

Simultaneous Measurement of Oscillation Parameters in Beam and Atmospheric Neutrino Data from Tokai-to-Kamioka and Super-Kamiokande Experiments

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¹¹ for the Degree of Doctor of Philosophy

¹²

13 **Simultaneous Measurement of**

14 **Oscillation Parameters in Beam and**

15 **Atmospheric Neutrino Data from**

16 **Tokai-to-Kamioka and**

17 **Super-Kamiokande Experiments**

18 *Abstract*

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Acknowledgements

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¹³² **Chapter 1**

¹³³ **Neutrino Oscillation Physics**

¹³⁴ When first proposed, neutrinos were expected to be massless fermions that only in-
¹³⁵ teract through weak and gravitational forces. This meant they were very difficult to
¹³⁶ detect as they can pass through significant amounts of matter without interacting. De-
¹³⁷ spite this, experimental neutrino physics has developed with many different detection
¹³⁸ techniques and neutrino sources being used today. In direct tension with **the** standard
¹³⁹ model physics, neutrinos have been determined to oscillate between different lepton
¹⁴⁰ flavours, requiring them to have mass.

¹⁴¹ **The observation techniques which lead to the discovery of the neutrino are doc-**
¹⁴² **umented in section 1.1.** The theory underpinning neutrino oscillation is described
¹⁴³ in section 1.2. **This section and** includes the approximations which can be made to
¹⁴⁴ simplify the understanding of neutrino oscillation in **a the** two-flavour approxima-
¹⁴⁵ **tion as well as how the medium in which neutrinos propagate can manipulate the**
¹⁴⁶ **oscillation probability. The past Past**, current, and future neutrino experiments are
¹⁴⁷ detailed in section 1.3, including the reactor, atmospheric, and long-baseline accelerator
¹⁴⁸ neutrino sources that have been used to successfully constrain oscillation **parameters**
¹⁴⁹ **determination. Finally, the current state of oscillation parameter measurements are**
¹⁵⁰ **summarised in section 1.4.**

¹⁵¹ 1.1 Discovery of Neutrinos

¹⁵² At the start of the 20th century, the electrons emitted from the β -decay of the nucleus
¹⁵³ were found to have a continuous energy spectrum [1,2]. This observation seemingly
¹⁵⁴ broke the energy conservation invoked within that period's nuclear models. Postulated
¹⁵⁵ in 1930 by Pauli as the solution to this problem, the neutrino (originally termed
¹⁵⁶ "neutron") was theorized to be an electrically neutral spin-1/2 fermion with a mass
¹⁵⁷ of the same order of magnitude as the electron [3]. This neutrino was to be emitted
¹⁵⁸ with the electron in β -decay to alleviate the apparent breaking of energy conservation.
¹⁵⁹ As a predecessor of **the today's** weak interaction model, Fermi's theory of β -decay
¹⁶⁰ developed the understanding by coupling the four constituent particles; electron,
¹⁶¹ proton, neutron, and neutrino, into a consistent model [4].

¹⁶² Whilst Pauli was not convinced of the ability to detect neutrinos, **the first obser-**
¹⁶³ **vations of the particle were made in the mid-1950s when neutrinos from a reactor**
¹⁶⁴ **were observed via the inverse β -decay (IBD) process, $\bar{\nu}_e + p \rightarrow n + e^+$ [5,6]. The**
¹⁶⁵ **detector consisted of two parts: a neutrino interaction medium and a liquid scintillator.**
¹⁶⁶ **The interaction medium was built from two water tanks. These were loaded with**
¹⁶⁷ **cadmium chloride to allow increased efficiency of neutron capture. The positron**
¹⁶⁸ **emitted from IBD annihilates, $e^+ + e^- \rightarrow 2\gamma$, generating a prompt signal and the**
¹⁶⁹ **neutron is captured on the cadmium via $n + ^{108}Cd \rightarrow ^{109^*}Cd \rightarrow ^{109}Cd + \gamma$, producing**
¹⁷⁰ **a delayed signal. **The experiment observed an increase in the neutrino event rate****
¹⁷¹ ****when the reactor was operating compared to when it was switched off, in much the****
¹⁷² ****same way as modern reactor neutrino experiments operate. An increase in the coinci-****
¹⁷³ ****dence rate was observed when the reactor was operating which was interpreted****
¹⁷⁴ ****as interactions from neutrinos generated in the reactor.****

175 After the discovery of the ν_e , the natural question of how many flavours of neutrino
176 exist was asked. In 1962, a measurement of the ν_μ was conducted at the Brookhaven
177 National Laboratory [7]. A proton beam was directed at a beryllium target, gen-
178 erating a π -dominated beam which then decayed via $\pi^\pm \rightarrow \mu^\pm + (\nu_\mu, \bar{\nu}_\mu)$, and
179 the subsequent interactions of the ν_μ were observed. **As the subsequent interaction of the neutrino generates muons rather than electrons, it was determined the**
180 **ν_μ was fundamentally different from ν_e .** The final observation to be made was
181 that of the ν_τ from the DONUT experiment [8]. Three neutrinos seem the obvi-
182 ous solution as it mirrors the known number of charged lepton (as they form weak
183 isospin doublets) but there could be evidence of more. Several neutrino experi-
184 ments have found anomalous results [9, 10] which could be attributed to sterile
185 neutrinos . **However, however** cosmological observations indicate the number of
186 neutrino species $N_{eff} = 2.99 \pm 0.17$ [11], **as measured from the cosmic microwave**
187 **background power spectrum, and Stanford Linear Accelerator found the number**
188 **of active neutrino flavours to be $N_\nu 2.9840 \pm 0.0082$** [12] **from measurements of the**
189 **Z-decay width.**

191 1.2 Theory of Neutrino Oscillation

192 As direct evidence of beyond Standard Model physics, a neutrino generated with
193 lepton flavour α can change into a different lepton flavour β after propagating some
194 distance. This phenomenon is called neutrino oscillation and requires that neutrinos
195 must have a non-zero mass (as seen in subsection 1.2.1). This **observation** is direct
196 evidence of beyond standard model physics. This behaviour has been characterised
197 by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) [13–15] mixing matrix which
198 describes how the flavour and mass of neutrinos are associated. This is analogous to
199 the Cabibbo-Kobayashi-Maskawa (CKM) [16] matrix measured in quark physics.

200 1.2.1 Three Flavour Oscillations

201 The PMNS parameterisation defines three flavour eigenstates, ν_e , ν_μ and ν_τ (indexed
202 ν_α), which are **assigned based upon eigenstates of** the weak interaction **flavour states**
203 and three mass eigenstates, ν_1 , ν_2 and ν_3 (indexed ν_i). Each mass eigenstate is the
204 superposition of all three flavour states,

$$|\nu_i\rangle = \sum_{\alpha} U_{\alpha i} |\nu_{\alpha}\rangle. \quad (1.1)$$

205 **Where** U is the PMNS matrix which **is unitary and connects correlates** the mass
206 and flavour eigenstates.

207 **Neutrinos interact with leptons of the same weak flavour eigenstate rather than**
208 **mass eigenstate. The weak interaction couples to flavour eigenstates so neutrinos**
209 **interact with leptons of the same flavour.** The propagation of a neutrino flavour
210 eigenstate, in a vacuum, can be re-written as a plane-wave solution to the time-
211 dependent Schrödinger equation,

$$|\nu_{\alpha}(t)\rangle = \sum_i U_{\alpha i}^{*} |\nu_i\rangle e^{-i\phi_i}. \quad (1.2)$$

212 The probability of observing a neutrino of flavour eigenstate β from one which
213 originated as flavour α can be calculated as,

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \sum_{i,j} U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* e^{-i(\phi_j - \phi_i)} \quad (1.3)$$

²¹⁴ The ϕ_i term can be expressed in terms of the energy, E_i , and magnitude of the
²¹⁵ three momenta, p_i , of the neutrino, $\phi_i = E_i t - p_i x$ (t and x being time and position
²¹⁶ coordinates). Therefore,

$$\phi_j - \phi_i = E_j t - E_i t - p_j x + p_i x. \quad (1.4)$$

²¹⁷ For a relativistic particle, $E_i \gg m_i$,

$$p_i = \sqrt{E_i^2 - m_i^2} \approx E_i - \frac{m_i^2}{2E_i}. \quad (1.5)$$

²¹⁸ Making the approximations that neutrinos are relativistic, the mass eigenstates
²¹⁹ were created with the same energy and that $x = L$, where L is the distance traveled by
²²⁰ the neutrino, Equation 1.4 then becomes

$$\phi_j - \phi_i = \frac{\Delta m_{ij}^2 L}{2E}, \quad (1.6)$$

²²¹ where $\Delta m_{ij}^2 = m_i^2 - m_j^2$. This, **teamed combined** with further use of unitarity
²²² relations results in Equation 1.3 becoming

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re \left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \right) \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E} \right) \\ + (-) 2 \sum_{i>j} \Im \left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \right) \sin \left(\frac{\Delta m_{ij}^2 L}{2E} \right). \quad (1.7)$$

²²³ Where $\delta_{\alpha\beta}$ is the Kronecker delta function and the negative sign **on the last term** is
²²⁴ included for the oscillation probability of antineutrinos.

²²⁵ Typically, the PMNS matrix is parameterised into three mixing angles, a charge
²²⁶ parity (CP) violating phase δ_{CP} , and two Majorana phases $\alpha_{1,2}$,

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric, Accelerator}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor, Accelerator}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Reactor, Solar}} \underbrace{\begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Majorana}}. \quad (1.8)$$

²²⁷ Where $s_{ij} = \sin(\theta_{ij})$ and $c_{ij} = \cos(\theta_{ij})$. The oscillation parameters are often
²²⁸ grouped; (1,2) as “solar”, (2,3) as “atmospheric” and (1,3) as “reactor”. Many
²²⁹ neutrino experiments aim to measure the PMNS parameters from a wide array of
²³⁰ origins, as is the purpose of this thesis.

²³¹ The Majorana phase, $\alpha_{1,2}$, **containing matrix** included within **the fourth matrix**
²³² **in** Equation 1.8 is only included for completeness. For an oscillation analysis ex-
²³³ periment, **any term in this oscillation probability calculation containing this phase**
²³⁴ **disappears any terms containing this phase disappear** due to taking the expectation

²³⁵ value of the PMNS matrix. Measurements of these phases are typically performed
²³⁶ by experiments searching for neutrino-less double β -decay [17].

²³⁷ A two flavour approximation can be attained obtained when one assumes the third
²³⁸ mass eigenstate is degenerate with another. As discussed in section 1.3, it is found
²³⁹ that $\Delta m_{21}^2 \ll |\Delta m_{31}^2|$. This results in the two flavour approximation being reasonable
²⁴⁰ for understanding the features of the oscillation. In this two flavour case, the mixing
²⁴¹ matrix becomes,

$$U_{\text{2 Flav.}} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix}. \quad (1.9)$$

²⁴² This culminates in the oscillation probability,

$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\alpha) &= 1 - \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right), \\ P(\nu_\alpha \rightarrow \nu_\beta) &= \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right). \end{aligned} \quad (1.10)$$

²⁴³ For Where $\alpha \neq \beta$. For a fixed neutrino energy, the oscillation probability is a sinu-
²⁴⁴ soidal function depending upon the distance over which the neutrino propagates. The
²⁴⁵ frequency and amplitude of oscillation are dependent upon the ratio of the $\Delta m^2 / 4E$
²⁴⁶ and $\sin^2 2\theta$, respectively. The oscillation probabilities presented thus far assume
²⁴⁷ $c = 1$, where c is the speed of light in vacuum. In more familiar units, the maxi-
²⁴⁸ mum oscillation probability for a fixed value of θ is given at $L[\text{km}] / E[\text{GeV}] \sim 1.27 / \Delta m^2$.
²⁴⁹ It is this calculation that determines the best L/E value for a given experiment to be
²⁵⁰ designed around for measurements of a specific value of Δm^2 .

²⁵¹ 1.2.2 The MSW Effect

²⁵² The theory of neutrino oscillation in a vacuum **is has been** described in subsection 1.2.1.
²⁵³ However, the beam neutrinos and atmospheric neutrinos originating from below the
²⁵⁴ horizon propagate through matter in the Earth. The coherent scattering of neutrinos
²⁵⁵ from a material target modifies the Hamiltonian of the system. This results in a change
²⁵⁶ in the oscillation probability. Notably, charged current scattering ($\nu_e + e^- \rightarrow \nu_e + e^-$,
²⁵⁷ propagated by a W boson) only affects electron neutrinos **compared to whereas** the
²⁵⁸ neutral current scattering ($\nu_l + l^- \rightarrow \nu_l + l^-$, propagated by a Z^0 boson) interacts
²⁵⁹ through all neutrino flavours equally. In the two-flavour **limit approximation**, the
²⁶⁰ effective mixing parameter becomes

$$\sin^2(2\theta) \rightarrow \sin^2(2\theta_m) = \frac{\sin^2(2\theta)}{(A/\Delta m^2 - \cos(2\theta))^2 + \sin^2(2\theta)}, \quad (1.11)$$

²⁶¹ where $A = 2\sqrt{2}G_F N_e E$, **with** N_e is the electron density of the medium and G_F is
²⁶² Fermi's constant. It is clear to see that there exists a value of $A = \Delta m^2 \cos(2\theta)$ for
²⁶³ $\Delta m^2 > 0$ which results in a divergent mixing parameter. This resonance is **due to**
²⁶⁴ **termed** the Mikheyev-Smirnov-Wolfenstein (MSW) effect (or more colloquially, the
²⁶⁵ matter resonance) which regenerates the electron neutrino component of the neutrino
²⁶⁶ flux [18–20]. The density at which the resonance occurs is given by

$$N_e = \frac{\Delta m^2 \cos(2\theta)}{2\sqrt{2}G_F E}. \quad (1.12)$$

At densities lower than this critical value, the oscillation probability will be much closer to that of vacuum oscillation. **For antineutrinos, $N_e \rightarrow -N_e$** [21]. The resonance occurring from the MSW effect depends on the sign of Δm^2 . Therefore, any neutrino oscillation experiment which observes neutrinos and antineutrinos which have propagated through matter can have some sensitivity to the ordering of the neutrino mass eigenstates.

1.3 Neutrino Oscillation Measurements

As evidence of beyond standard model physics, the 2015 Nobel Prize in Physics was awarded to the Super-Kamiokande (SK) [22] and Sudbury Neutrino Observatory (SNO) [23] collaborations for the first definitive observation of solar and atmospheric neutrino oscillation [24]. Since then, the field has seen a wide array of oscillation measurements from a variety of neutrino sources. As seen in subsection 1.2.1, the neutrino oscillation probability is dependent on the ratio of the propagation baseline, L , to the neutrino energy, E . It is this ratio that determines the type of neutrino oscillation a particular experiment is sensitive to.

As illustrated in Figure 1.1, there are many neutrino sources that span a wide range of energies. The least energetic neutrinos are from diffuse supernovae and terrestrial neutrinos at $O(1)$ MeV whereas the most energetic neutrinos originate from atmospheric and galactic neutrinos of $> O(1)$ TeV.

1.3.1 Solar Neutrinos

Solar neutrinos are emitted from fusion reaction chains at the center of the Sun. The solar neutrino flux, given as a function of neutrino energy for different fusion and

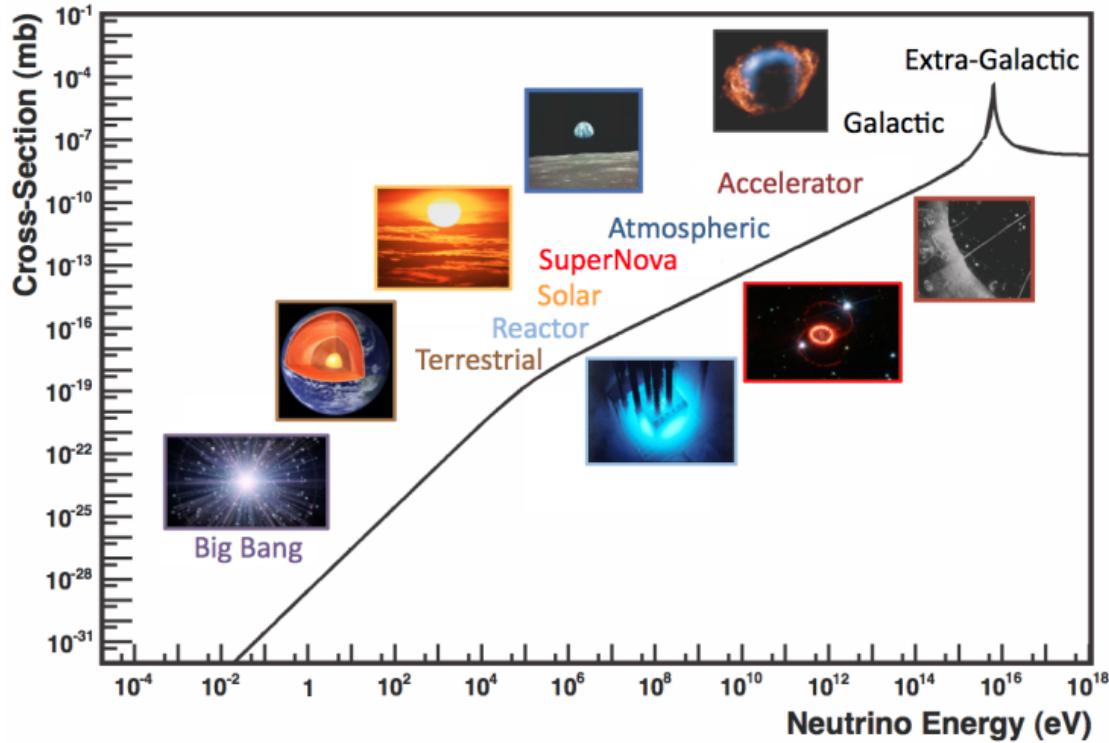


Figure 1.1: The cross-section of neutrinos from various natural and man-made sources as a function of neutrino energy. Taken from [25]

decay chains, is illustrated in Figure 1.2. Whilst proton-proton fusion generates the largest flux of neutrinos, the neutrinos are of low energy and are difficult to reconstruct due to the IBD interaction threshold of 1.8MeV. Consequently, most experiments focus on the neutrinos from the decay of 8B (via ${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$), which are higher energy.

The first measurements of solar neutrinos observed a significant reduction in the event rate compared to predictions from the Standard Solar Model [27, 28]. The proposed solution to this “solar neutrino problem” was $\nu_e \leftrightarrow \nu_\mu$ oscillations in a precursory version of the PMNS model [29]. The Kamiokande [30], Gallex [31] and Sage [32] experiments confirmed the ~ 0.5 factor deficit of solar neutrinos.

The conclusive solution to this problem was determined by the SNO collaboration [33]. Using a deuterium water target to observe 8B neutrinos, the event rate of charged current (CC), neutral current (NC), and elastic scattering (ES) interactions

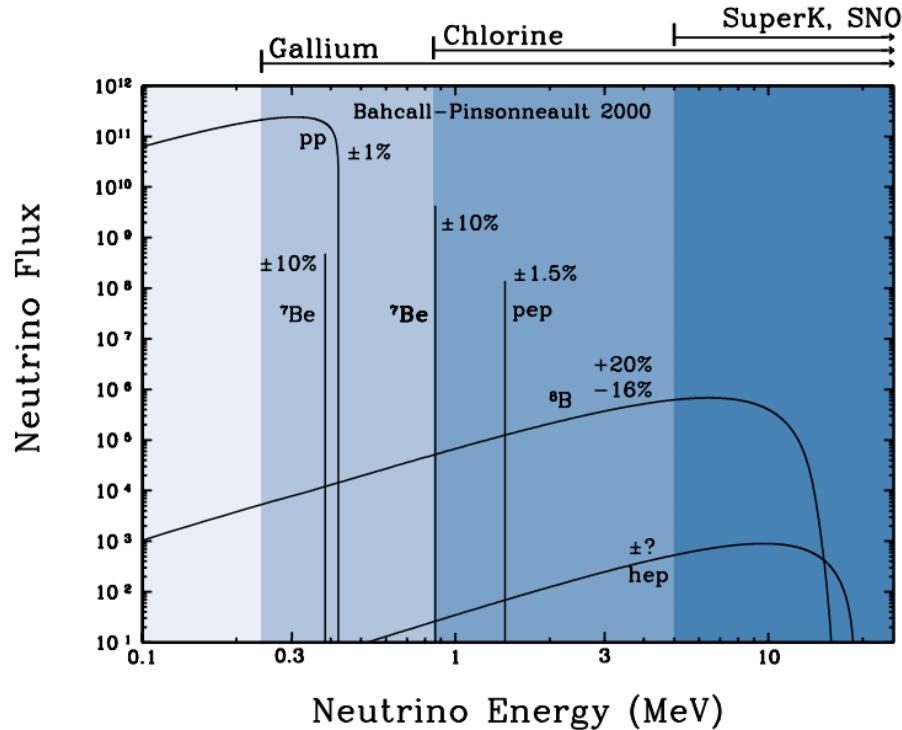
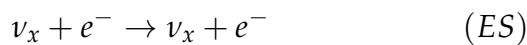
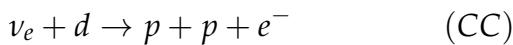


Figure 1.2: The solar neutrino flux as a function of neutrino energy for various fusion reactions and decay chains as predicted by the Standard Solar Model. Taken from [26].

(Given in Equation 1.13) was simultaneously measured. CC events can only occur for electron neutrinos, whereas the **other interaction NC channels are is** agnostic to neutrino flavour (**Although , and** the ES reaction **is more sensitive has a slight excess sensitivity** to electron neutrino interactions). This meant that there were direct measurements of the ν_e and ν_x neutrino flux. It was concluded that the CC and ES interaction rates were consistent with the deficit previously observed. Most importantly, the NC reaction rate was only consistent with the others under the hypothesis of flavour transformation.



³¹⁰ Many experiments have since measured the neutrino flux of different interaction
³¹¹ chains within the sun [34–36]. The most recent measurement was that of CNO neutrinos
³¹² which were recently observed with 5σ significance by the Borexino collaboration.
³¹³ Future neutrino experiments aim to further these spectroscopic measurements of
³¹⁴ different fusion chains within the Sun [37–39]. Solar neutrinos act as an irreducible
³¹⁵ background for dark matter experiments like DARWIN but oscillation parameter
³¹⁶ measurements can be made [40].

