a LArTPC, from that which would be expected from an absolutely pure scintillation medium. Absorption simply refers to the process of an impurity absorbing the UV scintillation photons, and re-emitting them at various wavelengths. Quenching, however, describes the process by which the impurities interact with the argon excimers, in such a way as to redistribute the excess energy into the kinematics of the impurity, rather than the emission of scintillation photons. It is seen that both processes reduce the SY for the detector. Both are caused by impurities present in the argon. These processes are therefore highly sensitive to the purity of LAr. For example, the oxygen levels must be maintained at less than 0.1 ppm, such that an optimal amount of light can reach the photon detectors unimpeded.

3.2 DUNE

The Deep Underground Neutrino Experiment (DUNE) is a next-generation long-baseline accelerator neutrino experiment [49], designed to be sensitive to CP violation in the lepton sector and neutrino oscillations. The primary detection technology used is LArTPCs. The experimental setup for DUNE is illustrated in Figure 3.7. With the accelerator neutrino beam based at Fermilab (on the right), DUNE consists of a Near Detector (ND) and a Far Detector (FD) (on the left) at the Sanford Underground Research Facility in South Dakota. The ND serves to characterise the neutrino content of the beam, which is directed at the FD. The FD can be used to detect neutrino interactions, where the weak flavour of a neutrino interacting via a charged current should be identified via the resultant outgoing lepton. The DUNE near detector will contribute by performing neutrino cross-section measurements, improving upon existing interaction models, and reducing uncertainties in the key physics goals outlined above.

3.2.1 Physics Programme

DUNE aims to determine the mass hierarchy of neutrino mass eigenstates ν_1, ν_2 and ν_3 . It also aims to make a precision measurement of the CP violating phase δ_{CP} via a measurement of the difference between muon neutrino and antineutrino oscillation behaviour over the long range. For this reason, it is critical that the muon neutrino and antineutrino content of the beam can be distinguished. In addition to this core physics programme, DUNE also aims to detect Solar neutrinos, for which it will require sensitivities down to ~ 10 MeV. It will also take part in the SuperNova Early Warning System (SNEWS), by which the flux of neutrinos arriving at Earth due to a supernova could provide hours of warning time to orient observational apparatus for the later-arriving photon flux.

3.2.2 Near Detector

By directly observing the unoscillated neutrino beam, the DUNE ND reduces uncertainties in neutrino production and beam modelling, thereby improving the precision of oscillation parameter measurements. The ND also allows for high precision neutrino cross section measurements on various nuclei, which inform

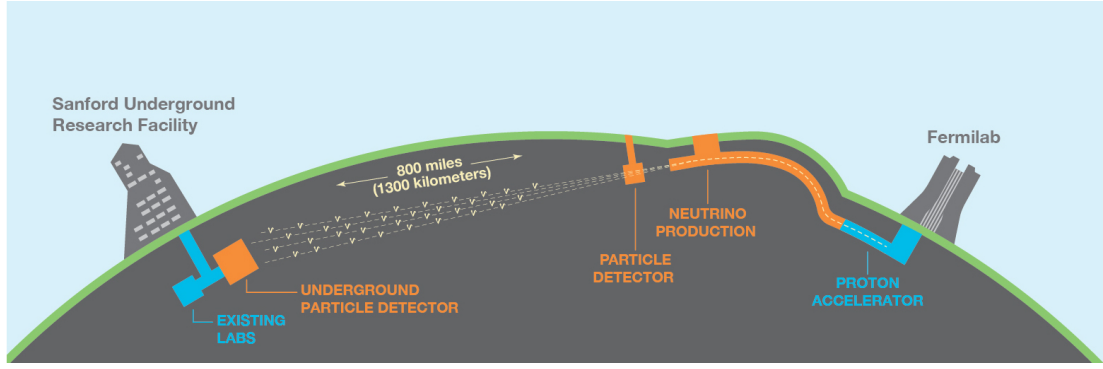


Figure 3.7 *A cartoon diagram of the DUNE experimental setup. The neutrino beam begins at the Fermilab accelerator complex on the right, and travels through the near detector (particle detector) onto the far detector (underground particle detector) on the left [56].*

the refinement of theoretical interaction models. A key component of the ND is the LArTPC, which can move perpendicular to the beam direction by up to 30 meters to sample different neutrino spectra. This capability to move on and off-axis relative to the beam direction enables precise reconstruction of neutrino energies, allowing DUNE to create a detailed map of interaction probabilities as a function of energy.

3.2.3 Far Detector

The FD itself is approximately 1480 m underground, and 1300 km away from the point at which the neutrinos are produced. It essentially consists of four 10 kt fiducial mass LArTPC modules. Currently, the first 10 kt module will implement the Horizontal Drift (HD) concept for LArTPC, where it is expected that the second module will use the Vertical Drift (VD) concept. In addition to a change in some electronics, these concepts simply refer to the orientation of the drift field, such that ionisation charge drifts horizontally for HD, and vertically (upward) in the VD setup. Further details on the VD concept will be outlined below when describing a DUNE prototype tested at CERN. A schematic of the four FDs at the underground research facility is shown in Figure 3.8.

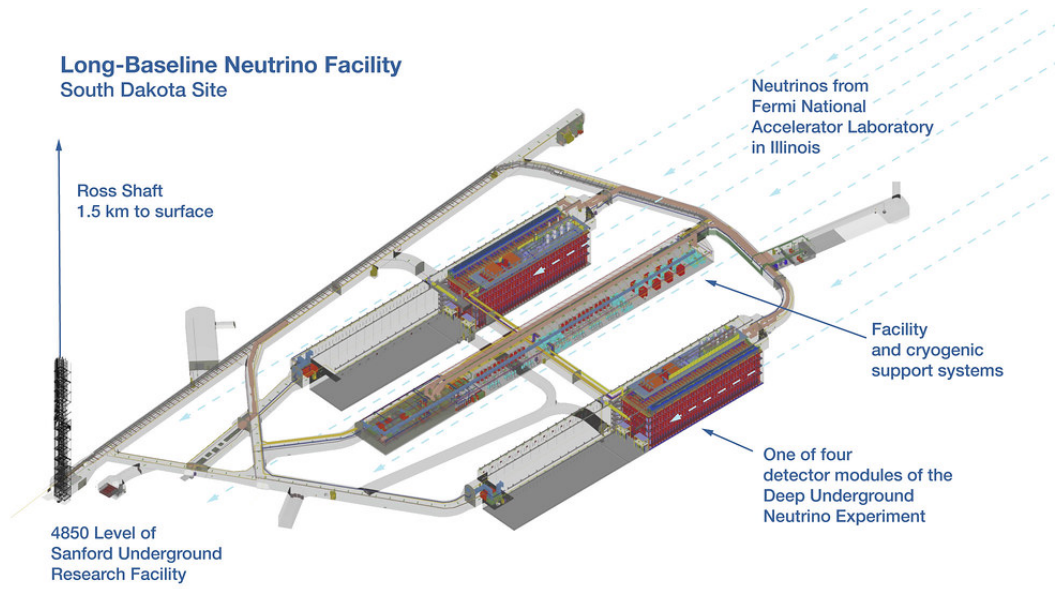


Figure 3.8 *A schematic of the DUNE Far Detector at the Sanford Underground Research Facility. The image shows the incoming neutrinos from the accelerator beam and the four 10 kt size LArTPC modules. Currently, concepts for the first 2 modules (those largely coloured in red) are in progress [56].*

3.2.4 Vertical Drift Cold Box - VDCB

The Vertical Drift Cold Box (VDCB) is a fully operational LArTPC, serving as a prototype FD for DUNE, at the Neutrino Platform at CERN. It has spatial dimensions of approximately $3.0 \times 3.4 \times 0.23 \text{ m}^3$, with a drift distance of 23 cm aligned with the vertical direction. The detector is situated at ground-level in the main hall at EHN1, exposed to a large flux of cosmic ray muons. It is this detector prototype that has been used to develop the DUNE Data Acquisition System (DAQ) and the self-triggering system therein. In particular, a significant part of the work done toward this thesis was centred around this prototype, using the streamed ionisation charge to form detector hits, which can be clustered together in real time, in order to issue triggering commands for permanent data storage to the DAQ system. A detailed description of this detector and the work related to it will be presented in Chapter 4.

3.3 MicroBooNE

The Micro Booster Neutrino Experiment (MicroBooNE) detector is a large LArTPC situated at Fermilab and is positioned on-axis to the Booster Neutrino Beam (BNB) approximately 470 m from the beam target. Here, “on-axis” means that the active volume of the LArTPC is aligned with the direction of the beam itself. In particular, the LArTPC is of size 2.6 m (x /drift direction) $\times$ 2.3 m (y /vertical direction) $\times$ 10.4 m (z /beam direction), contained within a large cylindrical cryostat. See Figure 3.9 for a schematic diagram.

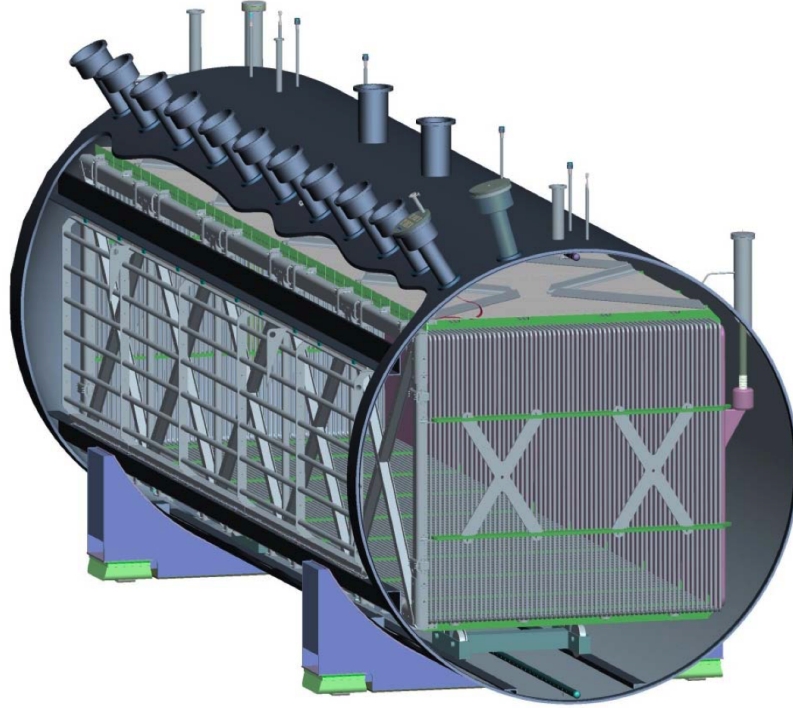


Figure 3.9 *A schematic of the MicroBooNE LArTPC detector, contained within a cylindrical cryostat. The BNB beam direction runs parallel to the length of the cylinder, whilst the TPC drift field is applied horizontally across the TPC in the diagram [48].*

The cryostat, maintaining a temperature of 87 K, contains 170 tonnes of LAr, of which approximately 87 tonnes is contained within the fiducial boundaries of the TPC. It is the latter portion of the LAr which is commonly referred to as the *active* volume. The electric field is applied across the TPC, and thus where ionising particles from potential neutrino interactions can be detected. Although the nominal field strength is 500 V/cm, the detector setup experienced technical difficulties and the actual field achieved was 273.9 V/cm. The detector itself was

operational from October 2015 through to March 2020.

Coincidentally, although MicroBooNE was not constructed to provide exposure to the Neutrino at the Main Injector (NuMI) beam, the detector is situated 600 m downstream of this neutrino beam. It is positioned such that it observes a relatively high *off-axis* exposure, at approximately 8° from the NuMI beam direction. Figure 3.10 demonstrates the exposure the MicroBooNE LArTPC has to the NuMI beam with respect to the BNB, via an aerial view on the right of the relevant beam targets and the LArTPC. This diagram is not to scale.

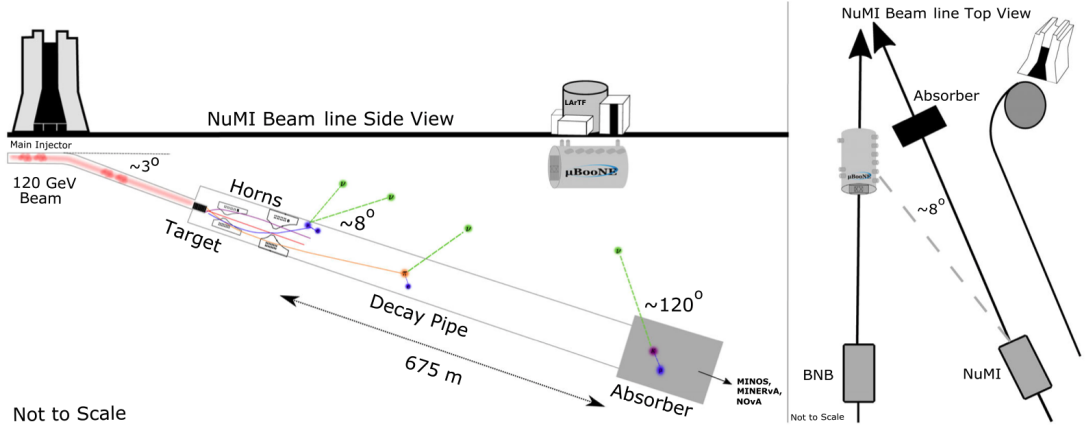


Figure 3.10 A diagram illustrating the off-axis exposure the MicroBooNE LArTPC detector observes from the NuMI beam flux. The left shows a side view of the NuMI beamline, whilst the right shows an aerial view of the MicroBooNE LArTPC position with respect to the BNB and NuMI beamlines. Not to scale. The detector was constructed to observe an on-axis flux of neutrinos with respect to the BNB beamline, which is represented by the bottom left dark rectangle in the aerial view. Similarly, the NuMI beam target is represented by the bottom right rectangle [57].

TPC Readout

The MicroBooNE LArTPC cathode is biased at a voltage of -70 kV, producing the electric field that drifts ionisation charge horizontally in the x direction toward the anode plane, where it is observed by 3 planes of wires - 2 induction and 1 collection. They are labelled U , V and Y respectively, where each plane of wires is biased to a different voltage, -110 V, 0 V and +230 V, respectively, to ensure the ionisation charge is observed by all three. The wires within each plane are all aligned parallel to each other, pitched at 3 mm. The planes themselves are oriented at 60° (U), -60° (V) and 0° (Y) to the vertical direction. This allows for

three 2D representations of the particle trajectories inside the TPC, see Figure 3.1, which are used in the 3D reconstruction of physics events.

The wires are sampled at a rate of 2 MHz, and the shape of the signals observed for the U (Induction 1), V (Induction 2) and Y (Collection) planes are shown in Figure 3.11. Electrons approaching the induction plane wires induce an electric field which reverses polarity upon passing the plane, resulting in a bipolar waveform signal. For the collection plane, the electrons are not merely passing by the wires but are physically collected, resulting in a unipolar waveform.

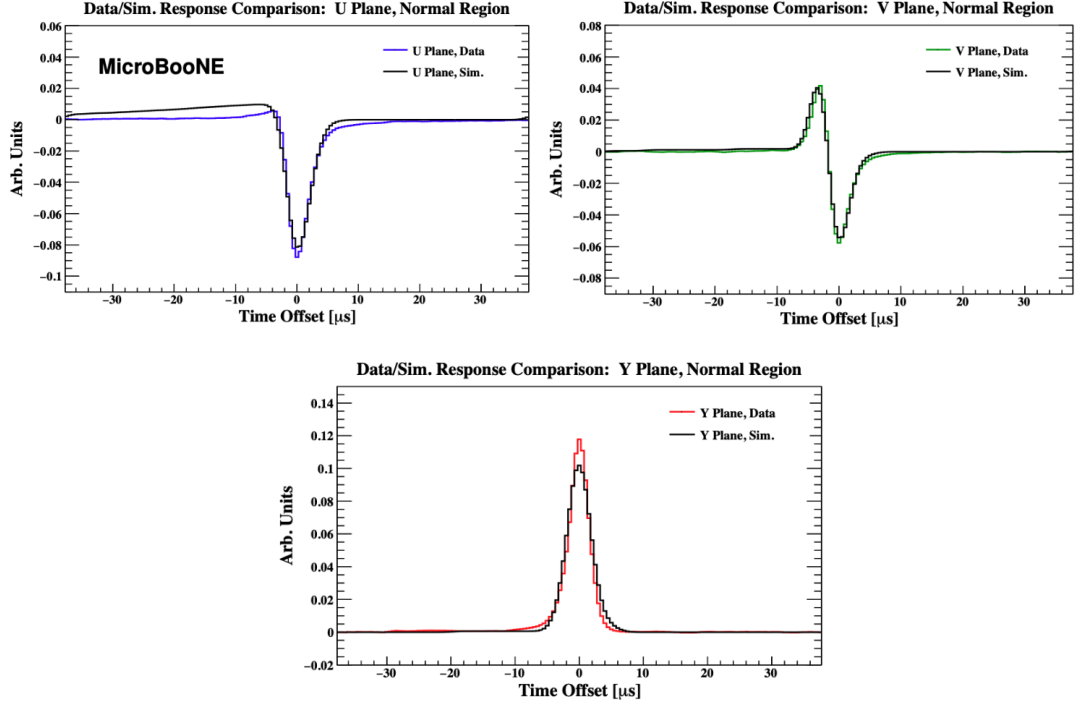


Figure 3.11 *A comparison of the simulated and observed anode wire field response signals for each of the U , V , and Y planes reveals that the induction planes (U and V) observe bipolar signals, while the collection plane (Y) wires observe unipolar waveforms. Time is given on the x -axes, and the measured charge, in arbitrary units, on the y -axes [58].*

The signal processing occurs both inside and outside the cryostat, which calls for two sets of electronics operating both in cryogenic temperatures, Cold Electronics (CE) and at room temperatures, Warm Electronics (WE). The CE amplify the TPC signals with excellent sensitivity due to the cryogenic temperatures, which are then converted to signals and sent to the WE ADC Front End (FE) module. It is this raw ADC information, that the reconstruction framework uses to form hits and reconstruct physics activity.

Scintillation Readout

In terms of scintillation detection, the MicroBooNE detector houses 32 8-inch Hamamatsu PMTs within the anode plane of the TPC readout wires. Before the photons reach the PMTs, they have to be wavelength-shifted, since the glass surface of the PMTs is opaque to the 128nm VUV scintillation light emitted by LAr. A common solution for this WaveLength Shifter (WLS) problem is to use TetraPhynyl Butadine (TPB), which is indeed what MicroBooNE employs to do this. TPB is coated onto an acrylic plate, positioned in front of the PMT and shifts the VUV photons into the visible spectrum, specifically 425 nm. The wavelength-shifted photons can then pass through the PMT entry window, made of borosilicate glass. The PMTs then convert the observed photons to electrical signals which are similarly used by the reconstruction framework, when looking for coincident light flashes with TPC signals. A diagram of the optical unit used for scintillation detection in MicroBooNE is shown in Figure 3.12.

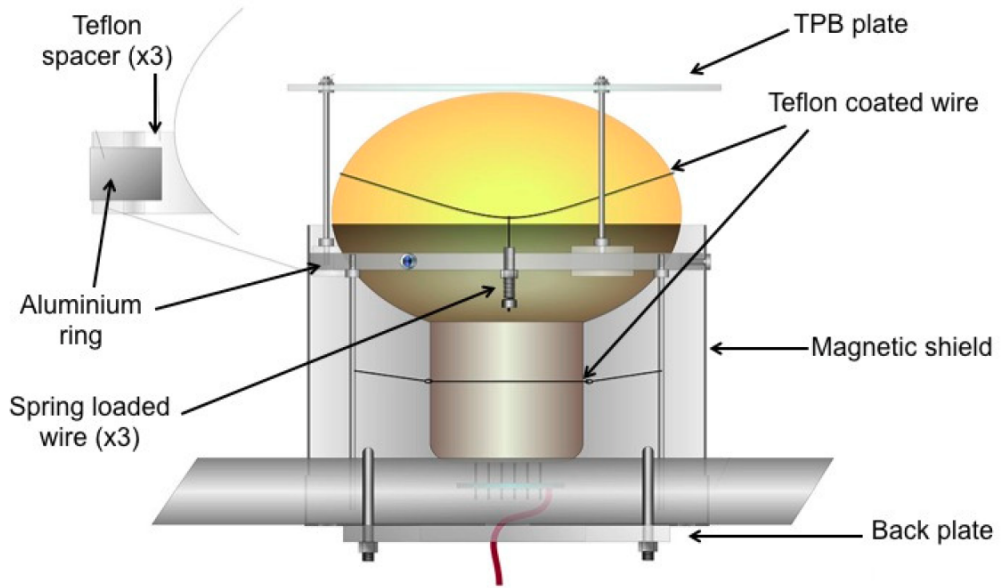


Figure 3.12 *A diagram of the optical unit design used in MicroBooNE to detect scintillation light. The TPB plate wavelength shifter is shown at the top, external to the Photomultiplier Tube (PMT) [48].*

Cosmic Ray Tagger

The fact that the MicroBooNE LArTPC is positioned at ground-level means that it is subject to the constant bombardment of cosmic rays. This consists of

muons passing through the active volume of the TPC and thus form a major background for the search of CC ν_μ and CC $\bar{\nu}_\mu$ events. An additional piece of apparatus that MicroBooNE employs is a Cosmic Ray Tagger (CRT), which is external to the cryostat. It is a system of several scintillation panels installed around the detector, coupled with an ongoing search for a coincident trigger on opposite sides of the detector. If two signals are detected within 150 ns, then it is assumed that a crossing muon has passed through the detector and thus labelled a cosmic event. A diagram of the CRT system is shown in Figure 3.13. The right hand side of this figure represents many possible trajectories of through-going muons, in brown.

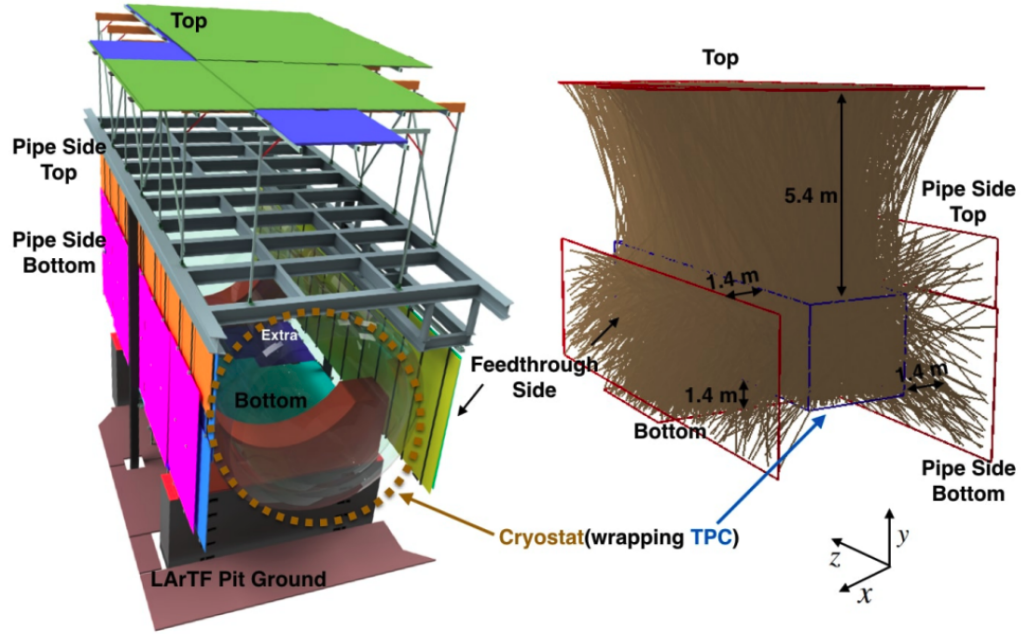


Figure 3.13 *An illustration of the Cosmic Ray Tagger (CRT) system implemented at MicroBooNE. The coloured panels surrounding the cryostat on the left represent the scintillation panels, from which one can search for coincident signals on opposite-facing panels, to indicate the presence of a detector-crossing muon. Many possible cosmic ray muon trajectories are depicted in brown in the adjacent diagram on the right [59].*

3.3.1 MicroBooNE Detector Performance

The MicroBooNE LArTPC detector was operational from October 2015 through to March 2020. The working period was divided into 5 runs, which will be

described in Chapter 3.4 in the context of exposure to the NuMI beam. Full run details are given in Table 3.2.

Light Yield Changes

During runs 1 - 3 operational time for MicroBooNE, a decline in the light yield was observed which is currently under investigation. To account for this in the software triggering system, which requires ≥ 9.5 photo-electrons, a charge triggering threshold change from 190 to 115 ADC in the PDS was used at sub-run number 16880. This means that any analysis that uses run 3, as does the work in this thesis, must treat the stages of the analysis separately, before and after that run number.

Run 3

The CRT was implemented for the run 3 working period of MicroBooNE, October 2017 to September 2018. Up to December 2017, there was an issue with the GPS timing system, which caused problems with merging the corresponding CRT data. For this reason, run 3 is split into two: run 3a and run 3b. Run 3b therefore corresponds to the period December 2017 to September 2018, where the timing system was fixed. It is the data collected from run 3b that is used for the cross section analysis in this thesis.

3.4 NuMI Beam at MicroBooNE

The Neutrinos at the Main Injector (NuMI) beam is produced by an accelerator complex at Fermilab [60], where the MicroBooNE LArTPC detector observes an off-axis flux exposure from it. This section will describe the NuMI beam in the context of detecting neutrino interactions at MicroBooNE, and using them for a cross section analysis. Neutrino production in general will be covered, in addition to an outline of the run exposure of the MicroBooNE detector to the NuMI beam, the simulated flux and the readout of NuMI-based data itself.

Neutrino beams are created by steering accelerated protons onto a target, usually carbon or beryllium-based, resulting in a cascade of hadrons, of which the charged ones can be focused with one or more magnetic horns. The hadrons eventually

decay, and the neutrinos produced from those decays are boosted in the direction of the beamline.

3.4.1 NuMI Beam

Neutrinos for the NuMI beamline are produced at the Fermilab accelerator complex by guiding high energy protons to collide with a graphite target. The protons begin as H^- ions, which are accelerated to 400 MeV in the LINear ACcelerator (LINAC). The electrons are then removed, leaving only the protons, which are further accelerated to 8 GeV by the Booster synchrotron. It is protons from this part of the accelerator complex that can be directed toward a Beryllium target for the BNB beamline. It is the BNB beam that the MicroBooNE LArTPC was constructed primarily for. Alternatively, the protons can be accelerated even further to 120 GeV via the Main Injector. This is what happens in the case of the NuMI beam, where they are then guided onto the graphite target. An illustration of the above processes is given in Figure 3.14

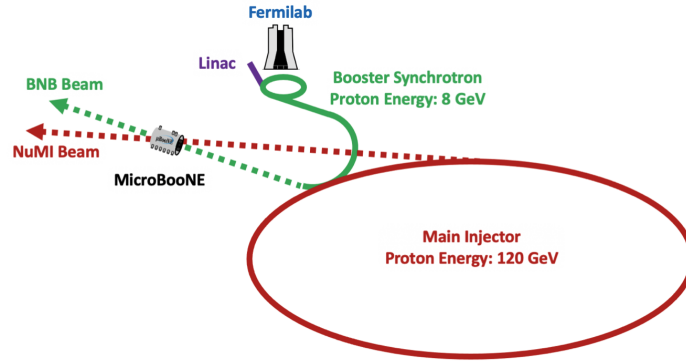


Figure 3.14 *A cartoon illustration of the Fermilab proton accelerator complex. Shown in the context of the BNB and NuMI beam exposures to the MicroBooNE detector [61].*

The hadrons produced by proton collisions onto the graphite target include charged and neutral, pions π and kaons K . The charged hadrons can be collimated via two van der Meer magnetic horns, in sequence. Depending on the polarity of the magnetic horn configuration, positive or negative hadrons can be focused toward the decay pipe, where the neutrinos are predominantly produced. A positive polarity, at +200 kA, known as Forward Horn Current (FHC) will focus positively charged hadrons (π^+ , K^+). On the other hand, a negative polarity, at -200 kA, known as Reverse Horn Current (RHC) will focus negatively charged

hadrons (π^- , K^-). The NuMI beamline benefits from the use of 2 magnetic horns, which are arranged such that any over-steering from the first can be corrected by the second. This can be seen by tracing the trajectory of the K^+ (green line) in Figure 3.15, which describes the trajectory of protons, into hadrons, into neutrinos at NuMI target whilst in FHC configuration. The first horn over-corrects the trajectory of the K^+ , and the second horn redirects it toward the decay pipe. The 675 m length of the decay pipe allows the focused hadrons to decay, producing the neutrinos that compose the beam. Any remaining hadrons that have not decayed, will be detected by a hadron monitor (not depicted in Figure 3.15 but positioned between the decay pipe and absorber) and stopped by the absorber, positioned at the end of the decay pipe. The absorber is a large, 5 m thick structure composed of aluminium, steel and concrete. The large majority of interactions in the absorber, around 80% of them, due to the beamline come from protons that have not interacted with the target. The remaining 20% of interactions are mostly made up of the hadrons that have not decayed in the decay pipe, plus some electrons and neutrons [60]. The highly penetrating nature of muons means that these are likely the only particles to have survived the absorber, neutrinos aside. A further 250 m of rock, interlaced with muon monitors serve to stop the muons, leaving only the neutrinos to continue their trajectory along the beam direction.

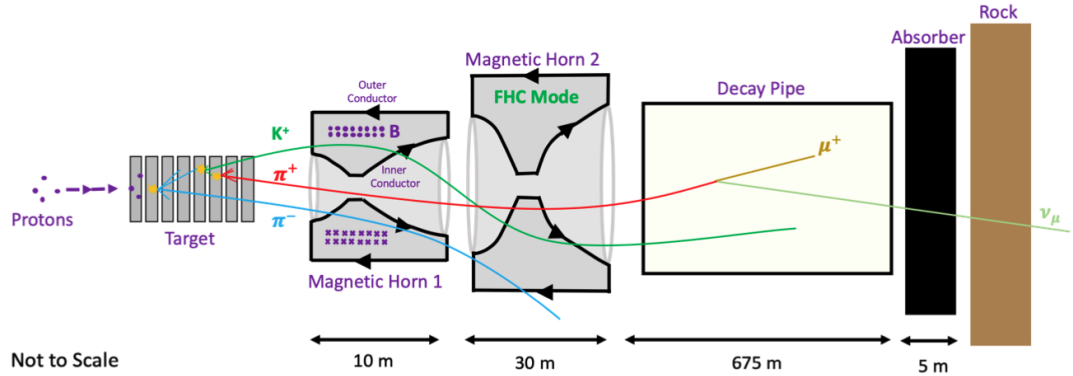


Figure 3.15 NuMI beam target and horn focusing diagram [61].

3.4.2 Neutrino and Antineutrinos

The neutrinos and antineutrinos produced by the NuMI beam come from the pions, kaons and muons. The decay modes of these primary hadrons (and muons), with branching ratios, are given in Table 3.1. This means that the beam in FHC

mode is composed dominantly of neutrinos, as opposed to antineutrinos, and so also referred to as neutrino mode. Similarly, the negatively charged hadrons focused in RHC mode mean that the beam is dominant in antineutrinos, and so also known as antineutrino mode. Table 3.1 reveals that regardless of the magnetic horn's polarity, the beam will have an intrinsic contamination of ν_e or $\bar{\nu}_e$, at the few per cent level. There will also be some contamination from $\bar{\nu}_\mu$ in FHC mode, and vice versa, ν_μ in RHC mode, since neutral particles, and charged particles travelling in the axial direction of the horns are not affected by the steering magnetic fields. However, the main decay processes by which each of the modes produce the beam are given by Equations 3.7 and 3.8.

Table 3.1 *The primary hadron (and muon) decay modes, as produced from the NuMI beam target, with branching ratios [2].*

Decay modes	Branching Ratio (%)
$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$	99.9877
$\pi^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e)$	0.0123
$K^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$	63.55
$K^\pm \rightarrow \pi^0 + e^\pm + \nu_e(\bar{\nu}_e)$	5.07
$K^\pm \rightarrow \pi^0 + \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$	3.353
$K_L^0 \rightarrow \pi^\mp + e^\pm + \nu_e(\bar{\nu}_e)$	40.55
$K_L^0 \rightarrow \pi^\mp + \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$	27.04
$\mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \nu_\mu(\bar{\nu}_\mu)$	100.0

$$\text{FHC (Neutrino Mode): } \pi^+ \rightarrow \mu^+ + \nu_\mu \text{ and } K^+ \rightarrow \mu^+ + \nu_\mu \quad (3.7)$$

$$\text{RHC (Antineutrino Mode): } \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \text{ and } K^- \rightarrow \mu^- + \bar{\nu}_\mu \quad (3.8)$$

3.4.3 NuMI & MicroBooNE

With respect to the NuMI beamline direction, the MicroBooNE LArTPC is situated in a relatively high off-axis position, as described above. A complete diagram including profile and aerial views is shown in Figure 3.10. It shows the detector positioned at an angle of approximately 8° in the horizontal and vertical directions. Due to the off-axis position of the detector, the neutrino flux observed is mainly the unfocused portion of the hadrons, and will therefore have a significant admixture of both neutrinos and antineutrinos, of the electron and muon flavours.

With this, the simulated fluxes of each neutrino type and flavour, as a function of their parent particle from the NuMI beam are presented in Figure 3.16. The fluxes presented here have been simulated using the Package to Predict FluX (PPFX) software package [62]. It uses existing experimental hadron production constraints, from NA49 [63] and MIPP [64], with horn-focusing modelling to constrain the flux predictions for the NuMI beam. The fluxes in Figure 3.16 are those to be observed by the MicroBooNE LArTPC detector due to the NuMI beam in the RHC configuration. A 60 MeV lower limit has been applied to each histogram, such that the muon decay neutrinos do not dominate the distributions. This does not affect anything in the analysis of this thesis, since a higher limit at 200 MeV will be applied, to benefit from the best reconstruction capabilities of the MicroBooNE LArTPC. The flux values here are given in terms of the number of protons delivered to the target, called protons on target (POT) from here on. The full units are $\nu/6 \times 10^{20} \text{ POT}/25 \text{ MeV}/\text{cm}^2$.

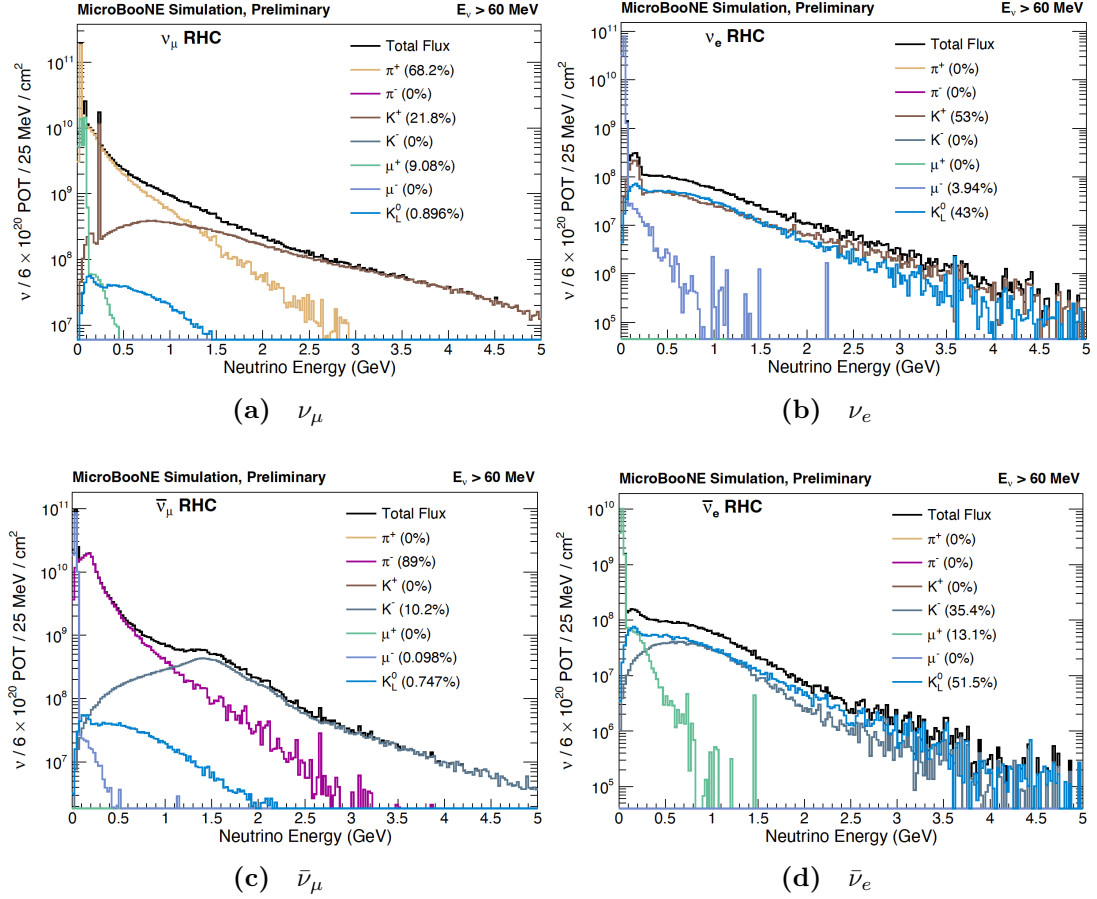


Figure 3.16 *PPFX simulated neutrino fluxes from the NuMI beam, observed by the MicroBooNE detector, each as a function of incoming neutrino energy. Each subplot includes a decomposition of the neutrino flux by the contributing neutrino parent particles [65].*

The run periods for the MicroBooNE detector in terms of exposure to the NuMI beam are summarised in Table 3.2. Run 2 observed two periods of RHC configured exposure, a brief one lasting 3 days in November 2016, and a longer one starting in February 2017. These were separated by a period of FHC exposure. The main analysis in this thesis uses data collected by MicroBooNE during the Run 3 period, where the beam was in antineutrino mode.

Table 3.2 *Run periods for MicroBooNE exposure to the NuMI beam in FHC and RHC modes with corresponding run numbers and dates.*

Run Period	NuMI FHC (+200 kA)	NuMI RHC (-200 kA)
Run 1	23 Oct 2015 - 2 May 2016	29 June 2016 - 29 July 2016
Run 2	14 Nov 2016 - 20 Feb 2017	11 Nov 2016 - 14 Nov 2016 20 Feb 2017 - 07 July 2017
Run 3	-	7 Nov 2017 - 6 July 2018
Run 4	26 Feb 2019 - 6 July 2019	20 Oct 2018 - 26 Feb 2019
Run 5	29 Oct 2019 - 20 March 2020	-

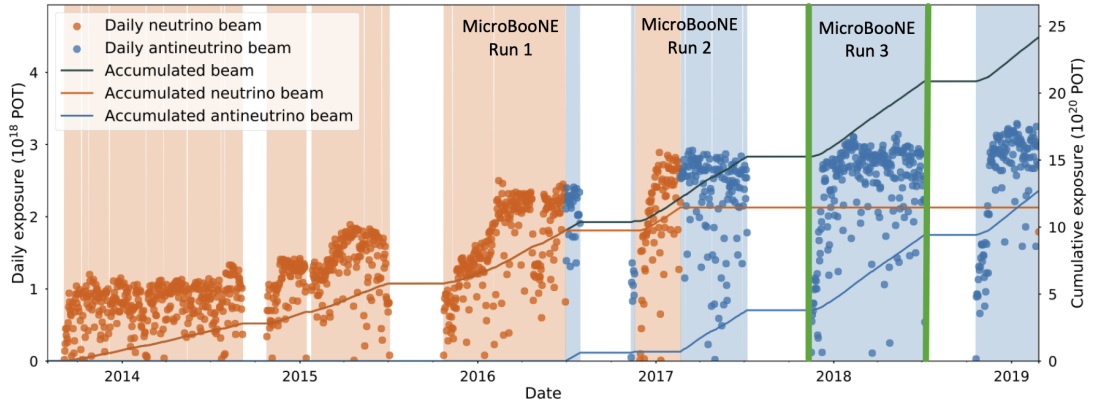


Figure 3.17 *Cumulative Protons On Target (POT) delivered to the NuMI target, describing the NuMI neutrino flux observed at MicroBooNE. Coloured circle data points correspond to a POT exposure for a single day, with the relevant scale on the left y-axis. The line plots show cumulative delivered POT over time, with the relevant scale on the right y-axis. Shaded vertical coloured bands are indicative of NuMI beam configurations during operational running periods of the MicroBooNE detector, where orange(blue) corresponds to the FHC(RHC) NuMI beam mode. The blue region between the two vertical green lines corresponds to the data used for the cross section analysis in this thesis. Adapted from [61].*

Given that the flux of neutrinos produced by a neutrino beam is proportional to the protons that collide with the target, a measure of the exposure a detector observes can be given in the number of POT. Figure 3.17 illustrates both the daily and cumulative POT delivered to the NuMI beam target, on the left and right y axes, respectively. The coloured regions correspond to NuMI beam configurations throughout the run periods in Table 3.2. Orange represents FHC, whilst blue represents RHC mode. Note that the analysis presented in this thesis corresponds to the data collected during the RHC Run 3 period, marked between the vertical

green lines in the figure. The corresponding exposure for which is approximately 5.0×10^{20} POT.

3.4.4 Flux Discrepancies

It was found during the late stages of this thesis analysis, that two issues with the flux simulations were present [65]:

1. **Geometry Description:** An entire steel shielding block directly above the beamline had been missed out in the geometry description during modelling, resulting in a larger-than-observed neutrino flux.
2. **Hadron Production Modelling:** The hadron production modelling within GEANT v4.9.2 included a bug related to kaon production, and needed to be upgraded to GEANT v4.10.4 which showed much better agreement with data.

There are several approaches to resolving this for the analysis below. The first, and most thorough includes a complete re-simulation of the MC samples. Another solution is a re-weighting scheme, which applies an additional weight to each *existing* MC event. This takes into consideration the original and new flux simulations, effectively applying the corrections for the updated NuMI flux modelling. A discussion of the flux modelling fixes, with a comparison before and after the required updates, is given in Appendix D. That discussion includes a complete resimulation comparison with a statistically independent sample. The analysis given in the main text uses a completely re-simulated MC sample, with the updated flux modelling. It is this updated flux that is used in the flux-integrated cross section calculations below.

3.5 Data Readout

This section will conclude the chapter by describing the method by which MicroBooNE chooses to readout data from the detector. During the operational run periods, MicroBooNE actually used two online triggering mechanisms in parallel, for each of the BNB and NuMI beams. It is the NuMI readout mechanism that is described here, and it is designed such that it has the best chances of

observing a neutrino interaction due to the NuMI beam, whilst filtering out the vast majority of the overwhelming flux of cosmic activity observed at ground-level.

3.5.1 Readout Windows

The *batches* of protons received at the Main Injector, from the Booster synchrotron are $1.6 \mu\text{s}$ long. The number of protons within each batch is approximately 5×10^{12} , and each batch is further divided into 81 proton *bunches*. A set of 6 proton batches are stored at the Main Injector for a total length of $9.6 \mu\text{s}$. This set is known as a beam *spill*. For the analysis used in this thesis, specifically data from Run 3, all 6 batches were combined within the spill, and correspond to approximately 3×10^{13} POT per spill. Upon beam-spill from NuMI, a signal is issued from the Fermilab Accelerator Division, which indicates to MicroBooNE LArTPC to initiate a *beamgate* window of $23.4 \mu\text{s}$, which marks the beginning of the readout process. This signal from Fermilab is known as the Hardware (HW) trigger. The readout process itself is illustrated in Figure 3.18.

