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Constraining Systematic Uncertainties at T2K using Near Detector Data

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Abstract

T2K is a long baseline neutrino oscillation experiment in Japan. It was designed to make precise measurements of the parameters governing neutrino oscillations, and has been taking data since 2011. A muon (anti-)neutrino beam is produced at the Japan Proton Accelerator Research Complex (J-PARC), and is aimed towards the Super-Kamiokande (SK) detector 295km away. In this analysis, Markov Chain Monte Carlo is used to fit the Monte Carlo prediction to data from the near detector, ND280, which measures the neutrino flux and interaction cross-sections before oscillation. The flux and interaction models are parametrised using external data, T2K beam line monitoring measurements, and theoretical calculations to set the prior values and uncertainties. Several updates have been made to the data samples, cross-section model, and fitting framework used for the 2020 oscillation analysis to maximise the constraint on these systematics, and reduce the impact they have on oscillation results. The near detector fit is crucial for T2K to make world-leading oscillation parameter measurements. The analysis presented here used ND280 data from T2K runs 2-9, corresponding to $X \times 10^{19}$ protons on target (POT), to reduce the uncertainty on the SK prediction from X% to Y%. The reduction of systematic uncertainties in detectors for future long baseline neutrino experiments is also investigated.

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1. Introduction

In the Big Bang, matter and anti-matter were created in equal parts. However, we know that when a matter particle meets its anti-particle the two immediately annihilate each other. This therefore prompts the question why does anything in the Universe still exist at all? If there were equal amounts which annihilated each other there should not be any remnants. Anecdotally, we see a vast abundance of matter compared to anti-matter in the observable Universe. This clearly indicates an asymmetry between matter and anti-matter, which has not yet been explained by the Standard Model of Particle Physics. This is one of the most fundamental unknowns in our understanding of the Universe, and the physical laws which govern it.

The symmetry between matter particles and their corresponding anti-matter particles is known as Charge-Parity (CP) symmetry. For the physics governing the two to be different, CP symmetry has to be violated. Although this has already been observed in the quark sector, it is not sufficient to alone explain the matter dominated Universe we observe. The PMNS mechanism for neutrino oscillations allows a CP violating phase, δ_{CP} , which could be non-zero.

T2K [6] is a long baseline neutrino oscillation experiment, originally designed to make precision measurements of the oscillation parameters $\sin^2\theta_{23}$, Δm_{32}^2 , and $\sin^2\theta_{13}$. However, one of the main focuses is now on measuring δ_{CP} to determine if CP is violated in neutrino oscillations, and if so by how much. As the statistics for both neutrinos and anti-neutrinos increases, and with the prospect of future neutrino oscillation experiments such as Hyper-Kamiokande [7] and DUNE [8] on the horizon, we will soon be able to determine the value of δ_{CP} . However, with the increase in statistics the treatment of systematics becomes more important. To achieve this, improvements to the neutrino interaction model are required.

The T2K near detector prediction is fitted to data to reduce systematic uncertainties from the cross-section, flux, and detector models used to build the MC prediction. This process typically reduces the uncertainty on event rates at the far detector, Super-Kamiokande, from X% to Y%, without which T2K would not be able to make world leading measurements of

1. Introduction

oscillation parameters.

This thesis presents the results of the near detector fit, as well as describing the updates to those models and the fitting framework for the 2020 Oscillation Analysis. Chapter 2 outlines the history of neutrino physics, from initial discovery to current open questions. It also describes the theory of both neutrino interactions, particularly those present in the T2K detectors, and neutrino oscillations.

The T2K experimental setup is detailed in Chapter 3, giving an overview of the beam-line, the on-axis near detector INGRID, the off-axis ND280, and the far detector Super-Kamiokande. The simulation used to predict measurements at each of the detectors is also described.

The statistical treatment of data is discussed in Chapter 4. This work is a Bayesian analysis, which uses Markov Chain Monte Carlo (MCMC) for fitting systematics to data. The MCMC method, and Bayesian techniques for post-fit analysis and interpretation are introduced here.

This is followed by a description of the near detector fit and inputs for the 2020 Oscillation Analysis in Chapter 5. Various improvements were made to the cross-section, flux, and detector models, as well as the fitting framework itself, since the previous analysis. The implementation of these, and the potential impact on the fit are discussed here.

The results of the fit are described in Chapter 6. First the validations of the model and fitting framework are shown, before the final results and impact at the far detector are presented.

In Chapter ??, the potential impact of a new technology for long baseline neutrino oscillation experiment near detectors is discussed, along with the current state of prototype studies for it. Finally, this thesis concludes with a summary and remarks of the results presented.

2. Neutrino Physics

Neutrinos are spin $\frac{1}{2}$ fermions with extremely small mass and zero electric charge. They only interact via the weak and gravitational forces, allowing them to travel great distances through matter without ever being affected by it, and so making them very difficult to detect. This has made neutrinos one of the most elusive particles, despite being one of the most abundant in the Universe.

This chapter gives an overview of the history of neutrino physics, from Wolfgang Pauli’s “desperate remedy” of an undetectable particle, to the 2015 Nobel prize winning results of SK [9] and SNO [10], as well as the relevant theory involved. Section 2.1 describes the initial evidence of the existence of neutrinos, and the discovery of the different flavours. The evidence of neutrino oscillations is presented in Section 2.2, separated by neutrino source. The theory behind the oscillation mechanism is introduced in Section 2.3, along with a discussion on the different interaction types relevant for long baseline neutrino oscillation experiments. Finally, Section 2.4 gives an overview of the current experimental status of neutrino oscillations, and the questions yet to be answered.

2.1. Neutrino Discovery

To comply with the conservation of energy, momentum, and spin, the electron produced from β decay should always have the same energy, as is the case for the resulting particle in both α and γ decays. This is because, assuming a 2-body process, the emitted particle is carrying away the energy difference between the initial and final nuclear states. However, using a magnetic spectrometer and a Geiger counter, James Chadwick measured a continuous energy spectrum from this process [11]. The vast majority of the emitted β particles had energies much lower than the expected value, but none had energies higher.

Neils Bohr initially proposed a statistical formulation of the conservation laws, suggesting individual decays could violate them as long as the overall average resulted in no net change. However, the upper limit on the measured β energies, which was confirmed by Ellis and

2. Neutrino Physics

Mott [12], contradicted this theory. If the conservation laws were invalid, any amount of energy would be available in at least a small fraction of decays.

To attempt to resolve the problem, Pauli [13] proposed another, undetected, fermion would need to also be produced by the decay, and that it would be light and have zero electric charge. This would explain the observed spectrum as there was a fixed limit on the available energy from the conservation laws, but the new particle would take a varying fraction of it, with the β taking the rest. The β can therefore have a varied energy spectrum up to the hard limit, as had been measured. Pauli originally called the new neutral particle a ‘neutron’.

In 1932, Chadwick discovered a massive neutral particle in the nucleus of atoms, which he also called a ‘neutron’. Initially Pauli did not distinguish between the two namesake particles. Two years later, Fermi devised a framework by which the light chargeless fermions could account for the missing energy [14] in β decay, in which he coined the name ‘neutrino’ for them, meaning ‘the little neutral one’.

In this theory of β decay, Chadwick’s neutron could decay to a proton, emitting a β and Pauli’s neutrino:

$$n \rightarrow p + e^- + \nu. \quad (2.1)$$

The neutrality and lightness of the neutrino meant they would be very difficult to detect, and it was not until 1956 that the first experimental observation took place, by Reines and Cowan [15]. Given the small chance of interaction, an extremely large flux of neutrinos was required, and so it was only with the advent of nuclear reactors that detection became viable.

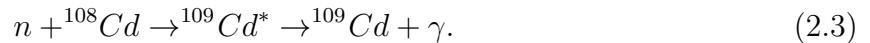
Two tanks of water sandwiched between 3 tanks of liquid scintillator containing 110 photomultiplier tubes (PMTs) were placed near the Savannah River Plant. It was predicted that anti-neutrinos could interact with protons via inverse β decay:

$$\bar{\nu} + p \rightarrow n + e^+. \quad (2.2)$$

The tanks of water provided a large amount of target protons for the anti-neutrinos to interact with, producing neutrons and positrons. Positron annihilation would then produce 2 γ rays, causing a flash in the scintillator liquid which could be detected by the PMTs.

The water was doped with 40kg of CdCl_2 , so that the free neutron could be detected via neutron capture:

2.1. Neutrino Discovery



The coincidence of a neutron capture 5 μs after a positron annihilation provided an unambiguous signature of an anti-neutrino reaction. This was the first experimental evidence of the existence of neutrinos.

A similar experiment by Ray Davis [16] in 1962 used a tank of chlorine doped water placed near the Brookhaven nuclear reactor, to search for the interaction:



However, no excess of Argon was detected. This along with the Reines and Cowan result lead to the theory of lepton number conservation. This meant that anti-neutrinos could not be produced from interactions involving leptons, and neutrinos could not be produced from interactions involving anti-leptons.

In 1962, Lederman, Schwartz, and Steinberger [17] explored the possibility of the existence of two separate neutrino flavours. Protons were initially accelerated to 15 GeV, before being impinged on a Beryllium target. This produced many pions, which decayed into muons and neutrinos:



A 13m steel shield then stopped the muons and any surviving pions, leaving a beam of neutrinos. A spark chamber was used to detect when these neutrinos interacted with target Aluminium sheets. An excess of muons compared to electrons was observed, showing that neutrinos produced with a muon, produce another muon when they interact. This proved that muon neutrinos were distinct from electron neutrinos. Measurements at CERN confirmed this result in 1963 [18].

When the tau lepton was discovered in 1975, it was expected that there would be a corresponding neutrino. The first direct detection of the tau neutrino was at the DONUT experiment [19] in 2000. Protons were accelerated to 800 GeV and impinged on 36 m of Tungsten. This produced D_s mesons, which quickly decayed to tau anti-neutrinos and tau leptons, which would then decay to produce a tau neutrino. A kink in the tau lepton's path detected using nuclear emulsion was used to identify the tau decay, and prove the existence of the tau neutrino.

The possibility of further neutrino flavours has been ruled out by measurements of Z decays

2. Neutrino Physics

at the Large Electron Positron (LEP) and the Stanford Linear Accelerator (SLAC) [20]. The width of the Z mass peak is the sum of the visible partial width (from decays to leptons and hadrons), and the invisible partial width (assumed to be from decays to N_ν , light neutrino species). Assuming each flavour contributes equally, N_ν was measured to equal 2.9840 ± 0.0082 . This result has been confirmed by measurements of the expansion rate of the early Universe, which is consistent with $N_\nu = 3.04 \pm 0.18$ [21].

However, this does not mean there cannot be further types of neutrino which do not interact via the weak force and are therefore unable to couple to the Z boson, known as sterile neutrinos. There are many experiments currently searching for sterile neutrinos, though no firm evidence has yet been detected. Furthermore, there could be more heavy neutrino flavours, which are just too massive to be produced in Z decays.

2.2. Neutrino Oscillations Evidence

Neutrino oscillations are now well established, with many experiments measuring various aspects of the phenomena in different regimes. This was not always the case, however. In this section, the early evidence for oscillations of all flavours, and potential steriles, is discussed.

2.2.1. Solar Neutrinos

Electron neutrinos are produced in the Sun by a number of different mechanisms. The largest flux comes from the nuclear fusion of 4 Hydrogen atoms into a Helium (the *pp* chain):



However, the energy of the resulting neutrinos is below detection threshold. Other mechanisms produce higher energy neutrinos but with a lower flux, as shown in Figure 2.1. Most solar neutrino experiments therefore measure the flux produced through Boron decay:



Ray Davies and John Bahcall devised an experiment to measure the flux of neutrinos produced via this mechanism in 1968 [22]. The design was similar to Davies' previous experiment, measuring the Argon produced in the reaction in Equation (2.4) using a 380 m^3 underground tank of chlorine-based cleaning fluid (C_2Cl_4) in the Homestake Mine.

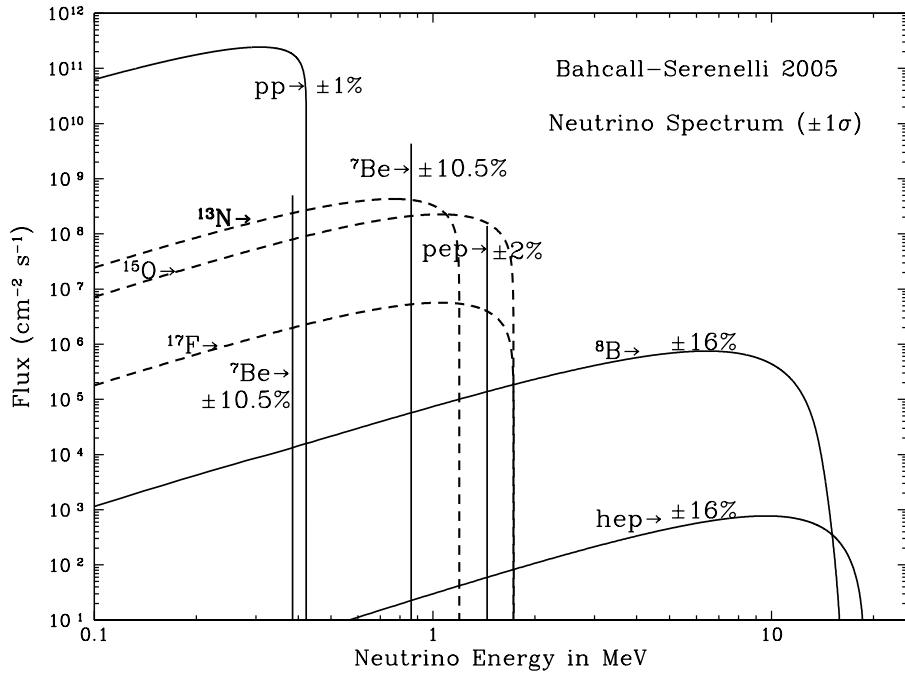


Figure 2.1.: Flux of solar neutrinos at Earth as a function of energy for different production mechanisms, according to Bahcall's solar model. Figure from [1].

Bahcall calculated the predicted number of neutrinos from the Sun from the B decay chain using the Standard Solar Model, as well as the number of Argon nuclei they would produce in the tank. However, consistently, only a third of the amount of neutrinos were detected than had been expected. The discrepancy between the predicted and measured number of neutrinos became known as The Solar Neutrino Problem.

Bruno Pontecorvo proposed a solution in 1968 [23], which involved neutrinos changing flavour as they propagated through space. This phenomenon, known as neutrino oscillation, was similar to the CKM [24] [25] formalism of quark mixing. Some of the electron neutrinos produced in the Sun would therefore change flavour before reaching the Earth, causing the flux deficits measured. However, this required a significant modification to the Standard Model of particle physics, that neutrinos have mass. The success of the massless theory of the neutrino meant that this explanation initially did not gain much support.

Instead, initial efforts focused on modifying the solar model so that the prediction fit the data. The model depended on accurate knowledge of the pressure and temperature inside the Sun's core, and so it was thought that if the temperature was lower than had been assumed in the prediction, then less neutrinos would be expected to be produced. However, advances in helioseismology allowed improved measurements of the core temperature which

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were consistent with the original value.

No modification to the solar model itself could accommodate the measured fluxes either. The overall reduced flux required a lower core temperature, whereas the measured shape of the energy distribution of the neutrinos required a higher temperature. This is because the different nuclear processes producing different neutrino energies have different temperature dependencies. Modifying the solar model in any way would always result in at least one of these discrepancies increasing.

Pontecorvo's resolution was still not widely accepted though. It was also suspected that there was something wrong with the experimental setup, but later results were consistent with the deficit.

In 1989, the Kamiokande experiment [26] measured the solar neutrino flux using a large water Cherenkov detector. The electron recoil from elastic scattering was used to detect electron neutrinos, but again measured a deficit to the predicted number.

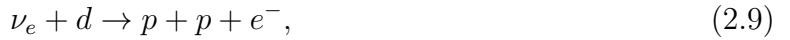
The GALLEX [27] and SAGE [28] experiments in the early 1990s also used radiochemical detection, but with Gallium to measure:



This interaction had a lower energy threshold, allowing measurement of the flux from the *pp* chain. Both experiments confirmed the discrepancy between prediction and measurement.

Despite the *pp* chain being better understood than *B* decay, the results of these experiments all relied upon the solar model and so were still not fully accepted.

The first model independent measurement of the solar neutrino flux came from the SNO experiment in 2002 [29]. SNO detected both the ν_e flux via charged-current interactions:



and the total ν flux via neutral-current interactions:



and:



The electron neutrino flux measured was consistent with the previous results, but the total flavour independent flux was consistent with the predicted values. This was strong evidence

2.2. Neutrino Oscillations Evidence

that electron neutrinos were changing flavour into muon and tau neutrinos before they got to the Earth.

2.2.2. Atmospheric Neutrinos

Interactions between cosmic rays and nuclei in the Earth's atmosphere produce neutrinos via pion decay:

$$\pi^+ \rightarrow \mu^+ \nu_\mu; \mu^+ \rightarrow e^+ \nu_e \nu_\mu \quad (2.12)$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu; \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \quad (2.13)$$

Atmospheric neutrinos typically have a higher energy than solar neutrinos, with the flux peaking between 1-10 GeV.

Reines [30] first measured the atmospheric neutrino flux at the Kolar Gold Fields mines in India in 1965. The measured flux was lower than had been predicted, a result which was confirmed by the IMB [31] and Kamiokande [32] experiments. The deficit was statistically convincing, but not significant enough to be considered compelling evidence of neutrino flavour change. These results became known as the Atmospheric Neutrino Anomaly.

The upgrade to the Kamiokande experiment, Super Kamiokande (SK), measured the flux of atmospheric ν_μ as a function of incoming angle in 1998. The data was split into upwards-going and downwards-going samples, allowing measurements at different distances from production. Upward-going neutrinos would have to travel through the Earth before reaching the detector, not just the distance from the atmosphere to the surface. In theory, since the neutrinos are produced isotropically in the atmosphere, there should be the same amount of upward-going and downward-going neutrinos. However, a large deficit of ν_μ was observed in the upward sample, as shown in Figure 2.2.

The dependence of the number of ν_μ observed on the distance travelled could be explained in the context of neutrino flavour mixing. The upward-going neutrinos were changing flavour as they propagated the longer distance through the Earth to the detector. The SK result was strong evidence of ν_μ disappearance through oscillation.

2.2.3. Reactor Neutrinos

Reactor neutrinos have a similar energy flux to the solar neutrinos, peaking between 1-10 MeV. Like atmospheric neutrinos, experiments for detecting reactor neutrinos can measure oscillations across different baselines.

2. Neutrino Physics

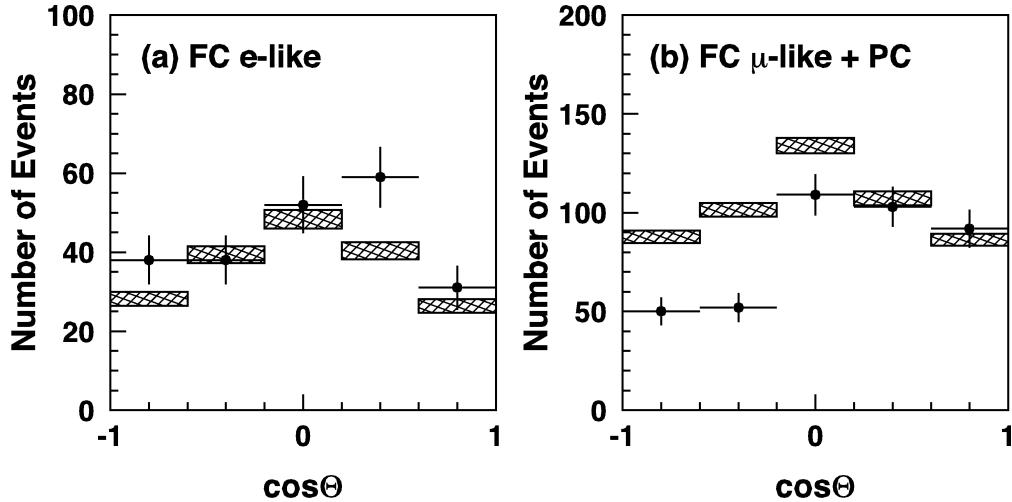


Figure 2.2.: The atmospheric neutrino flux as a function of angle from the first 414 days of Super-Kamiokande data. The boxes represent the prediction, the crosses represent the measured counts. Figure from [2].

The KamLAND experiment [33] measured the $\bar{\nu}_\mu$ flux from 55 nuclear power reactors across Japan, with a flux-weighted average baseline of 180 km. The number of $\bar{\nu}_\mu$ detected was smaller than would be expected if neutrinos could not change flavour, and the measured probability of oscillation as a function of energy and distance was in agreement with Pontecorvo's theory of neutrino flavour mixing. This provided further evidence that neutrinos oscillate while propagating through space.

Several reactor experiments, RENO [34], Double Chooz [35], Daya Bay [36], all with a baseline of ~ 1 km, have measured an excess of neutrinos at $E_\nu \sim 5$ MeV compared to prediction. This could either be due to poor flux modelling, or the existence of sterile neutrinos.

2.2.4. Accelerator Neutrinos

More recently, accelerators have been used to produce beams of neutrinos to study oscillations. This offers more control over the energies and baselines involved. Most long baseline (~ 100 km) accelerator experiments have two detectors, to measure the beam before and after oscillation. K2K [37], a long baseline (250 km) experiment in Japan, was the first to measure oscillations in such a way, using a beam of predominantly ν_μ . MINOS [38] also observed ν_μ disappearance consistent with the K2K result, with an even longer baseline (735 km). ν_e appearance in a ν_μ beam was discovered by the next generation experiments

2.3. Oscillation Theory

T2K and NOvA [39]. ν_τ appearance in a ν_μ beam was first observed by the OPERA [40] experiment in 2010, with a 730 km baseline.

Short baseline (~ 1 km) accelerator experiments are used to search for sterile neutrino oscillations, as well as measuring cross-sections. LSND [41] measured oscillation parameters in contradiction to other experiments in 2001, hinting at the existence of a sterile neutrino. However, subsequent experiments such as KARMEN [42] in 2001, ICARUS [43] in 2004, and MiniBooNE [44]¹ in 2007 did not agree with the LSND result. Currently there is no convincing evidence of the existence of any extra neutrino flavours.

2.3. Oscillation Theory

Neutrinos are produced in charge current weak interactions, and therefore are produced in a definite flavour state: electron, muon or tau. This is defined by the massive lepton they are produced with, conserving lepton number in the interaction. The existence of flavour mixing is a direct consequence of neutrinos having mass. If neutrinos are not massless, there exists some set of mass eigenstates, each with definite mass m_i . There is no reason that these should be equal to the flavour eigenstates, but as they both form a complete set the flavour states are each a linear combination of the mass states:

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle. \quad (2.14)$$

Similarly, the mass states are each superpositions of the flavour states:

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle, \quad (2.15)$$

where Roman subscripts are used to denote mass states, and Greek subscripts are used to refer to flavour states.

The lepton mixing matrix, U , relates the two sets of states in the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) formalism of neutrino oscillations [46]. If this were the identity matrix, the sets of eigenstates would be identical and neutrinos would not change flavour, but the experimental evidence described in Section 2.2 shows this is not the case. The PMNS matrix is often expressed in the form:

¹Later MiniBooNE results were more compatible with LSND [45], though both are still considered controversial.

2. Neutrino Physics

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \quad (2.16)$$

Each element, $U_{\alpha i}$, corresponds to the amplitude of the mass eigenstate i within the flavour eigenstate α . The flavour contents are shown in Figure 2.3, according to current best measurements. The left hand side is for the normal mass hierarchy, where $m_3^2 > m_2^2$, whereas the right handside is for the inverted mass hierarchy, where $m_2^2 > m_3^2$. It is known that $m_2^2 > m_1^2$ from solar neutrino measurements, but the nature of the mass hierarchy is not known beyond this. The signs of Δm_{32}^2 and Δm_{31}^2 are difficult to determine because the uncertainties on their values are so much larger than the size of Δm_{21}^2 . The sign therefore is negligible in oscillation calculations in experiments, compared to the uncertainties.

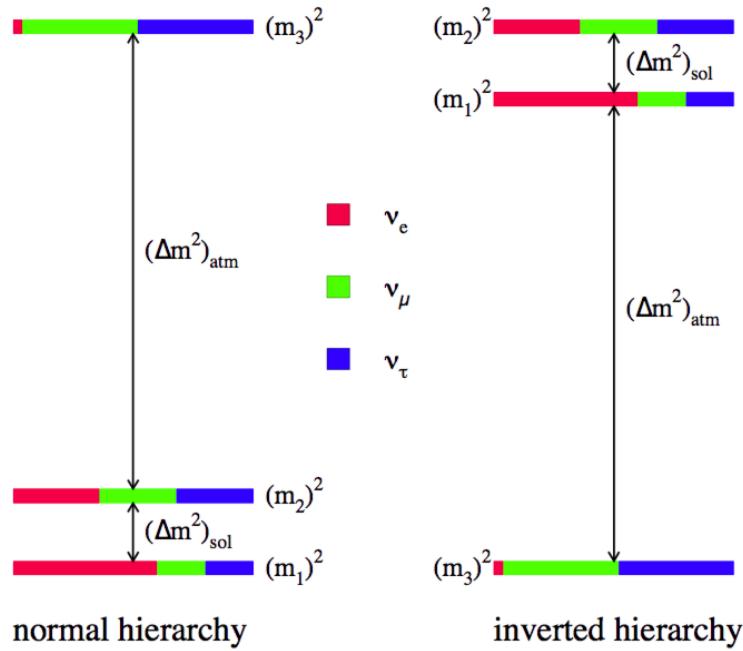


Figure 2.3.: The flavour content and mass differences of the three mass eigenstates, for both the normal and inverted hierarchys. Figure from [3].

The propagation of the mass eigenstates can be described by solutions to the plane wave equation:

$$|\nu_i(t)\rangle = e^{-i(E_i t - \bar{p}_i \cdot \bar{x}_i)} |\nu_i(0)\rangle, \quad (2.17)$$

where t is time of propagation, E_i is the energy of the mass eigenstate i , \bar{p}_i is the momentum, and \bar{x}_i is the position. $|\nu_i(0)\rangle$ is the initial state of the mass eigenstate.

In the lab frame:

$$p_i \cdot x_i = |\mathbf{p}_i|L, \quad (2.18)$$

where L is the distance travelled.

In the ultrarelativistic limit: $|\mathbf{p}_i| = p_i \gg m_i$, so:

$$p_i \cdot x_i = EL, \quad (2.19)$$

and the energy can be approximated as:

$$E_i = \sqrt{p_i^2 + m_i^2} \approx p_i + \frac{m_i^2}{2p_i} \approx E + \frac{m_i^2}{2E}, \quad (2.20)$$

where E is the total energy of the neutrino. Therefore, taking the natural units, $c = 1$, $t = L$:

$$E_i t \approx L \left(\frac{m_i^2}{2E} + E \right), \quad (2.21)$$

and so Equation (2.17) can be written as:

$$|\nu_i(t)\rangle = e^{-i\frac{m_i^2 L}{2E}} |\nu_i(0)\rangle. \quad (2.22)$$

The different mass eigenstates therefore propagate differently as they have different masses. Equation (2.15) can be interpreted as the probability of a mass eigenstate i interaction producing a charged lepton α , as the fraction of flavour α in eigenstate ν_i can be calculated as $|U_{\alpha i}^*|$. Although produced in a definite flavour state, as a neutrino travels away from its source the mass states become out of phase. The resulting interference means that the neutrino's wavefunction evolves to contain components from all three flavour states. The amplitude for a neutrino initially having flavour α , being detected as having flavour β after propagating a certain distance is:

$$\mathcal{A}(\nu_\alpha \rightarrow \nu_\beta) = \sum_i \sum_j \langle \nu_j | U_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha i}^* | \nu_i \rangle. \quad (2.23)$$

As charged leptons in the standard model only couple to neutrinos of the same flavour:

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$$\begin{aligned}
\delta_{\alpha\beta} &= \langle \nu_\alpha | \nu_\beta \rangle \\
&= \left\langle \sum_i U_{\alpha i}^* \nu_i \middle| \sum_j U_{\beta j}^* \right\rangle \\
&= \sum_{i,j} U_{\alpha i} U_{\beta j}^* \langle \nu_i | \nu_j \rangle \\
&= \sum_i U_{\alpha i} U_{\beta i}^*,
\end{aligned} \tag{2.24}$$

where $\delta_{\alpha\beta}$ is the Kronecker delta. The probability of the process of a neutrino oscillating from flavour α to β is then found to be:

$$\begin{aligned}
P(\nu_\alpha \rightarrow \nu_\beta) &= |\mathcal{A}(\nu_\alpha \rightarrow \nu_\beta)|^2 \\
&= \delta_{\alpha\beta} - 4 \sum_{i>j} \mathcal{R}(U_{\alpha i} \star U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) \\
&\quad + (-) 2 \sum_{i>j} \mathcal{I}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right),
\end{aligned} \tag{2.25}$$

where Δm_{ij}^2 is the difference in mass of mass eigenstates i and j , and the negative sign is for anti-neutrinos.

The PMNS matrix is often parametrised as 3 matrices in terms of 3 mixing angles, θ_{12} , θ_{13} , θ_{23} , and a CP-violating phase, δ_{CP} :

$$\begin{aligned}
U &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\
&= \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta_{CP}} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta_{CP}} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta_{CP}} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta_{CP}} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta_{CP}} & c_{23} c_{13} \end{pmatrix},
\end{aligned} \tag{2.26}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$. There are two extra complex phases which are only non-zero if neutrinos are Majorana particles [47]. Even if this is the case, they would be extremely difficult to measure experimentally, and they do not affect oscillation probabilities, so are not considered here.

This form of the unitary matrix is often used as it makes it easier to interpret the oscillation parameters, as they are separated by the different types of experiment in which they can be measured.

The first matrix contains terms only in θ_{23} , the mixing angle involved in most atmospheric neutrino oscillations. If ν_e are neglected, and atmospheric oscillations are considered as a two flavour process $\nu_\mu \rightarrow \nu_\tau$, then $\theta_{atm} \approx \theta_{23}$.

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The second matrix contains terms only in θ_{13} , the mixing angle involved in most reactor neutrino oscillations, and the CP -violating phase, δ_{CP} . If $\delta_{CP} \neq 0$, neutrinos oscillate differently to anti-neutrinos: $\nu_\alpha \rightarrow \nu_\beta \neq \bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$. However, when multiplied out δ_{CP} only appears in terms with other angles, and so can only be measured if these are all non-zero. This parametrisation of U emphasises the dependence on θ_{13} , as it is the smallest angle and was the last to be measured.

The third matrix contains terms only in θ_{12} , the mixing angle involved in most solar neutrino oscillations. If ν_τ are neglected, and solar oscillations are considered as a two flavour process $\nu_e \rightarrow \nu_\mu$, then $\theta_{sol} \approx \theta_{12}$.

This has all assumed the neutrinos have been propagating through a vacuum. In most circumstances, the neutrinos actually travel through matter, and so interactions with the medium must be accounted for. In the Earth, there are two types of interactions which can occur. These are charged current scattering of ν_e off an electron, and neutral current scattering of any flavour of neutrino off an electron, neutron, or proton. The neutral current scattering is flavour independent and so does not affect oscillation probabilities. The charged couple scattering however, only occurs for ν_e , and so needs to be considered in oscillation calculations. The effect increases with distance through matter travelled, and the electron density of the medium. The full treatment of how this process affects oscillations is known as the MSW effect [48], but is beyond the scope of this thesis.

As the Earth is made predominantly of matter rather than anti-matter, the MSW effect has a different impact for neutrinos than it does for anti-neutrinos. This produces an effect that mimics CP violation, causing $\nu_\alpha \rightarrow \nu_\beta \neq \bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$, and so careful treatment is required for measurements of δ_{CP} . At T2K, the average matter density between the near and far detectors of 2.6 g/cm^3 [49] has very little effect on the oscillation probabilities, but the matter effects are fully taken into account nonetheless.

Putting all this together, Equation (2.25) can therefore be written for the T2K detection channels, ν_μ ($\bar{\nu}_\mu$) disappearance and ν_e ($\bar{\nu}_e$) appearance, as:

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} (1 - \cos^2 \theta_{13} \sin^2 \theta_{23}) \sin^2 \frac{\Delta m_{32}^2 L}{4E}, \quad (2.27)$$

and

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$$\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) \approx & \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \\
& + \sin 2\theta_{23} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \frac{\Delta m_{21}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \\
& \times (\cos \frac{\Delta m_{32}^2 L}{4E} \cos \delta_{CP} - (+) \sin \frac{\Delta m_{32}^2 L}{4E} \sin \delta_{CP}).
\end{aligned} \tag{2.28}$$

Here, the negative sign in brackets is for anti-neutrinos. The neutrino and anti-neutrino disappearance probabilities in Equation (2.27) are identical, whereas the appearance probabilities in Equation (2.28) have opposing signs for the third term, allowing CP violation if $\delta_{CP} \neq 0$.

In these probabilities, the matter effect terms have been neglected as they are small, and the solar oscillation terms (involving Δm_{21}^2) have been neglected as T2K is not sensitive to these processes. They are however, taken into account in all oscillation calculations in T2K analyses.

Equations 2.27 and 2.28 show that the probability for oscillation is dependent on the mass splittings rather than the absolute values of the masses. This is perhaps unsurprising, as it is the differences in the mass eigenstates that cause oscillations. Neutrino oscillation experiments can therefore only measure the difference between the masses, and not the values themselves. However, if all neutrino states were massless the mass differences would also be zero. The evidence of neutrino oscillations outlined in Section 2.1 is therefore evidence that at least two of the three mass eigenstates have non-zero mass.

As well as the oscillation parameters, the probability is also dependent on the experimental parameters L and E . Therefore, by measuring the probability for oscillation at a known baseline and energy, the oscillation parameters can be determined. Using non-natural units:

$$\Delta m_{ij} \frac{L}{4E} = \Delta m_{ij}^2 (eV^2) \frac{1.27L(km)}{E(GeV)}, \tag{2.29}$$

meaning with a 295 km baseline and 0.6 GeV beam, T2K is sensitive to $\Delta m_{ij} \gtrsim 10^{-3} eV^2$.

This has all assumed that there are only 3 flavours of neutrino, in line with the measured values of the Z^0 decay width [20, 21]. However, there could exist sterile neutrinos, briefly discussed at the end of Section 2.1. In this case, the mixing matrix would need to be modified to accommodate oscillations involving these new neutrinos, and further mass states may be required.

2.3.1. Neutrino Interactions in Long Baseline Oscillation Experiments

To detect neutrino oscillations, it is inherently vital that the flavour composition of a flux of neutrinos is carefully analysed. As the number of neutrinos measured is a convolution of the flux, cross-section, detector efficiency, and oscillation probability, it is important each of these components is well understood to make an accurate measurement. Due to their low interaction rate and subsequent lack of data, neutrino cross-sections contribute significantly to the total uncertainty, and this is only going to become more pronounced with increased statistics for oscillation experiments. It is therefore essential to study neutrino interactions for precision measurements of oscillations to be made.

Equation (2.28) tells us that the probability of oscillation is dependent on the mixing angles, mass splittings, distance travelled, and energy of the neutrino. The oscillation parameters are fundamental properties of the Universe which cannot be changed. The probability of oscillation is what can be measured. This is essentially the number neutrinos of a given flavour after oscillation, divided by the number before². The length is a fixed, known quantity for accelerator based neutrino experiments. However, it is infeasible to produce a mono-energetic source of neutrinos. The oscillation parameters are therefore determined by the energy spectrum and number of each flavour neutrino.

As neutrinos cannot be detected directly, the number of neutrinos is inferred from the secondary particles produced when they interact. Inferring the number of incoming neutrinos of each flavour from the particles produced in the events requires a thorough understanding of all the interactions that could take place. If the cross-section for a flavour is not known accurately, the number of neutrinos of that flavour, and hence the oscillation probability, will be determined incorrectly.

The energy spectrum is reconstructed from a set of observables in a detector. To do this, the kinematics of the event must be well understood, otherwise the energy spectrum will be distorted, and hence the oscillation parameters incorrectly calculated. Understanding these kinematics is highly dependent on accurately identifying the type of interaction.

As neutrinos are electrically neutral and colourless, they can only interact via the weak force. We divide these interactions into two types: Charged Current (CC), mediated by the W^\pm boson, and Neutral Current (NC), mediated by the Z^0 boson.

The Feynman diagram for an example of an NC interaction, NC electron elastic scattering,

²This would be the probability for the disappearance channel. The probability for appearance would be the number of neutrinos of the appearing flavour after oscillation, divided by the number of the initial flavour before.

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is shown on the left hand side of Figure 2.4. A neutrino interacts with an electron, causing it to recoil, which can be detected. However, as this process could occur for any flavour of neutrino, detecting it is not useful for determining the flavour composition of a neutrino flux. For this reason, NC interactions are not useful for oscillation measurements.

The Feynman diagram for CC elastic scattering is shown on the right hand side of Figure 2.4. Here, the only neutrino flavour this is possible for is ν_e , and so a measurement of this process does tell us about the flavour composition of the neutrino flux. These events are therefore selected to be part of oscillation analyses. However, the experimental signature is identical to that of NC scattering, which could be any flavour. In this way, NC electron elastic scattering forms an irreducible background to CC elastic scattering events. These arguments can be extended to all NC and CC interactions: NC interactions produce charged leptons with flavour uncorrelated to the incoming neutrino, whereas CC interactions produce charged leptons which match the flavour of the incoming neutrino, and so can be used to determine if a neutrino has oscillated. The NC event rate is therefore simulated in the MC and used in the predicted event rates.

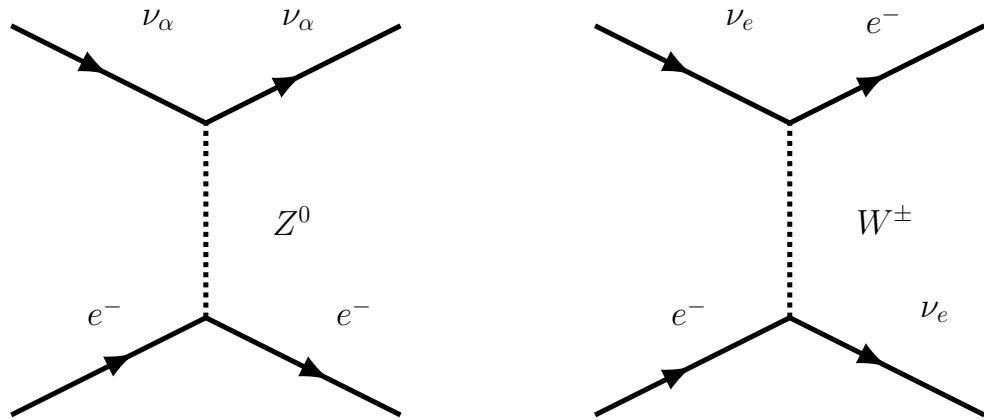


Figure 2.4.: Feynman diagrams for NC electron elastic scattering (left) and CC elastic scattering (right). The NC interaction can occur for any neutrino flavour $\alpha = e, \mu, \tau$, whereas the CC interaction can only occur for an incoming ν_e .

At T2K energies, there are 3 main types of interaction, but with a range of complex nuclear effects involved. At low energies, < 1 GeV, quasi-elastic (QE) scattering dominates, but nucleon-nucleon correlations and the distribution of nucleons within a nucleus need to be accounted for. QE events are called as such as the kinematics are similar to electron scattering, as the transfer of energy, Q^2 , is small. At intermediate energies, around 1 GeV, resonance production (RES) become important, where the nucleon is excited into a baryonic resonance, before decaying. At higher energies, deep inelastic scattering (DIS) dominates, with parton distribution functions becoming important. Feynman diagrams for these three

2.3. Oscillation Theory

processes are shown in Figure 2.5. The cross-section of these interactions for neutrinos (rather than anti-neutrinos) as a function of energy is shown in Figure 2.6. Although the individual interactions are understood fairly well, the transitions between these energy regimes are currently poorly modelled [50].