³¹⁷ 1.3.2 Atmospheric Neutrinos

³¹⁸ The interactions of primary cosmic ray protons in Earth’s upper atmosphere generate
³¹⁹ showers of energetic hadrons. These are mostly pions and kaons which when they
³²⁰ decay produce a natural source of neutrinos spanning energies of MeV to TeV [41].
³²¹ **This** The main decay is via

$$\begin{aligned} \pi^\pm &\rightarrow \mu^\pm + (\nu_\mu, \bar{\nu}_\mu) \\ \mu^\pm &\rightarrow e^\pm + (\nu_e, \bar{\nu}_e) + (\nu_\mu, \bar{\nu}_\mu) \end{aligned} \tag{1.14}$$

³²² such that for a single pion decay, three neutrinos are typically produced. The
³²³ atmospheric neutrino flux energy spectra as predicted by the Bartol [42], Honda
³²⁴ [43–45], and FLUKA [46] models are illustrated in Figure 1.3. The flux distribution
³²⁵ peaks at an energy of $O(10)\text{GeV}$. The uncertainties associated with these models
³²⁶ are dominated by the hadronic production of kaon and pions as well as the primary
³²⁷ cosmic flux.

³²⁸ Unlike long-baseline experiments which have a fixed baseline, the distance at-
³²⁹ mospheric neutrinos propagate is dependent upon the zenith angle at which they

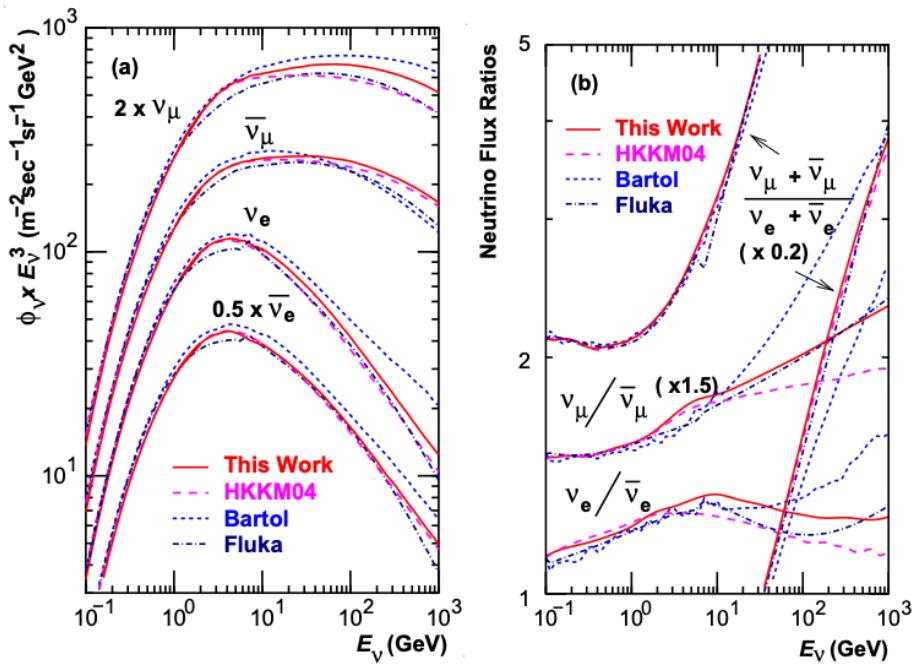


Figure 1.3: Left panel: The atmospheric neutrino flux for different neutrino flavours as a function of neutrino energy as predicted by the 2007 Honda model (“This work”) [43], the 2004 Honda model (“HKKM04”) [44], the Bartol model [42] and the FLUKA model [46]. Right panel: The ratio of the muon to electron neutrino flux as predicted by all the quoted models. Both figures taken from [43].

330 interact. This is illustrated in Figure 1.4. Neutrinos that are generated directly above
 331 the detector ($\cos(\theta) = 1.0$) have a baseline equivalent to the height of the atmosphere
 332 whereas neutrinos that interact directly below the detector ($\cos(\theta) = -1.0$) have to
 333 travel a length equal to the diameter of the Earth. This means atmospheric neutrinos
 334 have a baseline that varies from $O(20)\text{km}$ to $O(6 \times 10^3)\text{km}$. Any neutrino generated
 335 at or below the horizon will be subject to matter effects as they propagate through the
 336 Earth.

337 Figure 1.5 highlights the neutrino flux as a function of the zenith angle for different
 338 slices of neutrino energy. For medium to high-energy neutrinos (and to a lesser degree
 339 for low-energy neutrinos), the flux is approximately symmetric around $\cos(\theta) = 0$.
 340 To the accuracy of this approximation, the systematic uncertainties associated with
 341 atmospheric flux for comparing upward-going and down-going neutrino cancels. This

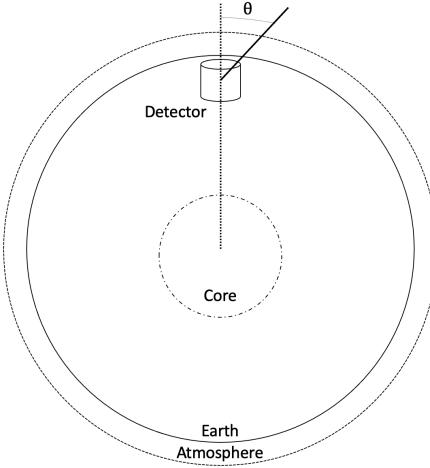


Figure 1.4: A diagram illustrating the definition of zenith angle as used in the Super Kamiokande experiment [47].

³⁴² allows the down-going events, which are mostly insensitive to oscillation probabilities,
³⁴³ to act as an unoscillated prediction (similar to a near detector in an accelerator neutrino
³⁴⁴ experiment).

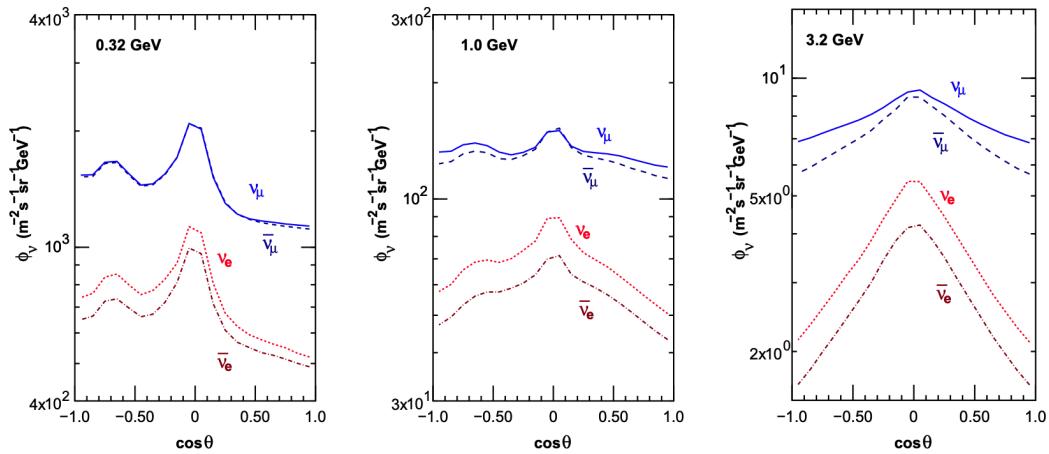


Figure 1.5: Prediction of ν_e , $\bar{\nu}_e$, ν_μ , $\bar{\nu}_\mu$ fluxes as a function of zenith angle as calculated by the HKKM model [45]. The left, middle and right panels represent three values of neutrino energy, 0.32GeV, 1.0GeV and 3.2GeV respectively. Predictions for other models including Bartol [42], Honda [43] and FLUKA [46] are given in [47].

³⁴⁵ Precursory hints of atmospheric neutrinos were observed in the mid-1960s search-
³⁴⁶ ing for $\nu_\mu^{(-)} + X \rightarrow X^* + \mu^\pm$ [48], although it was called an anomaly at the time of
³⁴⁷ measurement. This was succeeded with the IMB-3 [49] and Kamiokande [50] experi-

³⁴⁸ ments which measured the ratio of muon neutrinos compared to electron neutrinos
³⁴⁹ $R(\nu_\mu/\nu_e)$. Both experiments were found to have a consistent deficit of muon neutrinos,
³⁵⁰ with $R(\nu_\mu/\nu_e) = 0.67 \pm 0.17$ and $R(\nu_\mu/\nu_e) = 0.60^{+0.07}_{-0.06} \pm 0.05$. Super-Kamiokande
³⁵¹ (SK) [47] extended this analysis by fitting oscillation parameters in $P(\nu_\mu \rightarrow \nu_\tau)$ which
³⁵² found best fit parameters $\sin^2(2\theta) > 0.92$ and $1.5 \times 10^{-3} < \Delta m^2 < 3.4 \times 10^{-3} \text{ eV}^2$.

³⁵³ Since then, atmospheric neutrino experiments have been making precision mea-
³⁵⁴ surements of the $\sin^2(\theta_{23})$ and Δm^2_{32} oscillation parameters. Atmospheric neutrino
³⁵⁵ oscillation is dominated by $P(\nu_\mu \rightarrow \nu_\tau)$, where SK observed a 4.6σ discovery of ν_τ
³⁵⁶ appearance [51]. Figure 1.6 illustrates the current estimates on the atmospheric mixing
³⁵⁷ parameters from a wide range of atmospheric and accelerator neutrino observatories.

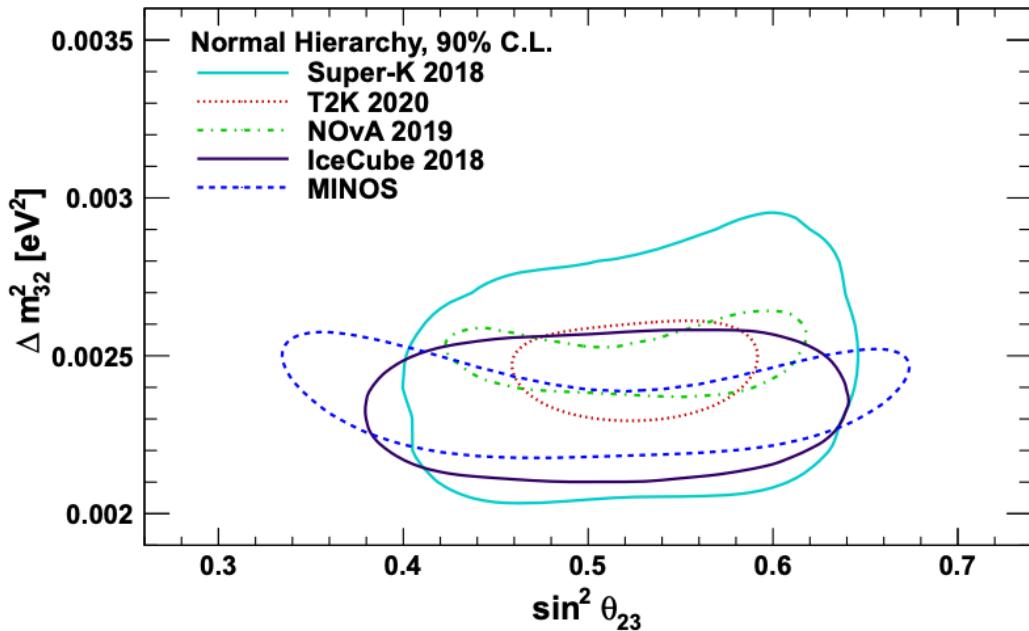


Figure 1.6: Constraints on the atmospheric oscillation parameters, $\sin^2(\theta_{23})$ and Δm^2_{32} , from atmospheric and long baseline experiments: SK [52], T2K [53], NOvA [54], IceCube [55] and MINOS [56]. Figure taken from [57].

³⁵⁸ 1.3.3 Accelerator Neutrinos

³⁵⁹ The concept of using a man-made “neutrino beam” was first realised in 1962 [58].
³⁶⁰ Since then, many experiments have followed which all use the same fundamental
³⁶¹ concepts. Typically, a proton beam is aimed at a target producing charged mesons that
³⁶² decay to neutrinos. The mesons can be sign-selected by the use of magnetic focusing
³⁶³ horns to generate a neutrino or antineutrino beam. Pions are the primary meson that
³⁶⁴ decay and depending on the orientation of the magnetic field, a muon (anti-)neutrino
³⁶⁵ beam is generated via $\pi^+ \rightarrow \mu^+ + \nu_\mu$ or $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$. The decay of muons and
³⁶⁶ kaons does result in an irreducible intrinsic electron neutrino background. In T2K,
³⁶⁷ this background contamination is $O(< 1\%)$ [59]. There is also an approximately
³⁶⁸ $\sim 5\%$ “wrong-sign” neutrino background of $\bar{\nu}_\mu$ generated via the same decays. **As**
³⁶⁹ **the beam is generated by proton interactions (rather than anti-proton interactions),**
³⁷⁰ **the wrong-sign component in the antineutrino beam is larger when operating in**
³⁷¹ **neutrino mode.**

³⁷² **The energy of each neutrino in the beam is dependent on the energy of the**
³⁷³ **initial proton beam. Therefore, tuning the proton energy allows Tuning the proton**
³⁷⁴ **energy in the beam and using beam focusing techniques allows** the neutrino energy
³⁷⁵ to be set to a value that maximises the disappearance oscillation probability in the L/E
³⁷⁶ term in Equation 1.10. This means that accelerator experiments are typically more
³⁷⁷ sensitive to the mixing parameters as compared to a natural neutrino source. However,
³⁷⁸ the disadvantage compared to atmospheric neutrino experiments is that the baseline
³⁷⁹ has to be shorter due to the lower flux. Consequently, there is typically less sensitivity
³⁸⁰ to matter effects and the ordering of the neutrino mass eigenstates.

³⁸¹ A neutrino experiment measures

$$R(\vec{x}) = \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(\vec{x}) \times P(\nu_\alpha \rightarrow \nu_\beta), \quad (1.15)$$

382 where $R(\vec{x})$ is the event rate of neutrinos at position \vec{x} , $\Phi(E_\nu)$ is the flux of neutrinos
 383 with energy E_ν , $\sigma(E_\nu)$ is the cross-section of the neutrino interaction and $\epsilon(\vec{x})$ is the
 384 efficiency **and resolution** of the detector. In order to leverage the most out of an
 385 accelerator neutrino experiment, the flux and cross-section systematics need to be
 386 constrained. This is typically done via the use of a “near detector”, situated at a baseline
 387 of $O(1)$ km. This detector observes the unoscillated neutrino flux and constrains the
 388 parameters used within the flux and cross-section model.

389 The first accelerator experiments to precisely measure oscillation parameters were
 390 MINOS [60] and K2K [61]. These experiments confirmed the $\nu_\mu \rightarrow \nu_\mu$ **oscillations**
 391 ν_μ **disappearance** seen in atmospheric neutrino experiments by finding consistent
 392 **mixing** parameter values for $\sin^2(\theta_{23})$ and Δm_{23}^2 . The current generation of accelera-
 393 tor neutrino experiments, T2K and NO ν A extended this field by observing $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
 394 and lead the sensitivity to atmospheric mixing parameters as seen in Figure 1.6 [62].
 395 The two experiments differ in their peak neutrino energy, baseline, and detection
 396 technique. The NO ν A experiment is situated at a baseline of 810km from the NuMI
 397 beamline which delivers 2GeV neutrinos. The T2K neutrino beam is peaked around
 398 0.6GeV and propagates 295km. The NO ν A experiment also uses functionally iden-
 399 tical detectors (near and far) which allow the approximate cancellation of detector
 400 systematics whereas T2K uses a plastic scintillator technique at the near detector and
 401 a water Cherenkov far detector. The future generation experiments DUNE [63] and
 402 Hyper-Kamiokande [64] will succeed these experiments as the high-precision era of
 403 neutrino oscillation parameter measurements develops.

⁴⁰⁴ Several anomalous results have been observed in the LSND [9] and MiniBooNE [10]
⁴⁰⁵ detectors which were designed with purposefully short baselines. Parts of the neu-
⁴⁰⁶ trino community attributed these results to oscillations induced by a fourth “sterile”
⁴⁰⁷ neutrino [65] but several searches in other experiments, MicroBooNE [66] and KAR-
⁴⁰⁸ MEN [67], found no hints of additional neutrino species. The solution to the anomalous
⁴⁰⁹ results **are is** still being determined.

⁴¹⁰ 1.3.4 Reactor Neutrinos

⁴¹¹ As illustrated in the first discovery of neutrinos (section 1.1), nuclear reactors are a very
⁴¹² useful man-made source of electron antineutrinos. For reactors that use low-enriched
⁴¹³ uranium ^{235}U as fuel, the antineutrino flux is dominated by the β -decay fission of ^{235}U ,
⁴¹⁴ ^{238}U , ^{239}Pu and ^{241}Pu [68] as illustrated in Figure 1.7.

⁴¹⁵ Due to their low energy, reactor electron antineutrinos predominantly interact
⁴¹⁶ via the inverse β -decay (IBD) interaction. The typical signature contains two signals
⁴¹⁷ delayed by $O(200)\mu\text{s}$; firstly the prompt photons from positron annihilation, and
⁴¹⁸ secondly the photons emitted ($E_{tot}^\gamma = 2.2\text{MeV}$) from de-excitation after neutron capture
⁴¹⁹ on hydrogen. Searching for both signals improves the detector’s ability to distinguish
⁴²⁰ between background and signal events [70]. Recently, SK included gadolinium dopants
⁴²¹ into the ultra-pure water to increase the energy released from the photon cascade to
⁴²² $\sim 8\text{MeV}$ and reduce the time of the delayed signal to $\sim 28\mu\text{s}$.

⁴²³ There are many short baseline experiments ($L \sim O(1)\text{km}$) that have measured the
⁴²⁴ $\sin^2(\theta_{13})$ and Δm_{23}^2 oscillation parameters. Daya Bay [71], RENO [72] and Double
⁴²⁵ Chooz [73] have all provided precise measurements, with the first discovery of a
⁴²⁶ non-zero θ_{13} made by Daya Bay and RENO (and **complimented complemented** by
⁴²⁷ T2K [73]). The constraints on $\sin^2(\theta_{13})$ by the reactor experiments lead the field and

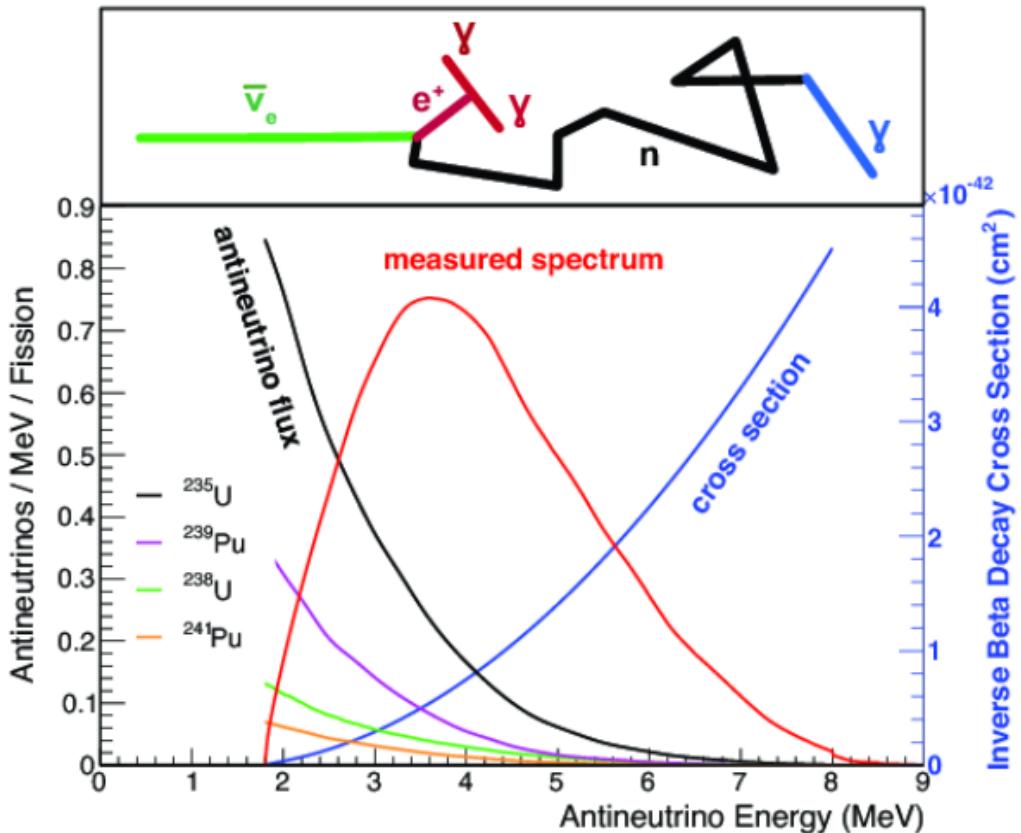


Figure 1.7: Reactor electron antineutrino fluxes for ^{235}U (Black), ^{238}U (Green), ^{239}Pu (Purple), and ^{241}Pu (Orange) isotopes. The inverse β -decay cross-section (Blue) and corresponding measurable neutrino spectrum (Red) are also given. Top panel: Schematic of Inverse β -decay interaction including the eventual capture of the emitted neutron. This capture emits a γ -ray which provides a second signal of the event. Taken from [69].

are often used as external inputs to accelerator neutrino experiments to improve their sensitivity to δ_{CP} and mass hierarchy determination. JUNO-TAO [74], a small collaboration within the larger JUNO experiment, is a next-generation reactor experiment that aims to precisely measure the isotopic antineutrino yields from the different fission chains. Alongside this, it aims to explain the ‘5MeV excess’ [75–77] by conducting a search for sterile neutrinos with a mass scale of around 1eV.

