Measuring Neutrino Oscillations in the NOvA and CHIPS Detectors

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I, Medbh Campbell, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.
Abstract

NOvA is a long baseline neutrino experiment which uses muon neutrinos produced by the NuMI beam at the Fermi National Accelerator Laboratory to measure muon neutrino disappearance and electron neutrino appearance, among other analyses. The Far/Near Extrapolation analysis framework (FNEX) was used to measure muon neutrino disappearance using the events observed by NOvA while the NuMI beam was in Forward Horn Current configuration (i.e. this analysis uses neutrino data, not antineutrino data). The values of the parameters measured in this analysis are $\sin^2 \theta_{23} = 0.499^{+0.098}_{-0.069}$ and $\Delta m_{32}^2 = 2.454^{+0.108}_{-0.119} \times 10^{-3}$ eV, which is consistent with the results of NOvA’s main muon neutrino disappearance analysis using the experiment’s usual framework, known as CAF.

The CHIPS detector is a water Cherenkov detector currently in construction. It will also use the NuMI beam to perform muon neutrino disappearance and electron neutrino appearance analyses. The necessary water clarity for a detector with a diameter of 25 m and a height of 6 m is discussed, as well as the results of testing water filtration systems. The filtration that will be used for the detector is a 10 µm carbon block filter and a 0.5 µm filter in series, with no reverse osmosis or ultraviolet sterilisation being used. This provides an attenuation length of $16.63 \pm 0.25$ m for light of 532 nm wavelength (green), so light with a wavelength of 405 nm (violet) would have an attenuation length of $133 \pm 2$ m. The greatest possible distance between a PMT and any point in the detector’s volume is approximately 26 m, so 133 m is sufficient for the detector to measure Cherenkov light produced anywhere in the detector.
Impact Statement

In collaborative research fields such as high energy physics, it can be difficult to isolate the impact of one individual’s contributions to the research field as a whole. While the research presented within this thesis may have no direct impact outside of the NOvA and CHIPS collaborations, the work of each member of the collaboration helps these experiments to leave their mark on particle physics.

Within NOvA, the development of the Far Near Extrapolation analysis framework (FNEX) as an alternative to the experiment’s usual analysis software (CAF) may make NOvA’s results less sensitive to systematic errors once enough data has been collected that NOvA is limited by systematics. NOvA is currently still limited by statistics, but the FNEX results presented in this thesis are still useful as a cross check for the results produced using CAF, which helps to reduce bias or errors in the analysis. I was part of the group that developed FNEX, mostly focussing on how systematics were applied in the code, and performed the $\mu$ disappearance analysis in chapter 3. I was part of the calibration team, specifically running the attenuation calibration described in chapter 2 and adding the fibre brightness variables to the Far Detector’s calibration. I generated the plots describing NOvA’s event selection in chapter 3, but was not involved in choosing the data cuts.

I performed the water clarity research discussed in this thesis, which has been used to select the level of water filtration needed for the CHIPS detector. As a water Cherenkov detector, filtered water with a long light attenuation length will be essential to the detector’s ability to track muons and therefore to measure the energy and trajectory of neutrinos.

Both NOvA and CHIPS have unique features that allow them to make an impact in the high energy physics field. NOvA is one of the leading neutrino oscillation experiments currently running. It has the longest baseline of any current neutrino experiment and uses two functionally identical detectors to reduce the effect of systematic errors, and so offers a significant contribution to global measurements of neutrino oscillation parameters. CHIPS will also further constrain neutrino oscillation parameters, especially $\delta_{CP}$, when combined with the results of NOvA, T2K, and eventually DUNE. It also aims to prove that large scale water Cherenkov detectors can be deployed and maintained in a more time and cost efficient manner. This could lead to an increase in the number and size of detectors in the future, increasing the amount of neutrino data available for analysis.
Contents

1 Neutrino Physics 11
  1.1 History of the neutrino ........................................ 11
    1.1.1 Initial proposal and measurement ......................... 11
    1.1.2 Evidence of oscillation .................................. 11
  1.2 Neutrino Physics Theory ...................................... 12
    1.2.1 Standard Model ............................................ 12
    1.2.2 Neutrino Oscillations ..................................... 14
    1.2.3 Muon neutrino disappearance ............................. 18

2 The NOvA Experiment 21
  2.1 Overview and Physics Goals ................................... 21
  2.2 The NuMI Beam .................................................. 21
    2.2.1 Off axis .................................................. 22
  2.3 Detectors ....................................................... 23
    2.3.1 Far detector ............................................... 26
    2.3.2 Near detector ............................................. 28
  2.4 Reconstruction ................................................ 28
  2.5 Simulation ...................................................... 32
  2.6 Calibration ..................................................... 32
    2.6.1 Attenuation Calibration .................................. 33
    2.6.2 Absolute Calibration ..................................... 38
    2.6.3 Lepton to Hadron Ratio .................................. 39

3 Measuring Muon Neutrino Disappearance in NOvA with FNEX 40
  3.1 Muon Neutrino Disappearance Signal .......................... 40
  3.2 FNEX ........................................................... 40
  3.3 Event Selection ................................................ 41
  3.4 Event information ............................................. 56
  3.5 Extrapolation ................................................... 56
  3.6 Systematics ..................................................... 56
  3.7 Results ........................................................ 64
    3.7.1 Comparison with CAF ..................................... 64
    3.7.2 Comparison with NOvA’s latest results and other neutrino experiments 71
List of Figures

1.1 The known elementary particles of the Standard Model can be categorised as quarks, leptons, and bosons. ................................................................. 13
1.2 Feynman diagrams showing a charged current (left) and neutral current (right) interaction. ................................................................. 14
1.3 The normal and inverted mass hierarchies. These diagrams show the proportions of each flavour eigenstate (represented by colours) that is present in each mass eigenstate (represented as horizontal lines). $\Delta m_{23}^2$ is labelled as $\Delta m_{\text{atm}}^2$ and $\Delta m_{12}^2$ as $\Delta m_{\text{sol}}^2$. .................................................. 17
1.4 A global fit of all available neutrino oscillation data in April 2018 ............... 19
2.1 Diagram of NuMI beam. ................................................................. 22
2.2 The simulated neutrino energy spectrum as seen on-axis, 735 km from the target (i.e. the MINOS far detector site) for the low, medium, and high energy tunings. 23
2.3 Plots of neutrino flux (left) and energy (right) as a function of the energy of the decaying pion on-axis and for several off-axis angles. ......................... 24
2.4 Simulation showing the rate of CC $\nu_\mu$ events assuming no neutrino oscillations. Calculated at a distance of 810 km from the beam origin for several off-axis angles. 24
2.5 Diagram of a single NOvA cell: this is constructed from PVC and filled with liquid scintillator. A charged particle passes through and the resulting scintillation light is carried by a wavelength shifting fibre to an APD. ......................... 25
2.6 Diagram of an APD. ................................................................. 26
2.7 Diagram of the NOvA Near Detector and Far Detector. The orange inset shows how planes of horizontal and vertical cells alternate. A person is shown for scale. 27
2.8 Location of the Far Detector and Fermilab. .................................... 27
2.9 The event display from a Far Detector $\nu_\mu$ event selected for the 2017 and 2018 analyses. The top image shows the data for the whole 550$\mu$s. The bottom image shows the single “slice” that contains the $\nu_\mu$ event (circled in red), and all hits that do not belong to the slice are grey. .................................................. 29
2.10 A zoomed in view of the interaction from figure 2.9, showing the reconstructed tracks. ................................................................. 30
2.11 Diagrams of a CC muon neutrino interaction, CC electron neutrino interaction, and NC interaction in the NOvA detectors, with the relevant Feynman diagram. 31
2.12 The $\frac{dE}{dx}$ of a muon as a function of the distance from the end of its track for simulated muons in the Far Detector. The $\frac{dE}{dx}$ is uniform to within 1.8% within the 100 cm to 200 cm window. ............................................................. 33
2.13 A hit is only used for attenuation calibration if there is also a hit in the neighbouring cells in the plane. In this example, only the central hit (darker red) would be used in the attenuation calibration.

2.14 The distribution of PE per cm as a function of $W$ (distance from the centre of the cell) in an X-view cell with a fibre brightness of 0, for a Far Detector simulated sample.

2.15 The threshold corrections according to equation 2.5 for all the vertical cells (left) and the horizontal cells (right) in the Far Detector that have a fibre brightness of 0. These plots are also produced for the other fibre brightnesses in the Far Detector, and for the main body and muon catcher of the Near Detector.

2.16 The results of a polynomial fit of the threshold correction as a function of cell and $W$ in figure 2.15.

2.17 The 1D profiles of the threshold correction factor $T$ as a function of cell (top) and $W$ (bottom) for X-view (left) and Y-view (right) cells. This is shown for each fibre brightness and for the previous calibration (shown in black, generally close to fibre brightness 5 or 6: fibre brightness was not included in the previous calibration).

2.18 The corrected profiles of PE per cm as a function of $W$ for data collected by a randomly selected plane and horizontal (left) and vertical (right) cell in the Far Detector, with the equation 2.6 fit for the calibration used in this thesis (red) and the previous calibration (black).

3.1 Plot of the ReMId PID value plotted against the CVN PID trained in 2018 for the signal MC, i.e. $\nu_\mu$ CC events that have been selected using truth information from the simulation. Events where either value is $\leq 0.7$ are rejected and not used in the analysis.

3.2 Plot of the ReMId PID value plotted against the CVN PID trained in 2018 for the cosmic data. Events where either value is $\leq 0.7$ are rejected and not used in the analysis.

3.3 Plot of the ReMId PID value plotted against the CVN PID trained in 2018 for the beam background. Events where either value is $\leq 0.7$ are rejected and not used in the analysis.

3.4 The CVN trained in 2017 for MC signal, cosmic data, and beam background. Events with a CVN value $\leq 0.1$ are rejected. Note the log scale on the Y axis.

3.5 Number of hits in the event. If there are $< 20$ or $> 399$ hits, the event is rejected.

3.6 The highest number of contiguous planes with hits in this event. If there are $< 5$ hits in contiguous planes, the event is rejected.

3.7 The distance between the top of the detector and the highest prong hit. If this distance is less than 60cm, the event is rejected.

3.8 The distance between the bottom of the detector and the lowest prong hit. If this distance is less than 12cm, the event is rejected.

3.9 The distance between the eastern side of the detector and the furthest east prong hit. If this distance is less than 16cm, the event is rejected.

3.10 The distance between the western side of the detector and the furthest west prong hit. If this distance is less than 12cm, the event is rejected.
3.11 The distance between the front edge of the detector and the furthest forward prong hit. If this distance is less than 18cm, the event is rejected. ................. 48
3.12 The distance between the back edge of the detector and the furthest back prong hit. If this distance is less than 18cm, the event is rejected. ................. 48
3.13 The number of cells between the front edge of the detector and the furthest forward hit in the event. If this is less than 2 planes, the event is rejected. .... 49
3.14 The number of cells between the back edge of the detector and the furthest back hit in the event. If this is less than 2 planes, the event is rejected. ............. 49
3.15 The number of cells the Cosmic Track would have to pass through to leave the detector: if this is less than 1, the event is rejected. Note the log scale on the Y axis. ................................................................. 50
3.16 The number of cells the Cosmic Track would have passed through from where it would have entered the detector: if this is less than 8, the event is rejected. Note the log scale on the Y axis. ................................................................. 50
3.17 The number of cells the Kalman Track would have to pass through to leave the detector: if this is less than 7, the event is rejected. Note the log scale on the Y axis. ................................................................. 51
3.18 The number of cells the Kalman Track would have passed through from where it would have entered the detector: if this is less than 7, the event is rejected. Note the log scale on the Y axis. ................................................................. 51
3.19 The cosine of the angle between the Kalman Track’s direction and the beam direction. If this value is less than 0.5, the event is rejected. ................. 52
3.20 The fraction of the event’s momentum that is transverse to the beam, calculated using prongs. If this value is greater than 0.9, the event is rejected. ........ 52
3.21 BDT PID trained to reject cosmic muons: if this value is less than 0.53, the event is rejected. ................................................................. 53
3.22 The purity and efficiency of the Far Detector selection. This plot uses MC to find the number of signal and beam background (i.e. NC) events, and cosmic data to find the number of cosmic events. The two sources are normalised by time. 54
3.23 The purity and efficiency of the Near Detector selection. This plot uses MC to find the number of signal and beam background (i.e. NC) events. ............. 55
3.24 The fraction of neutrino energy that becomes hadron energy after the interaction, plotted as a function of the reconstructed energy for simulated FHC muon neutrino events. The blue lines split the sample into four bins, each containing an equal number of events. ................................................................. 55
3.25 The ratio of the number of data events to the number of MC events in the Near Detector as a function of reconstructed energy. ............................... 57
3.26 The results of shifting a fake data spectrum by ±1σ and letting the fitter try to find the shift that was applied. ................................................................. 59
3.27 The change to the final fit values of \( \sin^2 \theta_{23} \) and \( \Delta m_{32}^2 \) when a ±1σ shift of each individual calibration and energy systematic is applied to fake data but no systematics are included in the fit. The “Calibration Shape” systematic is one sided, i.e. a negative shift is not physically possible. ............................... 60
3.28 The change to the final fit values of \( \sin^2 \theta_{23} \) and \( \Delta m_{32}^2 \) when a ±1σ shift of each individual MEC-related systematic is applied to fake data but no systematics are included in the fit. ................................................................. 60
3.29 The change to the final fit values of $\sin^2\theta_{23}$ and $\Delta m^2_{32}$ when a $\pm 1\sigma$ shift of each individual mass resonance systematic is applied to fake data but no systematics are included in the fit. ................................................. 61
3.30 The change to the final fit values of $\sin^2\theta_{23}$ and $\Delta m^2_{32}$ when a $\pm 1\sigma$ shift of each remaining systematic is applied to fake data but no systematics are included in the fit. The DIS $\nu n$ CC $1\pi$ and RPA resonance systematics are one sided, i.e. a negative shift is not physically possible. ................................................. 61
3.31 Result of the fit without systematics in the Near Detector. ................................. 65
3.32 Result of the fit without systematics in the Far Detector. ................................. 66
3.33 Result of the fit with systematics in the Near Detector. ................................. 67
3.34 Result of the fit with systematics in the Far Detector. ................................. 68
3.35 Contour showing the best fit point, and the $68\%$ and $90\%$ confidence levels. .... 70
3.36 Contour showing FNEX’s best fit point and $68\%$ and $90\%$ confidence levels (as shown in figure 3.35) and the CAF analysis’s results for the same dataset at $68\%$ and $90\%$ confidence levels. ................................................. 71
3.37 Comparison of several major experiments’ results from 2019. There is some overlap in all of the experiments, especially between NOvA and T2K. .......... 72

4.1 The locations of CHIPS and the MINOS and NOvA far detectors. The colour scale shows the flux of NuMI neutrinos where they emerge at different places, and the contours of peak $L_E = 300$ km/GeV and peak $L_E = 500$ km/GeV are shown in black and red respectively. ................................................. 74
4.2 CHIPS data may help to constrain $\delta_{CP}$ when combined with NOvA and T2K data. The red plot shows a future without CHIPS, while the green and blue plots show the effect of two potential timelines for CHIPS detector deployment on physicists’ ability to measure $\delta_{CP}$. ................................................. 74
4.3 Diagram of a moving source emitting a conical wavefront ................................. 75
4.4 Left: 3D CAD drawing of a plane, showing how the PMTs are angled. Right: photo of a plane. Each PMT has a Winston cone attached to help it to collect light. The large cylinder in the middle of the CAD drawing is to hold electronics, which are connected to the PMTs via CAT 5/6 cables that pass through the PVC pipes. ................................................. 78
4.5 A 3D CAD drawing of the barrel (left) and the top cap of the detector (right), i.e. the sides and “lid” of the detector. Note that the back half of the top cap is constructed from high density planes (as shown in figure 4.4) as that area will see more light from Cherenkov cones from neutrinos moving in the beam direction. 78
4.6 A simulated $\nu_\mu$ CC quasi-elastic event in the CHIPS detector. The top shows the sides of the cylinder as a single stretched out strip, while the two lower plots show the top and bottom caps. The colourful points show the locations of PMTs which have detected light and the magnitude of the charge (i.e. how much light each PMT detected). The dark purple line shows the reconstruction of the ring left by the Cherenkov cone that hits the boundaries of the detector. For this $\nu_\mu$ event, the outer boundaries of the ring are clearly defined. ......................... 80
4.7 A simulated $\nu_e$ CC quasi-elastic event in the CHIPS detector. Compared to the event shown in figure 4.6, the ring is smaller, and fully contained on the side of the detector. The ring is also much less well defined than the clear, easily reconstructed signal from the $\nu_\mu$.

5.1 Left: the pipe that is filled with water for these measurements. It is bolted to the wall exactly perpendicular to the floor. A transparent PVC pipe is used so the water level can be monitored. Markings on the pipe show the depth of the water at that point. A perspex plate and a rubber gasket seal the base of the pipe. Right: the housing for the laser (with the violet laser), whose position and angle can be adjusted.