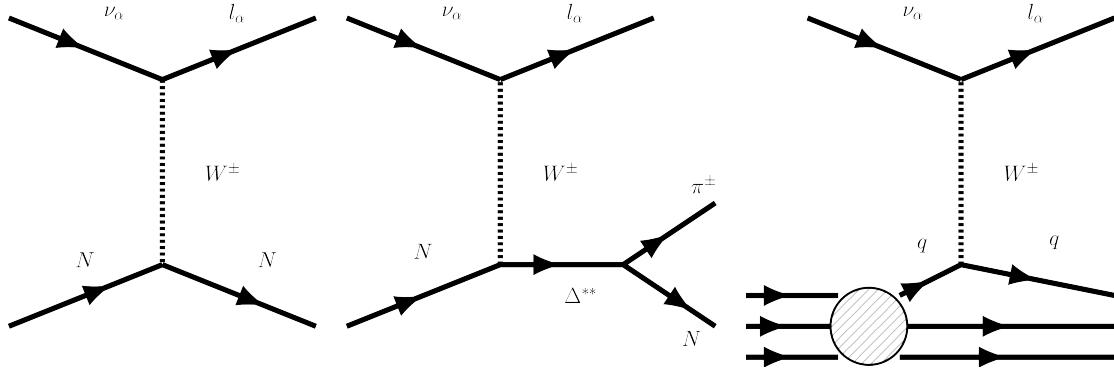


Figure 2.5.: Feynman diagram for CCQE (left), CC RES (center), and CC DIS (right) interactions.

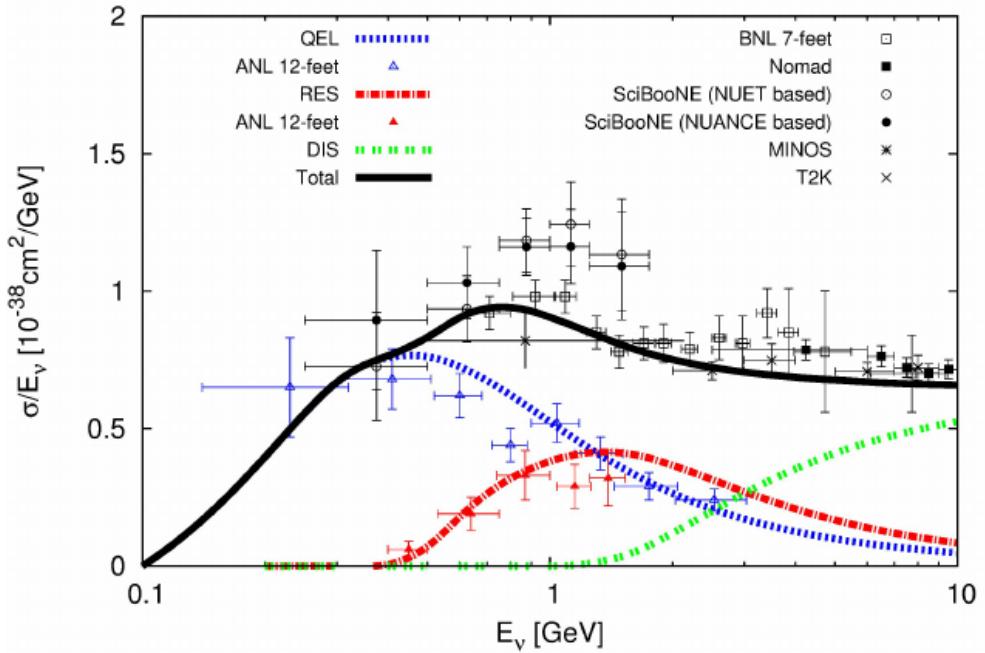


Figure 2.6.: Breakdown of the CC ν_μ cross-section for QE, RES, and DIS interactions, along with data from various experiments. Figure from [4].

The T2K neutrino beam peaks at 0.6 GeV, and so CCQE events dominate. CCQE interactions are well understood, and well constrained by data. Furthermore, as they are 2-body processes, and assuming the initial nucleon is at rest, the incoming neutrino energy, E_{rec} , can be reconstructed from the final state lepton's momentum and angle:

$$E_{rec} = \frac{m_p^2 - (m_n - E_b)^2 + m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos \theta_\mu)}, \quad (2.30)$$

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where m_p is the mass of the proton, m_n is the mass of the neutron, E_b is the binding energy of the neutron, and m_μ , E_μ , p_μ and $\cos \theta_\mu$ are the mass, energy, momentum, and angle of the final state lepton.

Equation 2.30 shows that accurate neutrino energy reconstruction depends on having an accurate value of the binding energy. The binding energy itself is the energy required for the incoming neutrino to release a nucleon from the target nucleus. This manifests itself as missing energy in the interaction. If an incorrect value for E_b is used in the reconstruction, an incorrect value of E_{rec} will be obtained, biasing the measurement of oscillation parameters. As the average binding energy per nucleon is not well constrained by external data, this is one of the dominant systematic uncertainties in previous T2K oscillation analyses.

The assumption that the initial state nucleon is at rest, is also not strictly true, particularly for low Q^2 events. Nucleons are constantly moving around, and the initial momentum distribution within a nucleus is not well modelled. This causes an uncertainty in the reconstruction of the neutrino energy.

As described in Section 5.2, T2K samples data by event topology as seen by the detector, whereby CCQE events are selected as CC 0 π . A large background in this sample comes from events where a neutrino interacts with a correlated pair of nucleons, known as 2p2h (two-particle-two-hole). An example 2p2h Feynman diagram is shown in Figure 2.7. Like CCQE events, this leaves a 0 π final state, meaning it is vitally important these interactions are well modelled. If 2p2h events are mistaken for CCQE, the neutrino energy will be incorrectly reconstructed, biasing the oscillation results.

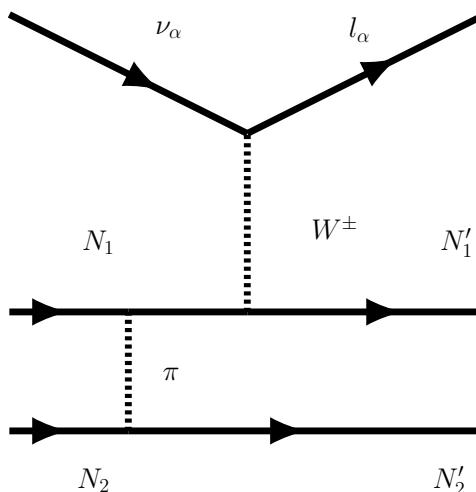


Figure 2.7.: Feynman diagram for a 2ph2 interaction. As they both produce 0 π final states, these events form a background to CCQE interactions.

The most dominant interaction type producing a 1 π final state is CC RES. These interac-

2.3. Oscillation Theory

tions are not as well understood as CCQE, and as they are three body processes the neutrino energy reconstruction is not as simple. If the pion produced is below detection threshold, the event will be classed as CC 0π , forming an irreducible background to CCQE events.

Coherent (COH) π production events, where the incoming neutrino interacts with an entire nucleus leaving it in the same final state as it was initially, also produce a 1π final state, as shown in Figure 2.8. Events on nuclei are less understood than events on nucleons, but a target of purely free neutrons would be impossible to construct in practice, and interactions on Hydrogen nuclei (purely protons) are only available to anti-neutrinos, which have a lower cross-section³. Nuclei targets are therefore used, and so coherent scattering events are inevitable.

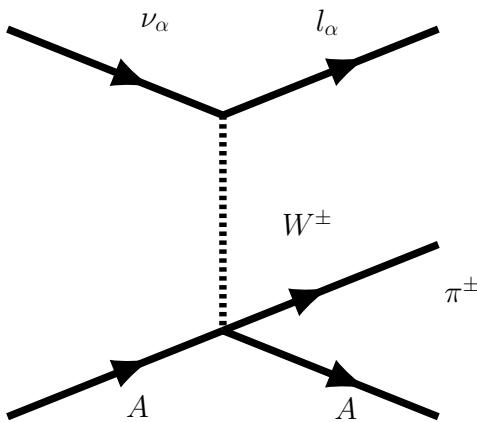


Figure 2.8.: Feynman diagram for a CC COH π production interaction.

As the energy increases, a larger Q^2 becomes available, and so inelastic events become accessible. In CC DIS interactions, the incoming neutrino scatters off an individual constituent quark rather than a nucleon or nucleus. As the hit quark recoils, the nucleon containing it fragments, producing multiple π s. These events are a significant fraction of the CC N π ($N > 1$) samples.

Final state interactions (FSI) can cause events to be miss-classified. The particles produced in the event can interact with other nucleons as they propagate out the nucleus. This can alter their momentum and direction significantly. The multiplicity of outgoing particles can also be changed, as they can be absorbed before leaving the nucleus, or produce more particles through collisions. FSI can therefore cause the particles leaving the nucleus to be different to those produced in the original interaction.

Although FSI doesn't generally affect the final state lepton, it can still have a big impact

³In fact, neutrino events on free electrons are even better understood than on free nucleons. However, the cross-sections for these interactions are much lower, and constructing a pure electron target is as infeasible as for neutrons.

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on oscillation results. For example, if the π produced in a CC RES event is absorbed before being detected, the event could be classified as CCQE. Equation (2.30) would not be valid though, and E_ν would not be reconstructed correctly.

2.4. Current Experimental Status

The current generation long baseline accelerator experiments, T2K and NOvA, are measuring the accelerator oscillation parameters to greater precision, as well as trying to determine δ_{CP} and the mass hierarchy. The short baseline neutrino oscillation experiments, such as MicroBooNE [51] and ICARUS, are searching for sterile neutrinos, and trying to resolve tensions with the LSND result. These form the Short Baseline Neutrino (SBN) program at Fermilab [52], along with the SBN near and far detectors, due to come online in 2020. The main aim of the SBN program is to unambiguously confirm or disprove previously anomalous measurements, as well as performing detailed studies of neutrino-nucleus interactions at the GeV energy scale.

The solar oscillation parameters are well constrained, but Borexino [53], is measuring neutrinos produced via the ^8B , ^7Be , *pep*, *pp* and CNO processes. SNO+ [54] will aim to confirm these results as well as performing detailed studies of the MSW effect.

The current atmospheric neutrino oscillation experiments, such as IceCube [55], ANTARES [56], and SK, are measuring the atmospheric parameters to increased precision, as well as studying specific zenith angles, and therefore baselines, to investigate the MSW effect.

$\sin \theta_{13}$ is being measured with increasing precision by the current reactor neutrino experiments, such as RENO, Double Chooz, Daya Bay, and KamLAND. They are also searching for steriles and trying to resolve tensions between the measured and predicted flux at $E_\nu \sim 5$ MeV. DANSS [57], NEOS [58], PROSPECT [59], STEREO [60] and SoLi δ [61] are all very short baseline reactor experiments ($L \sim 10$ m), and have each confirmed the 5 MeV. However, currently none have found significant evidence of a sterile neutrino.

Many solar, atmospheric, reactor, and accelerator neutrino experiments have been performed over many years, with the aim of measuring the key oscillation parameters to an increasing level of accuracy and precision. The Particle Data Group determine the current world-leading measurements of each of the parameters [62].

The best measurement of the solar parameters are from a global fit of solar and KamLAND data, using a constraint on θ_{13} from reactor and accelerator experiments for Δm_{21}^2 . This gives $\Delta m_{21}^2 = (7.53 \pm 0.18) \times 10^{-5}$ eV 2 , and $\sin^2 \theta_{12} = 0.3076^{+0.013}_{-0.012}$.

2.4. Current Experimental Status

The atmospheric parameters are best measured using a fit of T2K, SK, NOvA, MINOS, and IceCube data. These depend on the mass hierarchy, and the θ_{23} octant. For the normal hierarchy, this gives $\Delta m_{32}^2 = (2.444 \pm 0.034) \times 10^{-3}$ eV 2 , $\sin^2 \theta_{23} = 0.512^{+0.019}_{-0.022}$ (upper octant: $\sin^2 \theta_{23} > 0.5$), and $\sin^2 \theta_{23} = 0.542^{+0.019}_{-0.022}$ (lower octant: $\sin^2 \theta_{23} < 0.5$). For the inverted hierarchy, this gives $\Delta m_{32}^2 = (-2.55 \pm 0.04) \times 10^{-3}$ eV 2 , and $\sin^2 \theta_{23} = 0.536^{+0.023}_{-0.028}$.

A fit of data by reactor experiments Daya Bay, RENO, and Double Chooz is the most precise measurement of θ_{13} . This gives $\sin^2 \theta_{13} = (2.18 \pm 0.07) \times 10^{-2}$.

The best measurement of the CP violating phase comes from a fit of T2K, SK, and NOvA data. The T2K and SK results assume the normal hierarchy, and use a constraint on θ_{13} from reactor experiments. The NOvA result assumes the normal hierarchy and the upper θ_{23} octant ($\sin^2 \theta_{23} > 0.5$). This gives $\delta_{CP} = 1.37^{+0.18}_{-0.16}$.

2.4.1. Open Questions

For several decades now, neutrino experiments have been uncovering more and more information about neutrinos, and they're interactions. However, there are still several fundamental unknowns.

As mentioned in Section 2.4, current data suggests that δ_{CP} is non-zero. However, more statistics are needed to ambiguously conclude this, and if so, what it's value actually is, and if it corresponds to sufficient CP violation to account for the matter - anti-matter asymmetry we see in the Universe today. The next generation accelerator experiments, DUNE and HK, aim to obtain precise measurements of δ_{CP} .

The ordering of mass states is also still unknown. Although we know $m_2^2 > m_1^2$, we don't know if m_3^2 is higher or lower than the other two. Being such a fundamental property of neutrinos, not knowing the mass hierarchy limits our ability to measure many aspects of neutrino physics. Determining the hierarchy would allow more precise measurements of the other oscillation parameters, as well as having a big impact on our understanding of Supernovae. This is one of the aims of future accelerator experiments DUNE and HK, future atmospheric experiments SNO+ and IceCube, as well as the future reactor experiment JUNO [63].

Furthermore, the absolute scale of the masses are not known. Although we can measure the square of the mass differences, this tells us nothing about the actual values of the masses.

As well as this, the nature of the neutrino masses is unknown. Neutrinos could have Dirac masses, like all other fermions, or could have Majorana masses, meaning they are their own anti-particle. Knowing if neutrinos are Majorana or Dirac particles is very important for

2. Neutrino Physics

understanding the origin of small neutrino masses. Future neutrinoless double beta decay experiments, MAJORANA [64], nEXO [65], KamLAND-Zen [66], and SNO+ will be able to test the Majorana nature of neutrinos if the mass hierarchy is determined.

Finally, it is not known if the three flavours of neutrino that have already been detected are the only that exist. And if there are more, it is not known how many more there are, and how their masses compare to the active flavours. If proved to exist, sterile neutrinos could even be the elusive Dark Matter we infer exists in the Universe, but don't currently know what it is [67]. The SNB program will improve constraints on sterile neutrinos.

3. The T2K Experiment

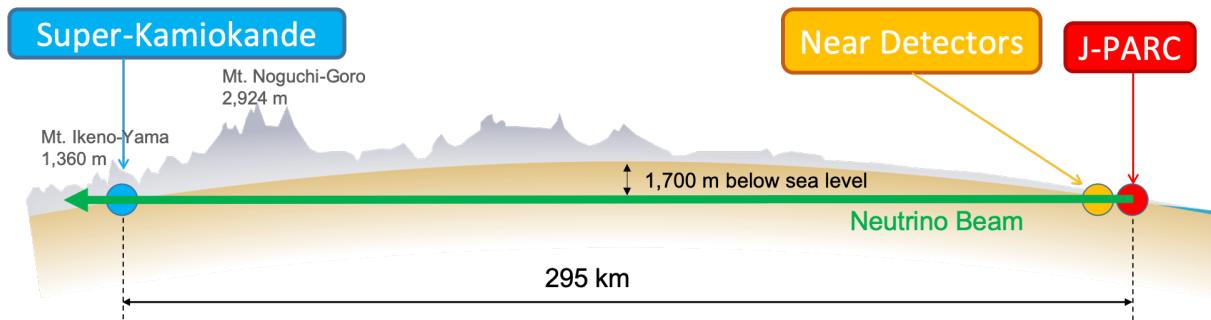


Figure 3.1.: The T2K experiment: Neutrinos are produced on the east coast of Japan, and are measured 280m upstream by the near detectors, and 295km away at the far detector, SK.

T2K is a long baseline neutrino oscillation experiment in Japan, which has been taking data since 2010. It was designed to precisely measure $\sin\theta_{13}$ by observing the appearance of (anti)-electron neutrinos in a (anti)-muon neutrino beam, and $\sin^2 2\theta_{23}$ and Δm_{23}^2 by observing muon neutrino disappearance. In 2014, T2K first detected electron-neutrino appearance [68]. NO ν A found consistent results in 2016 [69]. Since data taking began, T2K has made world leading measurements of $\sin\theta_{13}$, $\sin^2 2\theta_{23}$ and Δm_{23}^2 . The current main aims of T2K focus on excluding possible values of δ_{CP} and determining the neutrino mass ordering.

In this chapter, the three main components of the experiment, the neutrino production beamline, the near detector suite, and the far detector, SK, are introduced. A schematic diagram of this setup is shown in Figure 3.1. The beam is produced on the east coast of Japan, at the Japanese Proton Accelerator Research Complex (J-PARC), and is described in Section 5.4.2. The near detector (ND) suite is located 280m upstream of the beam source, where the ND280 and INGRID detectors measure the flux, cross-section, and direction of the beam. This is described in Section 3.2. 295km away in the west of Japan, the Super-Kamiokande water Cerenkov detector measures interactions after oscillation, and is described in Section 3.3.

At the ND suite, there are a number of different neutrino detectors. T2K was the first

3. The T2K Experiment

experiment to use the off-axis technique, whereby SK and ND280 are located 2.5° away from the axis of the beam. This focuses the energy distribution of the beam into a narrower peak, as described in Section 3.2. This technique requires an accurate measurement of the beam direction, which is performed by a second, on-axis detector INGRID.

As well as ND280 and INGRID, there are also detectors at the ND suite that are not directly used in the T2K oscillation analysis. The NINJA [70] experiment is designed to accurately measure the neutrino cross-section on water using nuclear emulsion techniques. The WAGASCI [71] and Baby MIND [72] experiments are designed to measure and constrain non-cancelling systematic uncertainties arising from the fact that ND280 and SK have different target materials. These will not be discussed any further, as data from these experiments is not used in this analysis.

3.1. Beamlne

The neutrino beamline at J-PARC [73] was newly constructed for the T2K experiment, and is fed by a system of 3 accelerator facilities: a linear accelerator (LINAC), a rapid cycling proton synchrotron (RCS), and the main ring synchrotron (MR). The accelerator complex is shown in Figure 3.2. H^- ions are first accelerated to 400 MeV by the LINAC, before being converted to H^+ ions by charge stripping foils as they are injected into the RCS. Here, they are further accelerated to 3 GeV in 25 Hz cycles, with 2 bunches per cycle.

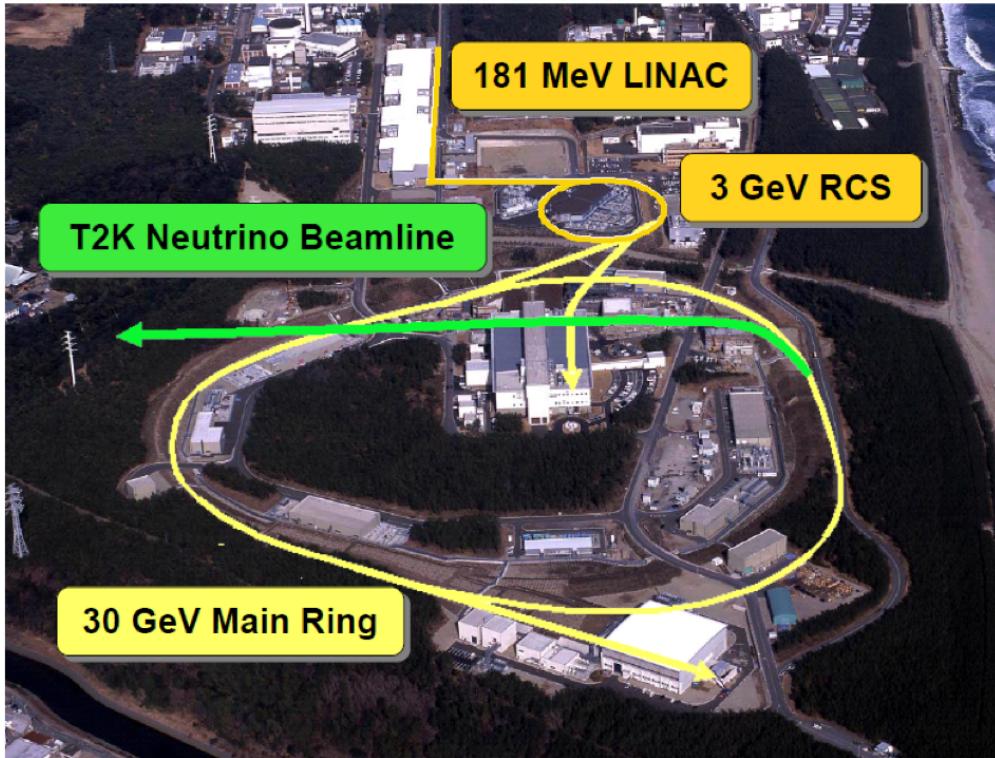


Figure 3.2.: The J-PARC accelerator complex, with the three main accelerators labelled.

3.1. Beamlne

Approximately 5% of the bunches are injected into the MR, where they are accelerated to 30 GeV. The rest are supplied to other experiments at J-PARC. The MR holds 8 bunches each of $\sim 3 \times 10^{14}$ protons. The beam is extracted from the MR by a set of 5 kicker magnets, which deflect the beam toward the neutrino beamline. The extraction happens in spills of 8 proton bunches, separated by 560 ns. The spill cycle is ~ 0.5 Hz, and a single spill has a total duration of approximately 5 μ s. A GPS system is used to link the timing of the information of the spills to the neutrino detector triggers, allowing better discrimination of backgrounds from the beam signal.

3.1.1. Neutrino Beamlne

The neutrino beamline consists of two sections, the primary and secondary beamlines. These are shown in Figure 3.3. In the primary beamline, the proton beam is deflected towards the secondary beamline. It is vital the profile, position, intensity, and beam loss are known to be able to produce the stable and consistent neutrino beam required. Beam monitors in the primary beamline perform these measurements.

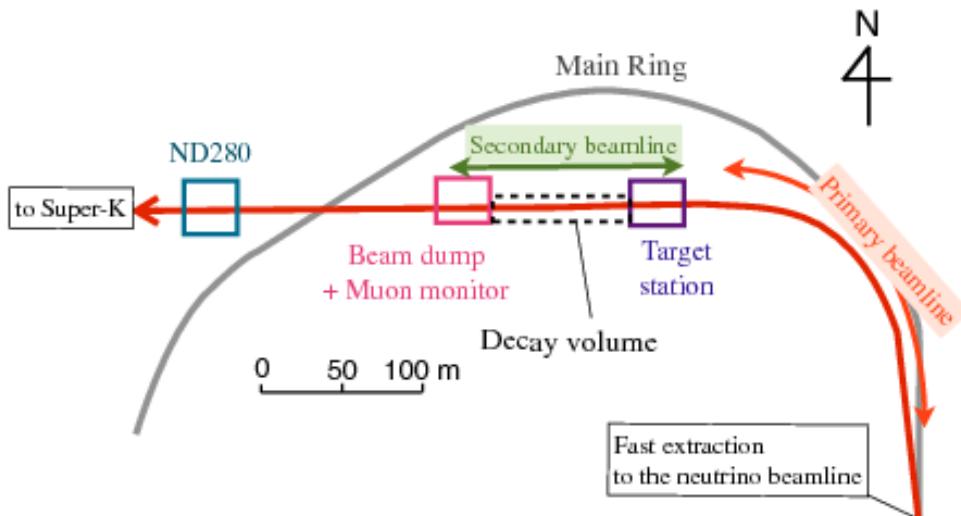


Figure 3.3.: The T2K neutrino beamline.

The secondary beamline contains the proton target station, decay volume, and beam dump and muon monitor. This is shown in Figure 3.4. The proton target station, contains the graphite target, an optical transition radiation monitor (OTR), and the magnetic focussing horns. The protons are impinged on the target, producing secondary muons, pions, and kaons. The target is a 91.4 cm long graphite rod with a diameter of 2.6 cm. Helium gas is used to cool the target, to offset the heating effect of the beam. It is surrounded by a 2 mm thick graphite sleeve and a 0.3 mm titanium casing.

The target station sits within the first of the focusing horns. This collects the secondary

3. The T2K Experiment

mesons, and they are then focused by the second and third horns. In each horn, a toroidal magnetic field is produced by coaxial conductors. The strength of the field reduces with $1/r$ where r is the distance from the beam axis. The horns are designed to operate at 320 kA (1.7 T), which increases the neutrino flux at SK by a factor of 16 compared to 0 kA.

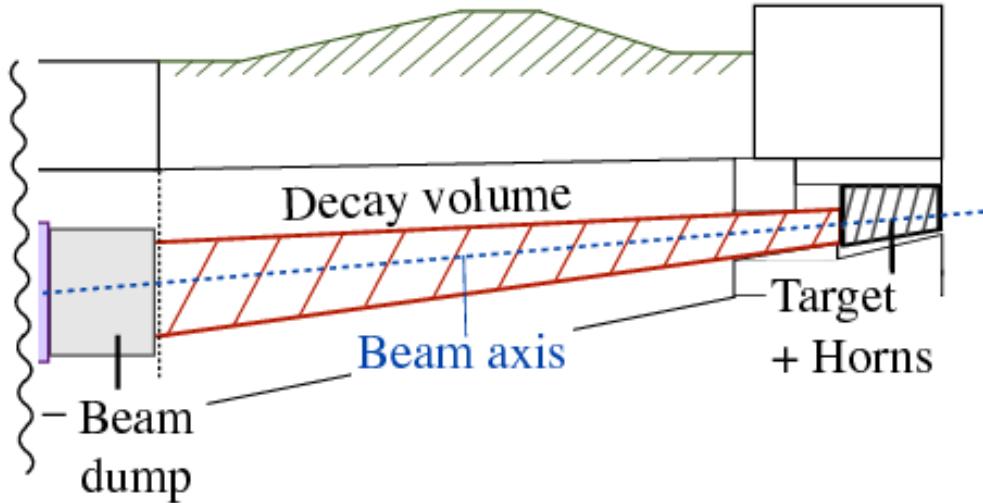


Figure 3.4.: Side view of the secondary beamlne, showing the target station and focusing horns, decay volume, and beam dump.

The current in the horns can be reversed to focus either positive or negatively charged mesons. The right sign particles are focused onto the beamlne, while the wrong sign particles are deflected away. The current required to focus positive mesons is referred to as forward horn current (FHC), and the current required to focus negative sign particles is referred to as reverse horn current (RHC).

The focused mesons then travel down the 96 m long steel tunnel decay volume. Here, neutrinos are produced via the following decay processes:

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ + \nu_\mu \\ K^+ &\rightarrow \mu^+ + \nu_\mu \end{aligned} \tag{3.1}$$

in FHC, and:

$$\begin{aligned} \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\ K^- &\rightarrow \mu^- + \bar{\nu}_\mu \end{aligned} \tag{3.2}$$

in RHC.

There is also a small contribution of ν_e and $\bar{\nu}_e$ from decays such as:

$$\begin{aligned} K^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\ \mu^+ &\rightarrow \pi^0 + e^+ + \nu_e \end{aligned} \tag{3.3}$$

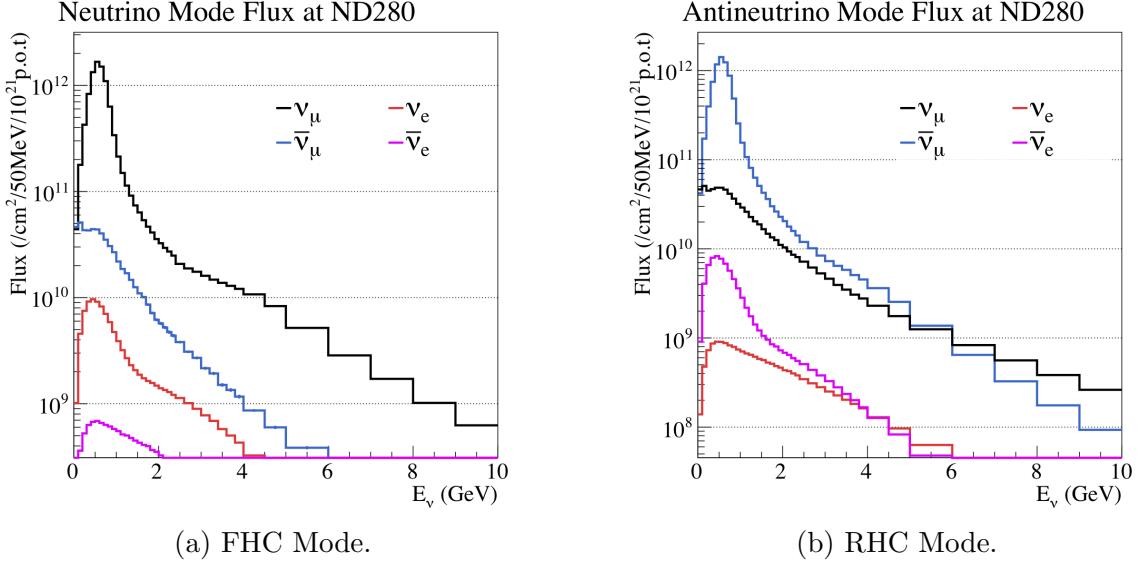


Figure 3.5.: Prediction of ND280 event rate broken down by neutrino species.

in FHC, and:

$$\begin{aligned} K^- &\rightarrow e^- + \nu_e + \bar{\nu}_\mu \\ \mu^- &\rightarrow \pi^0 + e^- + \nu_e \end{aligned} \tag{3.4}$$

in RHC.

In each mode, there is some contamination of the wrong sign neutrino due to imperfect horn focusing, as shown in Figure 3.5. As this is worse for RHC mode, and as anti-neutrinos have a much smaller cross-section than neutrinos, there are many more neutrino interaction in RHC mode than anti-neutrino interactions in FHC mode.

After the decay channel, there is a beam dump made up of 3.17 m of graphite and 2.4 m of iron. This stops all surviving mesons, and all muons below 5 GeV. Neutrinos and higher momentum muons reach the muon monitor (MUMON) beyond the beam dump. The MUMON consists of two independent detectors: Si PIN photodiodes, and ion chambers. These measure the muon profile on a bunch by bunch basis, which is a reliable measure of the beam direction and intensity as the majority of neutrinos in the beam are produced with a muon in a two-body decay. The MUMON measures the beam direction to an accuracy of 0.25 mrad, and the beam intensity to a precision of 3% [74].

It's not possible to count the total number of neutrinos produced in the beam, so the number of protons impinged on the target (POT) is used as a metric for the data collected by T2K. The total accumulated POT and beam power have been increasing since data taking

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began in 2010, as shown in Figure 3.6. Data from runs 2-9 are used in this analysis.

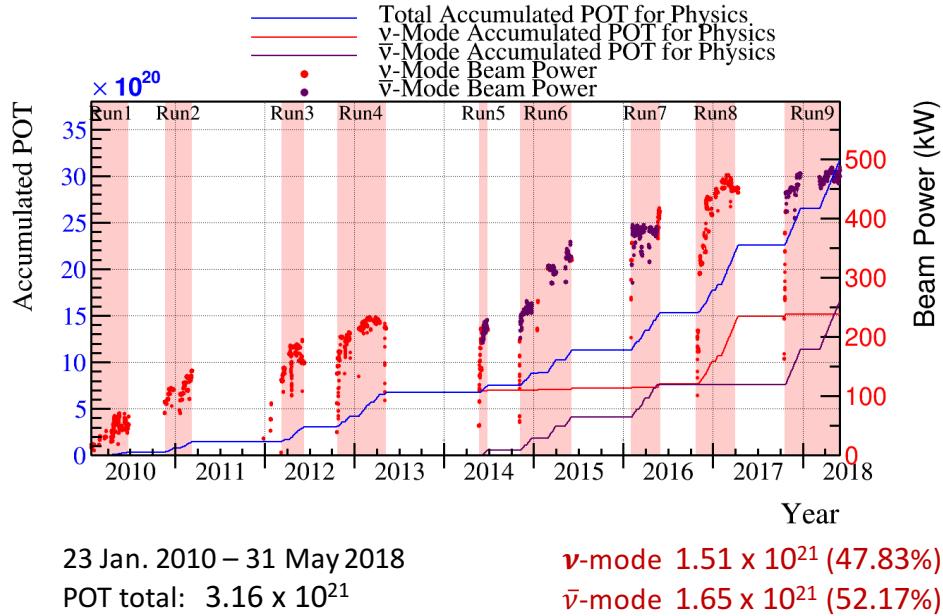


Figure 3.6.: The total accumulated POT and beam power at T2K for runs 2-9.

3.1.2. Off Axis Technique

Because neutrinos are produced in a two-body decay, and so some fraction of energy is taken by the second decay product, it is not possible to produce a mono-energetic beam. The oscillation probability depends on the neutrino energy, and so more accurate measurements of oscillation parameters can be made using a neutrino beam with a narrower spread of energies. The neutrino energy is given by [75]:

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta_{\pi\nu})}. \quad (3.5)$$

Figure 3.7 shows E_ν as a function of E_π for different values of $\theta_{\pi\nu}$. The E_ν distribution is flatter for larger $\theta_{\pi\nu}$, and so E_ν has a weaker dependence on E_π . At higher angles a narrower range of E_ν can therefore be produced from a wider range of E_π . This effect is highlighted in Figure 3.8, showing the predicted neutrino fluxes on and off-axis. A narrower beam spread is produced at 2.5° , but with a lower overall rate (the y-axis is normalised). The beam energy and off-axis angle are chosen such that the neutrino energy peaks at ~ 0.6 GeV, to maximise the probability of oscillation at the far detector by aligning the beam peak with the first oscillation dip. Going off-axis also reduces the wrong sign contamination in the beam.

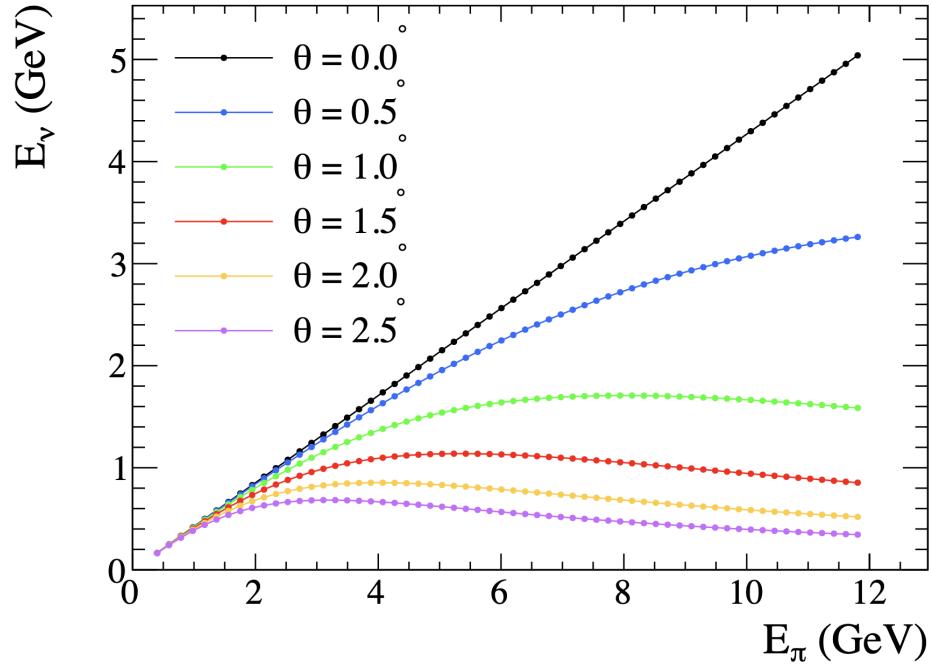


Figure 3.7.: Energy of neutrinos produced in two-body decay as a function of pion energy, for a variety of different off-axis angles.

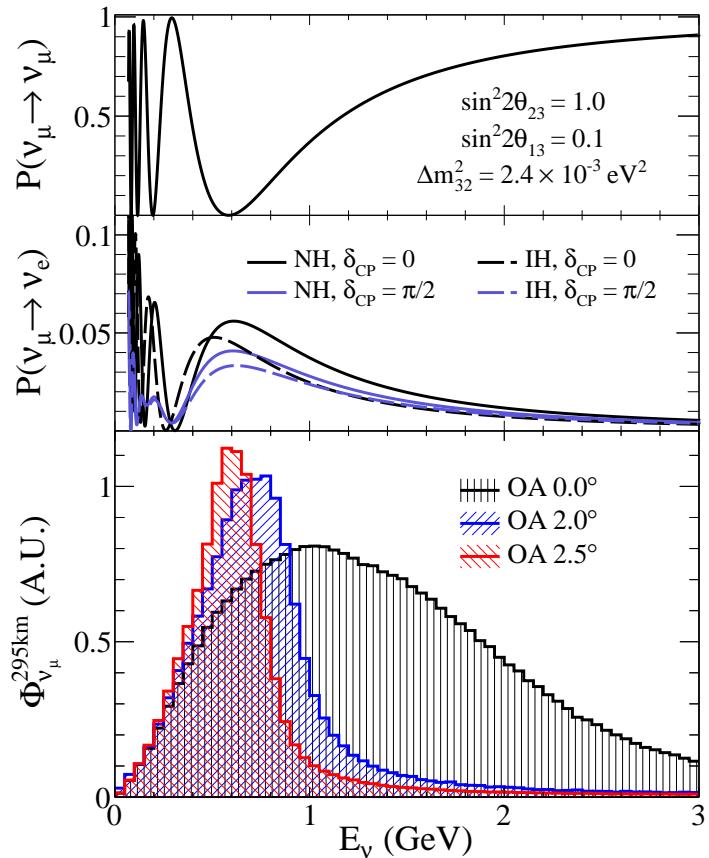


Figure 3.8.: Effect of off-axis angle on the predicted neutrino flux, normalised to arbitrary units, along with the oscillation and survival probabilities of ν_e and ν_μ respectively.

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3.1.3. The Neutrino Flux Simulation

A data-driven Monte-Carlo (MC) is produced to model the neutrino flux. The FLUKA2008 [76] software package was used to simulate 30 GeV proton interactions within the target. Measurements from the NA61/SHINE [77] experiment, which measures interactions of 30 GeV protons in a replica of the T2K target, are used to tune the simulation. The components of the beamline are modelled with the GEANT-4 [78] based JNUBEAM [79] software, and secondary interactions and interactions between particles which exit the target with the surrounding area are simulated with the GCALOR package [80]. Secondary particles are tracked until they decay to neutrinos, fall below the energy threshold to decay to neutrinos, or are absorbed in the beam dump. The predicted neutrino energy distributions for FHC mode are shown in Figure 3.5.

3.2. Near Detectors

The beam is first measured by two near detectors, ND280 and INGRID, 280 m away from the source. At this short distance, the probability of oscillation is negligible and so the unoscillated beam can be measured. The locations of the two detectors within the near detector suite are shown in Figure 3.9.

3.2.1. INGRID

The INGRID detector is located on the beam axis, and is designed to measure the beam profile and direction. From this, the beam angle at ND280 and SK can be determined to within 0.2 mrad, and the beam center to within 5 cm. Neutrino event rates are also measured to within 2%. These measurements are in good agreement with results from MUMON, as shown in Figure 3.10. A precise determination of the beam direction is necessary as a 1 mrad uncertainty corresponds to a 2-3% uncertainty on the beam energy.

INGRID achieves this precision by using 16 identical modules made of interleaved iron and scintillator. These are arranged in a 10 x 10 m cross shape centered on the primary proton beamline axis, with 2 modules off-axis outside the cross, as shown in Figure 3.11.