Kamland [78] is the only experiment to have observed reactor neutrinos using a long baseline (flux weighted averaged baseline of $L \sim 180\text{km}$) which allows it to have sensitivity to Δm_{12}^2 . Combined with the SK solar neutrino experiment, the combined

⁴³⁷ analysis puts the most stringent constraint on Δm_{12}^2 [79] ~~which is used as a prior uncertainty within accelerator neutrino experiments.~~

⁴³⁸ ~~which is used as a prior uncertainty within accelerator neutrino experiments.~~

⁴³⁹ 1.4 Summary

⁴⁴⁰ Since observing the first evidence of neutrino oscillations in the late 1990's, numerous
⁴⁴¹ measurements of the mixing parameters have been made. Many experiments use
⁴⁴² neutrinos as a tool for discovery of new physics (diffuse supernova background,
⁴⁴³ neutrinoless double beta decay and others) so the PMNS parameters are summarised
⁴⁴⁴ in the Particle Data Group (PDG) review tables. The analysis presented in this thesis
⁴⁴⁵ focuses on the 2020 T2K oscillation analysis presented in [80] where the 2018 PDG
⁴⁴⁶ constraints [81] were used. These constraints are outlined in Table 1.1.

| Parameter | 2018 Constraint |
|----------------------------------|--|
| $\sin^2(\theta_{12})$ | 0.307 ± 0.013 |
| Δm_{21}^2 | $(7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2$ |
| $\sin^2(\theta_{13})$ | $(2.12 \pm 0.08) \times 10^{-2}$ |
| $\sin^2(\theta_{23})$ (I.H., Q1) | $0.421^{+0.033}_{-0.025}$ |
| $\sin^2(\theta_{23})$ (I.H., Q2) | $0.592^{+0.023}_{-0.030}$ |
| $\sin^2(\theta_{23})$ (N.H., Q1) | $0.417^{+0.025}_{-0.028}$ |
| $\sin^2(\theta_{23})$ (N.H., Q2) | $0.597^{+0.024}_{-0.030}$ |
| Δm_{32}^2 (I.H.) | $(-2.56 \pm 0.04) \times 10^{-3} \text{ eV}^2$ |
| Δm_{32}^2 (N.H.) | $(2.51 \pm 0.05) \times 10^{-3} \text{ eV}^2$ |

Table 1.1: The 2018 Particle Data Group constraints of the oscillation parameters taken from [81]. The value of Δm_{23}^2 is given for both normal hierarchy (N.H.) and inverted hierarchy (I.H.) and $\sin^2(\theta_{23})$ is broken down by whether its value is below (Q1) or above (Q2) 0.5.

⁴⁴⁷ The $\sin^2(\theta_{13})$ measurement stems from the electron antineutrino disappearance,
⁴⁴⁸ $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$, and is take as the average best-fit from the combination of Daya Bay,
⁴⁴⁹ Reno and Double Chooz. It is often used as a prior uncertainty within other neu-

450 neutrino oscillation experiments, typically termed the reactor constraint. The $\sin^2(\theta_{12})$
451 parameter is predominantly measured through electron neutrino disappearance,
452 $P(\nu_e \rightarrow \nu_{\mu,\tau})$, in solar neutrino experiments. The long-baseline reactor neutrino ex-
453 periment Kamland also has sensitivity to this parameter and is used in a joint fit to
454 solar data from SNO and SK, using the reactor constraint. Measurements of $\sin^2(\theta_{23})$
455 are made by long-baseline and atmospheric neutrino experiments. The PDG value
456 is a joint fit of T2K, NO ν A , MINOS and IceCube DeepCore experiments. The latest
457 T2K-only measurement, provided at Neutrino2020 and is the basis of this thesis, is
458 given as $\sin^2(\theta_{23}) = 0.546^{+0.024}_{-0.046}$ [80]. The PDG constraint on Δm_{12}^2 is provided by the
459 KamLAND experiment using solar and geoneutrino data. This measurement utilised
460 a $\sin^2(\theta_{13})$ constraint from accelerator (T2K, MINOS) and reactor neutrino (Daya Bay,
461 RENO, Double Chooz) experiments. Accelerator measurements make some of the
462 most stringent constraints on Δm_{23}^2 although atmospheric experiments have more
463 sensitivity to the mass hierarchy determination. The PDG performs a joint fit of accel-
464 erator and atmospheric data, in both normal and inverted hierarchy separately. The
465 latest T2K-only result is $\Delta m_{32}^2 = 2.49^{+0.058}_{-0.082} \times 10^{-3} \text{ eV}^2$ favouring normal hierarchy [80].
466 The value of δ_{CP} is largely undetermined. CP-conserving values of 0 and π were
467 rejected with $\sim 2\sigma$ intervals, as published in Nature, although more recent analysis
468 have reduced the rejection intervals to 90%. Since the 2018 PDG publication, there has
469 been a new measurement of $\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$ [82], alongside updated
470 Δm_{23}^2 and $\sin^2(\theta_{23})$ measurements.

471 Throughout this thesis, several sample spectra predictions and contours are pre-
472 sented which require oscillation parameters to be assumed. Table 1.2 defines two sets
473 of oscillation parameters, with “Asimov A” set being close to the preferred values
474 from a previous T2K-only fit [83] and “Asimov B” being CP-conserving and further
475 from maximal θ_{23} mixing.

| Parameter | Asimov A | Asimov B |
|-----------------------|-------------------------------------|----------|
| Δm_{12}^2 | $7.53 \times 10^{-5} \text{ eV}^2$ | |
| Δm_{32}^2 | $2.509 \times 10^{-3} \text{ eV}^2$ | |
| $\sin^2(\theta_{12})$ | 0.304 | |
| $\sin^2(\theta_{13})$ | 0.0219 | |
| $\sin^2(\theta_{23})$ | 0.528 | 0.45 |
| δ_{CP} | -1.601 | 0.0 |

Table 1.2: Reference values of the neutrino oscillation parameters for two different oscillation parameter sets.

⁴⁷⁶

Chapter 2

⁴⁷⁷

T2K and SK Experiment Overview

⁴⁷⁸ As the successor of the Kamiokande experiment, the Super-Kamiokande (SK) collaboration has been leading atmospheric neutrino oscillation analyses for over two decades.

⁴⁷⁹ The detector has provided some of the strongest constraints on proton decay **limits** and **as well as** the first precise measurements of the Δm_{23}^2 and $\sin^2(\theta_{23})$ neutrino oscillation parameters. **Despite this, the The** ability of the detector to low-energy neutrino events has been significantly improved with the recent gadolinium doping of the ultra-pure water target. **section 2.1 describes the history, detection technique, and operation of the SK detector. The history, detection technique, and operation of the SK detector is described in section 2.1.**

⁴⁸⁷ The Tokai-to-Kamioka (T2K) experiment was one of the first long-baseline experiments to use both neutrino and antineutrino beams to precisely measure the charge parity violation within the neutrino sector. With the SK detector observing the oscillated neutrino flux, the T2K experiment observed the first hints of a non-zero $\sin^2(\theta_{13})$ measurement and continues to lead the field with the constraints it provides on $\sin^2(\theta_{13})$, $\sin^2(\theta_{23})$, Δm_{23}^2 and δ_{CP} . **section 2.2 documents the The** techniques which T2K uses in generating its neutrino beam as well as the near-detector used to constrain the flux and cross-section parameters **invoked within the systematic models used in this analysis are documented in section 2.2.**

⁴⁹⁶ 2.1 The Super-Kamiokande Experiment

⁴⁹⁷ The SK experiment began taking data in 1996 [84] and has had many modifications
⁴⁹⁸ throughout its lifespan. There have been seven defined periods of data taking as
⁴⁹⁹ noted in Table 2.1. Data taking began in SK-I which ran for five years. Between the
⁵⁰⁰ SK-I and SK-II periods, a significant proportion of the PMTs were damaged during
⁵⁰¹ maintenance. Those that survived were equally distributed throughout the detector
⁵⁰² in the SK-II era, which resulted in a reduced photo-coverage. From SK-III onwards,
⁵⁰³ repairs to the detector meant the full suite of PMTs was operational. Before the
⁵⁰⁴ start of SK-IV, the data acquisition and electronic systems were upgraded. Between
⁵⁰⁵ SK-IV and SK-V, a significant effort was placed into tank open maintenance and
⁵⁰⁶ repair/replacement of defective PMTs, a task for which the author of this thesis was
⁵⁰⁷ required. Consequently, the detector conditions were significantly different between
⁵⁰⁸ the two operational periods. SK-VI saw the start of the 0.01% gadolinium doped water.
⁵⁰⁹ SK-VII, which started during the writing of this thesis, has increased the gadolinium
⁵¹⁰ concentration to 0.03% for continued operation [85].

| Period | Start Date | End Date | Live-time (days) |
|--------|----------------|----------------|------------------|
| I | April 1996 | July 2001 | 1489.19 |
| II | October 2002 | October 2005 | 798.59 |
| III | July 2006 | September 2008 | 518.08 |
| IV | September 2008 | May 2018 | 3244.4 |
| V | January 2019 | July 2020 | 461.02 |
| VI | July 2020 | May 2022 | 583.3 |
| VII | May 2022 | Ongoing | N/A |

Table 2.1: The various SK periods and respective live-time. The SK-VI live-time is calculated until 1st April 2022. SK-VII started during the writing of this thesis.

511 2.1.1 The SK Detector

512 The basic structure of the Super-Kamiokande (SK) detector is a cylindrical tank with a
 513 diameter 39.3m and height 41.1m filled with ultrapure water [86]. A diagram of the
 514 significant components of the SK detector is [illustrated given](#) in Figure 2.1. The SK
 515 detector is situated in the Kamioka mine in Gifu, Japan. The mine is underground with
 516 roughly 1km rock overburden (2.7km water equivalent overburden) [87]. At this depth,
 517 the rate of cosmic ray muons is significantly decreased to a value of $\sim 2\text{Hz}$. The top of
 518 the tank is covered with stainless steel which is designed as a working platform for
 519 maintenance, calibration, and location for high voltage and data acquisition electronics.

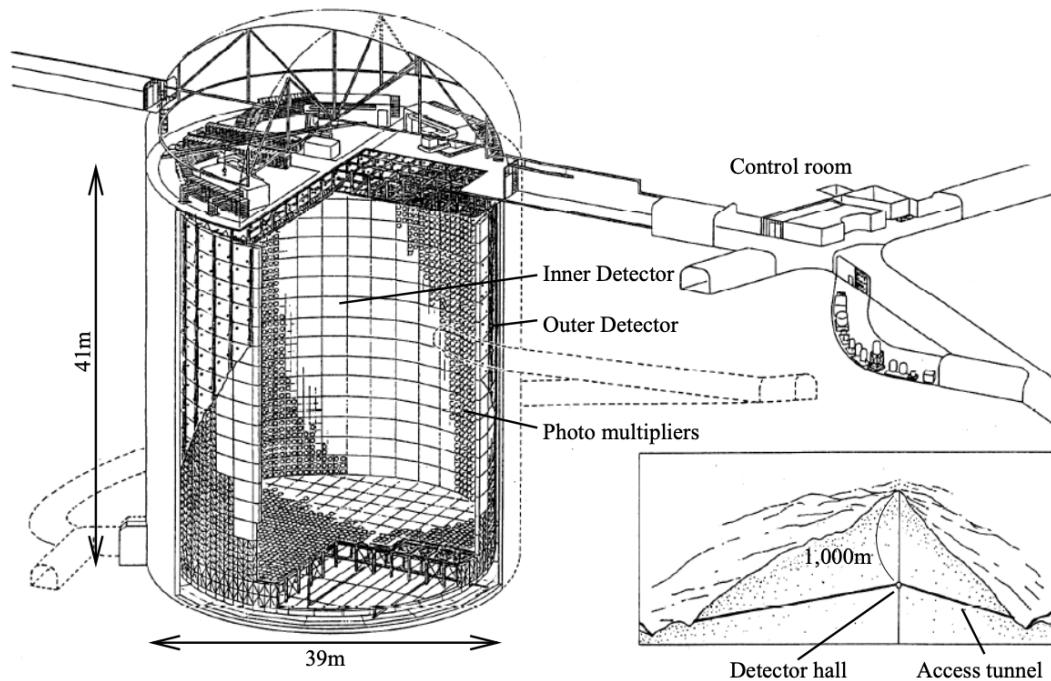


Figure 2.1: A schematic diagram of the Super-Kamiokande Detector. Taken from [88].

520 A smaller cylindrical structure (36.2m diameter, 33.8m height) is situated inside the
 521 tank, with an approximate 2m gap between this structure and the outer tank wall. The
 522 purpose of this structure is to support the photomultiplier tubes (PMTs). The volume
 523 inside and outside the support structure is referred to as the inner detector (ID) and

outer detector (OD), respectively. In the SK-IV era, the ID and OD are instrumented by 11,129 50cm and 1,885 20cm PMTs respectively [86]. The ID contains a 32kton mass of water. Many analyses performed at SK use a “fiducial volume” defined by the volume of water inside the ID excluding some distance to the ID wall. This reduces the volume of the detector which is sensitive to neutrino events but reduces radioactive backgrounds and allows for better reconstruction performance. The nominal fiducial volume is defined as the area contained inside 2m from the ID wall for a total of 22.5kton water [89].

The two regions of the detector (ID and OD) are optically separated with opaque black plastic. The purpose of this is to determine whether a track entered or exited the ID. This allows cosmic ray muons and partially contained events to be tagged and separated from neutrino events entirely contained within the ID. This black plastic is also used to cover the area between the ID PMTs to reduce photon reflection from the ID walls. Opposite to this, the OD is lined with a reflective material to allow photons to reflect around inside the OD until collected by one of the PMTs. Furthermore, each OD PMT is backed with $50 \times 50\text{cm}$ plates of wavelength shifting acrylic which increases the efficiency of light collection [87].

In the SK-IV data-taking period, the photocathode coverage of the detector, or the fraction of the ID wall instrumented with PMTs, is $\sim 40\%$ [87]. The PMTs have a quantum efficiency (the ratio of detected electrons to incident photons) of $\sim 21\%$ for photons with wavelengths of $360\text{nm} < \lambda < 390\text{nm}$. The proportion of photoelectrons that produce a signal in the dynode of a PMT, termed the collection efficiency, is $> 70\%$ [87]. The PMTs used within SK are most sensitive to photons with wavelength $300\text{nm} \leq \lambda \leq 600\text{nm}$ [87]. One disadvantage of using PMTs as the detection media is that the Earth’s geomagnetic field can modify its response. Therefore, a set of

549 compensation coils is built around the inner surface of the detector to mitigate this
550 effect [90].

551 As mentioned, the SK detector is filled with ultrapure water, which in a perfect
552 world would contain no impurities. However, bacteria and organic compounds can
553 significantly degrade the water quality. This decreases the attenuation length, which
554 reduces the total number of photons that hit a PMT. To combat this, a sophisticated
555 water treatment system has been developed [87, 91]. UV lights, mechanical filters,
556 and membrane degasifiers are used to reduce the bacteria, suspended particulates,
557 and radioactive materials from the water. The flow of water within the tank is also
558 critical as it can remove stagnant bacterial growth or build-up of dust on the surfaces
559 within the tank. Gravity drifts impurities in the water towards the bottom of the
560 tank which, if left uncontrolled, can create asymmetric water conditions between
561 the top and bottom of the tank. Typically, the water entering the tank is cooled
562 below the ambient temperature of the tank to control convection and inhibit bacteria
563 growth. Furthermore, the **rate of** dark noise hits within PMTs is sensitive to the PMT
564 temperature [92] so controlling the temperature gradients within the tank is beneficial
565 for stable measurements.

566 SK-VI is the first phase of the SK experiment to use gadolinium dopants within
567 the ultrapure water [85]. As such, the SK water system had to be replaced to avoid
568 removing the gadolinium concentrate from the ultrapure water [93]. For an inverse
569 β -decay (IBD) interaction in a water target, the emitted neutron is thermally captured
570 on hydrogen. This process releases 2.2MeV γ rays which are difficult to detect **due**
571 **to as the resulting** Compton scattered electrons ~~from a γ ray of this energy is are~~
572 very close to the Cherenkov threshold, limiting the number of photons produced.
573 Thermal capture of neutrons on gadolinium generates γ rays with higher energy
574 (**8MeV [70]**) meaning they are more easily detected. SK-VI has 0.01% Gd loading

575 (0.02% gadolinium sulphate by mass) which causes $\approx 50\%$ of neutrons emitted by IBD
576 to be captured on gadolinium [94, 95]. Whilst predominantly useful for low energy
577 analyses, Gd loading allows better $\nu/\bar{\nu}$ separation for atmospheric neutrino event
578 selections [96]. Efforts are currently in place to increase the gadolinium concentrate
579 to 0.03% for $\approx 75\%$ neutron capture efficiency on gadolinium [97]. The final stage of
580 loading targets 0.1% concentrate.

581 2.1.2 Calibration

582 The calibration of the SK detector is documented in [86] and summarised below. The
583 analysis presented within this thesis is dependent upon ‘high energy events’ (Charged
584 particles with $O(> 100)\text{MeV}$ momenta). These are events that are expected to generate
585 a larger number of photons such that each PMT will be hit with multiple photons.
586 The reconstruction of these events depends upon the charge deposited within each
587 PMT and the timing response of each individual PMT. Therefore, the most relevant
588 calibration techniques to this thesis are outlined.

589 Before installation, 420 PMTs were calibrated to have identical charge responses
590 and then distributed throughout the tank in a cross-shape pattern (As illustrated by
591 Figure 2.2). These are used as a standardised measure for the rest of the PMTs installed
592 at similar geometric positions within SK to be calibrated against. To perform this
593 calibration, a xenon lamp is located at the center of the SK tank which flashes uniform
594 light at 1Hz. This allows for geometrical effects, water quality variation, and timing
595 effects to be measured in-situ throughout normal data-taking periods.

596 When specifically performing calibration of the detector (in out-of-data taking
597 mode), the water in the tank was circulated to avoid top/bottom asymmetric water
598 quality. Any non-uniformity within the tank significantly affects the PMT hit proba-

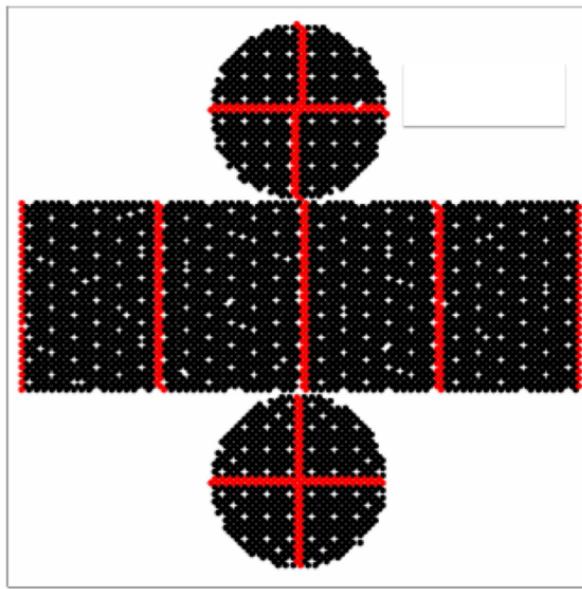


Figure 2.2: The location of “standard PMTs” (red) inside the SK detector. Taken from [86].

599 bility through scattering or absorption. This becomes a dominant effect for the very
 600 low-intensity light sources discussed later which are designed such that only one
 601 photon is incident upon a given PMT.

602 The “gain” of a PMT is defined as the ratio of the total charge of the signal produced
 603 compared to the charge of photoelectrons emitted by the photocathodes within the
 604 PMT. To calibrate the signal of each PMT, the “relative” and “absolute” gain values are
 605 measured. The relative gain is the variation of gain among each of the PMTs whereas
 606 the absolute gain is the average gain of all PMTs.

607 The relative gain is calibrated as follows. A laser is used to generate two measure-
 608 ments: a high-intensity flash that illuminates every PMT with a sufficient number of
 609 photons, and a low-intensity flash in which only a small number of PMTs collect light.
 610 The first measurement creates an average charge, $Q_{obs}(i)$ on PMT i , whereas the second
 611 measurement ensures that each hit PMT only generates a single photoelectron. For the
 612 low-intensity measurement, the number of times each PMT records a charge larger
 613 than 1/4 photoelectrons, $N_{obs}(i)$, is counted. The values measured can be expressed as

$$\begin{aligned} Q_{obs}(i) &\propto I_H \times f(i) \times \epsilon(i) \times G(i), \\ N_{obs}(i) &\propto I_L \times f(i) \times \epsilon(i), \end{aligned} \quad (2.1)$$

614 Where I_H and I_L is the intensity of the high and low flashes, $f(i)$ is the acceptance
 615 efficiency of the i^{th} PMT, $\epsilon(i)$ is the product of the quantum and collection efficiency
 616 of the i^{th} PMT and $G(i)$ is the gain of the i^{th} PMT. The relative gain for each PMT can
 617 determined by taking the ratio of these quantities.

618 The absolute gain calibration is performed by observing fixed energy γ -rays of
 619 $E_\gamma \sim 9\text{MeV}$ emitted isotropically from neutron capture on a NiCf source situated at
 620 the center of the detector. This generates a photon yield of about 0.004 photoelec-
 621 trons/PMT/event, meaning that $> 99\%$ of PMT signals are generated from single
 622 photoelectrons. A charge distribution is generated by performing this calibration over
 623 all PMTs, and the average value of this distribution is taken to be the absolute gain
 624 value.

625 As mentioned in subsection 2.1.1, the average quantum and collection efficiency
 626 for the SK detector is $\sim 21\%$ and $> 70\%$ respectively. However, these values do differ
 627 between each PMT and need to be calibrated accordingly. Consequently, the NiCf
 628 source is also used to calibrate the “quantum \times collection” efficiency (denoted “QE”)
 629 value of each PMT. The NiCf low-intensity source is used as the PMT hit probability
 630 is proportional to the QE ($N_{obs}(i) \propto \epsilon(i)$ in Equation 2.1). A Monte Carlo prediction
 631 which includes photon absorption, scattering, and reflection is made to estimate the
 632 number of photons incident on each PMT and the ratio of the number of predicted
 633 to observed hits is calculated. The difference is attributed to the QE efficiency of that
 634 PMT. This technique is extended to calculate the relative QE efficiency by normalizing
 635 the average of all PMTs which removes the dependence on the light intensity.