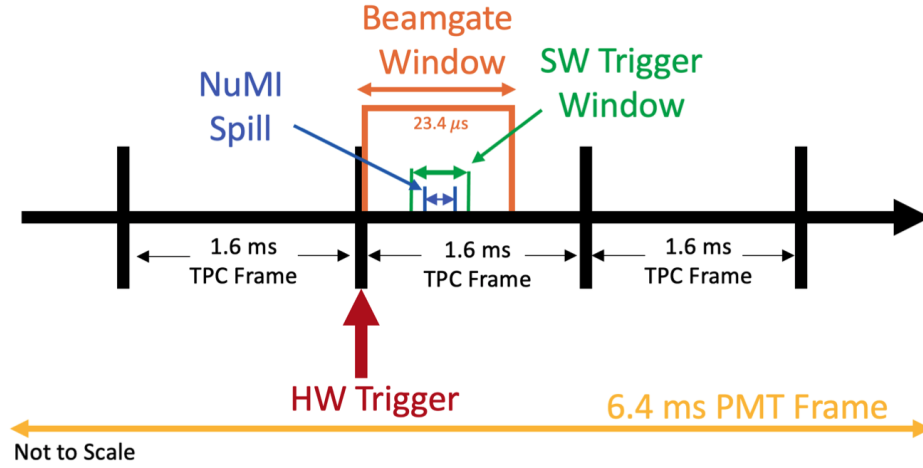


Figure 3.18 *Diagram of the NuMI beamgate triggering window, illustrating the various timescales involved and their relationships to one another [61].*

It can be seen that the spill from NuMI (blue) is centred within the beamgate window (orange), starting at $5.64 \mu\text{s}$ and ending at $15.44 \mu\text{s}$ relative to it. Only around 2% of the spills delivered by NuMI will result in a neutrino interaction within the MicroBooNE LArTPC, owing to the smallness of their cross section. For this reason, an additional software triggering window (green) is introduced to avoid consuming a large amount of resources, storing data devoid of any useful

events for later analysis. The software triggering for MicroBooNE simply requires that the number of photo-electrons (PE) detected by the PDS is ≥ 9.5 , within the SW trigger window, which is slightly wider than the NuMI spill window, starting at $4.69 \mu\text{s}$ and ending at $16.41 \mu\text{s}$ relative to the beamgate window. Around 14% of HW triggers surpass this requirement.

Chapter 4

Vertical Drift ColdBox - Muon Triggering

The DUNE Data Acquisition System (DAQ) aims to trigger the readout of interesting physics events, build and permanently store the raw data observed by both the TPC and PDS readout systems of the detectors [66]. To do this with the TPC, it continuously streams the raw ADC information from the sense wires, in the form of hits describing a segment of the ADC signal that has exceeded some hit-making threshold. This chapter will detail the successful development, implementation and demonstration of a specific event-type-targeting algorithm, the Horizontal Muon Algorithm (HMA) at the Neutrino Platform at CERN, EHN1 in December 2021 and in June 2022. The chapter begins with a description of the LArTPC used, where the geometry will motivate the development of a testing algorithm, the HMA. Following that, the DUNE Data Acquisition System is described, and the self-triggering system therein. The HMA development is discussed and the results of that work will be demonstrated via some basic event reconstruction. A small event display gallery is included in the Appendix [A](#).

4.1 The Vertical Drift Cold Box - VDCB

The Vertical Drift Cold Box (VDCB) is a fully operational prototype LArTPC. It sits at ground level at EHN1 and was constructed for the purposes of prototyping the ProtoDUNE Vertical Drift (VD) concept, another prototype for the full scale

DUNE Far Detector. The VD concept replaces the standard Horizontal Drift (HD) one, as described above, with the uniform electric field being applied across the vertical dimensions of the detector instead of horizontally. The wire-plane assemblies are also replaced with Charge Readout Planes (CRPs), which serve as the anode, directly opposite and above the cathode plane. A CRP at DUNE replaces the wire-planes with perforated Printed Circuit Boards (PCBs), using etched strips in place of wires. Installation of a CRP, hanged directly over the cathode at the EHN1 VDCB is shown in Figure 4.1.

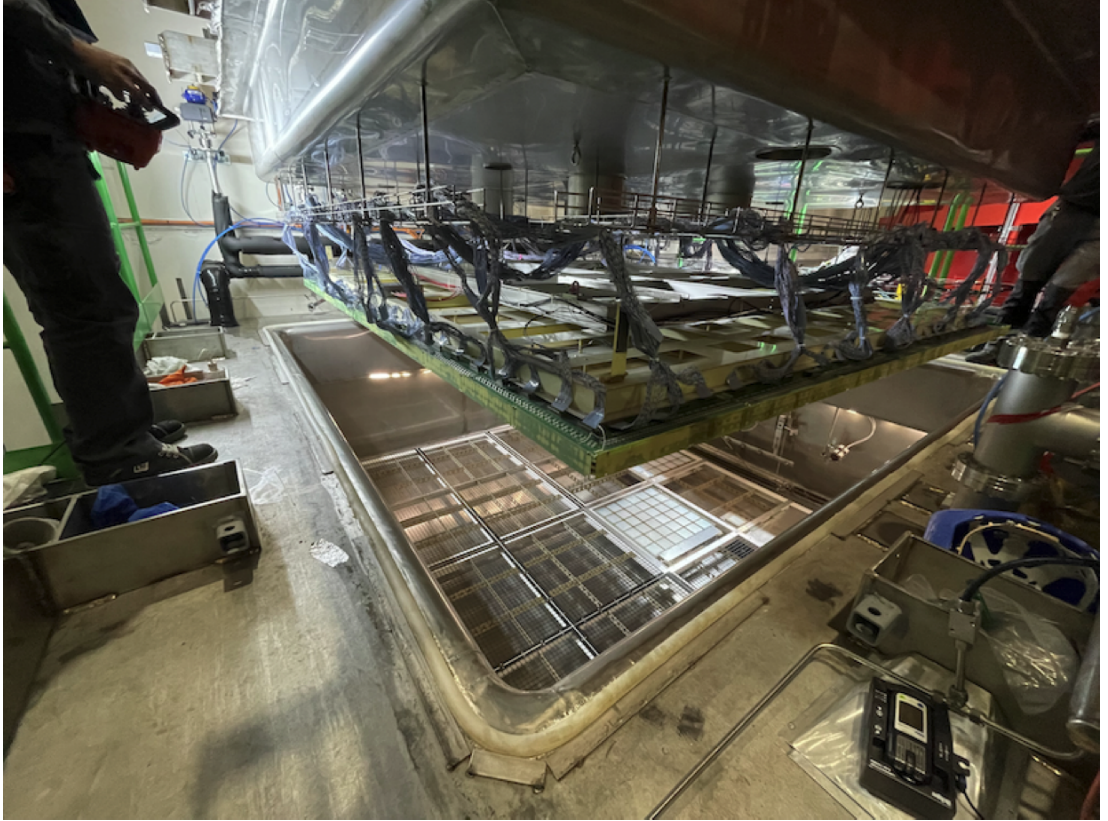


Figure 4.1 *A photograph showing the installation of the hanged CRP directly above the cathode, forming the prototype VDCB LArTPC for DUNE at the Neutrino Platform at CERN, EHN1 [66]*

Charge Readout Planes

The CRP contains two double-sided PCBs, where the innermost one has etched strips on the *reverse*-side, forming the first induction sense plane. The second PCB has two sets of etchings, the first forming the second induction plane, and on the reverse side, the collection plane etching strips. Figure 4.2 shows a simplified diagram of the etched anode plane strips configuration with respect to the cathode

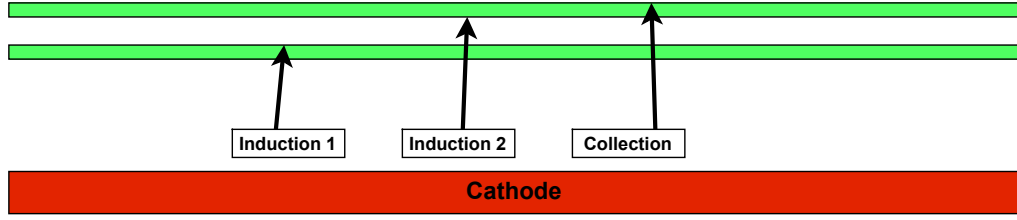


Figure 4.2 *A simplified diagram illustrating the configuration for each of the anode sense planes, etched into a face of the double-sided PCB boards (green panels). Also shown is the cathode (red panel) below the CRP.*

(red) and each of the PCBs (green). The strips serve as signal channels for the TPC and are pitched at approximately 7.5 mm and 5.0 mm for the induction and collection planes respectively. The orientation of the sense plane strips themselves are at $(0^\circ, 42^\circ, 90^\circ)$ with respect to the collection plane, for the collection, induction 1 and induction 2 planes, respectively. This is chosen to benefit most from the three 2D representations of particle trajectories within the LArTPC, aiding the excellent 3D reconstruction capabilities used in the Pandora reconstruction framework for DUNE [67].

The CRPs constructed for testing at EHN1 were altered further, to be able to test the readout electronics that would be positioned at the bottom and top of a VD LArTPC. These are referred to as Bottom Drift Electronics (BDE) and Top Drift Electronics (TDE), respectively. The CRP was effectively split in half, so that in testing, approximately half of the collection channels could be used for online triggering with either the BDE or TDE. An exploded diagram of the CRP, divided in this way is illustrated in Figure 4.3.

4.1.1 VDCB Geometry

The geometry of the VDCB will now be outlined, which is relevant to the 2021 and 2022 self-triggering testing runs, and the development of the trigger algorithms themselves, which are described after. The VDCB consists of a cathode, which lies on the bottom of the cold box, whilst the split CRP is hanged approximately 25 cm above it [66]. There were minor differences in the actual drift length observed between November (23.0 cm) and December (22.6 cm) 2021 and June (23.0 cm) 2022 runs, of approximately 0.4 cm. The following assumes a 23.0 cm drift length, unless specified otherwise. Figure 4.4 shows a schematic of a fully installed VDCB, viewed from the side. The top (cyan) object is the supporting

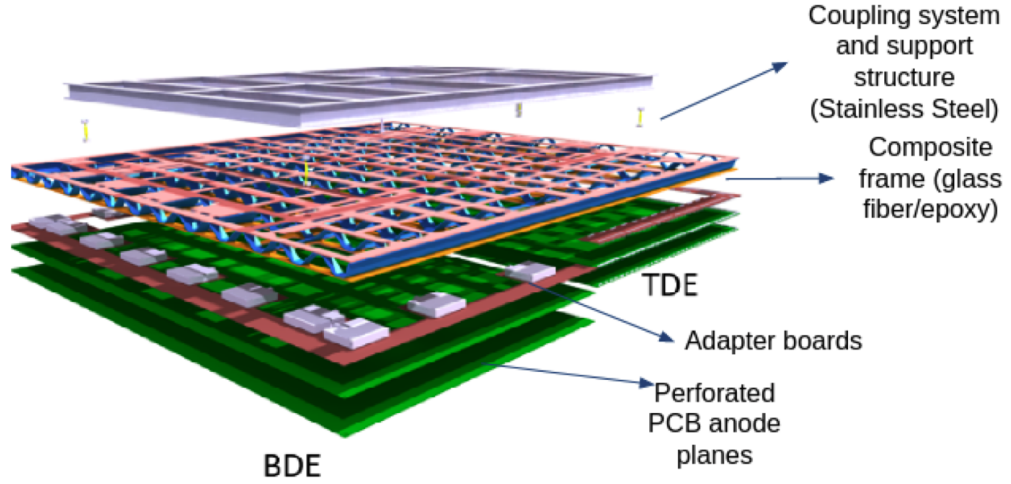


Figure 4.3 *An exploded 3D model diagram of a CRP used in the 2021 - 2023 LArTPC prototyping at CERN. It shows how the readout plane is divided into two halves, for testing the bottom (BDE) and top (TDE) drift electronics [66].*

structure, while the thin black strips beneath the yellow panel represent the PCBs of the CRP. Immediately below that, can be seen the CRP (grey), biased to -10.0 kV. The CRP is also referred to as the Charge Readout Unit (CRU) in what follows.

Top View

The CRP has in total 3200 readout channels, but is divided into two halves, for the two sets of electronics in the VD concept. The runs described below were taken with the bottom drift electronics (BDE), and thus refer to a halved-geometry of 1600 strip channels, 576 of which being collection channels. Figure 4.5 is a simplified aerial view diagram of the VDCB charge readout unit geometry with the drift direction x perpendicular to the page. The dashed blue horizontal lines represent approximately 2% of the actual number of collection plane strip channels for visibility, and run along the y axis. The z axis is then defined as the direction perpendicular to the collection channels, the vertical direction in the figure. The cathode lies beneath the CRP, invisible in this view.

With a view toward cosmic track detection, the green arrow in the BDE region depicts a possible cosmic muon trajectory with a large horizontal component in

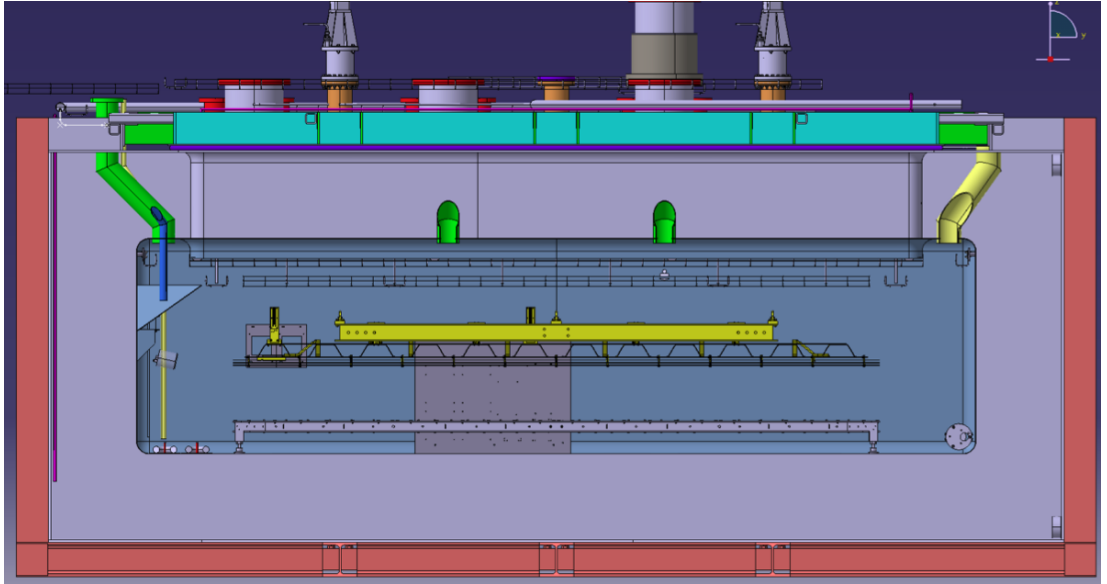


Figure 4.4 *A side view schematic of the VDCB used at EHN1, CERN for prototyping the VD concept LArTPC. The central yellow bar is a supporting structure for the readout plane, represented by many black lines immediately beneath it. Directly below that, the cathode can be seen as a grey horizontal thin band, equal length to the readout plane. [66].*

the collection plane view. It is seen that in this scenario, many collection plane channels are crossed before the particle exits the VDCB active volume. This observation is central to the development of the HMA below.

Side View

Figure 4.6 depicts the VDCB from the drift length x (vertical) and collection channel z (horizontal) plane. The collection channels are again shown in blue, this time running perpendicular to the page. In the $x - z$ plane, the cathode rested on the base of the cold box can be seen, represented by the horizontal pink line. The green arrow represents the same possible trajectory as in Figure 4.5 of a cosmic track passing through the BDE side of the VDCB with a large horizontal component.

With the reported values in [68] for drift field, E_{drift} , and knowledge of the drift time, t_{drift} , some key VDCB values for the runs used in this thesis are summarised in Table 4.1. VDCB Drift corresponds to the vertical separation between the cathode and CRP. It is seen that for drift speeds corresponding to approximately 1.5 m/ms, readout windows of 0.153 ms or, of roughly 0.2 ms, indicate a good

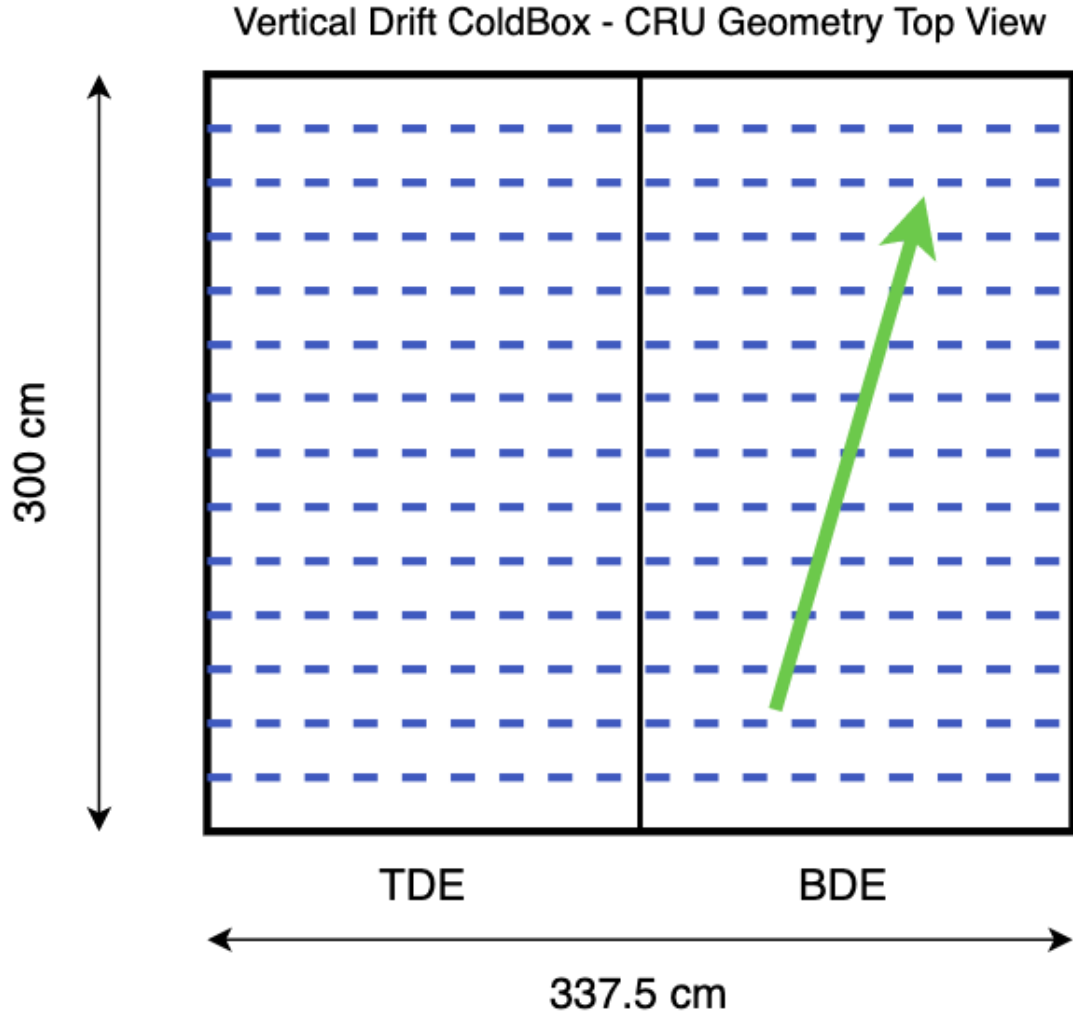


Figure 4.5 *Simplified, aerial view diagram of the VDCB CRP. It is divided into two halves, corresponding to the two sets of electronics in the vertical drift concept. The right side, BDE, corresponds to the geometry in which the June 2022 self-triggering runs took place. This half consists of 1600 readout channels, where 576 of those make up the relevant collection channels on which streamed signal were received at the trigger algorithms described in this thesis. The collection channels are aligned horizontally in the diagram and are depicted by the dashed blue lines. The number of dashed lines shown represents approximately 2% of the total collection channels for visibility. The green arrow represents a possible trajectory of a cosmic track passing through the BDE side of the VDCB with a large horizontal component. Induction channels are not shown.*

starting point for trigger algorithm development and testing. This corresponds to 10000, 50 MHz system clock cycles, which is the readout frequency used for the timestamps on the raw data in testing of CRP 1. In this context, timestamps are attached to software objects that are created during the online readout and

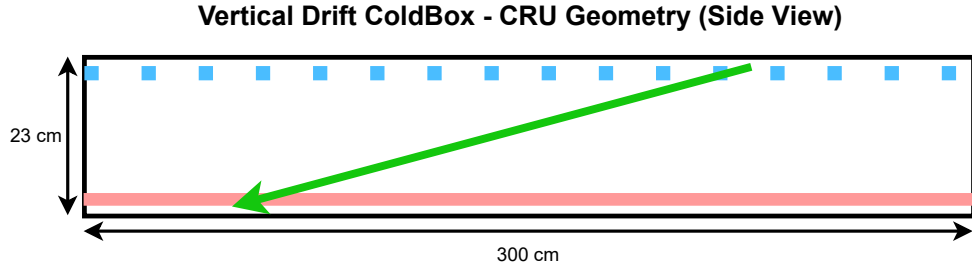


Figure 4.6 *Side view of the VDCB showing the drift length x (vertical) and collection channel z (horizontal) plane. This plane of view is the same as that of the event displays shown in the results section below. The pink line represents the cathode separated by a vertical distance of 23 cm from the CRP where the collection plane channels are depicted again in blue, this time running perpendicular to the page. The green arrow represents the same possible trajectory as in Figure 4.5, of a cosmic track passing through the BDE side of the VDCB with a large horizontal component of momentum.*

triggering of a detector.

In fact, the readout frequency of the CRP channels is actually 2 MHz. The timestamps used in the DAQ however, are scaled to match the readout frequency of the PDS which is 50 MHz, for synchronisation purposes. Work is ongoing to implement the concurrent use of PDS and TPC information to issue readout triggers. A readout window of 10000 clock cycles will be assumed in what follows. This ensures that the drift distance is more than compensated for, where 0.2 ms corresponds to roughly 30 cm of drift readout.

Table 4.1 *Key VDCB prototype detector values for the self-triggering run periods that are described in this thesis.*

Key Value	November 2021	December 2021	June 2022
E_{drift} [V/cm]	404	411	452
t_{drift} [μs]	154.4	150.7	145
v_{drift} [cm/ μs]	0.149	0.150	0.159
VDCB Drift [cm]	23.0	22.6	23.0

4.1.2 DUNE Data Acquisition - DUNE DAQ

The Data Selection (DS) working group within DUNE is charged with targeting specific event-type topologies using an online triggering system. The system

observes a continuous stream of ADC signal from both the TPC and PDS readout systems. The topic of the work relevant to this thesis was solely on the TPC readout, and so this section will limit the focus to TPC triggering in what follows.

DUNE DAQ Overview

A complete overview of the DUNE DAQ system is represented in Figure 4.7 by a flow chart diagram. This diagram coincides with the current concept for a DUNE FD module [66]. Interfaces with external systems are shown as grey boxes, whilst the core subsystems, or *modules* of the DAQ are shown as coloured rectangles. Terms that specifically refer to objects that are components of this diagram are referred to here in **bold** font. The modules which will be most relevant to this chapter are the **readout** and **trigger** subsystems, and the sub-flow charts they contribute to.

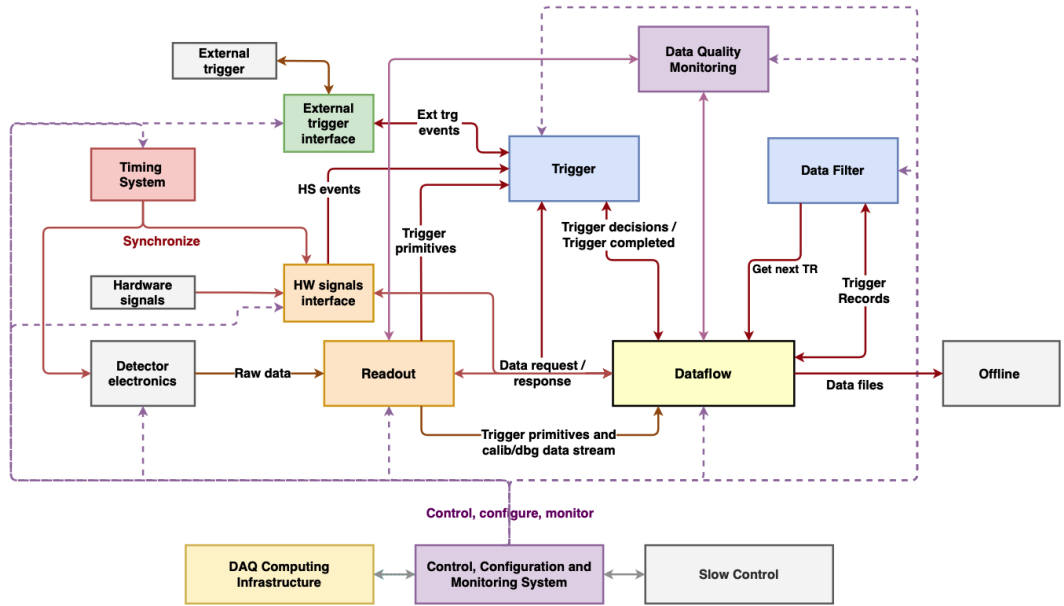


Figure 4.7 A flow chart illustrating the conceptual view of the DUNE DAQ system and the subsystems (modules) therein. External services are depicted by grey boxes, whilst the DUNE DAQ core modules are coloured. In general, the flow of data moves from left to right. The core modules of interest in this chapter are **readout**, **trigger** and **dataflow**, and the sub-flow diagrams they contribute to.

In particular, the **detector electronics** stream the raw ADC information, for each of the TPC channels to the **readout** subsystem. There, a down-sampling of the ADC streams occur. The readout searches for exceptional deposits of

charge on each strip, and constructs what are commonly called *hits*, or “Trigger Primitives” in DUNE, for each channel. Trigger primitives are described in detail below. These hits are passed to the **trigger** subsystem for fast online decision making, on whether or not to read out and store the raw data for a potential physics event. That decision making is typically based around clustering the Trigger Primitives in one way or another.

The decisions made by the **trigger** module are sent to the core module **dataflow**, which issues **data requests** back to the **readout** module. If successful, **readout** issues a response indicating such, which is then relayed from **dataflow** back to **trigger**. Successful triggering depends on the ability to issue triggering requests within the buffer time available to store raw data. It is anticipated that for DUNE, which will search for supernova bursts (SNBs), a buffer of at least 10 seconds will be required. Typical SNB algorithms, taking part in SNEWS have searches which look for a given number of neutrino events within the 10 second window [69].

Successful triggering decisions lead to the construction of **Trigger Records** (TRs), which may also be referred to as “Events”. A TR contains the triggering information, the raw ADC information and complete timing information that lead to the decision to read out that data. TRs are contained within the **data files**, which are streamed to offline permanent storage.

4.1.3 DUNE DAQ - Trigger System

Going one level deeper into Figure 4.7, the DUNE DAQ Trigger module is now described in detail. There is much terminology to be handled here, and so each term in **bold font** will also be summarised with a brief description below. In brief, the purpose of the trigger system is to accept as input from readout, a down-sampled representation of the raw detector data stream, known as **Trigger Primitives** (TPs) and output **Trigger Decisions** (TDs) based on chosen criteria. Those TDs lead to the request for data, from the readout module, to be written out for permanent storage. Successful TDs then lead to written **Trigger Records** (TRs). Figure 4.8 illustrates this flow of data that will be concerning the work below.



Figure 4.8 Dataflow for the trigger subsystem, showing the incoming TPs from the readout module to the TD reception at the dataflow module.

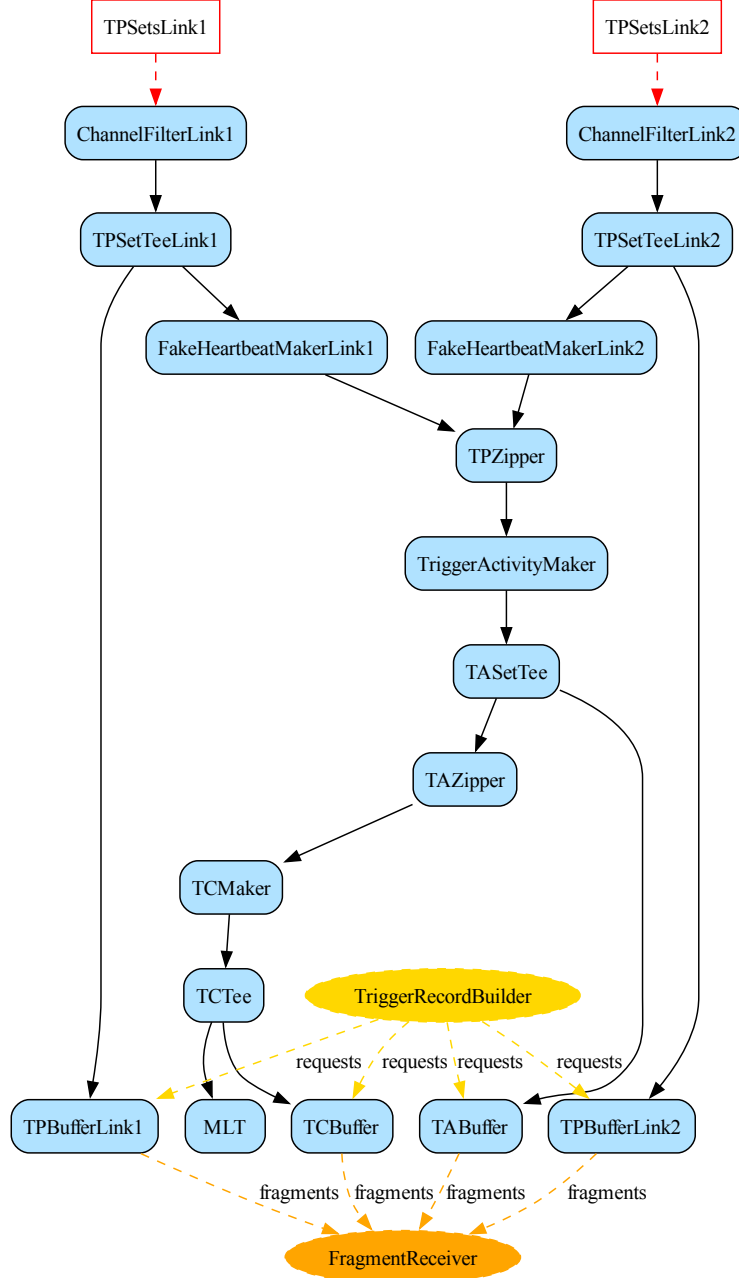


Figure 4.9 A flow chart representing an example configuration for a simplified 2-link trigger subsystem within the DUNE DAQ. The data flow generally falls from the top to the bottom, as indicated by the arrows. The trigger modules are described in the main text.

Figure 4.9 is an example configuration for a 2-link trigger subsystem within the DUNE DAQ. A link here can be thought of as an object which handles the information of 128 TPC channels, being streamed to the trigger module. They are both depicted by red rectangles in the figure. The diagram should be inspected alongside the terminology and module descriptions section below. A minimal, 2-link system is represented for the purposes of demonstration and clarity. A real VDCB system uses up to 12 links.

4.1.4 Terminology and Module Descriptions

- **Trigger Primitive (TP)** - A streamed *hit* on an ADC channel coming in from TPC or PDS system.
- **Trigger Activity (TA)** - A set of hits that have been accepted to be sent up to the next level in the trigger hierarchy. Typically these will be tracks and showers or other physics activity within the active volume of the TPC.
- **Trigger Activity Maker (TAMaker)** - A general module in charge of monitoring the incoming stream of TPs and issuing a localised activity trigger at the granularity of single APA/CRPs (and PDS units in the future). TAMakers have an associated algorithm, which can attempt to search the incoming TP stream for interesting physics activity. The TAs that the TAMaker produces are sent to the TCMaker.
- **Trigger Candidate (TC)** - A set of TAs that have been accepted to be sent up to the next level in the trigger hierarchy. Typically these will be single TAs for the VDCB, or TAs across multiple APAs for ProtoDUNE.
- **Trigger Candidate Maker (TCMaker)** - In analogy to the TAMaker, which identifies clusters of TPs representing activity across many TPC channels, the TCMaker identifies clusters of TAs across many APAs/CRPs. As an example, consider the following: The ProtoDUNE TPC is formed of two opposite facing anode walls, with a single cathode wall in the middle. This forms two adjacent TPCs, with opposite drift directions. For a cathode crossing muon in ProtoDUNE, a track is generated on two opposite facing APAs. To trigger on this, the TCMaker will need to combine the two corresponding tracks/TAs on the opposite APAs and issue a TC to the Module Level Trigger.

- **Trigger Decision (TD)** - The object that the **Module Level Trigger (MLT)** sends to the **Data Flow** module in order to issue the readout trigger command with a requested readout window, corresponding to the shape of the raw data that should be permanently stored for later analysis.
- **Trigger Record (TR)** - An object in a stored file, containing the raw data, TPs, TAs and TCs that may have led to its construction. The files containing them are currently stored in **hdf5** format.
- **Module Level Trigger (MLT)** - What might be anticipated to be called the *TDMaker*, is in fact at the edge of the trigger system, and is called the Module Level Trigger. As the name suggests, it is in charge of sending TDs to Dataflow for raw data contained within an entire DUNE FD module. However, for the VDCB, this corresponds to just a single CRP. Note the many CRPs that would be utilised by a DUNE FD module.
- **Zipper** - A general module in charge of combing inputs from multiple streams and outputting them in a single queue to the following module. As an example, consider a DAQ configured for running on the VDCB. A CRP has 12 links of available TPC channels for reading in. The readout application executes the TP finding processes on these inputs separately, and delivers them in the form of 12 queues to trigger. Whilst each stream itself is assumed to be time ordered, the time ordering between the 12 streams *is not*. It is the purpose of the zipper module in this example to merge the 12 input streams and output them to the TAMaker in a strictly time ordered fashion, into a single queue. Late TPs are rejected as *tardy* according to their system timestamps and dropped, since it is impossible to maintain time ordering when TPs of a earlier timestamp than those that have already been sent arrive at the zipper.
- **TXSets** - In practice, rather than dealing with individual TPs, TAs and TCs, these objects are combined into sets called TPSets, TASets. Generally the trigger system receives TPSets, it sends TPSets to the TAMaker, the TAMaker sends TASets to the TCMaker, etc.
- **FakeHeartbeatMaker** - One of the foundational assumptions of triggering on a raw data stream is the time-ordered property of its representation to the triggering mechanism. This requires waiting and timeouts for input streams to *catch up* before packaging data and sending up the trigger hierarchy. Consider the case above regarding the zipper. It is configured

with a maximum working time, within which it has to confirm that each input stream is represented with an active stream of data. The purpose of the FakeHeartbeatMaker is then to produce regular TPSets of a distinct type, which indicate the downstream modules that they have observed all the relevant information for triggering up to a certain point in time.

- **TPChannelFilter** - The very first module of the trigger system. As the name suggests, TPs can be filtered out based on their TPC channel. This is useful for things like testing on the VDCB. For example, to only present collection TPs to the TAMakers when searching for tracks, especially when the induction TP software was unsuitable for reliable TP generation. In that case, the TPs are filtered by plane, which makes use of an additional channel-to-plane map object within the module.
- **Tee** - DUNE DAQ has no inbuilt functionality for making copies of objects, so this module is a workaround for that. When the TPChannelFilter has processed the TPSets, the TPSet it chooses to send to the TAMakers are copied via a TPSetTee module, which sends one copy to a TPBuffer, and one through to the FakeHeartbeatMaker. Figure 4.9 helps to visualise this.
- **Buffer** - It is of interest to store the TPs, TAs and TCs that lead to stored Trigger Records (TRs) inside those TRs. The buffers service this ambition. There are TPBuffers, TABuffers and TCBuffers. They are received directly from the relevant Tee modules described above. Data requests are made to these buffers when a triggering decision is made (as well as to the raw data buffers in readout) as described in the Module Level Trigger above.

4.1.5 Trigger Algorithms in DUNEDAQ

In the context of the VDCB, the DUNEDAQ Trigger module observes an incoming stream of TPs, which are a representation of the raw ADC information on each sense channel of the TPC. Figure 4.10 is an example of a TP event display. TPs have several useful properties for triggering:

1. **Start Time:** The system time at which the ADC threshold was exceeded, and initiated the construction of a TP for a given channel.
2. **End Time:** Similarly, the system time at which the ADC value drops back *below* the hit-making threshold.

3. **Channel ID:** Each TP is constructed from an input ADC stream, which is associated with a unique wire channel for the TPC.
4. **ADC Integral:** Also known as ADC *sum*, it is the summed total of the ADC values, whilst the ADC is above the hit-making threshold, for a given hit-generating configuration in the Readout module.
5. **ADC Peak:** The highest ADC value recorded during the construction of the TP.
6. **Time Over Threshold:** The total amount of time, in DUNE DAQ system clock cycles, that the ADC signal was above the hit-making threshold, during the construction of this TP.

The TP event display in Figure 4.10 reveals the cosmic activity within the online VDCB CRP 4 during run 020472, April 2023, for 20 ms, where the colour of the TPs represents their ADC integral. The tracks that can be seen typically cross a few tens of contiguous channels, and typically correspond to the large flux of *vertically* traversing muons. The remaining singular TPs with low ADC can be attributed to detector effects such as electronic noise, or low energy physics backgrounds such as Ar^{39} beta decay.

The figure also reveals how the Trigger system observes the incoming stream of TP data, on each of the TPC channels. In particular, the overall goal of the TAMaker is to scan incoming TPs and signal to the TCMaker when an interesting piece of activity is found at the granularity of a single detector element. By default, only collection TPs are filtered through to the TAMaker for testing, where some algorithmic series of checks are performed over those hits, and if certain thresholds are exceeded, a TA is constructed and sent to the TCMaker. The successful creation of induction-based TPs, which is more difficult due to their bipolar signal shape, was used in some of the later 2023 runs for triggering concurrently with the collection TPs. The discussion here focuses only on collection channel TPs.

The TAMaker has a configurable, fixed size perceptive field of a CRP drift region whilst running. That corresponds to a window of time within which TPs are collected according to their start times, and this is called the window length. A good starting point for this value during algorithm development is the total drift time of the TPC. For the VDCB, this corresponds roughly to 10000 50 MHz clock cycles, or 0.2 ms. Note that this is approximately one of the vertical lengths of the tracks observed in Figure 4.10. The current collection of TPs, which will be

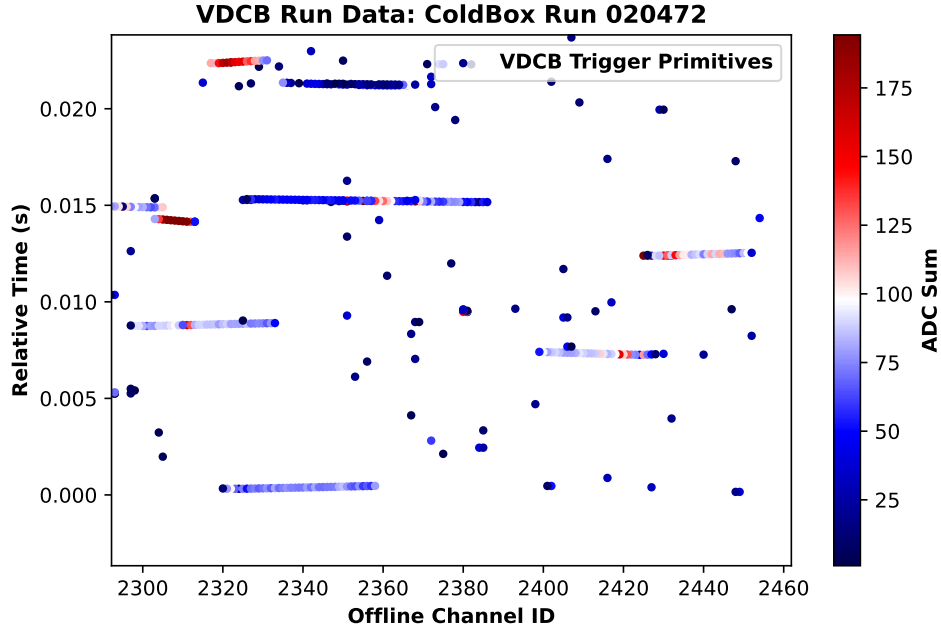


Figure 4.10 *An event display using TPs from the view of the collection plane in the VDCB. The channel numbers are shown on the x-axis, and the timestamp of the TPs is represented on the y-axis. A large flux of vertically travelling cosmic muons can be seen passing through a set of contiguous TPC channels. The colour of the TPs represent their ADC integral. This image is generated using TPs that were generated during VDCB run 020472.*

called the *input list*, is considered complete only when the addition of the next incoming TP would cause the time span of that collection to exceed the window length. At this point, the input list is passed to the algorithm activity checks.

Algorithmic Checks & TA Issuing

As a first example, an activity check might calculate the total ADC contribution of the current input list. It does this simply by summing the ADC integral values for each TP. If one wanted to issue a TA based on reaching a specific ADC value, then the algorithm can simply be configured to compare this to another configurable parameter representing that threshold, e.g. the `adc_threshold`. As a second example, a trigger might be required when a particularly high number of unique channels within the current time window have hits. Again, the algorithm could be supplied with a different configurable threshold to the TAMaker, e.g. `n_channels_threshold`. In the current example, when the current number of unique hits on collection channels within 0.2 ms exceeds that value, a TA is

issued to the TCMaker. When a TA is issued, the system has indicated interest in physics activity within the detector and it is then the job of the TCMaker to decide whether to issue a TC to the MLT, where a TD might be issued for TR storage. The current input list is then cleared, and a new list with the next incoming TP is started. The second example described in this paragraph is in fact exactly the *multiplicity* triggering mechanism that was used in the very first December 2021 VDCB self-triggering runs. The outcomes of those runs are discussed below.

When it is observed that the current TAMaker input list *does not* exceed a given threshold, the whole list is then shifted up in time by an amount that is defined by the next incoming TP start time, and the TPs in the current input list. The complete general decision flow for TA generation has now been defined. The input list that remains after a loop of the above process is passed back up the chain where TPs are added until the window is complete, and so on. The flow chart shown in Figure 4.11 summarises the algorithmic approach to TA generation as described here.

4.1.6 VDCB December 2021: Multiplicity Triggering

In December 2021, the first demonstration of self-triggering for the VDCB took place at CERN. For a set of data TPs that were stored in those runs, the multiplicity distribution of a sample trigger activity windows is shown in Figure 4.12. Multiplicity for a TA window is defined as the number of unique collection channels in a state of at least one hit, for the given window object. During run number 012623, the multiplicity triggering algorithm described above was used to create TDs, which lead to the TRs shown in Figure 4.13, and were successfully stored to disk. These are TRs 45, 46 and 47 of that run, from left to right, respectively. These are some of the first examples of successful self-triggering on the VDCB.