5.2 Left: the housing for the lens and photodiode is screwed onto the top of the pipe. Right: diagram showing a cross section of the lens and photodiode housing.

5.3 The absorption coefficient for water as a function of wavelength and frequency. Note that the absorption coefficient is the inverse of the attenuation length, the quantity used throughout this chapter.

5.4 Measurement of the attenuation of light in unfiltered water taken from the flooded mine pit where CHIPS will be placed, and the source of the water that the CHIPS detector will be filled with.

5.5 Stability of the ADC with a fixed water level.

5.6 Pit water filtered through a 10$\mu$m polypropylene filter with UV sterilisation.

5.7 Pit water filtered through a 5$\mu$m polypropylene filter with UV sterilisation.

5.8 Pit water filtered through a 5$\mu$m polypropylene filter and a 10$\mu$m carbon block filter, with UV sterilisation.

5.9 Pit water filtered through a 0.5$\mu$m filter and a 10$\mu$m carbon filter, with UV sterilisation.

5.10 First measurement taken with the green laser. The only change made to the system between the measurement shown in figure 5.9 was a long period of filtration and the change of laser.

5.11 Measurement taken using the green laser and using a 0.2$\mu$m filter.

5.12 Measurement taken using the violet laser and using a 0.2$\mu$m filter.

5.13 Measurement taken using the green filter after nearly a month of continuous filtering through the 0.2$\mu$m filter.

5.14 Measurement taken three days after turning off the UV.

5.15 Measurement taken eight days after turning off the UV.

5.16 Measurement taken nine days after turning off the UV: switched filter to 0.5$\mu$m the previous day.

5.17 Measurement taken ten days after turning off the UV.

5.18 Measurement taken eleven days after turning off the UV.

5.19 Filters at the mine pit in Minnesota.
Chapter 1

Neutrino Physics

1.1 History of the neutrino

1.1.1 Initial proposal and measurement

The existence of neutrinos was first theorised by Pauli in 1930 [1] to account for the continuous energy spectrum of $\beta$ decay measured by Chadwick in 1914 [2]. The continuous spectrum suggested that either energy was not conserved in $\beta$ decay or, as Pauli suggested, that there was a third body in the decay which had not yet been detected and carried no electrical charge.

However, neutrinos were not detected until 1956 [3], when Cowan and Reines observed anti-neutrinos produced in a nuclear reactor through beta decay

$$n \rightarrow p + e^- + \bar{\nu}_e$$  \hspace{1cm} (1.1)

before undergoing inverse beta decay in the detector’s target of water and cadmium

$$\bar{\nu}_e + p \rightarrow e^+ + n$$  \hspace{1cm} (1.2)

The positron would then annihilate with an electron (producing 2 photons), then after a delay of several microseconds the neutron would be captured by a nucleus producing a single photon. This distinctive signal (double photon, delay, single photon) was measured in the liquid scintillator detector, thus proving the existence of the neutrino [3].

The next major breakthrough in neutrino physics was the discovery that neutrinos have multiple flavours. This began with the detection of the muon neutrino in 1962 at the Brookhaven Laboratory, where neutrinos were observed to produce muons but not electrons [4].

In 1989 LHC experiments showed that there were three flavours of light neutrino, using their measurement of the Z boson’s mass and decay width [5]. This third flavour was directly observed by the DONUT experiment in 2000 when they observed 4 tau neutrinos [6].

1.1.2 Evidence of oscillation

In 1968, the Homestake experiment published the results of a measurement of solar neutrinos (electron neutrinos emitted by nuclear fusion reactions in the sun) [7]. However, they observed only a third of the number of neutrinos predicted by Bahcall’s paper of the same year [8]. As this deficit was confirmed by other experiments, including Kamiokande, SAGE, and GALLEX,
it became more unlikely that there was an error in Homestake’s measurement and the results became known as the solar neutrino problem.

The solution was neutrino oscillation. The first experimental evidence that the missing neutrinos had oscillated to another flavour came from SNO, whose heavy water Cherenkov detector was capable of measuring both charged current (CC) and neutral current (NC) reactions. The neutrino interactions that SNO measured are shown in equations 1.3, 1.4, and 1.5 [9].

\[
\begin{align*}
\nu_e + d & \rightarrow p + p + e^- \\
\nu_x + d & \rightarrow p + n + \nu_x \\
\nu_x + e^- & \rightarrow \nu_x + e^- 
\end{align*}
\]

where equation 1.3 is a CC interaction and the others are NC. The number of NC interactions is not affected by neutrino oscillations, as all flavours of neutrino may interact neutrally. The number of CC electron neutrino interactions is affected by neutrino oscillations: some electron neutrinos have oscillated to other flavours, so fewer electron neutrinos are passing through the detector and so fewer CC interactions will be observed.

As SNO could measure both CC and NC interactions, it could confirm Homestake and others’ results that there was a deficit of electron neutrinos, but could also observe that the number of neutrinos of all flavours was as predicted. The combination of the CC and NC data was consistent with the electron neutrinos oscillating to different flavours. SNO’s solar neutrino results were confirmed by KamLAND’s measurement of the disappearance of anti-neutrinos produced by nuclear reactors [10].

This allowed both experimentalists and theorists to move forward with measuring and constraining the mixing angles and mass differences that dictate those oscillations, in addition to trying to answer other questions about neutrinos: whether they are Dirac or Majorana leptons; what the cross-sections of various neutrino interactions are; what the neutrinos’ absolute masses are; whether there truly are only 3 neutrino flavours; why neutrinos have mass in the first place, and how they fit into the Standard Model.

1.2 Neutrino Physics Theory

1.2.1 Standard Model

The Standard Model represents current understanding of the fundamental particles, their interactions, and the forces acting upon them. Figure 1.1 shows the currently known fundamental particles.

The quarks have three mass generations, where each generation has a pair of positively and negatively charged quarks. The lightest generation is up and down, the quarks that make up protons and neutrons. The second generation is the charm and strange quarks, then the heaviest generation is top and bottom. There are three charged leptons - electron, muon, and tau, listed in order of increasing mass - and three neutral leptons, the neutrinos. Like the charged leptons, the three neutrino flavours are electron, muon, and tau. A neutrino can undergo a CC interaction with a lepton of the same flavour. Each quark and lepton has a corresponding antiparticle, with the possible exception of neutrinos which may be Majorana fermions. Majorana fermions are identical to their own antiparticles - this is possible because real wave equations can be used to describe neutral spin-$\frac{1}{2}$ particles, so their antiparticle’s wave
The known elementary particles of the Standard Model can be categorised as quarks, leptons, and bosons. In Figure 1.1, the quarks and the charged leptons make up matter (possibly excluding Dark Matter).

Also shown are the gauge bosons, which mediate the interaction of the matter particles through the fundamental forces. The gluons, \( g \), mediate the strong force, which occurs between quarks. The photon, \( \gamma \), mediates electromagnetic interactions, which occur between charged particles. Finally the \( W \) and \( Z \) bosons mediate the weak force.

The weak force is unique among the fundamental forces in several ways. Unlike photons and gluons, the \( W \) and \( Z \) gauge bosons are massive: the \( W^+ \) and \( W^- \) bosons each have a mass of \( 80.385 \pm 0.015 \) GeV and the \( Z \) boson has a mass of \( 91.1876 \pm 0.0021 \) GeV [11]. Weak interactions can change quark flavours, as seen in beta decay (see equation 1.1).

The weak force is the only force to violate parity symmetry (inverting the spatial coordinates), which it breaks by only acting on particles with a negative chirality, and antiparticles with a positive chirality. Chirality is a fundamental property of a particle, similar to spin. For massless particles, chirality is identical to helicity, which is the projection of a particle’s spin in the direction of its momentum:

\[
\sigma \cdot p \tag{1.6}
\]

When helicity is negative the particle is referred to as left handed, if it is positive the particle is referred to as right handed. For massive particles, helicity will change depending on the frame of reference but chirality will not. Because of their low mass, neutrinos are relativistic and can generally be treated as massless, i.e. their helicity and chirality can be treated as identical. All particles have a weak isospin, a quantity that is conserved in all weak interactions. For particles with a positive chirality, this is 0. Fermions with a negative chirality have a weak isospin of...
The weak force is also the only force to violate charge-parity (CP) symmetry, as seen in kaon decay. CP symmetry is the product of charge conjugation symmetry (interchanging particles with their antiparticles) and parity symmetry, and if it were conserved then equal amounts of matter and antimatter would have been produced at the beginning of the universe and annihilated. Evidently this didn’t happen and much more matter than antimatter exists, and studying neutrinos gives us a way of probing CP violation and may be able to provide insight on the imbalance between matter and antimatter.

Neutrinos only interact via the weak force. These can be either CC interactions or NC interactions, which are shown in figure 1.2. In a CC interaction an incoming neutrino will interact with a charged lepton of the same flavour by exchanging a $W^\pm$ boson. In a NC interaction, a non-sterile neutrino will interact with a charged lepton of any flavour, exchanging a $Z^0$.

The W and Z bosons, quarks, and charged leptons have mass due to the Higgs mechanism, which describes the interaction between the Higgs boson (the only scalar boson currently in the Standard Model) and the left- and right-handed forms of the relevant fundamental particle. However, neutrinos only have a left-handed form, so according to the Standard Model they should be massless.

They are not.

### 1.2.2 Neutrino Oscillations

Neutrinos interact according to their flavour eigenstate, but propagate according to their mass state. The mass state does not change as a function of time but the flavour eigenstate does, i.e. a neutrino will always have the same mass but may interact as any of the three flavours. This indicates that each mass eigenstate doesn’t correspond to a single flavour state but instead is a superposition of the three possible flavour eigenstates, and each flavour eigenstate is a superposition of the mass eigenstates. There are three distinct mass eigenstates, and at least two of these states are not massless.

The flavour eigenstates $\nu_\alpha$ and mass eigenstates $\nu_i$ can be represented as superpositions of
each other through the following equations:

\[
|\nu_i\rangle = \sum_{\alpha=1}^{3} U_{\alpha i} |\nu_\alpha\rangle
\]
\[
|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{i \alpha}^{\ast} |\nu_i\rangle
\]  (1.7)

where \( U \) is the PMNS (Pontecorvo, Maki, Nakagawa, Sakata) matrix [11]. This unitary matrix is usually written in terms of Euler angles, which are called mixing angles in this context, and the CP violation phase \( \delta \) as

\[
U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\]
\[
= \begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{23}s_{13} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}
\]  (1.8)

where \( c_{ij} \equiv \cos \theta_{ij} \) and \( s_{ij} \equiv \sin \theta_{ij} \).

To calculate the probability of neutrino oscillation from flavour \( \alpha \) to \( \beta \) in a vacuum, equation 1.7 must be written as a function of time \( t \)

\[
|\nu_\alpha(t \neq 0)\rangle = \sum_{i=1}^{3} U_{i \alpha}^{\ast} e^{-p_i \cdot x} |\nu_i\rangle
\]  (1.9)

where \( p_i \) is the four-momentum of \( \nu_i \) and \( x \) the position. If the neutrino is in the flavour state \( |\nu_\alpha\rangle \) at time \( t = 0 \) and \( |\nu_\beta\rangle \) at time \( t \) then the inner product is

\[
\langle \nu_\beta | \nu_\alpha \rangle = \sum_{j=1}^{3} \sum_{i=1}^{3} U_{\beta j} U_{i \alpha}^{\ast} e^{-ip_j \cdot x} \langle \nu_j | \nu_i \rangle
\]  (1.10)

as the mass state does not change, i.e. \( i = j \). The exponential term can be expanded to

\[
p_j \cdot x = E_j t - p \cdot x \\
= t \sqrt{|p|^2 + m_j^2} - p \cdot x
\]  (1.11)

Two approximations are usually applied. The first is the small mass approximation

\[
t \approx L \\
p \cdot x \approx |p| L
\]  (1.12)
where $L$ is the distance the neutrino has travelled between where it was at $t = 0$ and at $t \neq 0$. The second is a binomial approximation

$$\sqrt{|p|^2 + m_j^2} = |p| \sqrt{1 + \frac{m_j^2}{|p|^2}} \approx |p| \left(1 + \frac{m_j^2}{2|p|^2}\right)$$

$$\Rightarrow p_j \cdot x = |p| \left(1 + \frac{m_j^2}{2|p|^2}\right) - |p|L$$

$$= \frac{m_j^2L}{2|p|}$$

$$\approx \frac{m_j^2L}{2E_j}$$

With these, equation 1.10 becomes

$$\langle \nu_\beta | \nu_\alpha \rangle = \sum_{j=1}^{3} U_{\beta j} U_{\alpha j}^* e^{-\frac{m_j^2L}{2E_j}}$$

(1.14)

The probability $P_{\alpha \rightarrow \beta}$ of a neutrino oscillating from the flavour state $\alpha$ at time $t = 0$ to the flavour state $\beta$ at time $t$ is then given by

$$P_{\alpha \rightarrow \beta} = |\langle \nu_\beta(t) | \nu_\alpha(0) \rangle|^2$$

$$= \sum_{i=1}^{3} \sum_{j=1}^{3} U_{\alpha i} U_{\beta j}^* U_{\alpha j} U_{\beta i} e^{-\frac{m_i^2L}{2E_i}} e^{i \frac{m_j^2L}{2E_j}}$$

(1.15)

As $U$ is a unitary matrix (i.e. $U^* U = I$), this can be written as

$$P_{\alpha \rightarrow \beta} = \delta_{\alpha \beta} - 4 \sum_{i > j} \Re \left[ U_{\alpha i} U_{\beta j} U_{\alpha j}^* U_{\beta i}^* \right] \sin^2 \left( \frac{\Delta m_{ij}^2}{4E} L \right)$$

$$+ 2 \sum_{i > j} \Im \left[ U_{\alpha j} U_{\beta i} U_{\alpha i}^* U_{\beta j}^* \right] \sin^2 \left( \frac{\Delta m_{ij}^2}{2E} L \right)$$

(1.16)

The $\frac{L}{E}$ term in equation 1.16 is particularly important when designing accelerator experiments as the neutrino energy and the distance from the accelerator to the detector are known quantities, so $\frac{L}{E}$ can be tuned in the experiment’s design.

Different mixing angles and mass differences have an impact at different scales of $\frac{L}{E}$. For neutrinos generated in the atmosphere by cosmic rays colliding with nuclei, the dominant mixing angle and mass difference are $\theta_{23}$ and $\Delta m_{23}^2$. For neutrinos generated by nuclear reactions in the sun, $L$ increases by 6 orders of magnitude and $E$ decreases by 4 orders of magnitude (1 GeV is a typical cosmic neutrino energy [12], while over 91% of solar neutrinos are from the pp chain which produces $\nu_e$ with a maximum energy of around 0.4 MeV [13]) and $\theta_{12}$ and $\Delta m_{12}^2$ become dominant. For this reason $\Delta m_{23}^2$ is sometimes referred to as $\Delta m_{\text{atm}}^2$, and $\Delta m_{12}^2$ as $\Delta m_{\text{sol}}^2$.

The mass differences in equation 1.16 are all in terms of $\Delta m_{ij}^2$ which limits what oscillation experiments can tell us: while the magnitude of the difference between two mass states can be
Figure 1.3: The normal and inverted mass hierarchies. These diagrams show the proportions of each flavour eigenstate (represented by colours) that is present in each mass eigenstate (represented as horizontal lines). $\Delta m^2_{23}$ is labelled as $\Delta m^2_{atm}$ and $\Delta m^2_{12}$ as $\Delta m^2_{sol}$.

Measured, oscillation in a vacuum provides no way to determine which mass state is the heaviest or lightest. $m_2$ is defined as heavier than $m_1$, and resonant mass effects in the sun affect solar neutrino oscillations enough to define $m_1$ as the mass state with the largest electron neutrino component and $m_2$ is the mass state with the next largest electron neutrino component [14]. Otherwise, mass ordering is unknown: the two possibilities are the normal or inverted mass hierarchy, shown in figure 1.3.

Previous measurements of the parameters in equation 1.16 are summarised in table 1.1, including the mixing angles in the elements of $U$. This table is taken directly from the Particle Data Group [11]. While current data cannot determine the hierarchy (and therefore the signs of $\Delta m^2_{31}$ and $\Delta m^2_{32}$), it does affect measurements of the mass differences and mixing angles, so results for both possible hierarchies are shown. The second line of the table shows the current best fit of the mass difference between the heaviest and lightest neutrino mass states: values in brackets refer to the inverted hierarchy, otherwise values assume normal hierarchy. This is used again in the final line, showing the best fit of $\delta_{CP}$ and $2\sigma$ limits for each hierarchy.

For the mixing angles, $\Delta m^2_{31(32)}>0$ indicates normal hierarchy and $\Delta m^2_{32(31)}<0$ indicates inverted hierarchy. The effect of the hierarchy on the best fit value of $\sin^2 \theta_{13}$ is negligible, but is larger for $\sin^2 \theta_{23}$.