Each module consists of nine iron sheets and 11 tracking scintillator planes, as shown in Figure 3.12. Each scintillator plane contains 24 horizontal and 24 vertical bars of plastic scintillator. These bars are threaded with a wavelength shifting (WLS) fibre, which collects photons emitted in the plastic scintillator during energy deposition. The WLS fibres trans-

3.2. Near Detectors

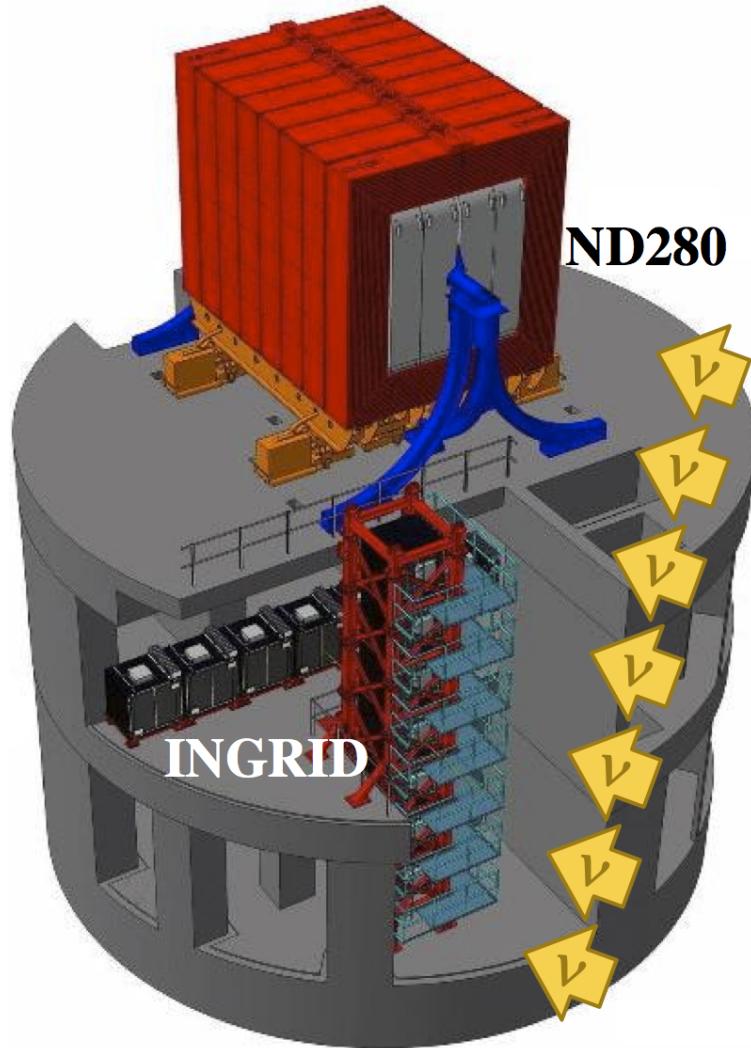


Figure 3.9.: The T2K near detector suite, 280 m from the beam source.

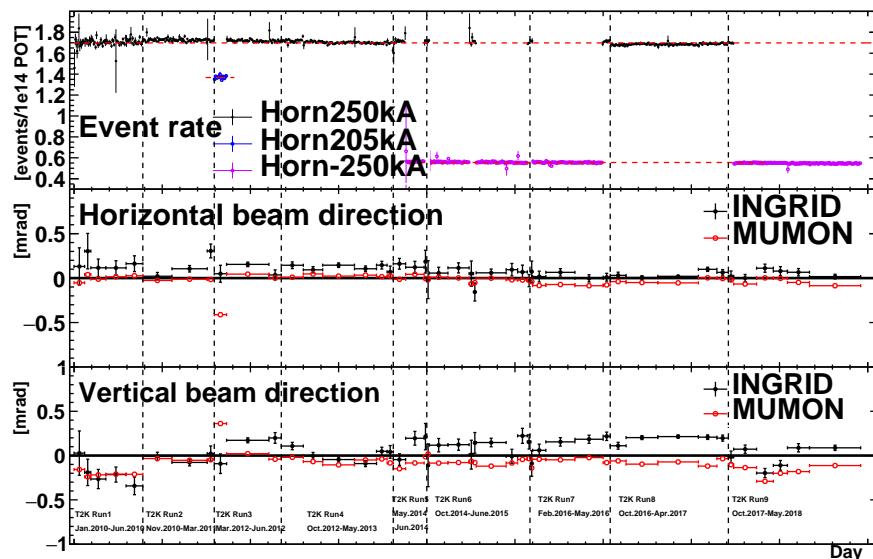


Figure 3.10.: INGRID and MUMON measurements of the beam direction and event rate for runs 1-9.

3. The T2K Experiment

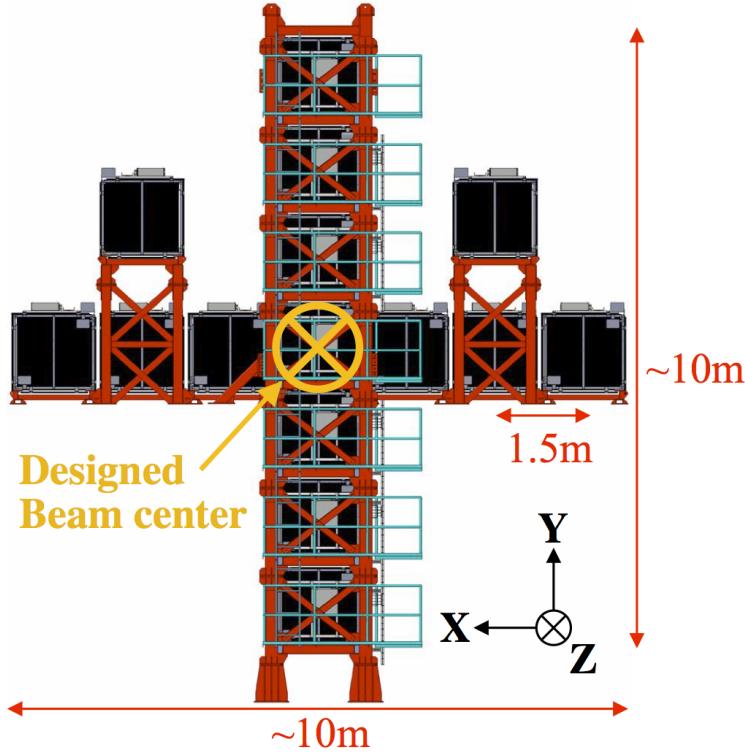


Figure 3.11.: The horizontal, vertical, and off-axis modules of the INGRID detector.

port photons to multi-pixel photon counters (MPPCs) at the end of each bar, and shift the spectrum of the light to the optimal region for MPPC readout. The MPPCs are avalanche photodiodes with a gain 1×10^6 , which convert photons into an electrical signal. This signal is readout by a set of Trip-T front-end electronics boards [81], each of which is connected to 48 MPPCs. The backend electronics are made up of readout merger modules (RMM), which read data from the detector, and clock modules, which send trigger signals and ensure all components of the detector are synchronised.

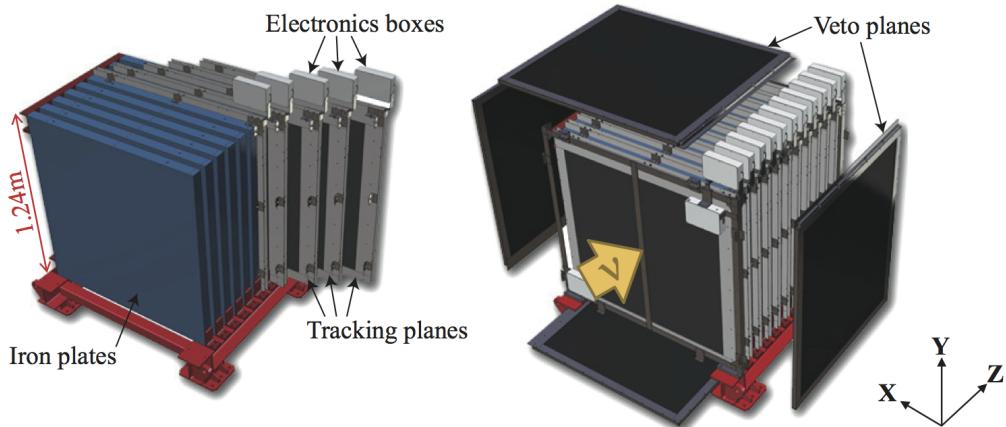


Figure 3.12.: The composition of an INGRID module.

The layered structure of each module is surrounded by scintillator planes to veto interac-

3.2. Near Detectors

tions occurring outside the fiducial volume. The total fiducial mass of iron in each module is 7.1 t, sufficient such that at nominal beam intensity, there are enough neutrino events to measure the beam direction on a day-by-day basis.

There is another 17th module, with a slightly different composition to the others. This module, known as the proton module, consists of only scintillator planes, but in smaller bars to give a finer granularity. It is designed to detect muons and protons from CCQE interactions on carbon in the plastic, to improve the MC simulation of the beamline and neutrino interactions. The proton module is located at the center of the cross, and like the other modules, is surrounded by veto planes. Figure 3.13 shows its composition.

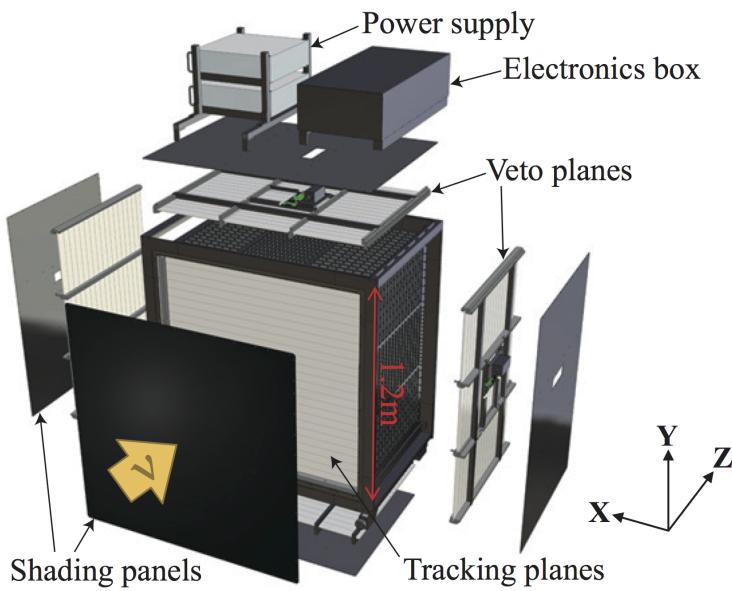


Figure 3.13.: The composition of the proton module in the INGRID detector.

3.2.2. ND280

The off-axis near detector, ND280, is designed to detect particles produced in neutrino interactions, to determine the event rate of various interaction modes and measure the unoscillated flux and energy of the beam in the direction of SK. This constrains systematic uncertainties allowing more accurate prediction of the event rates at the far detector. ND280 also measures neutrino interaction cross-sections at the 1 GeV energy scale.

As shown in Figure 3.14, ND280 consists of several sub-detectors. The tracker region contains two time projection chambers (TPCs) between three fine grained detectors (FGDs). The FGDs provide a target for neutrinos, and track particles close to the interaction vertex. The TPCs identify and measure the momentum of particles, particularly muons, which are produced in the event and leave the FGD the interaction vertex is in. The FGDs and TPCs are described in more detail in Sections 3.2.2.1 and 3.2.2.2.

3. The T2K Experiment

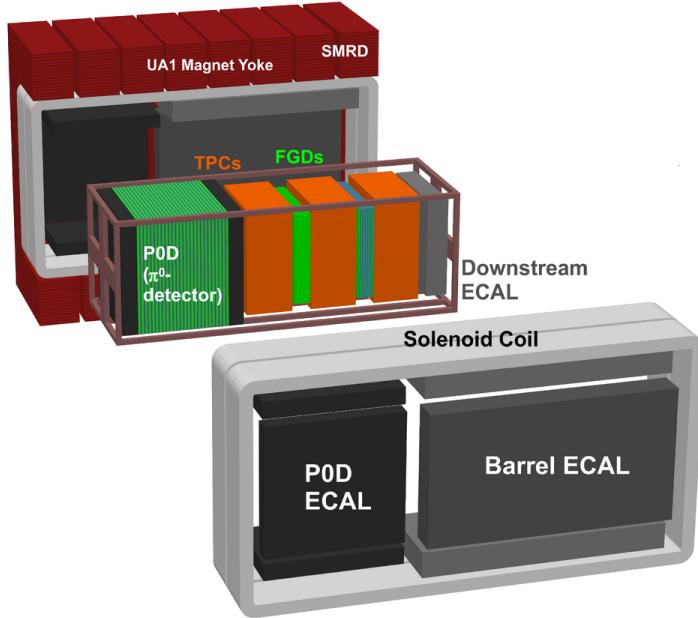


Figure 3.14.: Exploded view of ND280, showing it's sub-detectors.

Upstream of the tracker, the π^0 detector (P0D) detects NC events on water, the same target as in the far detector. This is described in Section 3.2.2.3. Both the tracker region and P0D are surrounded by electromagnetic calorimeters (ECals). The ECals are designed to measure the energy of photons produced in the inner detectors and reconstruct π^0 tracks from the FGDs. They are described in more detail in Section 3.2.2.4.

The whole detector sits within the UA1 magnet which produces a 0.2 T magnetic field. This allows accurate charge and momentum measurements in the TPCs. The magnet yoke is interleaved with scintillator, the side muon range detector (SMRD). This measures high angle muons exiting the detector, cosmic ray muons entering the detector, and interactions in the magnet and surrounding area. The magnet and SMRD are described in Section 3.2.2.5.

The same MPPCs used in INGRID are also used throughout ND280. These were chosen, rather than the more common photomultiplier tubes (PMTs), as they can be used within a magnetic field.

3.2.2.1. The Fine Grained Detectors

The FGDs provide the primary target for neutrino interactions in ND280. They are designed to be able to measure particles which don't exit themselves and enter a TPC. To achieve this, they are completely active, allowing them to measure vertex activity and short range tracks such as those from recoil protons. Short ranged particles tend to have low momentum

3.2. Near Detectors

and deposit lots of energy per track length, and so the FGDs need to be able to detect charged particles with fine granular resolution, to distinguish between tracks and determine their direction.

The FGDs are also used as a cosmic trigger for stopping pions, which allows the identification and reconstruction of subsequent Michel electrons. They are also used for measurements of the time-of-flight (TOF) of tracks to differentiate between forward-going positive and backward-going negative particles. As well as this, the FGDs have the best timing resolution of all the sub-detectors, and are used as the base for reconstructing tracks which pass through more than one sub-detector.

The two FGDs both contain 1.1 t of target mass, and consist of layers of scintillator bars. Each layer is 186.4 x 186.4 x 2.02 cm, and contains 192 bars in the horizontal direction and 192 bars in the vertical direction. The bars are covered in a reflective coating containing TiO_2 , and each are 96 x 96 x 186.4 cm. A WLS fibre runs down the centre of each bar to an MPPC at the end. The other end is mirrored by a vacuum deposition of aluminium.

The most upstream FGD (FGD1) is composed of 15 scintillator planes. The second FGD (FGD2) has 7 scintillator planes separated by layers of hollow corrugated polycarbonate sheets. These are filled with water, providing a water-scintillator hybrid target. The FGDs therefore measure interactions on CH in the scintillator, which is a common target in external neutrino scattering experiments, and H_2O , the far detector target. Nuclear effects cannot be accurately extrapolated between target nuclei, and so it useful to be able measure interaction rates on water at ND280.

The resolution and track length in the FGDs is too low to use dE/dx to identify particles which don't enter the TPCs, so the combination of integrated deposited energy and track length is used. These quantities are compared to theoretical values for different particles, as shown in Figure 3.15, allowing protons to be distinguished from other charged particles. In particular, accurately distinguishing protons and pions which stop in the FGDs is vital for correctly identifying the interaction type. Figure 3.15 shows data from both the neutrino beam, and cosmic trigger. The neutrino beam data contains particles identifiable as protons, muons, and pions, whereas the cosmic trigger data only contains particles identifiable as muons and pions, as would be expected.

3.2.2.2. The Time Projection Chambers

The three TPCs are located either side of each FGD, and provide high resolution tracking for both forward-going and backward-going particles. The majority of the particle identi-

3. The T2K Experiment

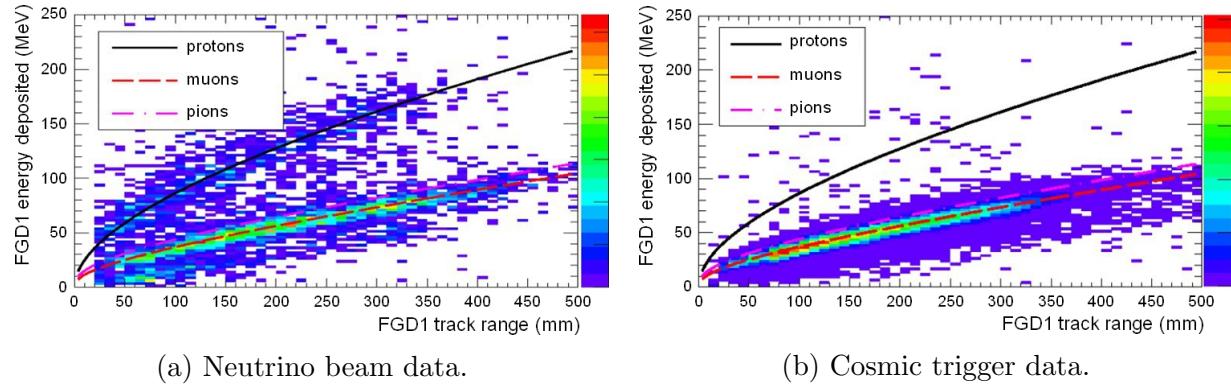


Figure 3.15.: Integrated deposited energy as a function of range for particles stopping in FGD1. The scatter plot shows data while the curves show the MC predictions for protons, muons, and pions.

fication and momentum measurements at ND280 take place inside them. The multiplicity and direction of tracks can be easily determined, as the TPCs detect events in 3 dimensions. The momentum of particles can be measured from the bending of tracks in the TPCs due to the magnetic field.

The construction of the three TPCs is identical. They consist of two concentric boxes, as shown in Figure 3.16. The inner box is filled with a drift gas consisting of an Ar:CF₄:C₄H₁₀ mixture at 95:3:2. The walls of the inner box form the field cage. The outer box walls are held at ground voltage, and the outer box is filled with CO₂, to provide electrical insulation between the boxes.

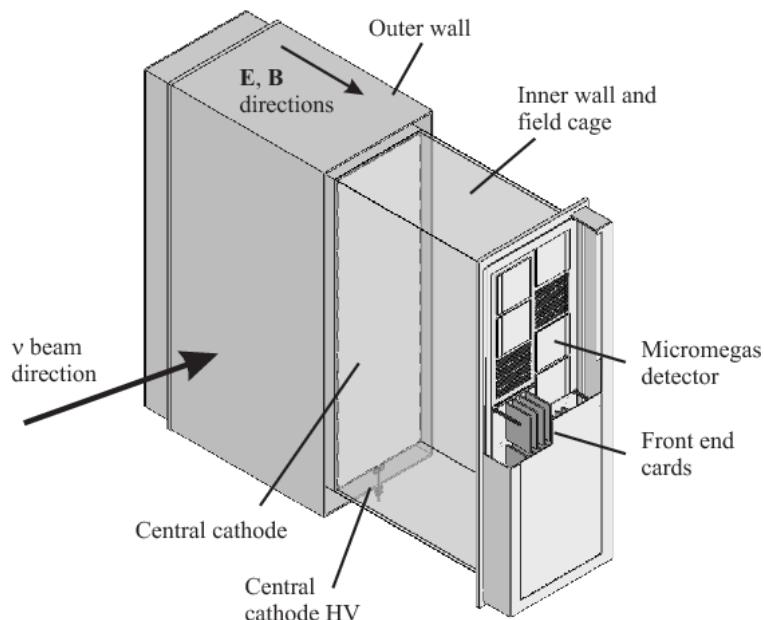


Figure 3.16.: Schematic diagram of a TPC module.

3.2. Near Detectors

The inner box contains the cathode, and the walls parallel to the cathode have a copper pattern, designed to produce a uniform electric field in the module aligned with the magnetic field. The TPC modules are made of non-magnetic materials as not to interfere with the field from the magnet.

When a charged particle passes through a TPC module, ionisation electrons are produced, which drift away from the cathode to readout planes on the walls of the inner box. Here, the electrons are multiplied and detected by micromegas detectors. The time and position of the electron signals at the readout planes give a 3D image of the particle track.

Particle identification is performed in the TPCs using, like in the FGDs, dE/dx . This is shown in Figure 3.17, as a function of momentum, for different particles. The dE/dx resolution is $7.8 \pm 0.2\%$, allowing electrons and muons to be distinguished.

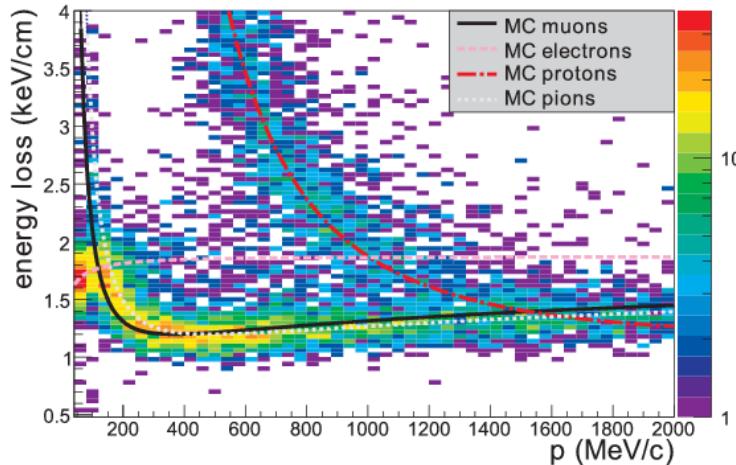


Figure 3.17.: Energy loss as a function of momentum for particles in one TPC. The scatter plot shows data while the curves show the MC predictions for protons, electrons, muons, and pions.

3.2.2.3. The π^0 Detector

The P0D was designed to measure the cross-section of the neutral current interaction $\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0 + X$ on water. This is one of the major backgrounds to ν_e appearance at the far detector, and so it is necessary to measure and constrain it.

The P0D is located upstream of the FGDs and TPCs. It consists of alternating layers of scintillator bars, brass and lead sheets, and water target bags, as shown in Figure 3.18. There are 40 modules, each made up of two triangular scintillator bars. The first layer contains 134 vertical bars, and the second 126 horizontal bars. Each bar contains a WLS fibre which is read out by an MPPC. The horizontal and vertical bars are 234 and 220 cm long respectively.

3. The T2K Experiment

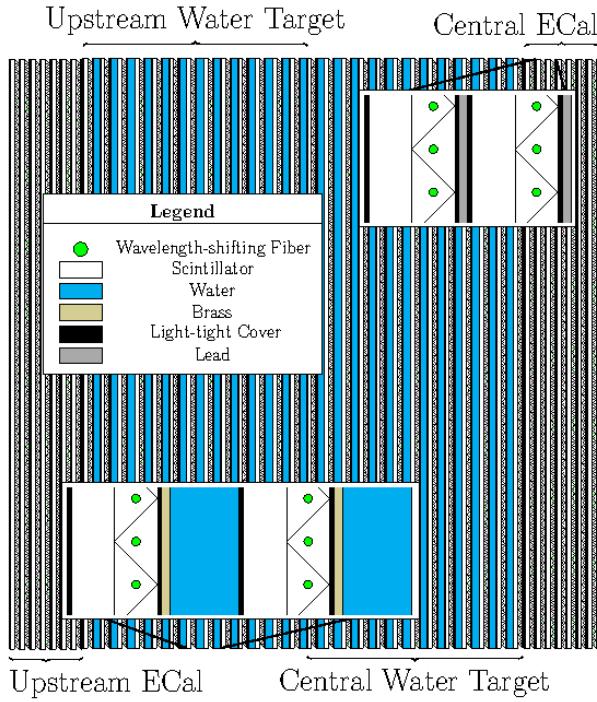


Figure 3.18.: A schematic diagram of the side on view of the P0D.

The water bags can be emptied, allowing measurements of the cross-section on H₂O by subtraction. The target mass is 16.1 t with water in the bags, and 13.3 t without water. The lead and brass sheets produce electron showers which can be detected, from photons emitted in π^0 decays.

3.2.2.4. The Electromagnetic Calorimeter

The primary purpose of the ECals is to tag and reconstruct π^0 s from the FGD, TPC, and P0D, by measuring the energy and direction of photon showers. It is also used to distinguish between pions and muons by shower shape. The ECal's near hermetic coverage of the inner detectors allows full reconstruction of events, and they also provide complimentary particle identification to the TPCs.

There are three sections of the ECal: the downstream ECal (DsECal) located after the last TPC, the barrel ECal surrounding the FGDs and TPCs, and the P0D ECal surrounding the P0D. These are shown in Figure 3.14. The barrel and downstream ECals are tracking calorimeters which reconstruct electromagnetic showers, particularly those from high-angle particles from the TPC. The P0D ECal is designed to tag energy escaping from the P0D and distinguish photons from muons, as the P0D reconstructs showers itself.

3.2. Near Detectors

Each ECal module consists of alternating layers of scintillator bars and lead sheets. The bars are 40 x 10 mm, and contain a WLS fibre which is read out by an MPPC. The lead sheets are 1.75 mm thick.

The downstream ECal has 34 layers of scintillator, corresponding to 11 electron radiation lengths. Alternate layers are orientated perpendicularly to each other. This gives two ‘views’, which can be combined to create 3D reconstructed tracks. The downstream ECal is 2300 x 2300 x 500 mm, and its total target mass is 4.80 t.

The 6 modules of the barrel ECal have 31 layers of scintillator, corresponding to 10 electron radiation lengths. These also alternate orientations similarly to the downstream ECal. The side barrel ECal modules are 4140 x 2500 x 462 mm, and their total target masses are 9.21 t. The top and bottom barrel ECals are 4140 x 1676 x 462 mm, and their total target masses are 6.62 t.

The 6 modules of the P0D ECal have only 6 layers of scintillator, each parallel to the beam. These are interspersed with 4 mm thick lead sheets. The side P0D ECal modules are 2898 x 2454 x 155 mm, and their target masses are 2.64 t. The top and bottom P0D ECal modules are 1584 x 2454 x 155 mm, and their target masses are 1.5 t.

3.2.2.5. The UA1 Magnet and Side Muon Range Detector

The TPC, FGD, P0D, and ECal all sit within the UA1 magnet, which provides a 0.2 T magnetic field. This allows the TPCs to measure the momentum of charged particles with a resolution of 10%, and determine their sign, which identifies if the interaction involved a neutrino or anti-neutrino. The magnet consists of water-cooled aluminium coils, which produce the field. The coils are supported by the return yoke, which is made up of 16 C-shaped iron elements. The internal volume of the magnet is 7.0 x 3.5 x 3.6 m, and the external volume is 7.6 x 5.6 x 6.1 m.

The nominal current is 2.7 kA, and this is monitored regularly to accurately calculate the field. This reduces the uncertainty on momentum measurements in the TPC. The uncertainty on the field measurement is 2×10^{-4} T.

Air gaps in the return yoke hold the modules of the SMRD. These are used to track high angle muons and measure their momentum, as well as providing a cosmic trigger. The SMRD consists of 192 horizontal and 248 vertical plastic scintillator modules. The horizontal modules are 9 x 686 x 955 mm, and the vertical modules are 9 x 892 x 955 mm. The scintillator modules contain a WLS fibre which is read out by an MPPC.

3. The T2K Experiment

3.2.2.6. The Data Acquisition System

The ND280 data acquisition (DAQ) system triggers the readout of information from each of the sub-detectors, as well as the storage of recorded data. The same system is used for both ND280 and INGRID.

There are three trigger requirements during physics runs: the beam trigger, when a beam spill occurs; the Trip-T cosmic trigger, when hits are seen on the opposite sides of the outer detectors (top and bottom SMRD, left and right SMRD, or P0D and downstream ECal) outside the beam window; and the FGD cosmic trigger, when hits are seen in both FGDs outside the beam window. These initiate a fixed time window during which data is recorded. Data is acquired from front-end electronic boards via optical Gigabit links, and event fragments from the sub-detectors are merged and logged.

3.2.3. Near Detector Simulation

The ND280 and INGRID geometries and the paths of final-state particles from neutrino interactions are simulated in GEANT-4. The neutrino interactions themselves are simulated using NEUT [82], an interaction generator written for the Super-Kamiokande and T2K experiments.

A custom software package, ElecSim, is used to simulate the response of the detector and electronics to energy deposited by particles that have propagated through the detectors. This involves simulating the light emitted from the energy deposition, the transport of that light through the bar and down the WLS fibres, and the subsequent response of the MPPCs. For the TPCs, ElecSim simulates the electron drift and response of the micromegas detectors.

3.3. Super-Kamiokande

The far detector, Super-Kamiokande, is a water Cherenkov detector located 295 km west of the near detector suite, in the Kamioka mine inside Mt. Ikenoyama. The mine provides 1 km of rock (or 2.7 km equivalent of water), shielding the detector from cosmic ray muons below 1.3 TeV, significantly reducing background rates. The detector is filled with 50 kt of pure water (25 kt fiducial volume), and, like ND280, lies 2.5° off-axis. Figure 3.19 shows the detector within the mine.

Super-Kamiokande has been searching for proton decay and measuring solar and atmospheric neutrino oscillations since 1996, and has been a far detector for a long baseline

3.3. Super-Kamiokande

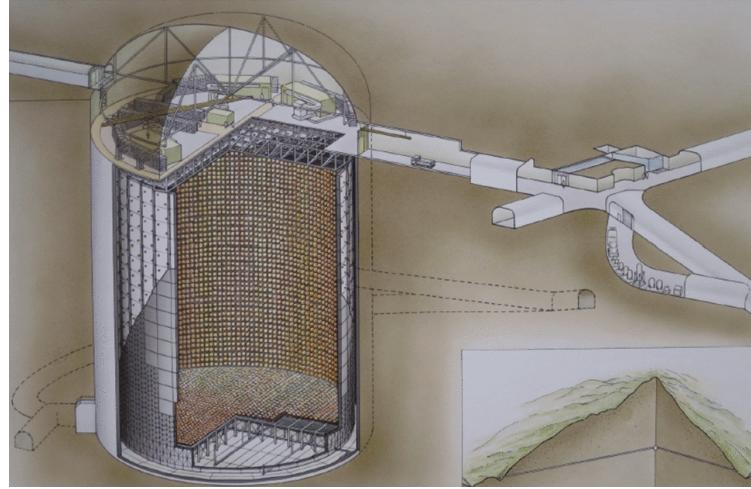


Figure 3.19.: The Super-Kamiokande detector within the Kamioka mine.

accelerator neutrino oscillation experiment since 1999, initially for K2K and now for T2K. Although it has undergone several updates during this period, the long running operation mean its behaviour is well understood. The atmospheric and cosmic ray muon data provide calibration samples completely separate from the T2K analysis, for which the simulated MC matches data to the percent level.

The detector is divided into the inner (ID) and outer (OD) detectors by a 55 cm cylindrical stainless steel and tyvek framework. The OD is 40.2 m in height with a radius of 35.8 m. It surrounds the ID with 2 m of water, serving as a shield from interactions in the surrounding rock. 1885 outward-facing 20 cm PMTs provide an active veto for cosmic ray muons with an efficiency of almost 100%, despite the fairly sparse PMT coverage. The beam timing window can be used to identify interactions in the OD from beam neutrinos.

The ID is 36.2 m in height with a radius of 33.8 m. It contains 11,129 inward-facing 50 cm PMTs, each with a combined quantum and collection efficiency of 20%, and a timing resolution of ~ 2 ns. The PMT coverage of the ID is 40%, which gives enough spatial resolution to sufficiently reconstruct the paths of particles produced in neutrino interactions inside the tank.

When charged particles travel through a medium of refractive index n at a velocity v_p larger than the speed of light in the medium, $v_\gamma = c/n$, Cherenkov radiation is emitted in a cone with opening angle $\theta_c = \arccos \frac{1}{n \cdot v/c}$, along the direction of the particle's path. In water, this is $\sim 42^\circ$. Neutrino interactions in the SK tank produce charged particles which, if above an energy threshold, can be detected by the emitted Cherenkov light. Photons from the cone form a ring shape on the walls of the tank, where they are detected by the PMTs.

3. The T2K Experiment

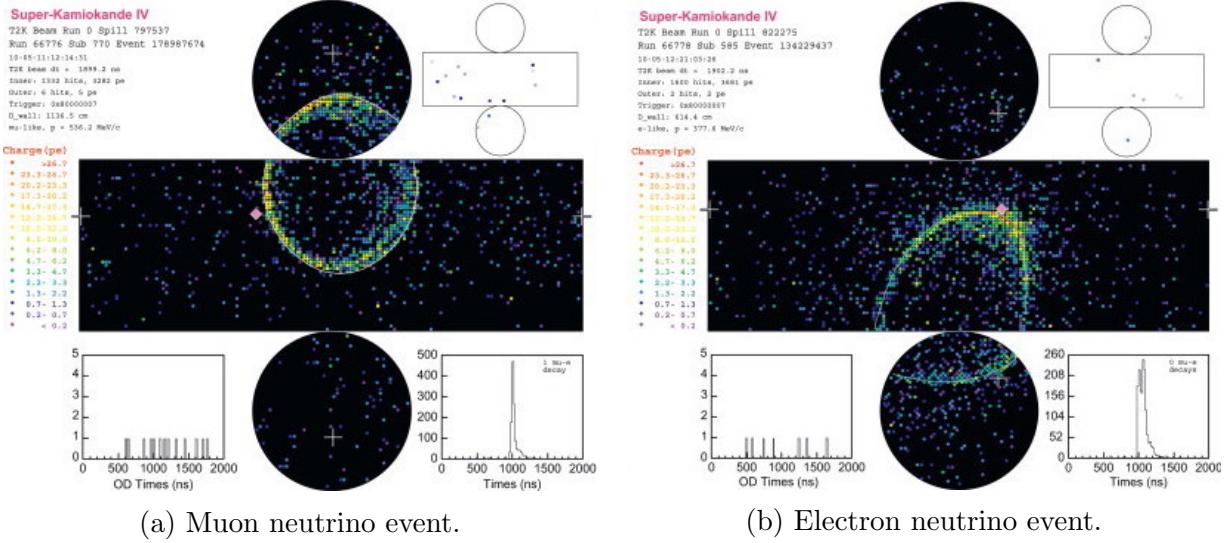


Figure 3.20.: SK ID event display, showing the Cherenkov ring PMT hits for an a) electron, and b) muon neutrino event.

This pattern, along with the hit timing, can be used to reconstruct the interaction vertex position, and the charge, momentum and direction of the produced particle.

CCQE interactions are the primary channels used to measure ν_μ disappearance and ν_e appearance at T2K. Discounting final state interactions, these events produce a charged lepton and a proton. The measured momentum and direction of the lepton can be used to reconstruct the neutrino energy, using Equation 2.30, but it is also vital for the lepton flavour to be determined, as this corresponds to the incoming neutrino flavour.

Discrimination between electrons and muons is achieved by separating Cherenkov rings by shape. As electrons are relatively light, they scatter off particles in the water and so travel a more convoluted path to the PMTs. At the T2K beam energies, they will also induce electromagnetic showers. Both of these phenomena cause the Cherenkov light to form a superposition of overlapping rings at the wall of the ID. This results in a fuzzy ring being seen in the PMTs.

Conversely muons, due to their relatively large mass, travel through the water without scattering, and so produce a sharp, clear Cherenkov ring. Examples of electron and muon Cherenkov rings detected at SK are shown in Figure 3.20.

An algorithm [83] is used to distinguish between fuzzy and sharp rings with high efficiency. The probability of a muon neutrino event being misidentified as an electron neutrino event is 0.7%. The number of different neutrino species events is used to calculate neutrino oscillation parameters in the full T2K oscillation analysis. However, as Super-Kamiokande does not

3.3. Super-Kamiokande

have a magnetic field, it is not able to differentiate between neutrino and anti-neutrino interactions. The neutrino and anti-neutrino content of the beam is therefore needed to be measured accurately at ND280. In this analysis, only data from ND280 is used, to constrain systematic uncertainties.

3.3.1. Far Detector Simulation

Neutrino interactions in the SK tank are modelled by the NEUT event generator. The simulation of produced particles through the detector is done using the GEANT-3 [84] based SKDETSIM software. Like in the beam production, hadronic interactions are simulated with the GCALOR package.

4. Statistical Treatment

The number of events measured at the far detector is a convolution of the cross-section, flux, detector efficiency, and probability of oscillation. As discussed in Section 2, neutrino interactions are rare and so the cross-section, flux, and detector models all compose of parameters with large uncertainties. The parameters of these models are degenerate with the oscillation parameters being calculated; a change in a single nuisance parameter mimics a change in oscillation parameter in terms of the effect on the kinematic distributions measured.

The aim of the near detector fit is to constrain the cross-section, flux, and detector systematics before oscillation, allowing more precise measurements of the oscillation parameters at SK. However, as there are several hundred nuisance parameters, fitting them all requires careful statistical treatment.

This analysis invokes a Bayesian approach, using the Markov Chain Monte-Carlo (MCMC) method to fit systematic parameters to data. This produces an N -dimensional posterior probability distribution, where N is the number of fit parameters. Post-fit central values and uncertainties are extracted from this distribution by marginalising over all other parameters, one by one. The near detector-only fit in this analysis is used to validate the model and fitting framework, before full joint near and far detector fits can be run.

This chapter describes the statistical treatment in the fit. The general approach to determining parameter values in Bayesian statistics is discussed in Section 4.1. Monte-Carlo methods are introduced in Section 4.2, and the theory behind MCMC is presented in Section 4.3. The methods used to estimate parameter values and assess the model’s ability to fit the data are outlined in Section 4.4.

4.1. Bayesian Inference and the T2K Likelihood

In Bayesian statistics, a hypothesis is tested by combining prior information with the likelihood of a dataset. The aim of all Bayesian analyses is to model the probability of both the data and model parameters, to produce a posterior probability distribution $P(\bar{\theta}|D)$, where

4. Statistical Treatment

$\bar{\theta}$ represents the model parameters, and D represents the data. From this, the post-fit parameter values and uncertainties can be extracted using the methods described in Section 4.4.1. The posterior probability distribution is related to the joint probability distribution, $P(D, \bar{\theta}) = P(D|\bar{\theta}) P(\bar{\theta})$, using Bayes' Theorem:

$$P(\bar{\theta}|D) = \frac{P(D|\bar{\theta})P(\bar{\theta})}{\int P(D|\bar{\theta})P(\bar{\theta})d\bar{\theta}}. \quad (4.1)$$

$P(D|\bar{\theta})$ is the probability of measuring the data D given the set of model parameter values $\bar{\theta}$. This is calculated by comparing the number of data events in each bin to the number of events in the Monte Carlo prediction using the given set of model parameters. The Poisson likelihood for a single bin is given by:

$$\mathcal{L}_{Bin} = \frac{\lambda(\bar{\theta})^n e^{-\lambda}}{n!}, \quad (4.2)$$

where n is the number of observed data events in the bin, and $\lambda(\bar{\theta})$ is the number of predicted MC events for model $\bar{\theta}$ in the bin. The total sample contribution to the log-likelihood is therefore given by:

$$-\log \mathcal{L}_{Sample} = \sum_{Bins} [\lambda(\bar{\theta}) - n + n \log \frac{n}{\lambda(\bar{\theta})}]. \quad (4.3)$$

This is then modified to include the MC statistical uncertainty, which accounts for the fact that there was not an infinite amount of MC generated. An additional penalty is added to the original sample likelihood, and a scaling factor, β , is applied to $\lambda(\bar{\theta})$:

$$-\log \mathcal{L}_{Sample} = \sum_{Bins} [\beta \lambda(\bar{\theta}) - n + n \log \frac{n}{\beta \lambda(\bar{\theta})} + \frac{(\beta - 1)^2}{2\sigma_\beta^2}]. \quad (4.4)$$

Fitting a new parameter, β , for each bin would introduce ~ 3000 new fit parameters, bringing the total number of parameters to an infeasibly high amount. Instead, it is assumed β follows a Gaussian distribution for each. By minimising $-\log \mathcal{L}$ with respect to β , β can be calculated analytically for each bin by solving:

$$\beta^2 + (\lambda \sigma_\beta^2 - 1)\beta - n \sigma_\beta^2 = 0, \quad (4.5)$$

where σ_β is the fractional uncertainty on the MC in a given bin. Equations 4.4 and 4.5 are derived in [85].

$P(\bar{\theta})$ contains the prior knowledge of the model parameters, which is driven by previous and external measurements. This is calculated as either a Gaussian or Flat uncertainty for

4.2. Monte Carlo Methods

each parameter, along with inter-parameter correlations:

$$-\log \mathcal{L}_{Systematic} = \sum_{Systematics} \frac{1}{2} [(X_i - \mu_i)(\mathbf{V})_{ij}^{-1}(X_j - \mu_j)], \quad (4.6)$$

where X_i is the value of parameter i with central value μ_i , and \mathbf{V} is the covariance matrix describing the relation between parameters i and j with \mathbf{V}_{ij} . In this analysis, the systematics are grouped by 3 covariance matrices from the beam flux, cross-section, and ND280 detector models.

The joint probability distribution is therefore given by:

$$P(D|\bar{\theta})P(\bar{\theta}) = \prod \mathcal{L}_{total} = \prod (\mathcal{L}_{Sample} \times \mathcal{L}_{Systematic}), \quad (4.7)$$

and so:

$$-\log \mathcal{L}_{Total} = \sum_{Bins} [\lambda(\bar{\theta}) - n + n \log \frac{n}{\lambda(\bar{\theta})}] + \sum_{Systematics} \frac{1}{2} [(X_i - \mu_i)(\mathbf{V})_{ij}^{-1}(X_j - \mu_j)]. \quad (4.8)$$

The integral in Equation 4.1 is often not analytically solvable in practice, and so Monte-Carlo methods are required to sample from the posterior to produce a distribution proportional to the posterior probability distribution up to a normalisation constant.