The x axis on each event display TR represents a TPC collection channel, while the y axis represents the DUNE DAQ system time in 2 MHz clock cycles. It is seen that each track or shower activity spans approximately 300-400 2 MHz cycles, or 0.15-0.20 ms, corresponding to the drift length of the VDCB, as expected. It is immediately apparent that the simple multiplicity trigger algorithm was able to isolate short snippets of activity within the VDCB, and trigger the storage of raw detector data as expected. The vast majority of these TRs were short

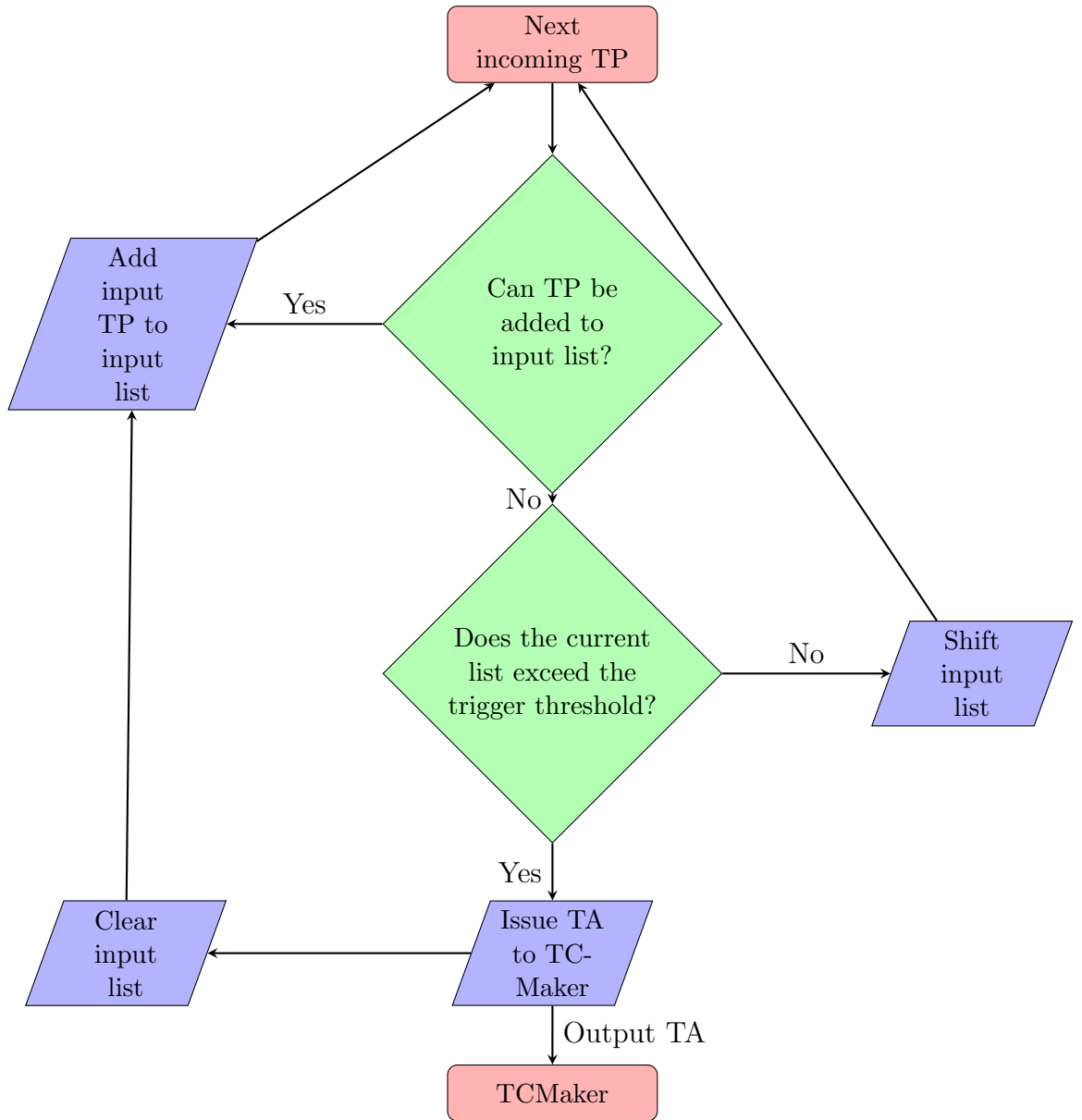


Figure 4.11 *Flow chart detailing the decision making process for TA generation based on incoming TPs, within the DUNE DAQ trigger subsystem. Red blocks represent the boundary of functionality within the TAMaker. Blue blocks represent an operation on the current TP input list. Green blocks represent a decision in the algorithm chain.*

tracks coming from the large vertical flux of cosmic muons. Occasionally, an electromagnetic shower might be captured, as seen in TR 45. Following this demonstration with a little less than 2 days detector time, the next steps were to implement the Horizontal Muon Algorithm (HMA) code in DUNEDAQ and take data using it in the next set of VDCB runs.

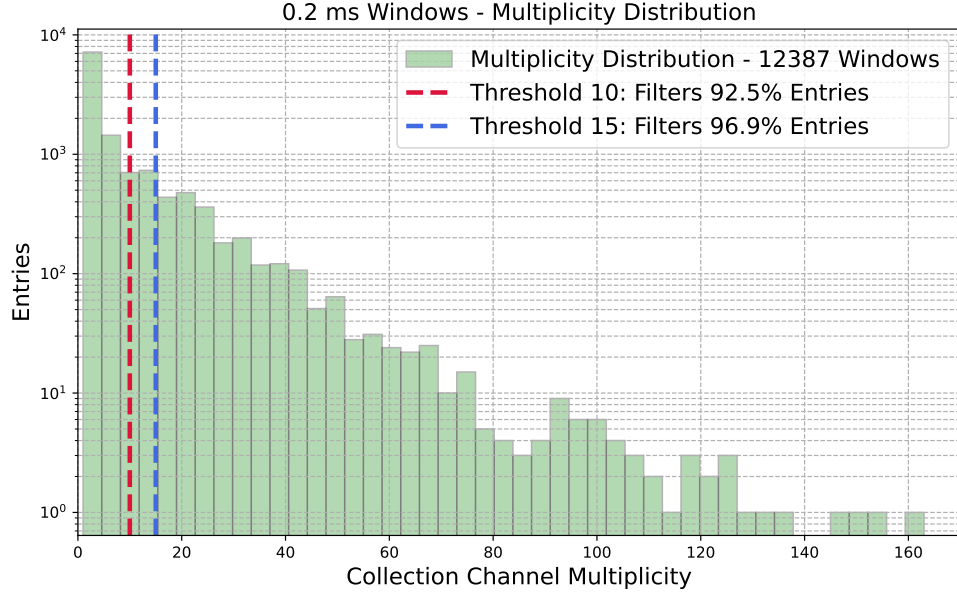


Figure 4.12 *The multiplicity distribution from 12387 Trigger Activity windows generated by 8.3 seconds of VDCB data TPs stored during the December 2021 runs. The threshold criteria at 10 and 15 hit channels, which were used for testing in self-triggering runs, are shown as vertical red and blue lines, respectively. The mean observed multiplicity from this sample is 9 collection channels.*

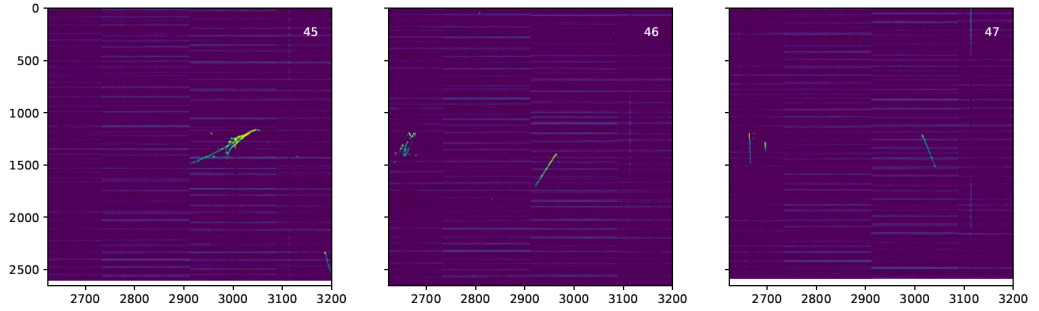


Figure 4.13 *Three event displays for stored TRs (labelled 45, 46 and 47 left to right) from the December 2021 VDCB multiplicity triggering run 012363, on CRP 1. 2 MHz clock cycles, i.e. $0.5 \mu\text{s}$, are represented on the y-axis, and collection channel ID values are given by the x-axes.*

4.2 Horizontal Muon Algorithm

After the successful self-triggering in December 2021, the next goal was to target more specific, less frequent activity, whilst filtering the relatively high flux of

vertically traversing cosmic muons. Without a dedicated particle beam, the obvious choice was to use the geometry of the cold box itself, and the relatively low frequency of cosmic muons travelling with a large horizontal component of momentum through it. This led to the concept of the Horizontal Muon Algorithm (HMA).

In terms of expected triggering rates, the flux of cosmic ray muons at sea level is known to be around $10000 \text{ m}^{-2} \text{ min}^{-1}$ [70]. It is also known that this flux varies with the zenith angle, ψ , following a cosine power law,

$$\phi = \phi_0 \cos^2(\psi), \quad (4.1)$$

where ϕ_0 is the peak flux occurring at $\psi = 0^\circ$, at zenith. Taking ϕ_0 to be approximately 166 muons per square meter per second, and the fact that the area subject to TP-based triggering is approximately 5 m^2 , the expected flux of muons traversing the detector at, for example, $\psi = 80^\circ$ should be of order,

$$5 \text{ m}^2 \times 166 \text{ muons m}^{-2} \text{ s}^{-1} \times \cos^2(80^\circ) \approx 25 \text{ muons s}^{-1}. \quad (4.2)$$

Given that the orientation of the collection plane channels used for triggering are all perpendicular to the length of the VDCB and horizontal, $\phi = 0^\circ$, there is an additional constraint on the azimuthal angle of the muons which can be detected using adjacency checking. This also varies with the azimuthal angle, but typically reduces the visibility of the total flux calculated above to roughly 10%. Thus, the expected approximate triggering rates for cosmic ray muons with large horizontal components in the VDCB is of order $O(1 - 10) \text{ Hz}$.

With the collection plane channels oriented perpendicular to the *length* of the BDE half of the VDCB, as in Figure 4.5, a search can be performed for activity with at least a given number of contiguous collection channels with hits, within the TA window input list. Given that the VDCB has a drift length of 23.0 cm, and the sense channels are pitched at approximately 5.0 mm, it makes sense to start the search at around 40-50 collection strips. Coupling this to the shallow drift length of the VDCB, this should have the effect of picking out passing muons that have a horizontal component of momentum *at least* as large as their vertical component.

Adjacency Checking

Figure 4.10 is an event display generated from a subset of the 8.3 seconds of streamed TPs from the April 2023 VDCB runs using CRP 4. It shows collection plane TPs only and is therefore a representation of what the TAMaker received as input. The vast majority of activity observed are single hits or very short tracks connecting less than 5 collection plane strips, in the x axis. The second most frequent types of activity are the longer tracks, connecting a few tens of adjacent collection strips. These correspond to the more vertical cosmic tracks, where a track crossing, say, 30 collection strips has a horizontal component of 15.0 cm in the collection view. Starting with the initial goal of targeting tracks with a larger horizontal than vertical component within the VDCB, i.e. targeting activity that spans more z (collection channel space) than x (drift space), a suitable contiguous channel threshold would be approximately 43 consecutive collection strips.

The above introduces the concept of adjacency checking. For each 10000 clock cycle input list of TPs observed by the TAMaker, i.e. an event, the maximum number of consecutive collection channels that have hits on them serves as the sentinel, which the recursive algorithm checks to determine if the threshold is breached. The events are now endowed with the property of *adjacency* which takes this as the definition. If *multiplicity* in Figure 4.12 is promoted to adjacency, the result is Figure 4.14. All events with an adjacency of less than 5 have been removed from the sample for visibility, so that only the track-like (adjacent) activities of z length at least 2.5 cm remain. Figure 4.14 shows the distribution of window adjacencies for the resulting sample of 2681 TP input lists seen by the TAMaker. It also shows the effect of applying a range of adjacency thresholds on those TA windows for triggering, where the critical point of 43 collection strips is shown as a dashed blue vertical line, filtering out 94.8% of all events with adjacency of at least 5. This is largely due to the relatively high flux of vertical cosmic rays to horizontal ones and will be commented on in the reconstruction section of the results below. The mean adjacency observed in this sample is 17.6, corresponding to a mean track length of 8.8 cm in the collection view.

Adjacency Tolerance

When triggering on activity with high adjacency, it is important to introduce a tolerance parameter to account for gaps in the track that can arise due to a

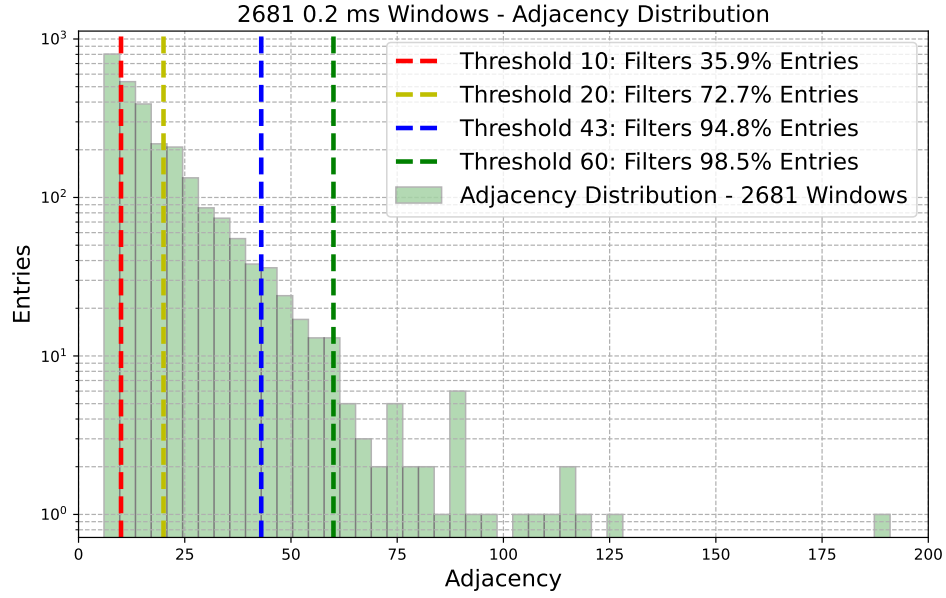


Figure 4.14 *Adjacency distribution for a sample of 2681 TA input lists from the December 2021 VDCB CRP 1 runs, that have adjacency of at least 5. Events with adjacency below this are removed from the sample for visibility. Vertical dashed and coloured lines illustrate the effect of applying adjacency threshold criteria on these events, and indicate the effect on the relative trigger rate. The mean adjacency observed in this sample is 17.6, corresponding to a mean track length of 8.8 cm in the collection view.*

variety of reasons. They can be broadly categorised into the following:

1. Detector effects, such as dead channels, or absent hits along a track.
2. Physics considerations such as ionisation recombination effects and Landau fluctuations in the charge deposits.

As an example, see the leading track in Figure 4.15. It is not uncommon for a chain of contiguous collection strip channels to be absent of hits within the track. The blue arrows highlight contiguous segments of 2 (bottom) and 4 (top) absent hits on the collection channels. One then needs a tolerance for the adjacency counting, and it is defined via the following assessment of the short TP data sample.

The full set of streamed TPs is replayed, through the DUNEDAQ trigger algorithm *offline*, where the tolerance allows a presumably much larger than observed gap of hits in a track, say of 20, and with an adjacency threshold of 40 such that the

algorithm configuration targets activities with a horizontal component as large as the vertical. The triggered windows are then considered to contain activity of interest for the HMA. By isolating the triggered tracks in terms of a set of TPs, a maximum gap of 4 collection channels was chosen from the distribution of those track gaps which accounts for over 99.99% of triggered tracks with 40 adjacency threshold. That is, tracks with gaps of at least 5 channels made up less than 0.01% of triggered windows. It was also found that triggering on 10000 clock cycle windows reaching the adjacency threshold with track gaps *over* 4 collection wires began to pass many instances of two independent tracks which are close in TPC channel space, resulting in many false positives for this algorithm. Thus, the maximum number of contiguous channels absent of hits was set to 4, and the adjacency counting stops if this is exceeded in any single window of TPs.

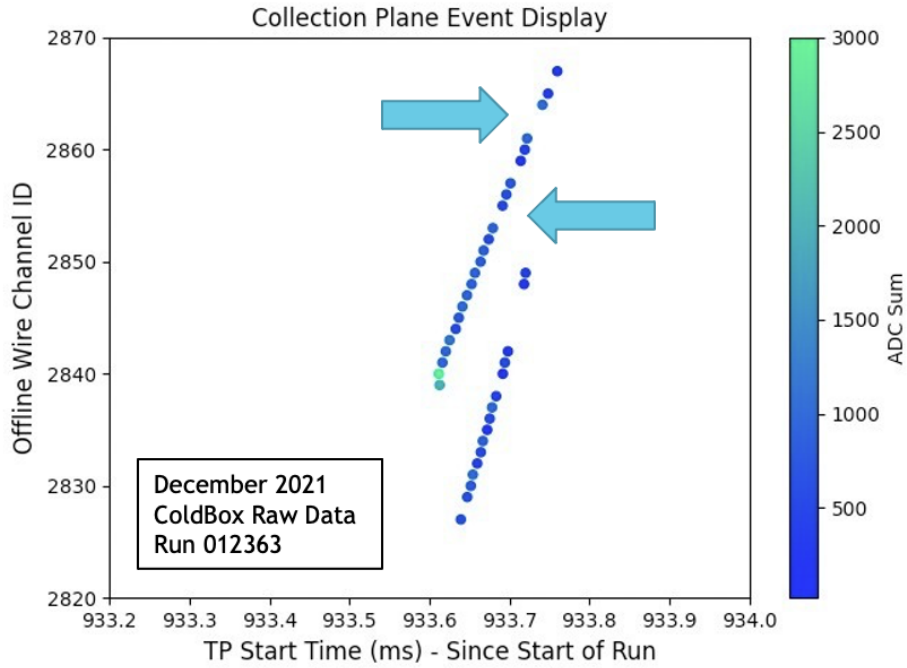


Figure 4.15 *An event display created using streamed TPs from the December 2021 VDCB runs. It is seen that where tracks are clearly present, it is not uncommon to have hits ‘missing’ in the otherwise contiguous chain of collection channel hits. For the leading (top) track in this figure, it is also seen that up to 4 channels are skipped before the continuation of the track. This is highlighted by the upper blue arrow. An analysis of the tracks contained within the TP data set led to a default gap tolerance for VDCB triggering of 4 collection plane channel strips.*

With the maximum gap determined from the distribution of gaps from low threshold triggering, there remains one number to be decided. This is the

adjacency tolerance itself, called the `adj_tolerance` in the code. The definition is the maximum number of channels one is prepared to skip, whilst not exceeding a maximum gap of 4, in order to continue the adjacency count for the current window. The exact value used is somewhat arbitrary, and so left as a configurable parameter for the HMA configuration generation in the DUNEDAQ software. However, from the June 2022 VDCB runs, a value of approximately 25 - 35% the value for the adjacency threshold is suggested, which is shown to yield the results below.

4.2.1 VDCB Triggered Events Reconstruction

Table 4.2 summarises some of the key VDCB runs that were taken with the HMA at various adjacency thresholds in 2022. Many runs were taken, increasing the adjacency threshold by 10 each time, but given that these were taken concurrently with other component-testing, not all runs were stable. Therefore, only the runs with sufficient data to report algorithm results are included here. The low-level reconstruction of the stored TRs into tracks and showers is described below using the LArDON package [68], and used to illustrate the performance of the HMA. Only runs with sufficient data were used in the distribution plots, corresponding to runs with adjacency thresholds of 60 and 100 collection channels. The analysis of algorithm performance will primarily be concerned with the distributions of the triggered track lengths and the angles through which they traverse the VDCB.

In what follows, a HMA run is referred to with the adjacency threshold used X , as HMAX. For example, HMA170 refers to a run taken with an adjacency threshold set to 170 collection channels, corresponding to a triggering activity with a horizontal component of at least 85.0 cm.

Table 4.2 *Key values of several self-triggering runs taken with the VDCB DUNE Prototype in 2022, using various adjacency thresholds with the HMA.*

Run Number	Threshold	TRs Stored	Trigger Rate (Hz)
013511	150	62	0.1
013539	170	1583	0.07
013599	100	52116	2.41
013600	60	10595	8.33
013637	60	23536	6.53
013648	100	33216	1.39

3D Track Length Distribution of Triggered Tracks

Figure 4.16 displays the distribution of 3D track lengths for all tracks within all TRs of the above-mentioned HMA60 (yellow) and HMA100 (magenta) VDCB runs. For direct comparison in terms of using no algorithm at all, the figure also contains all tracks found in TRs that were stored periodically, effectively taking random snapshots of the activity within the cold box at those intervals. It can be seen for this *Random* run (black), that the majority of reconstructed tracks correspond to the single peak at the drift length of the VDCB, indicative of the relatively large vertical flux of cosmic activity. Note that the TRs often contain tracks in addition to the triggered track owing to the high flux of cosmic rays at the ground-level of the VDCB at EHN1. The below histograms therefore include these as faded, translucent histograms. However, the darkened histograms for each run attempt to isolate specifically the triggered track by identifying the longest reconstructed track in the event.

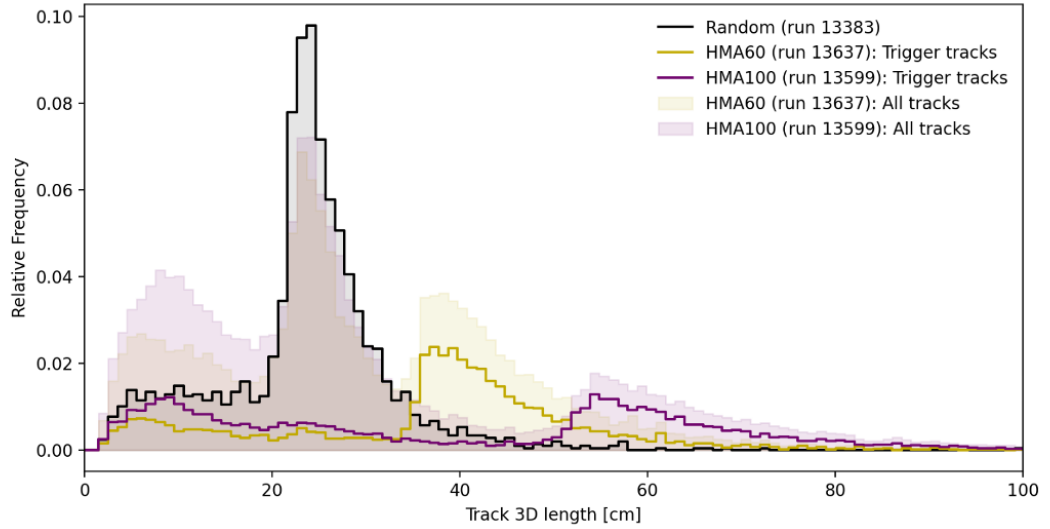


Figure 4.16 *Reconstructed 3D track length distributions for all tracks in all TRs of runs 013637 (adjacency threshold 60 - yellow), 013599 (adjacency threshold 100 - magenta) and a random run (black) where no algorithm was used. The 3D track length is represented on the x-axis in cm, whilst the relative frequency of those captured tracks, within the given run are represented on the y-axis. The peak of the random run is indicative of the many captured tracks corresponding to the VDCB drift length of 23.0 cm. The latter two peaks clearly show the adjacency thresholds extracting longer tracks. These correspond to 39.0 cm for 013637 and 55.0 cm for 013599.*

There are several distinct features of VDCB TRs that Figure 4.16 highlights. In terms of the peaks from left to right:

1. The first peak contains small tracks of activity that are contained in the vast majority of TRs, for all runs. The peak is highest for the highest threshold run, where the lower frequency of longer tracks means that the relative frequency of the shorter tracks makes up a larger contribution to that run. Further, the effect decreases in step with the adjacency threshold. Also, note that higher energy events lead to more reconstructed tracks due to delta rays and a larger number of adjacency gaps for example.
2. The second peak marks the drift length of VDCB and is indicative of the high flux of vertical cosmic rays at ground-level. This is strongest for the random run, where it is expected that the most probable physics activity from a random readout to be one or more vertical cosmic tracks. Note that the fraction of events containing tracks of this length is apparently independent of the adjacency threshold used in the HMA runs.
3. The third peak is the first evidence of the HMA isolating the longer tracks compared to the random run. The adjacency threshold of 60 collection strips results in a sharp rise after 35 cm, indicating that the requirement of activity longer than the drift length of the TPC is being achieved by the HMA.
4. The fourth and final peak further evidences this. The adjacency threshold of 100 results in a similar display, picking out even longer tracks starting at around 50 cm.

Angular Distribution of Triggered Tracks

Figure 4.17 displays the orientation of the same tracks as above, where the orientation is described by the angle θ with respect to the vertical drift axis. An angle approaching 90° is therefore approaching the horizontal, whereas θ approaching 180° indicates tracks with a larger vertical component.

Similarly to the above, the key features of Figure 4.17 can be summarised the three peaks from left to right:

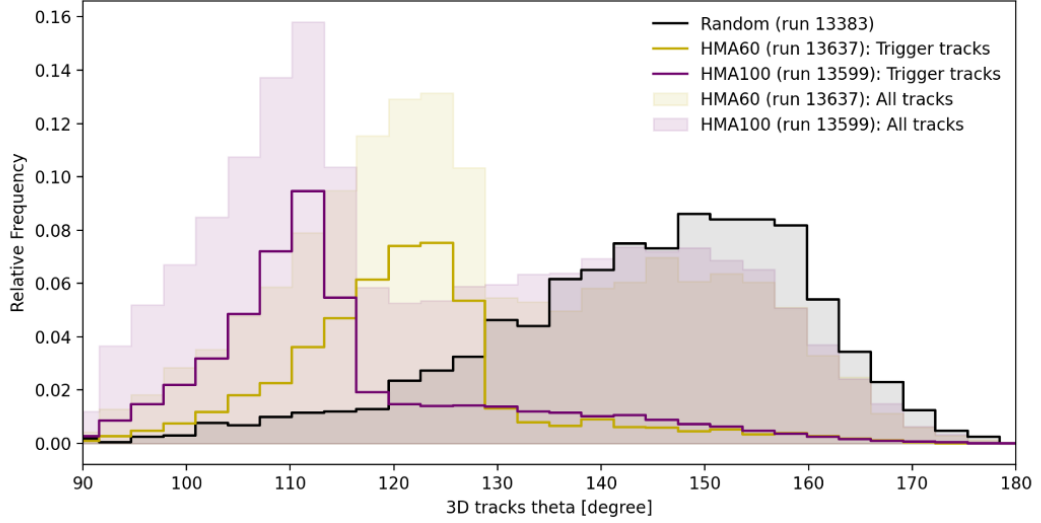


Figure 4.17 *Reconstructed 3D track angle distributions with respect to the vertical drift axis. These contain all tracks in all TRs of runs 013637 (adjacency threshold 60 - yellow), 013599 (adjacency threshold 100 - magenta) and a random run (black) where no algorithm was used. The peaks clearly indicate that by increasing the adjacency threshold of the Horizontal Muon Algorithm, tracks are selected that have an angle closer to 90° , i.e. they have a larger horizontal component. The random run has the majority of tracks with angles closer to 180° , indicating a larger vertical component.*

1. The first peak at around 110° is the closest to 90° and, as expected, this corresponds to the HMA run with the largest adjacency threshold of 100.
2. The second peak corresponds to the second closest peak to 90° at around 123° and corresponds to the HMA run with the second highest threshold of 60.
3. The third peak at 153° corresponds to the random trigger run, which is the closest to 180° , the tracks with the largest vertical component. The distribution has a slow trailing tail to the left in contrast to the sharp drops to the right of the HMA100 and HMA60 at 117° and 129° respectively. This is indicative of the impact of applying a threshold compared to random (periodic) triggering of readout.

4.3 LArTPC Triggering Conclusions and Further Work

Specific event-type-targeting has been performed and demonstrated using algorithms contained within the Trigger module of the DUNEDAQ software. The HMA successfully targeted extended pieces of activity across the collection channels of a fully operational prototype LArTPC, most commonly horizontal cosmic muon tracks. Now that simple self-triggering has been confirmed to work for this DUNE detector prototype, possible algorithms for more complex topologies can be considered. The inclusion of TPs from the induction channels could leverage the 3D imaging capabilities of a LArTPC. It is also anticipated that the search for specific event types can aid the study of the low energy response of LArTPCs, which is critical for SNB and solar neutrinos. In fact, a HMA170 triggering run captured a candidate Michel electron, stopping muon event, which can be used for just that.

Michel Electron Searches

Figure 4.18 is a raw event display of a candidate stopping muon event, emitting a Michel electron in the VDCB run 013539 with an adjacency threshold of 170 collection strips. In this display, the muon enters from the top left and travels with a large horizontal component of around 1.75 m. Clearly seen are the characteristic Bragg peak of a stopping muon on the right, before the short low energy electron ionisation track. For future testing runs at ground-level, a specific Michel triggering algorithm could be a future work on targeting more complex physics event topologies. Michel electron events are interesting to DUNE for a variety of reasons, including the investigation of the low energy response of LArTPCs such as MicroBooNE [71] and DUNE itself.

It is proposed that the HMA could be extended, to return the piece of activity with the highest adjacency, selecting muons that have a good chance of stopping within the TPC active volume. That track can then be searched for a Bragg peak, and a possible kink at the end of the Bragg peak, indicative of a decaying muon. Figure 4.19 (left) shows a simulated decaying muon event, within the VDCB, using the LArSoft event generation framework [72]. The muon was simulated with an initial energy of 300 MeV. For a MIP in LAr, there is a Most Probable Value

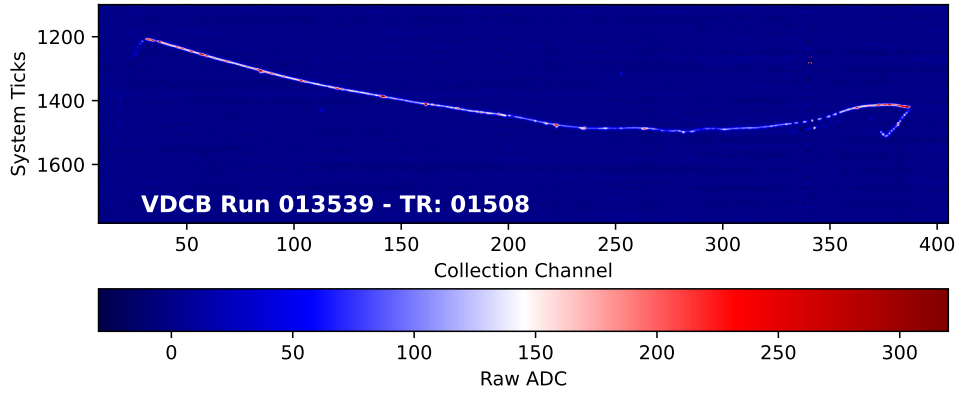


Figure 4.18 *An event display of a candidate stopping muon event, exhibiting a Bragg peak and signs of a Michel electron. Triggered by the Horizontal Muon Algorithm during VDCB run 013539, TR 1508. An adjacency threshold of 170 was used with the HMA.*

(MPV) for dE/dx of 1.8 MeV/cm, and the average is 2.1 MeV/cm. This means the simulated muon can be expected to traverse *a maximum* of approximately 150 sense channels before stopping, losing approximately 1 MeV/channel, with a channel pitch at 5 mm for the collection plane.

The Bragg peak could be searched for by tracing the running ADC mean along the large-adjacency activity. Using a convolution parameter makes this tracing less sensitive to the spiking in charge distribution due to Landau fluctuations. The peak could be identified by requiring the running mean to exceed $x \cdot \mu_{ADC}$, where μ_{ADC} is the total mean ADC along the activity and x is a configurable threshold to reach before signalling a potential Bragg peak. The right plot in Figure 4.19 illustrates this concept.

In this regime, the additional search for a kink at one end of the track could be searched for in the same way. The spatial gradient of the track can be traced, where a kink would be identified by a sharp change in that gradient at one end of the track. Figure 4.20 similarly illustrates this idea. Coupling the searches for a Bragg peak and a kink at the end of the longest activity returned by the HMA is one method proposed to perform a search for stopping muon events using the LArTPC self-triggering approach described in this chapter.

During the testing of the CRPs at CERN, a proof-of-concept algorithm was developed based on simulated Michel electron events, as described above. Figure 4.21 illustrates an example of a triggered event captured during a live run on the

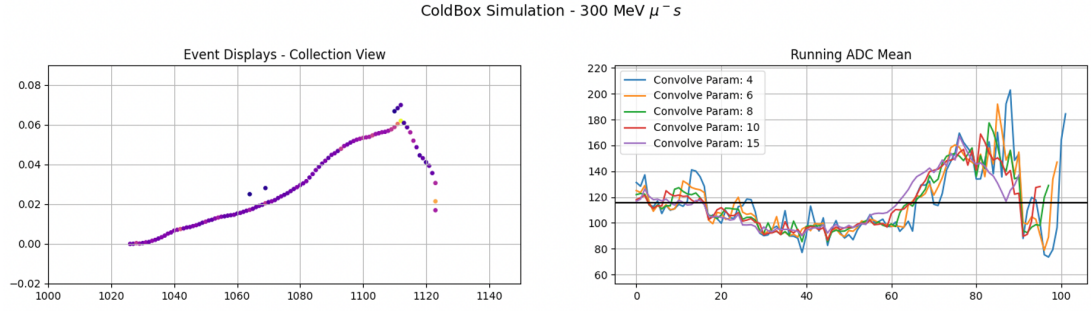


Figure 4.19 *A simulated stopping muon within the VDCB, using the LArSoft event generation framework. Simulated TPs are generated from the ADC deposits on channel strips. The equivalent event display for those TPs is shown (left). By tracing the running mean ADC of the track of TPs on the left, one can use a convolution parameter in an attempt to identify a potential Bragg peak at one end of the HMA-triggered track (right). The x-axes represent arbitrary collection channel IDs, whereas the y-axes are in arbitrary time units (left) and ADC units (right).*

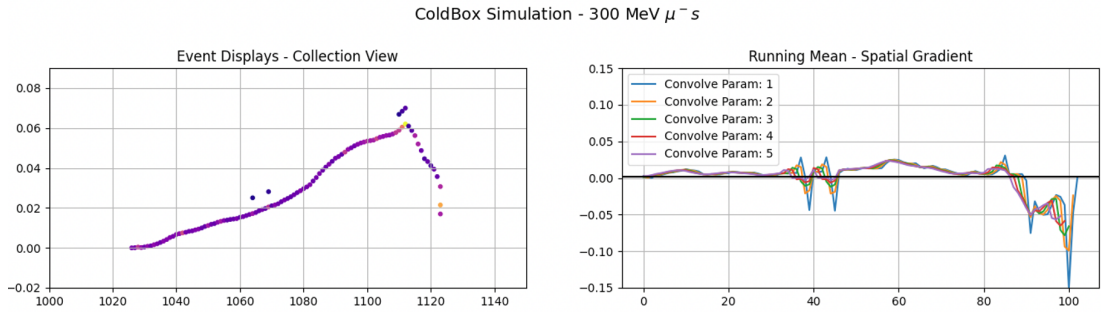


Figure 4.20 *A simulated stopping muon within the VDCB, using the LArSoft event generation framework. Simulated TPs are generated from the ADC deposits on channel strips. The equivalent event display for those TPs is shown (left). By tracing the spatial gradient of the track of TPs on the left, one can use a convolution parameter in an attempt to identify a potential kink at one end of the HMA-triggered track (right). The x-axes carry arbitrary collection channel IDs, whereas the y-axes are in arbitrary time (left) and spatial gradient (right) units. The spatial gradient is taken with respect to the collection channel view/direction.*

VDCB, using this dedicated stopping muon and Michel electron trigger algorithm [66]. This event shows a clear kink in the leading (top) track and a sharply increasing energy deposition toward the location of that kink, characteristic of a Bragg peak.

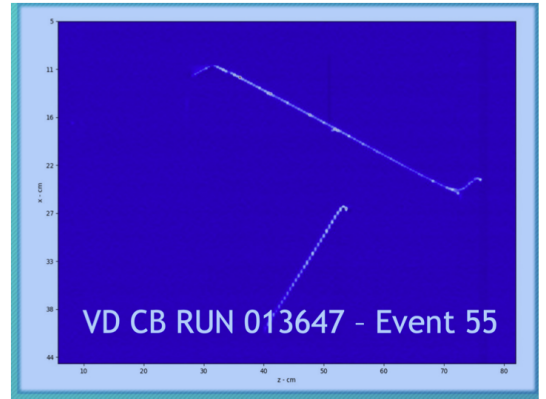
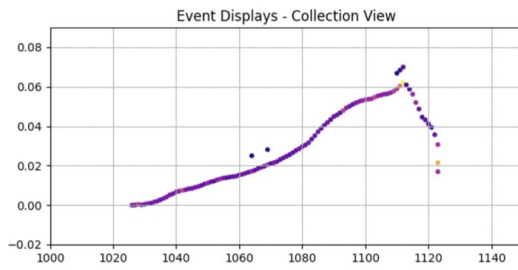


Figure 4.21 *A candidate stopping muon, Michel electron event, captured with the proof of concept algorithm based on the horizontal muon algorithm at CERN using further kink and Bragg peak checking [66].*

Chapter 5

Machine Learning for Neutrinos

This chapter will introduce Machine Learning (ML) in the context of neutrino experiments and introduce the `XGBoost` [73] python ML library, from which the Boosted Decision Tree (BDT) models were trained for the event selection process described in the main analysis of this thesis.

5.1 Machine Learning Overview

ML is a subcategory of Artificial Intelligence (AI). Where AI includes the simulation of human intelligence, wholesale, ML specifically refers to a model that *learns* from input data, without additional programming logic. AI is a large field which is currently contributing to many areas of research. Specifically, the sub-field of ML and Deep Learning (DL) within that have been demonstrated to be efficient tools in computer vision for particle physics experiments [74][75]. One such type of Artificial Neural Network (NN) is the Convolutional Neural Network (CNN), falling under the DL category, and makes use of a convolution operation on the input images to learn abstract features used for tasks such as classification or image segmentation. Since the advent of CNNs [74], and their dominance over the ImageNet challenge in 2012, 2014 [76][77][78], research into the use of these specific NN architectures for particle identification in particle physics detectors has been a very active area of research [79][80][75]. Indeed, current tools have been shown to outperform existing traditional non-ML-based reconstruction methods [81] and older ML techniques [82] in particle physics experiments.

5.1.1 Machine Learning in Particle Physics

Machine learning techniques provide a large number of uses in particle physics experiments. One of these is within the event simulations. Simulations of experiments are crucial to study the expected outcome of experiments before comparing them with observed data. Many of these simulations include the scintillation light of the detector-specific medium. This scintillation light is well known to be very computationally expensive and compromises have to be made for the simulations to be completed in reasonable time [83]. Generative Adversarial Networks (GANs) are ML tools where two or more NNs are trained against each other, to generate input that could plausibly be accepted by a discriminator tool and classified. The use of GANs has been studied to reproduce the effects of the current lookup library method for predicting the results of a full photon simulation [84]. Note that alternative methods to ML techniques which make predictions for the quantity of photon production in liquid argon to a precision of 10% are also given in [83]. These models are also reported to be useful for the simulation of that light in alternate mediums such as xenon. Most notably, the use of ML techniques for particle identification has been exploited in the MicroBooNE [85], NOvA [79] and DUNE [75] experiments. All of the above have used some variation of a CNN, which is an ML algorithm that learns to extract abstract, image-like features within the input images to perform a prediction or classification task. Further details on those are given in Appendix B.

5.1.2 Lepton Energy Reconstruction - Boosted Decision Trees

An example application of a Boosted Decision Tree (BDT), which is a different concept from a NN is described here. A BDT is an ML algorithm that learns a hierarchy of decisions based on a set of input features to perform a classification task. This hierarchy is what forms the tree structure. An application to the task of lepton energy reconstruction is discussed in the context of TITUS [86], a proposed intermediate-baseline, 2.1 kton water Cherenkov light detector to Hyper-Kamiokande. However, it could be applied to other more general geometry water Cerenkov detectors. The performance of the BDT was compared to a standard lookup method and to a standard NN from the Keras 1.2.2 library [86],

among other ML methods.

A total of 100000 generated images were used to train the ML tools, where 70000 were used for training and 30000 for testing. The Scikit-Learn BDT used the least absolute deviation estimator, which minimises the sum of absolute values between the true and predicted values. The BDT was observed to perform better than the lookup method across the entire energy range considered, for both muon and electron-type events. The performance is measured in terms of the fractional energy residual, given by $\Delta E/E = (E_{Rec} - E_{True})/E_{True}$. Here, E_{Rec} is the reconstructed lepton energy from the reconstruction method, and E_{True} is the true MC simulated lepton energy. The results for the various methods studied are summarised in Table 5.1, which show the mean fractional energy residuals, μ , and their respective resolutions for both sides of a fit to a bifurcated Gaussian, σ_L and σ_R , for left and right, respectively. The negative signs on all but one of the results indicate the tendency for energy reconstruction methods to underestimate the true lepton energies. The best energy resolutions were given by the BDT method, which not only largely outperforms the lookup methods but also provides better results than NNs. Separate analyses were performed for events within the energy ranges 200 - 600 MeV (where the bulk of neutrino events would be observed for TITUS) and 600 - 1400 MeV. It is the Scikit-Learn BDT that gives the best overall performance for lepton energy reconstruction.

Table 5.1 *Performance metrics of the methods used to reconstruct muon energies in the proposed TITUS intermediate-baseline detector for the energy range 200–600 MeV. Values represent the mean, μ , the left, σ_L and right, σ_R core resolutions, for each side of the fit distributions with respect to the fractional energy residuals, $\Delta E/E$. Reproduced from [86].*

Method	μ	σ_L	σ_R
Scikit-Learn BDT	$-0.48 \pm 0.04\%$	$2.86 \pm 0.02\%$	$3.39 \pm 0.03\%$
TMVA BDT	$-0.54 \pm 0.04\%$	$2.95 \pm 0.03\%$	$3.53 \pm 0.03\%$
Tensorflow NN	$-3.80 \pm 0.10\%$	$3.52 \pm 0.09\%$	$5.28 \pm 0.06\%$
TMVA NN	$-4.32 \pm 0.14\%$	$4.26 \pm 0.16\%$	$9.42 \pm 0.16\%$
Lookup Tables	$2.39 \pm 0.16\%$	$6.28 \pm 0.12\%$	$5.30 \pm 0.18\%$

In summary, the BDT is easy and fast to train, and outperforms all other methods considered here. It took 309 seconds to train on a commonly available 2.90 GHz dual-core Intel i5 processor. It is also easily implemented in other more general detector geometries. The results quoted here for Scikit-Learn BDT are comparable to the nominal ones produced by the likelihood function

techniques, which are reported by Super-Kamiokande [87]. A further enhanced BDT modelling ML library called **XGBoost** will be used in the main analysis of this thesis.

5.2 XGBoost BDT Models

The main cross section analysis described in this thesis has made extensive use of the eXtreme Gradient Boosting (**XGBoost**)[73] ML models to apply some form of threshold cut or classification for the event selection procedure. This section will outline what **XGBoost** is and give a description of the BDT ensemble models used below.