636 Due to differing cable lengths and readout electronics, the timing response between
637 a photon hitting the PMT and the signal being captured by the data acquisition can be
638 different between each PMT. Due to threshold triggers (Described in subsection 2.1.3),
639 the time at which a pulse reaches a threshold is dependent upon the size of the pulse.
640 This is known as the ‘time-walk’ effect and also needs to be accounted for in each PMT.
641 To calibrate the timing response, a pulse of light with width 0.2ns is emitted into the
642 detector through a diffuser. Two-dimensional distributions of time and pulse height
643 (or charge) are made for each PMT and are used to calibrate the timing response. This
644 is performed in-situ **whilst during** data taking with the light source pulsing at 0.03Hz.

645 The top/bottom water quality asymmetry is measured using the NiCf calibration
646 data and cross-referencing these results to the “standard PMTs”. The water attenuation
647 length is continuously measured by the rate of vertically-downgoing cosmic-ray
648 muons which enter via the top of the tank.

649 Dark noise is the phenomenon where a PMT registers a pulse that is consistent
650 with a single photoelectron emitted from photon detection despite the PMT being in
651 complete darkness. This is predominately caused by two processes. Firstly there is
652 intrinsic dark noise which is where photoelectrons gain enough thermal energy to be
653 emitted from the photocathode, and secondly, the radioactive decay of contaminants
654 inside the structure of the PMT. Typical dark noise rate for PMTs used within SK are
655 $O(3)$ kHz [87] **which equates to about 12 dark noise hits per 220ns**. This is lower than
656 the expected number of photons generated for a ‘high energy event’ (As described in
657 subsection 2.1.4) but instability in this value can cause biases in reconstruction. Dark
658 noise is related to the gain of a PMT and is calibrated using hits inside a time window
659 recorded before an event trigger [98].

660 2.1.3 Data Acquisition and Triggering

661 The analysis presented in this thesis only uses the SK-IV period of the SK experiment
662 so this subsection focuses on the relevant points of the data acquisition and triggering
663 systems to that SK period. The earlier data acquisition and triggering systems are
664 documented in [99, 100].

665 Before the SK-IV period started, the existing front-end electronics were replaced
666 with “QTC-Based Electrons with Ethernet, QBEE” systems [101]. When the QBEE
667 observes a signal above a 1/4 photoelectron threshold, the charge-to-time (QTC)
668 converter generates a rectangular pulse. The start of the rectangular pulse indicates
669 the time at which the analog photoelectron signal was received and the width of the
670 pulse indicates the total charge integrated throughout the signal. This is then digitized
671 by time-to-digital converters and sent to the “front-end” PCs. The digitized signal
672 from every QBEE is then chronologically ordered and sent to the “merger” PCs. It is
673 the merger PCs that apply the software trigger. Any triggered events are passed to the
674 “organizer” PC. This sorts the data stream of multiple merger PCs into chronologically
675 ordered events which are then saved to disk. The schematic of data flow from PMTs to
676 disk is illustrated in Figure 2.3.

677 The software trigger (described in [103]) operates by determining the number of
678 PMT hits within a 200ns sliding window, $N_{200\text{ns}}$. **This window** coincides with the
679 maximum time that a Cherenkov photon would take to traverse the length of the SK
680 tank [100]. For lower energy events that generate fewer photons, this technique is
681 useful for eliminating background processes like dark noise and radioactive decay
682 which would be expected to separate in time. When the value of N_{200} exceeds some
683 threshold, a software trigger is issued. There are several trigger thresholds used within
684 the SK-IV period which are detailed in Table 2.2. If one of these thresholds is met, the

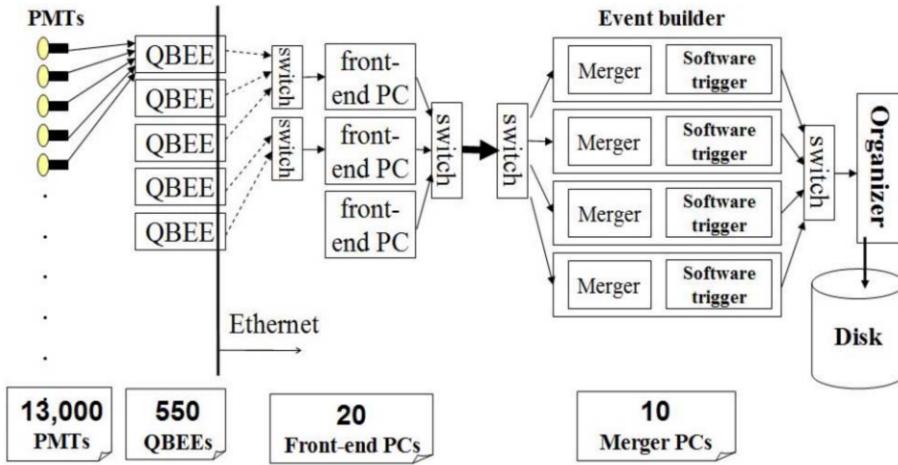


Figure 2.3: Schematic view of the data flow through the data acquisition and online system. Taken from [102].

685 PMT hits within an extended time window are also read out and saved to disk. In
 686 the special case of an event that exceeds the SHE trigger but does not exceed the OD
 687 trigger, the AFT trigger looks for delayed coincidences of 2.2MeV gamma rays emitted
 688 from neutron capture in a $535\mu\text{s}$ window after the SHE trigger. A similar but more
 689 complex “Wideband Intelligent Trigger (WIT)” has been deployed and is described
 690 in [104].

| Trigger | Acronym | Condition | Extended time window (μs) |
|-------------------|---------|----------------|--|
| Super Low Energy | SLE | >34/31 hits | 1.3 |
| Low Energy | LE | >47 hits | 40 |
| High Energy | HE | >50 hits | 40 |
| Super High Energy | SHE | >70/58 hits | 40 |
| Outer Detector | OD | >22 hits in OD | N/A |

Table 2.2: The trigger thresholds and extended time windows saved around an event which were utilised throughout the SK-IV period. The exact thresholds can change and the values listed here represent the thresholds at the start and end of the SK-IV period.

⁶⁹¹ 2.1.4 Cherenkov Radiation

- ⁶⁹² Cherenkov light is emitted from any highly energetic charged particle traveling
⁶⁹³ with relativistic velocity, β , greater than the local speed of light in a medium [105].
⁶⁹⁴ Cherenkov light is formed at the surface of a cone with characteristic pitch angle,

$$\cos(\theta) = \frac{1}{\beta n}. \quad (2.2)$$

⁶⁹⁵ where n is the refractive index of the medium. Consequently, the Cherenkov
⁶⁹⁶ momentum threshold, P_{thres} , is dependent upon the mass, m , of the charged particle
⁶⁹⁷ moving through the **media medium**,

$$P_{thres} = \frac{m}{\sqrt{n^2 - 1}} \quad (2.3)$$

⁶⁹⁸ For water, where $n = 1.33$, the Cherenkov threshold momentum and energy for
⁶⁹⁹ various particles are given in Table 2.3. In contrast, γ -rays are detected indirectly via
⁷⁰⁰ the combination of photons generated by Compton scattering and pair production.
⁷⁰¹ The threshold for detection in the SK detector is typically higher than the threshold
⁷⁰² for photon production. This is due to the fact that the attenuation of photons in the
⁷⁰³ water means that typically $\sim 75\%$ of Cherenkov photons reach the ID PMTs. Then the
⁷⁰⁴ collection and quantum efficiencies described in subsection 2.1.1 result in the number
⁷⁰⁵ of detected photons being lower than the number of photons which reach the PMTs.

| Particle | Threshold Momentum (MeV) | Threshold Energy (MeV) |
|----------|--------------------------|------------------------|
| Electron | 0.5828 | 0.7751 |
| Muon | 120.5 | 160.3 |
| Pion | 159.2 | 211.7 |
| Proton | 1070.0 | 1423.1 |

Table 2.3: The threshold momentum and energy for a particle to generate Cherenkov light in ultrapure water, as calculated in Equation 2.2 in ultrapure water which has refractive index $n = 1.33$.

706 The Frank-Tamm equation [106] describes the relationship between the number of

707 Cherenkov photons generated per unit length, dN/dx , the wavelength of the photons

708 generated, λ , and the relativistic velocity of the charged particle,

$$\frac{d^2N}{dx d\lambda} = 2\pi\alpha \left(1 - \frac{1}{n^2\beta^2}\right) \frac{1}{\lambda^2}. \quad (2.4)$$

709 where α is the fine structure constant. For a 100MeV momentum electron, approx-

710 imately 330 photons will be produced per centimeter in the $300\text{nm} \leq \lambda \leq 700\text{nm}$

711 region which the ID PMTs are most sensitive to [87].

712 2.2 The Tokai to Kamioka Experiment

713 The Tokai to Kamioka (T2K) experiment is a long-baseline neutrino oscillation exper-

714 iment located in Japan. Proposed in the early 2000s [107, 108] to replace K2K [109],

715 T2K was designed to observe electron neutrino appearance whilst precisely measuring

716 the oscillation parameters associated with muon neutrino disappearance [110]. The

717 experiment consists of a neutrino beam generated at the Japan Proton Accelerator

718 Research Complex (J-PARC), a suite of near detectors situated 280m from the beam

⁷¹⁹ target, and the Super Kamiokande far detector positioned at a 295km baseline. The
⁷²⁰ cross-section view of the T2K experiment is drawn in Figure 2.4.

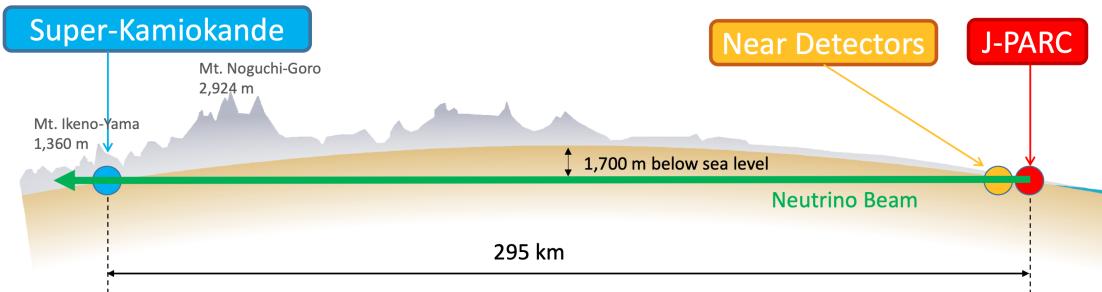


Figure 2.4: The cross-section view of the Tokai to Kamioka experiment illustrating the beam generation facility at J-PARC, the near detector situated at a baseline of 280m and the Super Kamiokande far detector situated 295km from the beam target.

⁷²¹ The T2K collaboration makes world-leading measurements of the $\sin^2(\theta_{23})$, Δm_{23}^2 ,
⁷²² and δ_{CP} oscillation parameters. Improvements in the precision and accuracy of param-
⁷²³ eter estimates are still being made by including new data samples and developing the
⁷²⁴ models which describe the neutrino interactions and detector responses [111]. Electron
⁷²⁵ neutrino appearance was first observed at T2K in 2014 [112] ~~which accompanied a~~
⁷²⁶ **7.3 σ significance of a non-zero $\sin^2(\theta_{13})$ measurement with 7.3 σ significance.**

⁷²⁷ The near detectors provide constraints on the beam flux and cross-section model
⁷²⁸ parameters used within the **fit oscillation analysis** by observing the unoscillated
⁷²⁹ neutrino beam. There are a host of detectors situated in the near detector hall (As
⁷³⁰ illustrated in Figure 2.5): ND280 (subsection 2.2.2), INGRID (subsection 2.2.3), NINJA
⁷³¹ [113], WAGASCI [114], and Baby-MIND [115]. The latter three are not currently used
⁷³² within the oscillation analysis presented within this thesis.

⁷³³ Whilst this thesis presents the ND280 in terms of its purpose for the oscillation
⁷³⁴ analysis, the detector can also make many cross-section measurements at neutrino
⁷³⁵ energies of $O(1)$ GeV for the different targets within the detector [116, 117]. These
⁷³⁶ measurements are of equal importance as they can lead the way in determining the

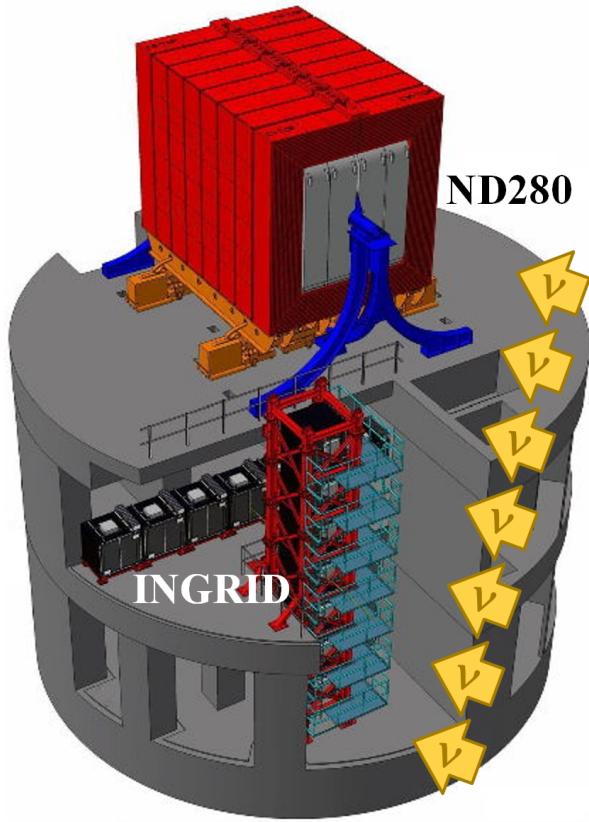


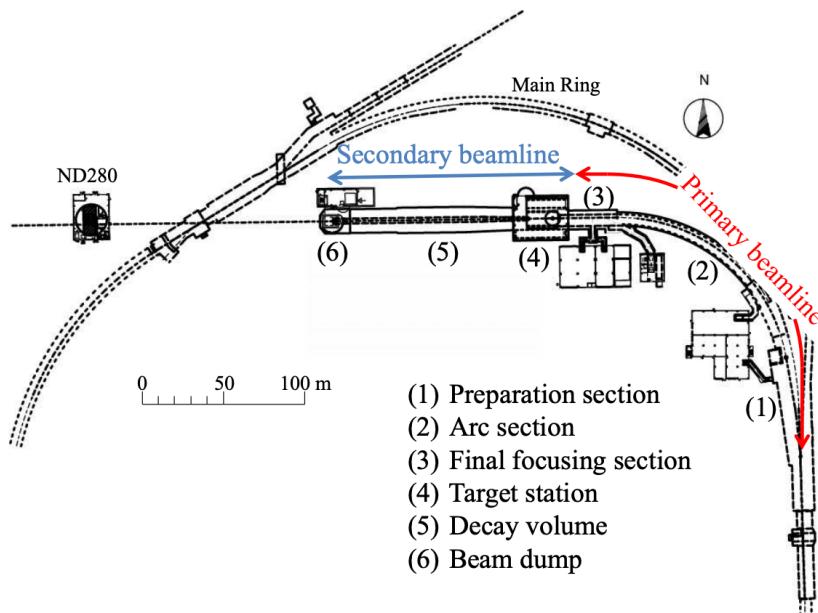
Figure 2.5: The near detector suite for the T2K experiment showing the ND280 and INGRID detectors. The distance between the detectors and the beam target is 280m.

⁷³⁷ model parameters used in the interaction models for the future high-precision era of
⁷³⁸ neutrino physics.

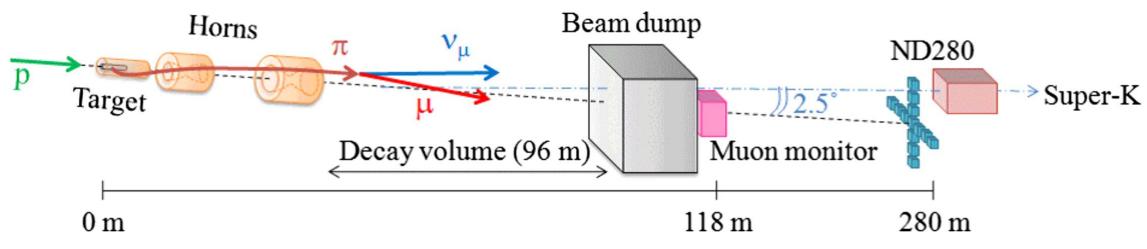
⁷³⁹ 2.2.1 The Neutrino Beam

⁷⁴⁰ The neutrino beam used within the T2K experiment is described in [59, 118] and
⁷⁴¹ summarised below. The accelerating facility at J-PARC is composed of two sections; the
⁷⁴² primary and secondary beamlines. Figure 2.6 illustrates a schematic of the beamline,
⁷⁴³ focusing mostly on the components of the secondary beamline. The primary beamline
⁷⁴⁴ has three accelerators that progressively accelerate protons; a linear accelerator, a rapid-
⁷⁴⁵ cycling synchrotron, and the main-ring (MR) synchrotron. Once fully accelerated by
⁷⁴⁶ the MR, the protons have a kinetic energy of 30GeV. Eight bunches of these protons,

⁷⁴⁷ separated by 500ns, are extracted per “spill” from the MR and directed towards a
⁷⁴⁸ graphite target (a rod of length 91.4cm and diameter 2.6cm). Spills are extracted at
⁷⁴⁹ 0.5Hz with $\sim 3 \times 10^{14}$ protons contained per spill.



(a) Primary and secondary beamline

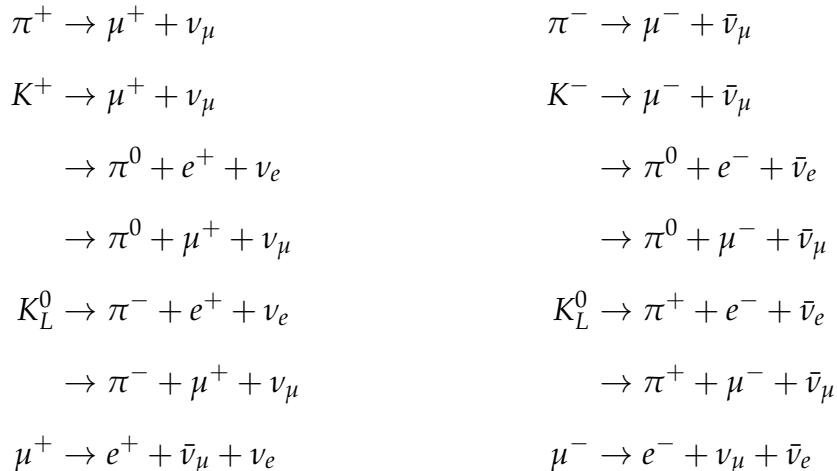


(b) Secondary beamline

Figure 2.6: Top panel: Bird's eye view of the most relevant part of primary and secondary beamline used within the T2K experiment. The primary beamline is the main-ring proton synchrotron, kicker magnet, and graphite target. The secondary beamline consists of the three focusing horns, decay volume, and beam dump. Figure taken from [118]. Bottom panel: The side-view of the secondary beamline including the focusing horns, beam dump and neutrino detectors. Figure taken from [119].

⁷⁵⁰ The secondary beamline consists of three main components: the target station, the
⁷⁵¹ decay volume, and the beam dump. The target station is comprised of the target, beam
⁷⁵² monitors, and three magnetic focusing horns. The proton beam interacts with the

⁷⁵³ graphite target to form a secondary beam of mostly pions and kaons. The secondary
⁷⁵⁴ beam travels through a 96m long decay volume, generating neutrinos through the
⁷⁵⁵ following decays [59],



⁷⁵⁶

⁷⁵⁷ The electrically charged component of the secondary beam is focused towards the
⁷⁵⁸ far detector by the three magnetic horns. These horns direct charged particles of a
⁷⁵⁹ particular polarity towards SK whilst defocusing the oppositely charged particles.
⁷⁶⁰ This allows a mostly neutrino or mostly antineutrino beam to be used within the
⁷⁶¹ experiment, denoted as “forward horn current (FHC)” or “reverse horn current (RHC)”
⁷⁶² respectively.

⁷⁶³ Figure 2.7 illustrates the different contributions to the FHC and RHC neutrino flux.
⁷⁶⁴ The low energy flux is dominated by the decay of pions whereas kaon decay becomes
⁷⁶⁵ the dominant source of neutrinos for $E_\nu > 3\text{GeV}$. The “wrong-sign” component,
⁷⁶⁶ which is the $\bar{\nu}_\mu$ background in a ν_μ beam, and the intrinsic irreducible ν_e background,
⁷⁶⁷ are predominantly due to muon decay for $E_\nu < 2\text{GeV}$. As the antineutrino **production**
⁷⁶⁸ cross-section is smaller than the neutrino cross-section, the wrong-sign component is
⁷⁶⁹ more dominant in the RHC beam as compared to that in the FHC beam.

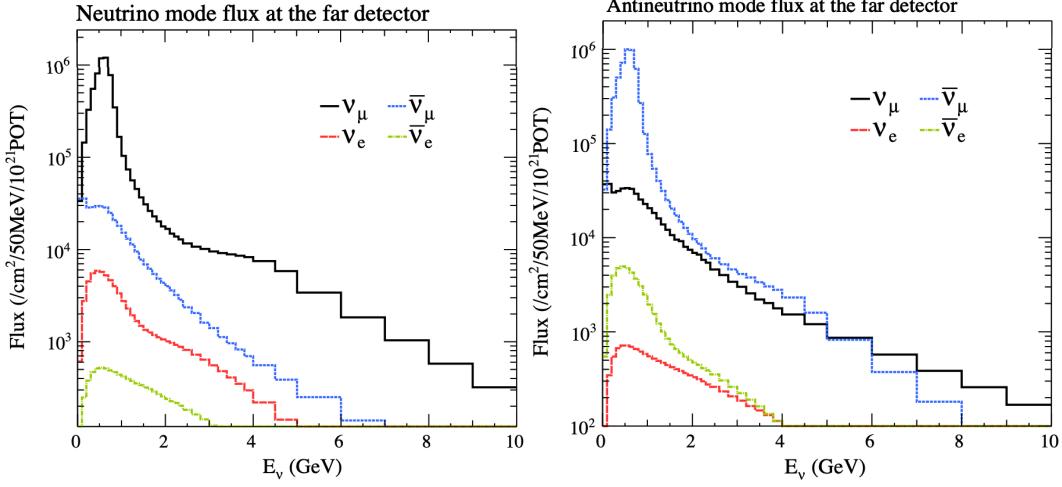


Figure 2.7: The Monte Carlo prediction of the energy spectrum for each flavour of neutrino (ν_e , $\bar{\nu}_e$, ν_μ and $\bar{\nu}_\mu$) in the neutrino dominated beam FHC mode (Left) and antineutrino dominated beam RHC mode (Right) expected at SK. Taken from [120].