4.2. Monte Carlo Methods

Monte Carlo simulation can be used to estimate mathematical functions and mimic the operations of complex systems with random sampling and statistical modelling. They provide a solution to the problem of high dimensionality and un-analytically solvable integrals by sampling distributions with a random walk through a given parameter space. Properties of the distribution such as parameter values and integrals can then be approximated from properties of the samples. This is often a much easier process than directly evaluating an integral, and so these methods are used in many fields from climate science, to economics, to computational biology.

The simplest approach for performing an integral is to throw a random point in a region of known volume that encompasses the target region. The reliance on random numbers is where the name ‘MC methods’ emanates from, referring to the famous casino in Monaco. The fraction of throws within the target region is multiplied by the known volume, to get an

4. Statistical Treatment

approximation of the target volume. The results are not an exact solution, and are dependent on the random throws sufficiently sampling the distribution. From the law of large numbers, the accuracy of this approximation improves with the number of points thrown.

This method is powerful as the full shape of the distribution does not need to be known to perform the calculation, just whether a point is inside or outside the target region. Evaluating a function at a single point is far easier than computing a full integral. However, this simple method can be very inefficient and require a large amount of throws to converge on the solution. If the area is not well chosen, substantial computing time is wasted evaluating points outside the target region which never contribute to the integral. Slow convergence is one of the main drawbacks of MC methods. Several techniques, such as MCMC, have been developed to minimise the unnecessary computation by using a semi-random walk through the parameter space.

4.3. Markov Chain Monte Carlo

A Markov Chain is produced by any algorithm that generates a new point, x_i which only depends on the previous generated point, x_{i-1} . The process is truly Markovian if predictions about future steps in the chain can be made by only knowing the current state, just as well as by knowing the whole history of the chain.

If a Markov chain gradually ‘forgets’ its initial state as more steps are added, it is said to converge. This means the initial state converges to a unique stationary distribution, such that the distribution is independent of the step number. Once convergence has been reached, all ensuing steps are samples from the stationary distribution.

The aim of MCMC methods is to produce a Markov chain with the posterior distribution $P(\bar{\theta}|D)$ as its stationary distribution. The chain steps through N dimensional space, where N is the number of model parameters. A single point in the chain then represents a set of values, one for each parameter, and is defined by a vector \bar{x} .

This way, the choosing of points at which to evaluate the distribution is done much more efficiently than just random sampling. The individual steps have a density proportional to the target distribution as the Markov chain performs a semi-random walk through the parameter space, and so less time is wasted sampling areas of low probability. The stationary distribution is only an approximation to the desired posterior, but more closely matches it as more steps are added.

MCMC methods are dependent on producing a Markov chain that converges. To reach

convergence, it is necessary that 3 conditions are met:

- **Irreducibility:** From any initial state, there is non-zero probability of reaching any other state. This prevents the chain getting stuck in local minima.
- **Aperiodicity:** The chain must not be periodic. This means the chain never gets stuck in a loop between the same states.
- **Recurrence:** All subsequent steps sample from the same stationary distribution once it has been reached. This means once staionarity has been achieved, adding more steps gives a more accurate approximation to the target distribution.

Any Markov chain which satisfies each of these criteria is ergodic, and will eventually converge. The total number of steps needed for convergence however differs from chain to chain. The procedures for testing convergence are described in Section 4.3.3.

Once a Markov chain has been produced which has the posterior distribution $P(\bar{\theta}|D)$ as its stationary distribution, has met the three criteria, and has reached convergence, it can be used to estimate the model parameters $\bar{\theta}$. The main difficulty comes from constructing a chain with the correct stationary distribution. In this analysis, this is achieved using the Metropolis-Hastings Algorithm.

4.3.1. The Metropolis Hastings Algorithm

The Metropolis Hastings algorithm was first developed by N. Metropolis for symmetric proposal distributions in 1953 [86], and was generalised to the asymmetric case by W. K. Hastings in 1970 [87]. It can be used to construct a Markov Chain that satisfies the regularity conditions, and therefore has a stationary distribution. A semi-random walk is directed through the parameter space, such that steps are distributed according to the posterior probability distribution. The algorithm consists of the following method:

1. **Initialisation:** Each parameter is set to its initial value.
2. **Proposal:** A new value is proposed for every parameter, according to the proposal function described in Section 4.3.2.

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3. **Acceptance:** The MC is reweighted to the new set of parameters and the test statistic calculated. The acceptance probability, α , is given for the $(n + 1)^{th}$ step by:

$$\alpha = \min[1, \log\mathcal{L}_{n+1} - \log\mathcal{L}_n]. \quad (4.9)$$

A random number is thrown from a uniform distribution in the range [0,1]. If this is $\geq \alpha$ the step is accepted. Otherwise the step is rejected, and the parameters are set back to the previous values.

4. **Repeat:** Steps 2 to 3 are repeated N times.

Steps with an improved likelihood are therefore always accepted. Steps to points with a lower posterior probability are less likely to be accepted, but crucially don't have a non-zero acceptance probability to prevent the chain from getting stuck in local minima. In this way the algorithm builds a distribution of points in the parameter space, with more points in regions of higher posterior probability and fewer points in regions of lower posterior probability. If the parameter space has been sufficiently explored, the density of points in the final chain is therefore proportional to the posterior probability distribution.

4.3.2. Step Proposal

The Metropolis Hastings algorithm ensures that the Markov Chain will always have a stationary distribution regardless of the form of the proposal function. However, it does not ensure that the chain will converge to the stationary distribution quickly. As only steps after convergence are used to sample the posterior probability distribution, results are obtained more efficiently if convergence is reached sooner.

In this analysis the form of the proposal function is a multivariate Gaussian. The central values are the parameter values at the current step, and the widths are the prior uncertainties multiplied by a scaling factor. The value of the scaling factor can be varied for different parameters, and the values used are tuned with respect to the criteria discussed in Section 4.3.3.

Correlations in the prior uncertainties are included in the proposal function. If this were not the case, steps would be likely go into regions which had low prior probability by contravening the correlations. These steps would then be very likely to be rejected, and so convergence would not be reached efficiently. Including the correlations in the proposal function

encourages the algorithm to step into regions of higher posterior probability, increasing the likelihood of steps being accepted.

4.3.3. Chain Diagnostics

The number of steps to run in the Markov Chain is a predetermined value which can be varied. The choice is usually a trade-off of requiring a small number of steps to reduce the computational expense and obtain results in a reasonable time, while still ensuring the chain has converged and sufficiently sampled the parameter space.

The width of the Gaussian proposal functions, known as the step sizes, can be tuned to encourage faster convergence, and so reduce the total number of steps needed. This is again a trade-off; it is important to thoroughly sample all regions, while not stepping out of areas of high posterior probability too often. One index which can be used to test the tuning of the Markov Chain is the acceptance rate of proposed steps. 0.23 is recommended as the optimum acceptance rate [88], though this is for chains of lower dimension than those used in this analysis.

The acceptance rate alone, however, is not a good gauge of how well the step sizes are tuned. There are a number of other tools with which convergence is tested after a fit, alongside the acceptance rate. The autocorrelation for each parameter is the correlation between the parameter values at different steps. For points k steps apart in the chain, referred to as a lag of k , the autocorrelation, a , is given by:

$$a = \frac{\sum_{i=1}^{N-k} (X_i - \bar{X})(X_{i+k} - \bar{X})}{\sum_{i=1}^N (X_i - \bar{X})^2}, \quad (4.10)$$

where X_i is the parameter value for the i^{th} step, \bar{X} is the mean parameter value in the chain, and N is the total number of steps. The autocorrelation for a single flux parameter is shown in Figure 4.1 for a number of different step sizes. Increasing the step size causes the autocorrelation to reduce quicker, though this would decrease the acceptance rate. In general, in this analysis the aim was for the autocorrelation of each parameter to reach < 0.2 at a lag of 10,000.

The trace of the parameter is the plot of its value at each step in the chain. This is used to ensure good mixing is achieved, and so the parameter space is well explored. The trace of a low energy flux at parameter is shown in Figure 4.2 for different step sizes. This shows how decreasing the step size, affects how the chain samples different regions of the posterior distribution.

Finally, batched means are also used to test the chain has converged. These are the mean

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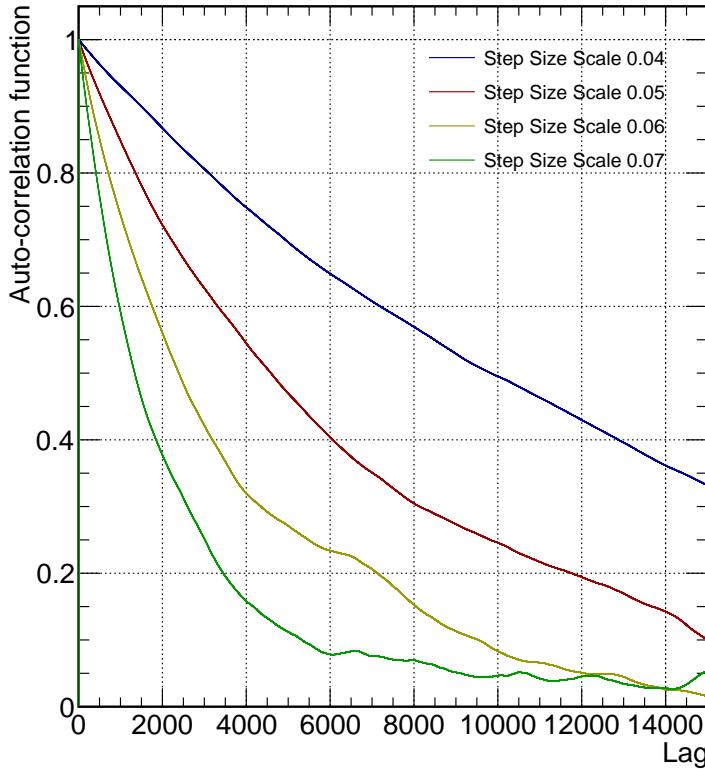


Figure 4.1.: The autocorrelation function for a low energy flux at parameter, at different values for the scaling applied to the step size.

of a given parameter over smaller consecutive subsets of steps. Once converged, these should be fairly constant, as shown in Figure 4.3 for a low energy flux parameter. In the second half of the chain, the batched means are within $\sim 2\%$. If the mean was varying drastically between batches, it would suggest stationarity had not been reached.

In this analysis, the general method used for step size tuning was to individually alter the width of the proposal function for each individual cross-section parameter until the autocorrelations were similar for all parameters. Then a further global scaling was applied to achieve the desired acceptance rate. Step size tuning, however, is not an exact science. When trying to reduce one parameter's autocorrelation, another parameter's could unexpectedly increase due to high dimensional correlations. One could always endeavour to further reduce autocorrelations, but once a reasonable set of tunings was found with good mixing, fairly consistent autocorrelations, and an acceptance rate close to the optimal value, no further time was spent trying to tune further.

Even with a well tuned Markov Chain, it is still desirable to run for as many steps as possible, to ensure good coverage. In this analysis, 6 chains of 800,000 steps were run in

4.3. Markov Chain Monte Carlo

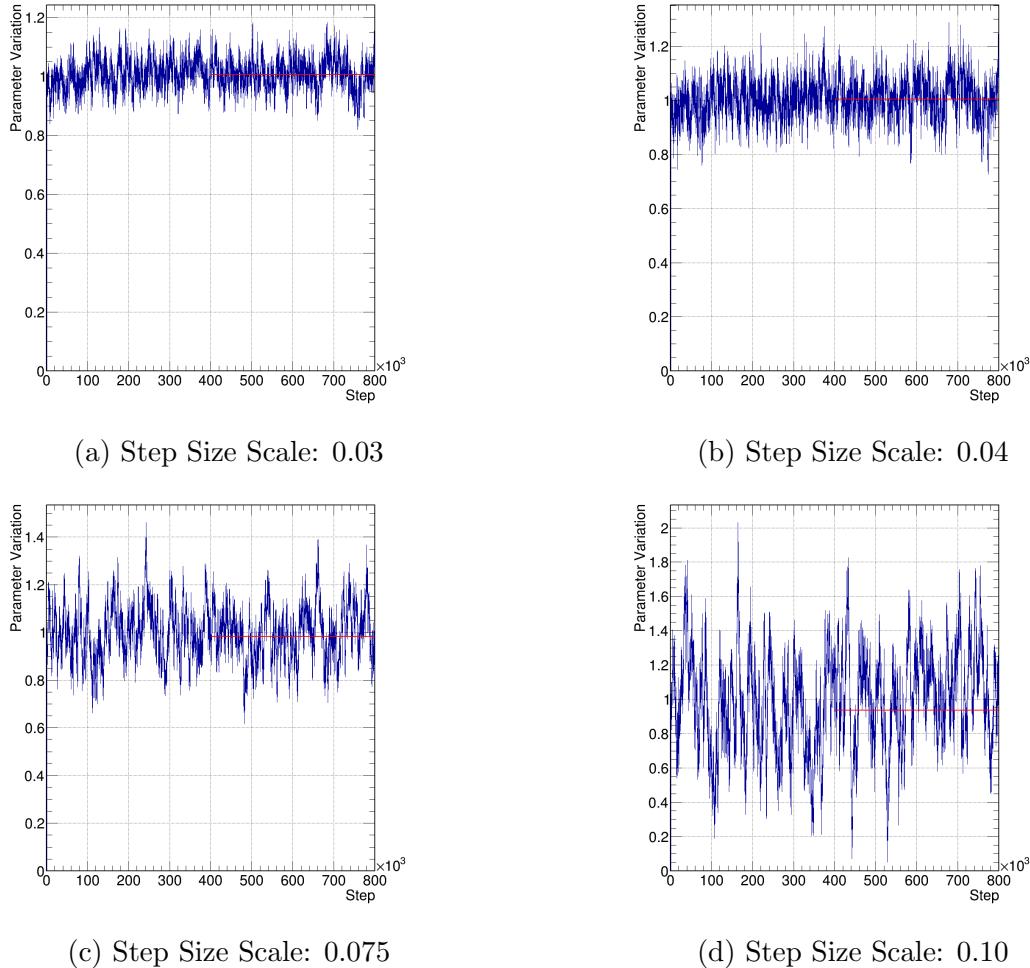


Figure 4.2.: The traces for a low energy flux parameter for different scalings of the step size. The red lines show the mean for the second half of the chain.

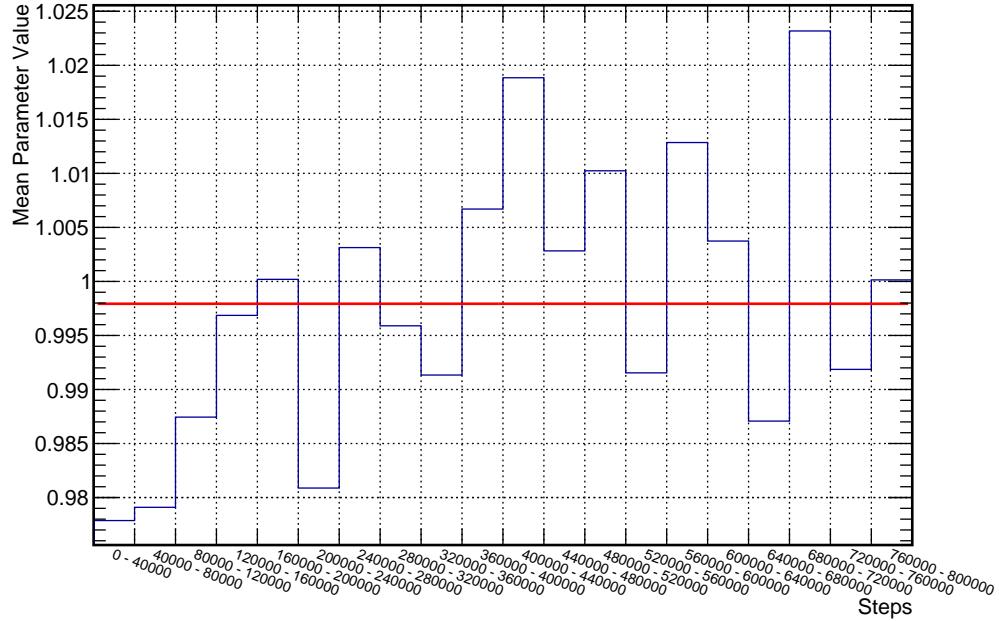


Figure 4.3.: The batched means for a low energy flux at parameter. The red line shows the total mean.

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parallel and then merged. However, not all steps are used in the final results. As the initial values of parameters in the chain are not necessarily in a region of high posterior probability, there is a ‘burn-in’ period before the chain reaches its stationary distribution.

The batched means and traces for individual parameters can be used to monitor the number of steps in the burn-in. Figure 4.3 shows the means initially being lower than the final converged values, while Figure 4.4 shows the parameter value starting higher than it’s final value, but quickly converging after 10,000 steps and then exploring the surrounding region.

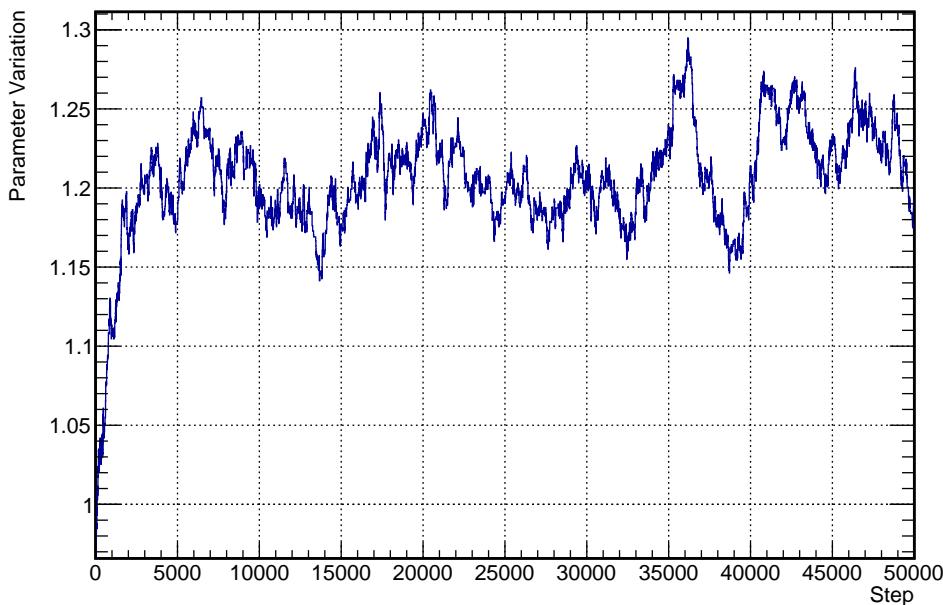


Figure 4.4.: The trace of the first 50,000 steps of high energy flux parameter, showing the initial burn-in phase before reaching the stationary distribution.

The trace of the systematic and sample contributions to the log-likelihood are also a good measure of when the burn-in period has finished. These are shown in Figure 4.5, for 6 merged chains each with 600,000 steps. The negative log-likelihoods converge once the stationary distribution has been reached after $\sim 20,000$ steps.

In general, a large amount of steps from the start of the chain should be rejected, to ensure convergence has been reached for all the steps used. In this analysis, the first 1/4 of steps of all chains are conservatively cut out as burn-in.

4.4. Postfit Treatment

In this analysis, the full ~ 700 dimensional posterior distribution is the final result which is propagated to the detector. However, interpreting the results for validations before joint

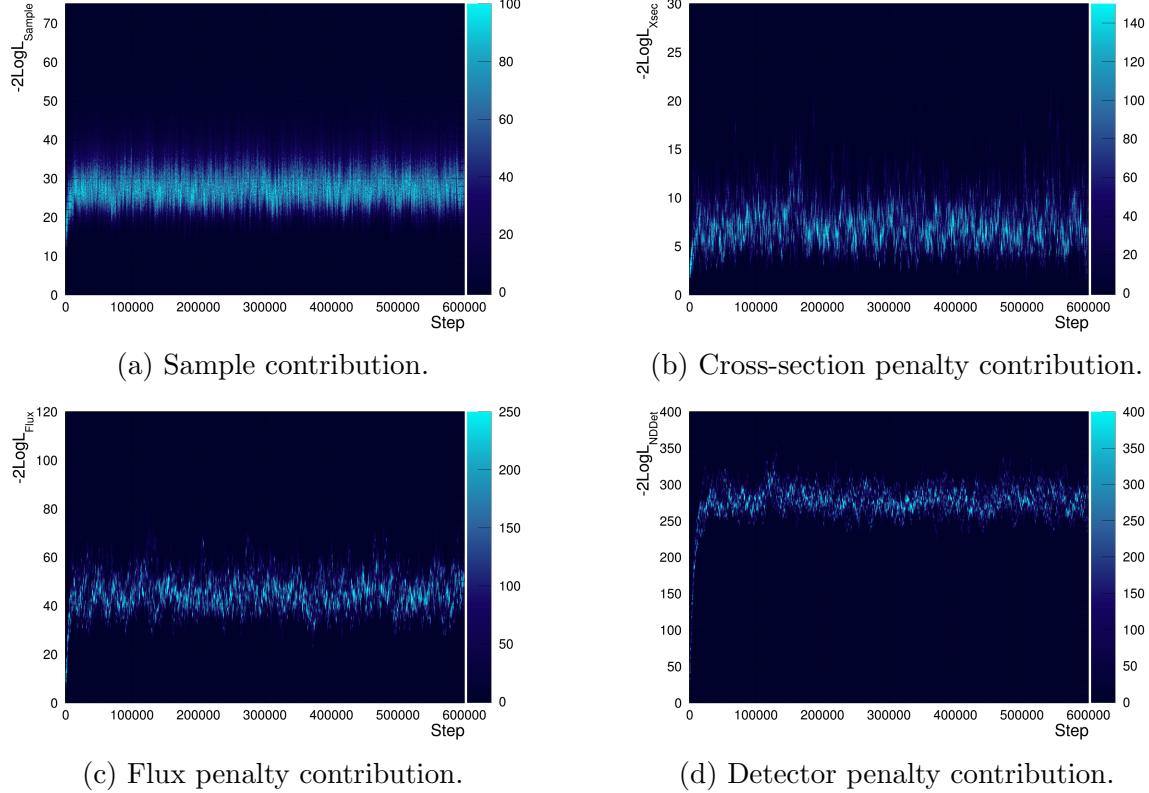


Figure 4.5.: Trace of the different contributions to the LLH for 6 merged chains each of 600,000 steps in total. The LLHs all converge within $\sim 20,000$ steps, though 150,000 are rejected as burn-in to ensure the stationary distribution has been reached.

fits is not feasible in this high a number of dimensions. Therefore information needs to be removed to be able to intuitively understand the results.

4.4.1. Parameter Value Extraction

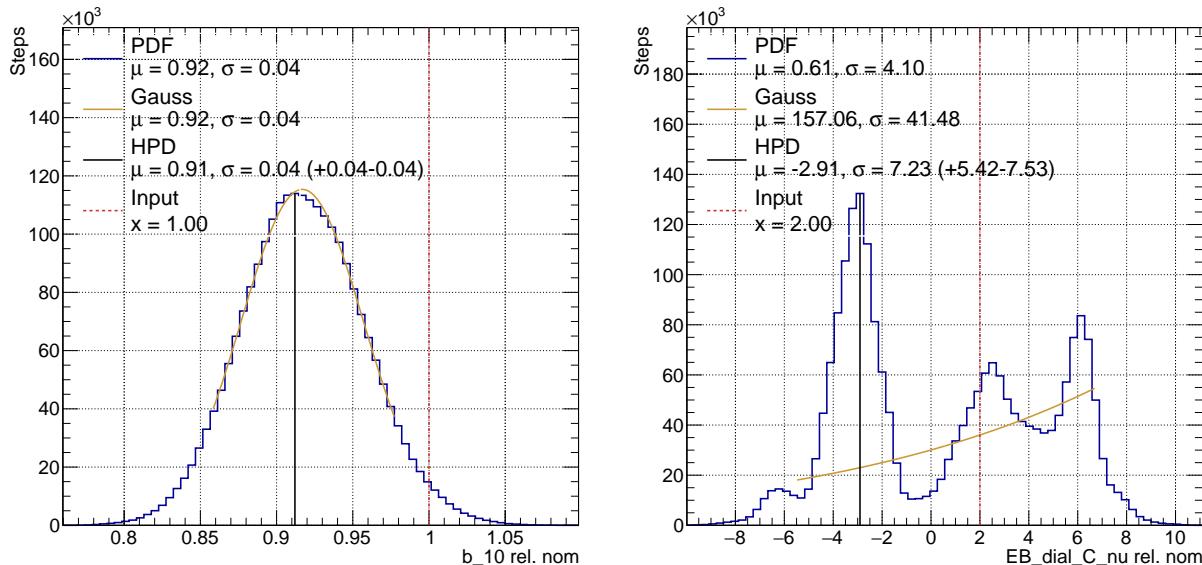
Interpreting individual parameter behaviour is achieved by marginalising over all parameters but one, one by one. This is equivalent to integrating the posterior distribution over all parameters but a single parameter of interest. For a parameter θ_i of model $\bar{\theta}$, the marginalised posterior given data, D , is given by:

$$P(\theta|D) = \int P(\bar{\theta}', \theta_i|D)d\bar{\theta}', \quad (4.11)$$

where $\bar{\theta}'$ is the parameter space over all model parameters but θ_i .

Figure 4.6 shows the resulting 1-dimensional projections for two individual fit parameters. This is equivalent to the parameter value at each step in the Markov Chain after burn-in. Central values and uncertainties for each parameter are extracted by three different methods.

4. Statistical Treatment



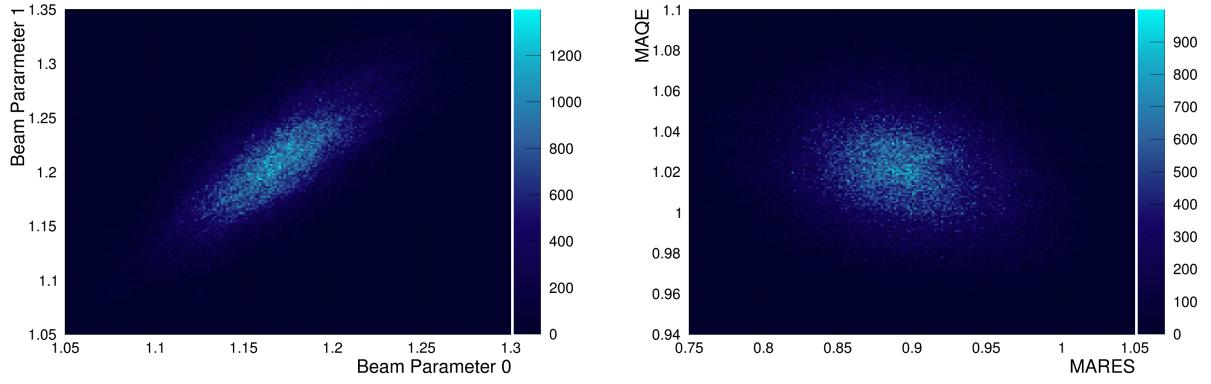
(a) A high energy FHC near detector beam parameter.
(b) The binding energy parameter for neutrino interactions on carbon.

Figure 4.6.: The 1-dimensional marginalised distribution for two fit parameters, showing the different methods of parameter extraction. The red lines show the prior central values, the gold lines show the fitted Gaussian distributions, and the black lines show the highest posterior density point.

Firstly, the arithmetic mean and RMS of the histogram are calculated and used as the postfit parameter value and error. Secondly, the highest posterior density, or mode, of the histogram is taken as the central value. The number of events in each bin is summed outwards from mode to obtain an asymmetric uncertainty. Finally, a Gaussian is fitted to the histogram and its mean and width are taken as the central value and uncertainty.

For a Gaussian distribution these three methods are equivalent, as shown in Figure 4.6a. However, non-Gaussian distributions and parameter correlations can lead to non-intuitive results when marginalised over, moving the region of high probability in the marginal posterior distribution. This is an expected, true effect, which does not indicate any bias in the fit. The three extracted values are compared to each other, with any differences highlighting non-Gaussian behaviour, as shown in Figure 4.6b. Non-Gaussianity is not necessarily concerning, but should be understood and considered when interpreting other parameter results.

None of the three extraction methods are incorrect, but none of them contain the whole true result either. Only the full ~ 700 dimensional distribution contains all the information of the final fit result. As this is what is propagated to SK, differences between the extracted 1D values is not an issue in itself.



(a) Two highly correlated beam parameters. (b) Two less correlated interaction parameters.

Figure 4.7.: The 2-dimensional marginalised distributions for two pairs of fit parameters.

The postfit values are also compared to those from the other T2K near detector fitting groups for validation. As the other group finds the single set of parameter values to minimise the test statistic, some differences are expected from marginalisation over non-Gaussian and correlated distributions. However, large discrepancies could indicate differences between the implementation of the fit in the two groups.

4.4.2. Postfit Covariance

A similar process is used to calculate the postfit covariance between parameters. All parameters are marginalised over but two, and this is repeated until each combination of two parameters have been projected onto. Figure 4.7 shows this for two pairs of parameters. This is equivalent to the values of each parameter at each step of the Markov Chain post burn-in. The covariance between the two parameters of interest is calculated from the arithmetic width of the distribution. This is the only method used to extract the covariance, as no shape is assumed for the 2-dimensional posterior.

Although reducing each of these 2-dimensional marginal posteriors to a single number removes information, the covariances are only used for comparisons with the other near detector fitting group and to highlight unexpected strong intra-parameter correlations. The full ~ 700 dimensional posterior distribution is all that is propagated to the far detector analysis.

4. Statistical Treatment

4.4.3. Posterior Predictions

Once the fit has finished, the results are used to produce the posterior predictive distributions with the final fitted parameters. However, as discussed in the previous sections, just marginalising over all but one parameter, one by one removes significant information from the full posterior. Although this is useful for intuitively interpreting the fit, removing information is not necessary for producing postfit event distributions. The method used in this analysis is as follows:

- Draw 20,000 post burn-in steps from the Markov Chain
- For each draw, reweight the MC to the set of parameter values for that step. For each fit bin in each sample, this gives 20,000 different number of events
- Fit a Gaussian to the distribution of number of events from all draws in each fit bin
- For each bin in each sample, the mean and width of the fitted Gaussian become the central value and uncertainty for the posterior prediction

In this way, a predictive distribution representative of the draws from the stationary distribution is produced. The comparison of this prediction to the data can be used to see if the model has enough freedom to closely reproduce the data through reweighting. Furthermore, plotting the LLH contribution from the posterior prediction to data for each bin in each sample highlights which regions are affecting the LLH calculation the most. It is desired that bins containing the most bins would be having the largest impact on the fit, and when this is not the case it should be fully understood why other regions are having unexpected significance. However, more involved methods are needed to truly test how well the model has been fit to the data.

4.4.4. Goodness of Fit

In this analysis, the distribution of fitted model parameters to data is found. However, this only determines how best to describe the data using the implemented model. If the model does not agree well with the data misleading results can be produced. It is therefore critical to be able to assess the goodness of fit for the final result.

As well as comparing the posterior predictive distributions to data, a p-value is calculated to see how well the model fits the data. This is done using the 20,000 draws used to produce the posterior predictions:

4.4. Postfit Treatment

- For each fit bin in each sample, the bin contents in the posterior prediction is fluctuated by drawing a random number from a Poisson distribution with a mean equal to the original bin content
- Calculate the LLH between the fluctuated prediction and the prediction
- For each draw:
 - Reweight the MC to the set of parameter values for that step
 - Calculate the LLH between the data and the draw
 - For each fit bin in each sample, the bin contents for the draw is fluctuated by drawing a random number from a Poisson distribution with a mean equal to the original bin content
 - Calculate the LLH between the fluctuated draw and the draw

The LLHs are calculated using Equation 4.3. The p-value is then calculated in two different ways:

$$p = \frac{N(-2LLH_{Data,Draw} < -2LLH_{DrawFluc,Draw})}{N_{Total}}, \quad (4.12)$$

and

$$p = \frac{N(-2LLH_{Data,Draw} < -2LLH_{PredFluc,Pred})}{N_{Total}}, \quad (4.13)$$

where $N(-2LLH_{Data,Draw} < -2LLH_{DrawFluc,Draw})$ is the number of draws for which the negative LLH is smaller for the data given the draw than for the fluctuation of the draw given the draw, $N(-2LLH_{Data,Draw} < -2LLH_{PredFluc,Pred})$ is the number of draws for which the negative LLH is smaller for the data given the draw than for the posterior prediction given the fluctuated posterior prediction, and N_{Total} is the total number of draws. Both methods give a measure of how likely we would be to have observed the data we did, or something more extreme, compared to random fluctuations of the model, if the fitted model describes nature.

The p-values can be calculated by plotting the 2-dimensional histograms of $-2LLH_{Data,Draw}$ vs $-2LLH_{DrawFluc,Draw}$ and $-2LLH_{Data,Draw}$ vs $-2LLH_{PredFluc,Pred}$ and calculating the proportion of steps below the line $y = x$. This is done for each sample individually, and as a total sum for all samples using the LLH contribution from every fit bin.

4. Statistical Treatment

Neither method of calculating the p-value is individually correct or incorrect, and neither should be interpreted as a binary measure of whether the model can or cannot describe the data. The p-values presented here should therefore not be taken as a single validation of the fit, but used along with final marginalised distribution to interpret the full results. Given that a significant amount of information has to be removed from the full ~ 700 dimensional posterior for it to be intuitively understood, using a measure of goodness of fit alongside the marginalised distributions is useful for extracting the full picture of the fit.

Generally a higher p-value is desirable and indicates a better fit to data, but there is no single threshold for which a higher p-value can be determined acceptable for all analyses¹. This should be determined before calculating the p-value, to avoid biasing the fit. In this analysis, it was decided a p-value greater than 0.05 for all samples would be an acceptable goodness of fit. *prolly want to use a less strong statement here given results*

¹Having a p-value greater than 0.05 and 0.1 are common choices to accept a fit.

5. The Near Detector Fit Setup

5.1. Motivation

When the number of neutrinos are measured at the far detector, it is a convolution of the beam flux, cross-section, detector efficiency, and the probability of oscillation:

$$N_{SK}^{\nu_\beta} = \phi_{SK}^{\nu_\alpha} \cdot \sigma^{\nu_\beta} \cdot \epsilon_{SK}^{\nu_\beta} \cdot P_{PMNS}(\nu_\alpha \rightarrow \nu_\beta), \quad (5.1)$$

where $N_{SK}^{\nu_\beta}$ is the number of neutrinos of flavour β , $\phi_{SK}^{\nu_\alpha}$ is the flux of neutrinos of flavour α at SK, σ^{ν_β} is the interaction cross-section for neutrinos of flavour β at SK, $\epsilon_{SK}^{\nu_\beta}$ is the detector efficiency of SK for neutrinos of flavour β , and $P_{PMNS}(\nu_\alpha \rightarrow \nu_\beta)$ is the probability that a neutrino produced as flavour α oscillates to flavour β before reaching SK.

There are degeneracies between the flux, cross-section, and detector efficiency models, and the PMNS parameters. A change in one of the nuisance parameters mimics the effect of a change in one of the parameters of interest. Therefore it is crucial to constrain the model parameters as much as possible. This is done using near detector data, where the number of neutrinos is measured before oscillation and so the nuisance parameters can be disentangled from the oscillation parameters. The near detector samples also have higher statistics than the SK statistics, and using them to constrain nuisance parameters decreases the uncertainty on the predicted event rate at SK from $X\%$ to $Y\%$. The constraint on systematic uncertainties at T2K comes almost entirely from the use of near detector data, as shown in Figure 5.1 by the postfit uncertainties of cross-section parameters from a near detector only fit, and joint near and far detector fit from the 2018 Oscillation Analysis. Figure 5.2, also from the 2018 Oscillation Analysis, shows the SK prediction with and without the near detector constraint. The uncertainty bands are much narrower when using near detector data in the prediction, further showing the significance of the near detector on the full fit. Without the near detector constraint, T2K would not be able to make the world leading oscillation measurements it does.

The parametrised models of the beam, cross-section, and near detector detector efficiencies

5. The Near Detector Fit Setup

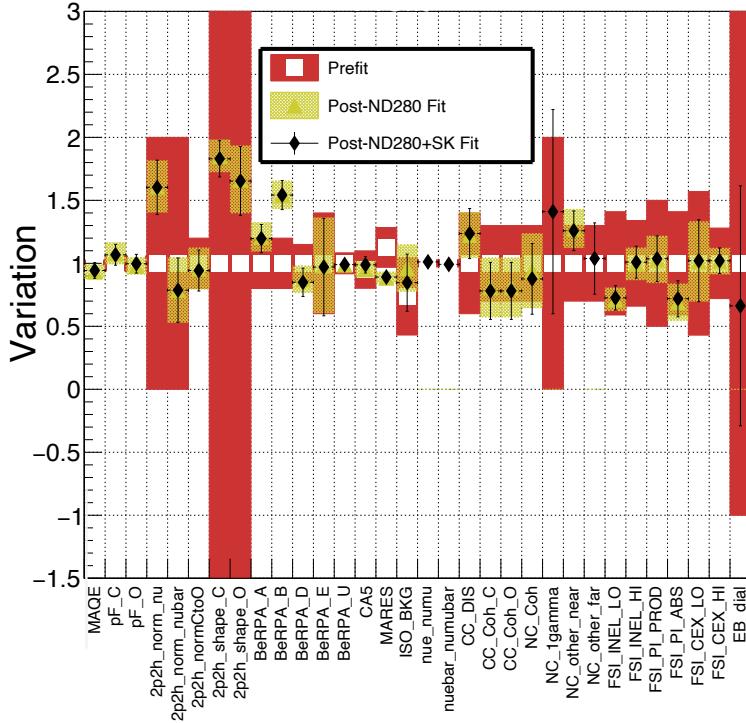


Figure 5.1.: The pre and postfit cross-section parameter uncertainties from a near detector only, and joint near and far detector fit for the 2018 Oscillation Analysis. The prior uncertainties are significantly reduced by the near detector only fit, but the inclusion of SK data does provide any further constraint.

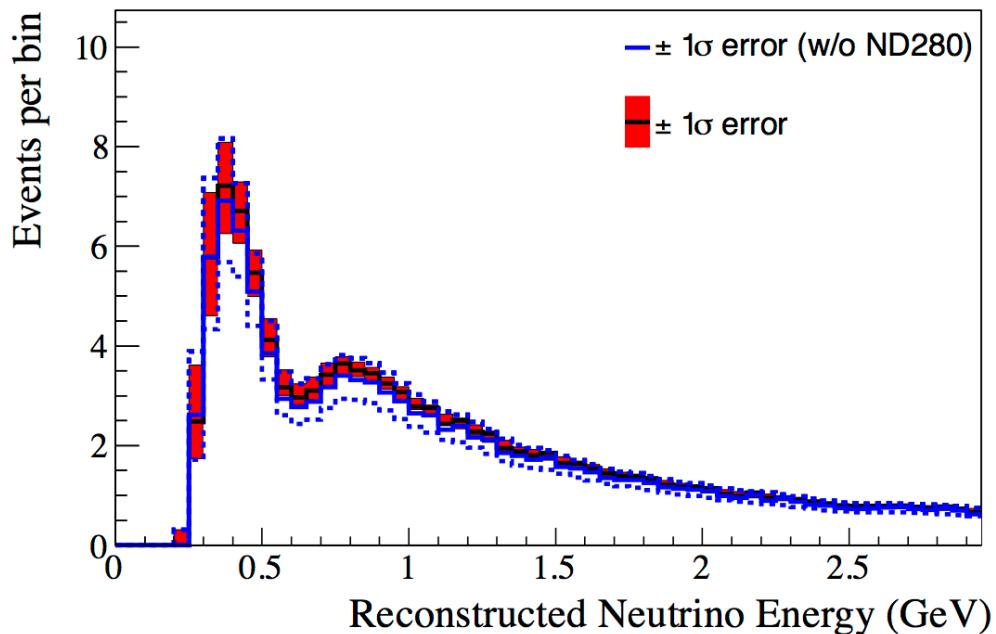


Figure 5.2.: The predicted event rate at SK, with and without the near detector fit constraint. Using near detector data to reduce systematics narrows the uncertainty on the prediction, allowing more precise oscillation measurements to be made.

used in the near detector fit are produced by different groups within T2K. The beam group uses data from beamline monitors and the on-axis INGRID to provide the beam flux model, the Systematics, Selections, and Validations (SSV) group provide a model of ND280 detector systematics, and the Neutrino Interactions Working Group (NIWG) provide the interaction model. For the full joint near and far detector fits, the T2K-SK group provides the SK detector model and selections. The parameters of these models affect the log likelihood in the fit through Equation 4.1.