5.2.1 XGBoost Overview

XGBoost is a popular machine learning algorithm that is used for supervised learning tasks, particularly for classification and regression problems. It belongs to the family of gradient boosting algorithms, which are ensemble learning techniques that build a strong predictive model by combining multiple weak learners (typically decision trees, which are used here) sequentially. Similarly to random forests, **XGBoost** models typically combine the predictions of multiple weaker decision trees, to obtain a stronger prediction overall. The difference between the two is that whilst random forests have many trees in parallel, **XGBoost** performs a technique called *boosting* on the set of trees in series.

Boosting: Suppose an ensemble of decision trees is made out of just two, t_1 and t_2 . **XGBoost** trains t_1 first, and a loss is obtained for the predictions of t_1 , $l(t_1)$. The next tree is then trained and combined into an ensemble of trees, $T = t_1 + \eta t_2$, and this second tree is trained such that $l(T) < l(t_1)$, using the gradient of the loss, with respect to the *previous* model's output. Here, η is a hyperparameter called the *learning rate*. It is in this way that the boosted ensemble of trees is created in the training of an **XGBoost** model. The number of trees used determines the number of iterations or *boosting rounds* to use when training the ensemble model.

Gradient Boosting and XGBoost

The key difference between normal gradient boosting and **XGBoost** are outlined as follows:

- Regularisation: **XGBoost** incorporates L_1 (lasso) and L_2 (ridge) regularisation to prevent overfitting, whereas traditional gradient boosting typically does not.
- Efficiency: **XGBoost** uses optimised data structures, such as block-sparse formats, and processes data in batches to speed up computation. It also employs techniques like feature importance ranking, which will be used in the analysis presentation below, and column subsampling to improve performance.
- Handling Missing Data: **XGBoost** can inherently handle missing values, determining optimal splits even when some data points are missing.

Loss Function

For classification tasks, such as those described in Chapter 6, **XGBoost** typically uses a binary logistic loss function. This function models the probability of a sample belonging to the positive (signal) class ($y = 1$) using a logistic function. The predicted probability for a given sample is expressed as:

$$p = \frac{1}{1 + e^{-f(x)}},$$

where $f(x)$ represents the output of the ensemble model for the input features x . The binary logistic loss is defined as:

$$L = -\frac{1}{N} \sum_{i=1}^N [y_i \log(p_i) + (1 - y_i) \log(1 - p_i)], \quad (5.1)$$

where y_i is the true label, p_i is the predicted probability for the i -th sample, and N is the total number of samples. This loss function informs the optimisation process by quantifying the discrepancy between the predicted probabilities and the true labels, which should be either 0 or 1 for a binary classification task. The

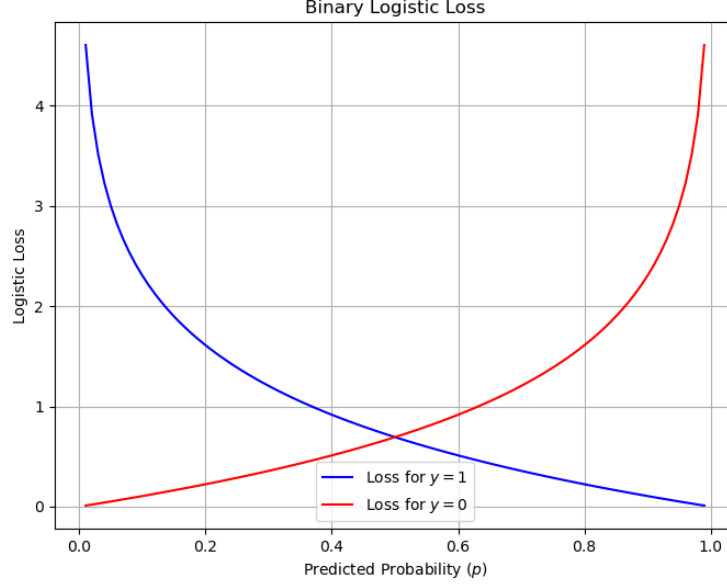


Figure 5.1 *XGBoost* loss function used for training the binary classification models used in this thesis. This is the binary logistic loss function, as in Equation 5.1.

loss function(s) for true positives ($y = 1$) and true negatives ($y = 0$) are shown in Figure 5.1.

Optimisation Procedure

The optimisation process in **XGBoost** builds trees sequentially to minimise the overall loss function. At each step t , the algorithm computes the gradient ($g_i = \frac{\partial L}{\partial f(x_i)}$) and the second-order derivative ($h_i = \frac{\partial^2 L}{\partial f(x_i)^2}$) of the loss with respect to the model output for each training sample i . Using these derivatives, the algorithm constructs a new decision tree that reduces the loss by fitting to the gradients.

The objective function at each step includes both the loss and a regularisation term:

$$\text{Obj} = \sum_{i=1}^N L(y_i, f_t(x_i)) + \Omega(f_t),$$

where $\Omega(f_t) = \gamma T + \frac{\lambda}{2} \sum_{j=1}^T w_j^2$ is the regularisation term, penalising the complexity of the tree. Here, T is the number of leaves, w_j are the leaf weights, γ controls the penalty on the number of leaves, and λ controls the penalty on leaf

weights. The new tree is added to the model:

$$f_{t+1}(x) = f_t(x) + \eta \cdot f_{\text{new}}(x),$$

where η is the learning rate.

Hyperparameters

Several key hyperparameters control the behaviour of **XGBoost** models during training:

- **Learning Rate (η):** This parameter scales the contribution of each new tree to the ensemble, helping to prevent overfitting. Typical values range from 0.01 to 0.3.
- **Max Depth:** The maximum depth of each tree determines its capacity to capture patterns. Deeper trees can model more complex patterns but risk overfitting. Common values are between 3 and 10.
- **Number of Estimators:** This specifies the number of boosting rounds (the number of trees). A higher value increases model capacity but also training time.
- **Regularisation Parameters (λ, α):** These control L_2 and L_1 regularisation on leaf weights, respectively, to reduce overfitting.

For the models that were trained for this analysis, all but the regularisation parameters above were varied from their defaults. The default values for λ (1) and α (0) were found to already be optimal for the classification tasks, where any deviation resulted in worse performance, for all tasks.

5.3 Training Approach and Features

In a given framework, a full Monte Carlo (MC) simulation sample has been reconstructed for analysis. For each event, a set of N reconstruction variables that could be used as features for training, $\{x_1, x_2, \dots, x_N\}$ is provided. Since it is MC, one also has access to the truth-level information as target labels for the data.

Label the data in a binary fashion, as signal or background, and denote those labels $\{s, b\}$. The **XGBoost** binary classifier is now provided with the training features $\{x_i\}$ and the truth (target) labels $\{y_i\}$ so that it will return a score in $[0, 1]$ for each event, indicating how signal-like that event is. Since the model uses the reconstruction variables only, the trained model can now provide a score for each real data event, indicating how signal-like that event is. **Note:** This approach to training models *does* imply a model-dependent result if used in an analysis, since it will make BDT score-based cuts which have been produced by a model trained on Monte Carlo simulation, which uses theoretical modelling.

Table 5.2 provides a complete listing for the training features used in the training of all models described in Chapter 6. Angles are given with respect to the NuMI beam direction. This may be used to cross reference with any feature importance plots or model descriptions that follow. Those variables that were of the highest importance to each classification task are described in greater detail in the following chapter.

Table 5.2 *XGBoost BDT training features used in this thesis with brief descriptions.*

Training Feature	Brief Description
<code>muon.energy</code>	Reconstructed energy of the assumed muon in the event (longest reconstructed track).
<code>trk.bragg_mip</code>	Track Bragg likelihood, MIPP.
<code>n_protons_tot</code>	Total number of reconstructed protons in the event.
<code>muon.candidate_pid</code>	PID score for identifying the muon candidate track, based on energy loss profile.
<code>muon.candidate_end_y</code>	Reconstructed y -coordinate of the end-point of the muon candidate track.
<code>muon.candidate_end_x</code>	Reconstructed x -coordinate of the end-point of the muon candidate track.
<code>muon.candidate_end_z</code>	Reconstructed z -coordinate of the end-point of the muon candidate track.
<code>trk1.theta</code>	Polar angle of the longest reconstructed track relative to the beam direction.

Continued on next page...

Training Feature	Brief Description
trk2_theta	Polar angle of the second-longest reconstructed track relative to the beam direction.
trk_bragg_mu	Track Bragg likelihood, for muons.
muon_theta	Polar angle of the reconstructed muon.
muon_phi	Azimuthal angle of the reconstructed muon.
contained_fraction	Fraction of the muon candidate track hits contained within the fiducial volume, to all hits in slice.
bdt_numuCC	Existing BDT score for identifying $\nu_\mu/\bar{\nu}_\mu$ charged current interactions.
n_showers_contained	Number of contained electromagnetic showers in the event.
topological_score	Score indicating the consistency of the event topology with expected neutrino interactions compared to cosmic-induced events.
trk1_phi	Azimuthal angle of the longest reconstructed track.
crtveto	Cosmic ray tagger veto flag, indicating possible cosmic ray contamination.
trk2_calor	Calorimetry information for the second reconstructed track.
trk_phi	Azimuthal angle of first reconstructed track.
_opfilter_pe_beam	Optical filter value indicating photoelectron counts in the beam region.
trk1_end_x	Reconstructed x -coordinate of the endpoint of the first reconstructed track.
_closestNuCosmicDist	Distance between the reconstructed neutrino vertex and the nearest cosmic track.
trk_chimu	Assessment of energy-loss matching to that expected of a muon.

Continued on next page...

Training Feature	Brief Description
<code>bdt_cosmic</code>	BDT score for identifying cosmic-ray-induced events.
<code>_opfilter_pe_veto</code>	Optical filter value indicating photoelectron counts.

All the **XGBoost**-based classification tasks in the main analysis of this thesis use an independent sample of 1,137,966 MC generated events, and 3,211,097 cosmic-induced events. Each model used an 80:10:10 split of the datasets for the training, testing and validation sets respectively, as per the standard practice in ML. Additionally, the hyperparameters were chosen based on a coarse grid search, using sklearn’s **GridSearchCV** tool [88].

This concludes the introduction to **XGBoost** BDT models, where the following chapters will elaborate on their use in much greater detail in the event selection chapter below.

Chapter 6

Event Selection: CC ν_μ and CC $\bar{\nu}_\mu$

This chapter will describe the event selection process for the reported measurements of inclusive CC ν_μ and CC $\bar{\nu}_\mu$ cross sections on argon. The signal definition for this selection is a charged-current muon neutrino *or* antineutrino event, that occurs within the fiducial volume of the MicroBooNE LArTPC, with an outgoing μ^-/μ^+ energy of at least 200 MeV.

A description of the samples used in the analysis is given, which includes a set of simulation and data reconstructed events. The event selection in particular is broken into two parts: (1) General and (2) ML-based selection requirements. The general event selection requires a single reconstructed neutrino per event from the reconstruction framework and applies several additional requirements to ensure high quality reconstructed data. The second stage uses three **XGBoost** ML models [73] to further purify the selected samples. The first model is used to efficiently remove cosmic activity, which forms a significant background to the outgoing muons in charged current muon neutrino interactions. The second is a generic background model, which is developed to clean the sample of the remaining neutrino event backgrounds. Finally, the third model, which attempts to separate the CC $\bar{\nu}_\mu$ from CC ν_μ in the selected signal sample, is described. The resulting split samples are then used in the cross section calculation framework which is the subject of the following chapter.

6.1 Simulation and Reconstruction at MicroBooNE

In general, a neutrino cross section measurement requires a good understanding of the backgrounds present in the data, such that their expected frequencies can be modelled and thus discounted from the event counts in the final selected sample. This section describes the simulation and modelling of the *expected* reconstructed data sample, in terms of signal neutrino interactions and backgrounds.

A cross section (σ) for a given particle interaction type represents the probability for that interaction to occur. It can be calculated using Equation 6.1

$$\sigma = \frac{N}{\phi N_t}, \quad (6.1)$$

where N is the total true number of signal interactions that occur and ϕ is the total incident flux of particles on a target to interact with. N_t is the number of targets exposed to ϕ which will represent nucleons within argon nuclei in the current case.

6.1.1 Predicted NuMI Flux

Dedicated simulation neutrino event generators, such as GENIE [89], accept as input an expected neutrino flux for the detector volume. They use theoretical neutrino cross section models alongside this flux to generate different types of neutrino interactions with their respective probability distributions and energies, within the detector volume. A full description of the simulated flux, for each neutrino type, as a function of their parent hadron from the NuMI target is given in Figure 3.16. This analysis is interested in selecting muon neutrinos and antineutrinos, and so the total fluxes for those neutrino types, and the electron flavour, from the NuMI beam in RHC (antineutrino) mode, are shown in Figure 6.1.

This figure shows the expected flux which has been constrained by the PPFX software package, as described in Chapter 3. The fractional contribution from the electron variety are largely dominated by the decay of stopping muons, which emit Michel electrons with a very well understood energy spectrum under 60

MeV. The sharp peaks within single bins arise from 2-body decays at rest from the neutrino parents. In particular, for the ν_μ , the single-bin peak at [230, 240] MeV corresponds to the 2-body decay of positive kaons $K^+ \rightarrow \mu^+ + \nu_\mu$, as given in Table 3.1. This figure represents the input flux that was provided to GENIE v3.0.6 for the simulation of neutrino interactions used in this analysis.

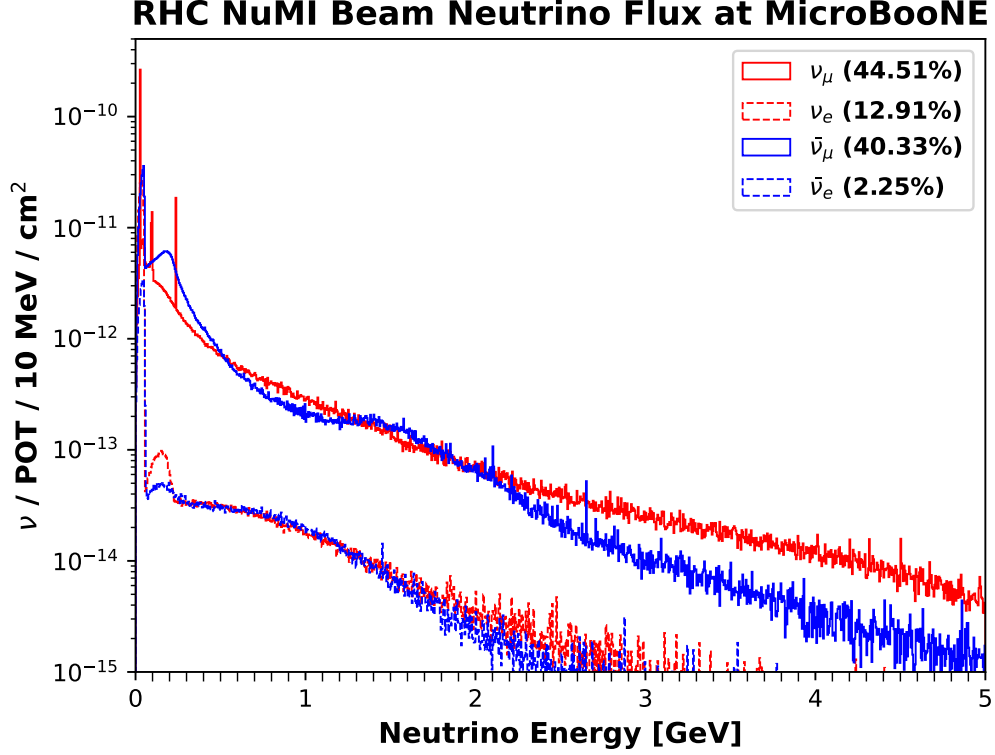


Figure 6.1 *Simulated flux of neutrinos to be observed by the MicroBooNE LArTPC due to the NuMI beam operating in RHC (antineutrino) mode. The fluxes are given as functions of the incoming neutrino energy, in GeV.*

GENIE - Cross Section Models

The GENIE software package is a tool for simulating neutrino interactions [89]. It is highly configurable, allowing users to provide specific input fluxes, target materials, and custom detector configurations. The cross section models used in the sample production for this analysis are the following:

- **Quasi-Elastic (QE)** The quasi-elastic cross section model uses one that focuses on intra-nuclear effects of neutrino interactions, the Nieves theoretical

model [90][91]. It includes the Random Phase Approximation (RPA), Final State Interaction (FSI) considerations and Coulomb corrections for the outgoing lepton. The RPA recognises that the weak couplings of nucleons within nuclei may be different from their free nucleon values, due to the strong interactions binding the nucleus together. Whilst the charge coupling is guaranteed to be conserved by the conservation of vector currents, it is possible for other weak couplings to change from their free form values. The FSI considerations refer to the interactions of the neutrino-daughter particles which can interact within the nucleus before exit, and the Coulomb corrections account for the momentum changes for the outgoing leptons. Further details on the nuclear effects on neutrino-nucleus interaction cross sections can be found in section 2.3.1.

- **Resonant Production (RES)** Resonant interactions can produce pions in the final state, and **GENIE** uses the Berger-Sehgal (BS) [92] and Kuzmin, Lyubushkin and Naumov (KLN) [93] models to describe them. The BS model incorporates the lepton mass into the cross section calculation, where the lepton mass effects the pion production rate, which in turn effects the total cross section for this process. In addition, the lepton flavour (electron or muon) have a large mass difference, and so at relatively low energies, ~ 1 GeV, the lepton mass effects are particularly pronounced. The BS approach uses the same formalism as the KLN model, which similarly incorporates lepton mass and spin in the cross section modelling.
- **Coherent (COH)** The cross section modelling for coherent pion production uses the Berger-Sehgal model [94]. This model uses the partially conserved axial vector current (PCAC) hypothesis to describe pion production when a neutrino is of low enough energy to interact with the nucleus as a whole.
- **Deep Inelastic Scattering (DIS)** Uses the Bodek-Yang (BY) model for neutrino interactions where the energies are high enough to resolve the internal quark-structure of nucleons, within the argon nuclei. The parton distribution functions (PDFs) are modified in such a way as to include lepton inelastic scattering cross sections to the GRV94 modelling [95] for DIS interactions.

6.1.2 Cosmic Background and Modelling

The constant bombardment of the MicroBooNE LArTPC with cosmic ray muons at ground-level means that searching for charged current muon neutrino or antineutrino interactions is especially difficult. The cosmic muons form a significant background portion of the signal selected data sample. This is because upon beam-spill, where only 2-3% of spills will induce a neutrino interaction within the detector, the software triggering system threshold can be exceeded by the presence of coincident cosmic activity producing scintillation light within the SW Trigger window, see Figure 3.18. The stored data is passed to the reconstruction framework which can survive the neutrino reconstruction search owing to the likely presence of a muon, which is a signature of the interactions of interest.

In order to best account for potential cosmic activity that can induce a successful trigger to readout, a large sample of data from the MicroBooNE LArTPC was taken during *Beam-Off* mode. In MicroBooNE nomenclature, this is also referred to as *External* events, or EXT. By issuing data-readout triggering commands whilst the beam is off, a large sample of what cosmic-triggered data events look like can be collected, and can be used to help rejection during the event selection of the data. This will in fact be the first use of an **XGBoost** model in section 6.4. In particular, the Run 3 period for MicroBooNE had been upgraded to use the Cosmic Ray Tagger (CRT), described in section 3.3, for which the related variables are included in the reconstruction chain and will aid the ML model separation of EXT from signal neutrino events.

In terms of simulating cosmic activity that can be coincident with a true neutrino interaction within the detector, MicroBooNE again uses a data-driven approach. It overlays data taken whilst the beam is off with the simulated neutrino interactions from **GENIE**. For this reason, the main Monte Carlo simulated neutrino interaction samples are called *Overlay* samples in MicroBooNE nomenclature [48].

6.1.3 Full Simulation Chain

Once a model of the neutrino flux observed by the detector has been established, it can be used to generate full simulation samples which are representations

of the neutrino interactions expected to be observed in the data collected whilst the beam is on. A detailed simulation is important for estimating the background content of the final selected signal samples. This is so that those background event counts can be subtracted from the total selected data event counts, before calculating a flux-integrated cross section. The simulation is also a requirement for performing supervised learning with the **XGBoost** BDT models. As described in section 5.2.1, the training of these models requires the input of reconstruction-based variables, *and* the MC truth-level information to provide target classification labels for each event.

Each stage of the simulation is carried out by a simulation and reconstruction framework, especially designed for liquid argon experiments. This software framework is called **LArSoft** (Liquid Argon Software) [72]. A complete outline of the steps for the simulation and reconstruction are as follows:

1. **Neutrino Interaction Generation (GENIE)**: As mentioned above, **GENIE** v3.0.6 was used to generate the neutrino interactions for the simulation samples in this thesis. **GENIE** accepts as input the predicted flux, and samples that flux to select a possible neutrino. It then uses a configured set of theoretical cross section models combined with the detector geometry description (the materials and shapes of them that compose the detector) to define the interaction mode. **GENIE** also then defines the daughter particles of this interaction and their kinematics, information which is used in the following simulation step.
2. **Particle Propagation (GEANT4)**: Geometry And Tracking version 4 (**GEANT4**) is a widely used tool in particle physics, which simulates the propagation of particles of given energies and momenta through a pre-defined geometry of materials. In this case, the geometry corresponds to the MicroBooNE LArTPC detector (and surrounding cryostat) and the information passed from the previous step is used to simulate a comprehensive list of physics processes which occur during particle propagation. That list is referred to as **QGSP_BERT**. This is a reference physics list provided by **GEANT4** which is routinely monitored and updated with each new release. **GEANT4** propagates the daughter particles, step-wise through the detector geometry, where the deposited energy per unit length is tracked and spent to create drifting ionisation charge deposits and scintillation light, for detection.
3. **Detector Response**: The third step in the simulation chain accepts input

from the **GEANT4** step to simulate the response of detector TPC sense wires and PDS to the ionisation charge and scintillation light, respectively. This simulation is configured based on the settings of the front-end, cold electronics ASICs, which use a gain of 14 mv/fC and shaping time-constant of 2 μ s in MicroBooNE. The addition of noise to the electronic signals is also simulated at this stage.

4. **Signal Processing:** Following the detector response simulation, which produces electronics signals sensed and shaped by the TPC and PDS electronics, the simulation dataset is now equivalent to the real data recorded by the TPC and PDS sub-systems. These raw waveforms are then processed into *hits*. The concept of a hit is analogous to the TPs that are formed in real time whilst the detector is online with the VDCB TPC prototype at CERN, described in chapter 4.

- (a) **TPC:** The raw waveforms first undergo 2D deconvolution. The dimensions here can be thought of as the number of signal-damaging effects considered in the deconvolving operation. Here, the first is electronics noise removal as usual and the second takes into account the ionisation diffusion effects described in chapter 3. After deconvolution, the resulting waveforms are now fit to be used for hit-finding. The waveforms are scanned, and Gaussian curves are fit where ionisation charge has induced a signal. In practice, this works far better for the unipolar collection wire signals, in contrast to the bipolar induction wire signals. These signal types are illustrated in Figure 3.11.
- (b) **PDS:** Similarly to the TPC signal processing, the PDS processing begins by searching for optical hits. To do this, the baseline of the ADC has to be monitored since fluctuations between hits can occur. Once the baseline has been established, a simple algorithm searching for the ADC exceeding a hit-finding threshold defines those optical hits. The second stage of PDS signal processing involves the search for optical *flash* objects. These are clustered and coincident hits across multiple PMTs of the MicroBooNE detector in the present case.

The hits and flashes produced for the TPC and PDS waveforms from this stage are the foundational units of information that are used for high-level event reconstruction and handled by the Pandora reconstruction framework in this thesis [67][96].

5. **Event Reconstruction (Pandora):** The final step in the simulation chain is the high-level event reconstruction. The information streamed from the LArTPC detector has been used to create hits and optical flashes, which are now passed to the Pandora multi-algorithm approach to search for and reconstruct neutrino events. All hits from the previous step serve as input to the first part of the Pandora chain called PandoraCosmic. Here, the hits provide 2D representations of particle activity, which are used to do 3D track reconstruction. All showers surrounding the track are assumed to be δ -rays, and the start point is assumed to be at the top of the detector, a large y coordinate, owing to the dominant vertical flux of cosmic ray muons. The resulting tracks are tagged, either as cosmic ray muons or not. Those that *are* tagged, have their associated hits removed from the event. The remaining hits serve as input to the next stage, PandoraNu. PandoraNu aims to reconstruct neutrino interactions. Regions of interest are searched for, and broken into event *slices*. A slice corresponds to a subset of data from the event, that could potentially be a neutrino interaction. A set of $O(100)$ algorithms process the hits, searching for tracks and showers. The result is a Particle Flow Particles (PFParticles) software object. Each neutrino slice has a vertex and a hierarchy of tracks and showers associated with it (each associated to a PFParticle), which each have properties such as dE/dx associated with them. An overview of the full event reconstruction phase is illustrated with flow charts in Figure 6.2.

From the start of step (4), both simulation and recorded data have the same input to the signal processing and even reconstruction steps. The result is a dataset of simulation and data, Pandora-reconstructed events. For the purposes of analyses in MicroBooNE, these are stored in ROOT ntuple files. The difference being that the GENIE simulated events have matching truth-level information, in the sense that the reconstructed properties of the simulated events can be cross-checked with the true particle activity that provided input to the chain.

6.1.4 Run 3b Samples

The analysis presented here uses samples corresponding to the run 3b working period of MicroBooNE, where the NuMI beam was in RHC configuration, see Table 3.2. This section will describe those samples that were used in the calculation of muon neutrino and antineutrino cross sections, that form the main

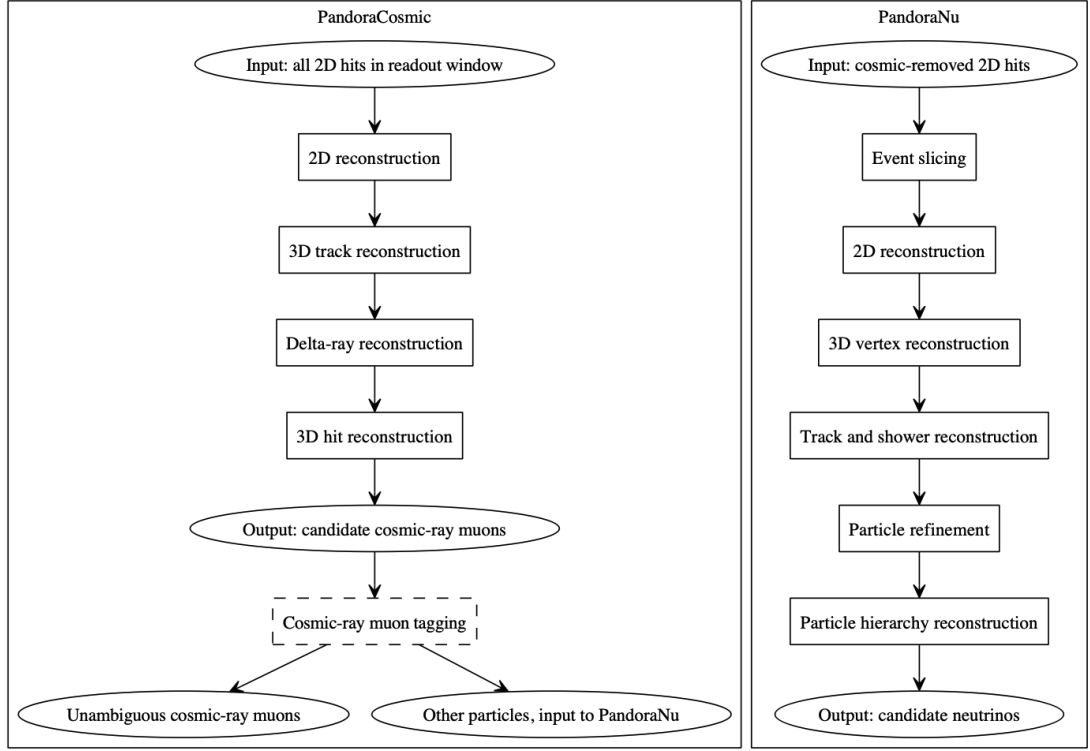


Figure 6.2 *Flow charts depicting an overview of the Pandora reconstruction chain, from input hits from step (4) in the main text, to the production of neutrino slices in step (5). All events are first passed to the PandoraCosmic processing first (left block), where surviving events (non-cosmic-tagged) are then passed to the PandoraNu workflow (right block) [96].*

results of this thesis. They include both data and simulation-based samples.

Signal Simulation

The neutrino event generator **GENIE** is used to produce neutrino interactions of the muon and electron variety inside the LArTPC, step 1 in section 6.1.3. The resulting simulation is overlaid with cosmic data taken whilst the beam was off. Recall that **GENIE** accepts as input the predicted flux of neutrinos for each flavour. From Figure 3.16, the flux exposure can be described in terms of the POT delivered to the NuMI target. In the case of run 3b, the equivalent simulated POT exposure was 2.644×10^{21} POT. Note that the effect of light yield decline, described in section 3.3.1, was incorporated into the simulation, and the sample had to be treated carefully, making a split in the dataset before and after subrun number 16880. This was done with the addition of a software triggering variable, both before (“pre-”) and after (“post-”) the scintillation threshold change.

Out-of-Cryostat (Dirt)

A type of background that has to be modelled is the interaction of neutrinos *outside* the cryostat, which can result in daughter particles entering the cryostat and leading to a software trigger. These are referred to as *Out-of-Cryostat* or *Dirt* events in MicroBooNE nomenclature, and in what follows. This is another GENIE simulated sample, which for run 3b used an equivalent exposure of 1.032×10^{21} POT.

Cosmic Activity (Beam-Off)

As described above, only 2% of the beam spills from NuMI will induce a neutrino interaction within the LArTPC. The remaining 98% of the time, it is entirely possible for cosmic activity to meet the requirements of the software triggering during the beamgate window, leading to a triggered event devoid of a neutrino interaction for analysis. The data-driven approach to deal with this is to record data whilst the beam is off, and use the number of events passing the SW trigger issued during empty HW triggers as a proxy for the *equivalent* POT delivered to the detector. This will be explained in detail below in the sample normalisation section. The number of HW triggers for the run 3b representative sample is 30123991.

Beam-On

The Beam-On sample corresponds to the data recorded when the NuMI beam was producing neutrinos, which the MicroBooNE detector was exposed to. The total POT for this sample was 5.0×10^{20} POT with 10,363,728 HW triggers.

There is an additional data selection filter for all of the above samples, which checks the quality of the sub-run periods within each run. This is known as the *good run* check. This check consists of:

1. Confirming the adequate performance of the data acquisition system.
2. Ensuring that reconstruction quality metrics, such as the number of mean reconstructed tracks throughout the run remains consistent.

3. Removing any sub-runs where there were known issues. For example, run 1 observed a noisy optical unit, resulting in erroneous triggers.

A summary of the samples used in this analysis, with equivalent triggers and POT, is given in Table 6.1. The equivalent POT and number of HW triggers are used to normalise the simulation and cosmic samples to the Beam-On data sample in the analysis. The total number of triggers for each sample is the sum of the triggers taken with the old threshold *before* the configuration change, and those taken with the new threshold *after* the threshold change at sub-run 16880. Additionally, the good run check has been applied. This means the summary table varies slightly from the raw unfiltered values stated above.

Sample Normalisation

In order to use these samples for a cross section analysis, the Overlay, Dirt and External samples each need to represent the same exposure as the Beam-On data sample. Since the neutrino flux exposure from the NuMI beam can be measured in terms of POT, the scaling factors for the Overlay and Dirt samples are simply given as

$$S_i = POT_{\text{Beam-On}}/POT_i \quad (6.2)$$

where i labels the simulated sample, and S is the factor by which all events will be weighted to match the Beam-On exposure.

In the case of normalising the cosmic sample, there is no actual or simulated POT value. Therefore, the number of issued HW triggers is used as a proxy for POT exposure, and so the scale factor for the cosmic sample, S_C , is given by

$$S_C = 0.98 \times HW_{\text{Beam-On}}/HW_C \quad (6.3)$$

The factor of 0.98 arises from the fact that one needs to remove the fraction of events that actually *are expected* to contain a neutrino interaction within the MicroBooNE LArTPC, due to the NuMI beam spill during a Beam-On data-taking run. This is approximately 2%, hence the multiplicative factor. To summarise, the normalisation factors, $\mathbf{S}$ for the relevant samples are also provided

in Table 6.1.

Table 6.1 *Run 3b analysis samples summary, showing the POT, HW triggers and event counts for each sample. The actual values are from the samples after having been processed for good run checks and taking the software-triggering-threshold change into account. Also shown are the normalisation scaling factors for each sample, used to enforce the equivalent representation of the Beam-On sample flux exposure.*

Sample	POT	HW Triggers	Event Count	S
Overlay (MC)	2.644×10^{21}	-	690825	0.18
Dirt	1.032×10^{21}	-	389264	0.44
External (Cosmic)	-	30123991	3211097	0.31
Beam-On (Data)	4.576×10^{20}	9460579	1104349	-

Analysis Topology Definitions

To proceed with the analysis, the event topologies that contribute to the data sample need to be clearly defined. These are:

- **Cosmic:** These are simply the reconstructed events that have originated from the beam-off sample, and lack MC truth-level information.
- **Dirt:** These events are MC simulation based, and correspond to all neutrino interactions that occur *outside* the cryostat, but the produced daughter particles have led to a SW trigger during a beam-spill. The remaining events are all neutrino interactions occurring inside the active volume of the LArTPC.
- **Neutral Current with Charged Pions (NC with $\pi^\pm$):** Neutral current neutrino interactions, that include at least one charged pion in the final state. These are represented separately from those NC events without charged pions, since they have very similar behaviour to muons in liquid argon, and therefore can form a significant background in the analysis.
- **Neutral Current (NC):** Neutral current neutrino interactions, that *do not* include a charged pion in the final state.
- **CC ν_e :** Charged current electron neutrino interactions. An interaction producing an electron in the final state.

- **CC $\bar{\nu}_e$:** Charged current electron antineutrino interactions. An interaction producing an positron in the final state.
- **CC ν_μ :** Charged current muon neutrino interactions. An interaction producing a muon in the final state. These will form part of the signal definition.
- **CC $\bar{\nu}_\mu$:** Charged current muon antineutrino interactions. An interaction producing an antimuon in the final state. These also form part of the signal definition.

The list of topology descriptions above provide a one-to-one mapping to those given in the legends of the stacked histogram distributions in the plots that follow.

Run 3b Sample

Figure 6.3 shows a stacked histogram of the Overlay, Dirt and Cosmic contributions for an equivalent NuMI POT exposure corresponding to run 3b of MicroBooNE. It is given as a function of reconstructed event energy. This sample has included the requirement of a single reconstructed Pandora neutrino slice, as described above. Overlaid onto this plot is the observed data (black) histogram. The topology definitions described above are included in the legend, and the bottom subplot displays the ratio of total observed data events per bin, to the summed simulation and cosmic contributions. This is simply referred to as Data / MC. Error bars in the top and bottom plots correspond to statistical uncertainties on the data, and the grey bands surrounding the line at $y = 1.0$ in the bottom subplot correspond to statistical uncertainty per bin on the MC and cosmic event counting. The reconstructed energy corresponds to the summed energy of all components of the slice reconstructed by Pandora, and is given in GeV. Initial observations of the sample show that the low energy portion (< 10 MeV) is overwhelmingly dominated by cosmic activity. This corresponds to low energy cosmic activity that has led to a SW trigger and a reconstructed neutrino slice.

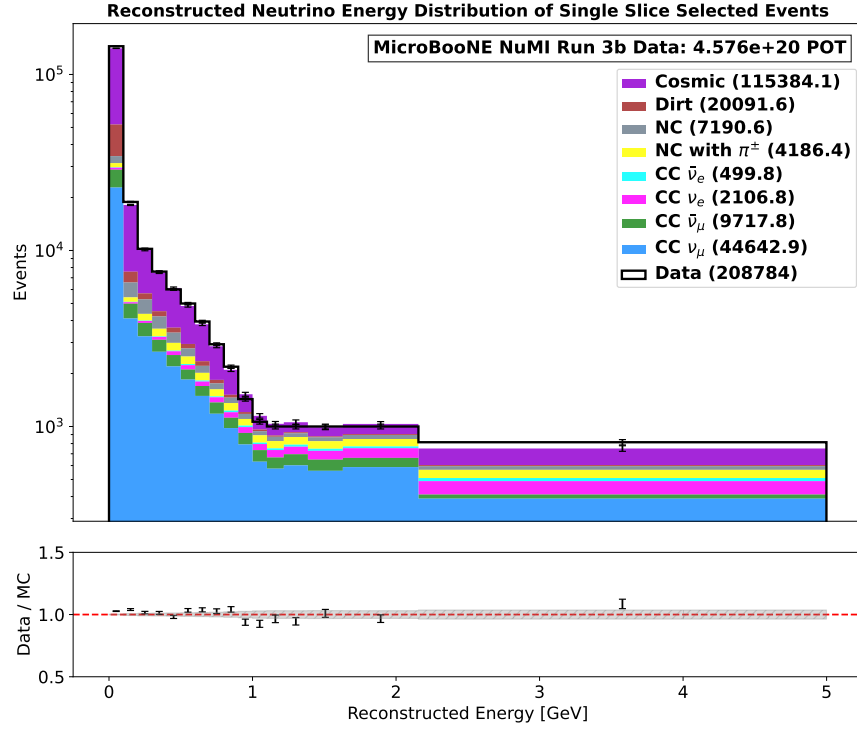


Figure 6.3 *Run 3b sample distribution as a function of reconstructed event energy in GeV, after a single neutrino slice requirement from the Pandora reconstruction. The event topology counts given in the legend have been normalised to the Beam-On POT exposure.*

6.2 General Neutrino Event Selection

This section will describe the general event selection requirements that were used in an attempt to obtain a sample that is relatively clean of cosmic contamination, and of high reconstruction quality such that it can be used for further analysis in the ML approach to neutrino and antineutrino separation. The signal definition at present is as follows:

Signal Definition: A charged-current muon neutrino or antineutrino event, that occurs within the fiducial volume of the MicroBooNE LArTPC, with an outgoing μ^-/μ^+ energy of at least 200 MeV.

The *fiducial* volume jargon requires some elaboration. In practice, reconstructing a neutrino interaction close to the boundaries of the TPC can be problematic. The SCE can distort interactions if it is near the sense wire planes or cathode. Or, the interaction can produce daughter particles which quickly escape the spatial boundaries of the TPC.

There are a total of 4 general event selection requirements. They are defined as follows:

1. **Single Neutrino Slice:** First, a requirement for a single reconstructed neutrino slice from the Pandora reconstruction framework. This is a clear necessity since a reconstructed event with a neutrino interaction vertex is needed to do any analysis with. The result of this requirement is the stacked distribution shown above in Figure 6.3.
2. **Fiducial Volume Vertex Containment:** Second, as mentioned above, it is important that the quality of reconstruction is good with regards to the neutrino interaction vertex and the daughter particles originating from that spatial location. For this reason, the candidate reconstructed neutrino vertex is required to be within 10 cm of the x , y and z coordinate boundaries of the MicroBooNE LArTPC.
3. **Reconstructed Muon:** Given that the signal events produce a muon in the final state, an additional requirement of at least one reconstructed muon-like track in the final state is made. This is done using several variables from the Pandora reconstruction output, as in other MicroBooNE analyses [46]. A long piece of activity with a track-score of at least 0.8 must first be identified. That track must originate within 4 cm of the interaction vertex, and be longer than 10 cm. The longest track-like object in the interaction slice is taken as a candidate muon.
4. **Reconstructed Muon Energy:** Finally, to ensure the best reconstruction quality is used, a reconstructed muon energy requirement of ≥ 200 MeV is made. Accurate event reconstruction below this region is notoriously difficult and would cause the cross section analysis to suffer large uncertainties here. This selection stage also helps largely to reject cosmic contamination, as can be seen from Figure 6.3.

The result of applying these 4 selection requirements on the initial sample is given in Figure 6.5. A summary of the signal efficiencies and purities, as a function of the selection requirements is given in Table 6.2. Note that the event counts correspond to all those satisfying the true signal definition above. This excludes events with true muon energies below 200 MeV, meaning that the counts *do not* match those in the stacked distribution plots, since those include events which have incorrectly been reconstructed with higher-than-true muon energies. The

counts are also normalised to the data POT exposure, such that they correspond to the expected total signal event counts within the data sample at each stage in the general selection process.

Table 6.2 *General selection requirements summary, showing signal event counts, efficiencies and purities as a function of each selection step. The values are given with respect to the signal definition events. Event counts have been normalised to the run 3b data-taking period NuMI POT exposure. The content of the selected sample is shown explicitly in Figure 6.5.*

Selection Requirement	Events	Purity (%)	Signal Efficiency (%)
Original Sample	36059.6	3.3	100.0
Single Neutrino Slice	30210.4	14.8	83.8
Vertex Containment	28640.2	27.5	79.4
Muon(s)	24879.7	33.8	69.0
Muon Energy	17604.3	45.7	48.8

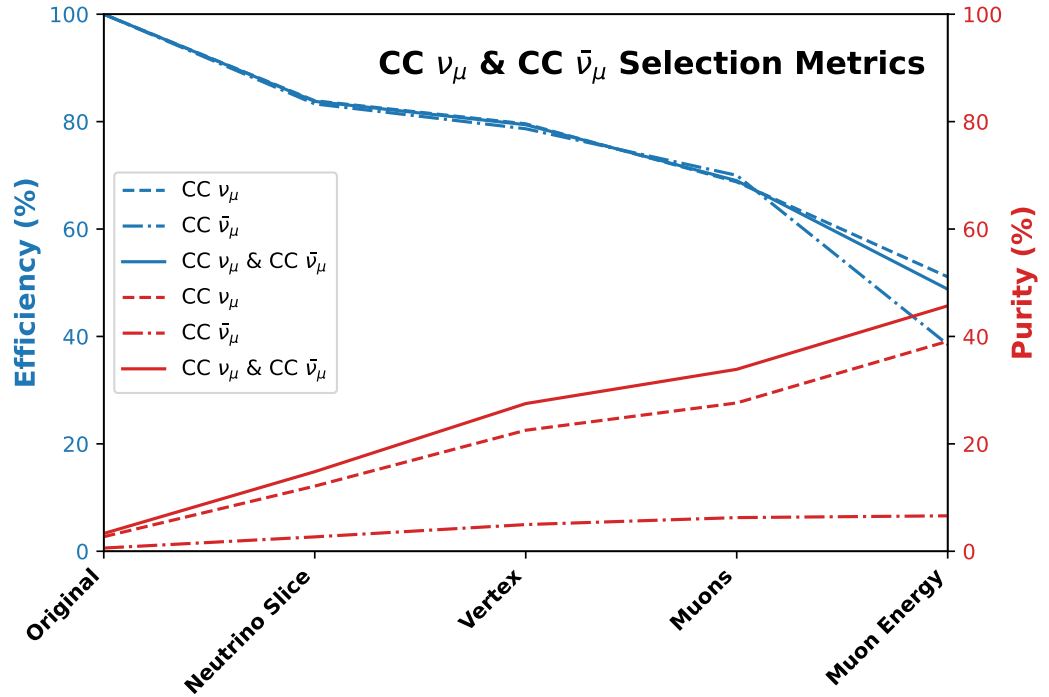


Figure 6.4 *Run 3b general selection requirement metrics, as a function of each selection step. Included are the signal efficiency (left) and purity (right) metrics for CC ν_μ and CC $\bar{\nu}_\mu$ individually, and their combination. It is observed that selection stages have similar impacts on the individual neutrino and antineutrino parts of the signal.*

Figure 6.4 complements Table 6.2 by plotting the signal efficiency and purity of

the separate CC ν_μ and CC $\bar{\nu}_\mu$ events, and their combination (the signal at this point) as a function of each of the basic selection requirements described here. The impact of each selection stage, on the efficiency and purity for both CC ν_μ , the CC $\bar{\nu}_\mu$ are very similar, illustrating that the general event selection process is not biased to either subset of events. The last selection stage, based on reconstructed muon energy does see a difference in the impact on efficiency of approximately 13%, which is suspected to be related to the difference in reconstruction quality of the neutrino and antineutrino events.