The beam dump, situated at the end of the decay volume, stops all charged particles

other than highly energetic muons ($p_\mu > 5\text{GeV}$). The MuMon detector monitors the penetrating muons to determine the beam direction and intensity which is used to constrain some of the beam flux systematics within the analysis [119, 121].

The T2K experiment uses an off-axis beam to narrow the neutrino energy distribution.

This was the first implementation of this technique in a long-baseline neutrino oscillation experiment after its original proposal [122]. Pion decay, $\pi \rightarrow \mu + \nu_\mu$, is a two-body decay. Consequently, the neutrino energy, E_ν , can be determined based on the pion energy, E_π , and the angle at which the neutrino is emitted, θ ,

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos(\theta))}, \quad (2.5)$$

where m_π and m_μ are the mass of the pion and muon respectively. For a fixed energy pion, the neutrino energy distribution is dependent upon the angle at which the neutrinos are observed from the initial pion beam direction. For the 295km baseline at

⁷⁸² T2K, $E_\nu = 0.6\text{GeV}$ maximises the electron neutrino appearance probability, $P(\nu_\mu \rightarrow \nu_e)$,
⁷⁸³ whilst minimising the muon disappearance probability, $P(\nu_\mu \rightarrow \nu_\mu)$. Figure 2.8
⁷⁸⁴ illustrates the neutrino energy distribution for a range of off-axis angles, as well as the
⁷⁸⁵ oscillation probabilities most relevant to T2K.

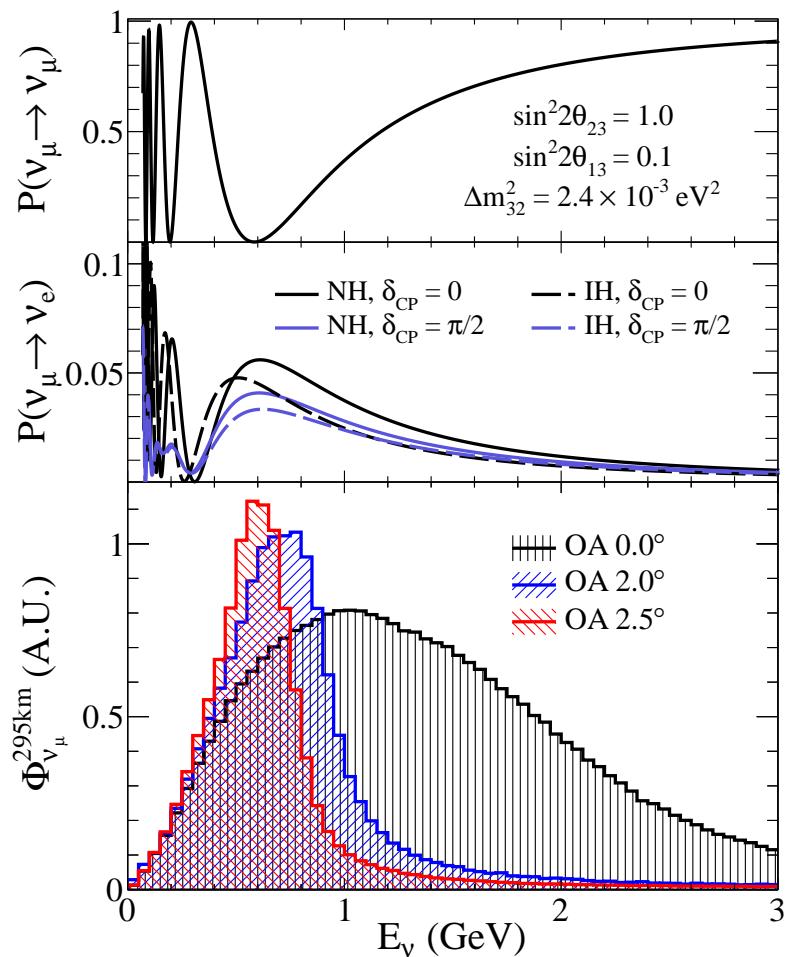


Figure 2.8: Top panel: T2K muon neutrino disappearance probability as a function of neutrino energy. Middle panel: T2K electron neutrino appearance probability as a function of neutrino energy. Bottom panel: The neutrino flux distribution for three different off-axis angles (Arbitrary units) as a function of neutrino energy.

⁷⁸⁶ 2.2.2 The Near Detector at 280m

⁷⁸⁷ Whilst all the near detectors are situated in the same “pit” located at 280m from the
⁷⁸⁸ beamline, the “ND280” detector is the off-axis detector which is situated at the same

789 off-axis angle as the Super-Kamiokande far detector. It has two primary functions;
 790 firstly it measures the neutrino flux and secondly it counts the event rates of different
 791 types of neutrino interactions. Both of these constrain the flux and cross-section
 792 systematics invoked within the model for a more accurate prediction of the expected
 793 event rate at the far detector.

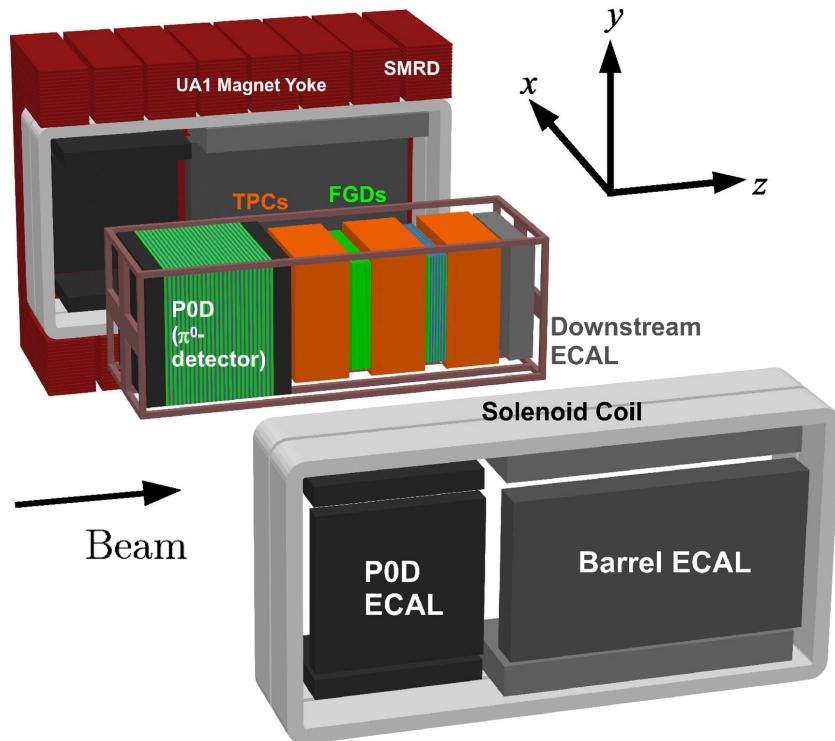


Figure 2.9: The components of the ND280 detector. The neutrino beam travels from left to right. Taken from [118].

794 As illustrated in Figure 2.9, the ND280 detector consists of several sub-detectors.
 795 The most important part of the detector for this analysis is the tracker region. This is
 796 comprised of two time projection chambers (TPCs) sandwiched between three fine
 797 grain detectors (FGDs). The FGDs contain both hydrocarbon plastics and water tar-
 798 gets for neutrino interactions and provide track reconstruction near the interaction
 799 vertex. The emitted charged particles can then propagate into the TPCs which pro-
 800 vide particle identification and momentum reconstruction. The FGDs and TPCs are
 801 further described in subsubsection 2.2.2.1 and subsubsection 2.2.2.2 respectively. The

802 electromagnetic calorimeter (ECAL) encapsulates the tracker region alongside the π^0
803 detector (P0D). The ECAL measures the deposited energy from photons emitted from
804 interactions within the FGD. The P0D constrains the cross-section of neutral current
805 interactions which generate neutral pions, which is one of the largest backgrounds in
806 the electron neutrino appearance oscillation channel. The P0D and ECAL detectors
807 are detailed in subsubsection 2.2.2.3 and subsubsection 2.2.2.4 respectively. The entire
808 detector is located within a large **yolk yoke** magnet which produces a 0.2T magnetic
809 field. This design of the magnet also includes a scintillating detector called the side
810 muon range detector (SMRD) which is used to track high-angle muons as well as
811 acting as a cosmic veto. The SMRD is described in subsubsection 2.2.2.5.

812 2.2.2.1 Fine Grained Detectors

813 The T2K tracker region is comprised of two fine grained detectors (FGD) and three
814 Time Projection Chambers (TPC). A detailed description of the FGD design, construc-
815 tion, and assembly is found in [123] and summarised below. The FGDs are the primary
816 target for neutrino interactions with a mass of 1.1 tonnes per FGD. Alongside this,
817 the FGDs are designed to be able to track short-range particles which do not exit the
818 FGD. Typically, short-range particles are low momentum and are observed as tracks
819 that deposit a large amount of energy per unit length. This means the FGD needs
820 good granularity to resolve these particles. The FGDs have the best timing resolution
821 ($\sim 3\text{ns}$) of any of the sub-detectors of the ND280 detector. As such, the FGDs are used
822 for time of flight measurements to **determine distinguish** forward going positively
823 charged particles from backward going negatively charged particles. Finally, any
824 tracks which pass through multiple sub-detectors are required to be track matched to
825 the FGD.

Both FGDs are made from square scintillator planes of side length 186cm and width 2.02cm. Each plane consists of two layers of 192 scintillator bars in an X or Y orientation. A wavelength shifting fiber is threaded through the center of each bar and is read out by a multi-pixel photon counter (MPPC). FGD1 is the most upstream of the two FGDs and contains 15 planes of carbon plastic scintillator which is a common target in external neutrino scattering data. As the far detector is a pure water target, 7 of the 15 scintillator planes in FGD2 have been replaced with a hybrid water-scintillator target. Due to the complexity of the nucleus, nuclear effects can not be extrapolated between different nuclei. Therefore having the ability to take data on one target which is the same as external data and another target which is the same as the far detector target is beneficial for reliable model parameter estimates.

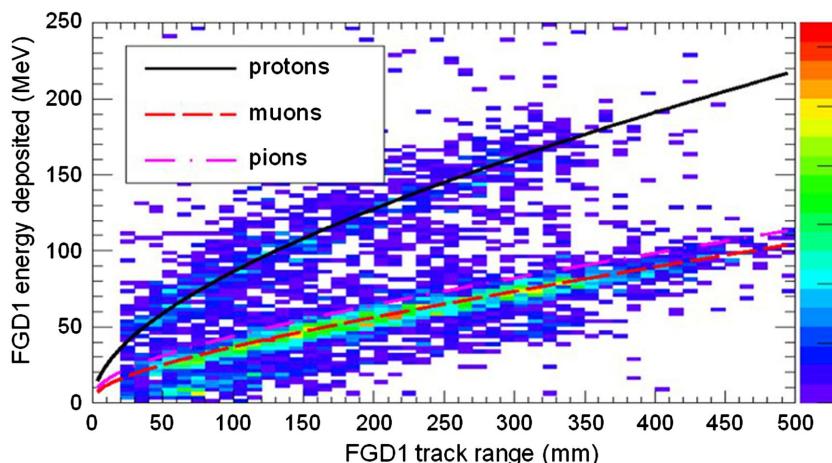


Figure 2.10: Comparison of data to Monte Carlo prediction of integrated deposited energy as a function of track length for particles that stopped in FGD1. Taken from [123].

The integrated deposited energy is used for particle identification. The FGD can distinguish protons from other charged particles by comparing the integrated deposited energy from data to Monte Carlo prediction as seen in Figure 2.10.

⁸⁴⁰ **2.2.2.2 Time Projection Chambers**

⁸⁴¹ The majority of particle identification and momentum measurements within ND280
⁸⁴² are provided by three Time Projection Chambers (TPCs) [124]. The TPCs are located
⁸⁴³ on either side of the FGDs. They are located inside of the magnetic field meaning the
⁸⁴⁴ momentum of a charged particle can be determined from the bending of the track.

⁸⁴⁵ Each TPC module consists of two gas-tight boxes, as shown in Figure 2.11, which
⁸⁴⁶ are made of non-magnetic material. The outer box is filled with CO₂ which acts as
⁸⁴⁷ an electrical insulator between the inner box and the ground. The inner box forms
⁸⁴⁸ the field cage which produces a uniform electric drift field of $\sim 275\text{V/cm}$ and **is filled**
⁸⁴⁹ **with** an argon gas mixture. Charged particles moving through this gas mixture ionize
⁸⁵⁰ the gas **mixture. The and the** ionised charge is drifted towards micromegas detectors
⁸⁵¹ which measure the ionization charge. The time and position information in the readout
⁸⁵² allows a three-dimensional image of the neutrino interaction.

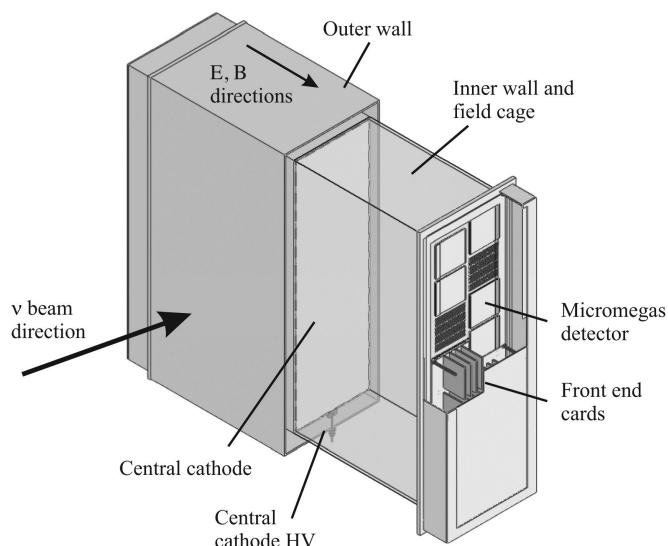


Figure 2.11: Schematic design of a Time Projection Chamber detector. Taken from [124].

⁸⁵³ The particle identification of tracks that pass through the TPCs is performed using
⁸⁵⁴ dE/dx measurements. Figure 2.12 illustrates the data to Monte Carlo distributions

of the energy lost by a charged particle passing through the TPC as a function of the reconstructed particle momentum. The resolution is $7.8 \pm 0.2\%$ meaning that electrons and muons can be distinguished. This allows reliable measurements of the intrinsic ν_e component of the beam.

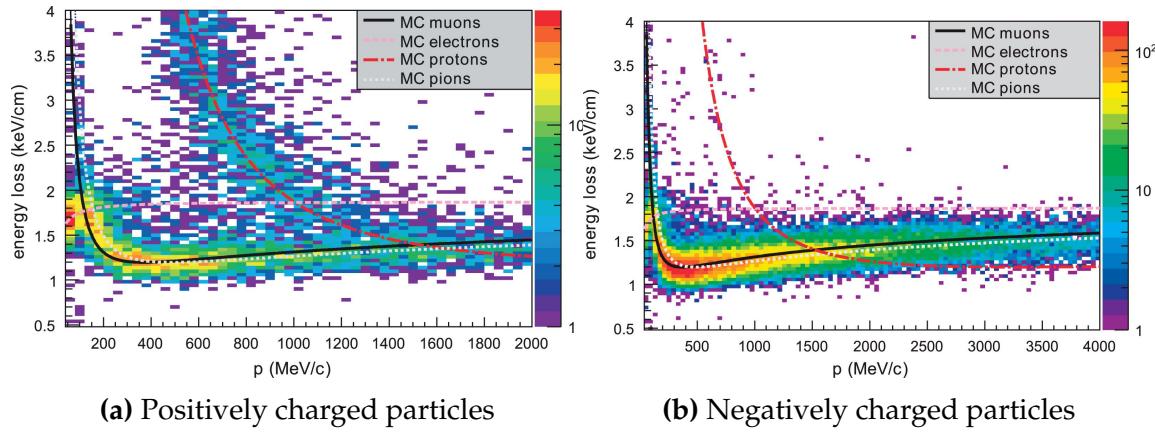


Figure 2.12: The distribution of energy loss as a function of reconstructed momentum for charged particles passing through the TPC, comparing data to Monte Carlo prediction. Taken from [124].

2.2.2.3 π^0 Detector

If one of the γ -rays from a $\pi^0 \rightarrow 2\gamma$ decay is missed at the far detector, the reconstruction will determine that event to be **electron-like a charge current ν_e -like event**. This is one of the main backgrounds hindering the electron neutrino appearance searches. **Therefore, the The** π^0 detector (P0D) measures the cross-section of the neutral current induced neutral pion production on a water target **to constrain this background**.

The P0D is a cube of approximately 2.5m length **.The P0D consists consisting** of layers of scintillating bars, brass and lead sheets, and water bags as illustrated in Figure 2.13. Two electromagnetic calorimeters are positioned at the most upstream and most downstream position in the sub-detector and the water target is situated in between them. The scintillator layers are built from two triangular bars orientated in opposite directions to form a rectangular layer. Each triangular scintillator bar is

- ⁸⁷¹ threaded with optical fiber which is read out by MPPCs. The high-Z brass and lead
⁸⁷² regions produce electron showers from the photons emitted in π^0 decay.

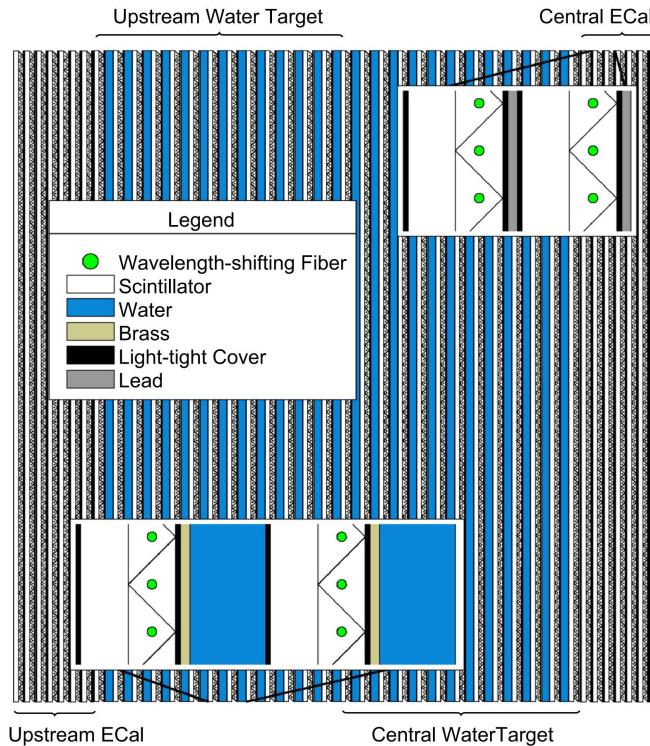


Figure 2.13: A schematic of the P0D side-view. Taken from [125].

- ⁸⁷³ The sub-detector can generate measurements of NC1 π^0 cross-sections on a water
⁸⁷⁴ target by measuring the event rate both with and without the water target, with the
⁸⁷⁵ cross-section on a water target being determined as the difference. The total active
⁸⁷⁶ mass is 16.1 tonnes when filled with water and 13.3 tonnes when empty.

⁸⁷⁷ 2.2.2.4 Electromagnetic Calorimeter

- ⁸⁷⁸ The electromagnetic calorimeter [126] (ECal) encapsulates the P0D and tracking sub-
⁸⁷⁹ detectors. Its primary purpose is to aid π^0 reconstruction from any interaction in
⁸⁸⁰ the tracker. To do this, it measures the energy and direction of photon showers from
⁸⁸¹ $\pi^0 \rightarrow 2\gamma$ decay. It can also distinguish pion and muon tracks depending on the shape
⁸⁸² of the photon shower deposited.

883 The ECal is comprised of three sections; the P0D ECal which surrounds the P0D,
 884 the barrel ECal which encompasses the tracking region, and the downstream ECal
 885 which is situated downstream of the tracker region. The barrel and downstream
 886 ECals are tracking calorimeters that focus on electromagnetic showers from high-angle
 887 particles emitted from the tracking sub-detectors. Particularly in the TPC, high-angle
 888 tracks (those which travel perpendicularly to the beam-axis) can travel along a single
 889 scintillator bar resulting in very few hits. The width of the barrel and downstream
 890 ECal corresponds to ~ 11 electron radiation lengths to ensure ~~$\sim 50\%$ of the energy~~
 891 ~~of the π^0 is contained a significant amount of the π^0 energy is contained~~. As the
 892 P0D has its own calorimetry which reconstructs showers, the P0D ECal determines
 893 the energy which escapes the P0D.

894 Each ECal is constructed of multiple layers of scintillating bars sandwiched between
 895 lead sheets. The scintillating bars are threaded with optical fiber and read out by
 896 MPPCs. Each sequential layer of the scintillator is orientated perpendicular to the
 897 previous which allows a ~~two-dimensional readout, which when temporal, information is included results in three-dimension event displays three dimensional event displays~~. The target mass of the P0D ECal, barrel ECal, and downstream ECal are 1.50,
 898 4.80 and 6.62 tonnes respectively.

901 **2.2.2.5 Side Muon Range Detector**

902 As illustrated in Figure 2.9, the ECal, FGDs, P0D, and TPCs are enclosed within the
 903 UA1 magnet. Originally designed for the NOMAD [127] experiment and reconditioned
 904 for use in the T2K experiment [128], the UA1 magnet provides a uniform horizontal
 905 magnetic field of ~~$0.2 \pm 2 \times 10^{-4}$ T 0.2T with an uncertainty of 2×10^{-4} T~~.