It is possible (within $3\sigma$) that mixing is maximal, i.e. the maximum number of muon neutrinos oscillate to a different flavour. Maximal mixing occurs at $|U_{\mu 3}|^2 = 0.5$, which is $\sin^2 \theta_{23} \cos^2 \theta_{13} = 0.5$ [15]. As $\sin^2 \theta_{13}$ is not zero, maximal mixing is close to but not exactly $\sin^2 \theta_{23} = 0.5$.

Figure 1.4 shows a global fit using all data that was available in April 2018 (the time of its publication) [16]. The terms NO and IO refer to the normal hierarchy (or mass ordering) and inverted hierarchy respectively. The 90%, 95%, and 99% confidence levels are shown in grey, blue, and magenta respectively, and the best fit point is shown using a star or circle depending
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best fit</th>
<th>$3\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{21}[10^{-5}\text{eV}^2]$</td>
<td>7.37</td>
<td>6.93 - 7.96</td>
</tr>
<tr>
<td>$\Delta m^2_{31(23)}[10^{-3}\text{eV}^2]$</td>
<td>2.56 (2.54)</td>
<td>2.45 - 2.69 (2.42 - 2.66)</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.297</td>
<td>0.250 - 0.354</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}, \Delta m^2_{31(32)} &gt; 0$</td>
<td>0.425</td>
<td>0.381 - 0.615</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}, \Delta m^2_{31(32)} &lt; 0$</td>
<td>0.589</td>
<td>0.384 - 0.636</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}, \Delta m^2_{32(31)} &gt; 0$</td>
<td>0.0215</td>
<td>0.0190 - 0.0240</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}, \Delta m^2_{32(31)} &lt; 0$</td>
<td>0.0216</td>
<td>0.0190 - 0.0242</td>
</tr>
<tr>
<td>$\delta/\pi$</td>
<td>1.38 (1.31)</td>
<td>2$\sigma$: (1.0 - 1.9) (2$\sigma$: (0.92 - 1.88))</td>
</tr>
</tbody>
</table>

Table 1.1: PDG’s published summary of measurements of neutrino oscillation parameters.

on the mass ordering for that fit.

### 1.2.3 Muon neutrino disappearance

In the case of muon neutrino disappearance, equation 1.16 becomes

$$P_{\mu \rightarrow \mu} = 1 - 4 \sum_{i>j} |U_{\mu i}|^2 |U_{\mu j}|^2 \sin^2 \left( \frac{\Delta m^2_{ij}}{4E} L \right)$$

(1.17)

When expanded, there are no $\sin \delta_{CP}$ terms in equation 1.17. The $\cos \delta_{CP}$ terms are small enough that $\delta_{CP}$ cannot be measured by most muon disappearance experiments, although it may be included as a nuisance parameter.

Because $\Delta m^2_{21}$ is two orders of magnitude smaller than $\Delta m^2_{23}$ and $\sin^2 \theta_{13}$ is much smaller than $\sin^2 \theta_{23}$ (as shown in table 1.1), neutrino oscillations can often be approximated with a two flavour model. The following approximations can be made:

$$\sin^2 \theta_{13} \approx 0$$
$$\cos^2 \theta_{13} \approx 1$$

$$\Delta m^2_{31} \approx \Delta m^2_{32} \equiv \Delta m^2_{atm}$$

(1.18)

With these simplifications, the relevant squared elements of the PMNS matrix (see equation 1.8) can be expressed as

$$|U_{\mu 1}|^2 \approx s^2_{12} c^2_{23}$$
$$|U_{\mu 2}|^2 \approx c^2_{12} c^2_{23}$$
$$|U_{\mu 3}|^2 \approx s^2_{23}$$

(1.19)

This leads to a two flavour approximation of equation 1.17:

$$P_{\mu \rightarrow \mu} \approx 1 - 4s^2_{23} c^2_{23} \sin^2 \left( \frac{\Delta m^2_{atm} L}{4E} \right)$$

$$\approx 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m^2_{atm} L}{4E} \right)$$

(1.20)
Figure 1.4: A global fit of all available neutrino oscillation data in April 2018 [16].
There are limitations to $\nu_\mu$ disappearance experiments using this two flavour approximation. Equation 1.20 is symmetric around $\theta_{23} = \pi/2$, which makes it impossible to determine the octant of $\theta_{23}$ in the case of non-maximal mixing.
Chapter 2

The NOvA Experiment

2.1 Overview and Physics Goals

NOvA (the NuMI Off-axis $\nu_e$ Appearance experiment) is a long baseline neutrino oscillation experiment based in the US. There are two detectors, referred to as the Near Detector and the Far Detector, which measure neutrinos produced by the NuMI (Neutrinos at the Main Injector) beam at the Fermi National Accelerator Laboratory (FNAL) in Illinois. The NuMI beam is a muon neutrino beam, described in more detail in section 2.2. The Near Detector is located underground 1km from the origin of the beam, and the Far Detector is located 810km away. Both detectors are placed 14.6mrad off-axis. The advantages of off-axis placement are detailed in section 2.2.1. They are functionally identical except for size, as the Far Detector is much larger than the Near Detector. Measurements at the Near Detector can be extrapolated out to the Far Detector to reduce systematic uncertainties by measuring beam energy and composition before oscillation. Both detectors are described in section 2.3.

As the name suggests, NOvA looks for $\nu_e$ appearance, where the $\nu_\mu$ produced by the NuMI beam have oscillated to $\nu_e$. This measurement constrains the possible values of $\theta_{13}$ and $\delta_{CP}$, and provides some insight on the mass hierarchy and the octant of $\theta_{23}$, which cannot be measured using the $\nu_\mu$ disappearance channel as equation 1.20 is symmetric about $\theta_{23}$. NOvA’s other main analysis concerns $\nu_\mu$ disappearance, which constrains the values of $\theta_{23}$ and $\Delta m^2_{32}$. There are also many other analyses in the experiment, including a joint analysis using both the $\nu_\mu$ disappearance and $\nu_e$ appearance channels, searches for sterile neutrinos, cross section measurements at the Near Detector, and other exotica.

2.2 The NuMI Beam

NOvA’s neutrino source is the NuMI beam. It is a muon neutrino beam operated by Fermilab’s accelerator division that was originally intended for the MINOS experiment, but has been upgraded for NOvA’s purposes. This included increasing the peak energy from 3 GeV to 7 GeV, and upgrading the beam power from 400 kW to 700 kW [17]: the 700 kW goal was first achieved in January 2017 and NuMI regularly runs at this power [18].

Figure 2.1 shows a diagram of the NuMI beam. Neutrinos are produced by accelerating protons to 120 GeV in the Main Injector and colliding them with a fixed graphite target in pulses of 10µs once every 1.33 s [19]. This 10µs pulse is referred to as a spill. The target was designed to maximise $\nu_\mu$ output, but also to be able to endure long-term direct exposure to the
proton beam without disintegrating. It consists of 47 graphite fins which each measure 20 mm by 15 mm by 6.4 mm. Multiple fins are used in order to maximise neutrino output: smaller volume targets reduce secondary meson interactions within the target, and multiple volumes increase the total fraction of the beam that strikes the target [19]. The fins are spaced out by 0.3 mm to give a total target length of 95.38 cm [19]. The high energy protons interact with the target to produce mesons, mostly kaons and pions. The mesons are focused into a decay pipe using magnetic horns - depending on the polarity of the horns, NuMI can focus either positively or negatively charged mesons to produce neutrinos or anti-neutrinos respectively. If positively charged mesons are used then the main reactions in the decay pipe are

\[
\pi^+ \rightarrow \mu^+ + \nu_\mu \\
K^+ \rightarrow \mu^+ + \nu_\mu
\]  

(2.1)

with branching ratios of 99.9% and 63.6% respectively [11]. This is called Forward Horn Current (FHC). If negatively charged mesons are focussed into the decay pipe, they will decay into anti-neutrinos. This is Reverse Horn Current (RHC). The beam was switched to anti-neutrino mode in 2017, and the 2018 analysis includes anti-neutrino data. However for the analysis discussed in this thesis, the beam was in neutrino mode for the entire data-taking period.

The distance between the target and the horns can be adjusted in order to change the energy of the neutrinos finally emitted: the closer the horns are to the target, the lower the neutrino energy.

For medium tuning, these distances become 1.3 m and 23 m, and for high energy tuning 3.96 m and 40 m. The resulting neutrino energies are shown in figure 2.2. The medium energy tuning is used for NOvA [17].

After the decay pipe, any remaining hadrons are stopped by the absorber (constructed from a core of steel and aluminium and an outer layer of steel and concrete blocks), then muons are absorbed by rock. There are monitors to provide insight on the muons’ energies. Neutrinos are not stopped by the absorber nor rock, and thus are the only particle left in the beam. The composition of this final neutrino beam is 93% $\nu_\mu$, 6% $\bar{\nu}_\mu$, and 1% $\nu_e + \bar{\nu}_e$ [20].

2.2.1 Off axis

The detectors are both located 14.6 mrad off-axis in order to provide a narrower energy peak. This is due to kinematic effects in two-body decays. Using conservation of momentum and
energy and neglecting the neutrino mass, the neutrino’s energy $E_\nu$ and flux $\phi_\nu$ following a pion decay can be described as

$$E_\nu = \frac{\left(1 - \frac{m_\pi^2}{m_\nu^2}\right) E_\pi}{1 + \gamma^2 \theta^2}$$  \hspace{1cm} (2.2)

$$\phi_\nu = \frac{2\gamma}{1 + \gamma^2 \theta^2}^2 \frac{A}{4\pi z^2}$$  \hspace{1cm} (2.3)

where $m_\pi$ and $E_\pi$ are the mass and energy of a pion, $\theta$ is the angle of the neutrino’s path, $\gamma$ is the pion’s Lorentz boost to move into the laboratory frame of reference, and $A$ is the cross-sectional area of a detector at distance $z$. The same is true of kaon decay, where $m_K$ and $E_K$ are substituted for $m_\pi$ and $E_\pi$ in equation 2.2. Figure 2.3 shows how the neutrino flux and energy vary according to these equations. In the right plot, it is shown that for an on-axis experiment $E_\nu$ will increase linearly with $E_\pi$, whereas off-axis experiments will see a more consistent $E_\nu$ for a wide range of $E_\pi$. This means an increased number of neutrino events at a specific energy, i.e. a narrower $E_\nu$ peak, as shown in figure 2.4.

NOvA is at an off-axis angle of 14.6 mrad (the red line in figures 2.3 and 2.4).

## 2.3 Detectors

Both of NOvA’s detectors are tracking calorimeters constructed from rigid, extruded PVC cells filled with liquid scintillator. The cells have a rectangular cross-section measuring 4 cm \(\times\) 6 cm and are as long as the width and height of the detector. When a charged particle passes through a cell, scintillation light is produced, which is transported to an Avalanche Photodiode (APD) using a loop of wavelength shifting fibre, as shown in figure 2.5.
Figure 2.3: Plots of neutrino flux (left) and energy (right) as a function of the energy of the decaying pion on-axis and for several off-axis angles [17].

Figure 2.4: Simulation showing the rate of CC $\nu_\mu$ events assuming no neutrino oscillations. Calculated at a distance of 810 km from the beam origin for several off axis angles [17].
Figure 2.5: Diagram of a single NOvA cell: this is constructed from PVC and filled with liquid scintillator. A charged particle passes through and the resulting scintillation light is carried by a wavelength shifting fibre to an APD [17].
The scintillator used by NOvA is mineral oil doped with 4.1 pseudocumene [17]. When a charged particle excites this compound it emits photons with wavelengths from 270 nm to 320 nm [21]. The mineral oil also contains two wavelength shifting compounds which emit photons in the range of 340 nm to 380 nm and 390 nm to 440 nm respectively [21]. The fibre can absorb wavelengths of 400 nm to 450 nm (blue) and emit them as green (490 nm to 550 nm) [17].

NOvA uses silicon Hamamatsu Avalanche Photodiodes (APDs) to observe the light emitted by each fibre. APDs are highly sensitive light detectors, a diagram of an APD pixel is shown in figure 2.6. Photons enter the APD and pass through a negatively charged layer (the N-Layer in figure 2.6) and the positively charged P-Layer, and pass into the depletion region. The depletion region is analogous to the neutral, “intrinsic” i region of a pin diode, but may be lightly p-doped and referred to as a \( \pi \)-region. In this region they excite free electrons and holes which flow to the cathode and anode respectively. Due to the high voltage applied across the APD, electrons in the depletion region increase in energy and collide multiple times generating more electron-hole pairs, a process which is referred to as an “avalanche” effect [22]. The APD will produce a current that is proportional to the number of photons that entered it.

NOvA uses APDs due to their high quantum efficiency and the uniformity of that quantum efficiency at the wavelengths emitted by the wavelength shifting fibres, specifically an 85% quantum efficiency in the 520 nm to 550 nm range [17]. All APDs are cooled to \(-15^\circ\text{C}\) to reduce noise. A single APD will read out the light from 32 cells, collecting light from both ends of a cell’s fibre in one pixel.

Cells are attached side by side to form planes. The flat sides of the planes are connected, alternating vertical and horizontal cells as shown in figure 2.7. This means that the horizontal (or vertical) position of a particle in a plane can be known to within a few centimetres and its vertical (or horizontal) position can be estimated from hits in neighbouring planes. By tracking a particle through many planes its path can be reconstructed.

### 2.3.1 Far detector

The Far Detector is located at Ash River, 810 km from the beam target: see figure 2.8. The 14 kiloton detector is 60 m long and 15.5 m in height and width. There are 384 cells per plane and the detector contains 896 planes, meaning that it has 344,064 cells in total. The active
Figure 2.7: Diagram of the NOvA Near Detector and Far Detector [23]. The orange inset shows how planes of horizontal and vertical cells alternate. A person is shown for scale.

Figure 2.8: Location of the Far Detector and Fermilab [24].
The volume is 65% [17].

The detector is on the surface, leading to a high level of background from cosmic muons and photons. The building housing the detector includes a 10 ft overburden of granite to act as shielding. Cuts are applied to the data to remove remaining background, these cuts will be described in detail in section 3.3.

2.3.2 Near detector

The Near Detector is located at Fermilab, 1.015 km from the beam target and 105 m underground. Because it is much closer to the neutrino source there is a higher flux of neutrinos, so the detector can be much smaller (290 tons) while still providing the necessary data for reducing systematics by extrapolating between detectors.

It has two sections, referred to as the main body and the muon catcher. The main body contains 192 planes with 96 cells per plane, and is 3.9 m in height and width and 12.8 m in length. The angular extent of the detector is 3.8 mrad with the centre of the detector placed 14.6 mrad off axis from the beam.

The muon catcher is shorter in height than the main body, with only 64 cells in the horizontal planes and shorter vertical cells to match the height of the detector. A 10 cm thick steel plate is placed after each pair of a horizontal and vertical plane in order to stop the muons. The main purpose of the muon catcher is to keep muons’ entire tracks within the detector, allowing their energy to be accurately reconstructed.

2.4 Reconstruction

The top image in figure 2.9 shows 550 µs of Far Detector data. The top half of the event display is an \(xz\) view, where the \(z\) axis is in the beam direction (roughly North) and the \(x\) axis is East-West. Every colourful point shows a vertical cell where energy was deposited. Energy deposits in cells are referred to as “hits”. The lower half shows the \(yz\) view, where the \(y\) axis is up-down, and energy deposits in horizontal cells are shown. The colours represent the charge deposited in each cell, presented in the bottom right histogram. The bottom left histogram shows the distribution of hit timing.

There are clearly many different interactions, particularly cosmic muons passing through the detector. A “slicer” algorithm is applied to collect hits that are close in space and time: ideally, each individual slice will contain one particle interaction. For example, a single slice might contain all the hits from a muon and a hadron emitted by a \(\nu_\mu\) interaction, but that slice would not include a cosmic muon a few planes away because those hits are too far from the current slice. The lower event display in figure 2.9 shows a single slice from this period of data which contains a neutrino interaction, which is circled in red and has a colour scale on the hits. Any hits that are not in this slice (i.e. are not related to this interaction) are coloured grey. Figure 2.10 zooms in on the slice containing an interaction.

For each slice, two tracking algorithms are applied to each slice to attempt to find particles’ paths in three dimensions. The Cosmic Tracker uses a window tracking algorithm which fits a line to five planes at a time to allow for curvature. It assumes that particles are moving in a \(-y\) direction, as cosmic muons come from the upper atmosphere. The Kalman Track assumes that the muon travels in the direction of the beam, South to North. It uses a Kalman filter: the position of the next hit is predicted using the track’s parameters. If there is a hit there
Figure 2.9: The event display from a Far Detector $\nu_\mu$ event selected for the 2017 and 2018 analyses. The top image shows the data for the whole 550$\mu$s. The bottom image shows the single “slice” that contains the $\nu_\mu$ event (circled in red), and all hits that do not belong to the slice are grey.
(within a region allowing for noise) and adding the new hit to the track will cause an increase in $\chi^2$ below a set boundary, then the hit is added to the track and the track’s parameters are updated [25]. Figure 2.10 shows the Kalman Track fit to the event from figure 2.9.