MaCh3 is one of two groups that fit near detector data at T2K. The Beam And ND280 Flux extrapolation task Force (BANFF) also perform near detector fits, but use MINUIT to find the global minimum of the likelihood by gradient descent, in contrast to MaCh3’s use of MCMC to sample the probability distribution discussed in section 4.3. The BANFF postfit covariance is propagated to two of the three far detector fitting groups at T2K. This has the disadvantage of assuming that the systematics are not Gaussian. MaCh3, by doing joint near and far detector fits, does not assume any shape on the systematics. However, to validate the model and fitting framework, near detector only fits are ran to compare with the BANFF.

In this section, the various inputs to the fit are described. The selections and samples used are detailed in Section 5.2 and studies of how they are binned are presented in Section 5.3. The models providing systematic uncertainties are discussed in Section 5.4, before the data used is outlined in Section 5.6.

5.2. Selections

The ND280 selections include both neutrino and anti-neutrino, and FGD1 and FGD2 interactions. Data is then divided by the topology of events, as observed by the detector. The aim of the selections are to group events in such a way that the underlying interaction mode can be identified so that systematics can be applied correctly. They allow us to translate as accurately as possible between what we see in the detector, such as an event with no outgoing pion tracks, to the actual physics of the event, such as a CCQE neutrino interaction. The selection criteria is optimised to select CC-inclusive interactions which originate in FGD1 or FGD2, and contain one reconstructed muon track of negative charge crossing the following TPC.

Events occurring inside FGD1 and FGD2 are separated as they will undergo a different reconstruction procedure, and be affected by different systematics. This is because of the

5. The Near Detector Fit Setup

water layers interleaving the plastic scintillators inside of FGD2, which are not present in FGD1. There therefore can be events on oxygen inside FGD2 but not FGD1. This means having separate FGD2 selections can isolate the constraint on systematics affecting events on oxygen, which is important as the far detector is filled with water. As well as this, the geometry of events in the two FGDs is different. Events in FGD1 can leave forward-going tracks which pass through FGD2 and both TPC 2 and 3, whereas events in FGD2 can only leave forward-going tracks in TPC 3.

Events are separated by whether the beam was in FHC or RHC mode as neutrino and anti-neutrino events will be affected by different systematics. For RHC, there are separate selections for wrong sign neutrino events. This is not the case for FHC, as the anti-neutrino cross-section on matter is so much smaller than for neutrinos. As the far detector is not magnetised, it is important to constrain systematics affecting neutrino and anti-neutrino interactions differently at the near detector, and so the separation of these selections is required.

The separation of events by topology allows more accurate identification of the interaction mode. In this analysis, events are divided into three topological groups: CC 0π , CC 1π , and CC Other. In total there are therefore 18 near detector samples: 2 FGDs x 3 neutrino signs x 3 π multiplicities. These samples are binned in the momentum and angle of the final state lepton, as these kinematic variables can be measured with good resolution in ND280. The sample and bin are all the information for a single data event that is used to compare to the MC.

The initial reconstruction of events is performed using an algorithm that fits clusters of hits in each TPC, and then adds hits in the upstream FGD to form a TPC-FGD track. The algorithm is described in more detail in [89]. The specific criteria used to define each selection are detailed in the following section.

5.2.1. FHC ν_μ

The FHC ν_μ selections are designed to initially produce a sample of CC-inclusive interactions which occur in FGD1 or FGD2, and contain one reconstructed muon track of negative charge crossing the following TPC. It is also required that events pass quality cuts and that the highest momentum negative track (HMNT) is identified as a muon. The following cuts define the sample:

- **Data Quality:** The event must occur within bunch time windows of the neutrino beam, and belong to a spill which is entirely flagged as having good global ND280 data

5.2. Selections

quality. Two events occurring within the same spill but different bunches are treated as independent events to avoid pile-up.

- **Total Multiplicity:** There must be at least one reconstructed track crossing the TPC in the event.
- **Quality and Fiducial Volume:** There must be at least one track reconstructed inside the FGD1 or FGD2 fiducial volume, and there must be at least one track with segments within at least one FGD and at least one TPC. The fiducial volume of the FGDs are defined as:

$$|x| < 874.51 \text{ mm}; |y| < 929.51 \text{ mm}; 136.875 < z < 446.955 \text{ mm}, \quad (5.2)$$

for FGD1, and:

$$|x| < 874.51 \text{ mm}; |y| < 929.51 \text{ mm}; 1481.45 < z < 1807.05 \text{ mm}, \quad (5.3)$$

for FGD2. x and y cuts also reject events with a vertex within 5 bars of the edge of the FGD module, and cuts in z reject events in the first module of each FGD. Short tracks with fewer than 19 clusters are also rejected as the reconstruction in the TPC is less reliable.

- **Upstream Background Veto:** Reconstruction failures can cause a muon that started further upstream to produce a track starting in the fiducial volume of one of the FGDs. Events with the second highest momentum track starting at least 150 mm upstream of the muon candidate are rejected to exclude such events. As well as this, events in FGD2 are rejected if a secondary track starts in the fiducial volume of FGD1.
- **Broken Track:** Events can be misreconstructed such that a single muon candidate track originating in the fiducial volume of one of the FGDs is broken into two components, one track only in the FGD and one that starts in the last layers of the FGD and passes through the TPC. The second track is therefore identified as a muon candidate. To cut these events, events with the muon candidate starting within 425 mm of the upstream edge of the FGD are rejected if there is also at least one FGD only track.
- **Muon PID:** Events with the HMNT crossing a TPC, starting inside the fiducial volume of an FGD, and identified as a negative particle, are potential muon candidates. The particle identification (PID) is then determined using the dE/dx measured in the

5. The Near Detector Fit Setup

TPCs. The energy deposited in the TPC is compared to the amount that would be expected if the particle were a muon, electron, pion or proton, which are shown for positive particles in Figure 3.17. The likelihood for particle type i is calculated by:

$$L_i = \frac{e^{-Pull_i^2}}{\sum_l e^{Pull_l^2}}, \quad (5.4)$$

where $l = \mu, \pi, e, p$, and the $Pull$ is given by:

$$Pull_i = \frac{dE/dx_{measured} - dE/dx_{expected,i}}{\sigma(dE/dx_{measured} - dE/dx_{expected,i})}. \quad (5.5)$$

Electrons are rejecting by requiring:

$$\frac{L_\mu + L\pi}{1 - L_P} > 0.8, \quad (5.6)$$

for tracks with $p < 500$ MeV/c. Protons and pions are cut by requiring:

$$L_\mu > 0.05. \quad (5.7)$$

This CC-inclusive selection is then divided by π multiplicity, which depends on the identification of pions. This is done in the TPCs and FGDs:

- **Secondary Track:** A secondary track separate from the muon candidate must be present in the event.
- **Bunch Matching:** The secondary track must be in the same time bunch as the muon candidate track.
- **Track Start Matching:** The secondary track must originate from the fiducial volume of the same FGD as the muon candidate track.
- **TPC Matching:** If the secondary and muon candidate tracks start in FGD1, the secondary track must also enter TPC 2. If the secondary and muon candidate tracks start in FGD2, the secondary track must also enter TPC 3.
- **TPC Quality:** There must be at least 18 clusters in the TPC.
- **Pion PID:** The number of charged pions is determined by the number of secondary tracks with PID determined in the TPC corresponding to a pion. For positive tracks,

5.2. Selections

the pion, positron and proton hypotheses are tested. For negative tracks, only the pion and electron hypotheses are tested. The pulls for each hypothesis are calculated and protons are rejected by requiring:

$$\frac{L_\mu + L_\pi}{1 - L_P} > 0.8, \quad (5.8)$$

for tracks with $p < 500$ MeV/c. Muons are then rejected by requiring:

$$L_\pi > 0.3. \quad (5.9)$$

The number of neutral pions is determined from the presence of positrons and electrons produced in their decay.

There are two methods by which information from an FGD can be used to identify if a particle with momentum too low or angle too high to enter a TPC is a pion. However, this can only be done for charged pions as electrons and positrons are not reconstructed.

- **FGD Reconstruction:** Secondary tracks in the FGD that don't start in the fiducial volume of the same FGD as the HMNT or that aren't fully contained within the FGD are rejected. Tracks that pass this cut and are in the same time bunch as the muon candidate are considered as pion candidates. The deposited energy in the FGD is then used to discriminate charged pions from protons.
- **Michel Electron:** Lower momentum pions which don't produce a track in an FGD can be identified from the Michel electron produced from the muon produced in the pion decay. To be identified as the delayed signal from a Michel electron, the hit cluster must have at least 7 hits in FGD1 or 6 hits in FGD2, and be outside the beam bunch window¹.

The number of pions identified by the TPC PID, Michel electron tagging, and FGD PID is then used to split the CC-inclusive selection into CC0 π , CC1 π and CCOther:

- **CC 0 π :** Contains events with no identified charged pions, electrons or positrons using TPC PID, no Michel electrons or charged pions in either FGD, and one negative muon candidate.

¹The muon has a 2.19 μ s decay time, causing the delay in the Michel electron signal

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- **CC 1 π :** Contains events where the sum of the number of positive pions identified in a TPC and the number of Michel electrons is one. For events with no Michel electrons the sum of positive pions in any TPC or FGD is one. Events with a negative pion, electron, or positron reconstructed in a TPC are rejected. It is also required there is one negative muon candidate.
- **CC Other:** Contains all events in the CC-inclusive selection that do not fall into the CC 0 π or CC 1 π sample. These are events with one negative muon candidate and either one or more reconstructed negative pions, one or more neutral pions reconstructed as electrons or positrons, or more than one positive pion reconstructed using TPC and FGD information.

5.2.2. RHC $\bar{\nu}_\mu$

The RHC $\bar{\nu}_\mu$ selections are designed to initially produce a sample of CC-inclusive interactions which occur in FGD1 or FGD2, similarly as for the FHC ν_μ . However, events must contain one reconstructed muon track of positive charge crossing the following TPC. The selection criteria are similar as those for the FHC ν_μ samples, but have extra cuts to account for the larger wrong sign background due to neutrinos having a larger cross-section on matter than anti-neutrinos:

- **HMT:** The background of ν events producing a π^+ misidentified as a μ^+ are reduced by requiring that the highest momentum positive track (HMPT) is the highest momentum track (HMT) in the event.
- **Upstream Background Veto:** This cut is more stringent for the RHC $\bar{\nu}_\mu$ samples. Events with tracks entering the fiducial volume of FGD1 from the upstream edge or coming from the P0D or magnet are rejected.
- **Muon PID:** PID is performed using the energy deposited in the TPC and calculating the likelihood for different particle hypotheses, in the same way as for FHC ν_μ samples. However, there are different requirements on the likelihoods for a positive muon candidate to be confirmed. Protons are rejected by requiring:

$$\frac{L_\mu + L_\pi}{1 - L_P} > 0.9, \quad (5.10)$$

for tracks with $p < 500$ MeV/c. Muons are then rejected by requiring:

$$L_\pi > 0.1. \quad (5.11)$$

The pion identification is performed in the same way as for FHC ν_μ , and the CC-inclusive sample is again split into CC0 π , CC1 π and CCOther.

5.2.3. RHC ν_μ

In RHC mode, there are still a significant amount of ν events due to the larger ν cross-section, and so a selection of these events is made. The same cuts as for the FHC ν_μ and RHC $\bar{\nu}_\mu$ are applied, but with the following exceptions:

- **HMT:** It is required that the HMNT in the event is the HMT.
- **Upstream Background Veto:** As for the RHC $\bar{\nu}_\mu$ samples, events with tracks entering the fiducial volume of FGD1 from the upstream edge or coming from the P0D or magnet are rejected.
- **Muon PID:** PID is performed in the same way as for the previous samples, using the energy deposited in the TPC and calculating likelihood for different particle hypotheses. However, there are different requirements on the likelihoods for a negative muon candidate to be confirmed. Protons are rejected by requiring:

$$\frac{L_\mu + L_\pi}{1 - L_P} > 0.7, \quad (5.12)$$

for tracks with $p < 500$ MeV/c. Muons are then rejected by requiring:

$$L_\pi > 0.1. \quad (5.13)$$

5.2.4. Updating to RHC Multi π Samples

In previous analyses, the RHC CC-inclusive samples were divided by track, rather than π multiplicity, into CC 1Track and CC NTracks. Before the 2020 analysis, there were much fewer RHC data events than FHC, and so the RHC samples could not be divided into so many sub-samples. In moving to RHC multi- π , the FHC selection criteria was unchanged, and the RHC selections only changed in the likelihood cuts for rejecting the muon hypothesis in pion identification:

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$$0.1 < L_\pi < 0.7. \quad (5.14)$$

The upper bound was designed to reject low momentum μ^+ in RHC events.

The RHC sample splitting proceeded by selecting events with one positive muon and no charged or neutral pions in the CC 1Track sample, and selecting all other CC-inclusive events in the CC NTracks sample. Validations of the updating of the fitting framework to accommodate the RHC multi- π samples are presented in Appendix C.

5.3. Binning

ND280 events are binned in the reconstructed momentum and angle of the outgoing lepton. The choice of binning is a trade-off of having coarse enough bins to have enough events in each to reduce the statistical error, while being fine enough to have good resolution in the peak regions. In general, the aim is to have > 20 raw MC events in every bin, which is approximately equivalent to having $\sim 1\text{-}2$ data events. Achieving this using uniform rectangular binning can result in bins outside the region of interest containing the largest amount of events, and contributing the most to the sample log-likelihood. Figure 5.3 shows this effect in the FHC sample binnings used for the 2017 Oscillation Analysis, and an intermediate uniform rectangular binning for the RHC samples. These plots only show up to 5000 GeV for FHC, and 1000 GeV for RHC, to show the peak regions more clearly. The full binning used here is the same for FGD1 and FGD2, and is as follows:

- **FHC ν_μ CC0 π :**

p (MeV/c): 0, 200, 300, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900, 950, 1000, 1050, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800, 2000, 2500, 3000, 5000, 30000.

cos θ : -1, 0.5, 0.6, 0.7, 0.76, 0.78, 0.8, 0.83, 0.85, 0.88, 0.89, 0.9, 0.91, 0.92, 0.925, 0.93, 0.935, 0.94, 0.945, 0.95, 0.955, 0.96, 0.965, 0.97, 0.975, 0.98, 0.985, 0.99, 0.995, 1.

- **FHC ν_μ CC1 π :**

p (MeV/c): 0, 300, 350, 400, 500, 600, 650, 700, 750, 800, 900, 1000, 1100, 1200, 1500, 2000, 3000, 5000, 30000.

cos θ : -1, 0.6, 0.7, 0.8, 0.85, 0.88, 0.9, 0.92, 0.93, 0.94, 0.95, 0.96, 0.97, 0.98, 0.99, 0.995, 1.

- **FHC ν_μ CCOther:**

p (MeV/c): 0, 300, 400, 500, 600, 650, 700, 750, 800, 900, 1000, 1100, 1250, 1500, 1750, 2000, 3000, 5000, 30000.

$\cos \theta$: -1, 0.6, 0.7, 0.76, 0.8, 0.85, 0.88, 0.89, 0.9, 0.91, 0.92, 0.93, 0.94, 0.95, 0.96, 0.97, 0.98, 0.99, 0.995, 1.

- **RHC $\bar{\nu}_\mu$ CC0 π :**

p (MeV/c): 0, 300, 400, 500, 550, 600, 650, 700, 750, 800, 900, 1000, 1100, 1200, 1500, 2000, 4000, 30000.

$\cos \theta$: -1, 0.6, 0.7, 0.8, 0.85, 0.9, 0.92, 0.93, 0.94, 0.95, 0.96, 0.965, 0.97, 0.975, 0.98, 0.985, 0.99, 0.995, 1.

- **RHC $\bar{\nu}_\mu$ CC1 π :**

p (MeV/c): 0, 500, 700, 900, 1300, 2500, 30000.

$\cos \theta$: -1, 0.7, 0.8, 0.9, 0.94, 0.96, 0.98, 0.99, 1.

- **RHC $\bar{\nu}_\mu$ CCOther:** **p (MeV/c):** 0, 600, 800, 1000, 1250, 1500, 2000, 4000, 30000.

$\cos \theta$: -1, 0.7, 0.8, 0.85, 0.9, 0.93, 0.95, 0.97, 0.98, 0.99, 1.

- **RHC ν_μ CC0 π :**

p (MeV/c): 0, 300, 500, 700, 800, 900, 1250, 1500, 2000, 4000, 30000.

$\cos \theta$: -1, 0.7, 0.8, 0.85, 0.88, 0.9, 0.92, 0.94, 0.96, 0.97, 0.98, 0.99, 1.

- **RHC ν_μ CC1 π :**

p (MeV/c): 0, 600, 800, 1500, 30000.

$\cos \theta$: -1, 0.7, 0.8, 0.86, 0.9, 0.94, 0.96, 0.97, 0.98, 0.99, 1.

- **RHC ν_μ CCOther:**

p (MeV/c): 0, 600, 1000, 1250, 2000, 4000, 30000.

$\cos \theta$: -1, 0.7, 0.8, 0.86, 0.9, 0.93, 0.95, 0.97, 0.99, 1.

For example, in the FGD1 CC0 π sample, the bins at low angle, (< 0.6), and low momentum, (~ 500 MeV), the bins span a large angle range (-1.0 - 0.6). Having such large bins causes them to contain a large amount of events. However, if they were divided to only span a smaller range of angles, the bins at the same angle but higher momentum would also be divided. As these regions are much more sparsely populated, splitting them further would result in there being insufficient number of events in those bins. The same is true for the high angle bins at higher momentum. These bins cover a large momentum range and are well populated; there are a relatively large amount of events with high momentum forward-going

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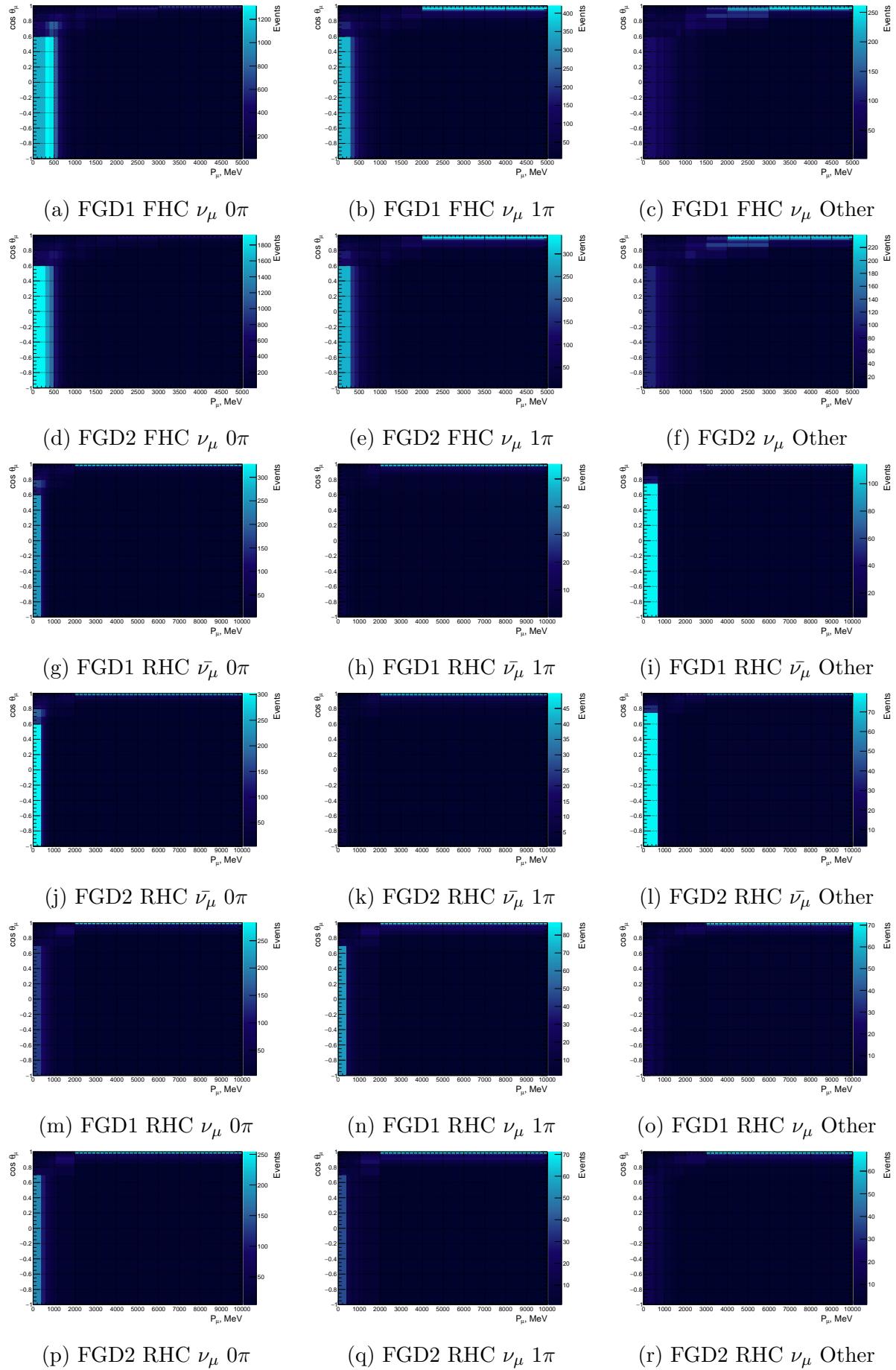


Figure 5.3.: Uniform rectangular binning of MC events for T2K runs 2-8.

muons. Splitting these bins though would mean the backward-going bins at the same high momentum would not be large enough and so would be too sparsely populated. This effect becomes more significant with the addition of more data.

5.3.1. Non-Uniform Rectangular Binning Studies

For the 2020 analysis, the MaCh3 near detector framework was updated to be able to use non-uniform rectangular binning². This means the bins can now be any arbitrary shape, including the original uniform rectangular binning which can still be used for validations of the changes to the fitting framework, and cross group checks with the other near detector fitter which did not move to non-uniform rectangular binning.

The following algorithm was used to define a non-uniform but still rectangular binning for each sample, without having to have the same binning for FGD1 and FGD2:

- The bin edges on the $\cos \theta$ axis are hard coded and constant, guided by the previous binning. This keeps the bins rectangular.
- For each $\cos \theta$ row, scroll across from 30 GeV down 0 GeV in 100 MeV steps.
- Once 50 unscaled MC events are reached, start a new bin
- If the last bin a row (the lowest momentum bin) has < 20 unscaled MC events, merge with the previous bin. Scroll through this merged bin in 5 MeV steps and split once half the events in the bin are reached.

The aim of this process was to produce as uniform a distribution of events in each bin as possible. This was not always possible, as regions of high density would require bins so small that they go below the resolution of the detector. The hard coded θ bin edges and momentum step sizes of 100 MeV were driven by this minimum bin size limit. The resolutions are calculated by plotting the reconstructed vs true kinematic variables, as shown in Figure 5.4, and taking the RMS at different slices of the 2D Gaussian. These RMSs, shown in Figures 5.5, give a gauge of the detector resolution, and so the minimum bin width for each variable in different regions.

For momentum, the RMS is fairly constant at approximately 100 MeV, for a momentum > 1000 MeV. It then reduces linearly between 1000 and 400 MeV, before levelling off at approximately 60 MeV below 300 MeV. Similarly, for the angle, the RMS is constant at approximately 0.08 below 0.96. It then reduces linearly up to a $\cos \theta$ of 1.0. However, given there would be a large uncertainty on the gradient for each variable's RMS, rather than

²Mechanically, this meant using ROOT [90] TH2Poly objects instead of TH2Ds.

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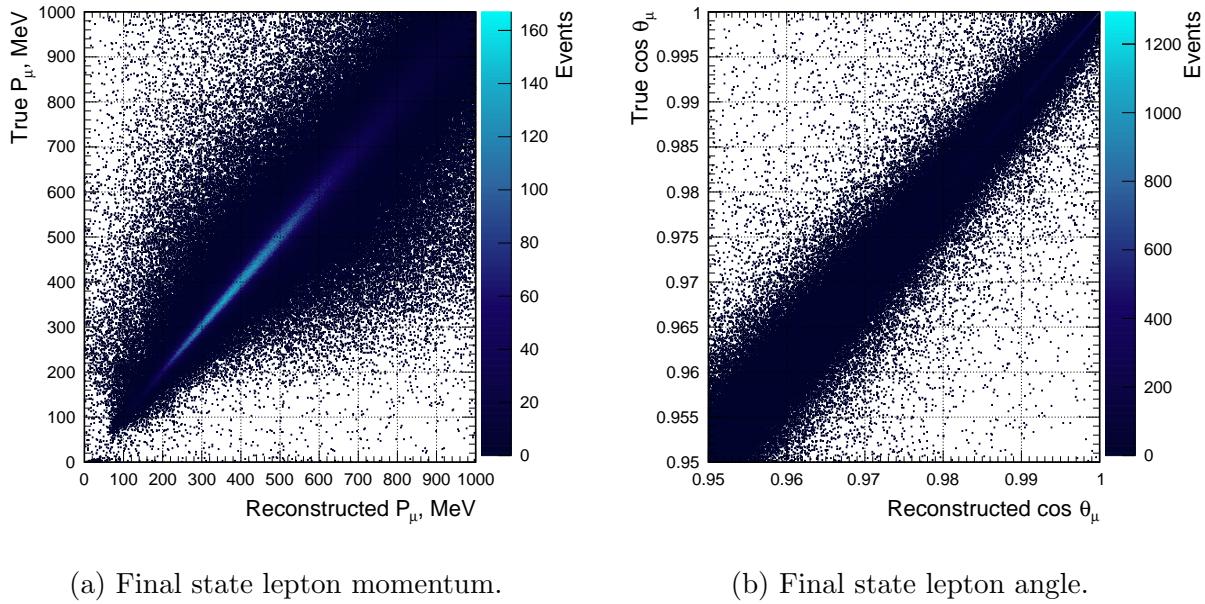


Figure 5.4.: True vs reconstructed lepton kinematic variables of CC-inclusive MC events from T2K runs 2-8.

varying the minimum bin size to trace out the change in RMS as closely as possible, it was safer to have a constant minimum size for all regions. This was chosen to be $0.01 \cos \theta$ in angle, and 100 MeV in momentum to be sure they are above the resolution in all regions.

The distribution of events binned by the scheme produced using the algorithm are shown in Figure 5.6. Full templates of the binning for each sample are shown in Appendix A, as it is not feasible to express the bin edges in text for non-uniform binning. Particularly for the FHC ν_μ and RHC $\bar{\nu}_\mu$ CC0 π samples, the bins containing the largest amount of events are in the peak regions at high angle and ~ 500 MeV. However, what is of more importance is the significant reduction in ranges of the z axis scales compared to the uniform binning. For example, the non-uniform binning for the RHC $\bar{\nu}_\mu$ CC0 π samples may not look like the most aesthetic representation of distributions, but the bin with the most events contains less than double the amount of the bin with the least. For the uniform binning, the bin with the most events contains ~ 250 times more than the amount in the bin with the least events. This prevents bins outside the peak contributing more to the LLH than the region of interest.

Using non-uniform binning significantly improves the sensitivity of the fit to changes in parameter values. This is evident in the Log-likelihood scans shown in Figure 5.7 for two selected interaction and flux parameters. A single parameter is set to different values while all others are kept at nominal, and the sample contribution to the LLH between the reweighted

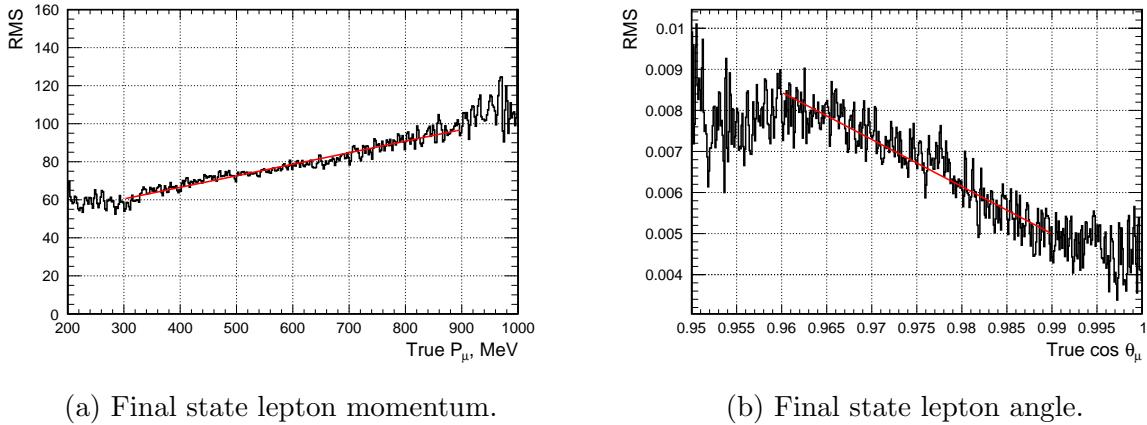


Figure 5.5.: The RMS of the true vs reconstructed lepton kinematic variables for CC-inclusive MC events from T2K runs 2-8, at different values of the true variables.

MC and nominal MC is calculated for each parameter value. The LLH scan process, and the parameters themselves, are described in more detail in Section 6.2 and Section 5.4 respectively.

The narrower likelihood distributions show that by using the non-uniform binning, moving a parameter further away from the nominal value will be less favoured than by using uniform binning. The ratio panel shows that the improvement is fairly constant across the range of the scan.

Further studies could be undergone to develop a non-rectangular fit binning. For instance, given the underlying distribution of events, using bins of constant Q^2 in the $p - \theta$ space may allow a better representation of events. However, given that the bin sizes are already close to the resolution of the detector, and that several iterations of non-uniform rectangular binning showed diminishing returns on improvements in sensitivity, this was not investigated for this analysis.

5.4. Systematics

The purpose of the near detector fit is to constrain systematic uncertainties so that accurate oscillation measurements can be made at the far detector. It is therefore vital that these systematics are understood.

In the near detector analysis, there are three sources of systematic uncertainties:

- **Interaction:** Systematics from uncertainties on neutrino interaction cross-sections.

5. The Near Detector Fit Setup

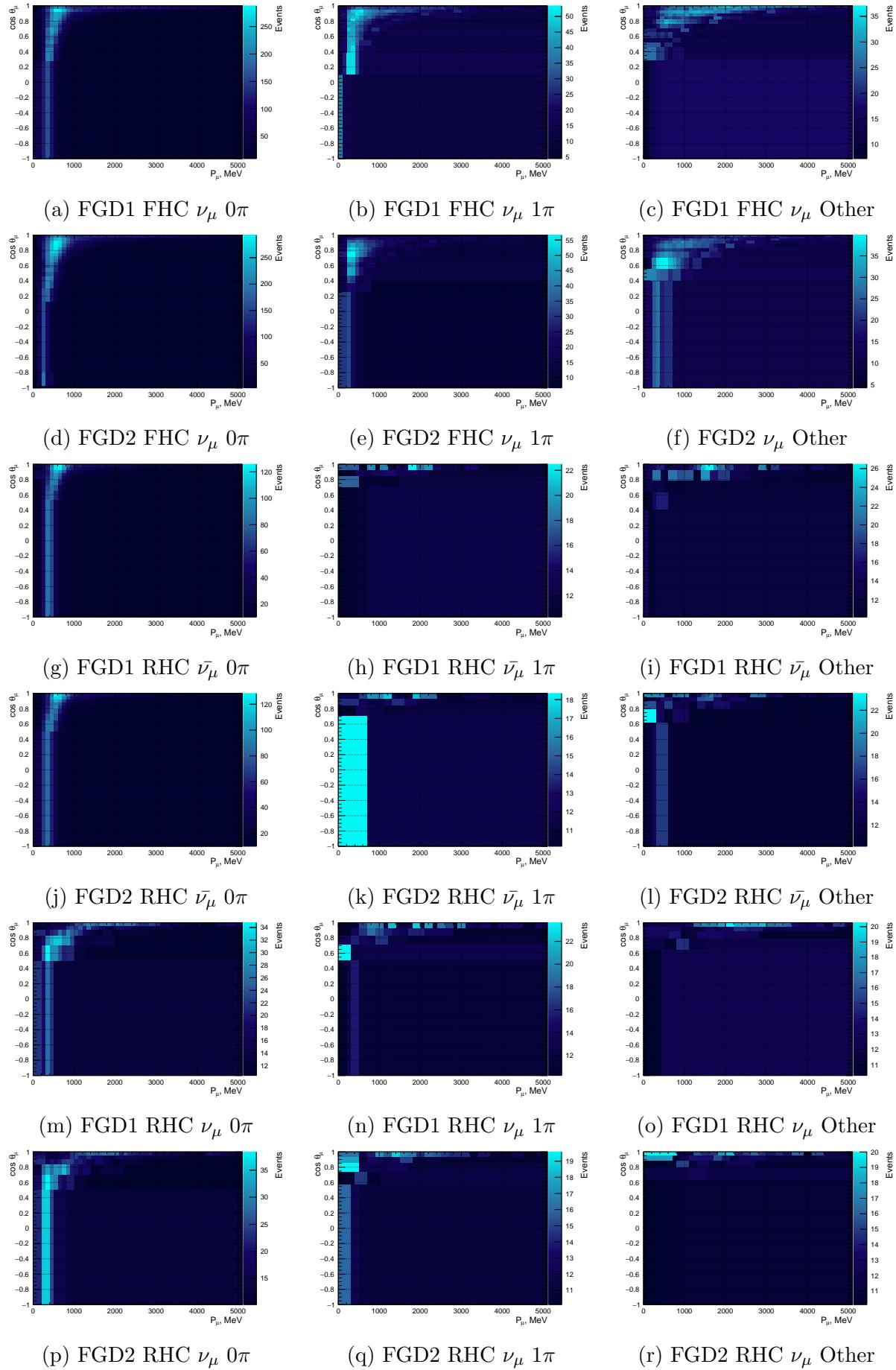


Figure 5.6.: Non-uniform rectangular binning of MC events for T2K runs 2-8.

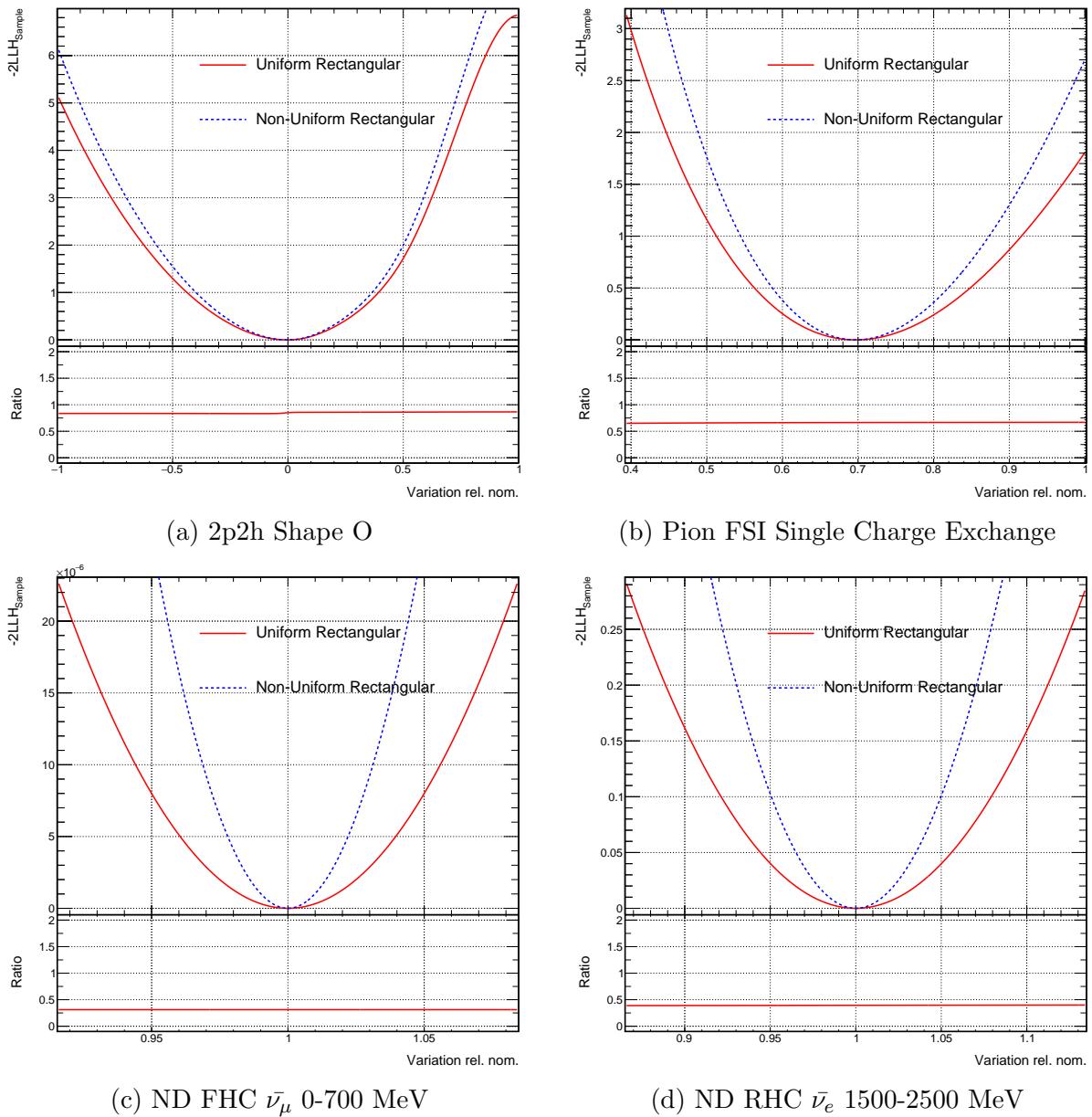


Figure 5.7.: Comparison of LLH scans using uniform and non-uniform rectangular fit binning, for two selected interaction and beam parameters.

- **Flux:** Systematics from uncertainties on the neutrino beam flux.
 - **Detector:** Systematics from uncertainties on the ND280 detector response and reconstruction.

The models of these three groups of systematics are parametrised, and each enter the fit through a covariance matrix. As a parameter is pulled from it's prior value, a penalty is added to the likelihood as shown in Equation 4.1. For systematics that are known to be constrained from external data, the likelihood penalty takes the form of a Gaussian. If there is no, or conflicting, data about a systematic, the likelihood penalty is just a constant. This

5. The Near Detector Fit Setup

is referred to as a ‘flat’ prior uncertainty.

5.4.1. Interaction

The MC prediction is produced using the NEUT 5.4.0 generator [82], as discussed in Section 3.2.3. The model for each interaction mode is therefore based on the models implemented in NEUT, with several modifications to tune to external data and additional theoretical calculations.

The uncertainties of these models are parametrised as shape or normalisation uncertainties, and applied to the interaction modes they correspond to on an event by event basis. For normalisation parameters, the weight applied to the event is just the value of the parameter. However, for shape parameters, the weight applied at different values of the parameter depends on kinematic variables of the event. Splined response functions are produced by evaluating the change in weight for an event at evenly spaced values of the parameter, and interpolating between them. The number of points varies by parameter but is always ≤ 10 . The spline is then evaluated at the parameter value at a given step in the fit, and the resulting weight applied to the event.

The parametrisation for each interaction mode proceeds using the following models:

- **CC Quasi-Elastic:**

The nominal MC is generated using a Spectral Function (SF) nuclear model from [91]. There is one splined parameter, M_A^{QE} , for the axial mass in the dipole form factor. Its prior is informed by bubble chamber data [5]. 8 normalisation parameters are applied, for different bins in Q^2 . The lowest 5 have width 0.05 GeV^2 , from 0.00 GeV^2 up to 0.25 GeV^2 . The highest 3 span the ranges from 0.25 GeV^2 to 0.50 GeV^2 , 0.50 GeV^2 to 1.00 GeV^2 , and $> 1.00 \text{ GeV}^2$. Their prior central values and uncertainties are tuned by MINER ν A data.

The neutrino energy of CCQE events is calculated using Equation 2.30, which is highly dependent on having an accurate value of the binding energy of the target nuclei. 4 parameters are used to fit the binding energies (for target $^{12}\text{C}/^{16}\text{O}$ and $\nu/\bar{\nu}$). These are neither shape nor normalisation parameters, and are described in more detail in Section 5.4.1.1.