906 Built into the UA1 magnet, the side muon range detector (SMRD) [129] monitors
907 high-energy muons which leave the tracking region and permeate through the ECal.
908 It additionally acts as a cosmic muon veto and trigger.

909 2.2.3 The Interactive Neutrino GRID

910 The Interactive Neutrino GRID (INGRID) detector is situated within the same “pit” as
911 the other near detectors. It is aligned with the beam in the “on-axis” position and mea-
912 sures the beam direction, spread, and intensity. The detector was originally designed
913 with 16 identical modules [118] (two modules have since been decommissioned) and a
914 “proton” module. The design of the detector is cross-shaped with length and height
915 10m × 10m as illustrated in Figure 2.14.

916 Each module is composed of iron sheets interlaced with eleven tracking scintillator
917 planes for a total target mass of 7.1 tonnes per module. The scintillator design is an X-Y
918 pattern of 24 bars in both orientations, where each bar contains wave-length shifting
919 fibers which are connected to multi-pixel photon counters (MPPCs). ~~The MPPCs con-~~
920 ~~vert detected photons into electrical signals via photodiodes. This is then read out~~
921 ~~by Trip-T front-end electronics and passed to the readout merging modules along~~
922 ~~with timing information from the clock module.~~ Each module is encapsulated inside
923 veto planes to aid the rejection of charged particles entering the module.

924 The proton module is different from the other modules in that it consists of entirely
925 scintillator planes with no iron target. The scintillator bars are also smaller than those
926 used in the other modules to increase the granularity of the detector and improve
927 tracking capabilities. The module sits in the center of the beamline and is designed to
928 give precise measurements of quasi-elastic charged current interactions to evaluate
929 the performance of the Monte Carlo simulation of the beamline.

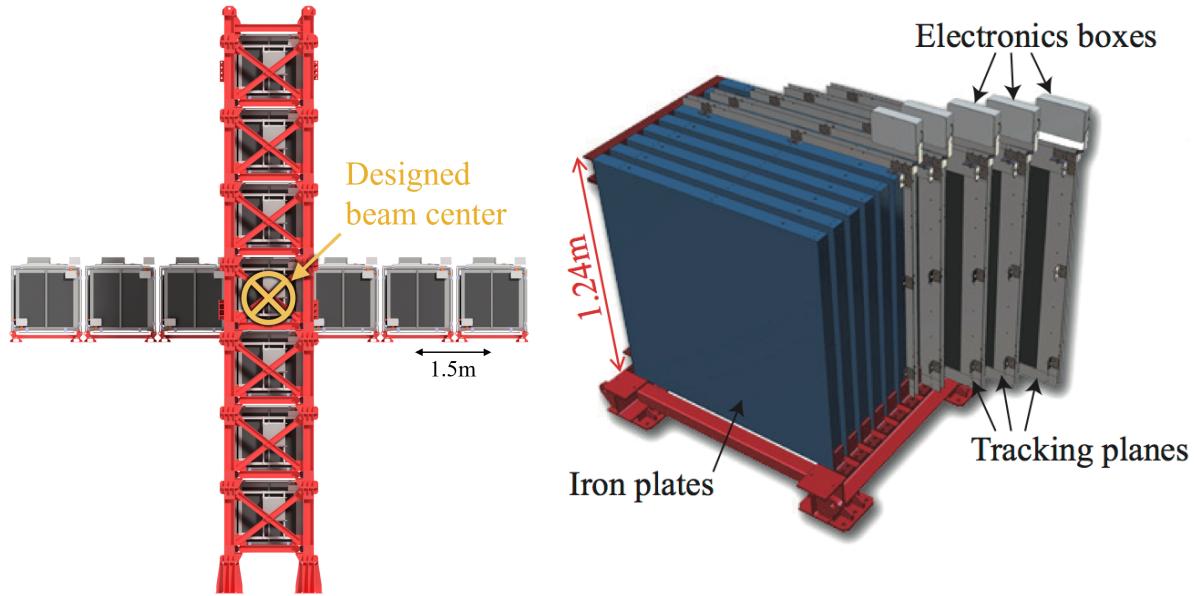


Figure 2.14: Left panel: The Interactive Neutrino GRID on-axis Detector. 14 modules are arranged in a cross-shape configuration, with the center modules being directly aligned with the on-axis beam. Right panel: The layout of a single module of the INGRID detector. Both figures are recreated from [118].

930 The INGRID detector can measure the beam direction to an uncertainty of 0.4mrad
 931 and the beam center within a resolution of 10cm [118]. The beam direction in both the
 932 vertical and horizontal directions is discussed in [130] and it is found to be in good
 933 agreement with the MUMON monitor described in subsection 2.2.1.

934

Chapter 3

935

Bayesian Statistics and Markov Chain 936 Monte Carlo Techniques

937 ~~The analysis throughout this thesis is based upon~~ This thesis presents a Bayesian
938 oscillation analysis. To extract the oscillation parameters, a Markov Chain Monte
939 Carlo (MCMC) method is used. This chapter explains the theory of how parameter
940 estimates can be determined using this technique and condenses the material found in
941 the literature [131–134].

942 The oscillation parameter determination presented within this thesis is built upon
943 a ~~a simultaneous fit to the near detector, far detector beam, and atmospheric neutrino data~~
944 ~~a simultaneous fit to neutrino beam data in the near detector, beam data~~
945 ~~at SK and atmospheric data at SK~~. In total, there are four oscillation parameters of
946 interest ($\sin^2(\theta_{23})$, $\sin^2(\theta_{13})$, Δm_{23}^2 , and δ_{CP}), two oscillation parameters to which
947 this study will not be sensitive ($\sin^2(\theta_{12})$, Δm_{12}^2) and many nuisance parameters
948 that control the systematic uncertainty models invoked within this study. ~~The systematic~~
949 ~~uncertainties can be grouped into categories depending on how they are~~
950 ~~defined: 574 bin-normalisations due to the near detector response, 45 bin-normali-~~
951 ~~sations to describe the far detector response to neutrino beam events, 27 parameters~~
952 ~~to describe the detector response to atmospheric neutrino events, 100 to model the~~
953 ~~bin-normalisation due to beam flux uncertainties, 18 which model the atmospheric~~
954 ~~flux uncertainties, and 87 to describe the correlated cross-section model. An alter-~~
955 ~~native parameterisation, where the far detector response is correlated between the~~

beam and atmospheric samples, replaces the bin normalisation parameters with 224 shift and smear systematics. Section Link to Systematics Chapter describes the systematic model in more depth.

The MCMC technique generates a multi-dimensional probability distribution across all of the model parameters used in the fit. To determine the parameter estimate of a single parameter, this multi-dimensional object is integrated over all other parameters. This process is called Marginalisation and is further described in subsection 3.3.1. Monte Carlo techniques approximate the probability distribution of each parameter within the limit of generating infinite samples. As ever, generating a large number of samples is time and resource-dependent. Therefore, an MCMC technique is utilised within this analysis to reduce the required number of steps to sufficiently sample the parameter space. This technique is described in further detail in subsection 3.2.1.

3.1 Bayesian Statistics

According to Bayesian Inference, observables and parameters of a statistical model are treated on an equal footing. To estimate model parameters $\vec{\theta}$ from some data D , one needs to define the joint probability distribution $P(D|\vec{\theta})$ which Bayesian inference treats observable data, D , and model parameters, $\vec{\theta}$, on equal footing such that a probability model of both data and parameters is required. This is the joint probability distribution $P(D, \vec{\theta})$ and can be described as by the prior distribution for model parameters $P(\vec{\theta})$ and the likelihood of the data given the model parameters $P(D|\vec{\theta})$,

$$P(D, \vec{\theta}) = P(D|\vec{\theta})P(\vec{\theta}). \quad (3.1)$$

977 The prior distribution, $P(\vec{\theta})$, describes all previous knowledge about the parameters
 978 within the model. For example, if the risk of developing health problems is known
 979 to increase with age, the prior distribution would describe the increase. For the
 980 purpose of this analysis, the prior distribution is typically the best-fit values taken
 981 from external data measurements with a Gaussian uncertainty. The prior distribution
 982 can also contain correlations between model parameters. In an analysis using Monte
 983 Carlo techniques, the likelihood of measuring some data assuming some set of model
 984 parameters is calculated by comparing the Monte Carlo prediction generated at that
 985 particular set of model parameters to the data.

986 It is parameter estimation that is important for this analysis and as such, we apply
 987 Bayes' theorem [135] to calculate the probability for each parameter to have a certain
 988 value given the observed data, $P(\vec{\theta}|D)$, which is known as the posterior distribution
 989 (often termed the posterior). This can be expressed as

$$P(\vec{\theta}|D) = \frac{P(D|\vec{\theta})P(\vec{\theta})}{\int P(D|\vec{\theta})P(\vec{\theta})d\vec{\theta}}. \quad (3.2)$$

990 The denominator in Equation 3.2 is the integral of the joint probability distribution
 991 over all values of all parameters used within the fit. For brevity, we say that the
 992 posterior distribution is

$$P(\vec{\theta}|D) \propto P(D|\vec{\theta})P(\vec{\theta}). \quad (3.3)$$

993 In subsection 3.3.1, we see that for the cases used within this analysis, it is reason-
 994 able to know the posterior to some normalisation constant.

995 3.2 Monte Carlo Simulation

996 Monte Carlo techniques are used to numerically solve a complex problem that does
997 not necessarily have an analytical solution. These techniques rely on building a large
998 ensemble of samples from an unknown distribution and then using the ensemble to
999 approximate the properties of the distribution.

1000 An example that uses Monte Carlo techniques is to calculate the area underneath
1001 a curve. For example, take the problem of calculating the area under a straight line
1002 with gradient $M = 0.4$ and intercept $C = 1.0$. Analytically, one can calculate the area
1003 under the line is equal to 30 units for $0 \leq x \leq 10$. Using Monte Carlo techniques,
1004 one can calculate the area under this line by throwing many random values for the x
1005 and y components of each sample and then calculating whether that point falls below
1006 the line. The area can then be calculated by the ratio of points below the line to the
1007 total number of samples thrown multiplied by the total area in which samples were
1008 scattered. The study is shown in Figure 3.1 highlights this technique and finds the area
1009 under the curve to be 29.9 compared to an analytical solution of 30.0. The deviation
1010 of the numerical to analytical solution can be attributed to the number of samples
1011 used in the study. The accuracy of the approximation in which the properties of the
1012 Monte Carlo samples replicate those of the desired distribution is dependent on the
1013 number of samples used. Replicating this study with a differing number of Monte
1014 Carlo samples used in each study (As shown in Figure 3.2) highlights how the Monte
1015 Carlo techniques are only accurate within the limit of a high number of samples.

1016 Whilst the above example has an analytical solution, these techniques are just as
1017 applicable to complex solutions. Clearly, any numerical solution is only as useful as its
1018 efficiency. As discussed, the accuracy of the Monte Carlo technique is dependent upon
1019 the number of samples generated to approximate the properties of the distribution.

1020 Furthermore, if the positions at which the samples are evaluated are not ‘cleverly’
 1021 picked, the efficiency of the Monte Carlo technique significantly drops. Given the
 1022 example in Figure 3.1, if the region in which the samples are scattered significantly
 1023 extends passed the region of interest, many calculations will be calculated but do
 1024 not add to the ability of the Monte Carlo technique to achieve the correct result. For
 1025 instance, any sample evaluated at a $y \geq 5$ could be removed without affecting the final
 1026 result. This does bring in an aspect of the ‘chicken and egg’ problem in that to achieve
 1027 efficient sampling, one needs to know the distribution beforehand.

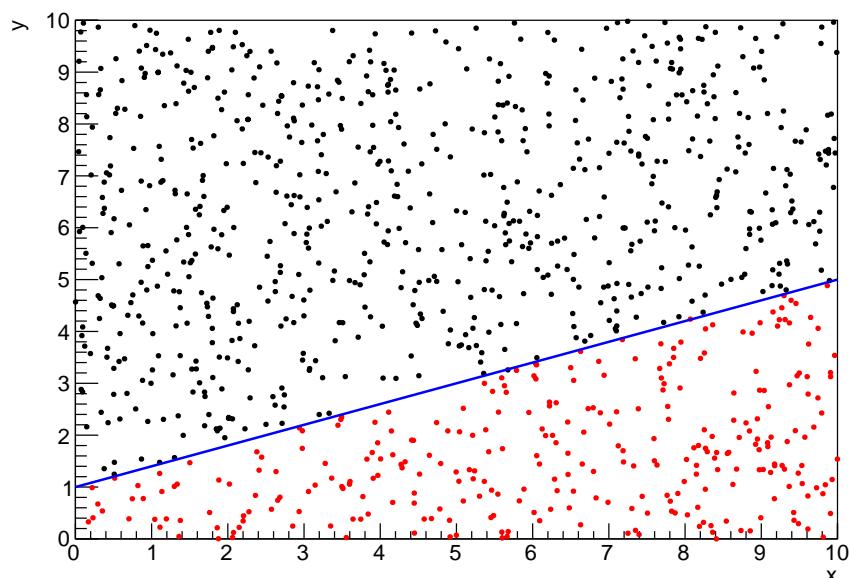


Figure 3.1: Example of using Monte Carlo techniques to find the area under the blue line. The gradient and intercept of the line are 0.4 and 1.0 respectively. The area found to be under the curve using one thousand samples is 29.9 units.

1028 3.2.1 Markov Chain Monte Carlo

1029 This analysis utilises a multi-dimensional probability distribution, with some dimen-
 1030 sions being significantly more constrained than others. This could be from prior
 1031 knowledge of parameter distributions from external data or un-physical regions in

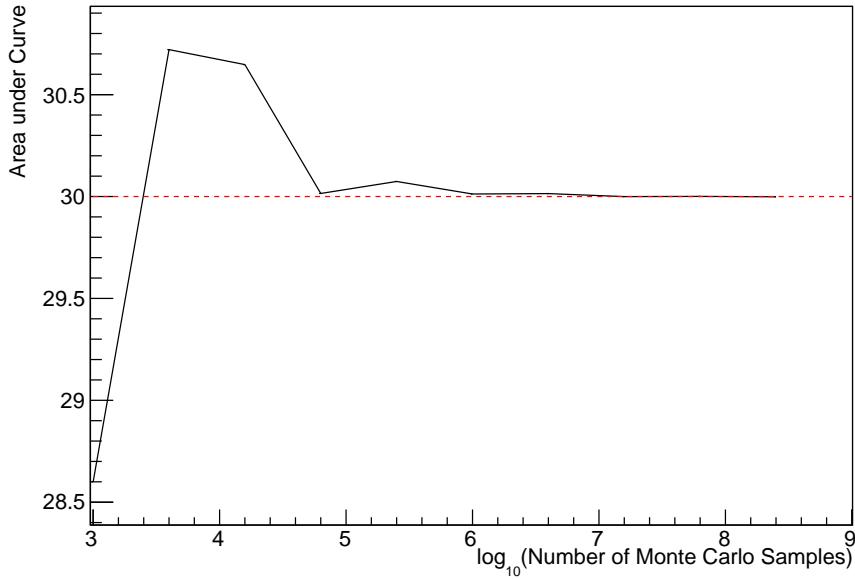


Figure 3.2: The area under a line of gradient 0.4 and intercept 1.0 for the range $0 \leq x \leq 10$ as calculated using Monte Carlo techniques as a function of the number of samples used in each repetition. The analytical solution to the area is 30 units as given by the red line.

which parameters can not exist. Consequently, the Monte Carlo techniques used need to be as efficient as possible. For this analysis, the Markov Chain Monte Carlo (MCMC) technique is chosen. An MCMC technique is a Monte Carlo technique that uses a Markov chain to select which points at which to sample the parameter distribution. This technique performs a semi-random stochastic walk through the allowable parameter space. This builds a posterior distribution which has the property that the density of sampled points is proportional to the probability density of that parameter. This does mean that the samples produced by this technique are not statistically independent but they will cover the space of the distribution.

A Markov chain functions by selecting the position of step \vec{x}_{i+1} based on the position of \vec{x}_i . The space in which the Markov chain selects samples is dependent upon the total number of parameters utilised within the fit, where a discrete point in this space is described by the N-dimensional space \vec{x} . In a perfectly operating Markov chain, the position of the next step depends solely on the previous step and not on the

1046 further history of the chain (\vec{x}_0, \vec{x}_1 , etc.). However, in solving the multi-dimensionality
1047 of the fit used within this analysis, each step becomes correlated with several of
1048 the steps preceding itself. This behaviour is further explained in subsection 3.2.3.
1049 Providing the MCMC chain is well optimised, it will begin to converge towards a
1050 unique stationary distribution. The period between the chain's initial starting point
1051 and the convergence to the unique stationary distribution is colloquially known as the
1052 burn-in period. This is discussed further in subsection 3.2.3. Once the chain reaches
1053 the stationary distribution, all points sampled after that point will look like samples
1054 from that distribution.

1055 Further details of the theories underpinning MCMC techniques are discussed
1056 in [132] but can be summarised by the requirement that the chain satisfies the three
1057 'regularity conditions':

- 1058 • Irreducibility: From every position in the parameter space \vec{x} , there must exist a
1059 non-zero probability for every other position in the parameter space to be reached.
- 1060 • Recurrence: Once the chain arrives at the stationary distribution, every step fol-
1061 lowing from that position must be samples from the same stationary distribution.
- 1062 • Aperiodicity: The chain must not repeat the same sequence of steps at any point
1063 throughout the sampling period.

1064 The output of the chain after burn-in (ie. the sampled points after the chain
1065 has reached the stationary distribution) can be used to approximate the posterior
1066 distribution and model parameters $\vec{\theta}$. To achieve the requirement that the unique
1067 stationary distribution found by the chain be the posterior distribution, one can use
1068 the Metropolis-Hastings algorithm. This guides the stochastic process depending on
1069 the likelihood of the current proposed step compared to that of the previous step.
1070 Implementation and other details of this technique are discussed in subsection 3.2.2.

¹⁰⁷¹ 3.2.2 Metropolis-Hastings Algorithm

¹⁰⁷² As a requirement for MCMCs, the Markov chain implemented in this technique must
¹⁰⁷³ have a unique stationary distribution that is equivalent to the posterior distribution.
¹⁰⁷⁴ To ensure this requirement and that the regularity conditions are met, this analysis
¹⁰⁷⁵ utilises the Metropolis-Hastings (MH) algorithm [136,137]. For the i^{th} step in the chain,
¹⁰⁷⁶ the MH algorithm determines the position in the parameter space to which the chain
¹⁰⁷⁷ moves to based on the current step, \vec{x}_i , and the proposed step, \vec{y}_{i+1} . The proposed step
¹⁰⁷⁸ is randomly selected from some proposal function $f(\vec{x}_{i+1}|\vec{x}_i)$, which depends solely
¹⁰⁷⁹ on the current step (ie. not the further history of the chain). The next step in the chain
¹⁰⁸⁰ \vec{x}_{i+1} can be either the current step or the proposed step determined by whether the
¹⁰⁸¹ proposed step is accepted or rejected. To decide if the proposed step is selected, the
¹⁰⁸² acceptance probability, $\alpha(\vec{x}_i, \vec{y}_i)$, is calculated as

$$\alpha(\vec{x}_i, \vec{y}_{i+1}) = \min\left(1, \frac{P(\vec{y}_{i+1}|D)f(\vec{x}_i|\vec{y}_{i+1})}{P(\vec{x}_i|D)f(\vec{y}_{i+1}|\vec{x}_i)}\right). \quad (3.4)$$

¹⁰⁸³ Where $P(\vec{y}_{i+1}|D)$ is the posterior distribution as introduced in section 3.1. To
¹⁰⁸⁴ simplify this calculation, the proposal function is required to be symmetric such that
¹⁰⁸⁵ $f(\vec{x}_i|\vec{y}_{i+1}) = f(\vec{y}_{i+1}|\vec{x}_i)$. In practice, a multi-variate Gaussian distribution is used to
¹⁰⁸⁶ throw parameter proposals from. This reduces Equation 3.4 to

$$\alpha(\vec{x}_i, \vec{y}_{i+1}) = \min\left(1, \frac{P(\vec{y}_{i+1}|D)}{P(\vec{x}_i|D)}\right). \quad (3.5)$$

1087 After calculating this quantity, a random number, β , is generated uniformly be-
1088 tween 0 and 1. If $\beta \leq \alpha(\vec{x}_i, \vec{y}_{i+1})$, the proposed step is accepted. Otherwise, the chain
1089 sets the next step equal to the current step and this procedure is repeated. This can be
1090 interpreted as if the posterior probability of the proposed step is greater than that of
1091 the current step, ($P(\vec{y}_{i+1}|D) \geq P(\vec{x}_i|D)$), the proposed step will always be accepted.
1092 If the opposite is true, ($P(\vec{y}_{i+1}|D) \leq P(\vec{x}_i|D)$), the proposed step will be accepted
1093 with probability $P(\vec{x}_i|D)/P(\vec{y}_{i+1}|D)$. This ensures that the Markov chain does not get
1094 trapped in any local minima in the potentially non-Gaussian posterior distribution.
1095 The outcome of this technique is that the density of steps taken in a discrete region is
1096 directly proportional to the probability density in that region.

1097 3.2.3 MCMC Optimisation

1098 As discussed in subsection 3.2.2, the proposal function invoked within the MH al-
1099 gorithm can take any form and the chain will still converge to the stationary distri-
1100 bution. ~~As discussed in Link to Analysis Strategy Section, this analysis performs~~
1101 ~~the Monte Carlo reweighting on an event-by-event basis. This requires significant~~
1102 ~~computational resources to perform a parameter fit~~ At each set of proposed param-
1103 eter values, a prediction of the same spectra has to be generated which requires
1104 significant computational resources. Therefore, the number of steps taken before
1105 the unique stationary distribution is found should be minimised as only steps after
1106 convergence add information to the ~~fit oscillation analysis~~. Furthermore, the chain
1107 should entirely cover the allowable parameter space to ensure that all values have
1108 been considered. Tuning the distance that the proposal function jumps between steps
1109 on a parameter-by-parameter basis can both minimise the length of the burn-in period
1110 and ensure that the correlation between step \vec{x}_i and \vec{x}_j is sufficiently small.