Additionally, hits within each slice are sorted into prongs. A prong is a collection of hits that are roughly in a straight line, and is intended to represent a particle shower. They combine both 2D views of the detector to form a 3D object, and have a start point, direction, and momentum. Prongs are constructed separately to tracks. Ideally a single prong contains all the hits belonging to an electron shower or a single hadron (whereas a track represents a muon). Hits may belong to more than one prong - for example, in the NC interaction shown in figure 2.11 the $\pi_0$ decays into two $\gamma$ very close together, and the algorithm might allocate some hits to both prongs [26]. Not all hits in the slice will belong to a prong. Prongs are used in data cuts for the $\nu_\mu$ disappearance analysis, and in the reconstruction of hadrons and electron showers.

The ability to identify different neutrino interactions is essential for all of NOvA’s analyses. Figure 2.11 shows a diagram of how CC interactions appear in the detector, along with a NC interaction. Both CC interactions include a hadron which causes a short, somewhat fuzzy track. The hadron’s energy is found using the sum of calorimetric energy deposited. Muons have a long track, which distinguishes muon neutrino CC events from electron neutrino CC interactions. The length of the track is used to find the muon’s energy. Meanwhile an electron will cause an electromagnetic shower: the electron emits gammas through bremsstrahlung, the gammas undergo pair production to produce more electrons and antielectrons which cause more bremsstrahlung and the process continues. This appears in the detector as a short burst of energy being deposited, and the energy is found through an algorithm that uses the reconstructed prongs. Section 2.6 provides more information on how the detector is calibrated.
Figure 2.11: Diagrams of a CC muon neutrino interaction, CC electron neutrino interaction, and NC interaction in the NOvA detectors, with the relevant Feynman diagram [26].
Two particle ID values are evaluated for all Kalman tracks: the Reconstructed Muon Identification algorithm (ReMId) and the later developed Convolutional Visual Network (CVN) each return a value between 0 and 1 for each track. The ReMId identifies muon tracks, and a value closer to 1 shows that a track is more likely to have been created by a muon. The CVN is a convolutional neural network that selects for muons that were produced by a beam $\nu_\mu$ CC event. CVN was retrained in 2017 and again in 2018 with new data each time. Section 3.3 provides more information about how these values are used to select events for the $\nu_\mu$ disappearance analysis. CVN is also used to select for other interactions in the detector, e.g. $\nu_e$ or cosmic muon interactions, in this thesis the CVN value refers to $\nu_\mu$ CC interactions unless otherwise specified.

The event in figure 2.9 has the short hadron track and long muon track distinctive of a $\nu_\mu$ CC event and was selected for the 2017 and 2018 analyses. Its 2018 CVN value is 0.972593.

### 2.5 Simulation

Events were simulated using GENIE version 2.12.2 and Geant4 version 4.10.1p03 [27]. GENIE’s default model was changed in three ways [28]:

- GENIE’s "Empirical MEC" model is used but after comparisons with earlier data a 20% increase in the yield of events was added.

- GENIE’s QE scattering model was adjusted based on predictions of long-range nuclear correlation effects computed with the Random Phase Approximation by the IFIC Valencia group.

- Non-resonant single pion production was reduced by 50%, again due to comparisons with data.

### 2.6 Calibration

Muon energy is calculated from track length, using the Bethe-Bloch equation. This equation describes the energy loss rate $\frac{dE}{dx}$ of muons in the detector:

$$\left\langle -\frac{dE}{dx}\right\rangle = K \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2mc^2\beta^2\gamma^2W_{max}}{I^2} - \beta^2 - \frac{\delta(\gamma\beta)}{2} \right]$$

(2.4)

$K$ represents the constant $K = 4\pi N_A r_e^2 m_e c^2$, which includes Avogadro’s number $N_A$, classical electron radius $r_e$, and the electron’s rest energy $m_e c^2$. $\frac{Z}{A}$ is the ratio of the atomic number to the mass number for the material that the muon is passing through, $I$ is the mean excitation energy of the material, $\delta$ is the density effect correction to ionisation energy loss. $\beta c$ is the muon’s velocity, and $\gamma$ is the muon’s relativistic gamma factor [29]. As the detector’s material is known, the $\frac{dE}{dx}$ can be calculated for various distances along the muon’s track. Figure 2.12 shows the simulated $\frac{dE}{dx}$ as a function of distance from the end of the muon track for a sample of simulated muons in the Far Detector. The minimum $\frac{dE}{dx}$ is calculated to be 1.7915 ± 0.0035 MeV/cm in the detector [29].

For hadrons and electrons the energy is calculated using the calorimetric energy deposited. Each detector is calibrated for data and simulation separately, using cosmic muon data and
simulated cosmic muons. Calibration for each detector is done in two stages, referred to as attenuation calibration and absolute calibration.

The energy registered by the APD can be expressed in units of photoelectrons, or PE. However, a different number of PE may be registered by the APD depending on where the energy was deposited in the detector, due to light being attenuated in the wavelength shifting fibre and other effects of the detectors’ geometries. The attenuation calibration measures constants and provides a formula to counteract these effects, and provide a corrected number of PE. The absolute calibration then provides a scaling factor to convert the corrected number of PE to GeV.

2.6.1 Attenuation Calibration

The overarching method for attenuation calibration is to select through-going cosmic muons and run the Cosmic Tracker reconstruction algorithm. A 2D histogram is plotted of the energy deposited in a cell per pathlength through that cell (in units of PE per cm), as a function of distance from the centre of the cell, \( W \). A 1D profile of this plot is generated, then corrections for threshold and shielding effects are applied before a polynomial fit is applied. The results of this fit are applied to the profiles of PE/cm that the absolute calibration uses to find a scaling factor of PE to GeV.

Attenuation calibration assumes that each muon deposits the energy per pathlength of a minimum ionising particle (or MIP) throughout the detector: the exact MIP energy is not used, only the assumption that there is an average value consistent across the detector [30]. The Cosmic Tracker finds cosmic muon events and the direction that each muon is moving in.

A hit (energy deposit) is only used if there are hits in the neighbouring cells in its plane (see figure 2.13). This reduces noise and variation in pathlength. The pathlength through this cell is estimated by averaging over the possible paths with that direction that could pass through the cell. Hits are rejected if the pathlength is greater than 10 cm (the cross-section of a cell is 4 cm × 6 cm).

A plot is generated of the energy deposited in a cell per pathlength through that cell (in

![Figure 2.12: The $dE/dx$ of a muon as a function of the distance from the end of its track for simulated muons in the Far Detector [29]. The $dE/dx$ is uniform to within 1.8% within the 100 cm to 200 cm window.](image)
Figure 2.13: A hit is only used for attenuation calibration if there is also a hit in the neighbouring cells in the plane. In this example, only the central hit (darker red) would be used in the attenuation calibration [30].

units of PE/cm), as a function of distance from the centre of the cell, $W$. Figure 2.14 gives an example of one of these plots for the Far Detector simulated sample. Each detector contains both vertical and horizontal cells: vertical cells have a resolution of a few cm in the X and Z dimensions but the Y position relies on the track reconstruction, so a vertical cell is referred to as an X-view cell. Horizontal cells are referred to as Y-view cells. Figure 2.14 shows the PE per cm distribution for an X-view cell near the centre of a plane in the Far Detector.

Some wavelength shifting fibres attenuate light more than others. The attenuation of each fibre was measured during the detectors’ construction. The distribution of attenuation lengths was split into nine quantiles. A “map” was generated for each detector of where the dimmer and brighter fibres are, this shows a fibre brightness rating between 0 and 8 for each cell. The fibre brightness is included in simulations. Because the Near Detector’s cells are shorter than the Far Detector’s, fibre brightness has a smaller effect and was neglected in this calibration (but may be included in the future). Figure 2.14 shows the distribution for a Far Detector cell with a fibre brightness of 0, i.e. the light is attenuated a lot in this cell.

1D profiles are generated from plots like figure 2.14 of the average PE per cm as a function of $W$.

For the calibration of Far Detector data, the 2D histogram and its profile are generated separately for each of the 344,064 cells. However, the simulated sample is smaller and does not have sufficient statistics for this approach. Also, simulations are uniform in each plane of the detectors (with the exception of the fibre brightness effects). For this reason, events are collected by view, fibre brightness, and that cell’s position in the plane. There are 384 cells per plane, nine quantiles of fibre brightness, and two views so this gives a total of 6912 profiles. For the calibration of Near Detector data, profiles are generated separately for each of the main body’s 18,432 cells but there is not enough data in the muon catcher (as the steel plates between the planes stops a lot of cosmic muons) so data is collated by view and by the cell’s position in the plane. For simulation calibration in the Near Detector, profiles are generated for each view and each cell in that view for the main body, and for each view and each cell in
that view for the muon catcher.

Due to the large size of the detectors, thresholds and self-shielding play a large role and a correction factor must be applied. These effects are larger in the Far Detector but are corrected for in both detectors. Thresholds mean that for a hit to be observed by an APD, it may need to have a slight upwards fluctuation in the number of photons produced by the scintillator otherwise all the photons will be attenuated away. The effect of self-shielding is that the average visible hits from MIPs are not truly spatially uniform in the detector. Both of these effects lead to an overestimation of the light produced by hits, and conversely real hit energies are underestimated on the order of tens of percent [30]. A combined threshold and shielding correction factor $T$ is calculated using truth information in the simulated cosmic muon sample, using the equation

$$T = \frac{PE}{\lambda} \frac{E_{\text{true}}}{E_{\text{mip}}}$$

(2.5)

where $PE$ is the simulated PE recorded at the APD, $\lambda$ is the number of PE which would be seen at the readout without the fluctuations for a simulated threshold, $E_{\text{true}}$ is the true energy deposited in the cell, and $E_{\text{mip}}$ is the energy expected in the cell based on the muon’s pathlength through that cell, in the absence of shielding.

Figure 2.15 shows the values of $T$ in the Far Detector for all the X-view and Y-view cells of a fibre brightness rating of 0. This is then smoothed out with a polynomial fit in order to facilitate the next stages of calibration and reduce noise effects. Figure 2.16 shows the result of these fits after being applied to the plots in figure 2.15. Figure 2.17 shows the profiles of $T$ as a function of cell and $W$ for each fibre brightness and for the previous analysis’s calibration. There is a periodic fluctuation of $T$ that occurs every 32 cells. This is due to the modular construction of the detector, where each plane was built from 12 modules of 32 cells, leading to some small geometric effects (extra glue, small misalignments between modules, etc.) that affect shielding.

35
Figure 2.15: The threshold corrections according to equation 2.5 for all the vertical cells (left) and the horizontal cells (right) in the Far Detector that have a fibre brightness of 0 [30]. These plots are also produced for the other fibre brightnesses in the Far Detector, and for the main body and muon catcher of the Near Detector.

Figure 2.16: The results of a polynomial fit of the threshold correction as a function of cell and $W$ in figure 2.15 [30].
Figure 2.17: The 1D profiles of the threshold correction factor $T$ as a function of cell (top) and $W$ (bottom) for X-view (left) and Y-view (right) cells. This is shown for each fibre brightness and for the previous calibration (shown in black, generally close to fibre brightness 5 or 6: fibre brightness was not included in the previous calibration).
Figure 2.18: The corrected profiles of PE per cm as a function of $W$ for data collected by a randomly selected plane and horizontal (left) and vertical (right) cell in the Far Detector, with the equation 2.6 fit for the calibration used in this thesis (red) and the previous calibration (black).

This factor of $T$ as a function of $W$, cell, and fibre brightness (Far Detector only) is used to correct the PE in the PE per cm histograms and profiles. The plots of threshold-corrected PE per cm as a function of $W$ for two example cells are shown in figure 2.18. The central part of this profile is fit to the equation

$$y = C + A \left( \exp \left( \frac{W}{X} \right) + \exp \left( -\frac{L + W}{X} \right) \right)$$  \hspace{1cm} (2.6)

where $y$ is the response, $L$ is the cell length, and $C$, $A$, and $X$ are free parameters. $X$ is the attenuation length. The results of the fit are stored a database and used to correct PE numbers before the absolute calibration.

### 2.6.2 Absolute Calibration

After accounting for a hit’s position in the detector, a scaling factor must be found to convert energy from PE to MeV.

The energy scale factor is found using

$$\text{calorimetric energy scale} = \frac{MEU_{\text{truth}}}{MEU_{\text{reco}}}$$  \hspace{1cm} (2.7)

where $MEU_{\text{truth}}$ is the mean MeV / cm deposited and $MEU_{\text{reco}}$ is the mean PE / cm after the attenuation calibration corrections have been applied.

In order to select stopping muons only, the reconstructed track must end at least 50 cm from any edge of the detector and there must be a Michel electron at the end of the track. Due to the reliance on track reconstruction, only tracks which pass certain reconstruction quality criteria are used: the track length must be $\geq 200$ cm; the track length in the $z$ direction must be $\geq 70$ cm; the track’s $z$ direction unit vector must be $> 0.2$; the fraction of hits in the slice that are included in the track must be $> 0.8$; the distance between the edge of the detector and the first hit in the track must be $\leq 10$ cm; the distance between trajectory points...
<table>
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<tr>
<th>Sample</th>
<th>MEU_{reco} PE / cm</th>
<th>MEU_{reco} error</th>
<th>MEU_{truth} MeV / cm</th>
<th>Scale (MeV / PE) ×10^2</th>
</tr>
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<td>4.468</td>
</tr>
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<td>1.785</td>
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</tr>
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</tr>
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</tr>
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<td>ND MC</td>
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<td>1.796</td>
<td>4.321</td>
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</table>

Table 2.1: Absolute calibration energy scale for Far Detector (FD) data and MC, and Near Detector (ND) data and MC [31]. There was a change in gain for the Far Detector between periods 2 and 3 so two MC samples are used.

must be ≤ 3× the mean distance between trajectory points; the cell hits per plane must be ≤ 6; the difference between x view plane number and y view plane number at the end of the track must be ≤ 3; the asymmetry between the number of x view planes with hits in them and y view planes with hits must be ≤ 0.1 [29]. These restrictions are intended to only select long, well-constructed, downward travelling tracks that originate outside the detector.

There are also hit quality criteria: it must be a tricell hit (see section 2.6.1 and figure 2.13); the pathlength through the cell must be < 10 cm; to remove any residual edge and threshold effects not corrected by the attenuation calibration, ND hits must have -100 cm < W < 100 cm and FD hits must have 200 cm < W < 600 cm; hits must be in the minimum ionising window, i.e. between 100 cm to 200 cm from the end of the track [29] [31].

The energy scale factor from equation 2.7 is calculated separately for the Near Detector and Far Detector, for data and MC, and for each data-taking epoch [31]. The energy scale for some samples is listed in table 2.1.

### 2.6.3 Lepton to Hadron Ratio

The calibration uses cosmic muons, but the detector’s response to leptons and hadrons is not identical. Extensive studies using simulations of hadronic and leptonic energy deposition in both CC and NC events shows that the ratio of leptonic to hadronic response is 1.26, and is consistent across the energies used in NOvA’s analyses [32].
Chapter 3

Measuring Muon Neutrino Disappearance in NOvA with FNEX

3.1 Muon Neutrino Disappearance Signal

This analysis observes the survival rate of $\nu_\mu$ produced by the NuMI beam in order to calculate the corresponding values of $\Delta m^2_{32}$ and $\theta_{23}$. The signal events are $\nu_\mu$ CC interactions in the Far Detector. The distinguishing features of this interaction are a long muon track and a deposit of energy near the vertex from one or more hadrons, as detailed in section 2.4.

3.2 FNEX

FNEX (Far to Near EXtrapolation) is an analysis software framework for analysing NOvA data. FNEX stores all relevant information about individual events for the entire analysis, and systematic and oscillation weights are applied to events. This distinguishes FNEX from NOvA’s main analysis software, the Common Analysis Format (CAF), which performs all of its analysis on histograms in order to reduce processing time. Using CAF, individual events are recorded into histograms as the initial step in the analysis, and the remaining analyses and fits are performed in terms of histograms, not events.

Currently NOvA’s $\nu_\mu$ disappearance analyses are limited by statistics, but if the experiment collects enough data to become limited by systematics then FNEX may produce a more precise result than CAF’s histogram-dependent analysis. Until then, FNEX is also a cross check for CAF.

The first step of the FNEX analysis is to apply data cuts (detailed in section 3.3), which discards background events that are not part of the analysis and would destroy the signal to noise ratio (and needlessly use a very large amount of memory). ROOT files are generated using the selected events, which store information used in the analysis as listed in section 3.4. These data files are used to produce neutrino energy spectra for the Far Detector for the data and MC. A MINUIT fit is used to find the oscillation parameters that minimise the $\chi^2$ for a statistics only fit, and this is repeated with systematics listed in section 3.6.
3.3 Event Selection

Multiple cuts are applied to the data in order to separate signal from background, where the signal is CC interactions involving muon neutrinos produced by the beam. Because FNEX is intended to principally be a crosscheck for CAF, the same cuts are used in this analysis as in the main analysis.