The sample represented in Figure 6.5 is the one that is used to continue the analysis. The next section will describe the novel use of ML techniques to further purify the sample of CC ν_μ and $\bar{\nu}_\mu$ events. It will also describe the consideration of several physics processes which can be used to train an XGBoost model for neutrino and antineutrino event separation.

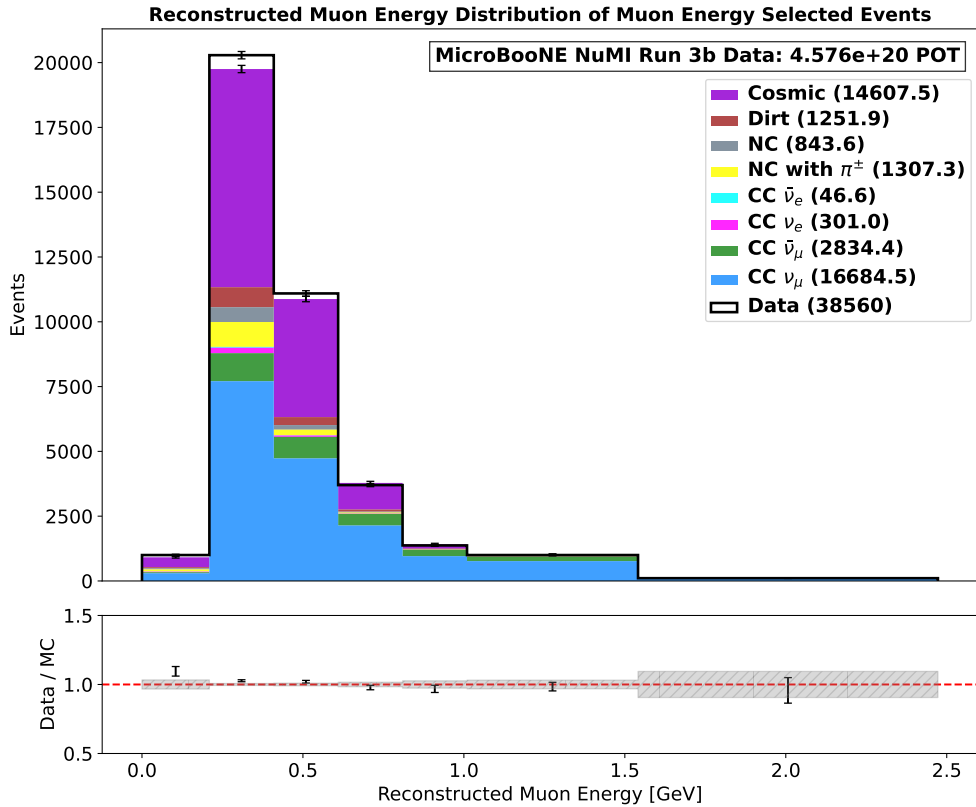


Figure 6.5 *Run 3b energy selected sample distribution as a function of reconstructed muon energy. All general selection requirements have been applied from the Pandora reconstruction variables. The event topology counts given in the legend have been normalised to the Beam-On POT exposure, providing an estimate of their respective contributions to the data sample.*

The composition of the background in the selected sample includes contributions from several sources that are not associated with ν_μ or $\bar{\nu}_\mu$ CC interactions. These background components are estimated as follows: electron neutrino and antineutrino CC interactions ($\nu_e\text{CC} + \bar{\nu}_e\text{CC}$) constitute 347.6 events, NC interactions with and without charged pions contribute 2,150.9 events, dirt interactions account for 1,251.9 events, and cosmic rays contribute a relatively large share of 14,607.5 events. Collectively, these backgrounds dominate the sample, with cosmic ray activity being the most substantial contaminant.

Given this composition, further purification of the sample is essential to enhance the signal-to-background ratio, particularly for this analysis focusing on ν_μ CC and $\bar{\nu}_\mu$ CC events. XGBoost-based BDTs are well-suited for this task due to their ability to handle complex classification problems. Using the reconstruction variables listed in Table 5.2, that describe event topology, kinematics, and detector response, XGBoost BDTs can effectively distinguish signal events from diverse background sources. Their robustness against feature correlations and overfitting, combined with efficient training and interpretability, makes them a powerful tool for achieving relatively pure ν_μ and $\bar{\nu}_\mu$ CC samples. This purification is crucial for minimising systematic uncertainties further downstream in the cross section analysis.

6.3 Boosted Decision Trees

The remaining part of the event selection stage of the analysis will be performed using several dedicated XGBoost BDT models, as mentioned above. In particular, there are three models used, corresponding to three classification tasks. They are as follows:

1. **Cosmic Removal:** The contamination of cosmic activity to the sample after the general selection requirements is still significant, approximately 39% of the total sample, see Figure 6.5. The first classification task is then dedicated to cleansing the sample of cosmic impurities.
2. **General Neutrino Event Background:** After cosmic removal, it can be seen that the large majority of the background to the CC ν_μ and CC $\bar{\nu}_\mu$ events are the NC events with and without charged pions, where the NC with pions make up 61% of the NC background. This classification task is

designed to remove muon (anti)neutrino event backgrounds in general.

3. **Neutrino and Antineutrino Separation:** Finally, and by far the most challenging task in this analysis, is the attempt to separate the resulting sample into CC ν_μ and CC $\bar{\nu}_\mu$ events, where they will each be used to calculate a cross section in the following chapter.

Each of these tasks will now be discussed in detail, with the resulting models and their performance in terms of training and making selection requirements for this analysis.

6.4 Cosmic Removal Model

As mentioned above, the vast majority of cosmic activity within a ground-level particle detector consists of vertical through-going muon tracks. It can then be anticipated that the important variables for training an **XGBoost** model to remove these events, should be related to the directionality of the reconstructed muon, in addition to the start and end positions of the tracks. Furthermore, recall that the run 3 period for MicroBooNE had upgraded to make use of the Cosmic Ray Tagger (CRT) which introduces a veto variable to the reconstruction chain. This essentially tags coincident through-going tracks using scintillation panels surrounding the cylindrical cryostat, with flashes contained within the beam-spill window, and so it is expected to be a very useful event feature for classification. A description of each of the most important training variables used for this model is given below, with a full breakdown of the model, including a plot of the relative importance of training variables.

Training Variables

The Pandora reconstruction variables that were expected to be useful for this model are:

- **Topological Score:** The topological score variable that is included in the standard reconstruction chain, is in fact the output of another ML model, specifically a Support Vector Machine (SVM). This score attempts to classify each Pandora neutrino slice within the event as either cosmic or

neutrino type, and so this should clearly help the first **XGBoost** model in this analysis. It varies in $[0,1]$, 0 being more cosmic-like and 1 more neutrino-like. The inputs to the SVM are entirely based on TPC information, and so are very reliable in comparison to scintillation-based variables.

- **CRT Veto:** This variable marks the presence of a coincident CRT hit with an optical flash during the beam-spill window. It is simply 0 or 1, where 1 indicates the presence of coincident signals.
- **Cosmic Flash Matching Score:** Flash matching scores are ratios of χ^2 -like variables. Flash matching takes the observed TPC information for a slice, and builds a model for the light that one would *expect* to see. There are models for both neutrino and cosmic slices. This means there are flash matching scores for both types, and the *ratio* of the two is the cosmic flash-matching score here. If the observed light model fits the cosmic hypothesis much better than the neutrino one, then there are grounds to reject the event as a cosmic impurity.
- **Track θ and ϕ :** The direction of the leading track in the neutrino slice will provide predictive power on whether this event was triggered by cosmic activity. That information is encoded in the spherical polar coordinates of the track, where θ is the polar and ϕ the azimuthal angles, which are given with respect to the BNB beamline direction, also the z direction of the MicroBooNE LArTPC.

It is important that the reconstruction-based variables used to train machine learning models in this analysis describe the data well, in order to have confidence in the use of those models for classification tasks such as this one.

For each model, the relative importance of each training variable will be shown graphically and the most important of those investigated with a data and simulation comparison. Feature importance in this context refers to the number of times the **XGBoost** model has used that variable to split the dataset during training time. This essentially indicates how *useful* that variable is in performing a classification task. All sample distributions shown are from the point that ML models were used in the analysis, i.e. from the point of the reconstructed muon energy cut.

The cosmic removal model shows excellent separation power and was trained on several variables, each included in the feature importance plot given in Figure 6.6.

As expected, the most important variables are those that relate to the topological score of the event, the cosmic flash-matching scores, the CRT veto tag and the directionality of the tracks contained within the event. These variables have been distributed for the simulation and data samples, and presented in Figure 6.8. All but the cosmic flash matching score show good agreement with data, and so an additional model was trained without the use of that variable. The adjusted feature importance for the updated model is given in Figure 6.7.

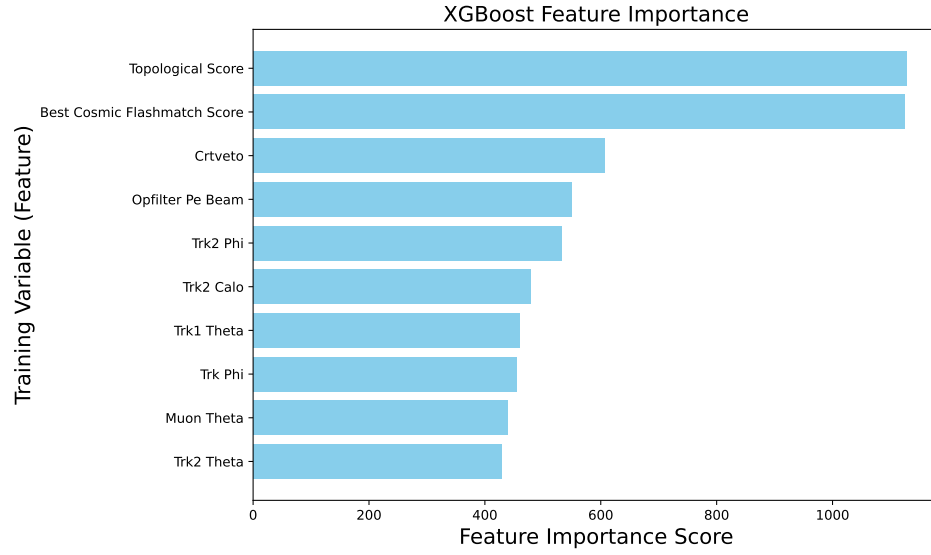


Figure 6.6 *A relative feature importance plot, demonstrating the reliance the cosmic removal **XGBoost** model has on the variables used to train it. Larger values correspond to a larger feature importance.*

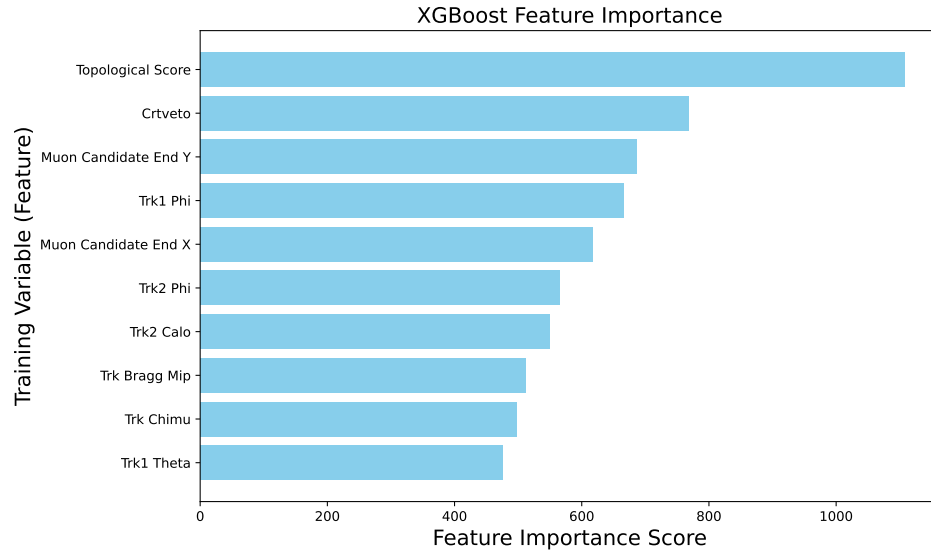


Figure 6.7 *A relative feature importance plot, showing the training variable importance for the retrained cosmic removal model after the cosmic flash matching score was removed. The model compensates by relying more on the CRT veto and track directionality variables.*

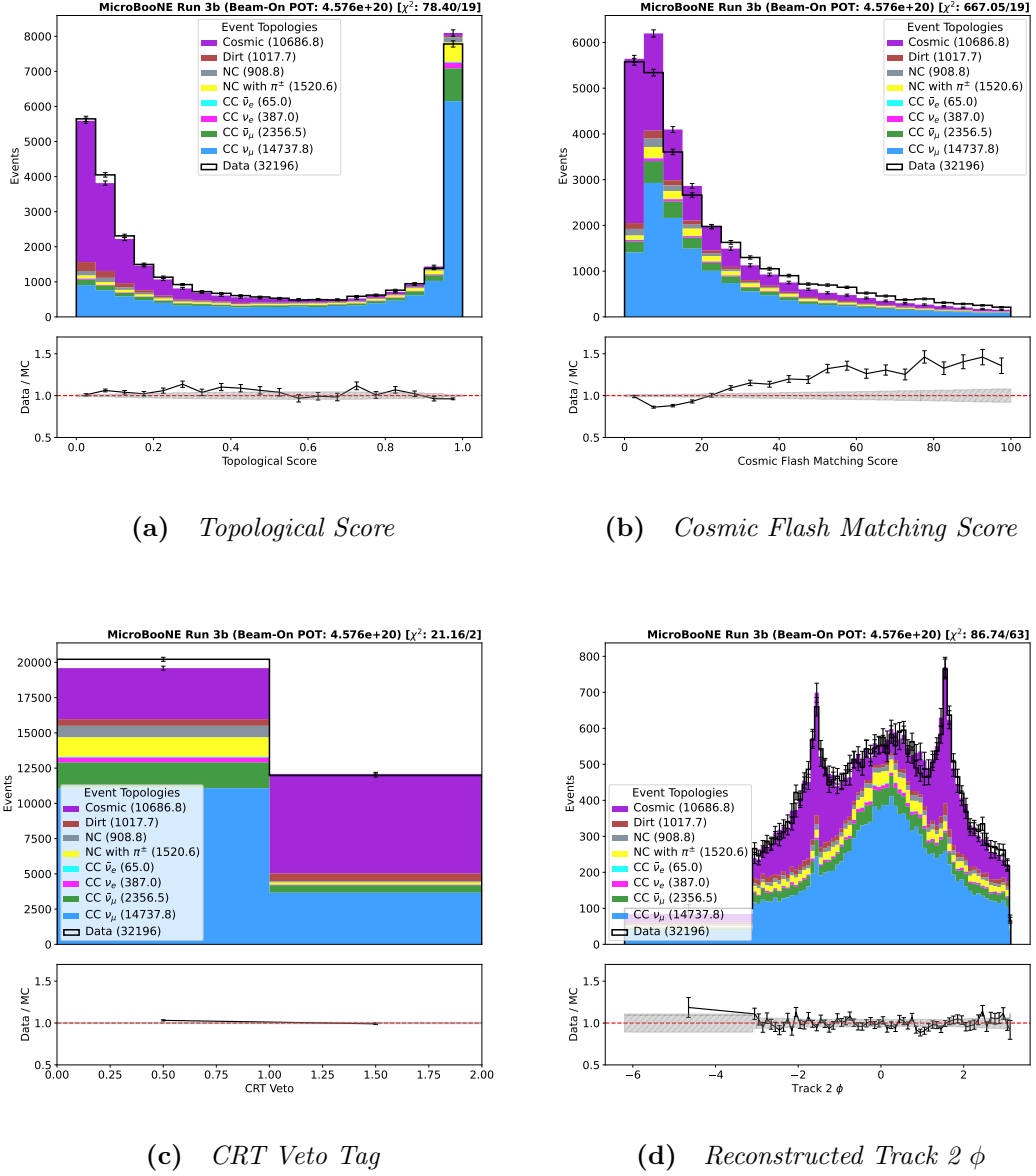


Figure 6.8 *Distribution plots for the most important training variables for the cosmic removal model. All show good agreement with data, apart from the cosmic flash matching scores. This provides confidence in the use of these variables to perform event classification on data using them.*

The retrained model learns to use the CRT veto variable more, and the reconstructed end positions of the leading tracks in place of the cosmic flash matching variable. It is this retrained model that was used in the cosmic removal task within the main analysis of this thesis.

6.4.1 Model Performance

The model was trained for 3000 iterations, with a maximum depth of 2 and a learning rate of 0.005 to prevent early overfitting. A summary of the cosmic removal **XGBoost** model is given by Table 6.3, with training curves and score distributions for training and testing data shown in Figure 6.9. The training and testing loss curves show no signs of overfitting and the score distribution shapes are similar between training and test datasets. The resulting score distribution, for the selected sample from the general selection requirements is displayed in Figure 6.10. Excellent separation power from this model is observed, with cosmic events peaking at a score of zero (background), with everything else peaking at a score of 1 (signal). Bins dominant in cosmic activity (the first 3 for example) show excellent agreement with data, as expected.

Table 6.3 *Model parameters of the XGBoost Cosmic BDT used for training.*

XGBoost Parameter	Value
n_estimators	3000
max_depth	2
learning_rate	0.005
test_size	0.1

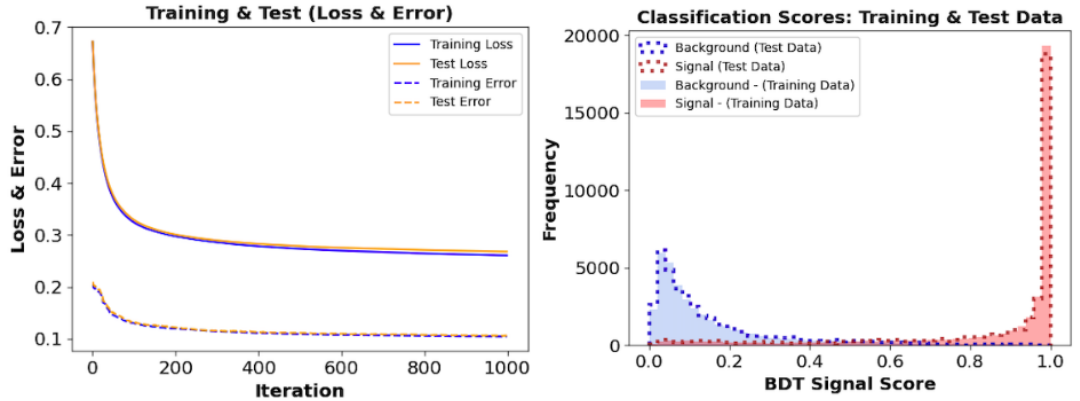


Figure 6.9 *Training and testing data loss and accuracy curves throughout training (left). Finalised distribution of BDT scores for the training and test data, showing good agreement between the distribution of scores on both datasets.*

With regards to using this trained model to make a useful selection requirement, this analysis uses a guiding metric defined by the product of the efficiency ϵ and the purity P , with respect the model signal scores. Figure 6.11 displays ϵ , P and their product $\zeta = \epsilon \times P$ as a function of the **XGBoost** model score. The red

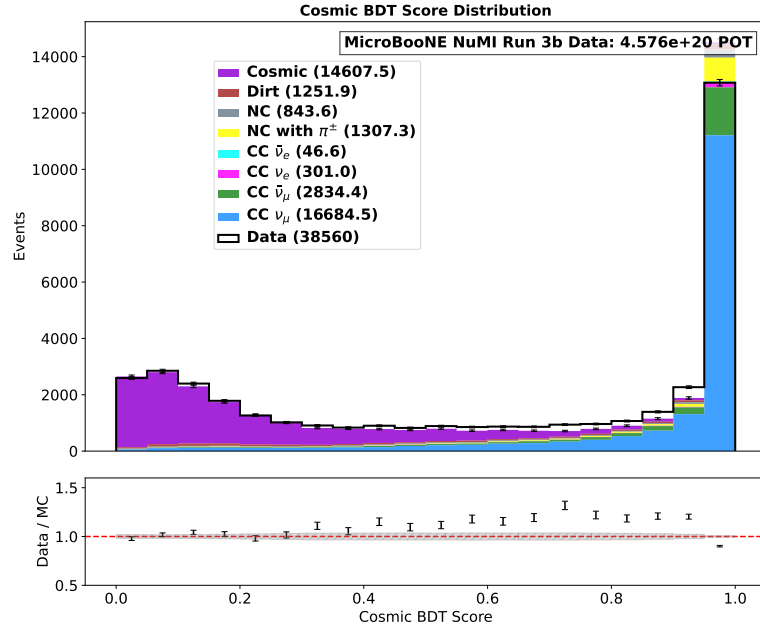


Figure 6.10 *A stacked distribution of the cosmic BDT model scores, demonstrating excellent separation power of the first ML selection requirement model.*

vertical dashed line indicates the maximum of ζ , the best BDT score that can be used to split the sample using this model, according to that metric. However, this approach also needs to consider the amount of contaminant that remains after this selection stage, since the resulting sample will be representative of the training dataset for the next classification task. In this case, a dominant background contribution from cosmic impurities will lead the next model to focus on removing this, rather than the NC neutrino interaction backgrounds. Therefore, this analysis prioritises purity, whilst using this metric as a guide to prevent losing efficiency. The actual value chosen was therefore 0.7, keeping all events equal to and above that score. This approach will be used in the following two models when removing general neutrino backgrounds, and separating the resulting sample into muon neutrino and antineutrino events. Using a threshold score of 0.7, a 34.0% increase in purity is observed, with only a 4.7% decrease in efficiency, as summarised by Table 6.4.

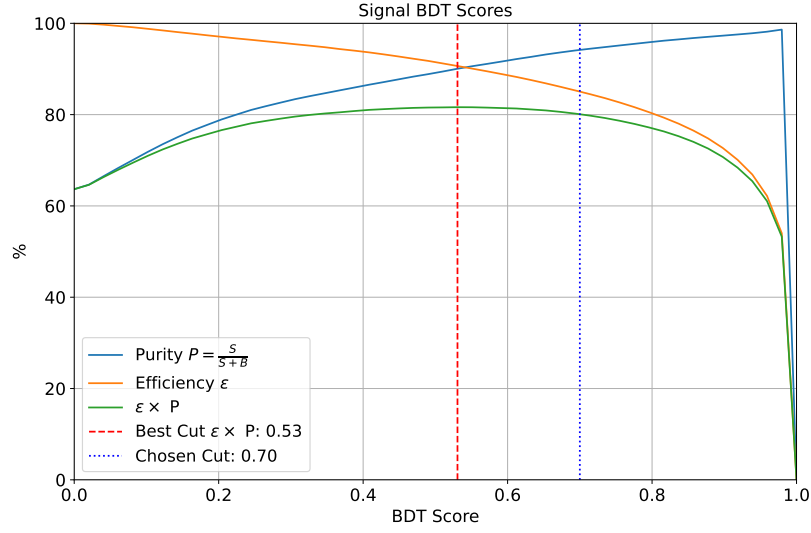


Figure 6.11 *The efficiency ϵ and purity P curves, with respect to selecting signal events, as a function of the cosmic removal BDT classification score. Also shown is the product of efficiency and purity, which is the metric used to guide ML model event selection in this thesis.*

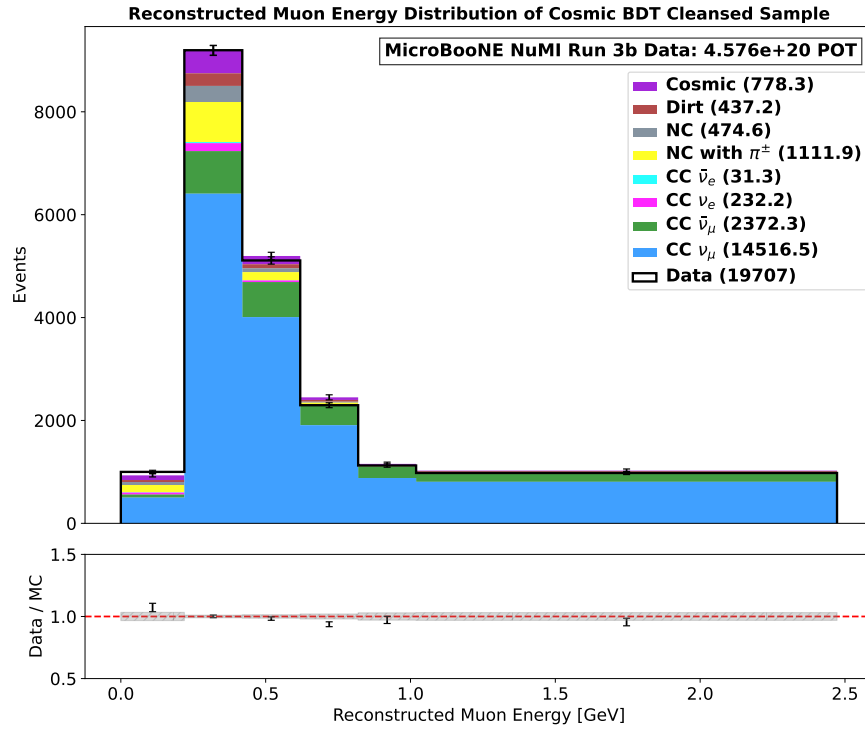


Figure 6.12 *The resulting sample, after applying the chosen model score threshold of 0.7 based on the cosmic removal BDT selection metrics.*

Table 6.4 *An updated table presenting the impact of the selection requirements, now including the first XGBoost model for cosmic removal. Event counts have been normalised to the run 3b data-taking period NuMI POT exposure.*

Selection Requirement	Events	Purity (%)	Signal Efficiency (%)
Original Sample	36059.6	3.3	100.0
Single Neutrino Slice	30210.4	14.8	83.8
Vertex Containment	28640.2	27.5	79.4
Muon(s)	24879.7	33.8	69.0
Muon Energy	17604.3	45.7	48.8
Cosmic BDT	15910.1	79.7	44.1

6.5 Combined CC ν_μ and $\bar{\nu}_\mu$ Selection Model

The input to the next model is shown by the cosmic cleansed sample, Figure 6.12. The remaining backgrounds are considered genuine signal neutrino event backgrounds, in the sense that, for example, their topologies have led to muon-like tracks in the reconstruction, which have not already been identified as having cosmic origin. Therefore, it is expected that the next classification task will be significantly more difficult. Since the flavour of a CC neutrino interaction can only be determined by the outgoing lepton, it is anticipated that the properties of the reconstructed muon in particular will be the most useful in training a model to separate the signal from the background. A summary of the hyperparameters used to train this model is given in Table 6.5. In comparison to the cosmic removal model, the depth was increased, whilst the learning rate decreased to allow the model to capture more complex relationships between background and signal events for separation.

Table 6.5 *A summary of the XGBoost event background BDT model parameters used for training.*

XGBoost Parameter	Value
n_estimators	5000
max_depth	3
learning_rate	0.001
test_size	0.1

Training Variables

- **Candidate Muon PID Score:** Since the muon is the signal of a charged-current ν_μ or $\bar{\nu}_\mu$ event, the confidence in the particle identification (PID) of it in the reconstruction must be high.
- **Hits Containment:** The fraction of reconstructed hits belonging to tracks or showers that are contained within the fiducial volume of the TPC, over the total number of hits within the neutrino slice.
- **Bragg Peak** The identification of a Bragg peak for the candidate muon track can add confidence that it is a true muon, and thus more likely a signal event. Variables related to Bragg peak identification are therefore expected to be helpful in background removal.
- **Muon MCS Consistency:** Multiple Coulomb Scattering (MCS) is a method to estimate the energy loss of a particle traversing liquid argon. The dE/dx derived from this can be compared to that expected of a muon, and so this variable is another measure of confidence in the muon candidate actually being a muon. This is clearly important for rejecting background events that do not truly contain a muon.

These are the top four most important variables for rejecting general background events. Care has been taken *not* to introduce variables related to the muon track angle with respect to the incoming neutrino here, since the analysis should avoid biasing signal antineutrino events over the neutrino ones, where the antineutrino cross section has a dependence on the polar angle of the outgoing lepton, as will be shown in section 6.6.1. Figure 6.13 shows the relative training feature importance distribution.



Figure 6.13 *A relative feature importance plot, demonstrating the reliance the genuine neutrino event background removal `XGBoost` model has on the variables used to train it. Larger values correspond to a larger feature importance.*

Indeed, the muon candidate PID score is the second most important variable, with several others relating to the multiple coulomb scattering consistency being used presumably in an attempt to determine the confidence in the leading track actually being a muon. The CRT veto variable continues to be used, which would help to remove any remaining cosmic contamination. Interestingly, the variable with the highest importance, the contained fraction, is the fraction of reconstructed hits in the `PFParticles LArSoft` object that are contained within the fiducial volume, relative to the full *active* volume. This allows the rejection of events where a lot of activity is outside the fiducial volume. The distributions of these variables are shown in Figure 6.14.

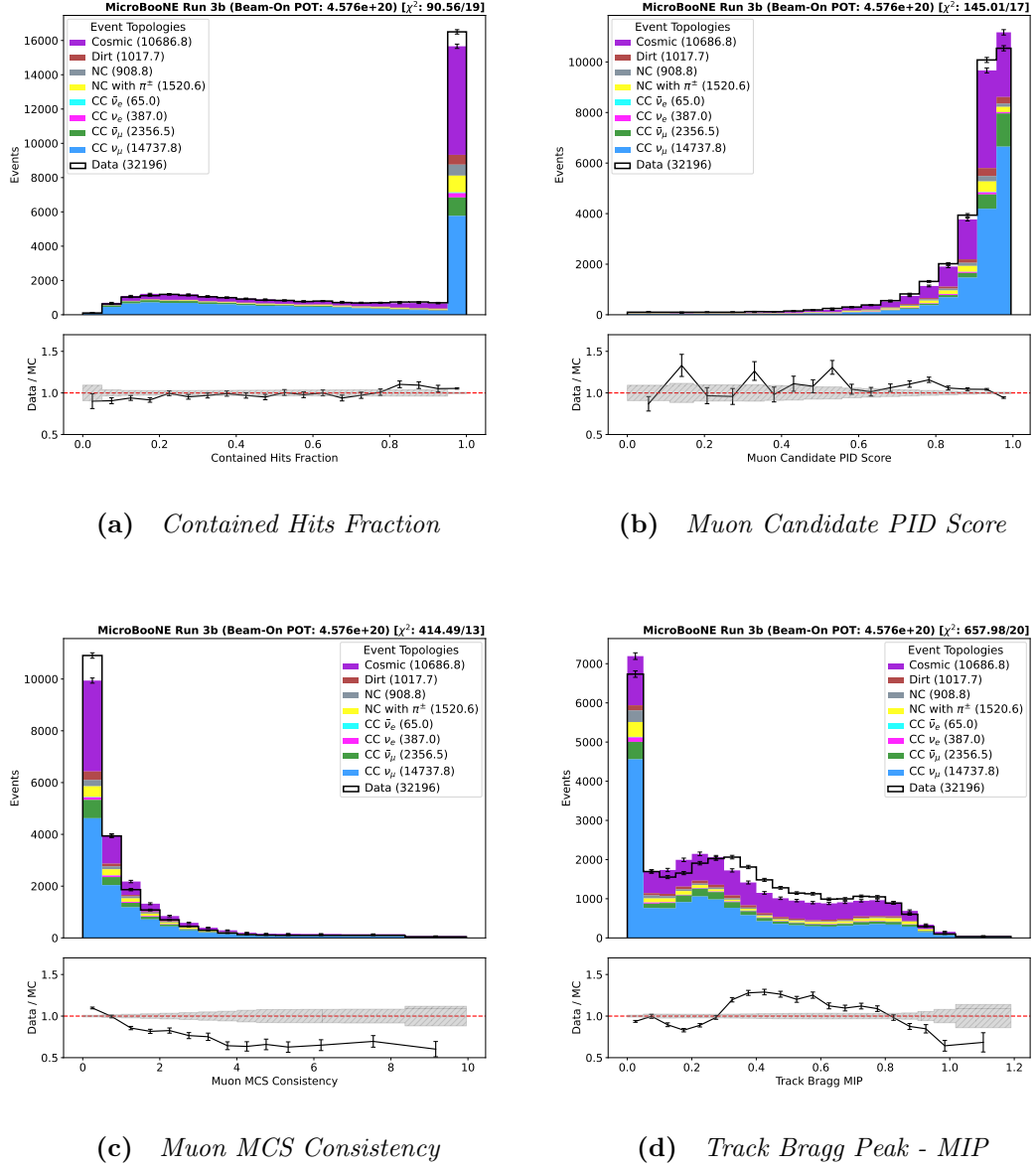


Figure 6.14 *Distribution plots for the most important training variables for the background removal model. The variables here generally show worse agreement with data, compared to the cosmic model. However, the contained fraction is by far the most important and shows good agreement with the data. Therefore, it was not deemed necessary to perform a retraining of this model. The second most important variable also shows reasonable agreement with data, supporting that decision.*

The two most important variables describe the data well, and so the relative poor agreement with data from the MCS consistency and Bragg peak reconstruction were not deemed important enough to warrant a retraining of the model.

6.5.1 Model Performance

The corresponding performance metrics during training and score distributions for training and testing data shown in Figure 6.15. The training and testing loss curves again show no signs of overfitting and the score distribution shapes are similar between training and test datasets.

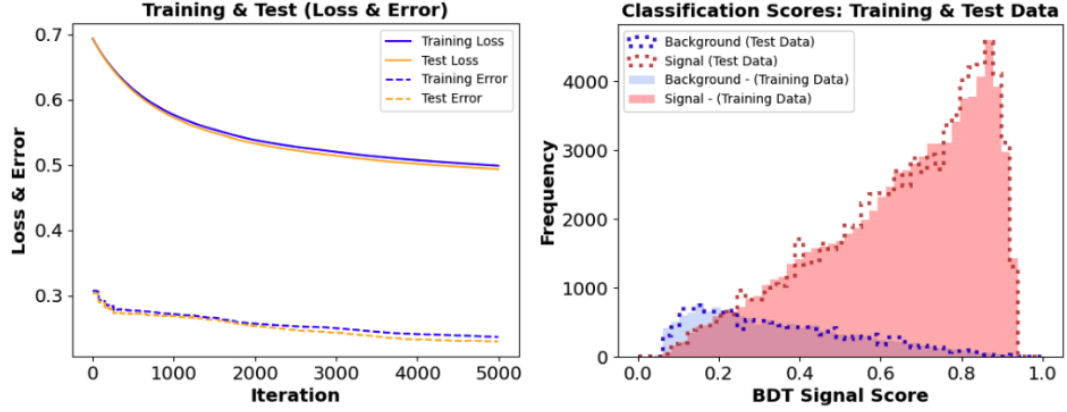


Figure 6.15 *Training and testing data loss and accuracy curves throughout training (left). Finalised distribution of BDT scores for the training and test data, showing good agreement between the distribution of scores on both datasets.*

Figure 6.16 shows the resulting score distribution for the general background model. It is seen that the separation here is largely statistical in comparison to the cosmic removal, Figure 6.10, where the signal events are indeed concentrated toward a score of 1. In particular, the remaining background, particularly the neutral current events with charged pions in the final state have been concentrated at scores below 0.5. It is observed that the sample generally observes a rough data-to-simulation agreement, up to the highest model scores (> 0.85). This is likely because a model is being trained for event selection in a model-dependent way.

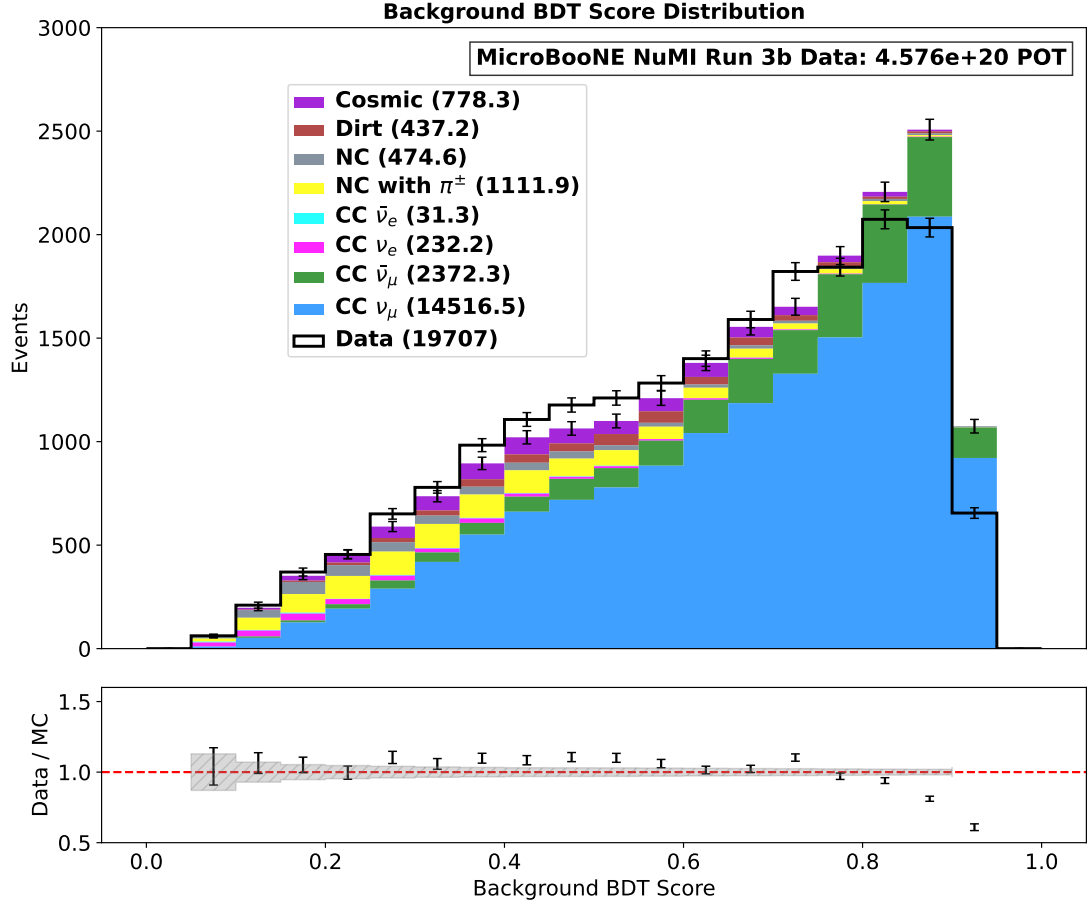


Figure 6.16 *Stacked distribution of events with respect to the general neutrino event background scores. Scores vary in $[0,1]$, where a score closer to 1 is indicative of a signal CC ν_μ or $\bar{\nu}_\mu$ event. There is generally good data-to-simulation agreement, apart from the two highest-scoring bins.*

Figure 6.17 plots the signal efficiency, purity and their product as a function of the model scores. The best score according to the ζ metric is given at 0.2. However, the analysis prioritises purity again, in anticipation of the final classification task that will attempt to separate CC ν_μ from CC $\bar{\nu}_\mu$ events. As such, searching along this curve until the relative flatness is lost, a threshold of 0.4 marked by a vertical dotted blue line is chosen. The resulting sample is shown in Figure 6.18, and an updated table of selection metrics is given in Table 6.6.

Table 6.6 *An updated table presenting the performance of the selection stages, now including the second **XGBoost** model for general neutrino event background removal. Event counts have been normalised to the run 3b data-taking period NuMI POT exposure.*

Selection Requirement	Events	Purity (%)	Signal Efficiency (%)
Original Sample	36059.6	3.3	100.0
Single Neutrino Slice	30210.4	14.8	83.8
Vertex Containment	28640.2	27.5	79.4
Muon(s)	24879.7	33.8	69.0
Muon Energy	17604.3	45.7	48.8
Cosmic BDT	15910.1	79.7	44.1
Background BDT	14397.6	86.4	39.9

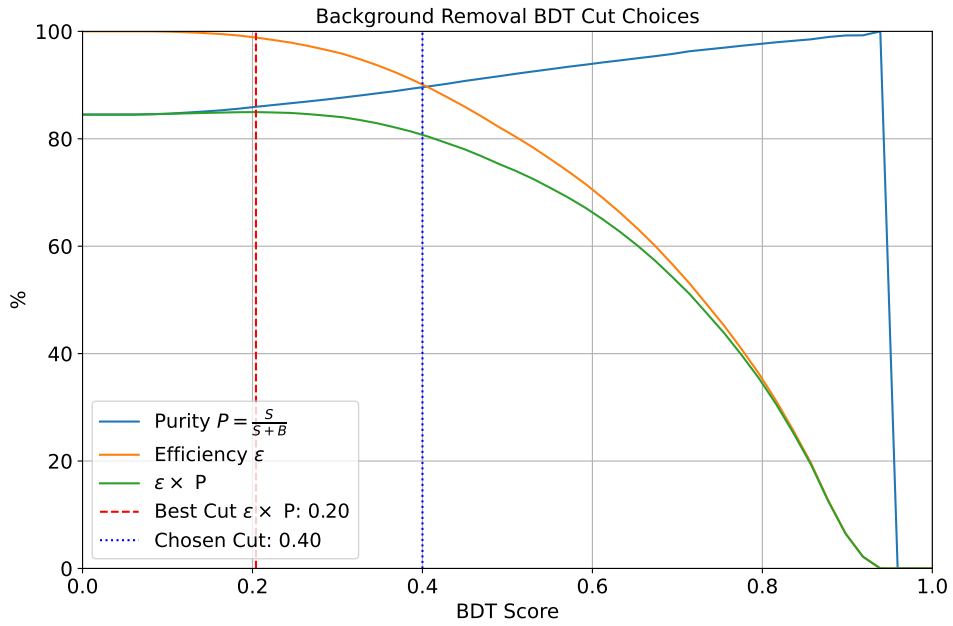


Figure 6.17 *Efficiency, purity and their product as a function of the general neutrino background rejection model scores. The best selection requirement according to the ζ metric is shown with a vertical dashed red line, and the metric chosen to prioritise purity for the final classification task is shown as a blue dotted line.*

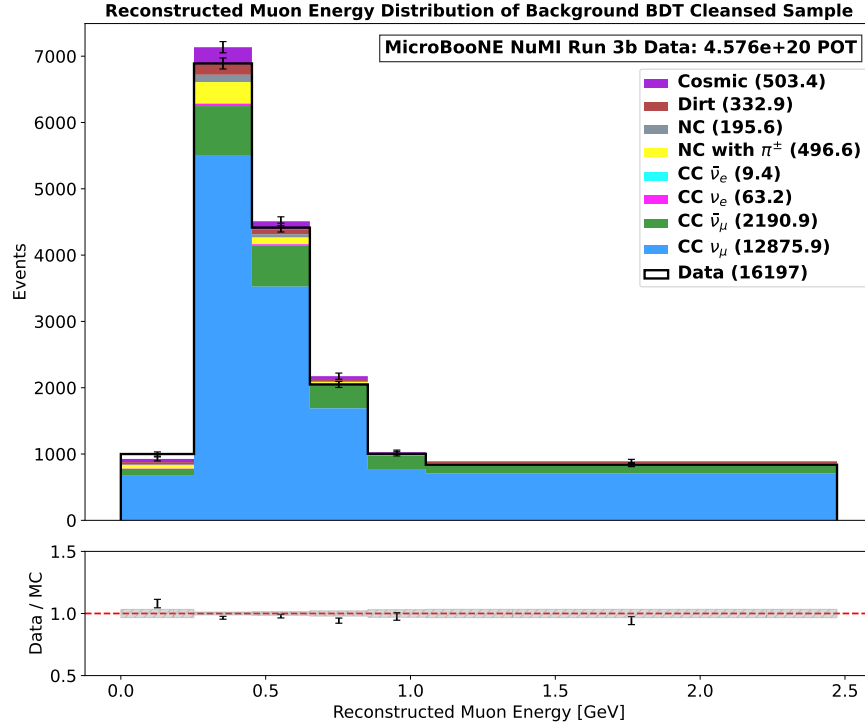


Figure 6.18 *Stacked distribution of selected signal CC ν_μ and $\bar{\nu}_\mu$ sample, as a function of reconstructed muon energy. The dominant sources of background now are the cosmic, neutral current with charged pions and dirt events.*

This section concludes with the signal selection efficiency and purity for each signal topology, and combined as a function of each of the general and ML-based selection requirements described so far, see Figure 6.19. In terms of efficiency, the impact of each stage is approximately equal, apart from the reconstructed muon energy step, discussed above. Furthermore, the final background removal described in this section does see a small impact difference of 2.5% between the signal CC ν_μ (46.4% $\rightarrow$ 41.8%) and CC $\bar{\nu}_\mu$ (33.7% $\rightarrow$ 31.6%) event efficiencies. By inspection of the variables the **XGBoost** model determines to be important, this appears to be at least partially due to the muon candidate particle identification (PID) score variable. One of the leading sources of background is NC neutrino interactions with charged pions in the final state, which have been reconstructed with a candidate muon in them. The muon identification scores follow a distribution in $[-1.0, 1.0]$, and it is observed that the CC ν_μ has a distribution similar to that of the NC events, when compared against the NC and CC $\bar{\nu}_\mu$ topologies. See Figure 6.20. A logarithmic y -axis scale is used to highlight the subtle difference in distribution shapes.