- **2-particle-2-hole:**

2p2h interactions are generated in NEUT using the NIEVES model [92]. Two shape parameters apply to 2p2h interactions, one for events on ^{12}C and one for events on

^{16}O . At one extreme it is entirely non-pionless- Δ -decay-like in accordance with the NIEVES model, and at the other extreme the shape is entirely pionless- Δ -decay-like, in accordance with the Martini model [93]. These two shape parameters have a 30% correlation.

There are additional shape parameters, to account for differences in the energy dependence of 2p2h interactions. At one extreme the shape is entirely consistent with the NIEVES model, and at the other it is consistent with the Martini model. There are 4 of these parameters in total: $\nu/\bar{\nu}$ and high/low E_ν . However, studies showed these could not be constrained using near detector data alone, so are fixed in near detector only fits. For the joint near and far detector fits in the oscillation analysis, the parameters are free in the fit.

Three normalisations are also applied, one for ν events, one for $\bar{\nu}$, and one for $^{12}C \rightarrow ^{16}O$ scaling. The latter is applied to events on ^{16}O multiplicatively with the other normalisations.

- **CC Resonance:**

The Rein-Sehgal model [94] is used to describe resonant π production in NEUT. Splines are used to parametrise the resonance axial mass, M_A^{Res} , the normalisation of the axial form factor, C_5^A , and the size of the $I = 1/2$ non-resonant background to $I = 3/2$ resonant π production. The prior central values and uncertainties are tuned using bubble chamber data [95]. There is a prior anti-correlation of 83% between M_A^{Res} and C_5^A , 1% between M_A^{Res} and $I = 1/2$, and 31% between C_5^A and $I = 1/2$. In the joint near and far detector fits, the $I = 1/2$ parameter is split into two, one for anti-neutrino events with $p_\pi < 200$ MeV, and one for all other $I = 1/2$ non-resonant background events. In the near detector only fit, the low p_π parameter is not fit, and the other $I = 1/2$ parameter applies to all $I = 1/2$ non-resonant background events.

- **CC Coherent Scattering:**

The Rein-Seghal model [96] is used to describe the coherent scattering events. However, measurements at MINER ν A show a 30% difference in cross-section from this model. Two normalisation parameters are fit, one for CC events on ^{12}C and one for CC events on ^{16}O each with a 30% prior uncertainty to account for this discrepancy. These are 100% correlated.

- **CC Deep Inelastic Scattering and Multi- π :**

The CC DIS and multi- π cross-section is calculated from ‘Parton Distribution Func-

5. The Near Detector Fit Setup

tions' (PDFs). In NEUT these are constructed using the GRV98 [97] model with corrections from Bodek and Yang [98]. Two shape parameters are applied, one for DIS and one for multi- π events, to account for uncertainty in the reliability of these corrections. One extreme corresponds to fully applying the corrections, and the other corresponds to not applying them at all.

Another shape parameter is applied to multi- π events, to account for differences in the π multiplicity models in different generators. If the π multiplicity model changes, this directly alters the multi- π cross-section (as it is required multi- π events contain $\leq 2\pi$ s). At one extreme, the multi- π cross-section is entirely reweighted to the AGKY model [99], at the other extreme it is entirely the nominal custom model in NEUT.

Two normalisation parameters are applied to CC DIS and multi- π events, one for ν and one for $\bar{\nu}$ interactions. This is to account for a difference between the high energy CC-inclusive cross-sections in NEUT and the PDG world average. The prior uncertainty is 3.5% for ν and 6.5% for $\bar{\nu}$.

- **CC Miscellaneous:**

A normalisation parameter with 100% uncertainty is applied to CC $1K$, 1η , and 1γ events.

- **CC Inclusive:**

Two normalisations are applied to CC interactions with $0.4 < E_\nu < 0.6\text{GeV}$, one for ν and one for $\bar{\nu}$ events. This is to account for the fact the relative effect of the Coulomb corrections, described in Section 5.5, is smaller at higher momentum. The uncertainties on these systematics are 2% and 1% for ν and $\bar{\nu}$ respectively, and they are 100% correlated.

- **Neutral Current:**

Like for CC Coherent scattering, NC scattering events receive a normalisation with 30% uncertainty. NC 1γ interactions are modelled with the Rein-Sehgal CC Res model. The cross-section is half the value calculated with more recent models [100], and so the prior weight applied is 2.0. As there is no external data to constrain the cross-section, the prior uncertainty is 100%.

NC π production is simulated using the same Rein-Sehgal model as for CC π production, and the same parameters are applied: C_5^A , M_A^{Res} and $I = 1/2$.

NC DIS, multi- π , 1η , and $1K$ are grouped together and receive the same normalisation

parameter (NC Other), with a 30% uncertainty. In the full joint analysis, a separate NC Other parameter is applied to near and far detector events.

- **Electron (Anti-)Neutrino:**

As all the other systematic uncertainties are determined for ν_μ interactions, a normalisation is applied to all ν_e and $\bar{\nu}_e$ events. This is to account for any unmodelled effects which affect $\nu_e/\bar{\nu}_e$ events but not $\nu_\mu/\bar{\nu}_\mu$. As these processes may be different for neutrinos and anti-neutrinos, there are two normalisations, one for ν_e and one for $\bar{\nu}_e$. The prior uncertainty is 2.8% and the two parameters are 50% anti-correlated.

- **Final State Interactions:**

The propagation of π s produced in neutrino interactions is simulated as a cascade implementation of the model described in [101]. There are 5 shape parameters representing the probability of different interactions at each step in the cascade. The 5 types of final state interaction parametrised are quasi-elastic scattering (at low and high energy), π production, π absorption, and charge exchange. The prior central values and uncertainties are tuned to π -nucleon scattering data [102].

When nucleon final state interactions produce π s, the π s are propagated with the above systematics. However, nucleon final state interactions are not accounted for in the MC.

A summary of the interaction parameters is shown in Table 5.1. The full prefit cross-section covariance matrix is shown in Figure 5.8.

5.4.1.1. Binding Energy

In the SF nuclear model, there isn't a single nuclear binding energy systematic uncertainty. Instead, external data is used to inform removal energy distributions which contain peaks corresponding to the nuclear shell structure. The peaks are shown for different initial nucleon momentum for the ground state in Figure 5.9.

Ideally, there would be systematic parameters for the height, width, and position of each of the peaks for each target nucleus. However, this was infeasible to implement on the time scale of this analysis. Instead, a global uncertainty of 6 MeV is applied to the removal energy in the SF nuclear model.

These binding energy systematics are implemented as neither shape nor normalisation parameters in the T2K oscillation analysis. Instead, the offset to the removal energy is propagated to a change in the $P_\mu - \theta_\mu$ distributions by directly shifting P_μ . It has been shown

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| Parameter | Events | Prior (Nominal) Central Value | Prior Uncertainty | Prior Shape | Type |
|---|---|----------------------------------|----------------------|----------------|---------------|
| M_A^{QE} | CCQE | 1.03 (1.21) GeV | 0.06 GeV | Gaus | Shape |
| 2p2h Norm ν | 2p2h, ν | 1.0 | 1.0 | Flat | Norm. |
| 2p2h Norm $\bar{\nu}$ | 2p2h, $\bar{\nu}$ | 1.0 | 1.0 | Flat | Norm. |
| 2p2h Norm C to O | 2p2h on O | 1.0 | 0.2 | Gaus | Norm. |
| 2p2h Shape C | 2p2h on C | 1.0 | 3.0 | Gaus | Shape |
| 2p2h Shape O | 2p2h on O | 1.0 | 3.0 | Gaus | Shape |
| 2p2h E dep low E ν | - | - | - | - | - |
| 2p2h E dep high E ν | - | - | - | - | - |
| 2p2h E dep low E $\bar{\nu}$ | - | - | - | - | - |
| 2p2h E dep high E $\bar{\nu}$ | - | - | - | - | - |
| Q^2 0 | CCQE; $0.0 < Q^2 < 0.05 \text{ GeV}^2$ | 0.495 (1.0) | 1.0 | Flat | Norm. |
| Q^2 1 | CCQE; $0.05 < Q^2 < 0.10 \text{ GeV}^2$ | 0.695 (1.0) | 1.0 | Flat | Norm. |
| Q^2 2 | CCQE; $0.1 < Q^2 < 0.15 \text{ GeV}^2$ | 0.78 (1.0) | 1.0 | Flat | Norm. |
| Q^2 3 | CCQE; $0.15 < Q^2 < 0.2 \text{ GeV}^2$ | 0.89 (1.0) | 1.0 | Flat | Norm. |
| Q^2 4 | CCQE; $0.2 < Q^2 < 0.25 \text{ GeV}^2$ | 0.93 (1.0) | 1.0 | Flat | Norm. |
| Q^2 5 | CCQE; $0.25 < Q^2 < 0.5 \text{ GeV}^2$ | 1.0 | 0.11 | Gaus | Norm. |
| Q^2 6 | CCQE; $0.5 < Q^2 < 1.0 \text{ GeV}^2$ | 1.0 | 0.18 | Gaus | Norm. |
| Q^2 7 | CCQE; $Q^2 < 1.0 \text{ GeV}^2$ | 1.0 | 0.40 | Gaus | Norm. |
| $E_b\nu C$ | CCQE on C; $E_\nu < 4 \text{ GeV}$; ν | 27 (25) MeV | 6 MeV | Gaus | p_μ Shift |
| $E_b\bar{\nu} C$ | CCQE on C; $E_\nu < 4 \text{ GeV}$; $\bar{\nu}$ | 25 MeV | 6 MeV | Gaus | p_μ Shift |
| $E_b\nu O$ | CCQE on O; $E_\nu < 4 \text{ GeV}$; ν | 31 (27) MeV | 6 MeV | Gaus | p_μ Shift |
| $E_b\bar{\nu} O$ | CCQE on O; $E_\nu < 4 \text{ GeV}$; $\bar{\nu}$ | 27 MeV | 6 MeV | Gaus | p_μ Shift |
| M_A^{RES} | CC Res, NC π^0 , NC π^\pm | 1.07 (0.95) GeV | 0.15 GeV | Gaus | Shape |
| C_5^A | CC Res, NC π^0 , NC π^\pm | 0.96 (1.01) | 0.15 | Gaus | Shape |
| $I_{1/2}$ non-res | CC Res, NC π^0 , NC π^\pm | 0.96 (1.30) | 0.40 | Gaus | Shape |
| $I_{1/2}$ non-res low p_π | - | - | - | - | - |
| CC norm ν | CC; $0.4 < E_\nu < 0.6 \text{ GeV}$; ν | 1.0 | 0.02 | Gaus | Norm. |
| CC norm $\bar{\nu}$ | CC; $0.4 < E_\nu < 0.6 \text{ GeV}$; $\bar{\nu}$ | 1.0 | 0.01 | Gaus | Norm. |
| CC ν_e/ν_μ | CC; ν_e | 1.0 | 0.028 | Gaus | Norm. |
| CC $\bar{\nu}_e/\bar{\nu}_\mu$ | CC; $\bar{\nu}_e$ | 1.0 | 0.028 | Gaus | Norm. |
| CC BY DIS | CC DIS; $W < 4.0 \text{ GeV}$ | 1.0 | 1.0 | Gaus | Shape |
| CC BY multi-π | CC multi- π ; $1.6 < W < 2.0 \text{ GeV}$ | 1.0 | 1.0 | Gaus | Shape |
| CC AGKY mult | CC multi- π ; $1.6 < W < 2.0 \text{ GeV}$ | 1.0 | 1.0 | Gaus | Shape |
| CC misc | CC1 γ , CC1K, CC1 η | 1.0 | 1.0 | Gaus | Norm. |
| CC DIS, multi-π norm ν | CC DIS, CC multi- π , ν | 1.0 | 0.035 | Gaus | Norm. |
| CC DIS, multi-π norm $\bar{\nu}$ | CC DIS, CC multi- π , $\bar{\nu}$ | 1.0 | 0.065 | Gaus | Norm. |
| CC coh C | CC Coherent on C | 1.0 | 0.3 | Gaus | Norm. |
| CC coh O | CC Coherent on O | 1.0 | 0.3 | Gaus | Norm. |
| NC coh | NC Coherent | 1.0 | 0.3 | Gaus | Norm. |
| NC 1γ | NC 1 γ | 1.0 | 1.0 | Gaus | Norm. |
| NC other near | NC DIS, multi- π , 1K, 1 η | 1.0 | 0.3 | Gaus | Norm. |
| NC other far | - | - | - | - | - |
| π FSI QE | CC Res, NC π^0 , NC π^\pm | 1.069 | 0.313 | Gaus | Shape |
| π FSI QE high E | CC Res, NC π^0 , NC π^\pm | 1.824 | 0.859 | Gaus | Shape |
| π FSI Abs | CC Res, NC π^0 , NC π^\pm | 1.002 | 1.102 | Gaus | Shape |
| π FSI Prod | CC Res, NC π^0 , NC π^\pm | 1.404 | 0.432 | Gaus | Shape |
| π FSI CX | CC Res, NC π^0 , NC π^\pm | 0.697 | 0.305 | Gaus | Shape |

Table 5.1.: The interaction parameters used in this analysis.

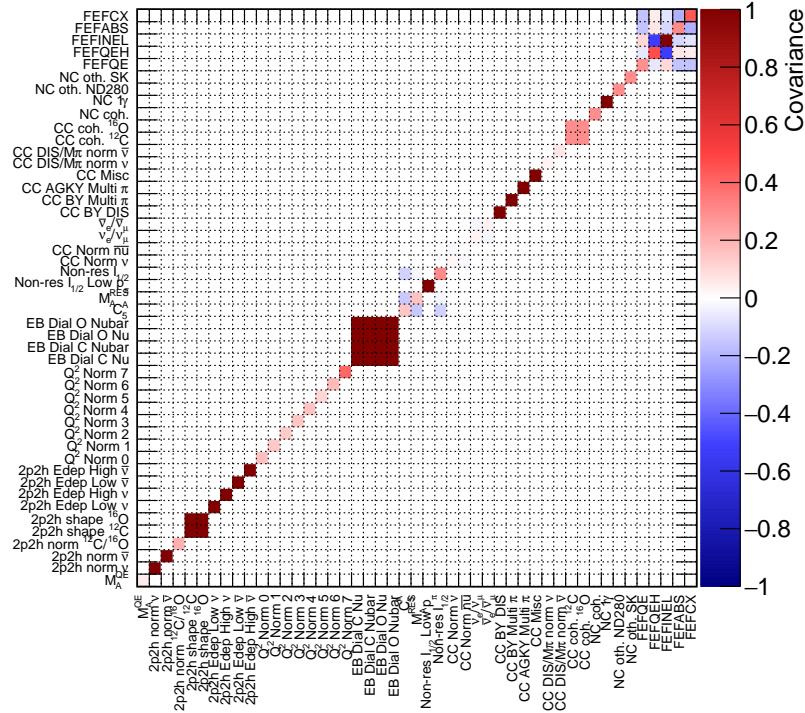


Figure 5.8.: The cross-section covariance matrix.

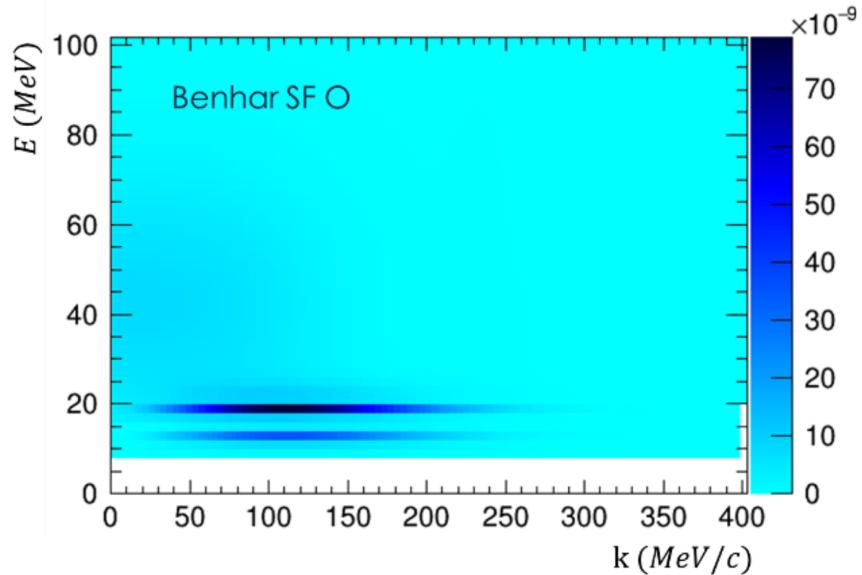


Figure 5.9.: Removal energy (' E ') at different values of the initial nucleon momentum (' k ') for the ground state in the SF model. Figure from [5].

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that changes in the removal energy do not cause significant changes in the distribution of θ_μ .

The SF model used was constrained using data from $e \rightarrow e'p$ experiments, which only applies to initial state protons, and therefore anti-neutrino CCQE interactions. The spectral function of initial state neutrons in neutrino CCQE interactions can not be constrained in the same way. The offset between the SF and Relativistic Mean-Field model predictions [103] for neutrons is ~ 4 MeV for oxygen and ~ 2 MeV for carbon.

There are therefore 4 binding energy parameters applied to CCQE events: for $^{12}C/^{16}O$ and $\nu/\bar{\nu}$. The $\bar{\nu}$ parameters have a prior central value of 25 MeV for ^{12}C , and 27 MeV for ^{16}O . The central value of the ν parameters are offset from their $\bar{\nu}$ counterparts by 2 and 4 MeV for ^{12}C and ^{16}O respectively. The parameters are correlated with each other as follows:

- $E_b\nu O$: 70% with $E_b\bar{\nu}O$, 77.77% with $E_b\nu C$, 65.27% with $E_b\bar{\nu}C$
- $E_b\bar{\nu}O$: 70% with $E_b\nu O$, 65.27% with $E_b\nu C$, 77.77% with $E_b\bar{\nu}C$
- $E_b\nu C$: 77.77% with $E_b\nu O$, 65.27% with $E_b\bar{\nu}O$, 70% with $E_b\bar{\nu}C$
- $E_b\bar{\nu}C$: 65.27% with $E_b\nu O$, 77.77% with $E_b\bar{\nu}O$, 70% with $E_b\nu C$

These values are derived in [5].

The effect of the $E_b\nu C$ parameter on the FGD1 FHC CC0 π sample is shown in Figure 5.10. Here, the parameter is set to $\pm 1\sigma$ while all other parameters are kept at nominal, and the ratio to the nominal MC is taken. As the binding energy parameter is increased, the final state lepton momentum is decreased. This is seen in the increase in number of events at lower momentum in Figure 5.10a. The opposite effect is seen for decreasing the binding energy parameter in Figure 5.10b.

To validate the implementation of this new type of parameter, Asimov fits (where the nominal MC is fitted to itself) with binding energy included were run. The Asimov fitting process is described in more detail in Section 6.4. The 1D posterior distributions for each of the 4 parameters are shown in Figure 5.11, with a fitted Gaussian distribution. As expected, the postfit values are close to the nominal values, and the distributions are approximately Gaussian.

However, for fits to data the posteriors contain many discontinuities as shown in Figure 5.13. This is not seen for other parameters. When reweighting, either by spline or normalisation, the change in the log-likelihood is continuous. As the parameter varies, the change in the penalty contribution, and the change in the number of events in each bin, and

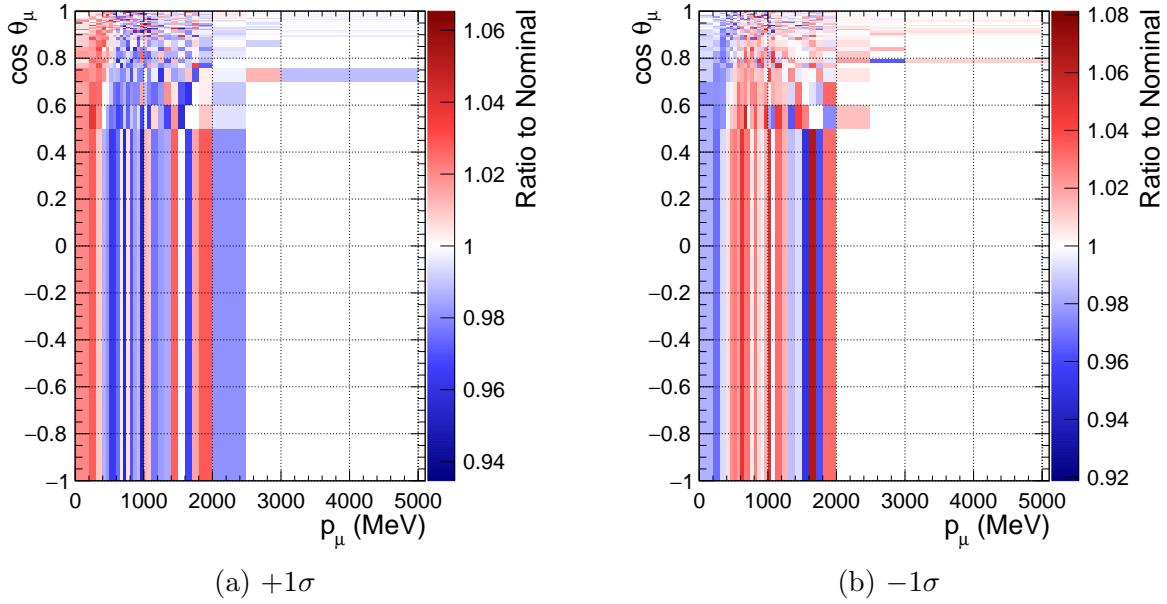


Figure 5.10.: Ratio of the FGD1 FHC CC0 π sample with $E_b\nu C$ parameter set to $\pm 1\sigma$ to the nominal MC.

therefore the sample contribution, are both smooth. However, for this direct shift in lepton momentum, the sample contribution to the likelihood only changes if an event crosses a bin boundary. There are therefore threshold values of each parameter where several events cross boundaries and cause discontinuous changes in the log-likelihood.

To show this is what causes the discontinuities, a fluctuated version of the nominal MC was produced. This was done by setting the number of events in each bin to be a random number from a Poisson distribution, with a mean equal to the nominal bin content. This ensured the number of events in each bin was an integer. The fluctuated MC was fitted to the nominal MC, and the posterior distributions for the E_b parameters are shown in Figure 5.13. The fact that these are non-Gaussian and discontinuous, despite them being continuous and Gaussian in the regular Asimov fit, shows that the effect is caused by the discrete shifts to integer events.

In previous analyses, the binding energy systematic was applied as a shape parameter. The change in removal energy was propagated to a change in the $P_\mu - \theta_\mu$ distributions by reweighting events. However, this method broke down at extreme values of the kinematic variables as changes in the removal energy could change the allowed phase space in unphysical ways. With this implementation, the removal energy was one of the dominant uncertainties in the T2K oscillation analysis. With the direct lepton momentum shift, the removal energy is now a sub-dominant systematic uncertainty, as shown in Section ??.

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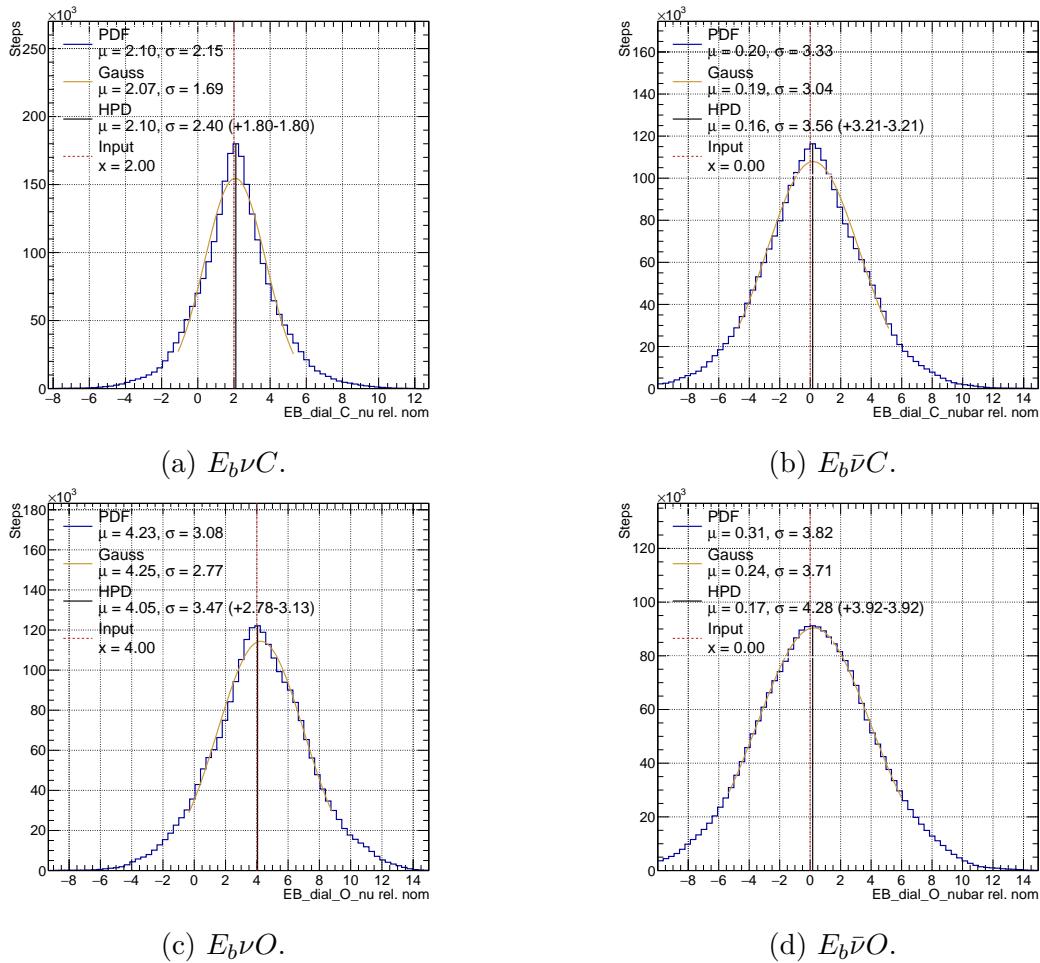


Figure 5.11.: Posterior distributions from the binding energy parameters from an Asimov fit.

something in the results section that shows this

5.4.2. Flux

The flux systematics are determined using the simulation described in Section 3.1.3. New data is used to regularly update and improve the modelling. This comes from external experiments such as NA61/SHINE [77], the T2K beam monitors, and the on-axis near detector INGRID. This analysis is the first to use flux systematics developed from simulation using data from a full T2K target replica, and not just a thinner replica version.

There are six sources of flux uncertainty:

- Alignment of the proton beam with the target.
- Number of protons on target.
- Interactions of protons and produced hadrons with the target.
- Alignment of the target with the focusing horns.

5.4. Systematics

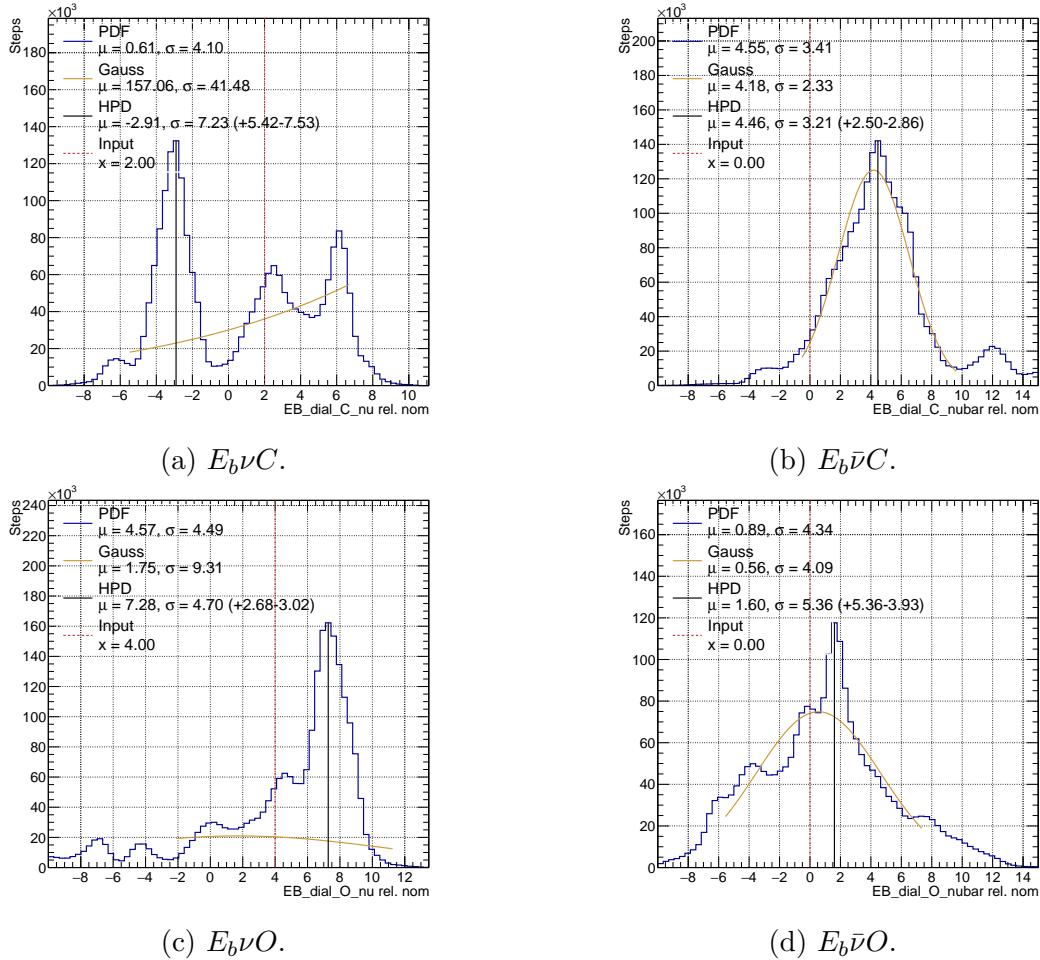


Figure 5.12.: Posterior distributions from the binding energy parameters from a data fit.

- The horn current and produced magnetic field.
- Modelling of materials in the target and decay volume.

The fractional sizes of the different sources of ND280 flux systematic are shown in Figure 5.14, for different neutrino signs. The hadron production contribution dominates, and the total uncertainty is $\sim 10\%$ around the beam peak energy at 600 MeV. The proton beam alignment becomes more significant around 1 GeV. The black dotted line shows the total flux uncertainty using the previous version of the model. This also used the full replica target tuning; the improvement comes from using the latest FLUKA [76] release. Similar results are seen for the SK flux uncertainties, shown in Figure 5.15. [Get better quality Plots](#)

The flux uncertainty model is parametrised as 100 true neutrino energy bin normalisations for each neutrino species, horn current mode, and detector. The binnings are as follows:

5. The Near Detector Fit Setup

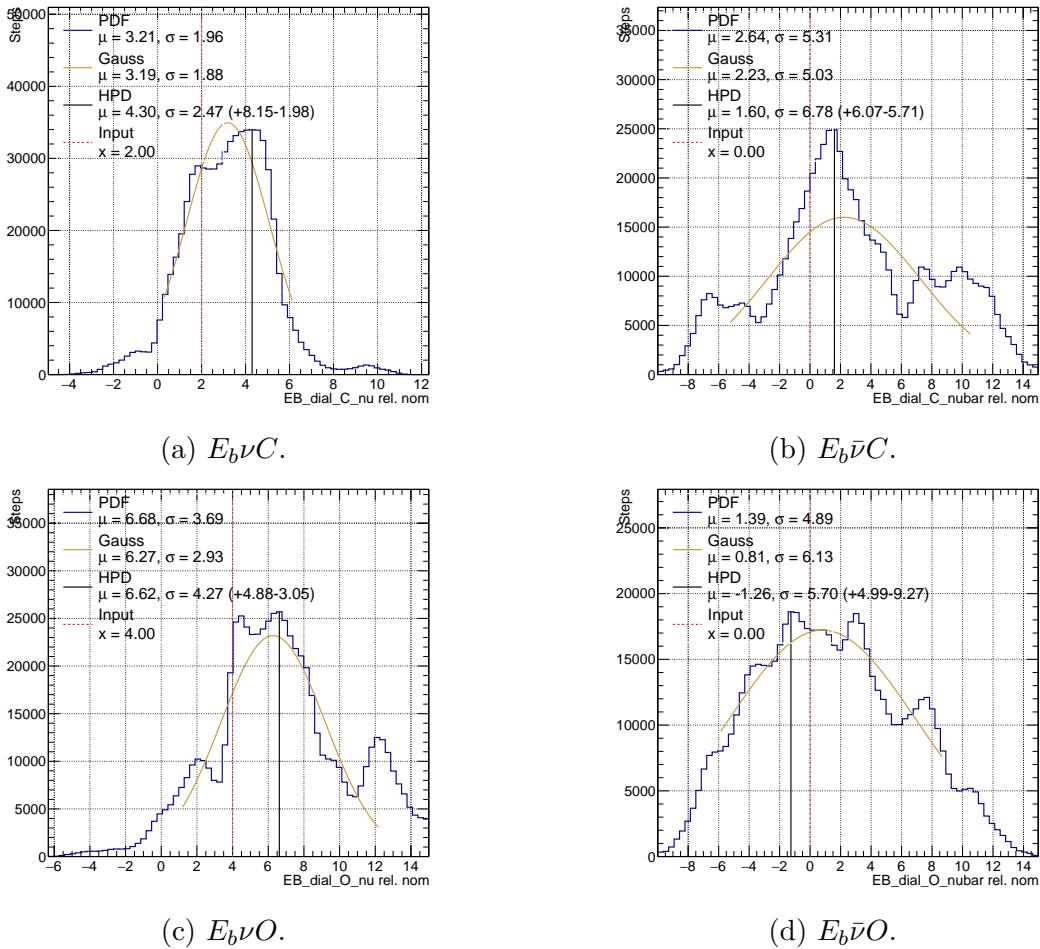


Figure 5.13.: Posterior distributions from the binding energy parameters from fit to fluctuated Asimov data.

- ND280 + SK, FHC ν_μ + RHC $\bar{\nu}_\mu$:

E_ν^{true} : 0, 0.4, 0.5, 0.6, 0.7, 1, 1.5, 2.5, 3.5, 5, 7, 30

- ND280 + SK, FHC $\bar{\nu}_\mu$ + RHC ν_μ :

E_ν^{true} : 0, 0.7, 1, 1.5, 2.5, 30

- ND280 + SK, FHC ν_e + RHC $\bar{\nu}_e$:

E_ν^{true} : 0, 0.5, 0.7, 0.8, 1.5, 2.5, 4, 30

- ND280 + SK, FHC $\bar{\nu}_e$ + RHC ν_e :

E_ν^{true} : 0, 2.5, 30

In total there are 100 flux parameters, 50 for ND280 and 50 for SK. The SK flux systematics are used in the near detector fit because of their high correlations with their ND280 counterparts. All flux systematics have a prior central value of 1.0, and Gaussian prior uncertainty with width equal to the standard deviation in the fractional covariance matrix,

5.4. Systematics

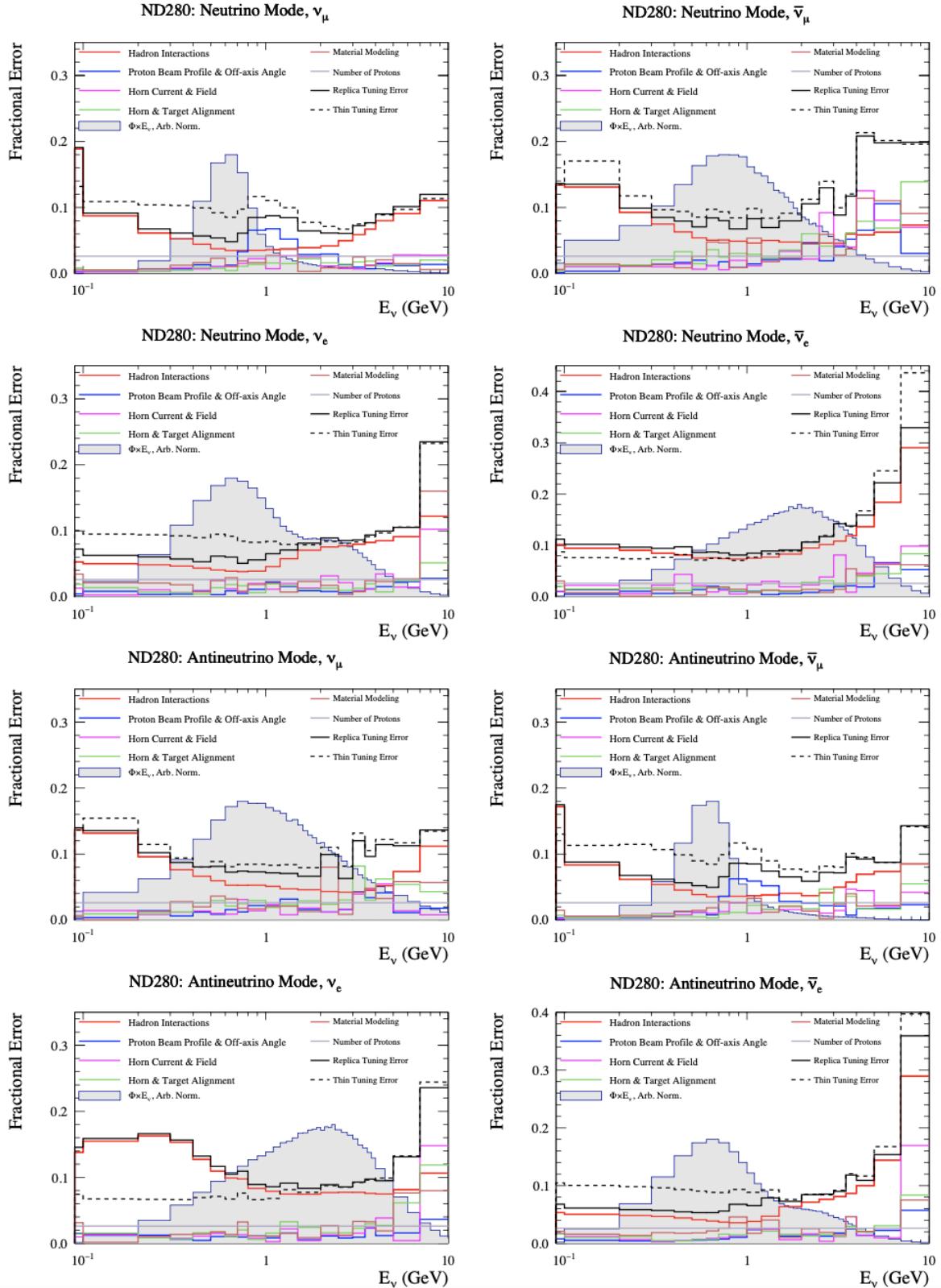


Figure 5.14.: Relative sizes of the sources of flux uncertainties in the ND280 flux parameters.