The main source of background is cosmic muons, which are produced when a cosmic proton or atomic nucleus (e.g. $^{++}$He) collides with the atmosphere. As the Far Detector is on the surface these muons can easily enter the detector. In addition to these muons, the beam neutrinos can produce interactions that are not the signal for this analysis, such as NC (neutral current) interactions from any flavour of neutrino, electron neutrino CC interactions, and a small number of tau neutrino CC interactions.

The most important data cut is on timing, which happens before the reconstruction stage. Only data collected in a 550 µs window around the beam spill are kept for the oscillation analysis. Data with no coincident spills are kept for calibration and cosmic muon studies, such as generating the plots shown in this section and finding optimal cut values.

The remaining cuts occur after reconstruction, and are applied to each slice. Each slice should contain one particle interaction. For example, if a cosmic muon passed through the detector at the same time as a signal event, they should be in separate slices unless both interactions are simultaneous and in the same cells of the detector. This way the signal event could be selected while the cosmic muon is rejected.

The explanatory plots in this section use GENIE MC generated events (see section 2.5 for more information about the simulation) to represent the $\nu_\mu$ CC signal and the beam background, and data taken when the beam was off (referred to as cosmic data) to represent the cosmic background. Truth cuts are applied to the GENIE MC used here: there must be a $\nu_\mu$ CC event in the slice for it to be classified as signal, and no $\nu_\mu$ CC event to be classified as background. No cuts are applied to the cosmic data, except for the requirements that the beam was off and the full detector was active (i.e. no blocks were switched off for maintenance, etc), so some of the slices used may contain no muons, only noise. These plots were generated using a representative sample of files from all periods of data-taking. The 1D plots are normalised by area.

Two particle ID values are evaluated for all Kalman tracks: ReMId identifies muons, and CVN identifies signal muons and has two versions, trained using 2017 and 2018 data respectively (see section 2.4 for more details). There are no significant differences between the datasets that the 2017 and 2018 CVN were each trained on, but using two different datasets and finding similar results shows that the networks are not overtrained. CAF studies showed that a combination of ReMId and both iterations of CVN is the most effective way to reject NC and electron neutrino CC events: if ReMId or the 2018 CVN return values $\leq 0.7$ or the 2017 CVN returns a value $\leq 0.1$ the event is rejected. Figures 3.1, 3.2, and 3.3 show plots of ReMId and the 2018 CVN for MC signal, cosmic data, and MC beam background events respectively. As muons are present in the signal and cosmic background, ReMId is high for both the signal MC and the cosmic data, while the CVN values are generally lower for cosmic interactions. Both values are lower for the beam background although there is some spread at lower ReMId values, mostly well below the cut value. Figure 3.4 shows the distribution of the 2017 CVN for the three samples.

The event is rejected if it has too few or too many hits, or if there are not enough hits in
Figure 3.1: Plot of the ReMId PID value plotted against the CVN PID trained in 2018 for the signal MC, i.e. $\nu_\mu$ CC events that have been selected using truth information from the simulation. Events where either value is $\leq 0.7$ are rejected and not used in the analysis.

Figure 3.2: Plot of the ReMId PID value plotted against the CVN PID trained in 2018 for the cosmic data. Events where either value is $\leq 0.7$ are rejected and not used in the analysis.
Figure 3.3: Plot of the ReMId PID value plotted against the CVN PID trained in 2018 for the beam background. Events where either value is \( \leq 0.7 \) are rejected and not used in the analysis.

Figure 3.4: The CVN trained in 2017 for MC signal, cosmic data, and beam background. Events with a CVN value \( \leq 0.1 \) are rejected. Note the log scale on the Y axis.
contiguous planes. Too few hits show the track may not have been reconstructed correctly so the energy may be inaccurate, or if the track is short it may not even be a muon track. Too many hits may indicate that there was a cosmic shower, rather than a muon. If there are not enough contiguous hits this may indicate the same problems, or the track may be very vertical, which indicates that it may be a cosmic muon. To be accepted, an event must have more than 20 hits and fewer than 399 hits, and at least 5 hits must be in contiguous planes. See figure 3.5 and figure 3.6 for plots of these cuts. In figure 3.5 it seems that the > 399 cut removes more signal events than background events: this is due to the plots being normalised by area and using approximately two orders of magnitude more cosmic data events than simulated signal events. Also, many of the signal events in this region would have a neutrino energy greater than 5 GeV which means they would not included in the analysis even without this cut.

There are many containment cuts, as the reconstructed energy may be inaccurate if an event is partially outside the detector. Containment cuts also help to reject cosmic background, as the path of a cosmic muon starts in the atmosphere, while the signal consists of a $\nu_\mu$ CC interaction that starts and ends within the detector. There may be simultaneous background and signal events, but unless they physically overlap in the same cells of the detector they should be separated into different slices, so the signal event would still be accepted. Many containment cuts are based on prongs. All prongs in the slice must be at least 60 cm from the top of the detector, 12 cm from the bottom and West side, 16 cm from the East, and 18 cm from the front and back of the detector. Figure 3.7 shows the cut on the distance from the top of the detector, 3.8 shows the cut on the distance from the bottom of the detector, 3.9 shows the cut on the distance from the Eastern side of the detector, 3.10 shows the cut on the distance from the Western side of the detector, 3.11 shows the cut on the distance from the front side of the detector, and 3.12 shows the cut on the distance from the back side of the detector. There may
be noise hits which are not included in any prongs which are closer to the edge, but all hits that are part of the interaction should be included in this cut. In addition, there must be at least 2 planes between all hits and the front of the detector, and between all hits and the back: see figures 3.13 and 3.14.

As another containment cut that also removes cosmic background, each track is traced both forwards and backwards beyond the vertices to count how many cells the track would have to pass through in order to leave the detector. The two tracking algorithms are the Cosmic Tracker, which uses a window tracking algorithm and assumes the muon travels downwards, and the Kalman Tracker, which assumes the muon travels forward. Tracing the Cosmic Track forward from its end vertex, it must have to pass through at least one cell before leaving the detector for the event to be accepted, and tracing the track backwards from its start must have to pass through at least 8 cells before the edge where the track would have entered the detector. If there has been a problem in the reconstruction and the number of cells to pass through cannot be evaluated, it is set to -5: the cut of one cell serves only to eliminate these cases (although it has been stricter in previous analyses). Figures 3.15 and 3.16 show these cuts. For the Kalman Track, the track must have to pass through at least 7 cells in either direction before the muon track would enter or leave the detector: see figures 3.17 and 3.18.

As a cosmic muon rejection cut, the cosine of the angle between the Kalman Track and the beam direction must be greater than 0.5, as shown in figure 3.19. This is intended to reject vertical tracks.

As another cosmic rejection cut to reject vertical tracks, the fraction of the event’s momentum that is transverse to the beam (calculated using prongs) must be less than 90%. This cut is shown in figure 3.20.
Figure 3.7: The distance between the top of the detector and the highest prong hit. If this distance is less than 60cm, the event is rejected.

Figure 3.8: The distance between the bottom of the detector and the lowest prong hit. If this distance is less than 12cm, the event is rejected.
Figure 3.9: The distance between the eastern side of the detector and the furthest east prong hit. If this distance is less than 16cm, the event is rejected.

Figure 3.10: The distance between the western side of the detector and the furthest west prong hit. If this distance is less than 12cm, the event is rejected.
Figure 3.11: The distance between the front edge of the detector and the furthest forward prong hit. If this distance is less than 18cm, the event is rejected.

Figure 3.12: The distance between the back edge of the detector and the furthest back prong hit. If this distance is less than 18cm, the event is rejected.
Figure 3.13: The number of cells between the front edge of the detector and the furthest forward hit in the event. If this is less than 2 planes, the event is rejected.

Figure 3.14: The number of cells between the back edge of the detector and the furthest back hit in the event. If this is less than 2 planes, the event is rejected.
Figure 3.15: The number of cells the Cosmic Track would have to pass through to leave the detector: if this is less than 1, the event is rejected. Note the log scale on the Y axis.

Figure 3.16: The number of cells the Cosmic Track would have passed through from where it would have entered the detector: if this is less than 8, the event is rejected. Note the log scale on the Y axis.
Figure 3.17: The number of cells the Kalman Track would have to pass through to leave the detector: if this is less than 7, the event is rejected. Note the log scale on the Y axis.

Figure 3.18: The number of cells the Kalman Track would have passed through from where it would have entered the detector: if this is less than 7, the event is rejected. Note the log scale on the Y axis.
Figure 3.19: The cosine of the angle between the Kalman Track’s direction and the beam direction. If this value is less than 0.5, the event is rejected.

Figure 3.20: The fraction of the event’s momentum that is transverse to the beam, calculated using prongs. If this value is greater than 0.9, the event is rejected.
Machine learning is also used for cosmic rejection. A boosted decision tree (BDT) was trained to distinguish between contained beam events and cosmic muon tracks which appear to be contained (according to the previously mentioned containment cuts), where a higher value indicates that a track is likely to come from a signal event. The inputs are (in decreasing importance): the CVN value where CVN is selecting for cosmic muon interactions; length of the Kalman track; the maximum height of either the Cosmic track or Kalman track; the $\chi^2$ difference between the Cosmic track assuming that the muon travels down and assuming that it travels up; the ratio of hits in the Kalman track to total hits in the slice; the cosine of the angle between the Kalman track and the beam direction; the sum of the number of cells the track would pass through forward from its end and backward from its start (the sum of the values shown in figures 3.15 and 3.16, or in figures 3.17 and 3.18) for either Kalman or the Cosmic track; the $y$ component of the Kalman track’s direction \[33\]. The value returned by the BDT must be at least 0.53. Figure 3.21 shows the distribution of this variable and the cut value.

Only events with an energy up to 5 GeV are used in this analysis. As shown in figure 2.4, if there were no oscillations the $\nu_\mu$ energy peak would be around 2 GeV.

Figure 3.22 shows the purity and efficiency after each cut has been applied. The beam MC (used to find signal and beam background events) and the cosmic data (used to find cosmic background events) are normalised by time, with a purity of approximately 99.6\% and efficiency of approximately 35\% after all cuts. This plot and the purity and efficiency estimates do not use the full data available and are not official.

The data cuts are similar for the Near Detector. Cosmic rejection is less important as the detector has a large overburden which shields it from cosmic muons, so there is no cut on the
Figure 3.22: The purity and efficiency of the Far Detector selection. This plot uses MC to find the number of signal and beam background (i.e. NC) events, and cosmic data to find the number of cosmic events. The two sources are normalised by time.

angle between the Kalman track and the beam, the cosmic muon rejection BDT PID, or the fraction of the event’s momentum that is transverse to the beam. The containment cuts are also retuned for the different geometry (see section 2.3.2 for more information about the Near Detector): the Kalman track’s vertex cannot be in the muon catcher, and only the primary muon track can be in the muon catcher. There are no cuts using the Cosmic Tracker’s track, and the Kalman track must have to pass through at least 5 cells to exit the detector when tracing forwards from the track’s endpoint, and 10 cells when tracing backwards from its start point. The purity and efficiency are shown in figure 3.23: the purity is approximately 99.4% and the efficiency is approximately 2%. Efficiency is less of a priority in the Near Detector due to the higher number of neutrino events compared to the Far Detector.

Once the signal events for the muon neutrino analysis are selected, they are separated by hadron energy fraction (this is the fraction of the event’s total reconstructed energy that comes from the hadron) into four separate energy spectra. The neutrino’s energy is the sum of the reconstructed lepton and hadron energy. The lepton energy can be reconstructed more accurately than the hadron energy, so events where a higher fraction of the total energy came from the lepton are better understood and more likely to be signal (most incorrectly selected NC and cosmic background fall into the fourth quadrant, as shown in the energy spectra in figures 3.32 and 3.34). For this reason, the muon neutrino disappearance analysis separates the data into four quadrants of hadron energy fraction, where each quadrant has an equal number of events: figure 3.24 shows the boundaries between the quadrants.
Figure 3.23: The purity and efficiency of the Near Detector selection. This plot uses MC to find the number of signal and beam background (i.e. NC) events.

Figure 3.24: The fraction of neutrino energy that becomes hadron energy after the interaction, plotted as a function of the reconstructed energy for simulated FHC muon neutrino events [34]. The blue lines split the sample into four bins, each containing an equal number of events.
3.4 Event information

Due to memory restrictions and the high number of MC events, only information that is directly useful is stored.

The energy of the neutrinos is central to the analysis. The reconstructed lepton and hadron energy of each event are stored as individual variables (instead of only storing the total neutrino energy) as some systematics affect one and not the other.

Several bookkeeping variables are stored in order to keep track of when each event occurred. This is necessary to ensure that the correct calibration is applied, to match up Near and Far Detector data for extrapolation, and to check for any special conditions in the detector or beam’s condition.

For MC events, truth information is stored in addition to the reconstructed information. When the data are being fit, the oscillated simulated spectrum is calculated according to the truth information (although the reconstructed energy is what is shown in plots and used in the fit). In order to calculate the effect of oscillations and systematics correctly, FNEX’s files contain the neutrino’s true energy and flavour, whether the interaction in the detector was CC or NC and if it was quasi-elastic.

3.5 Extrapolation

The main reason for using two detectors is to reduce systematic errors by extrapolating the difference between MC and data in the Near Detector to the Far Detector. Because they use the same detector technology and the same beam, it is assumed that most systematic errors in the MC will be identical in both the Near and Far Detector. To this end the Far Detector MC is weighted by the ratio between the Near Detector data and MC. The number of events in bin $i$ of the predicted Far Detector reconstructed energy spectrum after extrapolation $F_i^{predicted}$ is calculated using

$$F_i^{predicted} = \frac{N_{Data}^i}{N_{MC}^i} \times \sum_j F_j^{MC} \left( P_{\nu_\mu \rightarrow \nu_\mu} (E_{\nu}^{True}) \right)$$  \hspace{1cm} (3.1)

where $N_{Data}^i$ and $N_{MC}^i$ are the number of data and MC events respectively in bin $i$ of the Near Detector reconstructed energy spectrum (the binning is identical for both detectors). $F_j^{MC}$ is the $j$th simulated event in that bin, and $P_{\nu_\mu \rightarrow \nu_\mu} (E_{\nu}^{True})$ is the probability that that event will not have oscillated. This probability is calculated using the true energy of each event, which has a spread within the single bin of reconstructed energy.

Figure 3.25 shows a ratio of the total number of data events to the number of MC events in the Near Detector for a fit without systematics, and figures 3.31 and 3.33 include a ratio of data / MC for each quadrant of hadron energy fraction for the best fit of the data.

For comparison, the CAF analysis finds a true energy corresponding to each reconstructed energy bin via a reconstructed to true energy matrix and calculates the oscillation probability this way.

3.6 Systematics

In order to account for systematic errors, adjustments are made to the MC during the fit. Systematic errors can come from inaccuracies in the simulations, incorrect calibration of the
ND Ratio of Data Events to MC Events

Figure 3.25: The ratio of the number of data events to the number of MC events in the Near Detector as a function of reconstructed energy.

detectors, or other aspects of the detector not being fully understood. From a long list of possible adjustments to the GENIE simulations and event reconstruction, only the systematics which have the largest effect on the Far Detector spectrum are used. This shortlist was tested and refined by the $\nu_\mu$ disappearance analysis group using CAF, and then the chosen systematics were implemented in FNEX.

Some systematics relate to calibration. Studies of the calorimetric response were conducted using ND data and MC after calibration and the largest discrepancy found was the calorimetric response for protons, which was 5% lower in the data than in the MC, interpreted as a standard deviation (1$\sigma$) of 5% [35]. As these studies were not repeated for the Far Detector this may or may not be a relative effect that only applies to the Near Detector, so a relative calibration error of 5% is also considered [35]. Special datasets were generated where the calibration parameters are adjusted by $\pm$5% in one or both of the detectors to represent the absolute or relative calibration error. Energy spectra are generated from these datasets and histograms are made of the ratio between them and the nominal dataset. Because an entirely different dataset is used to calculate the effect of changes to the calibration, it is not possible to find the effect on each event, only the overall effect on the energy spectra: for this reason ratio histograms are used, instead of individual event weights. When the systematic is applied to the MC during the fit, each bin is weighted by the bin contents of the ratio histogram. The changes to the calibration that are simulated in the datasets are to scale the calibration up and down in both detectors (referred to as the absolute calibration systematic), or just one detector (the relative calibration systematic), and the shape of the calibration fit (calibration shape systematic).