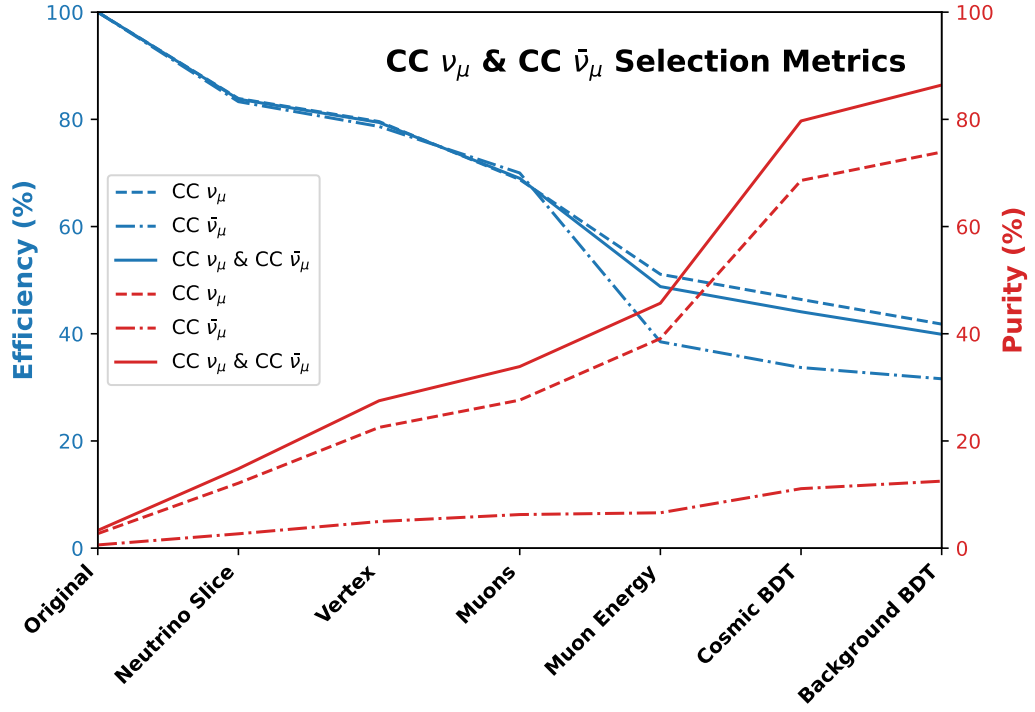


Figure 6.19 Combined $CC \nu_\mu$ and $\bar{\nu}_\mu$ selection chain plot, showing signal efficiencies (left axis) and purities (right axis) as a function of each selection step.

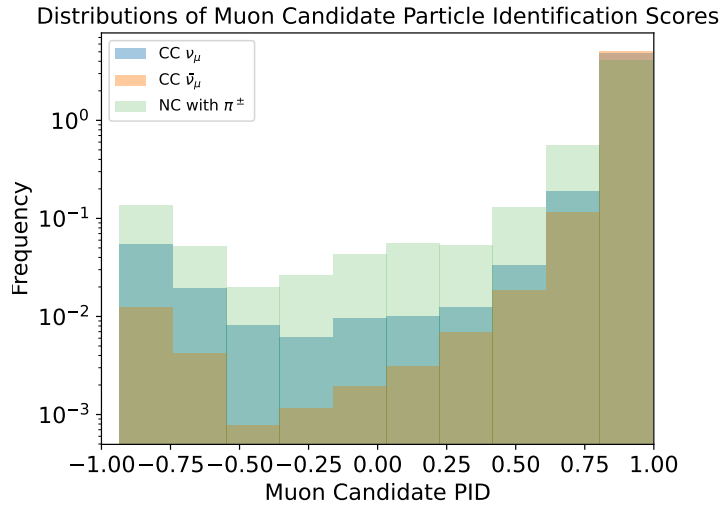


Figure 6.20 NC , $CC \nu_\mu$ and $\bar{\nu}_\mu$ topologies distributions for the muon candidate particle identification scores. The $CC \nu_\mu$ events can be seen to follow a distribution similar to that of the NC background events, rather than the $CC \bar{\nu}_\mu$. The variable is one of the most important used in the background rejection model, and the likely cause of a relative efficiency impact difference of 2.5% in the event selection process.

6.6 CC ν_μ and $\bar{\nu}_\mu$ Separator Model

The final **XGBoost** model in this analysis will be used in an attempt to separate charged-current muon neutrino and antineutrino events. This is the most challenging task for this analysis, since in the absence of a magnetic field, both μ^- and μ^+ behave in essentially the same way in liquid argon. There are, however, a few physics considerations that could provide potential handles on this. These will be described first, in the context of useful training variables for the model. The model performance will be discussed, before using it to obtain a relatively pure sample of charged-current antineutrino events, which are used in the cross section analysis that follows this chapter. The training parameters used for this model are summarised in Table 6.7 and match that of the background removal model.

Table 6.7 *A summary of the XGBoost neutrino and antineutrino separator BDT model parameters used for training.*

XGBoost Parameter	Value
n_estimators	5000
max_depth	3
learning_rate	0.001
test_size	0.1

6.6.1 $\nu/\bar{\nu}$ Event Separation: Physics Considerations

Muon Absorption

The muons, $\mu^\pm$, that come to a stop inside the active volume of the TPC display a characteristic Bragg peak consisting of a large dE/dx deposit, before decaying to either an electron or positron. In the case of the muon, 75% of these will be absorbed by Ar nuclei, and not produce a Michel electron. The Feynman diagram describing the absorption process is illustrated in Figure 6.21. On the other hand, the antimuon absorption into Ar nuclei is effectively impossible due to Coulombic repulsion, and so those that stop inside the detector should decay with a shower-producing positron. Hence, in general one should expect the presence of small showers at the end of a muon track to be indicative of antineutrino events, whereas the rate of Michel electron reconstruction would be much lower. Unfortunately,

the efficiency and quality of Michel reconstruction at present is of little benefit to this classification task, and the analysis will therefore need to lean on other physics concepts for muon and antimuon separation.

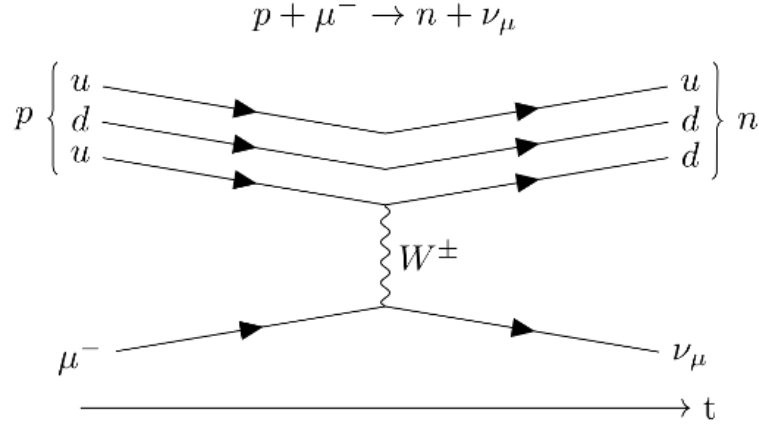


Figure 6.21 *Feynman diagram describing muon absorption. For muons that will stop inside the LArTPC, approximately 75% will be absorbed into Ar nuclei. Antimuons will not undergo this process, and so the rate of observed Michel electrons compared to positrons is expected to be significantly lower.*

Helicity Suppression

Secondly, helicity considerations lead to the expectation that the CC antineutrino process should have more forward-going leptons with respect to the incoming antineutrino, as mentioned in section 2.3.2. That is, the cross section has a dependence on the polar angle of the outgoing lepton, given by Equation 6.4.

$$\frac{d\sigma_\nu}{d\Omega} = \frac{G_F^2 \hat{s}}{4\pi^2} \quad \text{and} \quad \frac{d\sigma_{\bar{\nu}}}{d\Omega} = \frac{G_F^2 \hat{s}}{16\pi^2} (1 + \cos \theta)^2 \quad (6.4)$$

On the other hand, the CC neutrino process *does not* exhibit this angle dependence, and it is therefore expected that the trained model should use the directionality of the outgoing lepton as an aid to distinguish the two. The Feynman diagrams illustrating the helicity considerations are shown in Figure 6.22.

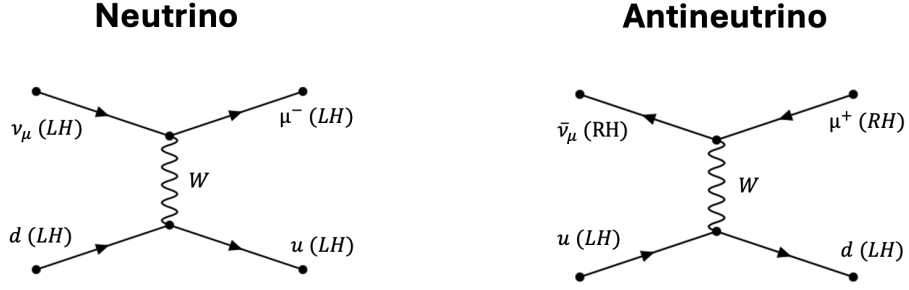


Figure 6.22 *Feynman diagram illustrating helicity considerations for neutrino and antineutrino interactions. Treating the neutrinos as chiral Dirac spinors leads to an angular dependence only for the antineutrinos.*

Additional Proton Tracks

Finally, the neutrinos will interact with neutrons in Ar nuclei, converting them to protons via $\nu_\mu + n \rightarrow \mu^- + p$, where the proton should have enough energy to escape the nucleus. In lighter nuclei, H for example, this isn't a problem. However, heavier nuclei complicate matters via intra-nuclear FSI effects. Hence the use of *additional* proton tracks, where the presence of one or more proton tracks is expected to be more likely for a muon neutrino candidate event. Alternatively, the antineutrinos will convert a proton into a neutron during a charged-current interaction, $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$. Since neutrons hold no overall electric charge, they are effectively invisible to the LArTPC. The normalised distributions for the number of reconstructed protons for muon neutrinos and antineutrinos are given in Figure 6.23, showing a clear difference in shape. This supports the above consideration for neutrino and antineutrino event separation.

6.6.2 Model Outcome

The performance metrics during training and score distributions for the final BDT model in this analysis are shown in Figure 6.24. The training and testing loss curves show no signs of overfitting even after the relatively large number of boosting rounds. The score distribution shapes are also still similar shapes for the training and test datasets.

The trained model allows the determination of the most useful variables to make the classification. The relative importance distribution is given in Figure 6.25.

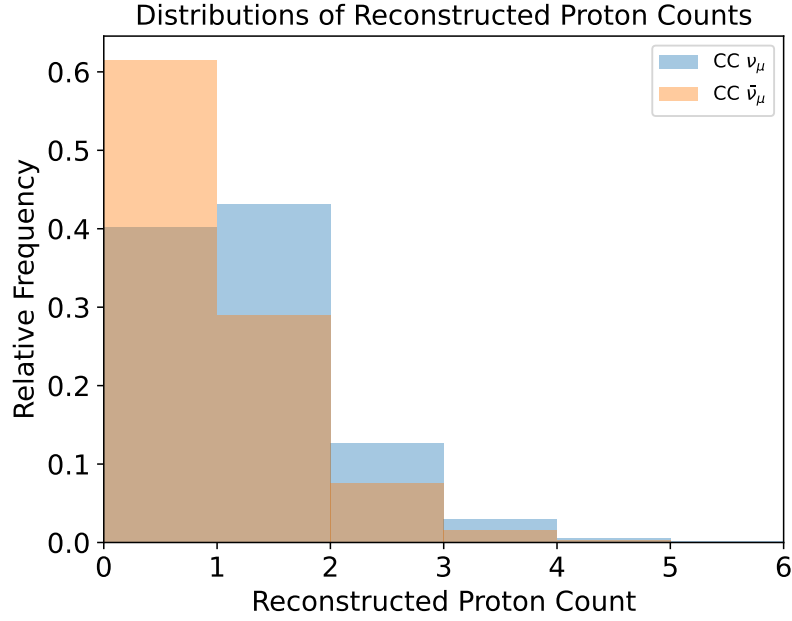


Figure 6.23 *Reconstructed proton count distributions (normalised) for muon neutrino and antineutrino charged-current interactions. The clear difference in shape supports the consideration to use this variable as a feature for the neutrino-antineutrino separator `XGBoost` model.*

These are referenced in terms of a score, which is based on the relative frequency of use for that variable over the total number of predictors (iterations) in the training cycle. Some observations are immediately apparent, with respect to the physics considerations given above:

1. The number of reconstructed proton tracks is the most frequently used variable to attempt classification between the neutrino and antineutrino events. This is expected from the reasoning given above.
2. The directionality of the outgoing lepton (muon) is the second most important feature, and this is captured in terms of both the muon ϕ and θ angles, given with respect to the BNB beam direction, also the z coordinate the of the detector geometry in reconstruction.
3. The end positions of the muon candidates seem to play a role in the predictive power of this model. In particular, the end position in the x coordinate is the second most useful variable. It is expected this is similarly due to the dependence on the polar angle of the outgoing muon; the more forward-going muons from antineutrino events are likely to have tracks terminating in a concentrated area of the active volume of the TPC.

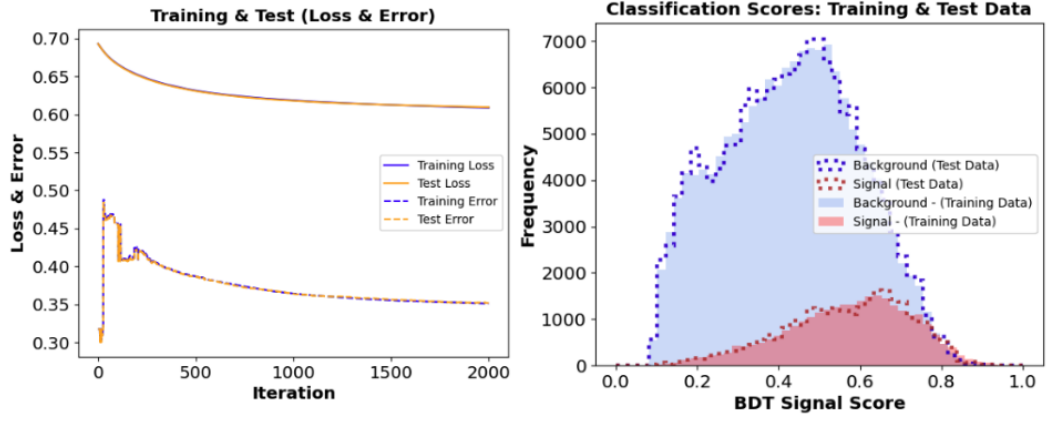


Figure 6.24 *Training and testing data loss and accuracy curves throughout training (left). Finalised distribution of BDT scores for the training and test data, showing good agreement between the distribution of scores on both datasets.*

The feature importance is given in Figure 6.25 confirm that variables related to the reconstructed proton count and track directionality are the most important, in addition to the endpoint of the candidate muon track. These feature distributions are displayed in Figure 6.26, where all of them see good agreement with data. This justifies their use in training a classification model.

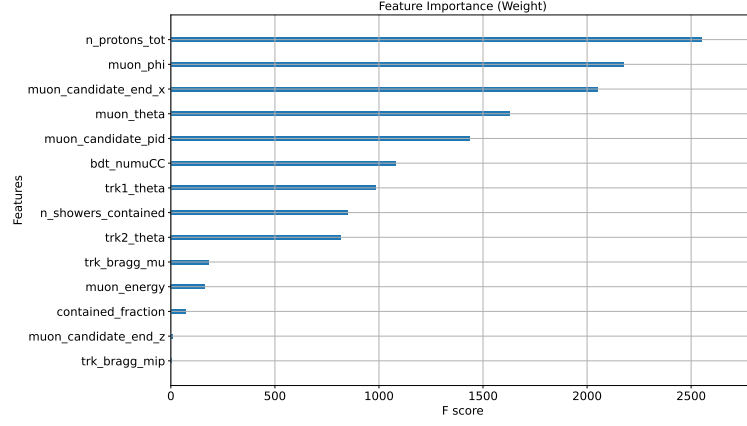


Figure 6.25 The feature importance plot for the neutrino and antineutrino separator model. This plot supports the claim that the number of reconstructed protons in the final state, coupled with the directionality of the outgoing lepton (muon) are the most important predictor variables in separating charged-current muon neutrino and antineutrino events.

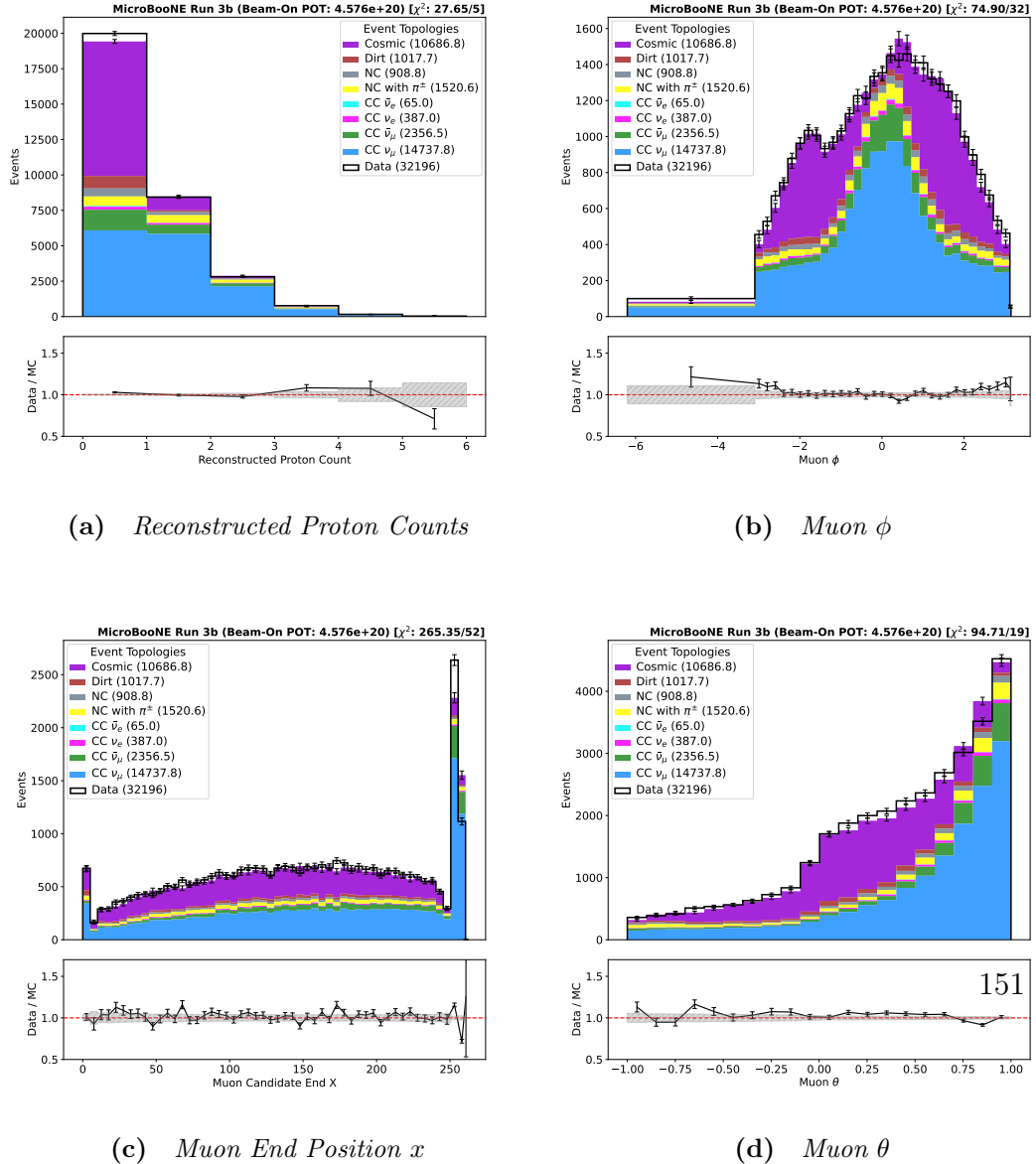


Figure 6.26 Distribution plots for the most important training variables for the neutrino and antineutrino separator model.

The distribution of scores on the data sample is shown in Figure 6.27. It is clear the model can provide an element of statistical separation, and deciding the score threshold for the selection requirement is done again by considering the ζ metric.

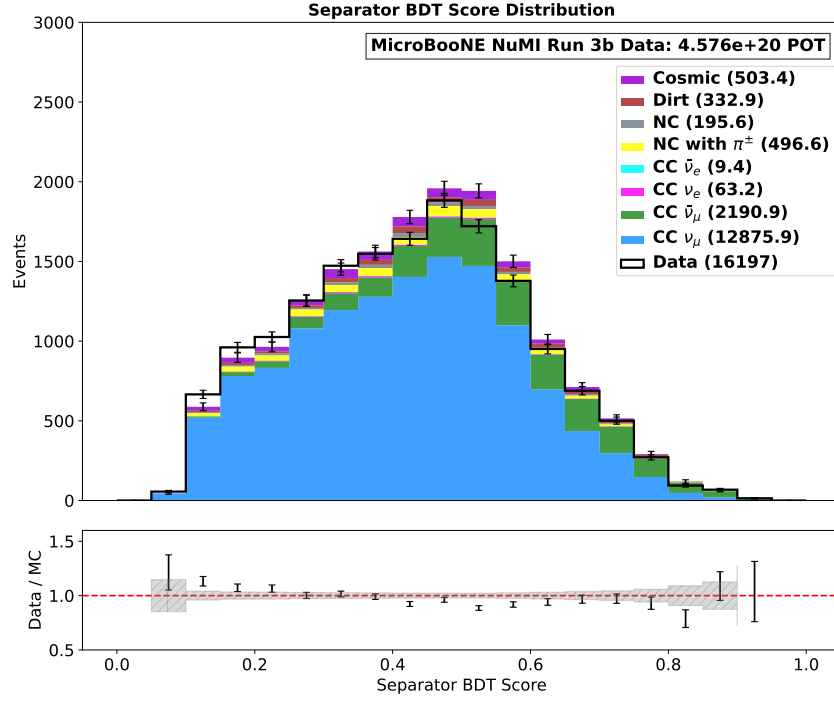


Figure 6.27 *Neutrino and antineutrino event separator model scores, with 0 indicating more muon neutrino-like, and 1 indicating a more signal muon antineutrino-like event. Statistical separation can be observed, with a larger density of CC ν_μ events on the left, and similar for CC $\bar{\nu}_\mu$ on the right.*

6.7 Final Selected Samples

To conclude this chapter, the separator model is now used to split the sample into relatively pure CC ν_μ and CC $\bar{\nu}_\mu$ sub-samples. These will be used in the following chapter for cross section analyses. Defining CC ν_μ as the signal, the efficiency and purity metrics are plotted as functions of the classification score in Figure 6.28. As before, their product ζ is also shown as a green curve.

The maximum of the BDT score selection metric in terms of selecting CC ν_μ is given at 0.82. In the interests of maintaining sufficient data and purity for the CC $\bar{\nu}_\mu$ sample also, this requirement is adjusted to a little below this value at 0.77. This has been done so the resulting sample of CC $\bar{\nu}_\mu$ has a dominant

contribution of signal events, whilst having minimal impact on the final selected CC ν_μ sample. These samples are each summarised next.

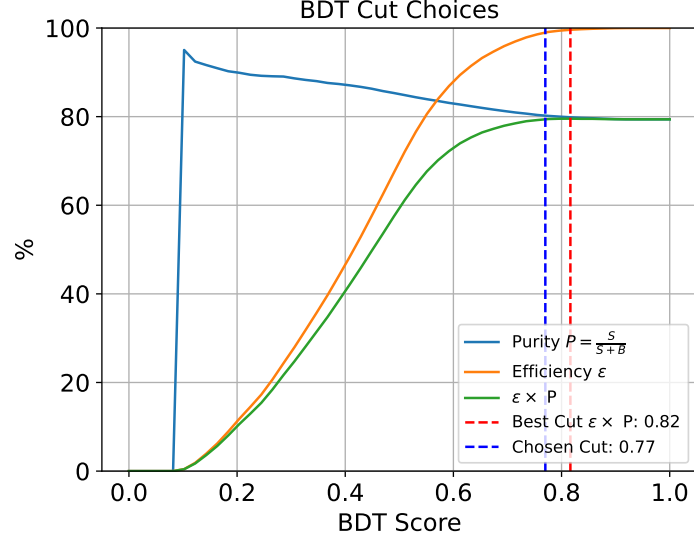


Figure 6.28 *Neutrino and antineutrino event separator model selection metrics, as a function of the model scores. Here, CC ν_μ is treated as the signal, and the selected sample is everything equal to and below the score on the x axis, since the model was trained to recognise CC $\bar{\nu}_\mu$ as the signal before.*

Charged Current Muon Neutrinos

The final selected sample of CC ν_μ events is presented in Figure 6.29. The purity and efficiency per bin are also shown in Figure 6.30. Good data-to-simulation ratios are observed, with relatively good consistency (a small variation) in efficiency and purity across reconstructed energy space. This is indicative that the selection has not biased toward any particular phase space of the signal CC ν_μ events. The **XGBoost** model selection has led to a sample of approximately 12200 signal events, with a signal purity of 74.6% and an overall efficiency of 41.3%. Note that these figures are for signal events that include true muon energies of 0.2 GeV or more. The stacked distribution in Figure 6.29 event counts include events that have been incorrectly binned into higher-than-true reconstructed energies.

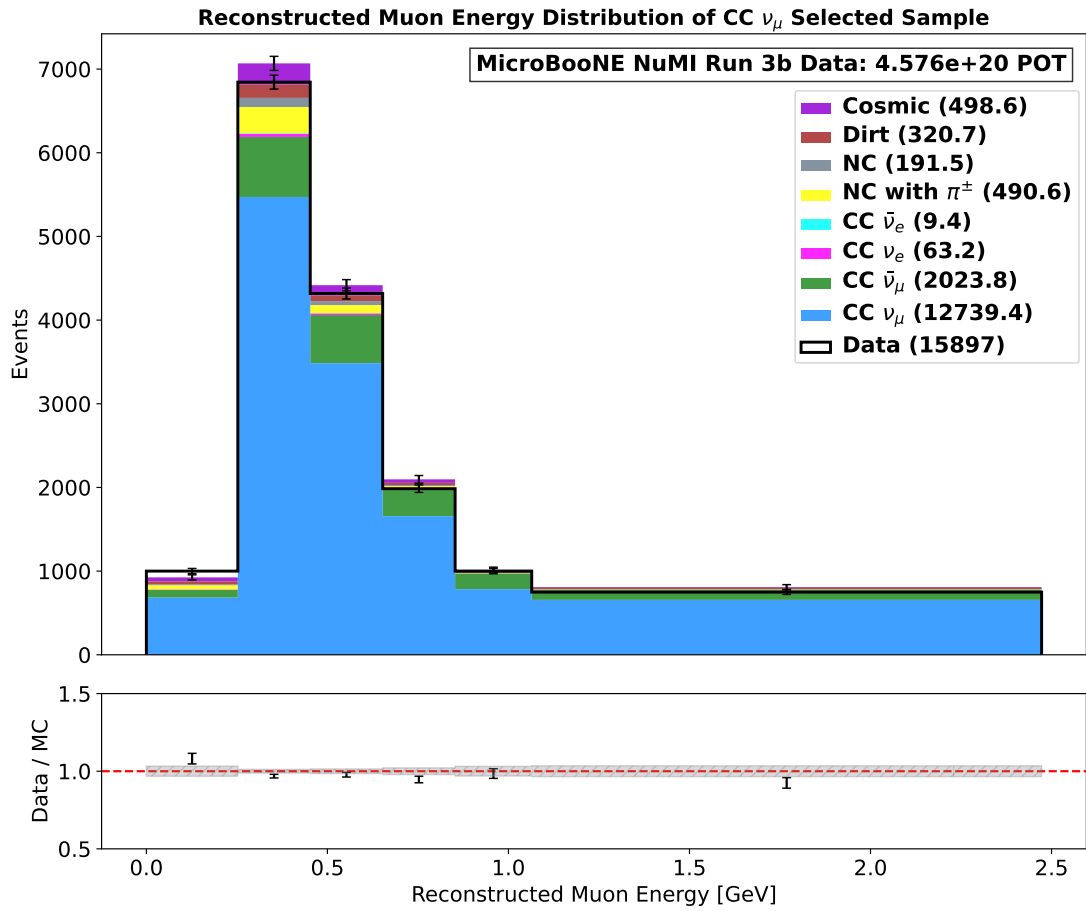


Figure 6.29 Selected sample of CC ν_μ events as a function of reconstructed muon energy.

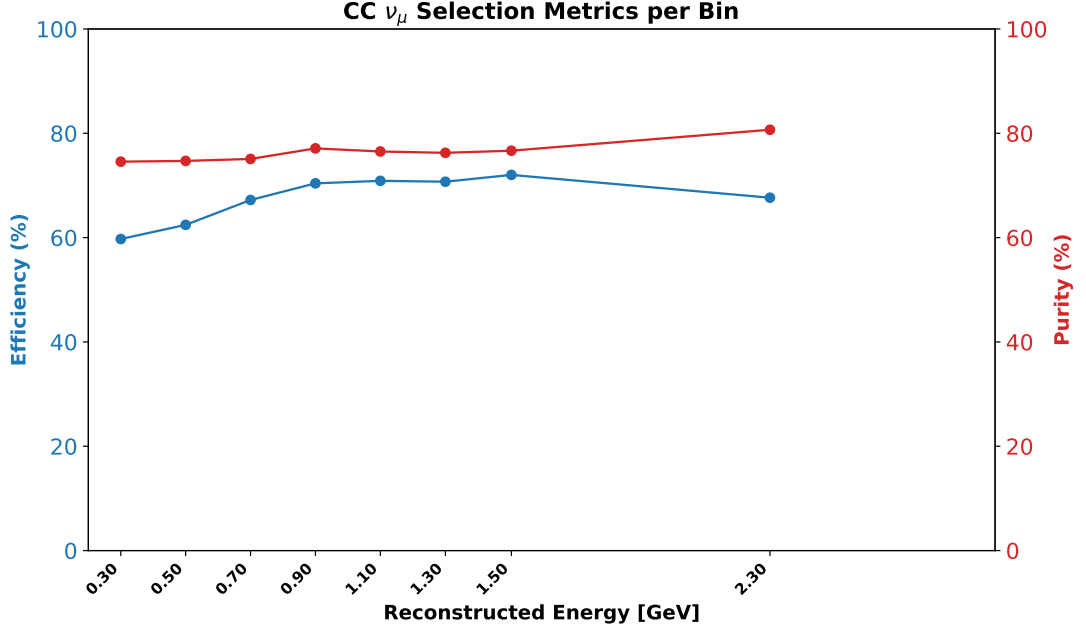


Figure 6.30 Selection metrics of CC ν_μ events, as a function of reconstructed event energy. The relatively small variation in purity and efficiency of these curves is indicative of minimal bias across the reconstructed energy space.

Charged Current Muon Antineutrinos

Similar to the above, Figure 6.31 shows the complementary sample of CC $\bar{\nu}_\mu$ events, made by making the XGBoost model selection requirement, keeping everything *above* the threshold value of 0.77. The selection metrics as a function of reconstructed energy are also presented in Figure 6.32. The x axis tick labels correspond to bin-center values. The threshold was chosen so that the signal contribution is the dominant one whilst maximising statistics, with a purity of approximately 48.2%, and an overall efficiency of 2.4%.

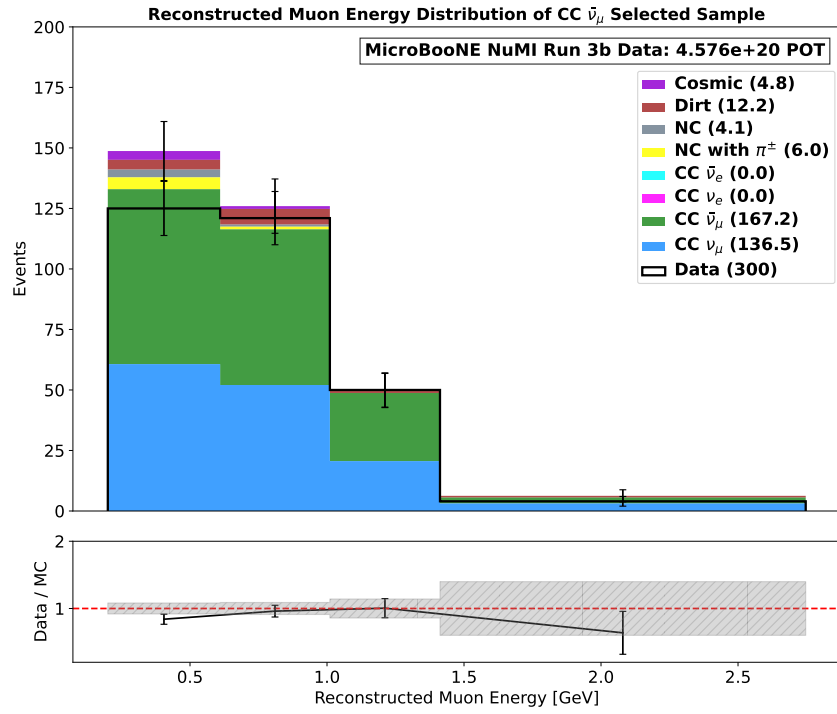


Figure 6.31 Selected sample of CC $\bar{\nu}_\mu$ events as a function of reconstructed muon energy.

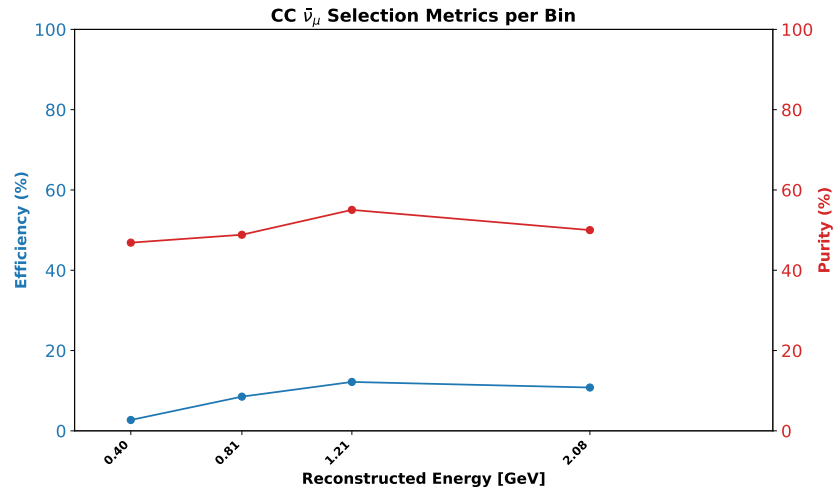


Figure 6.32 Selection metrics of CC $\bar{\nu}_\mu$ events, as a function of reconstructed muon energy. The relatively small variation in purity and efficiency of these curves is indicative of minimal bias across the reconstructed energy space.

6.7.1 Summary

An event selection chain has been developed to obtain a relatively pure sample of CC ν_μ and CC $\bar{\nu}_\mu$ events from a sample of neutrino interactions in the MicroBooNE detector, whose neutrino flux originates from the highly off-axis exposure to the NuMI neutrino beam. The data sample has been reconstructed using the Pandora framework, where the reconstruction variables were used for (a) a general event selection process, and (b) training an ML-based series of selection requirements using three **XGBoost** BDT models. The selected samples have been cleansed of cosmic impurities and neutrino event backgrounds. The final classification task managed to provide enough statistical separation on a largely CC ν_μ dominated sample to provide a complementary splitting into neutrino and antineutrino samples, which will now be used for cross section analyses.

Chapter 7

Cross Section Measurements

This chapter will use the extracted samples of muon neutrino and antineutrino events to calculate total flux-integrated cross sections for each of the charged current interactions. A description of the approach to systematic and statistical uncertainties is included, before presenting the final results.

7.1 Cross Section Calculation

This analysis uses the selected samples of Beam-On events presented in the previous chapter, and as such, the number of signal events in each sample will need to be extracted from the total event count N_{BO} . This will be achieved by subtracting the number of background contamination events, B which is estimated from the Monte Carlo simulation. Thus, the number of signal events in our data sample is given by $N_{Signal} = N_{BO} - B$. Equation 6.1 for a general total cross section is then updated by taking $N \rightarrow N_{Signal}$.

The integrated flux values ϕ_i , where $i = \{\nu_\mu, \bar{\nu}_\mu\}$, are given in units of $\nu / \text{POT} / \text{cm}^2$. They are integrated from the distributions shown in Figure 6.1. A lower limit of 200 MeV is applied to this integration in line with the signal definition given above. The integrated flux value for muon neutrino(antineutrino) is $1.8084(2.0131) \times 10^{-10} \nu / \text{POT} / \text{cm}^2$. An additional factor for the measured POT exposure from the NuMI beam is then required, P . This corresponds to the run 3b value of 4.576×10^{20} POT. The flux has been simulated for the *entire* active volume of the LArTPC. An additional scaling factor S to account for the

flux observed by the fiducial volume requirement used in this analysis is used. S is then the fraction of the fiducial volume with respect to the full active volume.

An efficiency factor ϵ_i is applied, to account for the efficiency of the event selection procedure for a given topology i . Therefore N_{Signal}/ϵ_i corresponds to an estimate of the total number of signal interactions that occurred for the run 3b NuMI beam exposure. The form of the cross section equation for this analysis is now given by Equation 7.1,

$$\sigma_i = \frac{N_{BO} - B}{\phi_i \epsilon_i P S N_t}. \quad (7.1)$$

The large mass of liquid argon serves as the target for the neutrino interactions. Specifically, the cross sections presented here are *per nucleon*, and so the total number of targets available for interaction is calculated according to Equation 7.2,

$$N_t = \frac{\rho_{Ar} V A N_N}{m_{mol}}. \quad (7.2)$$

Here, ρ_{Ar} is the density of liquid argon, 1.3836 g/cm³. The volume V corresponds to the fiducial volume used in the analysis, which is 5.1188×10^7 cm³. $A = 6.022 \times 10^{23}$ molecules/mol is Avogadro's number, $N_N = 40$ is the number of nucleons constituting an Ar⁴⁰ nucleus. The $m_{mol} = 39.95$ g/mol is the mass of one mole of argon. Plugging in these values leads to $N_t = 4.2704 \times 10^{31}$ nucleons. A summary of the parameters described in this section is given in Table 7.1.

GENIE Predictions

The measured cross section will be compared to a prediction made by the simulation samples, produced by GENIE as described in the previous chapter. This GENIE prediction for the flux-averaged cross section σ_i^{GENIE} is similarly calculated by

$$\sigma_i^{GENIE} = \frac{N_{Signal}^{MC}}{\phi_i P S N_t}, \quad (7.3)$$

where N_{Signal}^{MC} is the total number of simulated signal events, weighted to the

Table 7.1 *Parameter values as used in the cross section equations in the main text, given alongside their units.*

Parameter	Value [Units]
σ	[cm ² /nucleon]
N_t	4.2704×10^{31}
ϕ_{ν_μ}	1.8084×10^{-10} [ν POT ⁻¹ cm ⁻²]
$\phi_{\bar{\nu}_\mu}$	2.0131×10^{-10} [ν POT ⁻¹ cm ⁻²]
P	4.576×10^{20} [POT]
S	0.827
ϵ_i	41.78% (ν_μ), 2.42% ($\bar{\nu}_\mu$)
ρ_{Ar}	1.3836 [g/cm ³]
V	5.1188×10^7 [cm ³]
A	6.022×10^{23} [molecules/mol]
N_N	40
m_{mol}	39.95 [g/mol]
N_{Signal}^{MC}	29483.2 (ν_μ), 6576.5 ($\bar{\nu}_\mu$)

Beam-On data sample POT, that fulfil the signal criteria outlined above. For the CC ν_μ and CC $\bar{\nu}_\mu$, the number of signal events are 29483.2 and 6576.5, respectively. Note that there is no background to be removed here since the MC simulation comes with the matching truth-level information. Thus, the number of signal interactions is known exactly for this calculation, and there is also no efficiency factor required. The GENIE predictions according to the above procedure for the muon neutrino and antineutrino cross sections are given in Equations 7.4 and 7.5. Uncertainties given are statistical based on the N_{Signal}^{MC} , N_t and P variables.

$$\sigma_{\nu_\mu}^{GENIE} = [9.89 \pm 0.23(\text{stat})] \times 10^{-39} \text{ cm}^2/\text{nucleon} \quad (7.4)$$

$$\sigma_{\bar{\nu}_\mu}^{GENIE} = [1.98 \pm 0.06(\text{stat})] \times 10^{-39} \text{ cm}^2/\text{nucleon} \quad (7.5)$$

7.2 Uncertainty Calculations

This section describes the approach to estimating the statistical and systematic uncertainties when calculating the flux-integrated cross sections presented in this thesis. The MC simulation sample shown up to this point is henceforth referred to as the Central Value (CV) estimation, and corresponds to the values *around which*, variations in the simulation will be applied to investigate the effects on the selected event distributions. The uncertainties themselves are derived from those effects on the selected event counts, thus varying the measured cross sections.