1111 The effect of changing the width of the proposal function is highlighted in Figure 3.3.
1112 Three scenarios, each with the same underlying stationary distribution (A Gaussian of
1113 width 1.0 and mean 0.), are presented. The only difference between the three scenarios
1114 is the width of the proposal function, colloquially known as the ‘step size σ ’. Each
1115 scenario starts at an initial parameter value of 10.0 which would be considered an
1116 extreme variation. For the case where $\sigma = 0.1$, it is clear to see that the chain takes
1117 a long time to reach the expected region of the parameter. This indicates that this
1118 chain would have a large burn-in period and does not converge to the stationary
1119 distribution until step ~ 500 . Furthermore, whilst the chain does move towards the
1120 expected region, each step is significantly correlated with the previous. Considering
1121 the case where $\sigma = 5.0$, the chain approaches the expected parameter region almost
1122 instantly meaning that the burn-in period is not significant. However, there are clearly
1123 large regions of steps where the chain does not move. This is likely due to the chain
1124 proposing steps in the tails of the distribution which have a low probability of being
1125 accepted. Consequently, this chain would take a significant number of steps to fully
1126 span the allowable parameter region. For the final scenario, where $\sigma = 0.5$, you can see
1127 a relatively small burn-in period of approximately 100 steps. Once the chain reaches
1128 the stationary distribution, it moves throughout the expected region of parameter
1129 values many times, sufficiently sampling the full parameter region. This example is a
1130 single parameter varying across a continuous distribution and does not fully reflect
1131 the difficulties in the many-hundred multi-variate parameter distribution used within
1132 this analysis. However, it does give a conceptual idea of the importance of selecting
1133 the proposal function and associated step size.

1134 As discussed, step size tuning directly correlates to the average step acceptance
1135 rate. If the step size is too small, many steps will be accepted but the chain moves
1136 slowly. If the opposite is true, many steps will be rejected as the chain proposes steps
1137 in the tails of the distribution. Discussion in [138] suggests that the ‘ideal’ acceptance

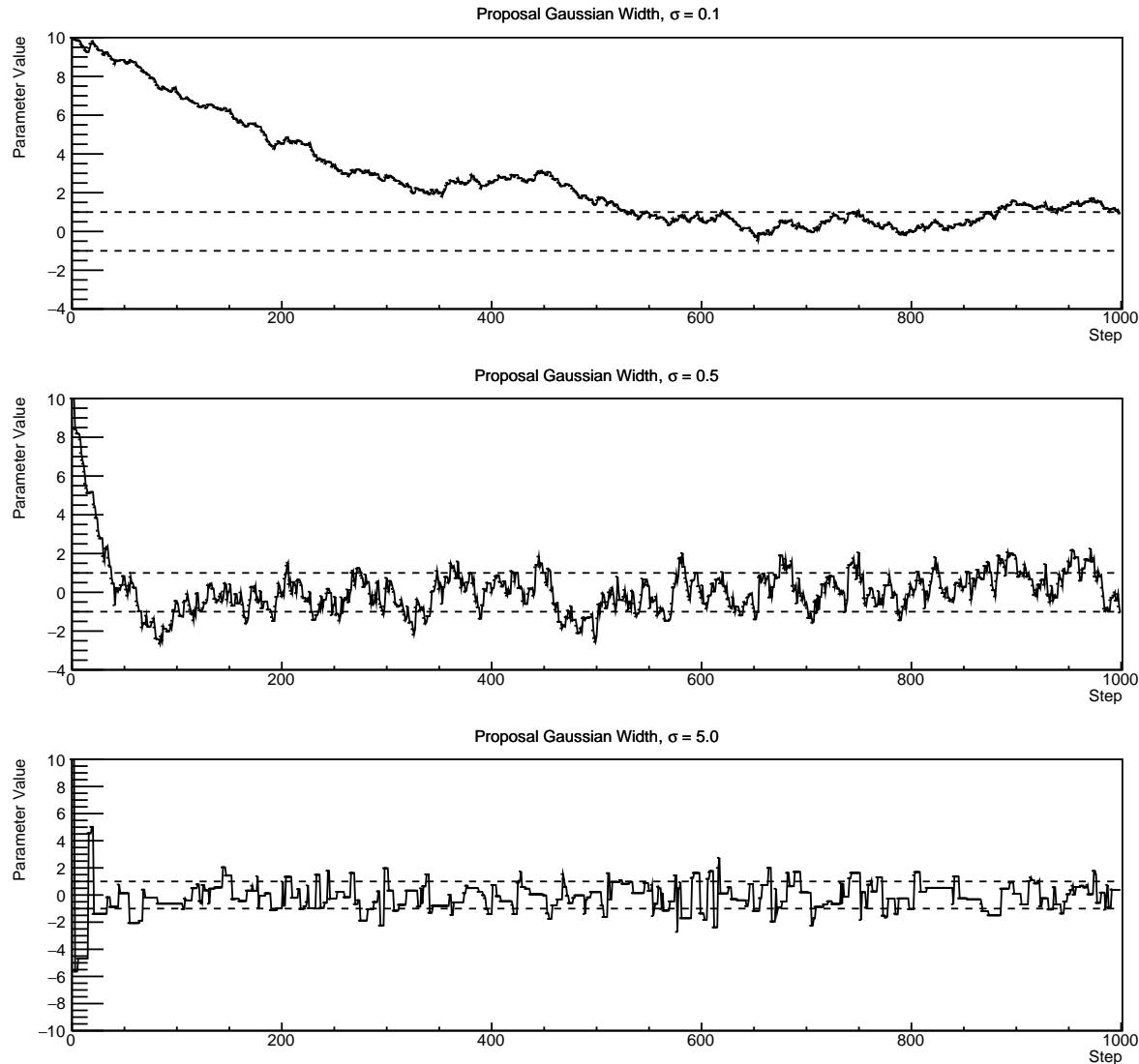


Figure 3.3: Three MCMC chains, each with a stationary distribution equal to a Gaussian centered at 0 and width 1 (As indicated by the black dotted lines). All of the chains use a Gaussian proposal function but have different widths (or ‘step size σ ’). The top panel has $\sigma = 0.1$, middle panel has $\sigma = 0.5$ and the bottom panel has $\sigma = 5.0$.

¹¹³⁸ rate of a high dimension MCMC chain should be approximately $\sim 25\%$. An “ideal”

¹¹³⁹ step size [138] of

$$\sigma = \frac{2.4}{N_p}, \quad (3.6)$$

where N_p is the number of parameters included in the MCMC fit. However, the complex correlations between systematics mean that some parameters have to be hand tuned and many efforts have been taken to select a set of parameter-by-parameter step sizes to approximately reach the ideal acceptance rate.

Figure 3.3 highlights the likelihood as calculated by the fit in DB: Link to AsimovA Sensitivity Section as a function of the number of steps in each chain. In practice, many independent MCMC chains are run simultaneously to parallelise the task of performing the fit. This figure overlays the distribution found in each chain. As seen, the likelihood decreases from its initial value and converges towards a stationary distribution after $\sim 1 \times 10^5$ steps. ~~Each fit (whether it be different asimov fits or data fit) will have a different set of preferred parameter values which results in a different stationary distribution. For each fit presented in this thesis, a burn-in period of 1×10^5 steps was found to be sufficient.~~

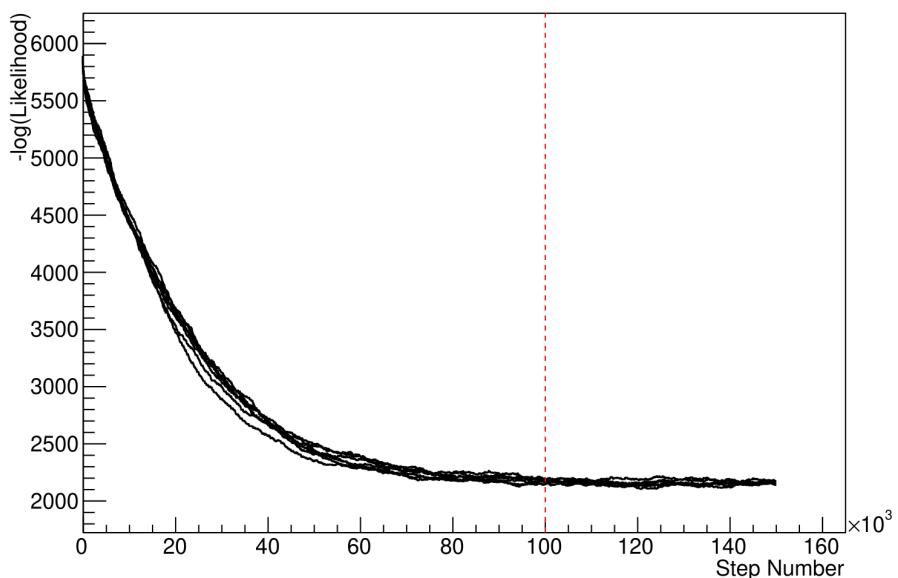


Figure 3.4: The log-likelihood from the fit detailed in DB: Link to AsimovA Sensitivity Section as a function of the number of steps accumulated in each fit. Many independent MCMC chains were run in parallel and overlaid on this plot. The red line indicates the 1×10^5 step burn-in period after which the log-likelihood becomes stable.

1153 Multiple configurations of this analysis have been performed throughout this
1154 thesis where different samples or systematics have been used. For all of these
1155 configurations, it was found that a burnin period of 1×10^5 was sufficient in all
1156 cases.

1157 3.3 Understanding the MCMC Results

1158 Whilst Link and Link describe how to interpret Bayesian statistics and explains the
1159 MCMC techniques used within this analysis, there is no mention of how to inter-
1160 pret the output of the chain. The previous sections have described how to generate
1161 the posterior probability distribution using Bayesian MCMC techniques. How-
1162 ever, this analysis focuses on oscillation parameter determination. The posterior
1163 distribution output from the chain is a high dimension object, with as many dimen-
1164 sions as there are parameters included in the fit oscillation analysis. However, this
1165 multi-dimensional object is difficult to conceptualize so parameter estimations are
1166 often presented in one or two-dimensional projections of this probability distribution.
1167 To do this, we invoke the marginalisation technique highlighted in subsection 3.3.1.

1168 3.3.1 Marginalisation

1169 The output of the MCMC chain is a highly dimensional probability distribution
1170 which is very difficult to interpret. From the standpoint of an oscillation analysis
1171 experiment, the one or two-dimensional ‘projections’ of the oscillation parameters of
1172 interest are most relevant. Despite this, the best fit values and uncertainties on the
1173 oscillation parameters of interest should correctly encapsulate the correlations to the
1174 other systematic uncertainties (colloquially called ‘nuisance’ parameters). For this joint
1175 beam and atmospheric analysis, the oscillation parameters of interest are $\sin^2(\theta_{23})$,

1176 $\sin^2(\theta_{13})$, Δm_{23}^2 , and δ_{CP} . All other parameters (Including the oscillation parameter
 1177 this fit is insensitive to) are deemed nuisance parameters. To generate these projections,
 1178 we rely upon integrating the posterior distribution over all nuisance parameters. This
 1179 is called marginalisation. A simple example of this technique is to imagine the scenario
 1180 where two coins are flipped. To determine the probability that the first coin returned
 1181 a ‘head’, the exact result of the second coin flip is disregarded and simply integrated
 1182 over. For the parameters of interest, $\vec{\theta}_i$, we can calculate the marginalised posterior by
 1183 integrating over the nuisance parameters, $\vec{\theta}_n$. In this case, Equation 3.2 becomes

$$P(\vec{\theta}_i|D) = \frac{\int P(D|\vec{\theta}_i, \vec{\theta}_n)P(\vec{\theta}_i, \vec{\theta}_n)d\vec{\theta}_n}{\int P(D|\vec{\theta})P(\vec{\theta})d\vec{\theta}} \quad (3.7)$$

1184 Where $P(\vec{\theta}_i, \vec{\theta}_n)$ encodes the prior knowledge about the uncertainty and correlations
 1185 between the parameters of interest and the nuisance parameters. In practice, this
 1186 is simply taking the one or two-dimensional projection of the multi-dimensional
 1187 probability distribution.

1188 Whilst in principle an easy solution to a complex problem, correlations between the
 1189 interesting and nuisance parameters can bias the marginalised results. A similar effect
 1190 is found when the parameters being marginalised over have non-Gaussian probability
 1191 distributions. For example, Figure 3.5 highlights the marginalisation bias in the
 1192 probability distribution found for a parameter when requiring a correlated parameter
 1193 to have a positive parameter value. Due to the complex nature of this oscillation
 1194 parameter fit presented in this thesis, there are **certainly** correlations occurring between
 1195 the oscillation parameters of interest and the other nuisance parameters included in
 1196 the fit.

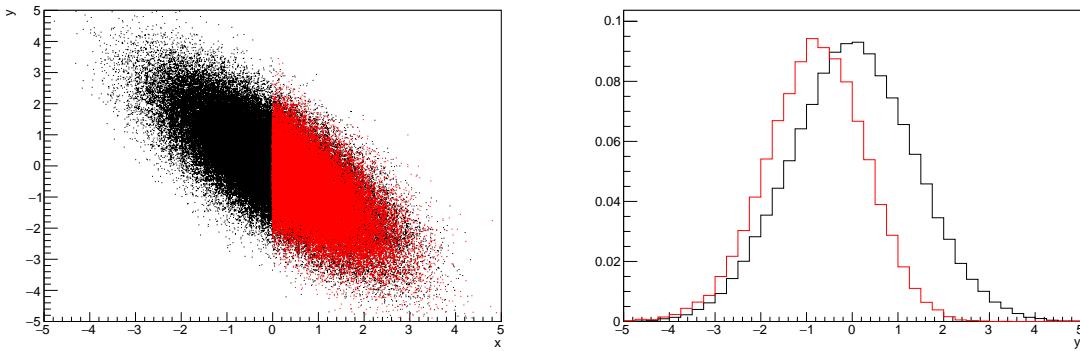


Figure 3.5: Left: The two dimensional probability distribution for two correlated parameters x and y . The red distribution shows the two dimensional probability distribution when $0 \leq x \leq 5$. Right: The marginalised probability distribution for the y parameter found when requiring the x to be bound between $-5 \leq x \leq 5$ for the black and red distribution, respectively.

¹¹⁹⁷ 3.3.2 Parameter Estimation and Credible Intervals

¹¹⁹⁸ The purpose of this analysis is to determine the best fit values for the oscillation
¹¹⁹⁹ parameters that the beam and atmospheric samples are sensitive to: $\sin^2(\theta_{23})$, $\sin^2(\theta_{13})$
¹²⁰⁰, Δm_{23}^2 , and δ_{CP} . Typically, the results presented take the form of one or two-dimension
¹²⁰¹ marginalised probability distributions for the appearance ($\sin^2(\theta_{13})$ and δ_{CP}) and
¹²⁰² disappearance ($\sin^2(\theta_{23})$ and Δm_{23}^2) parameters. The posterior probability density
¹²⁰³ taken from the output MCMC chain is binned in these parameters. The parameter
¹²⁰⁴ best-fit point is then taken to be the value that has the highest posterior probability.
¹²⁰⁵ This is performed in both one and two-dimensional projections.

¹²⁰⁶ However, the single best-fit point in a given parameter is not of much use on its
¹²⁰⁷ own. We would also like to determine the uncertainty, or credible interval, on that
¹²⁰⁸ best-fit point. The definition of the 1σ credible interval is that we have 68% belief that
¹²⁰⁹ the parameter is within those bounds. For a more generalised definition, the credible
¹²¹⁰ interval is the region, R , of the posterior distribution that contains a specific fraction of
¹²¹¹ the total probability, such that

$$\int_R P(\theta|D)d\theta = \alpha \quad (3.8)$$

1212 Where θ is the parameter on which we calculate the credible interval. This technique
1213 then calculates the $\alpha \times 100\%$ credible interval.

1214 In practice, this analysis uses the highest posterior density (HPD) credible intervals
1215 which are calculated through the following method. First, the probability distribution
1216 is area-normalised such that it has an integrated area equal to 1.0. The bins of proba-
1217 bility are then summed from the highest to lowest until the sum exceeds the 1σ level
1218 (0.68 in this example). This process is repeated for a range of credible intervals, notably
1219 the 1σ , 2σ and 3σ along with other levels where the critical values for each level can
1220 be found in [139]. This process can be repeated for the two-dimensional probability
1221 distributions by creating two-dimensional contours of credible intervals rather than a
1222 one-dimensional result.

1223 3.3.3 Bayesian Model Comparisons

1224 Due to the matter resonance, this analysis has some sensitivity to the mass hierarchy
1225 of neutrino states (whether Δm_{23}^2 is positive or negative) and the octant of $\sin^2(\theta_{23})$
1226 . The Bayesian approach utilised within this analysis gives an intuitive method of
1227 model comparison by determining which hypothesis is most favourable. Taking the
1228 ratio of Equation 3.3 for the two hypotheses of normal hierarchy, NH , and inverted
1229 hierarchy, IH , gives

$$\frac{P(\vec{\theta}_{NH}|D)}{P(\vec{\theta}_{IH}|D)} = \frac{P(D|\vec{\theta}_{NH})}{P(D|\vec{\theta}_{IH})} \times \frac{P(\vec{\theta}_{NH})}{P(\vec{\theta}_{IH})}. \quad (3.9)$$

1230 The middle term defines the Bayes factor which is a data-driven interpretation of
 1231 how strong the data prefers one hierarchy to the other. For this analysis, equal priors
 1232 on both mass hierarchy hypotheses are chosen ($P(\vec{\theta}_{NH}) = P(\vec{\theta}_{IH}) = 0.5$). In practice,
 1233 the MCMC chain proposes a value of $|\Delta m_{23}^2|$ and then applies a 50% probability
 1234 that the value is sign flipped. Consequently, the Bayes factor can be calculated from
 1235 the ratio of the probability density in either hypothesis. This equates to counting the
 1236 number of steps taken in the normal and inverted hierarchies and taking the ratio. The
 1237 same approach can be taken to compare the upper octant (UO) compared to the lower
 1238 octant (LO) hypothesis of $\sin^2(\theta_{23})$.

1239 Whilst the value of the Bayes factor should always be shown, the Jeffreys scale [140]
 1240 (highlighted in Table 3.1) gives an indication of the strength of preference for one model
 1241 compared to the other. Other interpretations of the strength of preference of a model
 1242 exist, e.g. the Kass and Raferty Scale [141].

| $\log_{10}(B_{AB})$ | B_{AB} | Strength of Preference |
|---------------------|----------------|--|
| < 0.0 | < 1 | No preference for hypothesis A (Supports hypothesis B) |
| $0.0 - 0.5$ | $1.0 - 3.16$ | Preference for hypothesis A is weak |
| $0.5 - 1.0$ | $3.16 - 10.0$ | Preference for hypothesis A is substantial |
| $1.0 - 1.5$ | $10.0 - 31.6$ | Preference for hypothesis A is strong |
| $1.5 - 2.0$ | $31.6 - 100.0$ | Preference for hypothesis A is very strong |
| > 2.0 | > 100.0 | Decisive preference for hypothesis A |

Table 3.1: Jeffreys scale for strength of preference for two models A and B as a function of the calculated Bayes factor ($B_{AB} = B(A/B)$) between the two models [140]. The original scale is given in terms of $\log_{10}(B(A/B))$ but converted to linear scale for easy comparison throughout this thesis.

1243 3.3.4 Comparison of MCMC Output to Expectation

1244 ~~Whilst not important for the extraction of oscillation parameters, understanding~~
1245 ~~how the data constrains the model parameters is important to the understanding~~
1246 ~~of this analysis. To ensure the fit is performing well, a best-fit spectra is produced~~
1247 ~~using the posterior probability distribution and compared with the data, allowing~~
1248 ~~easy by-eye comparisons to be made.~~ A simple method of doing this is to perform a
1249 comparison in the fitting parameters (For instance, the reconstructed neutrino energy
1250 and lepton direction for T2K far detector beam samples) of the spectra generated by
1251 the MCMC chain to ‘data’. This ‘data’ could be true data or some variation of Monte
1252 Carlo prediction. This allows easy comparison of the MCMC probability distribution
1253 to the data. To perform this, N steps from the post burn-in MCMC chain are randomly
1254 selected (Where for all plots of this style in this thesis, $N = 3000$). From these, the
1255 Monte Carlo prediction at each step is generated by reweighting the model parameters
1256 to the values specified at that step. Due to the probability density being directly
1257 correlated with the density of steps in a certain region, parameter values close to the
1258 best fit value are most likely to be selected.

1259 In practice, for each bin of the fitting parameters has a probability distribution
1260 of event rates, with one entry per sampled MCMC step. This distribution is binned
1261 where the bin with the highest probability is selected as the mean and an error on
1262 the width of this probability distribution is calculated using the approach highlighted
1263 in subsection 3.3.2. Consequently, the best fit distribution in the fit parameter is not
1264 necessarily that which would be attained by reweighting the Monte Carlo prediction
1265 to the most probable parameter values.

1266 A similar study can be performed to illustrate the freedom of the model parameter
1267 space prior to the fit. This can be done by throwing parameter values from the prior

₁₂₆₈ uncertainty of each parameter. This becomes troublesome for parameters with no
₁₂₆₉ prior uncertainty as the range is technically infinite. Where applicable solutions to
₁₂₇₀ remove these have been addressed.

1271 **Chapter 4**

1272 **Simulation, Reconstruction, and Event
1273 Selections**

1274 As a crucial part of the oscillation analysis, an accurate prediction of the expected
1275 neutrino spectrum at the far detector is required. This includes modeling the flux
1276 generation, neutrino interactions, and detector effects. All of the simulation packages
1277 required to do this are briefly described in section 4.1. The reconstruction of neutrino
1278 events inside the far detector, including the `fiTQun` algorithm, is documented in
1279 section 4.2. This also includes data quality checks of the SK-V data which the author
1280 performed for the T2K oscillation analysis presented at Neutrino 2020 [80]. Finally,
1281 section 4.3 describes the steps taken in the SK detector to trigger on events of interest
1282 whilst removing the comparatively large rate of cosmic ray muon events.