In addition to these more nuanced calibration systematics, there is also a shift of the leptonic energy. After extensive studies, the uncertainty in GEANT4’s simulation of muon energy loss, detector mass, and detector composition were conglomerated into an absolute lepton energy shift and a relative lepton energy shift. For $+1\sigma(-1\sigma)$ absolute lepton energy shift, the muon’s track length is increased (decreased) by 0.94% in both detectors [35]. If the muon is in the Near Detector and part of the track is in the muon catcher, the segment in the muon catcher is increased by a further 0.69%. For the relative energy shift, the track length of muons in the Far
Detector is increased (decreased) by 0.135% and the track length of muons in the Near Detector is decreased (increased) by 0.135% for a $+1\sigma$ ($-1\sigma$) change, and a further 0.75% ($-0.75\%$) in the Near Detector’s muon catcher.

There are a large number of variables in GENIE that can be adjusted and are included as systematics, as the precise tuning of some of these can adjust NOvA’s energy spectra. In all of these cases, the weighting comes from the GENIE user manual [36]. The GENIE user manual lists the axial mass for charged-current quasi-elastic scattering, and the axial and vector masses for charged-current and neutral-current resonance neutrino production as the dominant systematics for neutrino interactions in NOvA’s energy range [36]. These masses are variables in the form factors used to calculate the differential cross-section for neutrino quasi-elastic scattering and resonance neutrino systematics [37], so uncertainty in the precise value of these variables can affect NOvA’s spectra. These systematics are referred to as MaCCRES (axial mass in CC resonance neutrino production) with an uncertainty of 20% on the axial mass, MaNCRES (axial mass in NC resonance neutrino production) with an uncertainty of 20%, MaCCQE (axial mass in CC quasi-elastic neutrino scattering) with an uncertainty of +20% for $+1\sigma$ and -15% for $-1\sigma$, and MvCCRES (vector mass in CC resonance neutrino production) with an uncertainty of 10% [36]. Shifting any of these variables up or down changes the cross section for the related interaction, and so affects the weight for certain events: in FNEX, these weights are stored for each event and applied during the fit.

There are six systematics related to varying the meson exchange current (MEC) model in GENIE. In the distribution of the differential cross section as a function of energy transfer, there is a dip in the region between the quasi-elastic peak and the resonance peak - this dip can be modelled using an accurate MEC model [38]. NOvA uses six systematics to describe the possible adjustments to the MEC model in GENIE that could affect the neutrino energy spectra. The first is adjusting the shape of the energy spectrum of the incoming neutrino: this systematic is called MEC $E_{\nu}$ shape and is applied separately to $\nu$ and $\bar{\nu}$ events. The two MEC shape systematics affect the shape of the model itself for neutrinos and antineutrinos respectively. The fraction of initial nucleon pairs that are neutron-proton or neutron-neutron can also be adjusted: this systematic is referred to as the MEC Init. NP Frac in the plots in this section, and is applied separately to neutrinos and antineutrinos.

The effect of random phase approximation is included in the form of two systematics, RPA shape resonance and RPA shape enhancement. Both of these are GENIE variables stored as weights for each event. RPA resonance is a one-sided systematic that can only have $\geq 0\sigma$, a negative value of sigma does not make sense physically.

Specific conditions of Deep Inelastic Scattering (DIS) can be weighted up or down as a systematic to probe the effect of inaccurate modelling of the effect. CAF-led studies showed that $1\sigma$ corresponds to a 10% shift in any specific channel of DIS: the channels simulated are all combinations of NC or CC interactions, collisions between a neutrino or antineutrino with a neutron or proton, and the production of between zero and three pions. When each of these channels was weighted by 10% the only significant systematic was found to be for the case of a neutrino colliding with a neutron in a CC interaction that produces a pion is included as a systematic. Other conditions were rarer or the resulting pion(s) were more likely to be recognised as background and rejected.

While the $\nu_\mu$ disappearance analysis is not sensitive enough to $\delta_{CP}$ to measure it, the variable can still have a small effect on the shape of the energy spectrum due to matter effects, so it is included as a systematic. The effect of changing the value of $\delta_{CP}$ has enough of an effect
Figure 3.26: The results of shifting a fake data spectrum by $\pm 1\sigma$ and letting the fitter try to find the shift that was applied.

To adjust the exact shape of the confidence level contours and so it is included in the list of systematics.

Tests are run to show that these systematics can be applied to the MC during a fit to match how the data changes. A high statistics fake data spectrum is generated with a $+1\sigma$ or $-1\sigma$ shift and then that variable is allowed to float in the fit. If the systematic is affecting the MC in the expected way, and has a large enough effect that outweighs the added weight of the nuisance parameter, the result of the fit should be identical to what was applied to the fake data. The result of this test for each systematic is shown in figure 3.26. Note that the Calibration Shape, DIS, and RPA resonance systematics are one-sided, i.e. a negative shift is impossible. Some other shifts cannot achieve the correct fit because the effect of the systematic on the spectrum is smaller than the effect of the nuisance parameter on the total $\chi^2$. This is usually because that systematic only affects NC or $\nu$ events, which make up a small part of the total number of events.

To find the effect of each individual systematic on the final fit of $\theta_{23}$ and $\Delta m_{32}^2$, the $+1\sigma$ or $-1\sigma$ shift is applied to the fake data but the systematic is fixed to a $0\sigma$ shift in the fit, while $\theta_{23}$ and $\Delta m_{32}^2$ float. The results of these tests are shown in figures 3.27, 3.28, 3.29, and 3.30 and summarised in tables 3.1 and 3.2.
Figure 3.27: The change to the final fit values of $\sin^2 \theta_{23}$ and $\Delta m^2_{32}$ when a $\pm 1\sigma$ shift of each individual calibration and energy systematic is applied to fake data but no systematics are included in the fit. The “Calibration Shape” systematic is one sided, i.e. a negative shift is not physically possible.

Figure 3.28: The change to the final fit values of $\sin^2 \theta_{23}$ and $\Delta m^2_{32}$ when a $\pm 1\sigma$ shift of each individual MEC-related systematic is applied to fake data but no systematics are included in the fit.
Figure 3.29: The change to the final fit values of $\sin^2 \theta_{23}$ and $\Delta m^2_{32}$ when a $\pm 1\sigma$ shift of each individual mass resonance systematic is applied to fake data but no systematics are included in the fit.

Figure 3.30: The change to the final fit values of $\sin^2 \theta_{23}$ and $\Delta m^2_{32}$ when a $\pm 1\sigma$ shift of each remaining systematic is applied to fake data but no systematics are included in the fit. The DIS $\nu n$ CC $1\pi$ and RPA resonance systematics are one sided, i.e. a negative shift is not physically possible.
<table>
<thead>
<tr>
<th>Systematic</th>
<th>Effect on $\sin^2 \theta_{23}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$+1\sigma$</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Abs. Calib.</td>
<td>+0.0033 (+0.59%)</td>
</tr>
<tr>
<td>Calib. Shape</td>
<td>-0.0063 (-1.14%)</td>
</tr>
<tr>
<td>Reco. $E_\mu$ Shift</td>
<td>+0.0011 (+0.198%)</td>
</tr>
<tr>
<td>Rel. Calib.</td>
<td>-0.0051 (-0.913%)</td>
</tr>
<tr>
<td>Rel. Reco. $E_\mu$ Shift</td>
<td>-0.0014 (-0.247%)</td>
</tr>
<tr>
<td>MEC $E_\nu$ Shape: $\nu$</td>
<td>+0.0002 (+0.0409%)</td>
</tr>
<tr>
<td>MEC $E_\bar{\nu}$ Shape: $\bar{\nu}$</td>
<td>+0.0001 (+0.0188%)</td>
</tr>
<tr>
<td>MEC Shape: $\nu$</td>
<td>+0.0031 (+0.564%)</td>
</tr>
<tr>
<td>MEC Shape: $\bar{\nu}$</td>
<td>+0.0001 (+0.0184%)</td>
</tr>
<tr>
<td>MEC Init. NP Frac: $\nu$</td>
<td>-0.0001 (-0.0137%)</td>
</tr>
<tr>
<td>MEC Init. NP Frac: $\bar{\nu}$</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>GENIE MaCCQE Shape</td>
<td>+0.0013 (+0.24%)</td>
</tr>
<tr>
<td>GENIE MaCC Res.</td>
<td>-0.0006 (-0.112%)</td>
</tr>
<tr>
<td>GENIE MaNC Res.</td>
<td>+0.0007 (+0.121%)</td>
</tr>
<tr>
<td>GENIE MvCC Res.</td>
<td>-0.0004 (-0.0704%)</td>
</tr>
<tr>
<td>DIS $\nu n$ CC $1\pi$</td>
<td>-0.0004 (-0.0736%)</td>
</tr>
<tr>
<td>RPA CCQE Shape Enh.</td>
<td>+0.0007 (+0.121%)</td>
</tr>
<tr>
<td>RPA Res.</td>
<td>-0.0041 (-0.0737%)</td>
</tr>
</tbody>
</table>

Table 3.1: Table showing the effect of each individual systematic on the value of $\sin^2 \theta_{23}$ when fitting fake data and allowing the oscillation variables to float but fixing the systematic at 0. See figures 3.27, 3.28, 3.29, and 3.30 for a visual representation of the changes to the best fit values of $\sin^2 \theta_{23}$ and $\Delta m_{23}^2$ by each systematic.
**Table 3.2:** Table showing the effect of each individual systematic on the value of $\Delta m_{\nu 23}^2$ when fitting fake data and allowing the oscillation variables to float but fixing the systematic at 0. See figures 3.27, 3.28, 3.29, and 3.30 for a visual representation of the changes to the best fit values of $\sin^2 \theta_{23}$ and $\Delta m_{\nu 23}^2$ by each systematic.

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Effect on $\Delta m_{\nu 23}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$+1\sigma$</td>
</tr>
<tr>
<td>Abs. Calib.</td>
<td>+0.03 (+1.2%)</td>
</tr>
<tr>
<td>Calib. Shape</td>
<td>-0.01 (-0.285%)</td>
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<tr>
<td>Reco. $E_\mu$ Shift</td>
<td>-0.01 (-0.462%)</td>
</tr>
<tr>
<td>Rel. Calib.</td>
<td>+0.003 (+0.118%)</td>
</tr>
<tr>
<td>Rel. Reco. $E_\mu$ Shift</td>
<td>-0.001 (-0.058%)</td>
</tr>
<tr>
<td>MEC $E_\nu$ Shape: $\nu$</td>
<td>+0.005 (+0.185%)</td>
</tr>
<tr>
<td>MEC $E_\nu$ Shape: $\bar{\nu}$</td>
<td>+0.0002 (+0.00785%)</td>
</tr>
<tr>
<td>MEC Shape: $\nu$</td>
<td>-0.01 (-0.26%)</td>
</tr>
<tr>
<td>MEC Shape: $\bar{\nu}$</td>
<td>+0.0002 (+0.00794%)</td>
</tr>
<tr>
<td>MEC Init. NP Frac: $\nu$</td>
<td>+0.003 (+0.109%)</td>
</tr>
<tr>
<td>MEC Init. NP Frac: $\bar{\nu}$</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>GENIE MaCCQE Shape</td>
<td>-0.004 (-0.182%)</td>
</tr>
<tr>
<td>GENIE MaCC Res.</td>
<td>-0.01 (-0.489%)</td>
</tr>
<tr>
<td>GENIE MaNC Res.</td>
<td>+0.0007 (+0.0293%)</td>
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<tr>
<td>GENIE MvCC Res.</td>
<td>-0.01 (-0.305%)</td>
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<tr>
<td>DIS $\nu_n$ CC $1\pi$</td>
<td>+0.001 (+0.0463%)</td>
</tr>
<tr>
<td>RPA CCQE Shape Enh.</td>
<td>-0.002 (-0.0941%)</td>
</tr>
<tr>
<td>RPA Res.</td>
<td>+0.01 (+0.28%)</td>
</tr>
</tbody>
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Table 3.2: Effect of each individual systematic on the value of $\Delta m_{\nu 23}^2$ when fitting fake data and allowing the oscillation variables to float but fixing the systematic at 0.
### Results of fit without systematics

<table>
<thead>
<tr>
<th>Oscillation parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{23}$</td>
<td>0.798</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.512</td>
</tr>
<tr>
<td>$\Delta m^2_{32}$</td>
<td>$2.426 \times 10^{-3}$ eV</td>
</tr>
<tr>
<td>$\delta_{CP}$</td>
<td>0</td>
</tr>
<tr>
<td>$\Delta m^2_{21}$</td>
<td>$7.530 \times 10^{-5}$ eV</td>
</tr>
<tr>
<td>$\theta_{13}$</td>
<td>0.145</td>
</tr>
<tr>
<td>$\theta_{12}$</td>
<td>0.587</td>
</tr>
<tr>
<td>$\rho$</td>
<td>2.840 g/cm$^3$</td>
</tr>
<tr>
<td>$L$</td>
<td>810 km</td>
</tr>
</tbody>
</table>

Table 3.3: Result of the fit without systematics. The parameters marked “FREE” were free parameters in the fit. $\rho$ is the average density of the Earth, $L$ is the distance the neutrinos have travelled.

### 3.7 Results

A statistics only fit of the data is shown in figures 3.31 and 3.32. The colours represent the different parts of the MC: the largest contribution comes from the $\nu_\mu \rightarrow \nu_\mu$ signal (solid green), but there are also contributions from the $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ background and other flavours of neutrino and antineutrino, along with NC interactions and cosmic muons. The background is largest in the Far Detector’s fourth quadrant of hadronic energy fraction.

The best fit of $\sin^2 \theta_{23}$ and $\Delta m^2_{32}$ are 0.512 and $2.426 \times 10^{-3}$ eV respectively. Without including systematics, this is not truly representative of the data and errors would be inaccurate.

Using all of the systematics takes a prohibitively long time and large amount of computing resources so only the most significant (according to the CAF analysis) are used: these relate to relative and absolute calibration and its shape, relative and absolute hadronic energy shifts, leptonic energy shifts, MEC shape for $\nu s$ and the axial mass resonance for charged current (see section 3.6 for the full description of these systematics). Using the contour to find the errors at a 68% confidence level, the oscillation parameters are found to be $\sin^2 \theta_{23} = 0.499^{+0.068}_{-0.069}$ and $\Delta m^2_{32} = 2.454^{+0.108}_{-0.119} \times 10^{-3}$ eV, the best fit is shown in figures 3.33 and 3.34. This is not a significant change to the fit without systematics shown in figure 3.32. This best fit with systematics is used in the contour in figure 3.35 which shows the $1\sigma$ and $2\sigma$ confidence levels.

To generate this contour, a $50 \times 50$ grid of points in the parameter space is used. A fit is run at each point in the grid where $\theta_{23}$ and $\Delta m^2_{32}$ are fixed but the systematic parameters are allowed to float. The $\chi^2$ of this point is compared to the value of $\chi^2$ at the best fit point to make a plot of $\Delta \chi^2$ and contours are drawn showing the level of confidence with which any potential set of oscillation parameters can be rejected.

#### 3.7.1 Comparison with CAF

The results of the CAF analysis of the same data is shown in figure 3.36, overlaid in grey with the results of the FNEX analysis described here. There are some small differences, most significantly in the $\Delta m^2_{32}$ dimension. The dataset used and the selection are identical, but due to
Figure 3.31: Result of the fit without systematics in the Near Detector.
Figure 3.32: Result of the fit without systematics in the Far Detector.
Figure 3.33: Result of the fit with systematics in the Near Detector.
Figure 3.34: Result of the fit with systematics in the Far Detector.
## Results of fit with systematics

### Oscillation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$\theta_{23}$</td>
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<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.499</td>
</tr>
<tr>
<td>$\Delta m_{32}^2$</td>
<td>$2.454 \times 10^{-3}$ eV</td>
</tr>
<tr>
<td>$\delta_{CP}$</td>
<td>$1.022\pi$</td>
</tr>
<tr>
<td>$\Delta m_{21}^2$</td>
<td>$7.530 \times 10^{-5}$ eV</td>
</tr>
<tr>
<td>$\theta_{13}$</td>
<td>0.145</td>
</tr>
<tr>
<td>$\theta_{12}$</td>
<td>0.587</td>
</tr>
<tr>
<td>$\rho$</td>
<td>2.840 g/cm$^3$</td>
</tr>
<tr>
<td>$L$</td>
<td>810 km</td>
</tr>
</tbody>
</table>

### Systematics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP MEC Shape $\nu$ Weight</td>
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</tr>
<tr>
<td>NP Calibration Shape Weight</td>
<td>0.214</td>
</tr>
<tr>
<td>NP Reconstructed Leptonic E Shifter</td>
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</tr>
<tr>
<td>NP RPA RES Weight</td>
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</tr>
<tr>
<td>NP MEC $E_\nu$ Shape Weight</td>
<td>-0.098</td>
</tr>
<tr>
<td>NP Absolute Calibration Weight</td>
<td>0.071</td>
</tr>
<tr>
<td>NP RPA CCQE Shape Enhancement Weight</td>
<td>-0.065</td>
</tr>
<tr>
<td>NP Relative Reconstructed Leptonic E Shift</td>
<td>0.056</td>
</tr>
<tr>
<td>NP $M_a$ CC QE Weight</td>
<td>-0.054</td>
</tr>
<tr>
<td>NP $M_a$ RES Weight</td>
<td>0.035</td>
</tr>
<tr>
<td>NP MEC Initial NP Fraction $\nu$ Weight</td>
<td>-0.034</td>
</tr>
<tr>
<td>NP Relative Calibration Weight</td>
<td>0.026</td>
</tr>
<tr>
<td>NP $M_a$ NC RES Weight</td>
<td>-0.023</td>
</tr>
<tr>
<td>NP $M_\nu$ CC RES Weight</td>
<td>0.020</td>
</tr>
<tr>
<td>NP MEC Shape $\bar{\nu}$ Weight</td>
<td>0.004</td>
</tr>
<tr>
<td>NP MEC Initial NP Fraction $\bar{\nu}$ Weight</td>
<td>0.004</td>
</tr>
<tr>
<td>NP MEC $E_\nu$ Shape $\bar{\nu}$ Weight</td>
<td>-0.001</td>
</tr>
</tbody>
</table>

Table 3.4: Result of the fit with systematics. The parameters marked “FREE” were free parameters in the fit, parameters marked “NP” were nuisance parameters.
Figure 3.35: Contour showing the best fit point, and the 68% and 90% confidence levels.
the different methods of considering systematic errors CAF is able to include more systematics than FNEX. The differences between the contours are most likely due to the difference in systematics used and how the systematics are applied (i.e. CAF’s histogram approach instead of FNEX’s event-by-event approach).