5. The Near Detector Fit Setup

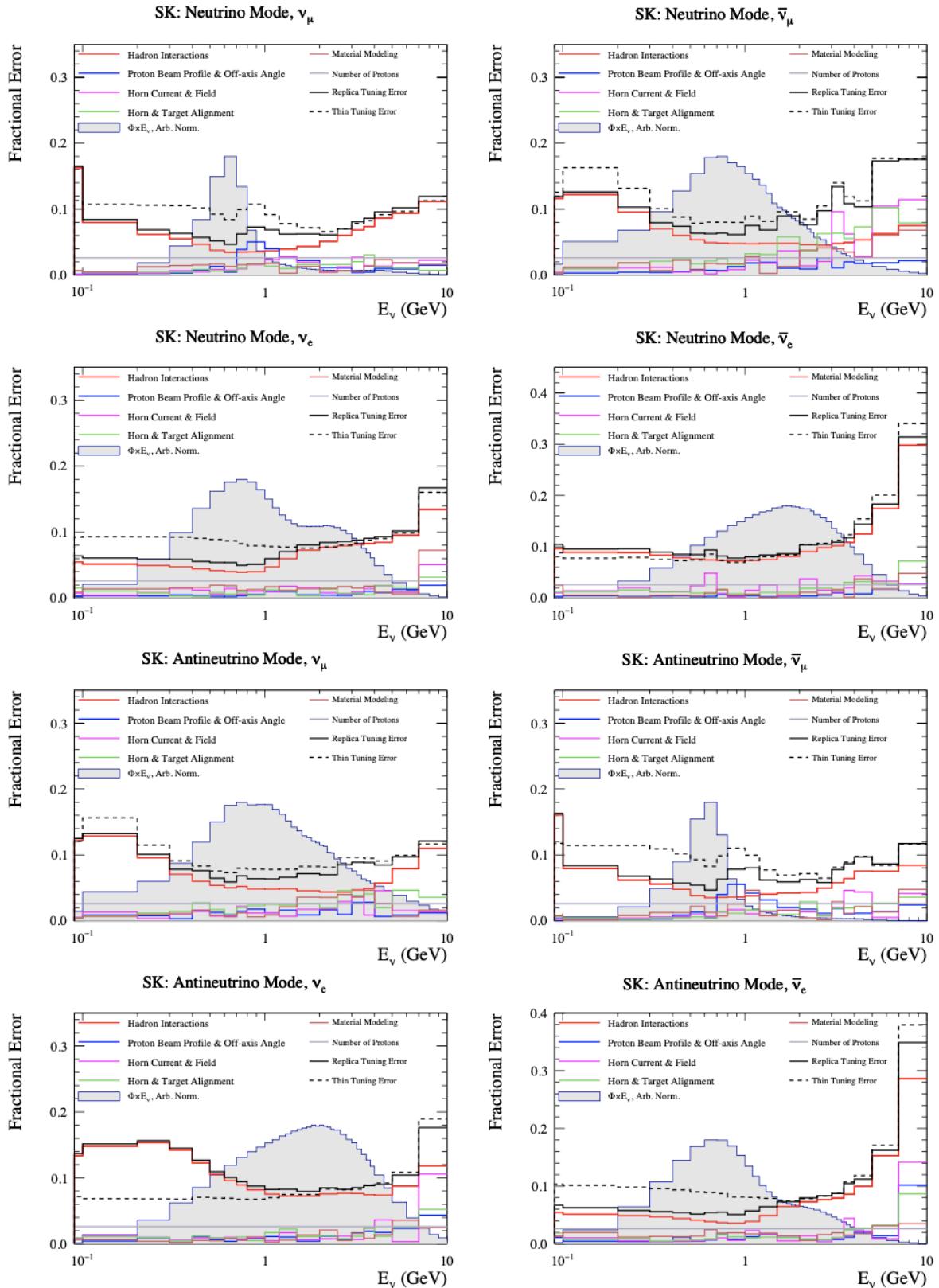


Figure 5.15.: Relative sizes of the sources of flux uncertainties in the SK flux parameters.

shown in Figure 5.16.

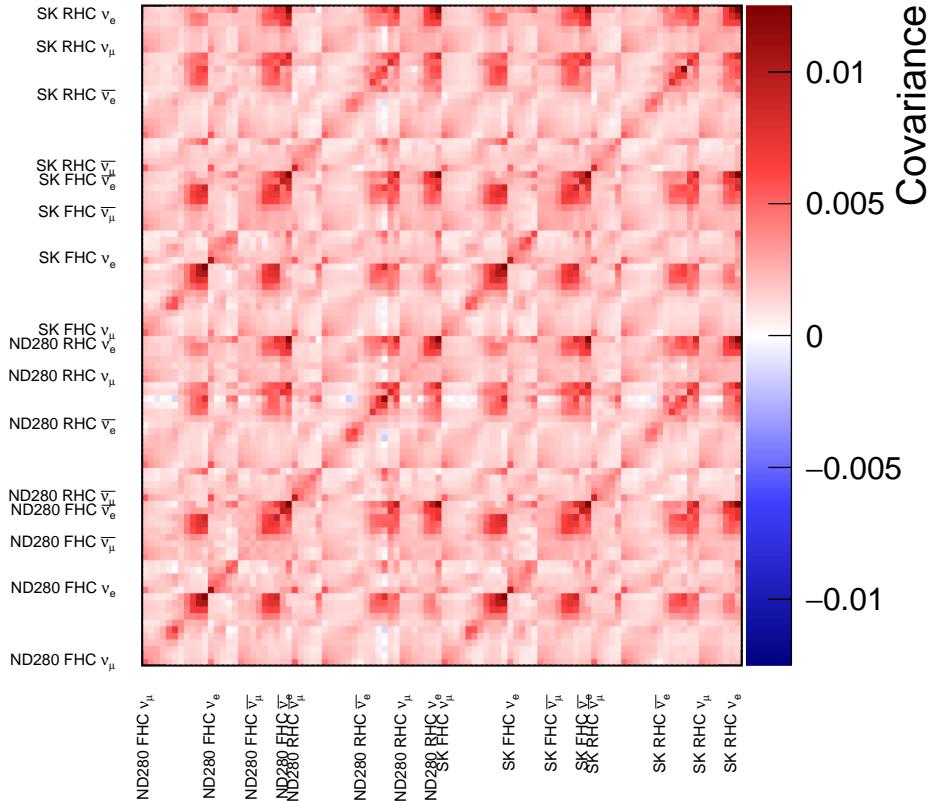


Figure 5.16.: The flux covariance matrix.

5.4.3. Detector

The ND280 detector systematicss are modelled using bin normalisation parameters. The underlying systematics are initially varied to see the change to the number of events in each $p_\mu - \cos\theta_\mu$ bin. These systematics are divided into 17 groups:

- **TPC Field Distortions:** The magnetic field applied in ND280 is not perfectly uniform, and so there are field distortions in the TPCs. These are measured by calibration lasers with the magnet both on and off.
- **TPC Momentum Scale:** The uncertainty in the magnetic field causes an uncertainty in the measured momentum within the TPC. Four hall probes within ND280 provide scaling factors applied to the field strength on the MC.
- **TPC Momentum Resolution:** There is a discrepancy between the MC and data momentum resolutions in the TPCs, which is not well understood. To account for this, MC TPC tracks are smeared so that the resolution matches that of data.
- **TPC PID:** The pulls between the measured and predicted energy loss is used to

5. The Near Detector Fit Setup

identify particles in the TPC, as discussed in Section 3.2.2.2. The difference between the mean MC and data pulls is applied as a systematic uncertainty on the TPC PID.

- **TPC Cluster Efficiency:** There are differences between the reconstruction of clusters of hits in the data and MC. An uncertainty is applied, correlated between horizontal and vertical clusters to account for this. It is calculated using control samples of both beam and cosmic trigger events.
- **TPC Tracking Efficiency:** The efficiency of the TPC reconstruction algorithm successfully merging hits into tracks is measured for control samples of both beam and cosmic trigger events. The difference between the efficiencies obtained for data and MC is applied as a systematic.
- **TPC Charge ID Efficiency:** There are two sources of uncertainty in the TPC charge identification: the efficiency of the initial TPC charge being correct, and the probability of the TPC charge sign being reversed in the overall charge identification. The TPC Charge ID uncertainty is applied as the probability of the overall charge being different from the TPC reconstructed charge.
- **TPC-FGD Matching Efficiency:** The efficiency of matching FGD and TPC tracks was calculated using a control sample of events with a high angle with respect to the neutrino beam that passed through at least two TPCs. The difference in the efficiency found for data and MC is applied as a systematic.
- **FGD PID:** The pulls between the measured and predicted energy loss is used to identify particles in the FGD, as discussed in Section 3.2.2.1. The difference between the mean MC and data pulls is applied as a systematic uncertainty on the FGD PID.
- **FGD Time of Flight:** For tracks passing through FGD1 and FGD2, the hit times in each FGD are used to determine the direction of the track. The uncertainty on the time of flight can therefore affect which FGD the event was reconstructed as having occurred in. Analysis rather than control samples were used to measure the time of flight for data and MC events. All reconstructed time of flights are smeared with the discrepancy as an uncertainty.
- **FGD Hybrid Tracking Efficiency:** The efficiency of reconstructing FGD-only tracks in the presence of FGD-TPC matched tracks is calculated for a set of GEANT-4 generated stopping protons and pions in a control sample of events with either one reconstructed track entering the TPC or two tracks which both enter the TPC. The

difference between the efficiencies for data and MC is applied as a systematic uncertainty.

- **Michel Electron Efficiency:** The efficiency of detecting Michel electrons depends on the probability of the electron producing enough hits in the FGD to pass the selection cut, and the purity of the cut itself. The efficiency was measured for a control sample of cosmic trigger events, and was defined as the probability to detect a Michel electron that was expected from the presence of a stopped muon in the FGD.
- **Out of Fiducial Volume (OOFV) Background:** Events outside the fiducial volume can be misreconstructed as being inside the fiducial volume. These could be events that occurred in the first two layers of FGD1, the first layer of FGD2, or in one of the other sub-detectors. The background rate was calculated for beam trigger events, and the discrepancy between the measurement for data and MC is applied as a systematic uncertainty.
- **Sand Muon Background:** Interactions from beam neutrinos can occur in the sand outside the near detector pit but look similar to events in the FGDs, forming a background rate. The rate from a dedicated simulation is compared to data to calculate the associated uncertainty.
- **Pile-Up:** Out-of-fiducial volume events being coincident with in-fiducial volume CC-inclusive events in the FGDs can lead to CC-inclusive events being rejected by the external veto cut described in Section 5.2. The difference in number of events per bunch in the data and MC is applied as systematic uncertainty to account for this effect.
- **Pion Secondary Interactions (SI):** Pions produced by neutrino interactions at ND280 can interact within the detector. This causes pion detection inefficiencies. An uncertainty is applied to account for this effect, calculated from the difference between pion SI cross-sections measured in data and MC.
- **FGD Mass:** The uncertainty on the FGD masses affects the number of target nuclei, and so can change the total event rate. Differences between the measured and simulated FGD masses are applied as a systematic uncertainty.

Each of these systematics is applied in one of three different ways:

5. The Near Detector Fit Setup

| Systematic Source | Type | Prior Shape |
|---------------------------------------|-----------------|-------------|
| B Field Distortions | Observable | Flat |
| TPC Momentum Scale | Observable | Gaussian |
| TPC Momentum Resolution | Observable | Gaussian |
| TPC PID | Observable | Gaussian |
| TPC Cluster Efficiency | Efficiency-Like | Gaussian |
| TPC Tracking Efficiency | Efficiency-Like | Gaussian |
| TPC Charge ID Efficiency | Efficiency-Like | Gaussian |
| TPC-FGD Matching Efficiency | Efficiency-Like | Gaussian |
| FGD PID | Observable | Gaussian |
| FGD ToF | Observable | Gaussian |
| FGD Hybrid Tracking Efficiency | Efficiency-Like | Gaussian |
| Michel Electron Efficiency | Efficiency-Like | Gaussian |
| OOFV Background | Normalisation | Gaussian |
| Sand Muon Background | Normalisation | Gaussian |
| Pile-Up | Normalisation | Gaussian |
| Pion Secondary Interactions | Normalisation | Gaussian |
| FGD Mass | Normalisation | Gaussian |

Table 5.2.: ND280 detector systematics, and their propagation type and prior uncertainty shape.

- **Observable Variable Systematic:** These are smearings that are applied to reconstructed variables. The selection algorithm is then rerun, and so smeared events can change their topology, selection, and which track is the lepton candidate.
- **Efficiency-Like Systematics:** These are uncertainties on detection and reconstruction efficiencies, which are applied as weights to the event after selection.
- **Normalisation Systematics:** These are overall normalisation changes applied directly to events to scale rates up or down.

The type of each of the 17 systematics is shown in Table 5.2, along with whether they have a Gaussian or flat prior uncertainty.

In theory, these systematics could be applied on an event by event basis and fitted individually. However, this is not computationally feasible on the timescales required for the oscillation analysis. Instead, each systematic is varied 2000 times and the MC reweighted. This gives a distribution of 2000 number of events for each $p_\mu - \cos\theta_\mu$ bin. The mean and

5.4. Systematics

width of a Gaussian fitted to each of these distributions becomes the prior central value and uncertainty for a normalisation parameter applying to that bin. However, the number of fit bins is large, and so to reduce the number of fit parameters, adjacent bins with similar responses to the systematic variations are merged, so the detector binning is coarser than the fit binning. Studies of different detector binnings are presented in Section 5.4.3.1.

This process assumes the shape of the underlying systematics is Gaussian. This is the case for the majority of bins, four of which are shown in Figure 5.17. In previous analyses, the MC stats uncertainty was included in the ND280 detector covariance instead of as an extra term in the log-likelihood calculation, and so a Gaussian fitted to the distribution of number of events in each bin with and without the MC stats uncertainty are shown. However, several bins exhibit non-Gaussian behaviour, as shown in Figure 5.18.

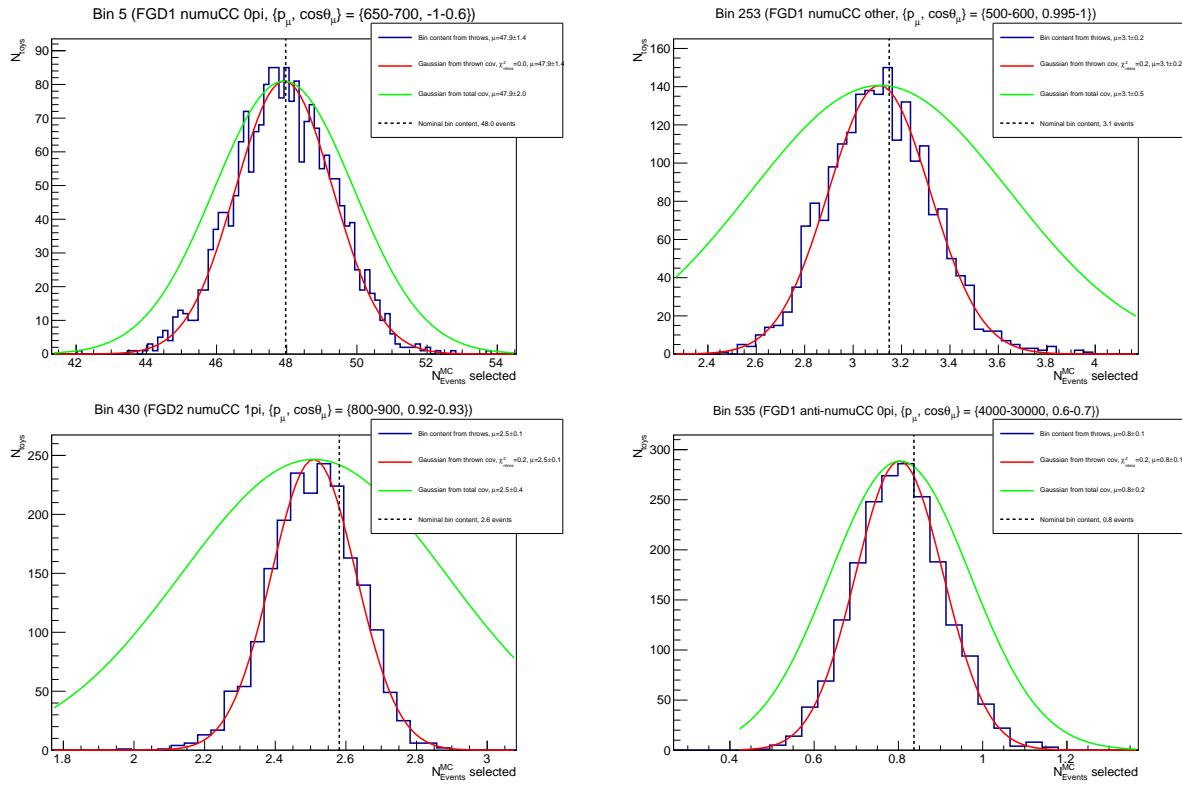


Figure 5.17.: Distribution of number of events in selected Gaussian distributed bins after 2000 throws of all detector systematics. The red and green lines show Gaussians fitted with and without the MC statistical uncertainty included, and the dotted black line shows the nominal number of events.

To investigate which of the underlying detector systematics is causing the non-Gaussianity, each was switched off one-by-one and the variations repeated. It was found that when all systematics but the Pion SI are left on, the distributions in the misbehaving bins are more Gaussian. These are shown in Figure 5.19. These suggest that the pion SI is the only one of the detector systematics with a significantly non-Gaussian distribution. As the effect only manifests in a small number of bins, it is not too concerning for this analysis.

5. The Near Detector Fit Setup

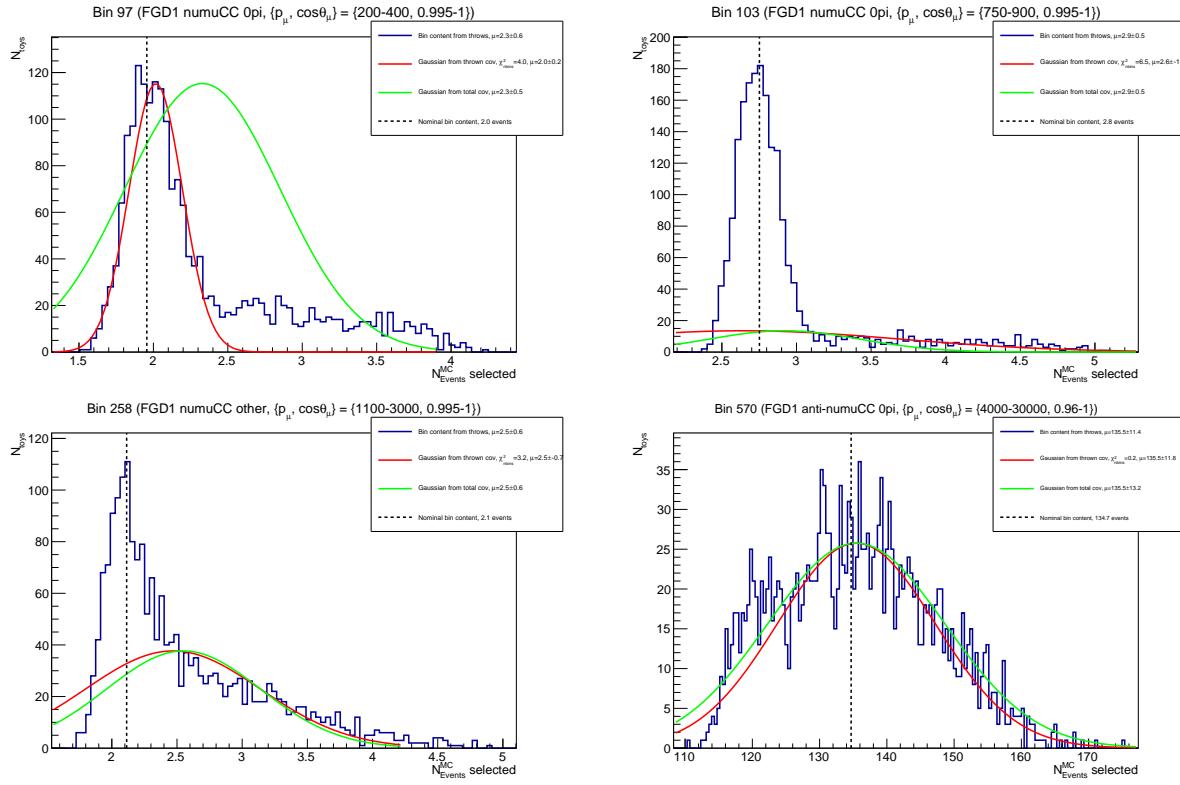


Figure 5.18.: Distribution of number of events in selected non-Gaussian distributed bins after 2000 throws of all detector systematics. The red and green lines show Gaussians fitted with and without the MC statistical uncertainty included, and the dotted black line shows the nominal number of events.

5.4.3.1. Detector Binning

The choice of detector binning is a trade-off of having as close to the fit binning as possible to obtain more accurate results, without introducing an infeasibly large number of fit parameters. To investigate the effect of merging detector bins, detector covariances with different binnings were produced. The binnings were produced by requiring different criteria to merge adjacent bins. These criteria were based on the number of events in a bin before applying the detector systematics, the change in the number of events by applying the systematics, and the difference between the covariance of bins. These correspond to merging bins with few events, bins where the effect of the systematics are small, and bins with similar response to the systematics respectively. The exact criteria for merging bins used were:

- < 1 event in a bin, or < 1 event change from applying the systematics, or < 10% difference in covariance between bins. This produced 179 merged bins.
- < 1 event in a bin, or < 1 event change from applying the systematics, or < 5% difference in covariance between bins. This produced 574 merged bins.

5.4. Systematics

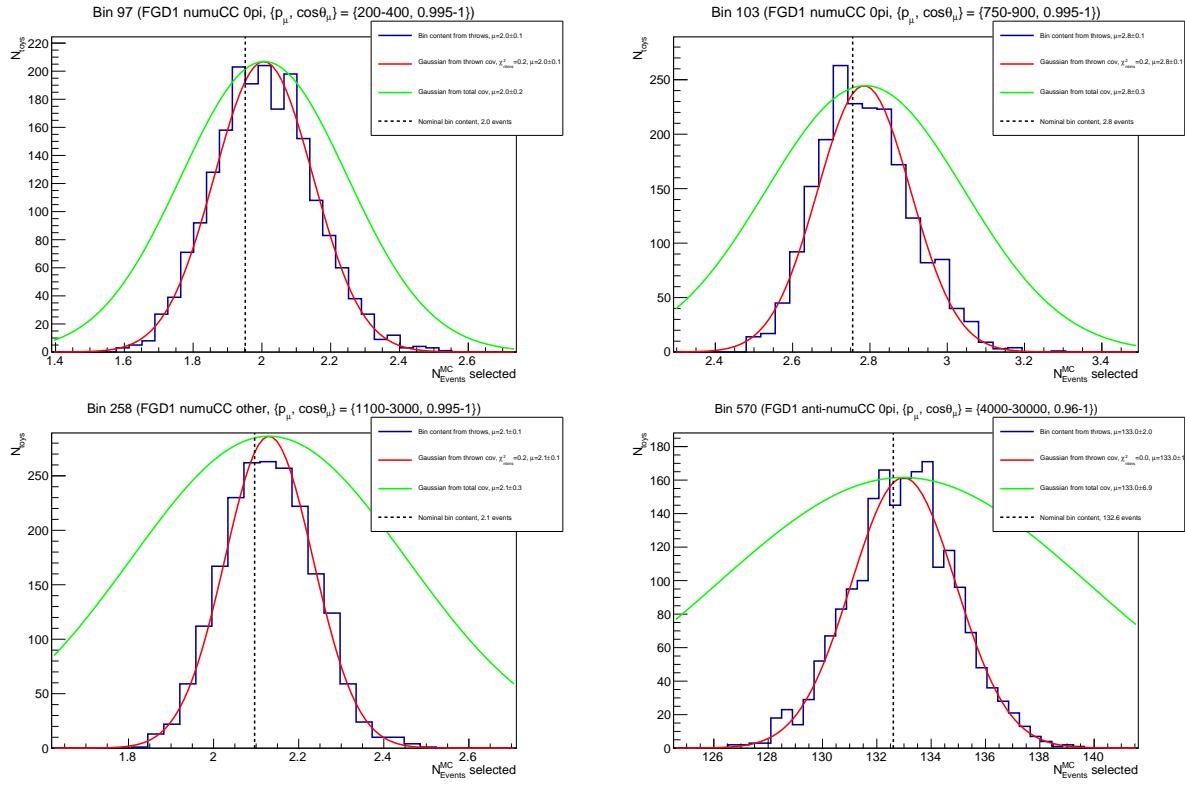


Figure 5.19.: Distribution of number of events in selected bins after 2000 throws of all detector systematics but the pion SI. The red and green lines show Gaussians fitted with and without the MC statistical uncertainty included, and the dotted black line shows the nominal number of events.

- < 1 event in a bin, or < 0.5 event change from applying the systematics, or < 5% difference in covariance between bins. This produced 1347 merged bins.

A covariance using the fit binning as the detector binning was also produced. As in these studies the fit binning used was the uniform-rectangular set defined in Section 5.3, this corresponded to 4238 bins.

Fits were run using each of these 4 detector covariances, using an intermediate cross-section model including parts of the 2017 analysis parametrisation described in [104], and parts of the 2020 analysis parametrisation described in Section 5.4.1. To avoid tuning the detector binning on data, fake data was produced by setting the cross-section parameters to their best fit values from the 2017 analysis and reweighting the nominal MC. The MC was then fitted to this fake data.

The result of the fits are shown in Figure 5.20 for the flux parameters, and Figure 5.21 for the cross-section parameters. Although there are several differences between the postfit parameter values, there is no consistent trend of having more bins being closer to the fit binning result, and they are all consistent within uncertainties. Although the 179 fit bin fit

5. The Near Detector Fit Setup

is often the most different from the 4238 (fit binning) detector bin fit.

Furthermore, when the postfit chains are used to produce posterior predictive distributions at the far detector, there is very little difference seen, as shown in Figure 5.22. This suggests that there are several regions of minima in the ~ 700 dimensional parameter space which correspond to the same result at SK.

As the far detector prediction was robust to the different detector bin mergings, and previous analyses have shown that having ~ 600 detector parameters does not cause any issues with fit convergence³, the 574 bin detector covariance was chosen as the optimum bin merging. The binning is as follows:

- **FHC ν_μ CC0 π :**

p (MeV/c): 0., 300., 1000., 1250., 1500., 2000., 3000., 5000., 30000.

cos θ : -1.0, 0.6, 0.8, 0.85, 0.9, 0.92, 0.98, 0.99, 1.0

- **FHC ν_μ CC1 π :**

p (MeV/c): 0., 300., 400., 700., 800., 1000., 1500., 2000., 5000., 30000.

cos θ : -1.0, 0.6, 0.8, 0.9, 0.92, 0.94, 0.96, 0.98, 0.99, 1.0

- **FHC ν_μ CCOther:**

p (MeV/c): 0., 300., 400., 700., 800., 900., 1250., 2000., 3000., 5000., 30000.

cos θ : -1.0, 0.6, 0.8, 0.85, 0.9, 0.92, 0.96, 0.98, 0.99, 1.0

- **RHC $\bar{\nu}_\mu$ CC0 π :**

p (MeV/c): 0., 300., 2000., 4000., 30000.

cos θ : -1., 0.6, 0.8, 0.9, 0.96, 1.

- **RHC $\bar{\nu}_\mu$ CC1 π :**

p (MeV/c): 0., 500., 30000.

cos θ : -1, 0.7, 1.

- **RHC $\bar{\nu}_\mu$ CCOther:**

p (MeV/c): 0., 600., 800., 30000.

cos θ : -1., 0.7, 0.95, 0.97, 1.

- **RHC ν_μ CC0 π :**

p (MeV/c): 0., 300., 1500., 30000.

cos θ : -1., 0.7, 1.

³For the 2017 analysis, 556 detector bins were used.

- **RHC ν_μ CC1 π :**

p (MeV/c): 0., 600., 800., 30000.

$\cos \theta$: -1, 0.7, 1.

- **RHC ν_μ CCOther:**

p (MeV/c): 0., 600., 30000.

$\cos \theta$: -1., 0.7, 1.

In this analysis, another detector covariance was also used for separate fits ran in parallel with the 574 detector bin fits. These fits used the full non-uniform fit binning as the detector binning. This was possible in this analysis as the MC statistics uncertainty was taken out of the detector covariance. This reduced the terms in the diagonal of the covariance, allowing the number of fit parameters to be reduced using principal component analysis. The two detector covariances used are shown in Figures 5.23 and 5.24.

5.5. Prefit Corrections and Scalings

A number of corrections and reweightings are applied to the MC prediction to account for well understood discrepancies between MC and data. These ‘one-time’ weights are applied before the fit, are not varied in it.

- **POT:** A scaling is applied to every MC event to account for the fact that a vast amount more MC POT is produced for each run than data POT. The weight applied to each event depends on the run, and is the ratio of the total data POT with good data quality flag to MC POT in the run.
- **Pile Up:** The detector efficiency in data is lower than in MC because of the coincidence between neutrino events and interactions involving sand muons. This needs to be applied as MC neutrino interactions within the magnet are simulated separately from sand muons. The correction applied depends on the run, and which FGD the event occurred in.
- **Detector:** Precise control studies are used to inform corrections due to well known hardware and reconstruction deficiencies in the TPC dE/dx and PID. These are applied on an event by event basis, and are discussed in more detail in [89].
- **Flux:** A correction is made to the nominal neutrino flux for tunings to updated replica target data. The value of the weight applied depends on the run and neutrino

5. The Near Detector Fit Setup

| Target | p_{μ^+} Shift (MeV) | p_{μ^-} Shift (MeV) |
|--------|-------------------------|-------------------------|
| C | +2.6 | -3.6 |
| O | +3.3 | -4.3 |

Table 5.3.: Momentum shifts applied to final state leptons in CC events.

energy.

- **Coulomb:** When the lepton produced in a CCQE neutrino interaction leaves the nucleus, it is either electrostatically attracted to or repulsed by the nucleus, depending on its charge. This increases or decreases the momentum of the lepton. To model this, a shift in momentum is applied to CC events. The value of the shift is tuned to electron scattering data [105], and depends on the target nucleus and sign of the lepton, as shown in Table 5.3.

All of these one-time corrections (apart from the Coulomb shifts and E_b parameters), along with the systematics that vary in the fit, are applied as multiplicative weights on an event-by-event basis.

5.6. Data

T2K has been taking data in distinct run periods since 2010, in both FHC and RHC beam mode. The beam power has been steadily increasing over this time, as shown in Figure 3.6.

MC is produced for each run period individually, so that run-by-run effects such as the beam and detector configurations, and tunings to in-situ beam measurements, can be accounted for.

Table 5.4 shows the amount of MC POT produced in each run, along with the amount of data taken with good data quality flag (defined as POT collected with all sub-detectors of ND280, and the data acquisition system online). Over runs 2-9, the overall efficiency of good data taking was $\sim 69\%$.

Vastly more MC is produced than data, with the weights and corrections described in the previous sections bringing the MC prediction comparable to data.

Runs with an ‘a’ or ‘w’ suffix refer to whether the P0D was filled with water (w) or air (a) during the run. These are separated, despite being part of the same global run, as the MC

| Run | Beam Mode | Data POT (x10 ¹⁹) | MC POT (x10 ¹⁹) |
|-----|-----------|-------------------------------|-----------------------------|
| 2a | FHC | 3.59457 | 167.99 |
| 2w | FHC | 4.33765 | 120.375 |
| 3 | FHC | 15.8103 | 307.766 |
| 4a | FHC | 17.8338 | 361.225 |
| 4w | FHC | 16.4302 | 361.215 |
| 5 | RHC | 4.3468 | 221.103 |
| 6 | RHC | 34.0928 | 346.986 |
| 7 | RHC | 24.3782 | 332.995 |
| 8a | FHC | 41.5013 | 361.098 |
| 8w | RHC | 15.8053 | 254.225 |
| 9 | RHC | 20.5391 | 245.61 |

Table 5.4.: Collected and generated POT for the run periods used in this analysis.

production requires different geometries to be used for these two different configurations. Runs without a suffix had a consistent P0D filling for the entire run. This was water for runs 5, 7, and 9, and air for runs 3 and 6.

The most recent data taking period, run 10, finished in February 2020, but had not been through the full processing in time for this analysis. Run 1 was not included as not all of the sub-detectors of ND280 were online.

5. The Near Detector Fit Setup

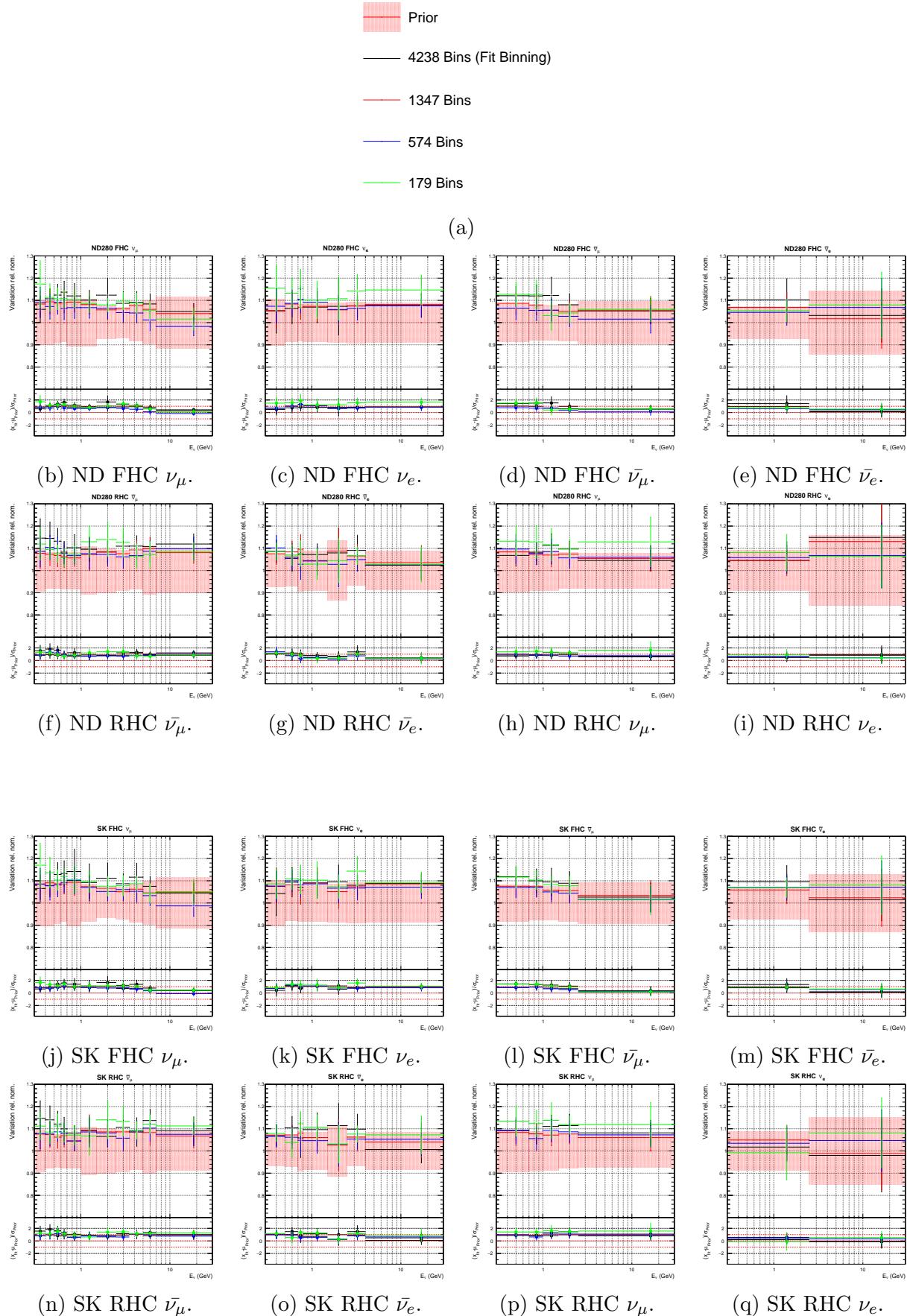


Figure 5.20.: Flux parameters for fake data fits using different detector binnings.

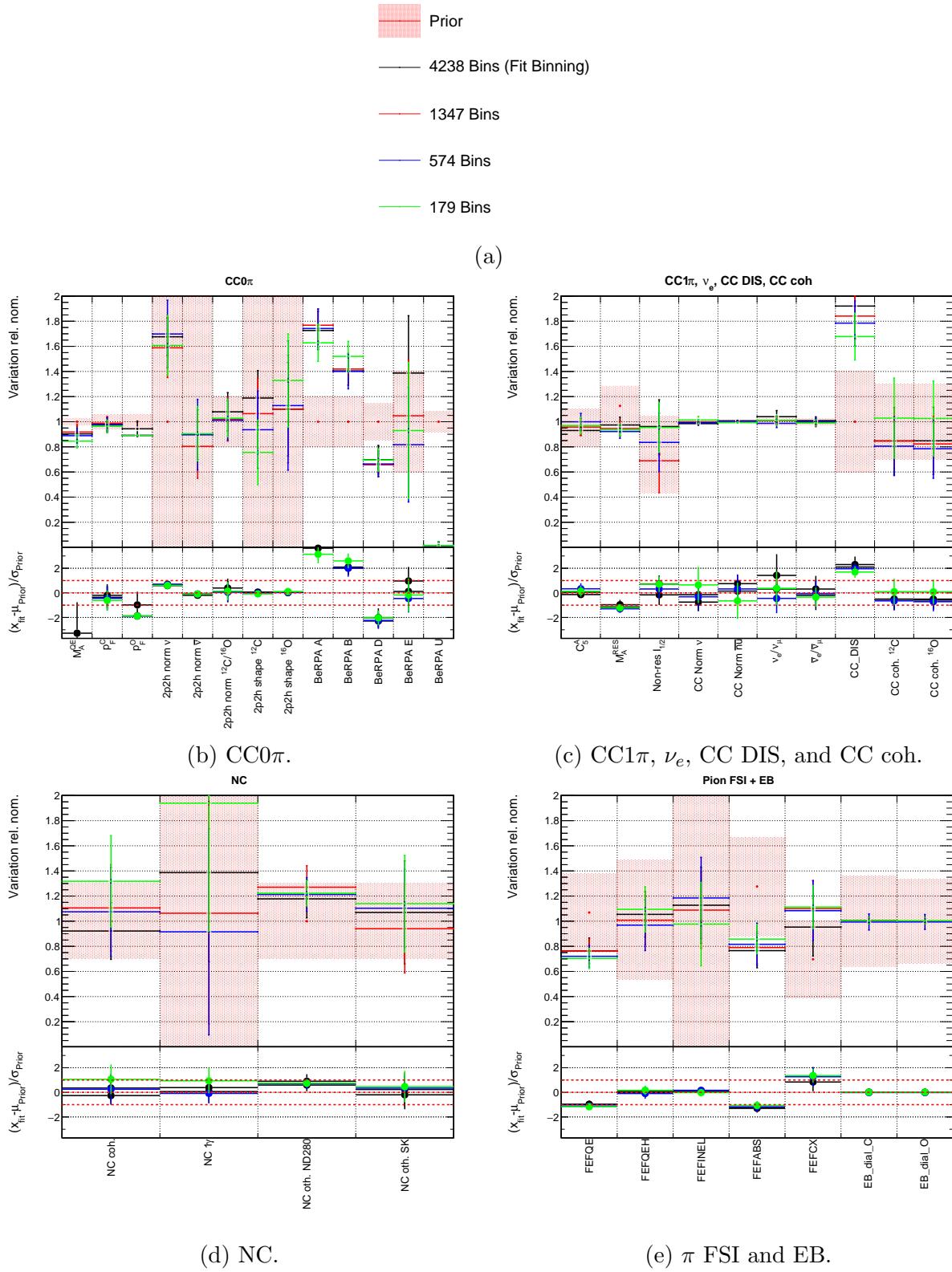


Figure 5.21.: Interaction parameters for fake data fits using different detector binnings.

5. The Near Detector Fit Setup

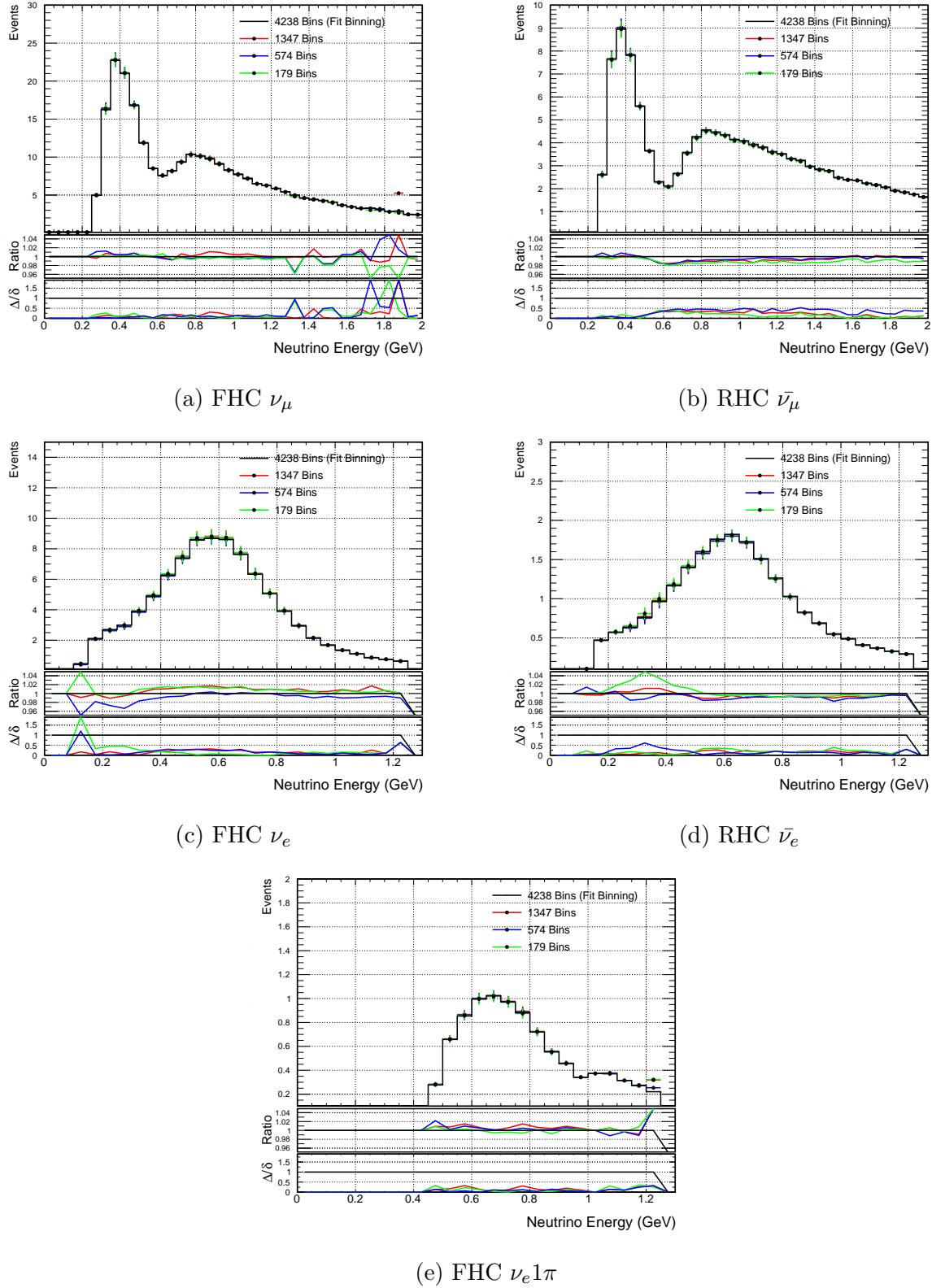


Figure 5.22.: SK posterior predictive distributions from near detector fits using different binnings for the detector covariance.