7.2.1 Statistical Uncertainties

Regarding the statistical uncertainties in the cross section measurements, there are several sources of statistical uncertainty, originating from the measured data Beam-On event counts, N_{BO} and the estimated number of backgrounds, B from MC simulation. Since the selection efficiency ϵ is also estimated based on MC event counts, there is a source of statistical uncertainty from that factor too. All other statistical uncertainties are absorbed by the systematic variations. The total statistical uncertainty on the cross section measurement is then given by Equation 7.6,

$$(\delta\sigma)^{stat2} = \sum_i \left(\frac{\partial\sigma}{\partial k_i} \right)^2 \delta k_i^{stat2}. \quad (7.6)$$

Here, $k_i \in \{N_{BO}, B, \epsilon\}$, and δk_i represents the statistical uncertainty on the value. Both N_{BO} and B are simple event counts, following a Poisson distribution, and so their standard deviations are given by their square root values. That is, $\delta N_{BO} = \sqrt{N_{BO}}$ and $\delta B = \sqrt{B}$. The above are results of the error propagation rule, and the statistical uncertainty on the efficiency is handled in the same way. Given that the selection efficiency is defined as $\epsilon = N_{Sel}^{MC} / N_{Signal}^{MC}$, where N_{Sel}^{MC} is the number of selected simulated signal events, and N_{Signal}^{MC} is the total number of available simulated signal events to be selected before any selection requirements, the statistical uncertainty on ϵ is calculated as

$$\delta\epsilon^{stat2} = \left(\frac{\delta N_{Sel}^{MC stat}}{N_{Signal}^{MC}} \right)^2 + \left(\frac{N_{Sel}^{MC} \times \delta N_{Signal}^{MC stat}}{N_{Signal}^{MC2}} \right)^2, \quad (7.7)$$

where $\delta N_{Sel}^{MC\ stat} = \sqrt{N_{Sel}^{MC}}$ and $\delta N_{Signal}^{MC\ stat} = \sqrt{N_{Signal}^{MC}}$.

7.2.2 Systematic Uncertainties

The MicroBooNE collaboration takes two main approaches to estimating the systematic uncertainties of a measured result. These include:

- (a) **Event Re-Weighting** (Multi-Universe): The CV events each have many parameters. Each parameter subject to the re-weighting mechanism is sampled N times, corresponding to the number of *universes* this variation would like to consider. For example, suppose the neutrino modelling used in the GENIE event generator is dependent on the incoming neutrino energy and momentum. These can be varied many times to account for the uncertainty in the model.
- (b) **Sample Re-Simulation** ($\pm 1\sigma$): An entirely new sample is generated, where the parameter of interest has been varied by $\pm 1\sigma$. The full selection chain must be used to process these samples, and the resulting cross sections calculated independently. These are used in the context of detector-based variations below.

There are four main sources of systematic uncertainty, and they are as follows:

1. **Cross Section Modelling [XSEC]** GENIE accepts an input flux of particles, and a set of cross section models, also known as *Splines*, to determine the neutrino interactions one might expect to occur within the detector volume. The cross section modelling variations use the re-weighting approach described above to address the impact of varying these models on the measured cross sections.
2. **Re-Interactions [REINT]** Daughter particles of neutrino interactions, such as $\pi^\pm$ and p will re-interact as they traverse the detector. The cross section modelling of these re-interactions is varied to account for the changes this would have on the reconstruction capabilities of signal events. This variation uses the re-weighting approach.
3. **Detector Response [DETVAR]** The re-simulation approach is used to treat the uncertainties related to the response of the detector [97]. New MC samples are generated for the following broad categories of variations:

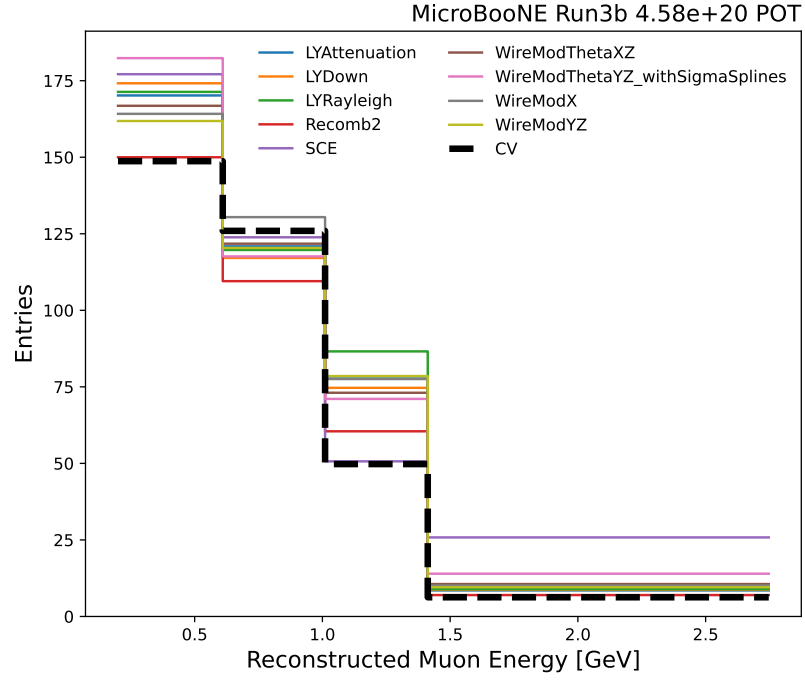
- **Scintillation** Two samples were generated for the treatment of light yield in detector effects. The first is Light Yield Down (LYDown) which decreases the yield by 35% to simulate the effect of decreased light yield over the running lifetime of the MicroBooNE detector. The second sample increases the Rayleigh scattering length from the CV of 60 cm to 90 cm. This is in response to recent measurements of the Rayleigh scattering length in noble elements, ranging in [60 cm, 100 cm] [98][99].
- **Wire Modifications** These samples use data-based comparisons with simulation to modify the simulation waveforms deconvolved from the charge readout [97]. This is done in several variables, including the x (Drift) direction, denoted WireModX in what follows. WireModX in particular takes into account effects such as longitudinal diffusion for example.
- **Space Charge Effect (SCE) & Recombination** A further two samples were simulated to estimate the uncertainties due to the SCE and recombination effects. The SCE sample used an alternate mapping to correct for the displacement of spatial information as in Figure 3.4. The second accounts for electron-ion Recombination (Recomb) by varying parameters within the Modified Box model (MBM), discussed in Chapter 3.

A summary of each of the detector variations used, with a short description is given in Table 7.2.

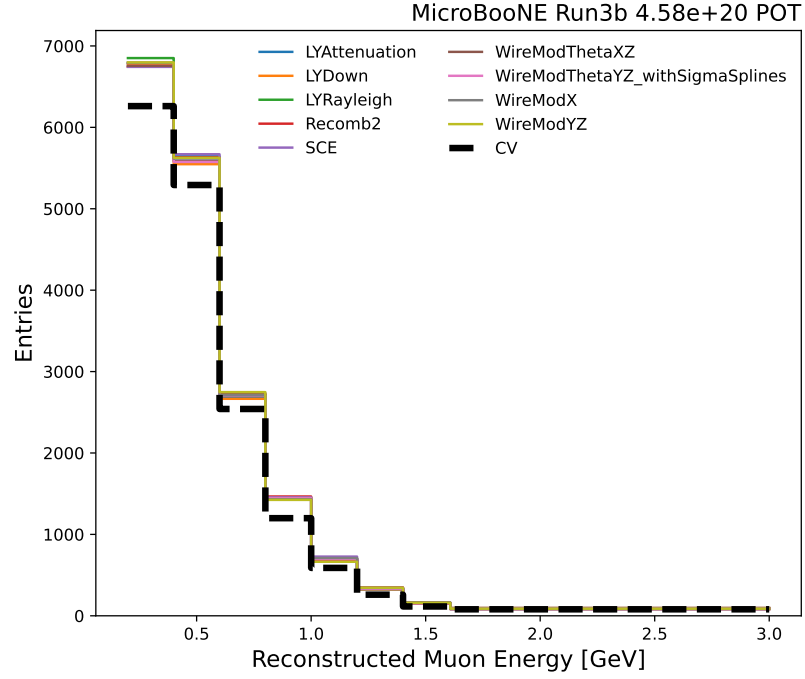
4. **Flux Predictions [FLUX]** The predicted flux of neutrinos observed by the detector is provided by the PPFx software package, as described above. The package relies heavily on hadron production modelling, at the point of proton-graphite collisions. The hadron production modelling is therefore varied to account for this. The observed flux is also dependent on the beamline geometry, and so the geometry description of the beamline with respect to the detector also undergoes some systematic variations to account for this.

For each of the selected samples, Figures 7.1a and 7.1b present the effect of each detector variation on the sample spectrum.

The remaining systematic variations, which are not detector-related, use the re-weighting method. They are summarised in Table 7.3. These include the



(a) $CC \bar{\nu}_\mu$ Sample



(b) $CC \nu_\mu$ Sample

Figure 7.1 *Impact of the detector variations (coloured histograms) on the selected event counts for the muon antineutrino (top) and neutrino (bottom) samples, as a function of reconstructed muon energy. These variations use a completely re-simulated sample, where the difference in event counts represents a 1σ uncertainty with respect to that variation. The central value (CV) is shown as a black dashed histogram.*

Table 7.2 *A listing of additional re-simulated samples used to estimate the systematic uncertainties related to the detector response. Each variation is also given a brief description.*

Detector Variation	Description
LYDown	Decrease the light yield by 35%
LYAttenuation	Additional 8m absorption length added to simulation
LYRayleigh	Increase scattering length from 60 cm to 90 cm
Recomb	Adjust β parameter in MBM (-13%)
SCE	Correctional map to fix SCE distortions.
WireModX	Varied waveforms in x (Drift)
WireModYZ	Varied waveforms in y (Vertical) and z (Beam)
WireModThetaXZ	Varied waveforms in θ_{xz} plane
WireModThetaYZ	Varied waveforms in θ_{yz} plane

sources categorised under the Flux, XSec and Reint types described above. In particular, the All_UBGenie constitutes a large list of cross section based tunable parameters, where a full listing is given in Appendix C. These essentially include parameters affecting each of the interaction modes, hadronisation and FSI parameters. Figures displaying the impact of each of the uncertainty sources listed in Table 7.3, for both selected samples of events are shown below.

The following is a full presentation of the systematic variations that were used for the selected samples of muon neutrino and antineutrino events in the cross section analysis of this thesis. In the figures, the left hand column corresponds to muon antineutrino samples, whilst the right gives the neutrino samples. The black dashed histograms in the figures represent the central values (CV) of each variation, i.e. those of the primary selected sample. The blue histograms are for the remaining variations not related to the detector. They represent variations on the event counts for the given sample, with respect to that variation. Figures with > 2 blue histograms represent variations that have used many samplings of the variation parameter(s), such as the reinteractions. Variations with 2 blue histograms represent single standard deviations around the central value.

In addition to all of the above systematic uncertainties, an extra 2% and 1% systematic uncertainty on the Beam-On POT counting and number of targets, respectively, is considered.

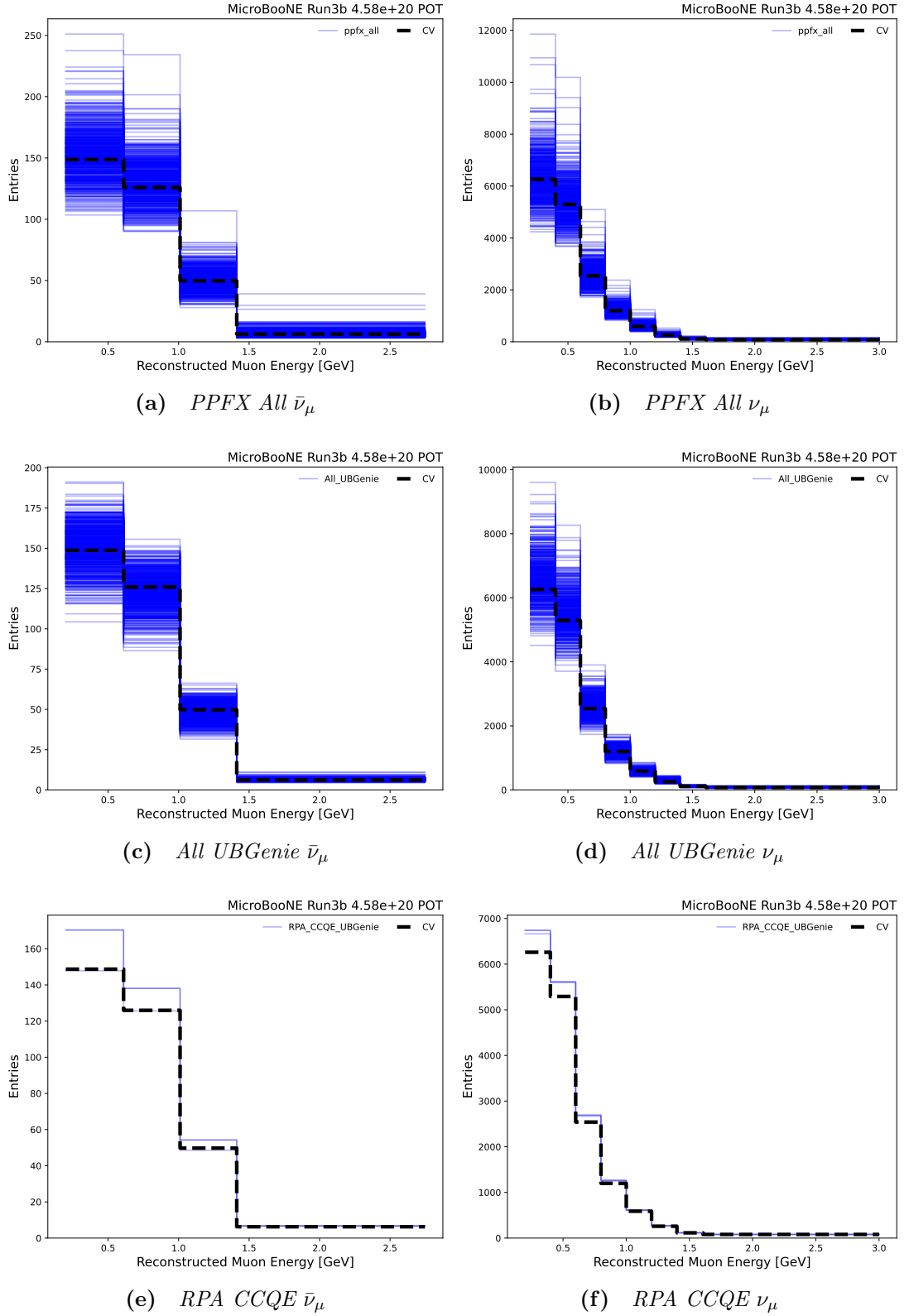
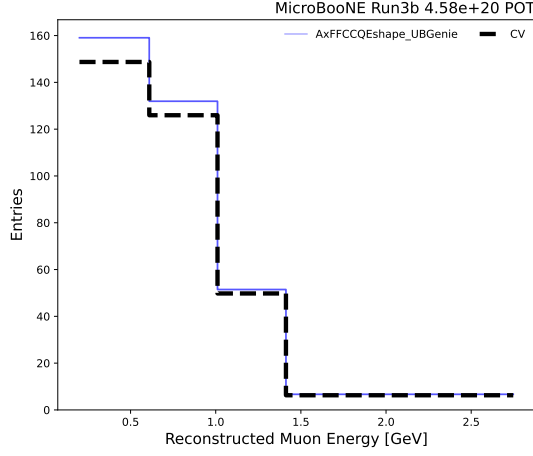
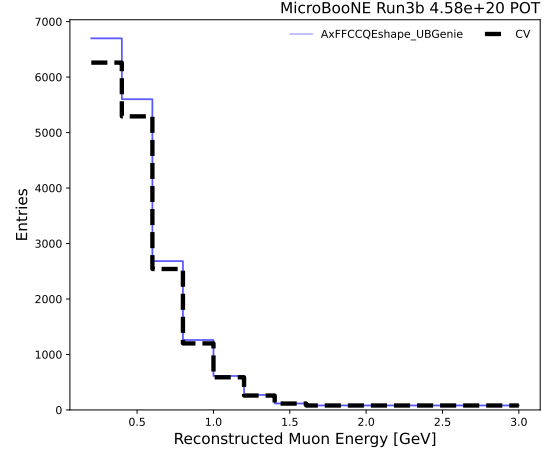


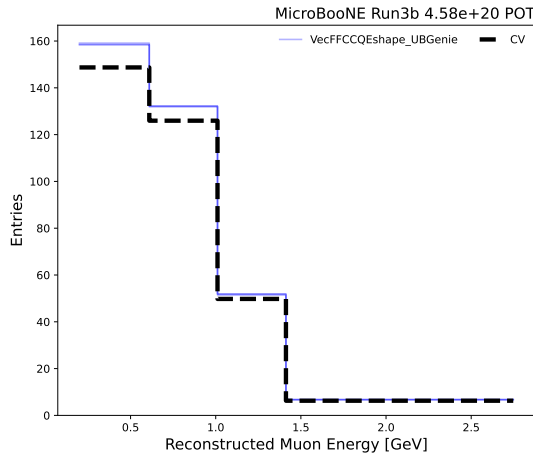
Figure 7.2 *Systematic Uncertainties of the distribution of reconstructed muon energies determined for the various sources as described in the main text. The PPFX, UBGenie and RPA CCQE variations are included here.*



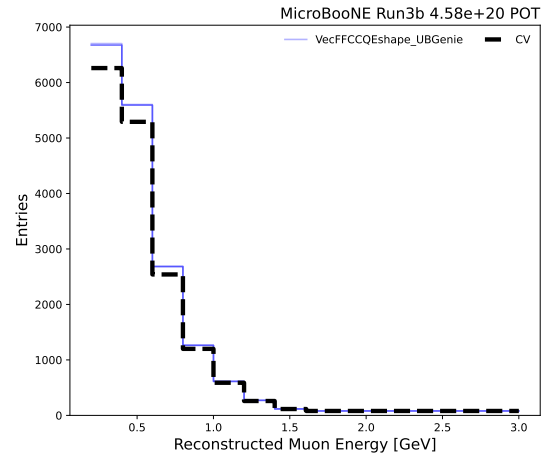
(a) Axial Form Factor $\bar{\nu}_\mu$



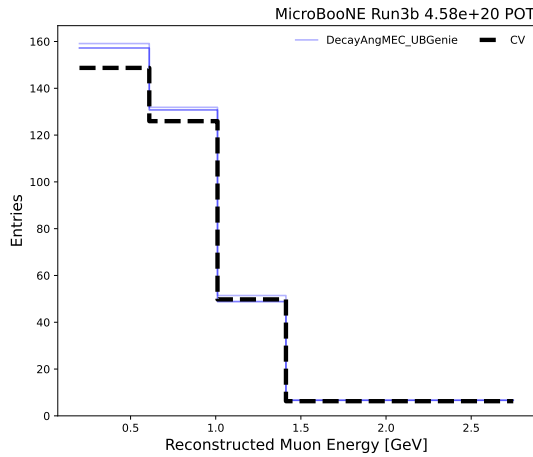
(b) Axial Form Factor ν_μ



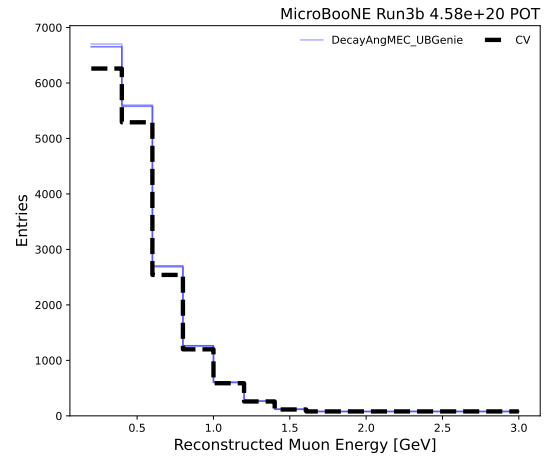
(c) Vector Form Factor $\bar{\nu}_\mu$



(d) Vector Form Factor ν_μ

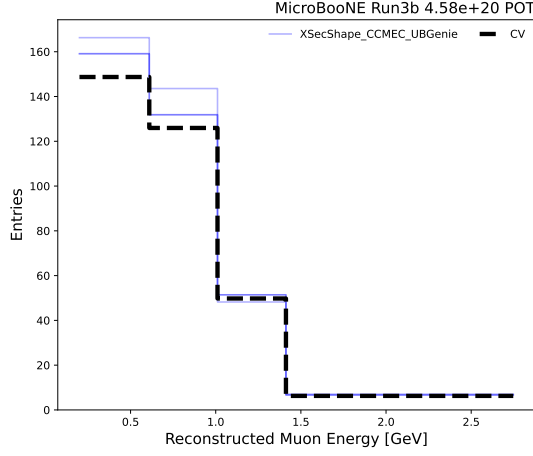


(e) Angular Distribution of Nucleon Cluster $\bar{\nu}_\mu$

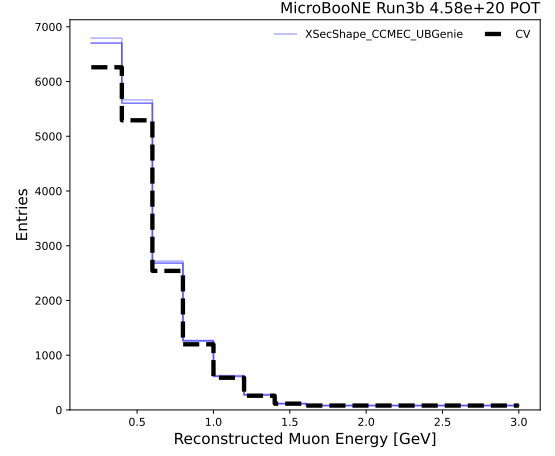


(f) Angular Distribution of Nucleon Cluster ν_μ

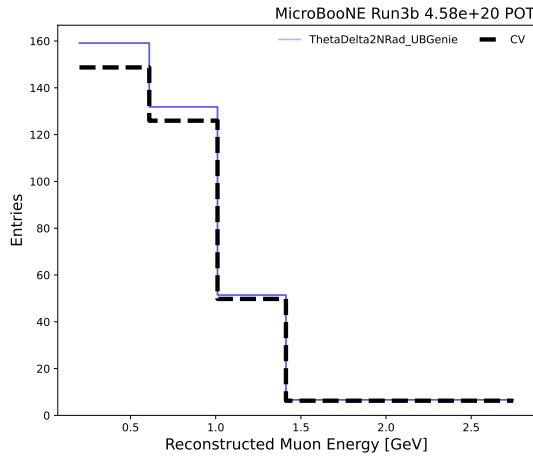
Figure 7.3 Systematic Uncertainties of the distribution of reconstructed muon energies determined for the various sources as described in the main text. The Axial Form Factor, Vector Form Factor and Angular Distribution of Nucleon Cluster variations are included.



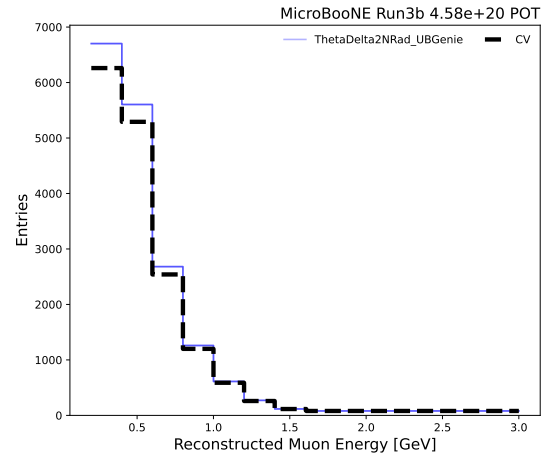
(a) *Cross Section Shape MEC $\bar{\nu}_\mu$*



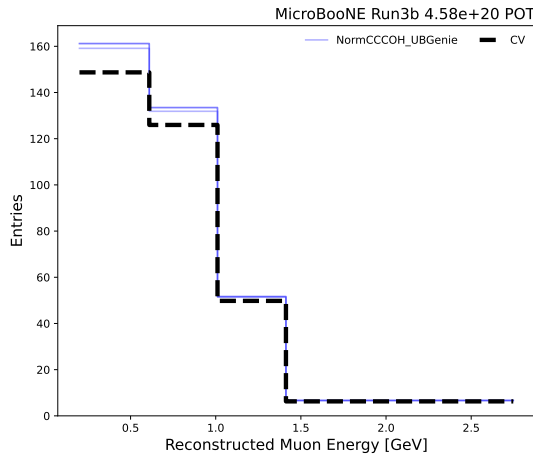
(b) *Cross Section Shape MEC ν_μ*



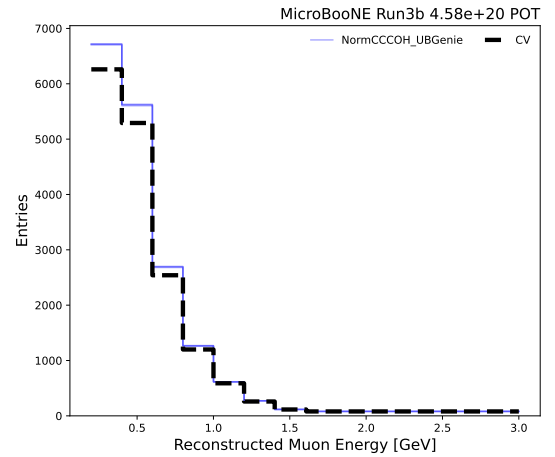
(c) *Angular Distribution $\Delta \rightarrow N + \pi \bar{\nu}_\mu$*



(d) *Angular Distribution $\Delta \rightarrow N + \pi \nu_\mu$*

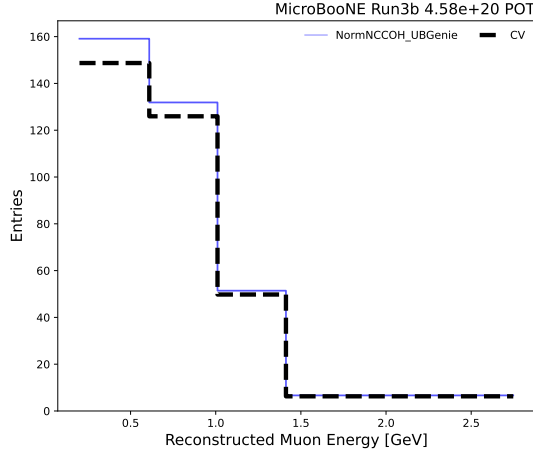


(e) *Scale Coherent π Production CC $\bar{\nu}_\mu$*

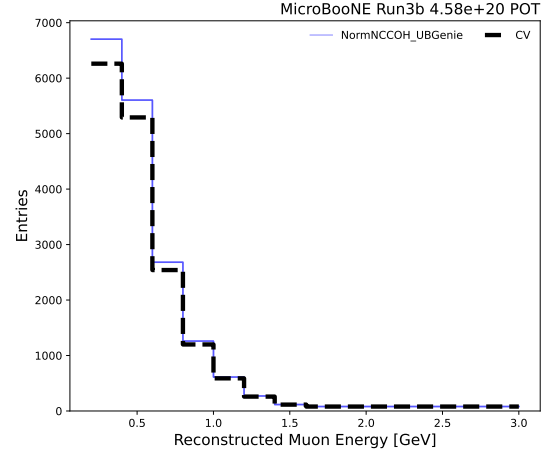


(f) *Scale Coherent π Production CC ν_μ*

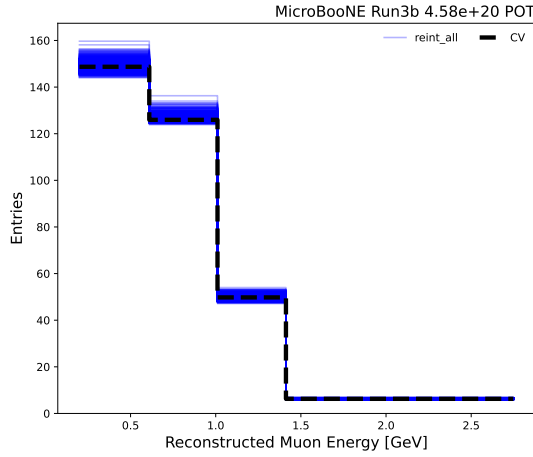
Figure 7.4 *Systematic Uncertainties of the distribution of reconstructed muon energies determined for the various sources as described in the main text. The Cross Section Shape MEC, Angular Distribution $\Delta \rightarrow N + \pi$ and Scale Coherent π Production variations are included.*



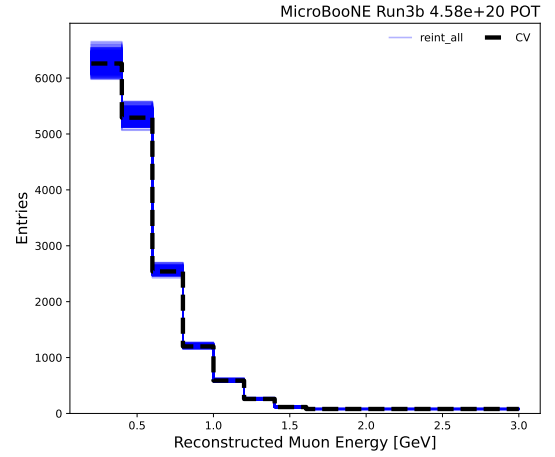
(a) *Scale Coherent π Production NC $\bar{\nu}_\mu$*



(b) *Scale Coherent π Production NC ν_μ*



(c) *Reinteractions, $\pi^\pm$ and protons $\bar{\nu}_\mu$*



(d) *Reinteractions, $\pi^\pm$ and protons ν_μ*

Figure 7.5 *Systematic Uncertainties of the distribution of reconstructed muon energies determined for the various sources as described in the main text. The Scale Coherent π Production NC and Reinteractions, $\pi^\pm$ and protons variations are included.*

Table 7.3 *The systematic variations that use the re-weighting method with a given number of universes, N_{Uni} . Those with 2 universes vary the given parameter(s) by one σ . Variations with more than 2 universes sample the parameter(s) N_{Uni} times and take the uncertainty as one σ of the resulting distribution.*

Systematic Variation	Type	N_{Uni}
Hadron production modelling, impacting observed flux	Flux	600
GENIE All (All_UBGenie) (Details in Appendix C)	XSec	600
Random Phase Approximation Corrections (RPA)	XSec	2
Axial Form Factor (AxFFCCQEshape)	XSec	2
Vector Form Factor (VecFFCCQEshape)	XSec	2
Angular distribution of nucleon cluster (DecayAngMEC)	XSec	2
Varies shape of the differential cross section. (XSecShape_CCMEC)	XSec	2
Interpolates angular distribution $\Delta \rightarrow N + \pi$ (ThetaDelta2NRad)	XSec	2
Scaling factor for π production CC. (NormCCCOH)	XSec	2
Scaling factor for π production NC. (NormNCCOH)	XSec	2
Reinteractions, including $\pi^\pm$ and protons. (Reint_all)	Reint	1000

7.2.3 Fractional Contributions

Figure 7.6 shows the fractional contribution of each systematic variation, and the total statistical uncertainty, with respect to the total measured cross section for each sample. The relatively small amount of data for the antineutrino sample clearly shows (a) a larger fractional statistical uncertainty, but also (b) that it is more susceptible to systematic variations. In particular, the recombination detector variation, where the β parameter of the MBM is adjusted, impacts the measured cross section by 48.2%. The muon neutrino sample benefits from excellent statistics, and observes a relatively low impact from the equivalent systematic variations, across the board.

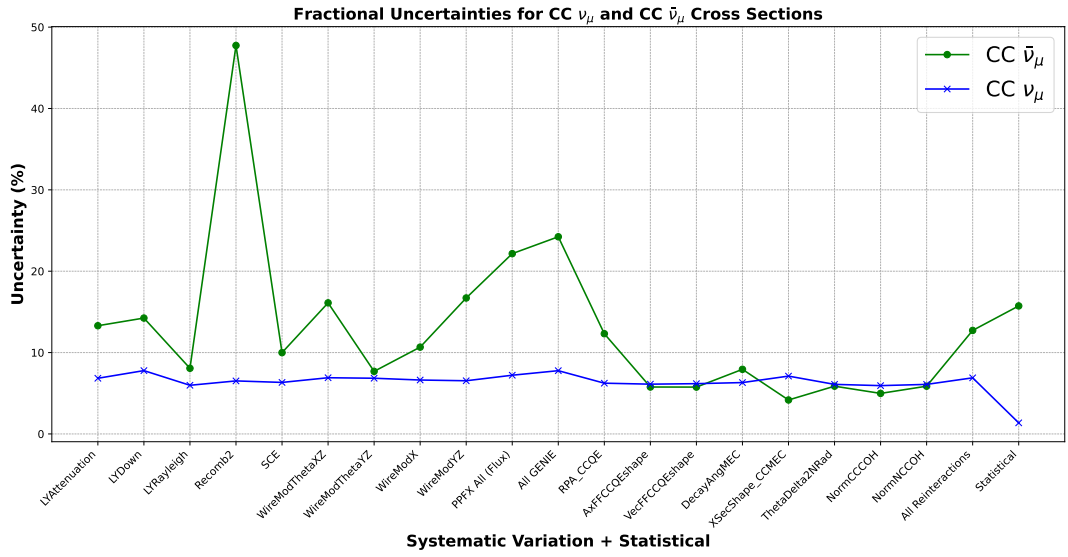


Figure 7.6 Fractional uncertainties for the muon neutrino and antineutrino samples, for each systematic variation. The full contribution from the statistical uncertainty is also included. Values are given as percentages of the measured cross section value. The total statistical error on the antineutrino sample with much fewer events is immediately apparent on the far right.

7.3 Cross Section Results

The analysis presented in this thesis has attempted to separate a mixed sample of charged current muon neutrino and antineutrino events, observed by the MicroBooNE LArTPC detector, from the off-axis flux of the NuMI beam, in RHC mode. It has then used those separated samples to calculate individual flux-integrated cross sections for those event types. This chapter will now conclude by presenting the results of those calculations.

The measured flux-integrated cross sections for charged current muon neutrino and neutrino interactions are given by Equations 7.8 and 7.9. Both systematic and statistical uncertainties are included separately. Values are given in cm^2 per nucleon. The results are also graphically illustrated in Figure 7.7, with the theoretical predictions from the GENIE event generator framework included with shaded error bands for each. Both theoretical predictions are within the uncertainties of their respective measured results. The final values used for the calculations are presented in Table 7.4.

Table 7.4 *The final values used in the cross section measurements for charged current muon neutrino and antineutrino interactions on argon. The B composition has been expanded to show a detailed breakdown of the background contributions for each sample. Recall that additional background from poor low energy reconstruction into higher-than-true energy bins increases the MC background contribution compared to the sample plots. The bottom row shows the estimated number of signal events selected for each sample.*

Parameter	Value CC ν_μ	Value CC $\bar{\nu}_\mu$
N_{BO}	15897	300
B (Total)	4146.5	171.2
MC Backgrounds	3327.1	154.2
Cosmic Activity	498.6	4.8
Dirt interactions	320.7	12.2
ϵ	41.35%	2.42%
$N_{BO} - B$	11750.5	128.8

$$\sigma_{CC\bar{\nu}_\mu} = [1.60 \pm 0.25(\text{stat}) \pm 0.72(\text{sys})] \times 10^{-39} \text{ cm}^2/\text{nucleon} \quad (7.8)$$

$$\sigma_{CC\nu_\mu} = [9.54 \pm 0.13(\text{stat}) \pm 2.18(\text{sys})] \times 10^{-39} \text{ cm}^2/\text{nucleon} \quad (7.9)$$

This analysis is the first attempt to separate a heavily mixed sample of muon neutrino and antineutrino interactions without a magnetic field, using machine learning techniques, and use the results for a flux-integrated total cross section measurements. They correspond to a mean ν_μ energy of 2107 MeV and a mean $\bar{\nu}_\mu$ energy of 1408 MeV.

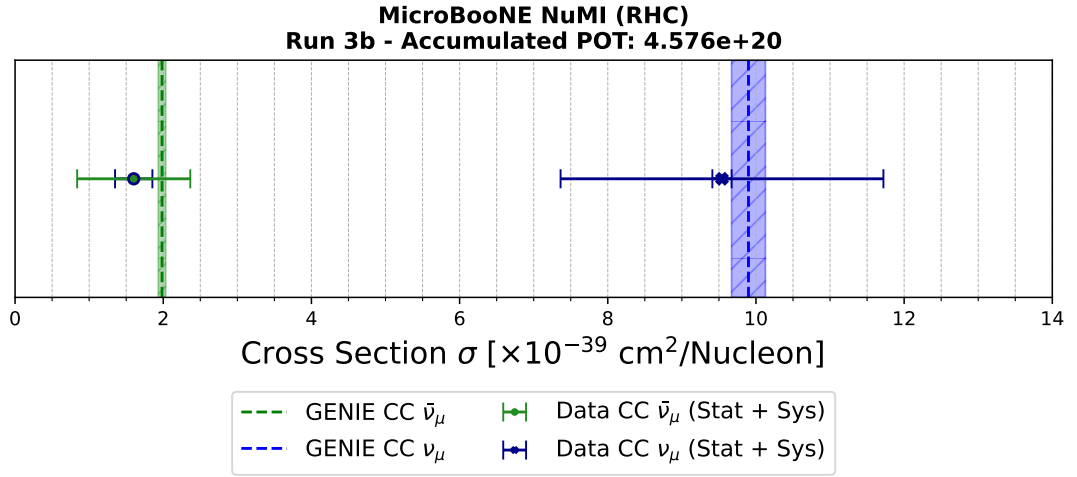


Figure 7.7 *Flux integrated total cross sections for muon neutrino, $\langle E_\nu \rangle = 2107 \text{ MeV}$, and antineutrino, $\langle E_{\bar{\nu}} \rangle = 1408 \text{ MeV}$, samples, selected from the NuMI beam exposure observed by the MicroBooNE detector. Error bars include both statistical and systematic uncertainties. The vertical dashed lines correspond to GENIE theoretical predictions, and the shaded regions surrounding them correspond to the statistical uncertainty of those predictions. Both experimentally measured results are observed to agree with the theoretical predictions within their corresponding uncertainties.*

Chapter 8

Conclusions

This thesis presented a detailed investigation into the targeting of muons in LArTPCs. This has included research and development into the online triggering of data readout for DUNE, and for targeting specific neutrino interactions within the current MicroBooNE dataset to make neutrino and antineutrino cross section measurements.

The successful development of software triggering algorithms to target specific event topologies was demonstrated using a DUNE prototype at the CERN neutrino platform. Whilst rejecting the relatively large flux of more vertically traversing cosmic ray muons, the Horizontal Muon Algorithm was able to trigger the readout of data related to the less frequent cosmic muons with a larger horizontal component of momentum. This was achieved using recursive checks based around a configurable adjacency threshold, using the collection plane TPC sense channels to search for clusters of neighbouring hits. A similar method by which one could search for stopping muon events, which include a Michel electron was proposed and successfully demonstrated with a proof-of-concept algorithm.

The cross section analysis using data from MicroBooNE used a novel approach based on advanced machine learning techniques to select and separate an admixture of charged current muon neutrino and antineutrino events. The separated samples were successfully used to calculate flux-integrated total cross sections for both neutrino and antineutrino samples. The events were recorded during the data-taking phase called run 3b of the MicroBooNE detector, whilst observing a highly off-axis flux of muon neutrinos from the NuMI neutrino beam. The total flux observed for this analysis was equivalent to 4.576×10^{21} POT.

The data was reconstructed using the Pandora event reconstruction framework, and the variables calculated therein contribute to the training features for the **XGBoost** BDT models used in the event selection procedure. In total, an estimated 11750.5(128.8) selected signal CC ν_μ ($\bar{\nu}_\mu$) events were selected for the cross section measurements. They lead to the calculated results which are in agreement with the **GENIE** neutrino event generator:

$$\sigma_{CC\nu_\mu} = [9.54 \pm 0.13(\text{stat}) \pm 2.18(\text{sys})] \times 10^{-39} \text{ cm}^2/\text{nucleon}$$

$$\sigma_{CC\bar{\nu}_\mu} = [1.60 \pm 0.25(\text{stat}) \pm 0.72(\text{sys})] \times 10^{-39} \text{ cm}^2/\text{nucleon}$$

Further Work

The large data sample obtained for the CC ν_μ sample lends itself to the extension of a differential cross section measurement. This is a work in progress, where the outgoing lepton energy and lepton polar angle with respect to the incoming neutrino are the target variables to obtain a measurement of $d\sigma/dE_\mu$ or $d\sigma/d\theta_\mu$. The work involves using a Wiener-SVD filter to unfold the selected sample from reconstructed space into an estimated truth space. This has the benefit that theorists do not require a detailed understanding of the nuances of the MicroBooNE detector and reconstruction framework when comparing theoretical predictions to experimental measurement.

As alluded to in the neutrino and antineutrino separation task in Chapter 7, the analysis would benefit from further work on the reconstruction capabilities of Michel electrons. This requires a good understanding of the lower energy response of LArTPCs considered here. It is also highlighted that the BDT models were trained on simulated samples which are based on an input set of theoretical cross section models. Further work might include the regeneration of those samples with a varied set of models to investigate the impact on the extracted samples and measured cross sections. An improved reconstruction efficiency of Michel electrons would likely enable the separator BDT model to use this as a further handle for improved classification performance. This is currently being scoped via the use of MC truth-level information, using the presence of a Michel electron to generate a testing feature for use in model training. In practice, this does indeed aid the classification task. However, it is also noted that a large weighting on the Michel variable leads the model to classify signal events that have a muon

stopping inside the detector, which places constraints on the muon energies or angles that can be considered. This research advances (anti)muon targeting and cross section measurement techniques with neutrino detectors, as the era passes where theoretical work is required to be tested beyond the Standard Model.

Appendix A

Horizontal Muon Triggering: Event Gallery

This section contains a small event display gallery, showing a few of the triggered and stored events using the HMA for various thresholds at the CERN neutrino platform, using the VDCB prototype for DUNE. There are three runs presented here, corresponding to adjacency thresholds of 100, 150 and 170 collection strips. The details of these runs are summarised in Table [A.1](#).

Table A.1 *Key details of the self-triggering runs taken with the VDCB DUNE Prototype, using adjacency thresholds of 100, 150 and 170 with the HMA.*

Run Number	Threshold	TRs Stored	Trigger Rate (Hz)
013648	100	33216	1.39
013511	150	62	0.10
013539	170	1583	0.07

A.1 HMA 100

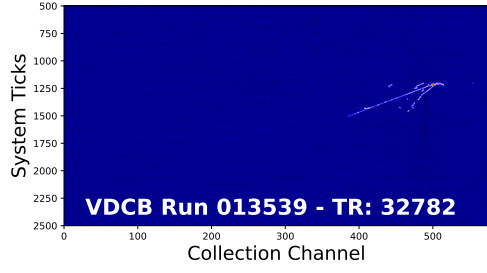
An adjacency threshold of at least 100 collection strips corresponds to physics activity with a horizontal component of at least 50 cm in the VDCB. Being the lowest threshold considered here, it is not uncommon to see more vertically oriented tracks coincident with the triggered activity in the same TR. This effect is reduced for increasingly large thresholds, see Figure [A.1](#).