### 3.7.2 Comparison with NOvA’s latest results and other neutrino experiments

Since this analysis, NOvA has continued to take data, mostly using the NuMI beam in RHC mode to produce anti-neutrinos. In June 2019 NOvA published results [39] using the same $8.85 \times 10^{20}$ POT of FHC data represented in this thesis and an additional $12.33 \times 10^{20}$ POT of RHC data: the results are shown in figure 3.37, along with the 90% CL results of other major experiments.

As experiments collect more data and systematics are modelled more accurately, the results should continue to converge. Planned experiments such as CHIPS and DUNE will also contribute to the overall picture of neutrino oscillation.
Figure 3.37: Comparison of several major experiments' results from 2019 [39]. There is some overlap in all of the experiments, especially between NOvA and T2K.
Chapter 4

The CHIPS Experiment

4.1 Overview

CHIPS is a neutrino oscillation experiment using a cylindrical water Cherenkov detector located 7mrad off-axis with respect to the NuMI beam, 710km from the NuMI target. The planned location of the CHIPS detector is shown in figure 4.1. See section 2.2 for more details on the NuMI beam, and section 4.2 for more information about water Cherenkov detectors.

The CHIPS experiment aims to prove that it is possible to construct the next generation of neutrino detectors quickly and affordably. As neutrino research progresses, detectors are growing larger and increasingly complex, with a matching increase in cost. If this continues then it will no longer be practical to build neutrino detectors that are sensitive enough to add to current knowledge. To keep production costs down and maintain a feasible schedule, CHIPS uses commercially available materials to construct a detector that uses known technology to detect neutrinos.

As a water Cherenkov detector, CHIPS will be able to detect and differentiate between muon and electron neutrinos. This means that it can observe $\nu_e$ appearance (in addition to $\nu_\mu$ disappearance), which allows it to measure CP violation and combine its results with that of T2K and NOvA to help to further constrain $\delta_{CP}$. Figure 4.2 shows two potential deployment timelines for CHIPS, both showing that it can make a meaningful contribution.

In the summer of 2019 a 7kT CHIPS prototype was deployed without walls: the top and bottom caps of the cylinder have PVC planes holding PMTs, but the sides of the cylinder are bare. The deployment method was shown to be successful, and this prototype will test whether the liner can prevent water and light from entering the detector, whether data can be collected and relayed to shore, and whether the water filtration system can maintain water clarity. There are plans to open the liner, put the walls in, and redeploy the detector in 2020.

4.2 Water Cherenkov Detectors

CHIPS uses water to fill its detector volume for two main reasons: this type of detector has already been proven to work, and it is much cheaper. Sourcing water from the detector’s site is far cheaper than using liquid scintillator (as NOvA does), or liquid argon (as DUNE will). The main cost associated with using water is the cost of pumps and filters: chapter 5 details the measurements to find the necessary level of filtration. The other advantage of a water
Figure 4.1: The locations of CHIPS and the MINOS and NOvA far detectors [40]. The colour scale shows the flux of NuMI neutrinos where they emerge at different places, and the contours of peak $\frac{E}{L} = 300$ km/GeV and peak $\frac{E}{L} = 500$ km/GeV are shown in black and red respectively.

Figure 4.2: CHIPS data may help to constrain $\delta_{CP}$ when combined with NOvA and T2K data. The red plot shows a future without CHIPS, while the green and blue plots show the effect of two potential timelines for CHIPS detector deployment on physicists’ ability to measure $\delta_{CP}$ [41].
Cherenkov detector is that this technology has been used successfully for years, reducing the need for a long research and development period.

These detectors use Cherenkov radiation. When a charged particle moves through a dielectric medium faster than the speed of light in that medium \((c_n)\) where \(n\) is the medium’s refractive index, the particle emits electromagnetic radiation. As the charged particle moves through the medium it excites the electrons of atoms in its path, which must then emit radiation to return to the ground state. If the source of this excitation were at rest, the radiation would be observed as spherical waves of light. However, as the source is moving faster than the speed of light in the medium, the wavefront is in the shape of a cone as shown in figure 4.3: at point \(x_1\) radiation is emitted to a radius of \(r_1\), when the source has moved to point \(x_2\) the initial wavefront has a radius of \(r_3\) and a new spherical wavefront has been emitted to a radius of \(r_2\). In figure 4.3 this is shown for two distinct points, but in reality this is a continuous effect on the path of the charged particle. This produces a cone, similar to the wake behind a boat [42].

This shockwave will be in the shape of a cone with an angle of \(\theta\), which can be found using

\[
\cos \theta = \frac{1}{n\beta}
\]

where \(n\) is the refractive index of the medium and \(\beta\) is the ratio of the speed of the moving charged particle to the speed of light in a vacuum. For pure water at 20\(^\circ\)C, the value of \(n\) is 1.33. The shockwave for a particle of charge \(q\) travelling at speed \(v\) will be in the form of electromagnetic waves whose frequency \(\omega\) is governed by the Frank-Tamm formula

\[
\frac{d^2 E}{dx d\omega} = \frac{q^2}{4\pi} \mu(\omega) \omega \left( 1 - \frac{c^2}{v^2 n^2(\omega)} \right)
\]

where \(\frac{d^2 E}{dx d\omega}\) describes the energy emitted per unit distance travelled \(dx\) and unit frequency \(d\omega\), and \(\mu(\omega)\) is the permeability of the material. Permeability \(\mu\) and refractive index \(n\) may vary as a function of electromagnetic wave frequency \(\omega\). The factor of \(\omega\) in equation 4.2 leads to more energy being emitted at higher frequencies, resulting in more light being released as ultraviolet electromagnetic radiation, and at the violet to blue end of the visible light spectrum.

Neutrinos do not emit Cherenkov radiation as they have no electromagnetic charge. However, both NC and CC interactions result in the emission of charged particles, which can emit...
Cherenkov radiation. By reconstructing the light cone, a detector can establish important information about the interaction. The cone’s vertex and direction show where the interaction happened and the direction that the neutrino was moving in, which can be important for beam experiments that reject anything that did not come from the direction of their neutrino source. The opening angle of the cone $\theta$ shows the speed of the charged particle using equation 4.1, which can then be used to find the energy of that particle and neutrino.

The shape of the cone can show whether the charged particle is a muon or an electron. The Cherenkov radiation produced by a muon moving through the detector will be a single, well-defined cone. However, an electron moving fast enough to produce Cherenkov radiation (i.e. $v > \frac{c}{n}$) will produce an electromagnetic shower, where the original electron emits photons via bremsstrahlung which then convert into an electron and positron via pair production, and the cycle continues. This shower of electrons, positrons, and photons will result in overlapping Cherenkov cones which appear in the detector as a “fuzzy” cone. Using this method to differentiate between electrons and muons that are emitted from CC interactions shows the flavour of the neutrino in that interaction.

4.2.1 Examples of Water Cherenkov Detectors

As previously stated, water Cherenkov detectors are a proven technology and there are multiple examples of existing and planned water Cherenkov detectors.

The largest current example of a liquid water Cherenkov detector is Super-Kamiokande, a 50 kiloton detector located underground at the Kamioka Observatory of the Institute for Cosmic Ray Research in Japan. The detector uses 11,146 Hamamatsu R3600 50 cm diameter photomultiplier tubes which provide approximately 40% coverage [43]. The detector first started taking data in 1996 and is the far detector for the T2K neutrino oscillation experiment.

Water Cherenkov detectors do not always enclose a volume of liquid water: for example, IceCube uses a cubic kilometre of ice in Antarctica. 5160 spherical Digital Optical Modules (DOMs) are deployed in the naturally occurring Antarctic ice, between 1.5 km and 2.5 km under the surface. While T2K needs to purify their water to ensure that it is clear enough, the ice in IceCube is naturally ultraclear. IceCube is primarily used to detect high-energy astrophysical neutrinos and became fully operational in 2010 [44].

CHIPS is not the only future water Cherenkov detector being planned. KM3NeT is a neutrino detector in the process of being deployed in three locations in the Mediterranean Ocean. Like IceCube, KM3NeT will use spherical DOMs attached to long vertical strings, three of which have been installed. KM3NeT’s DOMs will each contain 31 3” PMTs, and 18 DOMs are connected together in each string using Dyneema cable that stretches between the ocean floor (which is 2500 to 4500 m below the surface) and a submerged buoy near the surface. Dyneema cable is a lightweight alternative to steel cables with similar strength, but with neutral buoyancy and corrodes less in salt water. The shallowest PMTs are located approximately 1 km below the surface to provide shielding from cosmic muons and from sunlight and other light pollution, the deepest DOMs will be 100 m above the ocean floor, and there is 36 m of vertical spacing between each DOM [45]. 115 strings will be placed at each of the three locations. KM3NeT aims to have completed construction in all three locations by 2020 [46].
Table 4.1: Table showing the resolution to which the vertex of a neutrino interaction can be reconstructed for different PMT types and coverage, for both $\nu_e$ and $\nu_\mu$ events. The “Geometry” column shows the diameter of the PMT in inches and the percentage of coverage. The remaining columns show the resolution of the position of the interaction vertex, the time at which it occurred, the direction that the neutrino was moving in, and its energy. Taken from [47].

<table>
<thead>
<tr>
<th>Sample</th>
<th>Geometry</th>
<th>Vertices Reconstruction Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pos. (cm)</td>
<td>Time (ns)</td>
</tr>
<tr>
<td>CCQE $\nu_e$</td>
<td>10”, 10%</td>
<td>35</td>
</tr>
<tr>
<td>CCQE $\nu_\mu$</td>
<td>3”, 10%</td>
<td>35</td>
</tr>
<tr>
<td>CCQE $\nu_\mu$</td>
<td>3”, 6%</td>
<td>38</td>
</tr>
<tr>
<td>CCQE $\nu_e$</td>
<td>10”, 10%</td>
<td>47</td>
</tr>
<tr>
<td>CCQE $\nu_\mu$</td>
<td>3”, 10%</td>
<td>44</td>
</tr>
<tr>
<td>CCQE $\nu_\mu$</td>
<td>3”, 6%</td>
<td>51</td>
</tr>
</tbody>
</table>

4.3 The CHIPS Detector

CHIPS’s five main steps to building an affordable and effective detector are: using a location that makes use of an existing neutrino source and cosmic shielding; constructing the detector’s planes using cheap, readily available materials that do not require specialised skills; optimising the number and positioning of PMTs; using commercially available microprocessors and electronic components; and finding a commercially available water filtration system that can achieve the necessary clarity.

The CHIPS detector will be located 7 mrad off axis from the NuMI beam (see figure 4.1 for a map), submerged in an existing flooded mine pit which will provide the water to fill the detector, an overburden to shield the detector from cosmic muons, and support the mechanical structure.

The detector is a cylinder, 25 m in diameter and 6 m in height and containing 7 kT of water. The frame is constructed from PVC pipe which holds PMTs. The PVC structure is built in the form of rectangular, two-dimensional planes (see figure 4.4). Each plane holds 15 or 30 PMTs depending on its location in the detector. The PVC pipe, connectors, and glue are commercially available. Plane construction is a simple process requiring no specialised technicians. The planes are then combined into a large cylinder with top and bottom caps, with PMTs facing inwards, as shown in figure 4.5. Some planes on the top and bottom caps are irregularly shaped to form a circle. The PVC structure is supported by steel end caps on the top and bottom of the cylinder with Dyneema cables connecting them. The entire structure is contained within a sealed plastic liner which prevents light from entering and water from entering or leaving the detector.

The PMTs provide 6% coverage. Simulations have shown that this is sufficient (see table 4.1). The PMTs are angled towards the beam and more densely populated in the areas where beam neutrinos are more likely to be detected, see figures 4.4 and 4.5. Many top cap planes have upward facing PMTs to act as a veto against downward moving cosmic muons.

The majority of the PMTs are 88 mm HZC PMTs, while the 480 back wall PMTs are 3” Hamamatsu R6091. The HZC PMTs use electronics designed by the KM3NeT experiment. The back-wall PMTs were provided by the NEMO3 experiment and the electronics have been
Figure 4.4: Left: 3D CAD drawing of a plane, showing how the PMTs are angled. Right: photo of a plane [48]. Each PMT has a Winston cone attached to help it to collect light. The large cylinder in the middle of the CAD drawing is to hold electronics, which are connected to the PMTs via CAT 5/6 cables that pass through the PVC pipes.

Figure 4.5: A 3D CAD drawing of the barrel (left) and the top cap of the detector (right), i.e. the sides and “lid” of the detector. Note that the back half of the top cap is constructed from high density planes (as shown in figure 4.4) as that area will see more light from Cherenkov cones from neutrinos moving in the beam direction.
developed by the CHIPS collaboration, including designing boards to power the PMTs, acquiring data from them, and fanning out signals to and from them. The aim is to be able to adapt to any kind of PMTs that are available. Generally it would be possible to keep the anode grounded and use a Cockroft-Walton board to apply a negative voltage to the cathode, but CHIPS’ PMTs will make direct contact with the water in the detector (which is at ground) which can attract electrons within the PMT to the glass, potentially causing glass scintillation and significant noise [49]. For this reason, CHIPS developed a Cockroft-Walton board that generates a positive voltage, in order to hold the anode at a positive charge and keep the cathode grounded.

The entire detector is contained within a sealed plastic liner which will be welded onsite. This prevents light from entering the detector: at 60 m depth, there is still a small amount of light that could interfere with the PMTs. The liner also prevents water from moving in and out of the detector: this helps to keep the water pure enough that light from events near the centre of the detector can be seen by the PMTs at the edge. To this end water is continuously pumped to the shore to be filtered and back to the detector. Chapter 5 covers the extensive testing that was done to find the necessary level of filtration. If water from the lake were allowed to enter the detector then the filtered water could be contaminated, risking algae blooms and bacteria growth that would interfere with water clarity.

The detector that was deployed in 2019 is intended to be a starting point (as indicated by the timeline in figure 4.2) and the detector volume can be increased in two ways. The first is simply to build more identical detectors in the same location, which would increase the data collected without significant changes to background, systematic errors etc. The other potential method is to pull the existing detector out of the flooded mine pit using a crane, open the liner, and attach additional rings of planes.

Simulations show that the detector will be able to reconstruct and differentiate between the Cherenkov rings of electron neutrinos and muon neutrinos (see section 4.2 for more details on Cherenkov radiation), as shown in figures 4.6 and 4.7. In the simulations used to generate these plots, the water has an attenuation length of 50 m.
Figure 4.6: A simulated $\nu_\mu$ CC quasi-elastic event in the CHIPS detector [50]. The top shows the sides of the cylinder as a single stretched out strip, while the two lower plots show the top and bottom caps. The colourful points show the locations of PMTs which have detected light and the magnitude of the charge (i.e. how much light each PMT detected). The dark purple line shows the reconstruction of the ring left by the Cherenkov cone that hits the boundaries of the detector. For this $\nu_\mu$ event, the outer boundaries of the ring are clearly defined. The reconstruction found a $\mu_-$ with a vertex at (-4.750, 3.094, -0.138) m travelling in the direction of (0.969, 0.239, 0.067) with an energy of 2.409 GeV. The true event was a $\mu_-$ with a vertex at (-5.230, 3.038, -0.037) m travelling in the direction of (0.972, 0.230, 0.045) with an energy of 2.363 GeV.
Figure 4.7: A simulated $\nu_e$ CC quasi-elastic event in the CHIPS detector [50]. Compared to the event shown in figure 4.6, the ring is smaller, and fully contained on the side of the detector. The ring is also much less well defined than the clear, easily reconstructed signal from the $\nu_\mu$. The reconstruction (purple line) found an electron with a vertex at (-2.081, -5.837, -3.350) m travelling in the direction of (0.429, -0.889, 0.220) with an energy of 1.356 GeV. The true event was an electron with a vertex at (-2.122, -5.693, -3.375) m travelling in the direction of (0.402, -0.889, 0.220) with an energy of 1.051 GeV.
Chapter 5

Water attenuation

5.1 The importance of water clarity in CHIPS

It is essential to have clear water in CHIPS so that Cherenkov light on one side of the detector can be seen by PMTs on the opposite side.