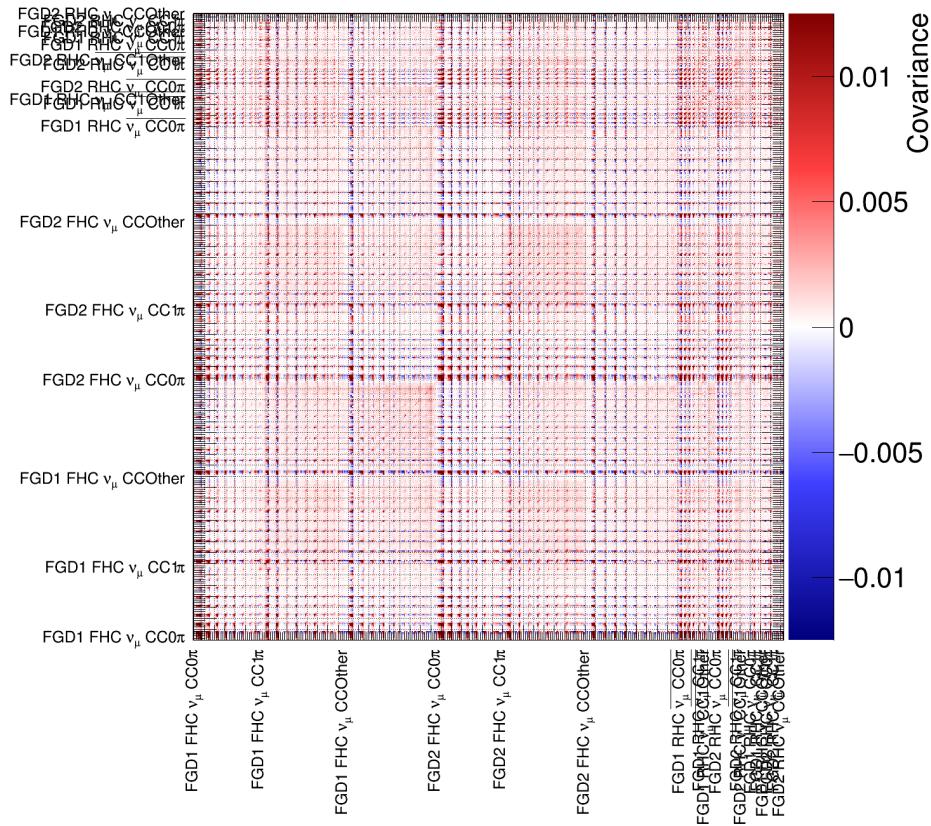


Figure 5.23.: The ND280 detector covariance matrix with 574 merged bins.

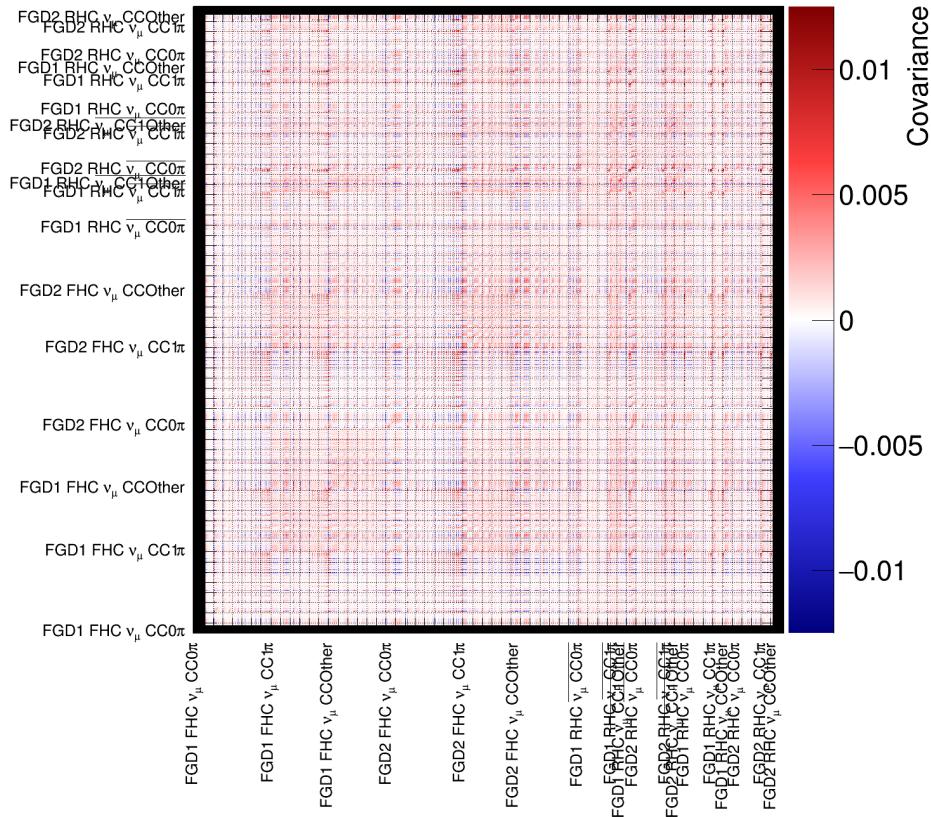


Figure 5.24.: The ND280 detector covariance matrix with the full 3071-bin non-uniform fit binning.

6. 2020 Near Detector Fit Results

6.1. Nominal MC

6.2. Log Likelihood Scans

6.3. Parameter Variations

6.4. Asimov Fit

6.5. Data Fit

6.6. Cross Group Validations

6.7. Posterior Predictions

6.8. Finer Fit and Detector Binning

6.8.1. Asimov Fits

6.8.2. Data Fits

6.8.3. Posterior Predictions

6.9. Oscillation Parameter Sensitivity

7. Conclusions

Appendices

A. Selection Binning

Templates for the fit binning for each sample are presented in this section, as it is not feasible to express the bin edges in text for non-uniform binning. Figure A.1 shows the x-axis range reduced to 0-5000 MeV so that the smaller bins in the peak can be seen. Figure A.2 shows the full distributions out to 30 GeV, for each sample.

A. Selection Binning

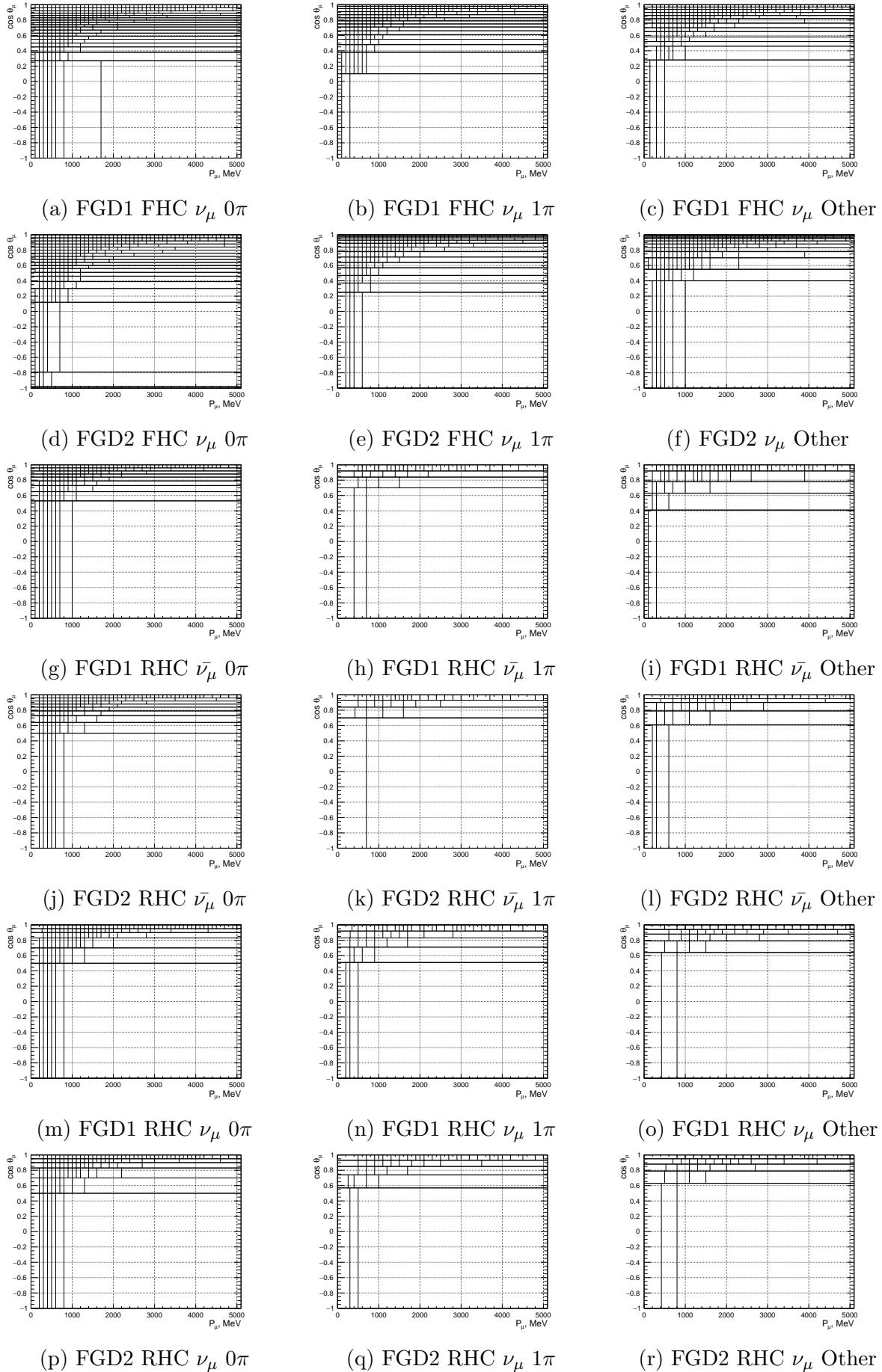


Figure A.1.: Non-uniform rectangular binning used in this analysis for each sample. The x-axis is reduced to better show the smaller bins at low momentum and high angle.

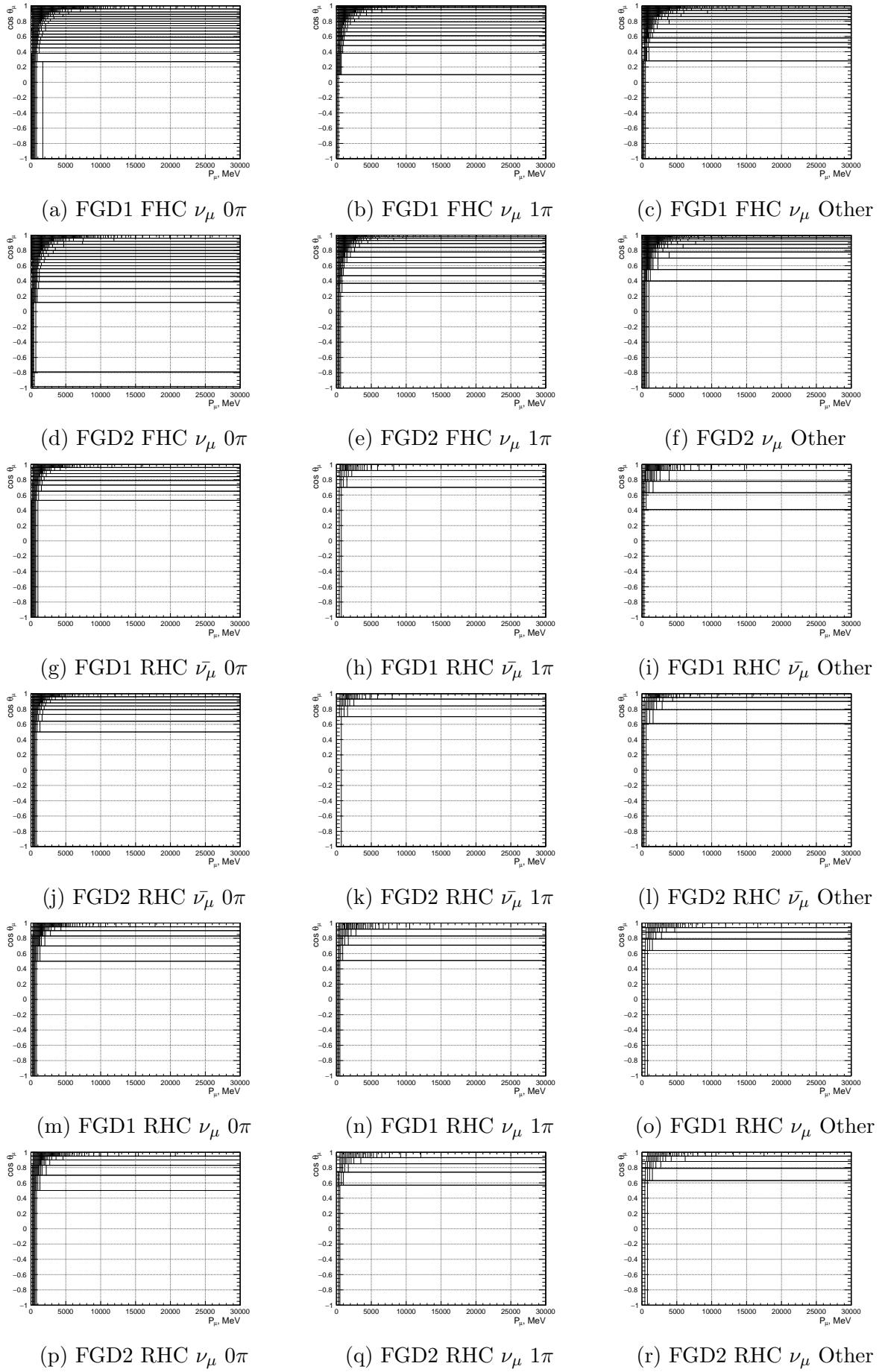


Figure A.2.: Non-uniform rectangular binning used in this analysis for each sample.

B. Alternative Fit Studies

B.1. FGD1 and FGD2 Only Fits

B.2. FHC and RHC Only Fits

B.3. New and Old Data Only Fits

B.4. Flat MAQE Prior and Less Q^2 Freedom

C. RHC Multi Pi Samples Validation

Various fits were run to validate the implementation of the RHC samples being divided by π rather than track multiplicity. Data fits using only runs 2-4 and 8 were run, as the FHC sample should be unaffected by the changes. The results are shown in Figures C.1 and C.2, and as expected, there is no difference using the RHC multi- π or RHC multi-track sample implementations.

To see the full impact of the change in samples, Asimov and data fits were run with the multi- π and track implementations, using FHC and RHC data (runs 2-8). The Asimov fit results, shown in Figures C.3 and C.4, are very similar for the two samples. The slight differences are due to marginalisation effects, and the two fits are entirely compatible. There is a very slight reduction in uncertainties using the RHC multi- π samples, showing a small improvement in sensitivity.

The data fits using both FHC and RHC data have more differences. The flux parameters, shown in Figure C.5, are pulled further from nominal at low energies. The oscillatory shape of the pulls in energy are similar for the two selections, and postfit values are consistently within 1σ of each other. The ND and SK flux parameters have similar behaviour.

The interaction parameters, shown in C.6, also have fairly significant differences. The 2p2h normalisations for ν and $\bar{\nu}$ are both closer to nominal using the mulit- π samples, whereas the 2p2h shape parameter on C is pulled about 1σ further. The CC1 π parameters are very compatible for the two selections, but the CC DIS parameter is closer to nominal for the mulit- π samples. The NC Other (NC1 π and NC DIS) is the only NC parameter to show any differences, being pulled $> 1\sigma$ higher. For the π FSI parameters, the high energy quasi-elastic and π absorption parameters are closer to nominal, whereas the charge exchange parameter is pulled further away for the mulit- π samples.

Overall the fits are largely compatible, with parameters mostly being within 1σ for the two selections, and often being closer to nominal for multi- π .

These validation fits were run using an intermediate cross-section model made up of the one used for the 2017 Oscillation Analysis, which is described in more in [104], plus normalisations

C. RHC Multi Pi Samples Validation

for the CC ν and $\bar{\nu}$ cross-section, Coulomb corrections, and binding energy dials.

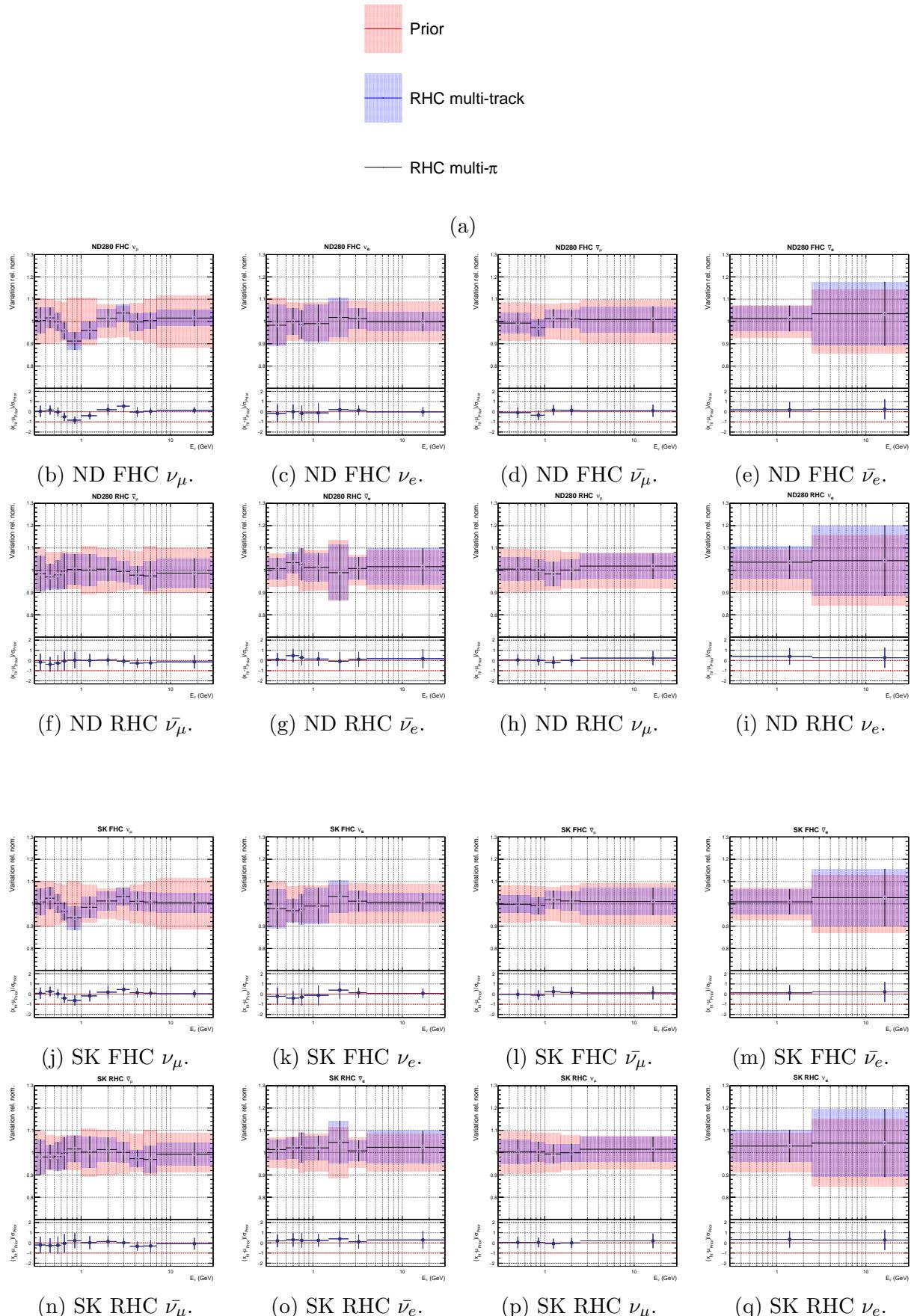


Figure C.1.: Flux parameters for Asimov fits using FHC only data.

C. RHC Multi Pi Samples Validation

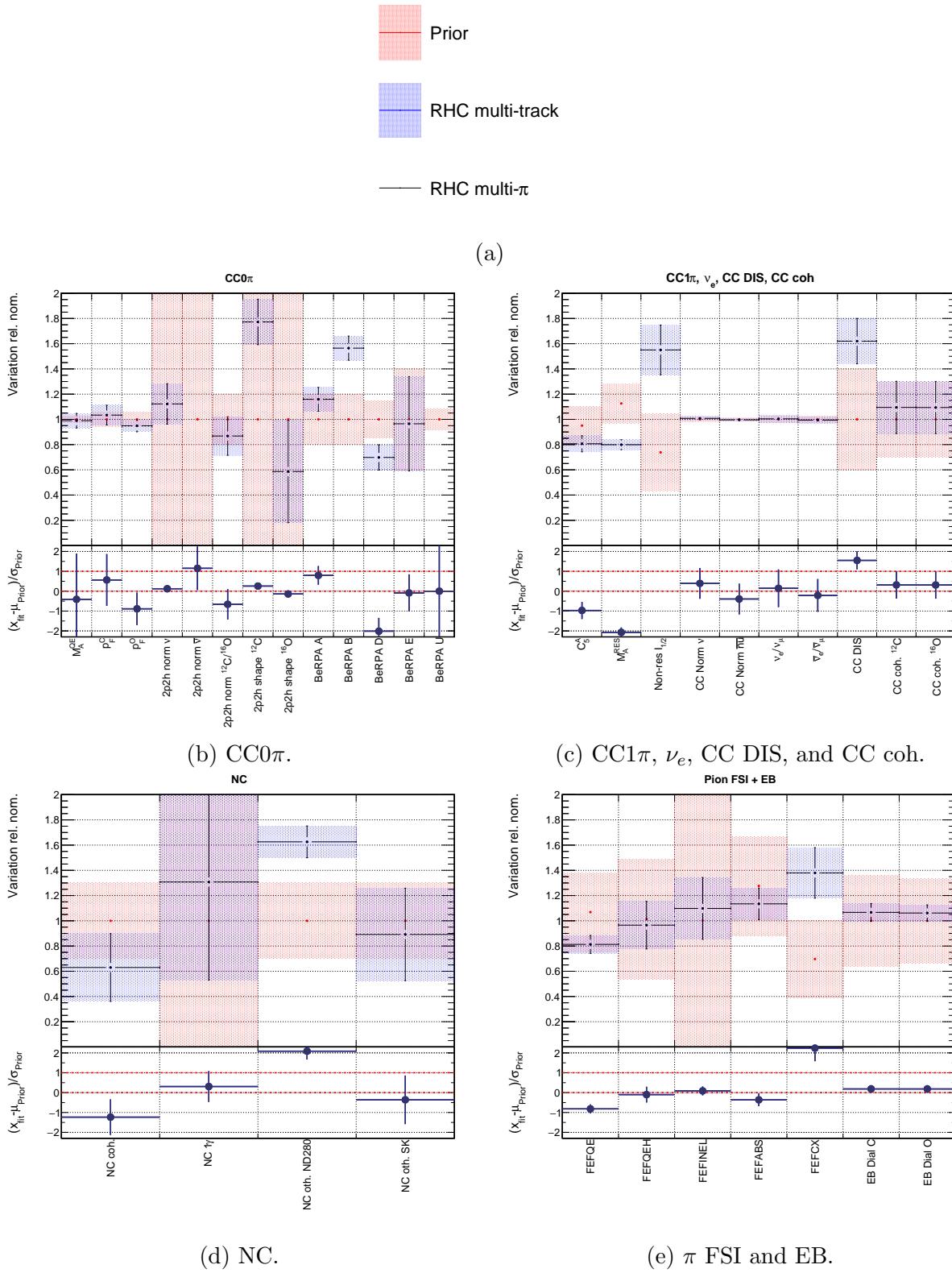


Figure C.2.: Interaction parameters for data fits using FHC only data.

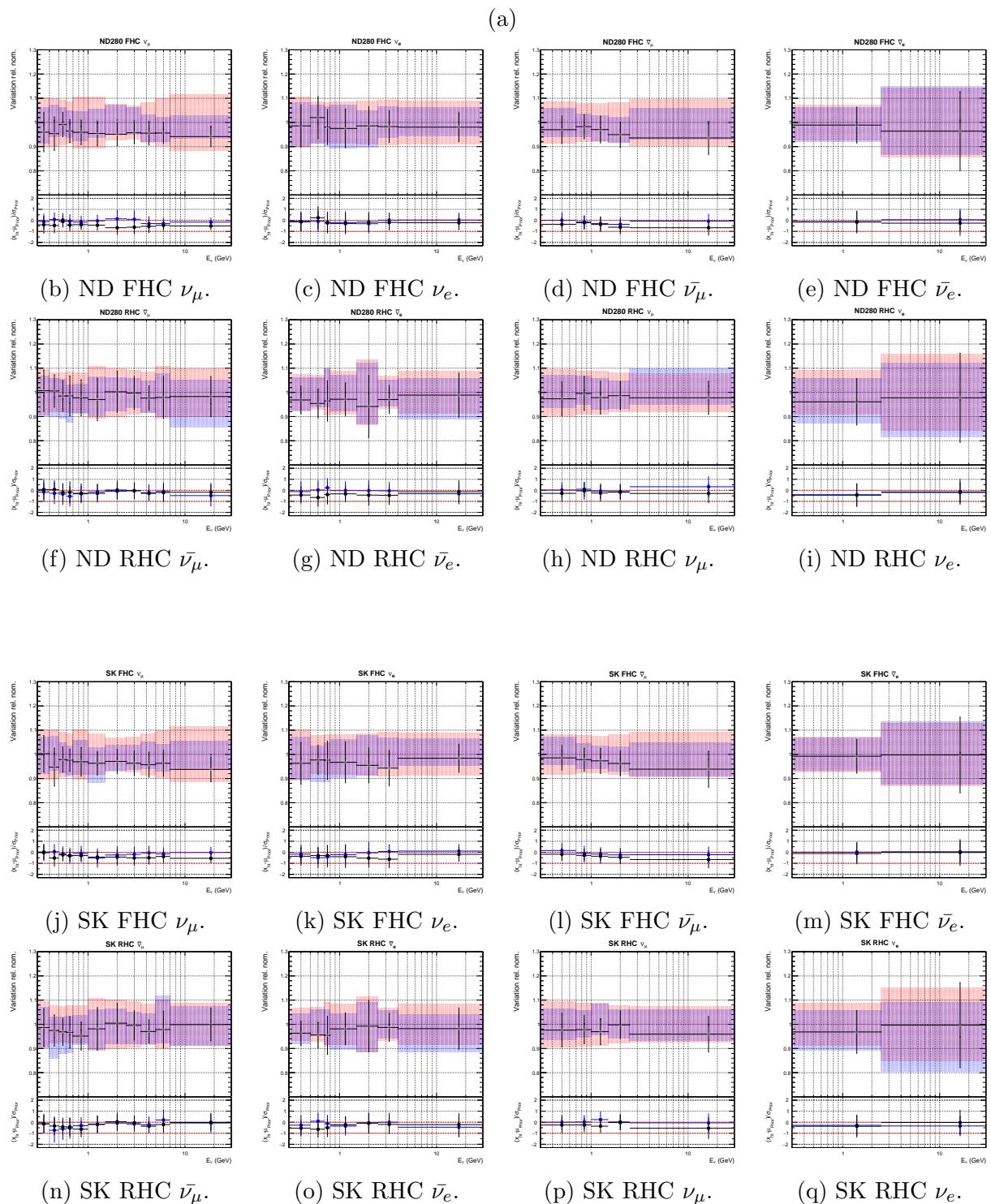
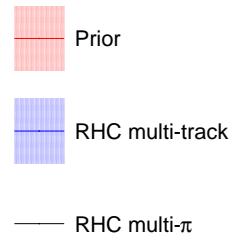


Figure C.3.: Flux parameters for Asimov fits using FHC and RHC data.

C. RHC Multi Pi Samples Validation

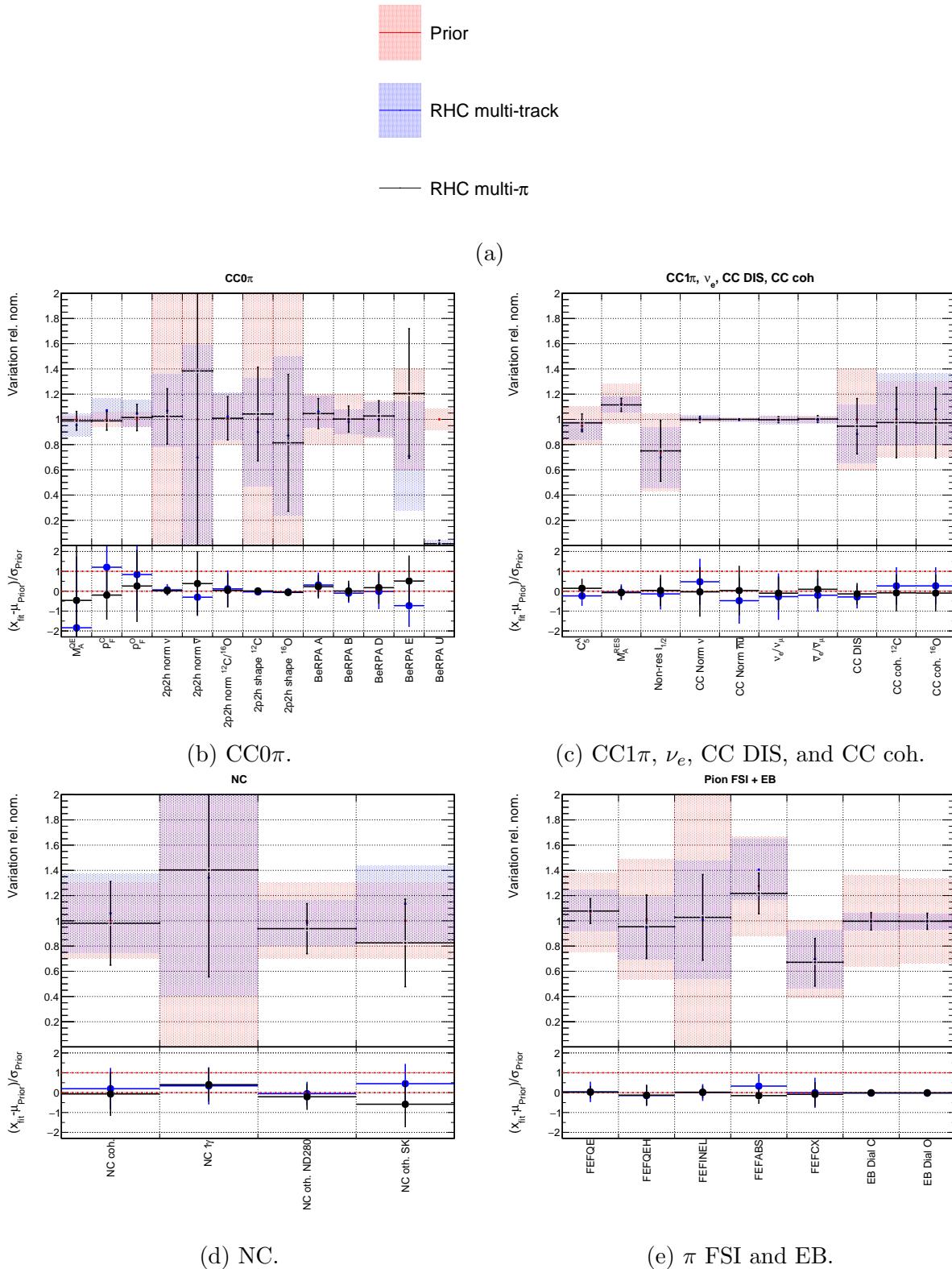


Figure C.4.: Interaction parameters for Asimov fits using FHC and RHC data.

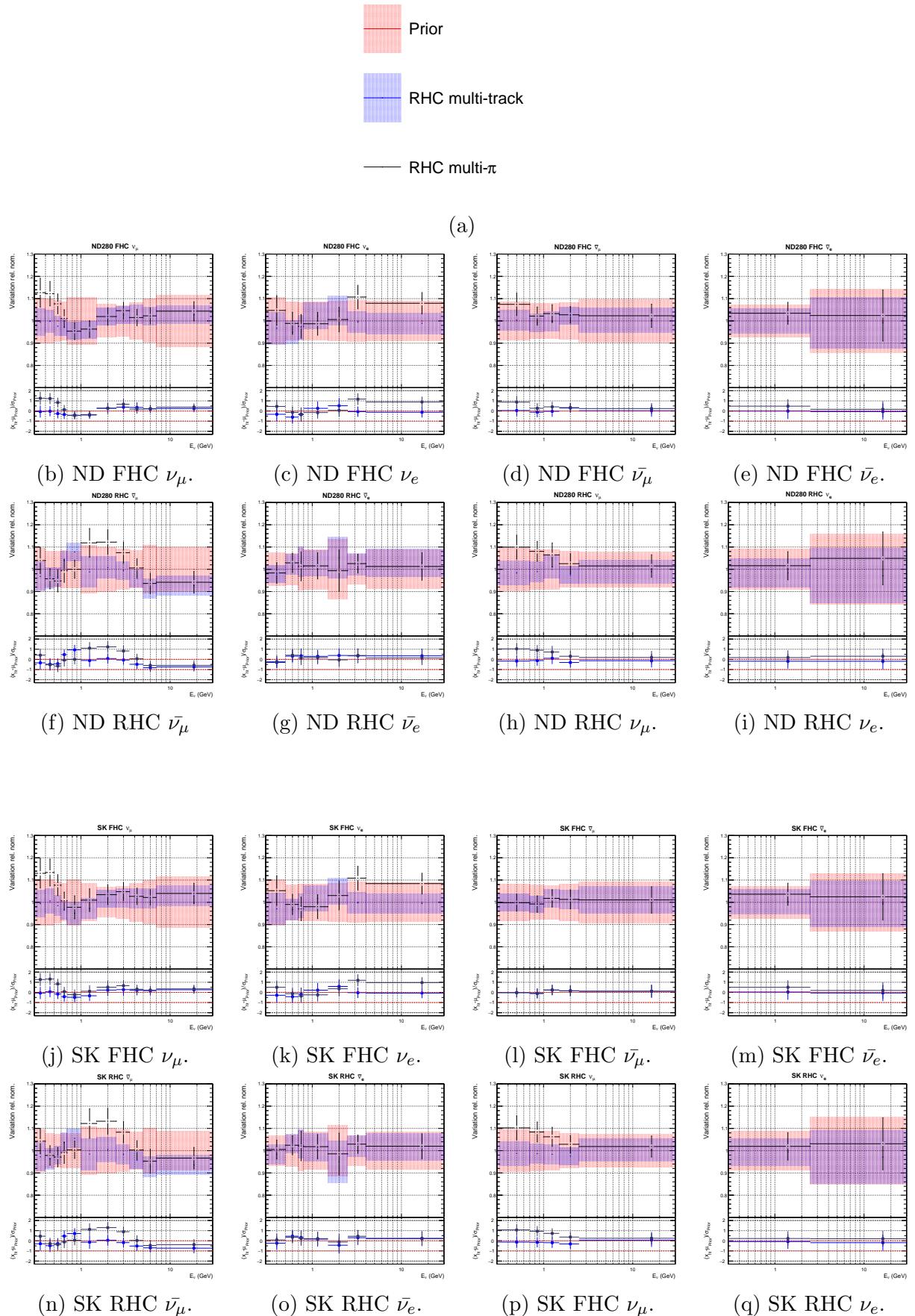


Figure C.5.: Flux parameters for data fits using FHC and RHC data.

C. RHC Multi Pi Samples Validation

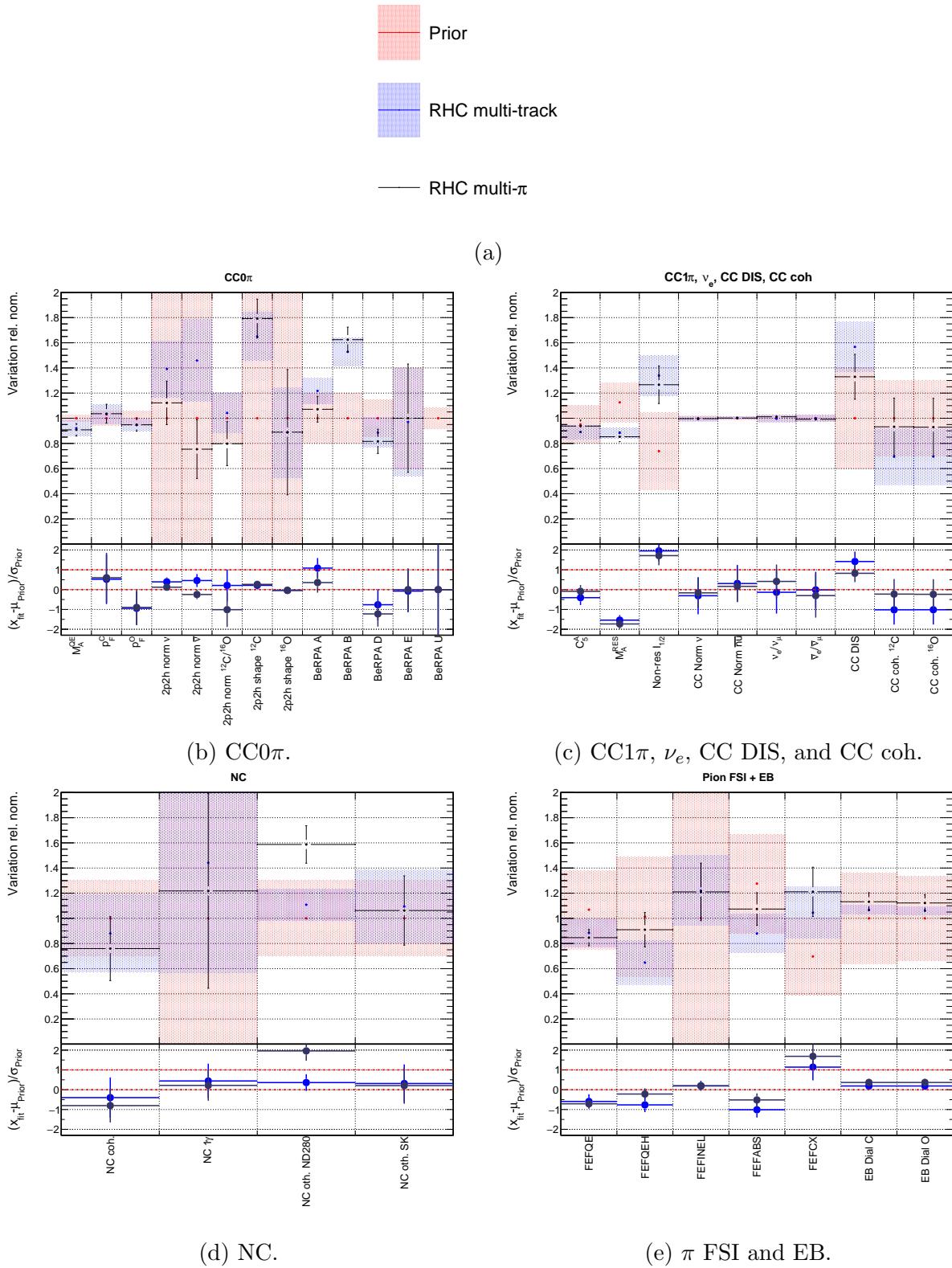


Figure C.6.: Interaction parameters for data fits using FHC and RHC data.

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