A.2 HMA 150

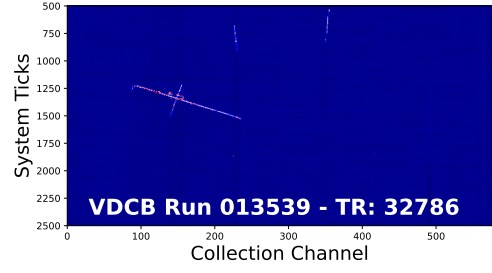
An adjacency threshold of at least 150 collection strips corresponds to physics activity with a horizontal component of at least 75 cm in the VDCB. This threshold had the effect of reducing the trigger rate to approximately 10% of that from the 100 threshold, see Figure [A.2](#).

A.3 HMA 170

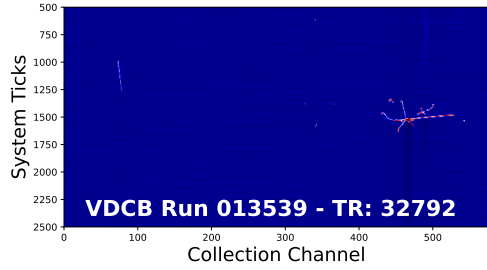
An adjacency threshold of at least 170 collection strips corresponds to physics activity with a horizontal component of at least 85 cm in the VDCB, see Figures [A.3](#) and [A.4](#). In particular, [A.4c](#) shows a track passing the entire length of the BDE side of the VDCB, corresponding to an activity with a horizontal component of at least 2.8 m.



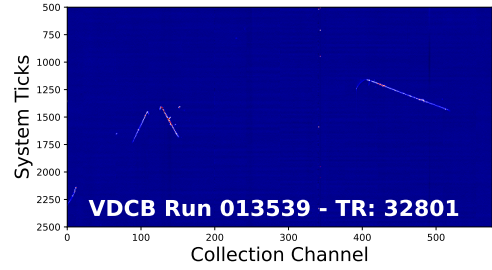
(a)



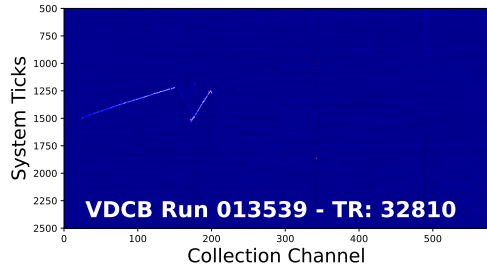
(b)



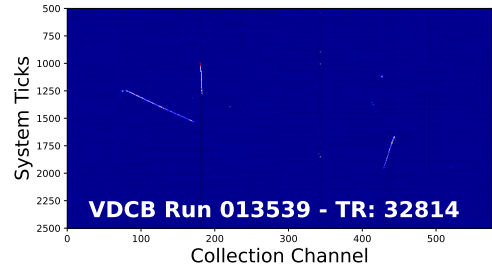
(c)



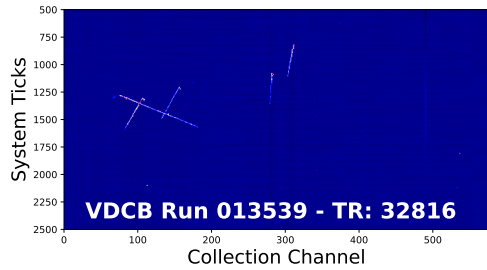
(d)



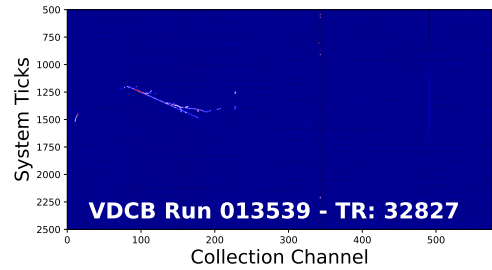
(e)



(f)

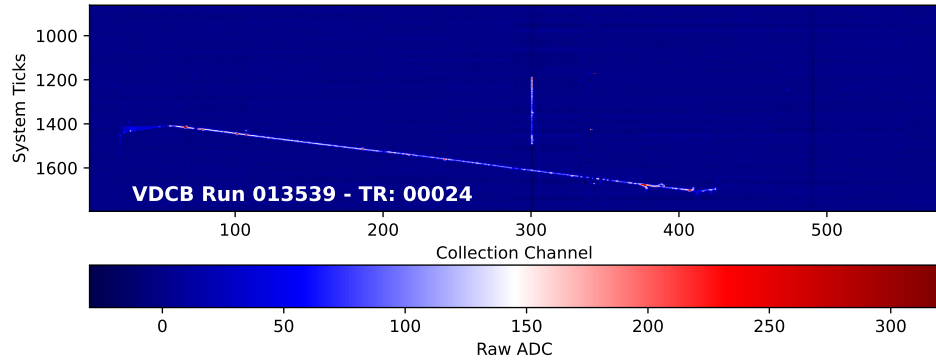


(g)

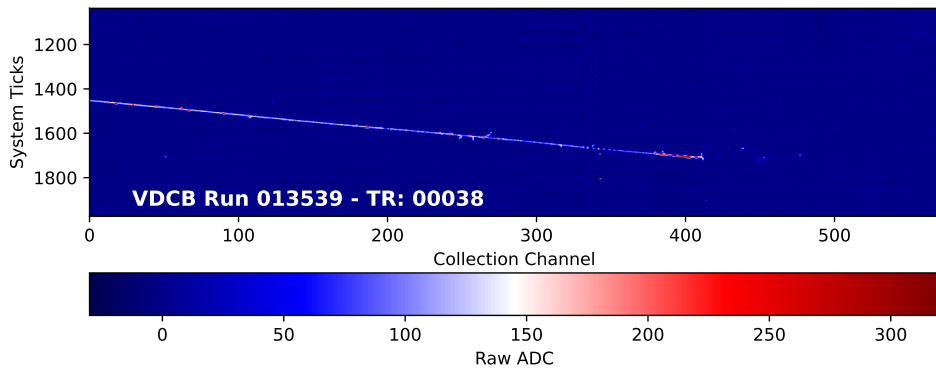


(h)

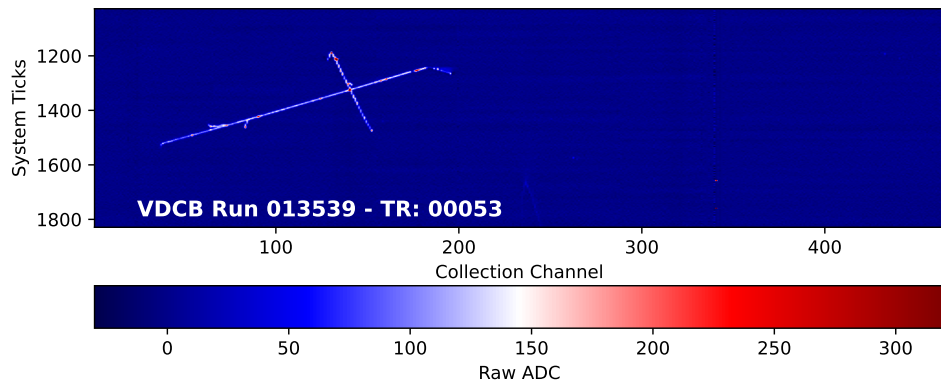
Figure A.1 *An event display gallery for one of the runs taken on the VDCB DUNE prototype LArTPC at CERN. This run used the HMA with an adjacency threshold of 100 collection strips.*



(a)

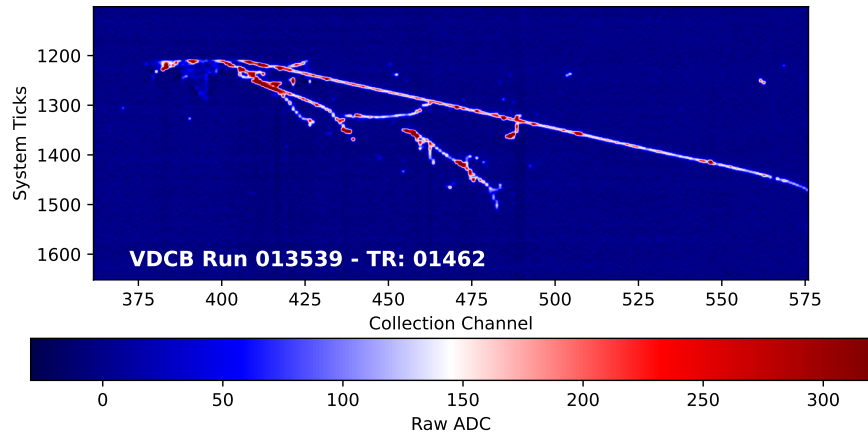


(b)

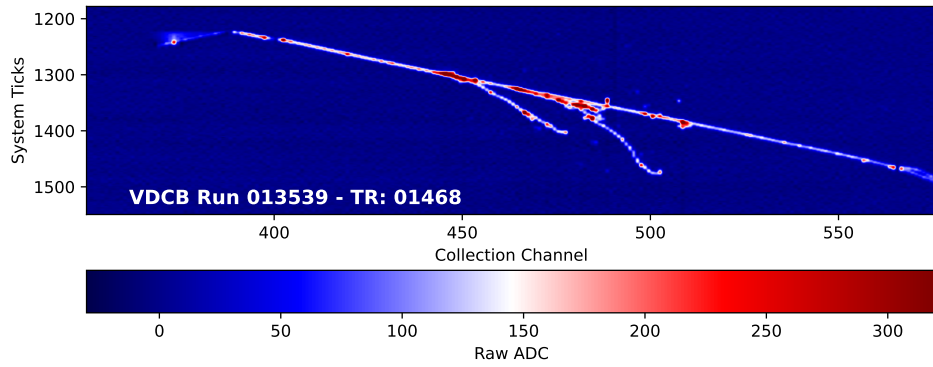


(c)

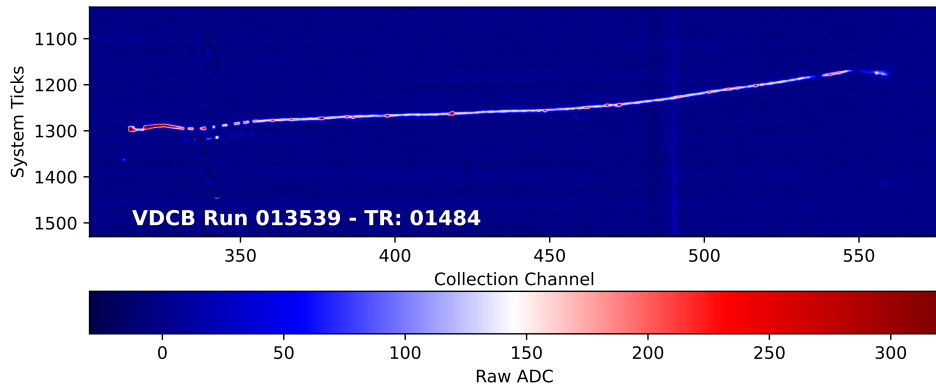
Figure A.2 *An event display gallery for one of the runs taken on the VDCB DUNE prototype LArTPC at CERN. This run used the HMA with an adjacency threshold of 150 collection strips.*



(a)



(b)



(c)

Figure A.3 *An event display gallery for one of the runs taken on the VDCB DUNE prototype LArTPC at CERN. This run used the HMA with an adjacency threshold of 170 collection strips.*

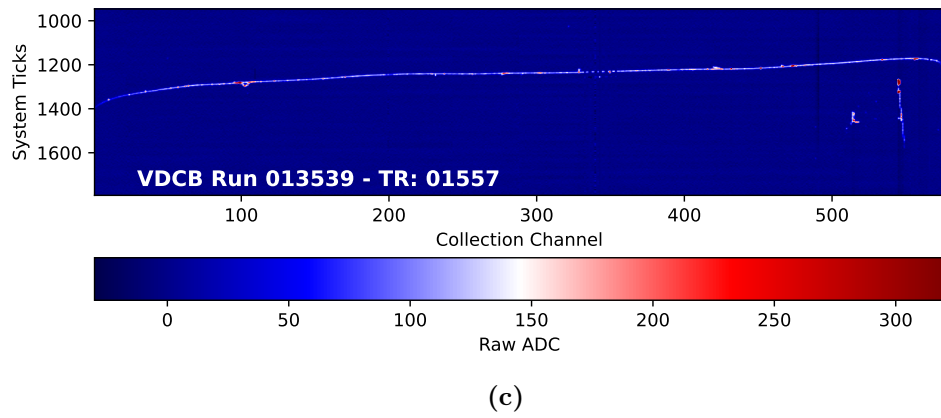
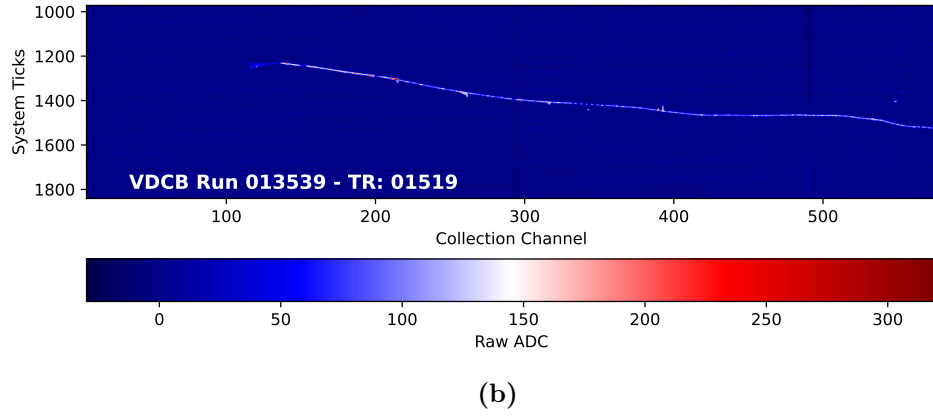
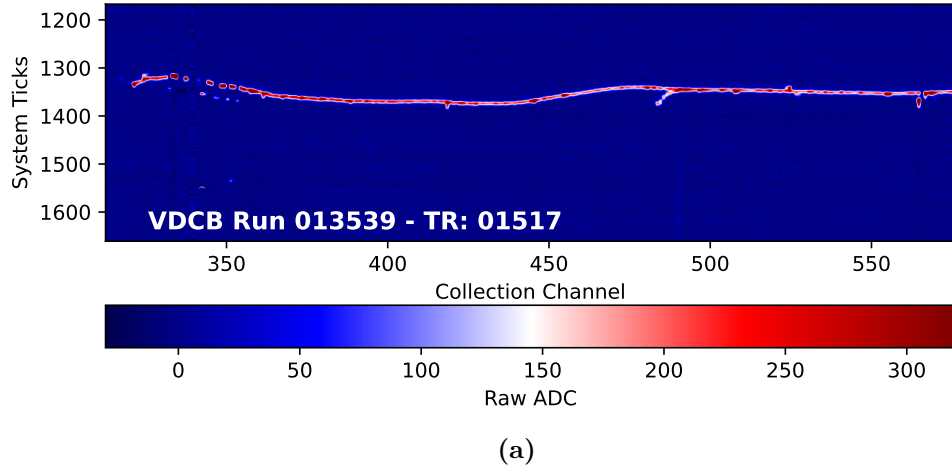


Figure A.4 *An event display gallery for one of the runs taken on the VDCB DUNE prototype LArTPC at CERN. This run used the HMA with an adjacency threshold of 170 collection strips.*

Appendix B

Machine Learning in Neutrino Experiments

B.1 Machine Learning in Neutrino Experiments

In what follows, the application of some ML techniques to neutrino oscillation experiments will be discussed. Each technique has something unique to offer, which demonstrates the wide-reaching capabilities and potential of ML in particle physics.

B.1.1 MicroBooNE - Event Classification with CNNs

MicroBooNE is a neutrino experiment which uses LArTPC detector technology, with a goal of investigating the low energy excess of electron neutrino events ($E_\nu < 500$ MeV) observed in MiniBooNE [100]. In the reconstruction and analysis chain, two NNs of the CNN variety are used. The first, called a Sparse Semantic Segmentation Convolutional Neural Network (SparseSSNET) [101], is used to label the interaction topology as a track or shower type in a semantic segmentation task. This is an improvement on the preceding CNN called U-RESNET [102]. For both models, an analysis of the performance on stopping muon and CC neutral pion, π^0 events was performed. Further down the analysis chain, the second CNN is used for multi-particle identification (MPID) [85], which outputs probabilities for certain particles to be contained within the event. The

use of the two CNNs in the main analysis chain, mentioned above will be discussed here.

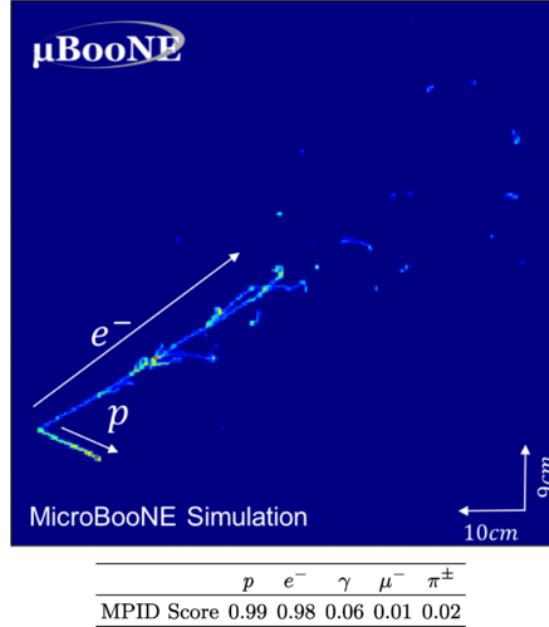


Figure B.1 *An example of an image produced from the MicroBooNE LArTPC, showing the relative sparsity of information when compared with everyday photographs [85].*

Traditionally, CNNs have been developed for the task of identifying objects in everyday photographs [103]. In this case, the relative pixel-to-pixel information is useful and warrants the computationally expensive dense architecture of a standard CNN. However, the image-like data that LArTPCs produce is largely void of this information density, with around 99.5% of pixels making up a block colour background, see Figure B.1. The useful information is contained within the geometry of the interaction vertex, and the shape of the tracks and showers surrounding it.

The primary advantage of sparse algebras over dense ones is that they are less CPU intensive. Some MicroBooNE-specific examples of this include the following:

1. The use of a sparse network architecture was studied for the task of identifying neutrino interaction events as track-like or shower-like. This is a classification task, and where U-RESNET required 2 weeks to train [104], the new sparse algebra required only 8 hours.
2. U-RESNET also required the cropping of original 3456×1600 pixel images to sets of $64 \times 512 \times 512$ pixel images using a cropping algorithm (CRA).

SparseSSNET does not require the cropping of the original input images to 64 images, already introducing a factor of roughly 60 saving on processing time.

3. SparseSSNET also boasts a factor of 10 improvement in training time per image. For a 512×512 pixel image, U-RESNET required 5s per image, whereas the sparse architecture requires only 0.5s, where these performance tests were completed on a commonly available Intel core i7-8750H CPU 2.2 GHz [101].
4. The time required to analyse the current MicroBooNE open data set is reduced from approximately 2267 days for the dense architecture to around 1 day for the sparse one. The reduction in memory requirements for SparseSSNET makes it possible to train on commonly available computing resources, and is therefore much cheaper.

CNN Neutrino Event Classifier - NOvA

NuMI Off-axis ν_e Appearance (NOvA) is another neutrino experiment, with a detector sensitive to θ_{13} . NOvA has studied the use of a CNN called the Convolutional Visual Network (CVN) and its performance in neutrino event classification for event reconstruction [79]. Unlike the BDT models mentioned above, the CVN does not require detailed reconstruction-based information. It predicts whether events are charged current (CC) μ, e, τ or neutral current (NC). In the case of CC searches, NC events constitute part of the background. These event categories are then subdivided into either quasi-elastic (QE), resonant (RES) or deep inelastic scattering (DIS). These can produce charged and neutral pions, which typically contribute significant backgrounds for CC $\nu_\mu/\bar{\nu}_\mu$ and CC $\nu_e/\bar{\nu}_e$ event searches respectively.

The CVN architecture is largely based on GoogLeNet, which took part in the 2014 ImageNet classification challenge (ILSVRC 2014) mentioned above. It came first with a top 5 error of 6.67% [78]. It takes advantage of something called an inception module, which is inspired by the older network called Inception, also developed by Google. An inception module takes as the input the output from the previous layer (the feature maps) and uses varied size kernels to extract abstract features of different scales. These are then concatenated into a single output. Unlike GoogLeNet which accepts a single image as input, the CVN has access to

two distinct views of the same event. This leads to an architecture which processes the (x - z view, or X) and (y - z view, or Y) views in parallel and independently of each other. Figure B.2 illustrates the first few layers of the CVN and helps to visualise this.

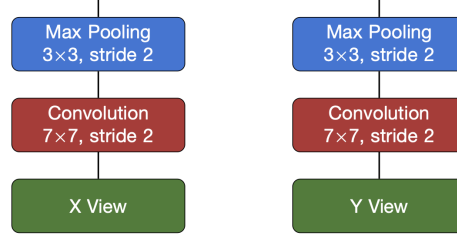


Figure B.2 *A simplified illustration of part of the CVN architecture used in [79]. The X and Y views of the detector form the input to the CVN which are passed to green boxes accordingly. The subsequent convolutional and max pooling layers act on each image separately until the resulting feature maps are concatenated deeper in the network.*

Furthermore, the number of inception modules included in these parallel sections of the network was reduced from nine, as used in GoogLeNet, to three without loss of predictive power. This is because the images seen in the NOvA detector are far simpler than those used in the ImageNet classification challenge. The CVN has 10 outputs, corresponding to CC and NC events, with each of the 3 CC sub-categorised into QE, RES and DIS as described above. The predicted probability for an event to be a ν_l CC would then be the sum of ν_l CCQE, ν_l CCRES and ν_l CCDIS for example.

NOvA’s CVN was trained on 80% of the 4.7 million simulated images, which included the 2.1% intrinsic ν_e contamination of a ν_μ dominant beam. The remaining 20% of the sample was used for validation, also called *testing* in [79]. They also used augmentation techniques to expand the dataset size which has the effect of reducing over-training, whereby the model learns the pattern of the training dataset and fails to generalise to new, unseen examples. The training was relatively fast, and required a full week of GPU hours on a pair of NVIDIA Tesla K40s, using MiniBatch Gradient Descent with a batch size of 32. The regularisation techniques described here allowed for excellent generalisation to new data, which can be seen in Figure B.3 by the lack of deviation between the test and training data losses.

The performance of the CVN on a statistically independent set of data is summarised in the stacked-score plots in Figure B.4. The left plot details the

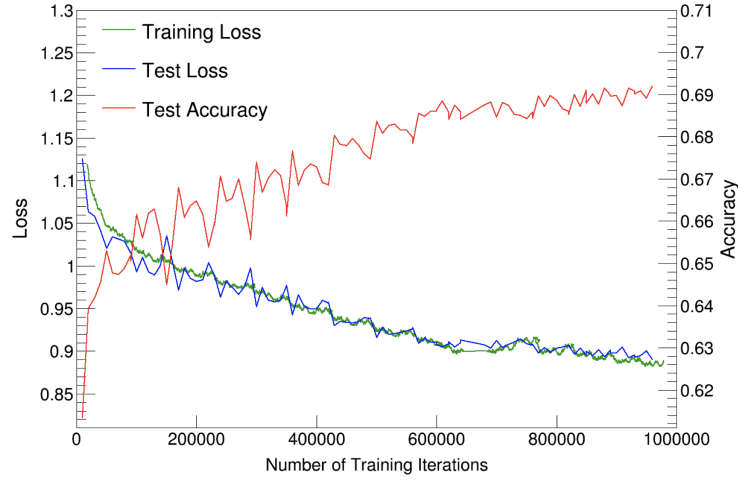


Figure B.3 *Evolution of the loss for both the training (green line) and testing (blue line) data as a function of the iteration number during training, for the NOvA CVN model. Also included is the model accuracy on the test data (red line). The matching loss for both sets of data is an excellent indicator that the model is not over-fitting the training data [79].*

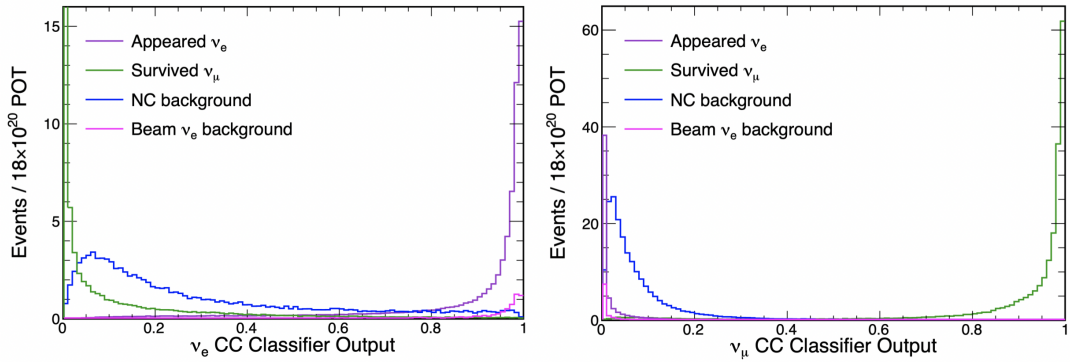


Figure B.4 *Classifier output score distributions, detailing the performance of the CVN on unseen test data that is statistically independent of the training data. Excellent separation of electrons from muons and NC background for CC ν_e events is observed (left). Intrinsic ν_e are indistinguishable from signal events and so are classified as CC ν_e events as expected. Excellent separation of CC ν_μ events from other categories is also observed (right) [79].*

results for ν_e CC events, and the right for the CC ν_μ events. Excellent separation for both classifiers is observed, that of CC ν_e events (left plot) and CC ν_μ events (right plot). The only significant remaining background for the CC ν_e classifier is the intrinsic ν_e to the beam, which are indistinguishable from signal events to the CVN. In summary, the efficiencies quoted in [79] exceeded the existing algorithm solutions for event classification. For CC ν_μ classification, this is 58% compared

to the quoted value of 57% in previous NOvA work. For the CC ν_e classification this is 49% against the quoted 35% which is an impressive improvement. The main backgrounds for CC ν_e and CC ν_μ events are those containing π^0 and $\pi^\pm$ respectively and continued to pose a challenge. It is apparent that events with $\pi^\pm$ in the final state contribute to the backgrounds in the analyses for the CC ν_μ and $\bar{\nu}_\mu$ cross section measurements in the main text.

Appendix C

Treatment of Systematic Uncertainties

C.1 GENIE Tunable Parameters

A full listing of the tunable parameters in the All_UBGenie neutrino interaction modelling is provided in Figure C.1. The estimated effects of the generator are made by resampling the parameters 600 times, and taking the standard deviation, 1σ , around those sampled parameter distributions as the contributed uncertainty to the All_UBGenie systematic variation given in the main text.

	Parameter	Description	CV	Uncertainty
0	MaCCQE	CCQE axial mass	1.10 GeV	0.1
1	CoulombCCQE	Value of Coulomb potential used in corrections for CCQE	Valencia	30%
2	MaNCEL	Axial mass for NCEL	0.96 GeV	25%
3	EtaNCEL	Empirical parameter used to account for sea quark contribution to NCEL form factor	0.12	30%
4	NormCCMEC	Energy-independent normalization for CCMEC	1.66	0.5
5	NormNCMEC	Energy-independent normalization for NCMEC	1	100%
6	FracPNCMEC	Fraction of initial nucleon pairs that are pn	Valencia	20%
7	FracDeltaCCMEC	Relative contribution of diagrams to total MEC cross section	Valencia	30%
8	MaCCRES	CCRES axial mass	1.12 GeV	20%
9	MvCCRES	Shape-only CCRES axial mass	0.84 GeV	10%
10	MaNCRES	NCRES axial mass	1.12 GeV	20%
11	MvNCRES	NCRES vector mass.	0.84 GeV	10%
12	NonRESBGvpNC1pi	Non-resonant background normalization for p NC1	0.1	50%
13	NonRESBGvpNC2pi	Non-resonant background normalization for p NC2	1	50%
14	NonRESBGvnNC1pi	Non-resonant background normalization for n NC1	0.3	50%
15	NonRESBGvnNC2pi	Non-resonant background normalization for n NC2	1	50%
16	NonRESBGvbarpNC1pi	Non-resonant background normalization for p NC1	0.3	50%
17	NonRESBGvbarpNC2pi	Non-resonant background normalization for p NC2	1	50%
18	NonRESBGvbarvNC1pi	Non-resonant background normalization for n NC1	0.1	50%
19	NonRESBGvbarvNC2pi	Non-resonant background normalization for n NC2	1	50%
20	NonRESBGvpCC1pi	Non-resonant background normalization for p CC1	0.0077	50%
21	NonRESBGvpCC2pi	Non-resonant background normalization for p CC2	0.79	50%
22	NonRESBGvnCC1pi	Non-resonant background normalization for n CC1	0.13	50%
23	NonRESBGvnCC2pi	Non-resonant background normalization for n CC2	2.12	50%
24	NonRESBGvbarpCC1pi	Non-resonant background normalization for p CC1	0.13	50%
25	NonRESBGvbarpCC2pi	Non-resonant background normalization for p CC2	2.12	50%
26	NonRESBGvbarvCC1pi	Non-resonant background normalization for n CC1	0.0077	50%
27	NonRESBGvbarvCC2pi	Non-resonant background normalization for n CC2	0.79	50%
28	AhtBY	AHT higher-twist parameter in the Bodek-Yang model scaling variable w	0.54	25%
29	BhtBY	BHT higher-twist parameter in the Bodek-Yang model scaling variable w	0.305	25%
30	CV1uBY	CV1u valence GRV98 PDF correction parameter in the Bodek-Yang model	0.291	30%
31	CV2uBY	CV2u valence GRV98 PDF correction parameter in the Bodek-Yang model	0.189	40%
32	AGKYxF1pi	Hadronisation parameter, applicable to true DIS interactions only	-0.385	20%
33	AGKYpT1pi	Hadronisation parameter, applicable to true DIS interactions only	1/6.625	3%
34	MFP	Mean free path	hA2018 model	20%
35	MFPN	Nucleon mean free path	hA2018 model	20%
36	FrCEX	Fractional cross section for charge exchange	hA2018 model	50%
37	FrInel	Fractional cross section for inelastic scattering	hA2018 model	40%
38	FrAbs	Fractional cross section for absorption	hA2018 model	30%
39	FrCEXN	Fractional cross section for nucleon charge exchange	hA2018 model	20%
40	FrInelN	Fractional cross section for nucleon inelastic scattering	hA2018 model	50%
41	FrAbsN	Fractional cross section for nucleon absorption	hA2018 model	40%
42	RDecBR1gamma	Decay branching ratio (BR)	Nominal BR	50%
43	RDecBR1eta	Decay branching ratio	Nominal BR	50%

Figure C.1 *All_UBGenie tunable parameters, using a resampling of 600 universes to estimate systematic uncertainties on the extracted samples. The corresponding estimated uncertainties are included in the rightmost column [61].*

Appendix D

NuMI Beam Flux

This appendix outlines the issues that were found with the neutrino flux simulations during the late stages of this thesis analysis. It also describes the fixes that were applied [65], showing a much-improved agreement with data in terms of neutrino interaction samples used in the main analysis.

D.1 NuMI Beam Flux Simulation

During the cross section analysis of this thesis, there were two issues found with the predicted flux of the NuMI beam observed by the MicroBooNE LArTPC detector.

1. **Geometry Description:** The propagation of particles in simulation requires a full description of the surrounding environment in terms of the materials and their geometry. In the initial simulation of the particles leaving the NuMI target, an entire row of steel shielding blocks around the beamline had been missed out in the geometry description during modelling, resulting in a larger-than-observed neutrino flux prediction at MicroBooNE. The solution to this was to re-simulate with the updated geometry, where the added shielding would partially resolve the overestimate of neutrino interactions that occur within the LArTPC.
2. **Hadron Production Modelling:** The hadron production modelling within GEANT v4.9.2 included a bug related to the kaon re-interaction cross

section, and needed to be upgraded to **GEANT** v4.10.4 which showed much better agreement with data. In particular, the kaon production modelling which dominates the flux observed by MicroBooNE was much improved by making the transition in **GEANT**. That change also included a much updated *FTFP-BERT* physics process list, which was further relevant to the hadron production modelling.

The analysis in this thesis is concerned with MicroBooNE data where NuMI was operating in the RHC (antineutrino) mode. The original sample, before the flux modelling updates is shown in Figure D.1. A clear overestimate of simulation-based neutrino interactions is present after around 1 GeV, when compared to data, where the cosmic activity is no longer dominant.

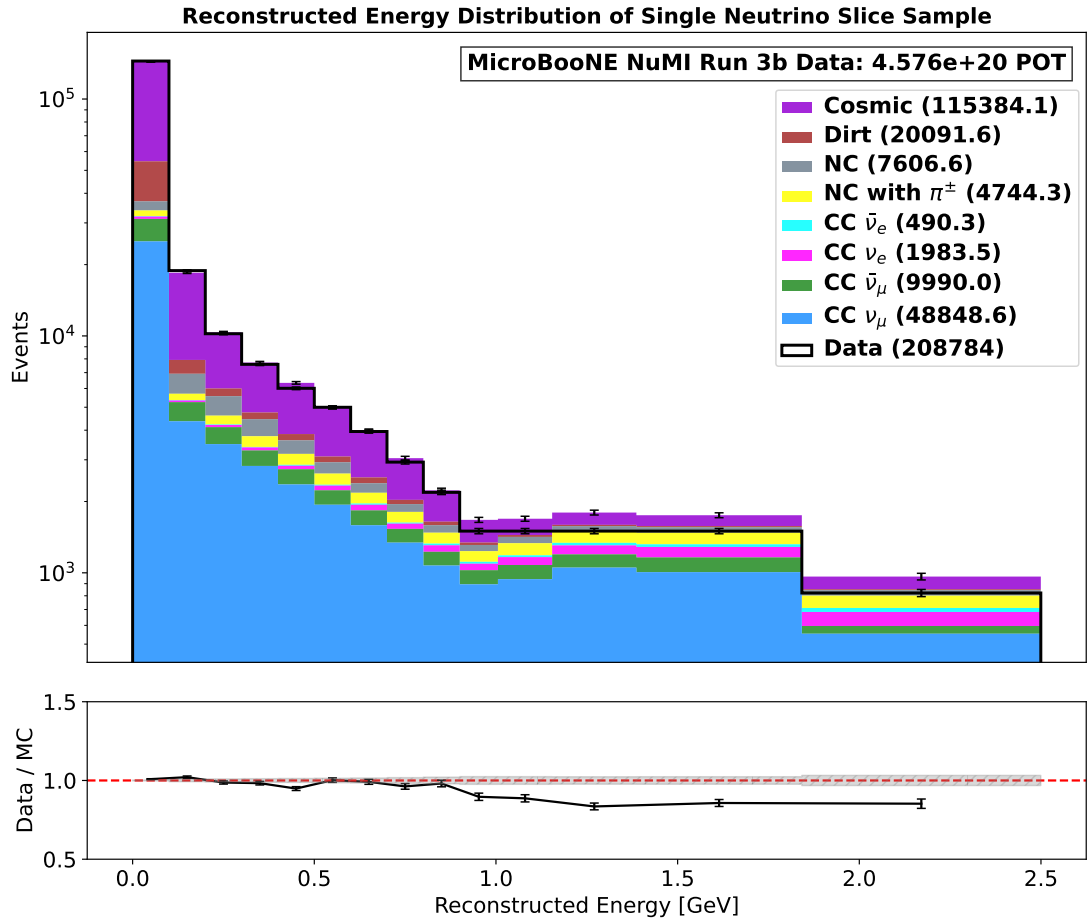


Figure D.1 *MicroBooNE run 3b simulated neutrino sample as a function of reconstructed event energy, before the flux modelling updates were applied. A clear overestimate of simulation-based events is observed after around 1 GeV.*

The simulated flux comparisons, before and after the changes described above

and for each neutrino flavour are given graphically in Figure D.2. An overall reduction in the observed flux is observed across the entire relevant energy range. Further, the equivalent sample presented above, in Figure D.1 is reproduced with a completely re-simulated, statistically independent sample, and is presented in Figure D.3.

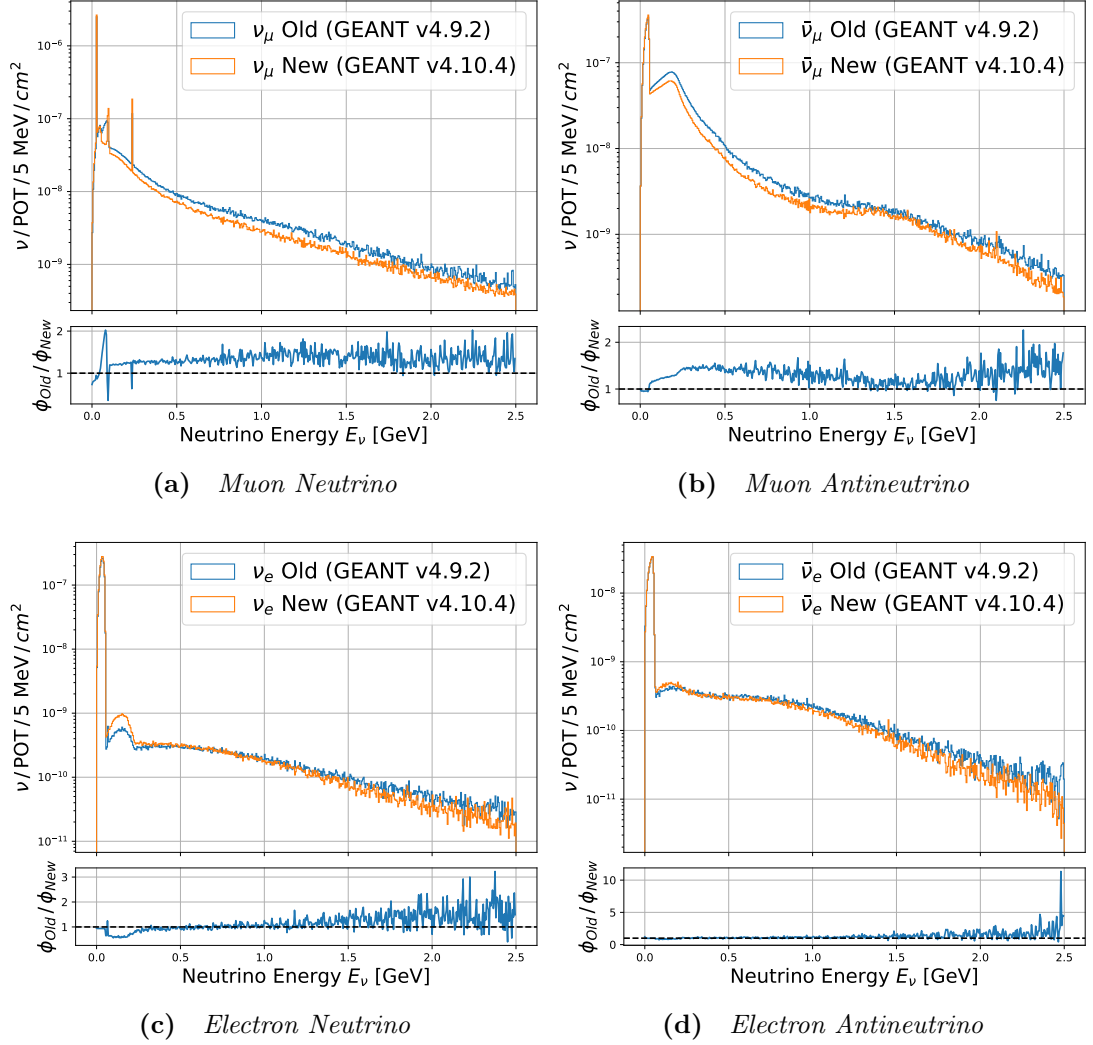


Figure D.2 Four figures, showing the simulated flux comparisons as a function of neutrino energy, for each neutrino flavour, before and after the flux modelling updates described in the text. A clear reduction in the estimate of neutrinos observed by the MicroBooNE LArTPC is observed across the total energy range concerned.

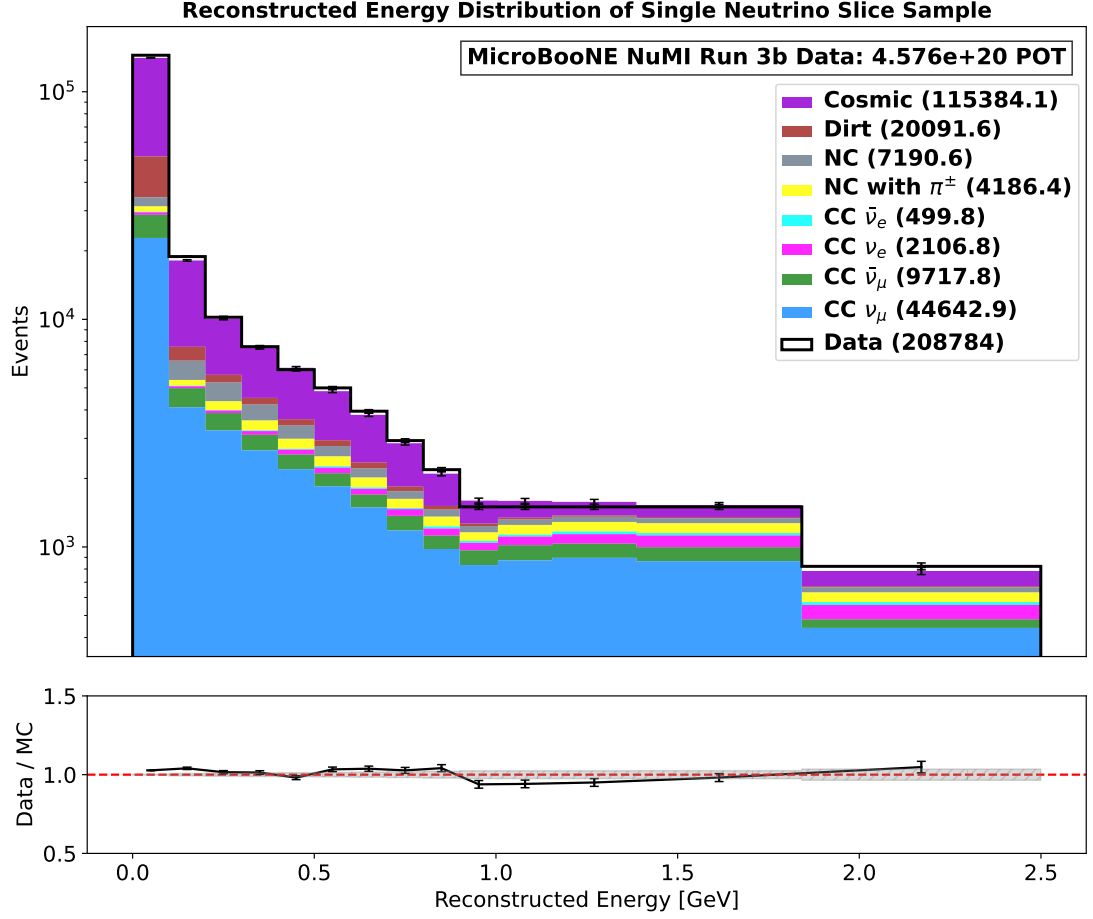


Figure D.3 *MicroBooNE run 3b resimulated neutrino sample as a function of reconstructed event energy, after the flux modelling updates were applied. There is a clear improvement of simulation-based events, observed compared to the region ≥ 1 GeV.*

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