Light is absorbed and scattered as it passes through any material. The intensity of light \( I \) measured at a distance \( l \) from its source can be described by an exponential equation

\[
I = I_0 e^{-l/a}
\]  

(5.1)

where \( I_0 \) is the light intensity at the source and \( a \) is the Bulk Attenuation Length (BAL) of the material that the light is passing through. The BAL relies only on the material that the light is passing through (water, in this case), as opposed to the Technical Attenuation Length (TAL) in a detector which relies on the BAL and also the geometry of the detector and reflective properties of the surface [51]. Throughout this chapter attenuation length refers to the BAL of liquid water, as this could be measured and optimised before the detector is built.

All water Cherenkov detectors need water with a high attenuation length and must consider how best to achieve this. For example, Super-K has an extensive water purification system which uses: a 1 µm mesh filter to remove larger particulates, a heat exchanger to reduce PMT noise and bacteria growth, a UV steriliser to kill any remaining bacteria, a cartridge polisher to remove heavy ions, a reverse osmosis system to continue removing particulates, a tank to dissolve air with reduced amounts of radon to increase the efficiency of the next step, a vacuum degasifier to remove radon and oxygen dissolved in the water (radon is a background for Super-K, while oxygen encourages bacteria growth), an “ultra filter” constructed from hollow fibre membrane filters to remove particulates as small as 10 nm, and finally a membrane degasifier to reduce dissolved radon and oxygen even further [52].

Extensive tests were run to find the optimal level of filtration for CHIPS. These focussed mainly on how fine the main filtration medium would need to be, and whether UV sterilisation or reverse osmosis would be necessary. The aim was to have an attenuation length of at least 30 m at violet wavelength, preferably more. This would allow Cherenkov light from one corner of the detector to be seen at the opposite corner.
Figure 5.1: Left: the pipe that is filled with water for these measurements. It is bolted to the wall exactly perpendicular to the floor. A transparent PVC pipe is used so the water level can be monitored. Markings on the pipe show the depth of the water at that point. A perspex plate and a rubber gasket seal the base of the pipe. Right: the housing for the laser (with the violet laser), whose position and angle can be adjusted.
Figure 5.2: Left: the housing for the lens and photodiode is screwed onto the top of the pipe. Right: diagram showing a cross section of the lens and photodiode housing.
5.2 Experimental set-up

As shown in figure 5.1, a laser was placed at the base of a PVC pipe which was filled with water and then gradually drained, stopping drainage regularly to take measurements using a photodiode, shown in figure 5.2, at the top of the pipe [53]. More details of the apparatus are provided here, and more information about the method and analysis are provided in the following section.

Two different lasers were used in the experiment, both bought from Thorlabs. A violet laser with a wavelength of 405 nm (model number CPS405) was initially used, which is close to the wavelength of Cherenkov radiation. Later a green laser with a wavelength of 532 nm (model number CPS532) was used. As shown in figure 5.3, the absorption coefficient is higher for longer wavelengths, meaning that the attenuation length of green light is shorter than for violet light by a factor of approximately 8. This makes it possible to measure very clear water (i.e. water with a very long attenuation length) without needing a longer pipe.

Keeping the laser centred and pointed directly up is essential, otherwise refraction may cause more or less light to fall on the photodiode. To ensure the laser was below the exact centre of the pipe a plum bob was attached to the top of the pipe and lowered. The laser is held in a kinematic mount which has small screws that allow small adjustments to be made to the laser’s angle (see figure 5.1) while grid paper was placed over the top of the pipe: the spot of laser light would move across the paper as the angle was adjusted, when the spot was centred on the paper the laser was correctly aligned. This level of precision was deemed sufficient because a lens with focal length of 5 cm is held at the top of the pipe at the correct distance from the photodiode to focus the light onto its centre: the lens’s housing is shown in figure 5.2.
The pipe used was a roughly 2.5 m long clear PVC pipe which is bolted to the wall to keep it vertical and unaffected by vibrations on the floor, shown in figure 5.1. The pipe is clear so that the height of the water can be measured at any time. Both ends of the pipe are threaded to ensure that everything attached to it is aligned by screwing it on. At the bottom of the pipe is a flat perspex plate with a small 1/4” hose attachment to allow water to enter and drain from the pipe, placed away from the centre to avoid the laser beam. The plate is separated from the pipe by rubber, so its angle can be adjusted - if light does not pass through the perspex at a 90° angle it will be refracted and not point directly at the photodiode.

The final check for laser and perspex alignment is to once more cover the top of the pipe with grid paper and fill the pipe with water, stopping at regular intervals to allow the water to settle and ensure that the light had not moved across the paper.

Tap water was used for initial setup and testing of the system. However, the CHIPS detector will be filled with filtered water from the mine pit so it was important to get samples from the same source to test. Most of the tests were conducted on water stored in a 50 gallon barrel, but it was occasionally helpful to work with smaller samples which would be stored in 5 gallon jugs or buckets. Open containers were covered with tinfoil to prevent dust etc. from entering, but holes were left for the tubes between the storage and filter or pipe.

All filters used are commercially available. Most of the filters are 10” which is the standard for home filtration systems, although 20” filters will be used in CHIPS (due to the large volume of water that needs to be filtered). Water was pumped through the filters constantly whenever measurements were not being taken to prevent bacteria growth.

The water is directed between the filters, the storage barrel/bucket, and the pipe by inputting commands to a BeagleBone Black which is connected to two pumps and two servos. The BeagleBone can turn each pump on and off, and use the servos to choose where to pump the water to.

The stability of the set-up was measured and some additions were necessary. When measurements were taken with the laser shining on the photodiode with either the perspex plate and a small amount of water or with nothing but air between them, the recorded light intensity was unstable: this effect was greatly reduced when teflon tape was placed over the photodiode to diffuse the light. In addition, the light intensity became higher than expected when the pipe was full: the cause was narrowed down to reflections between the surface of the water and the lens. To prevent this, a 30 cm extension was added to the top of the pipe (not shown in figure 5.1) to separate the lens and water, and the final point of each measurement is excluded when the data is fit.

5.3 Method

To begin a measurement, the fill pump is turned on for 130 s, allowing the pipe to fill with water. This aerates the water, so it is allowed to settle for 20 minutes before measurements begin. During this time the depth of the water is measured. The photodiode is connected to the Beaglebone via a small electrical circuit which powers the photodiode and amplifies its signal to a region that the Beaglebone is comfortable with (0 to 1.8 V) before sending the signal to the Beaglebone where it is stored for analysis. This circuit also protects the Beaglebone by preventing the electrical signal from being large enough to cause damage.

The ADC count is measured five times and averaged, with 0.1 s between each measurement. This is repeated every 30 s over the course of five minutes with a constant water depth. The
Figure 5.4: Measurement of the attenuation of light in unfiltered water taken from the flooded mine pit where CHIPS will be placed, and the source of the water that the CHIPS detector will be filled with.

result is ten ADC measurements following each change in the depth of water that the laser must pass through, showing the change in attenuation length as the water settles over the five minutes.

This is repeated for five depths of water between a full pipe and an almost empty pipe. Some measurements shown here use more than five depths, as adjustments to the method were being continuously attempted to ensure the most accurate final results. The pipe is never allowed to drain fully during a measurement as water droplets on the perspex base scatter the light so this doesn’t give an accurate measurement of the light intensity with no water.

The ten sets of five measurements are plotted as separate graphs. A fit is applied to each using Minuit. Generally only the final measurement at each depth is used, as the water is most settled at this point. A two parameter fit is sufficient, using equation 5.1 and allowing $I_0$ and $a$ to float.

## 5.4 Results

### 5.4.1 Control measurements

The first measurement with unfiltered pit water is shown in figure 5.4, showing that the attenuation length of violet light in unfiltered water from the mine pit is $2.47 \pm 0.08$ m.

The stability of the system was measured by partially filling the pipe with filtered water and measuring the ADC without changing the water depth. This showed the variation of ADC over a period similar to the time it takes for one attenuation length measurement, an example is shown in figure 5.5.
5.4.2 Violet laser, UV sterilisation

A 10 μm polypropylene filter was installed into the system in combination with the UV steriliser. The best result obtained with this filter and the violet laser was 10.16 ± 0.47 m, as shown in figure 5.6.

The 10 μm filter was replaced with a 5 μm polypropylene filter. However, there was no significant change in attenuation length, as presented in figure 5.7 which shows the attenuation length as 9.11 ± 0.44 m.

This lack of improvement suggests that the problem is not particulates between 5 μm and 10 μm, but something else. Carbon filters were proposed and a 10 μm carbon block was added to the system in addition to the 5 μm polypropylene and the UV steriliser. The best result achieved with this combination was 19.86 ± 1.421 m, shown in figure 5.8. This showed that including a carbon block filter would be an important part of the final filtration system for the CHIPS detector.

However, adding a carbon block still did not give the desired attenuation length, so a finer filter was tried. The 5 μm filter was replaced with a 0.5 μm filter, the 10 μm carbon block and UV steriliser were kept in the system. The attenuation length increased greatly, but was approaching the limitations of the system. Figure 5.9 shows two measurements taken on the same day, i.e. there is no significant difference in the filtration between each measurement. It was concluded that the system was not sensitive enough to measure attenuation lengths on this scale as the systematic errors were too large when compared to the total change in ADC count between the depth of water when the pipe was full and empty. For reference, for a 50 m attenuation length measured using a maximum depth of 2.2 m, the light intensity when the pipe is full would be 95.7% of the light intensity when the pipe was empty (this result was
Figure 5.6: Pit water filtered through a 10 µm polypropylene filter with UV sterilisation.

Figure 5.7: Pit water filtered through a 5 µm polypropylene filter with UV sterilisation.
found by rearranging equation 5.1). If the ADC reading when the pipe is empty is 2200, this would correspond to a reading of 2105 when the pipe is full, similar to what is seen in figure 5.9.

In order to measure attenuation lengths on this scale the pipe would need to be extended (which was not practically possible in the laboratory), or use a different wavelength of laser. Changing the wavelength would theoretically reduce the attenuation length by a constant factor so that it could be accurately measured and the result for violet light could be extrapolated.

5.4.3 Green laser, UV sterilisation

As discussed in section 5.2, a green laser can be used to probe longer wavelengths. Figure 5.10 shows the first measurement taken using a green Thorlabs laser, after having filtered the pit water continuously through the 0.5µm filter, the 10µm carbon block and UV steriliser for approximately two months. The attenuation length was 16.63 ± 0.25 m, which is equivalent to approximately 133 ± 2 m when converted to the violet wavelength, which is good enough for CHIPS.

To ensure that a finer filter could not give a significant improvement that would be worth the additional cost, the 0.5µm filter was replaced with a 0.2µm filter. The result of this measurement is shown in figure 5.11, with an attenuation length of 19.51 ± 0.43 m (156 ± 4 m for violet light).

To show that the lower attenuation lengths were the result of changing the laser and not a sudden drop in water clarity, a measurement was taken with the violet laser under the same conditions as in figure 5.11, on the same day after changing the laser and checking alignment. This is shown in figure 5.12. The fit is not accurate, but comparing the small difference between
Figure 5.9: Pit water filtered through a 0.5 μm filter and a 10 μm carbon filter, with UV sterilisation.
Figure 5.10: First measurement taken with the green laser. The only change made to the system between the measurement shown in figure 5.9 was a long period of filtration and the change of laser.

the ADC when the pipe is full and empty shows that the attenuation length is long, resulting in the systematic errors being similar in size to the changes in ADC between each measurement.

5.4.4 UV Sterilisation

UV sterilisers are generally used in water filtration systems to reduce bacteria levels. Several measurements were taken to establish whether one would be necessary for CHIPS. Measurements were taken periodically after turning off the UV steriliser. The water circulation system is not closed and is in a well heated room.

Water continued to filter through the 0.2 µm filter and 10 µm carbon block for this period. Figure 5.14 shows the effect after three days and figure 5.15 shows the effect after eight days with no UV sterilisation.

At this stage the 0.2 µm filter was replaced with a 0.5 µm filter to find the effect of using a slightly coarser filter with no sterilisation. Figure 5.16 shows the measurement taken 1 day after changing the filter, which is nine days after the sterilisation was switched off, figure 5.17 after ten days with no sterilisation, and figure 5.18 after eleven days: the attenuation lengths were 22.0 ± 0.8 m, 20.4 ± 0.6 m, and 21.8 ± 0.8 m respectively. It was concluded that the effect of using UV sterilisation was minimal as all three measurements were the same within errors.

It was decided that this expensive step was not necessary for the CHIPS detector’s water filtration.
Figure 5.11: Measurement taken using the green laser and using a 0.2\textmu m filter.

Figure 5.12: Measurement taken using the violet laser and using a 0.2\textmu m filter.
Figure 5.13: Measurement taken using the green filter after nearly a month of continuous filtering through the 0.2 µm filter.

Figure 5.14: Measurement taken three days after turning off the UV.
Figure 5.15: Measurement taken eight days after turning off the UV.

Figure 5.16: Measurement taken nine days after turning off the UV: switched filter to 0.5 µm the previous day.
Figure 5.17: Measurement taken ten days after turning off the UV.

Figure 5.18: Measurement taken eleven days after turning off the UV.
5.5 Final filtration for the CHIPS detector

The final decision was to use 10 µm carbon block filters and 0.5 µm polypropylene filters, and to not use UV sterilisation. This is expected to give a BAL of 133 ± 2 m for violet light, which is greater than the minimum requirement of 30 m. The 0.2 µm filters did give a longer attenuation length, but the change (an increase of 17%) was not significant enough to justify the increase in cost given that the attenuation length using the 0.5 µm polypropylene filters is more than sufficient for the planned detector size.

20 inch filters (instead of the 10 inch filters that were used for testing) are used in parallel due to the higher flow rate. The set up is shown in figure 5.19.
Chapter 6

Conclusion

Neutrinos have gone from being an “undetectable” theoretical particle to offering a unique way to probe physics beyond the Standard Model. Both existing and future neutrino detectors have become a major component of international HEP endeavours.

Since its first publication in 2016 [55], NOvA has contributed to global constraints on neutrino oscillation parameters through its analyses of muon neutrino disappearance, electron neutrino appearance, and joint analyses of these two signals. It uses Fermilab’s NuMI beam of muon neutrinos and two functionally identical liquid scintillator detectors. The Near Detector is located onsite at Fermilab, 1.015 km from the NuMI target, and the Far Detector 810 km away and 14 mrad off-axis, giving NOvA the longest baseline of any current neutrino oscillation experiment.

As it collects more data, NOvA will move from being limited by statistics towards being limited by systematics. In this case, its usual histogram based analysis software (also known as CAF) may or may not become less effective so an alternative analysis software framework, FNEX, has been developed. At present, FNEX is most helpful as a cross check to CAF’s results, ensuring that NOvA’s results are not biased by the software. The results of the FNEX analysis of FHC data collected by NOvA are $\sin^2 \theta_{23} = 0.499^{+0.098}_{-0.069}$ and $\Delta m^2_{32} = 2.454^{+0.108}_{-0.119} \times 10^{-3}$ eV$^2$, with confidence levels shown by the contour in figure 3.35.

CHIPS was partially deployed in the summer of 2019 in Hoyt Lakes, Minnesota. Deployment will be completed in 2020. It is a water Cherenkov detector that will also use Fermilab’s NuMI beam to measure muon neutrino disappearance and electron neutrino appearance. CHIPS aims to show that it is possible to quickly and affordably construct a neutrino detector that can contribute to global fits and constraints of neutrino oscillation parameters. It uses PMTs provided by KM3Net and borrowed from NEMO, the CHIPS team have developed the electronics systems to power and read the data from the NEMO PMTs. The mechanical structure of the detector is constructed from commercially available PVC pipes. The detector will be located 7mrad off-axis from the NuMI beam, in a pre-existing flooded mine pit that will provide the water to fill the detector and the overburden to protect it from cosmic muons.

As a water Cherenkov detector, CHIPS needs to be filled with water that is clear enough that light from one side of the structure can be measured by PMTs on the opposite side. This would require water with an attenuation length of at least 30 m. To this end, extensive measurements of water clarity were carried out for various levels of filtration to find the best commercially available option for filtering the water from the pit. The water clarity was tested by placing a violet or green laser at the base of a pipe and a focussing lens and photodiode at
the top of the pipe and measuring the light intensity for various depths of water. It was found that when water from the mine pit is filtered through a 10 µm carbon block in series with a 0.5 µm polypropylene filter with no UV sterilisation it has an attenuation length of 133 ± 2 m, which is greater than the 30 m requirement.
Bibliography