1283 **4.1 Simulation**

1284 In order to generate a Monte Carlo prediction of the expected event rate at the far
1285 detector, all the processes in the beam and atmospheric flux, neutrino interaction, and
1286 detector need to be modeled. Each of these parts is individually modeled and each of
1287 them is detailed below.

1288 The beamline simulation consists of three distinct parts: the initial hadron inter-
1289 action modeled by FLUKA [142], the target station geometry and particle tracking

performed by JNUBEAM, [143, 144] and any hadronic re-interactions simulated by GCALOR [145]. The primary hadronic interactions are $O(10)\text{GeV}$, where FLUKA matches external cross-section data better than GCALOR [146]. However, FLUKA is not very adaptable so a small simulation is built to model the interactions in the target and the output is then passed to JNUBEAM and GCALOR for propagation. The hadronic interactions are tuned to data from the NA61/SHINE [147–149] and HARP [150] experiments. The tuning is done by reweighting the FLUKA and GCALOR predictions to match the external data multiplicity and cross-section measurements, based on final state particle kinematics [146]. The culmination of this simulation package generates the predicted flux for neutrino and antineutrino beam modes which are illustrated in Figure 2.7.

The atmospheric neutrino flux predictions are simulated by the HKKM model [43, 45]. The primary cosmic ray flux is tuned to AMS [151] and BESS [152] data assuming the US-standard atmosphere '76 [153] density profile and includes geomagnetic field effects. The primary cosmic rays interact to generate pions and muons. The interaction of these secondary particles to generate neutrinos is handled by DPMJET-III [154] for energies above 32GeV and JAM [45, 155] for energies below that value **DB: Question for Giles: Why different generators for above/below 32GeV?**. These hadronic interactions are tuned to BESS and L3 data [156, 157] using the same methodology as the tuning of the beamline simulation. The energy and cosine zenith predictions of $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$ flux are given in Figure 1.3 and Figure 1.5, respectively. The flux is approximately symmetrical and peaked around the horizon ($\cos(\theta_Z) = 0.0$). This is because horizontally-going pions and kaons can travel further than their vertically-going counterparts resulting in a larger probability of decaying to neutrinos. The symmetry is broken in low-energy neutrinos due to geomagnetic effects, which modify the track of the primary cosmic rays. Updates to the HKKM model are currently ongoing [158].

Once a flux prediction has been made for all three detectors, NEUT 5.4.0 [159, 160] models the interactions of the neutrinos in the detectors. For the purposes of this analysis, quasi-elastic (QE), meson exchange (MEC), single meson production (PROD), coherent pion production (COH), and deep inelastic scattering (DIS) interactions are simulated. These interaction categories can be further broken down by whether they were propagated via a W^\pm boson in Charged Current (CC) interactions or via a Z^0 boson in Neutral Current (NC) interactions. CC interactions have a charged lepton in the final state, which can be flavour-tagged in reconstruction to determine the flavour of the neutrino. In contrast, NC interactions have a neutrino in the final state so no flavour information can be determined from the observables left in the detector after an interaction. This is the reason why NC events are assumed to not oscillate within this analysis. Both CC and NC interactions are modeled for all the above interaction categories, other than MEC interactions which are only modeled for CC events. The SK detector is only sensitive to charged particles, so all charged current interactions are simulated whilst only neutral current processes that produce charged mesons (NCDIS, NCCOH, and NCProd) are modeled. NC MEC interactions can only produce charged particles through secondary re-interactions which is a low cross-section process.

As illustrated in Figure 4.1, CC QE interactions dominate the low-energy cross-section of neutrino interactions. The NEUT implementation adopts the Llewellyn Smith [161] model for neutrino-nucleus interactions, where the nuclear ground state of any bound nucleons (neutrino-oxygen interactions) is approximated by a spectral-function [162] model that simulates the effects of Fermi momentum and Pauli blocking. The cross-section of QE interactions are controlled by vector and axial-vector form factors parameterised by the BBBA05 [163] model and a dipole form factor with $M_A^{QE} = 1.21\text{GeV}$ fit to external data [164], respectively. NEUT implements the Valencia [165] model to simulate MEC events, where two nucleons and two holes in the nuclear target are produced (Often called 2p2h interactions).

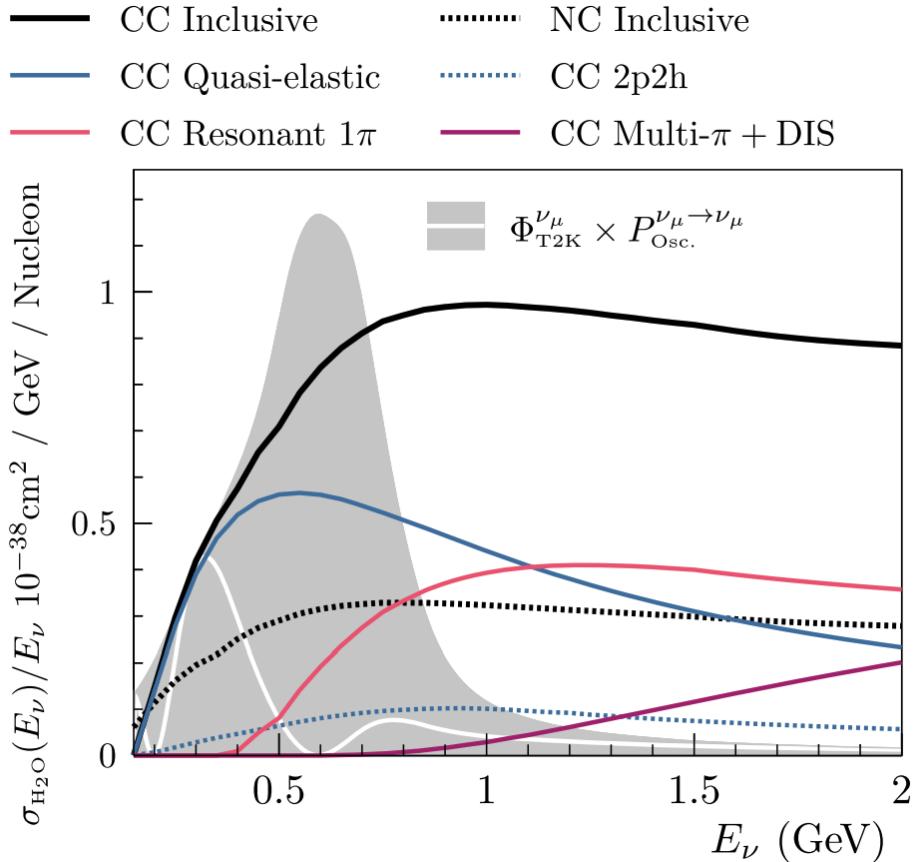


Figure 4.1: The NEUT prediction of the ν_μ -H₂O cross-section overlaid on the T2K ν_μ flux. The charged current (black, solid) and neutral current (black, dashed) inclusive, charged current quasi-elastic (blue, solid), charged current 2p2h (blue, dashed), charged current single pion production (pink), and charged current multi- π and DIS (Purple) cross-sections are illustrated. Figure taken from [159].

For neutrinos of energy $O(1)\text{GeV}$, PROD interactions become dominant. These predominantly produce charged and neutral pions although γ , kaon, and η production is also considered. To simulate these interactions, the Berger-Sehgal [166] model is implemented within NEUT. It simulates the excitation of a nucleon from a neutrino interaction, production of an intermediate baryon, and the consequential decay to a single meson or γ . Pions can also be produced through COH interactions, which occur when the incoming neutrino interacts with the entire oxygen nuclei target leaving a single pion outside of the nucleus. NEUT utilises the Berger-Sehgal [167] model to simulate these COH interactions.

1352 DIS and multi- π producing interactions become the most dominant for energies
1353 $> O(5)\text{GeV}$. PYTHIA [168] is used to simulate any interaction with invariant mass,
1354 $W > 2\text{GeV}/c^2$, which produces at least one meson. For any interaction which produces
1355 at least two mesons but has $W < 2\text{GeV}/c^2$, the Bronner model is invoked [169].
1356 Both of these models use Parton distribution functions based on the Bodek-Yang
1357 model [170–172].

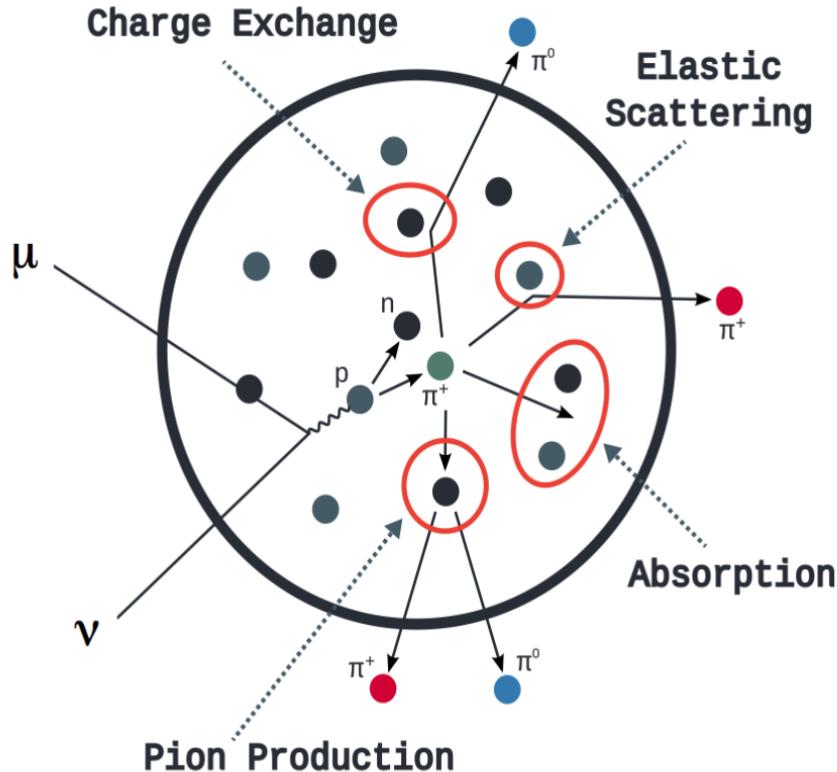


Figure 4.2: Illustration of the various processes which a pion can undergo before exiting the nucleus. Taken from [173].

1358 Any pion which is produced within the nucleus can re-interact through final state
1359 interactions before it exits, as illustrated by the scattering, absorption, production, and
1360 exchange interactions in Figure 4.2. These re-interactions alter the observable particles
1361 within the detector. For instance, if the charged pion from a CC PROD interaction is
1362 absorbed, the observables would mimic a CC QE interaction. To simulate these effects,

1363 NEUT uses a semi-classical intranuclear cascade model [159]. This cascade functions by
1364 stepping the pion through the nucleus in fixed-length steps equivalent to $dx = R_N/100$,
1365 where R_N is the radius of the nucleus. At each step, the simulation allows the pion
1366 to interact through scattering, charged exchange, absorption, or production with an
1367 interaction-dependent probability calculated from a fit to external data [174]. This
1368 cascade continues until the pion is absorbed or exits the nucleus.

1369 Once the final state particle kinematics have been determined from NEUT, they
1370 are passed into the detector simulation. The near detectors, ND280 and INGRID, are
1371 simulated using a GEANT4 package [118,175] to simulate the detector geometry, particle
1372 tracking, and energy deposition. The response of the detectors is simulated using
1373 the elecSim package [118]. The far detector simulation is based upon the original
1374 Kamiokande experiment software which uses the GEANT3-based SKDETSIM [118,176]
1375 package. This controls the interactions of particles in the water as well as Cherenkov
1376 light production. The water quality and PMT calibration measurements detailed in
1377 subsection 2.1.2 are also used within this simulation to make accurate predictions of
1378 the detector response.

1379 4.2 Event Reconstruction at SK

1380 Any above Cherenkov threshold event which occurs in SK will be recorded by the
1381 PMT array, where each PMT records the time and accumulated charge. This recorded
1382 information is shown in event displays similar to those illustrated in Figure 4.3. To
1383 be useful for physics analyses, this series of PMT hit information needs to be recon-
1384 structed to determine the particle's identity and kinematics (or track parameters):
1385 four-vertex, direction, and momenta. This is because the charge and timing distribu-
1386 tion of photons generated by a particular particle in an event is dependent upon its

1387 initial kinematics. The concept of distinguishing electron and muon events is from the
 1388 “fuzziness” of the ring. Muons are heavier and less affected by scattering or showering
 1389 meaning they typically produce “crisp” rings. Electrons are more likely to interact
 1390 via electromagnetic showering or scattering which results in larger variations of their
 1391 direction from the initial direction. Consequently, electrons typically produce “fuzzier”
 1392 rings compared to muons.

1393 For the purposes of this analysis, the `fitQun` reconstruction algorithm is utilised.
 1394 Its core function is to compare a prediction of the accumulated charge and timing
 1395 distribution from each PMT, generated for a particular particle identity and track
 1396 parameters, to that observed in the neutrino event. It determines the preferred values
 1397 by minimising a likelihood function which includes information from PMTs which
 1398 were hit and those that were not hit. The `fitQun` algorithm improves upon the APFit
 1399 reconstruction algorithm which has been used for many previous SK analyses. APFit
 1400 fits the vertex from timing information and then fits the momentum and direction
 1401 of the particle from PMT hits within a 43 deg Cherenkov cone (which assumes an
 1402 ultra-relativistic particle). It then fits the particle identity once the track parameters
 1403 have been fit. Conversely, `fitQun` performs a simultaneous fit of particle kinematics
 1404 and identity, improving both the accuracy of the fit parameters and the rejection of
 1405 neutral current π^0 events [177,178]. The `fitQun` algorithm is based on the key concepts
 1406 of the MiniBooNE reconstruction algorithm [179] and is described in [180] which is
 1407 summarised below.

1408 An event in SK can consist of multiple particles. For example, a charge current
 1409 muon neutrino interaction can generate two particles that have the potential of gen-
 1410 erating Cherenkov photons: the primary muon, and the secondary decay-electron
 1411 from the muon. To ensure both subevents are reconstructed separately, each event is
 1412 divided into time clusters which are called “subevents”. The number of subevents is

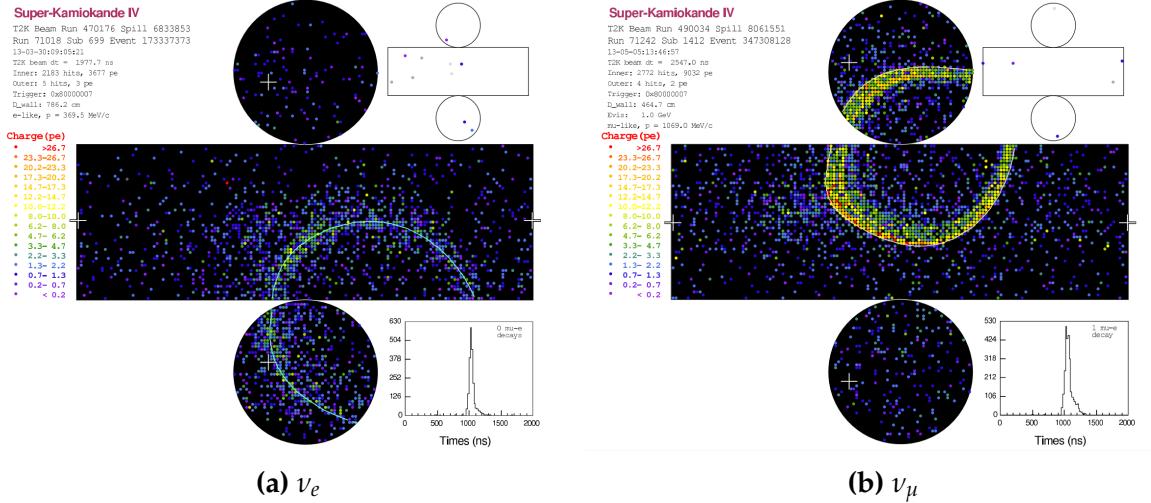


Figure 4.3: Event displays from Super Kamiokande illustrating the “crisp” ring from a muon and the typically “fuzzy” electron ring. Each pixel represents a PMT and the color scheme denotes the accumulated charge deposited on that PMT. Figures taken from [181].

equal to the number of decay electrons minus one (the primary event). To find all the subevents in an event, a vertex goodness metric is calculated for some vertex position \vec{x} and time t ,

$$G(\vec{x}, t) = \sum_i^{\text{hit PMTs}} \exp \left(-\frac{1}{2} \left(\frac{T_{Res}^i(\vec{x}, t)}{\sigma} \right)^2 \right) \quad (4.1)$$

where

$$T_{Res}^i(\vec{x}, t) = t^i - t - |R_{PMT}^i - \vec{x}| / c_n \quad (4.2)$$

is the residual hit time. It is the difference in time between the PMT hit time, t^i , of the i^{th} PMT and the expected time of the PMT hit if the photon was emitted at the start of the vertex. R_{PMT}^i is the position of the i^{th} PMT, c_n is the speed of light in

water and $\sigma = 4\text{ns}$ which is comparable to the time resolution of the PMT. When the proposed fit values of time and vertex are close to the true values, $T_{Res}^i(\vec{x}, t)$ tends to zero resulting in subevents appearing as spikes in the goodness metric. The proposed fit vertex and time are grid-scanned, and the values which maximise the goodness metric are selected as the “pre-fit vertex”. Whilst this predicts a vertex for use in the clustering algorithm, the final vertex is fit using the higher-precision maximum likelihood method described below.

Once the pre-fit vertex has been determined, the goodness metric is scanned as a function of t to determine the number of subevents. A peak-finding algorithm is then used on the goodness metric, requiring the goodness metric to exceed some threshold and drop below a reduced threshold before any subsequent additional peaks are considered. The thresholds are set such that the rate of false peak finding is minimised while still attaining good data to Monte Carlo agreement. To improve performance, the pre-fit vertex for each delayed subevent is re-calculated after PMT hits from the previous subevent are masked. This improves the decay-electron tagging performance. Once all subevents have been determined, the time window around each subevent is then defined by the earliest and latest time which satisfies $-180 < T_{Res}^i < 800\text{ns}$. The subevents and associated time windows are then used as seeds for further reconstruction.

For a given subevent, the `fitQun` algorithm constructs a likelihood based on the accumulated charge q_i and time information t_i from the i^{th} PMT,

$$L(\Gamma, \vec{\theta}) = \prod_j^{\text{unhit}} P_j(\text{unhit}|\Gamma, \vec{\theta}) \prod_i^{\text{hit}} \{1 - P_i(\text{unhit}|\Gamma, \vec{\theta})\} f_q(q_i|\Gamma, \vec{\theta}) f_t(t_i|\Gamma, \vec{\theta}), \quad (4.3)$$

where $\vec{\theta}$ defines the track parameters; vertex position, direction vector and momenta, and Γ represents the particle hypothesis. $P_i(\text{unhit}|\Gamma, \vec{\theta})$ defines the probability of the i^{th} tube to not register a hit given the track parameters and particle hypothesis. The charge likelihood, $f_q(q_i|\Gamma, \vec{\theta})$, and time likelihood, $f_t(t_i|\Gamma, \vec{\theta})$, represent the probability density function of observing charge q_i and time t_i on the i^{th} PMT given the specified track parameters and particle hypothesis.

As the generation and propagation of the optical photons are independent of the PMT and electronics response, it is natural to split the calculation into two. Firstly, the expected number of photoelectrons (or predicted charge), $\mu_i = \mu_i(\vec{\theta}, \Gamma)$, at the i^{th} PMT is calculated. This value is then substituted into the likelihood function. This allows the charge likelihood density $f_q(q_i|\mu_i)$ and unhit probability $P_i(\text{unhit}|\mu_i)$ to be expressed via quantities that are only dependent on the response of the PMT.

The predicted charge is calculated based on contributions from both the direct light and the scattered light. The direct light contribution is determined based on the integration of the Cherenkov photon profile along the track. PMT angular acceptance, water quality, and calibration measurements discussed in subsection 2.1.2 are included to accurately predict the charge probability density at each PMT. The scattered light is calculated in a similar way, although it includes a scattering function that depends on the vertex of the particle and the position of the PMT. The charge likelihood is calculated by comparing the prediction to the observed charge in the PMT.

The time likelihood is approximated to depend on the vertex \vec{x} , direction \vec{d} , and time t of the track parameters as well as the particle hypothesis. The expected time for PMT hits is calculated by assuming unscattered photons being emitted from the midpoint of the track, S_{mid} ,

$$t_{exp}^i = t + S_{mid}/c + |R_{PMT}^i - \vec{x} - S_{mid}\vec{d}|/c_n, \quad (4.4)$$

where c is the speed of light in a vacuum. The time likelihood is then expressed in terms of the residual difference between the PMT hit time and the expected hit time, $t_{Res}^i = t^i - t_{exp}^i$. The particle hypothesis and momentum also affect the Cherenkov photon distribution. These parameters modify the shape of the time likelihood density since in reality not all photons are emitted at the midpoint of the track. As with the charge likelihood, the contributions from both the direct and scattered light to the time likelihood density are calculated separately, which are both calculated from particle gun studies.

The track parameters and particle identity which maximise $L(\Gamma, \vec{\theta})$ are defined as the best-fit parameters. In practice MINUIT [182] is used to minimise the value of $-\ln L(\Gamma, \vec{\theta})$. The `fitQun` algorithm considers an electron-like, muon-like, and charged pion-like hypothesis for events with a single final state particle, denoted “single-ring events”. The particle’s identity is determined by taking the ratio of the likelihood of each of the hypotheses. For instance, electrons and muons are distinguished by considering the value of $\ln(L(e, \vec{\theta}_e)/L(\mu, \vec{\theta}_\mu))$ in comparison to the reconstructed momentum of the electron hypothesis [180]. This distance from this criteria is termed the PID parameter and is illustrated in Figure 4.4.

The `fitQun` algorithm also considers a π^0 hypothesis. To do this, it performs a fit looking for two standard electron-hypothesis tracks which point to the same four-vertex. This assumes the electron tracks are generated from photon-conversion so the electron tracks actually appear offset from the proposed π^0 vertex. For these fits, the conversion length, direction, and momenta of each photon are also considered as track

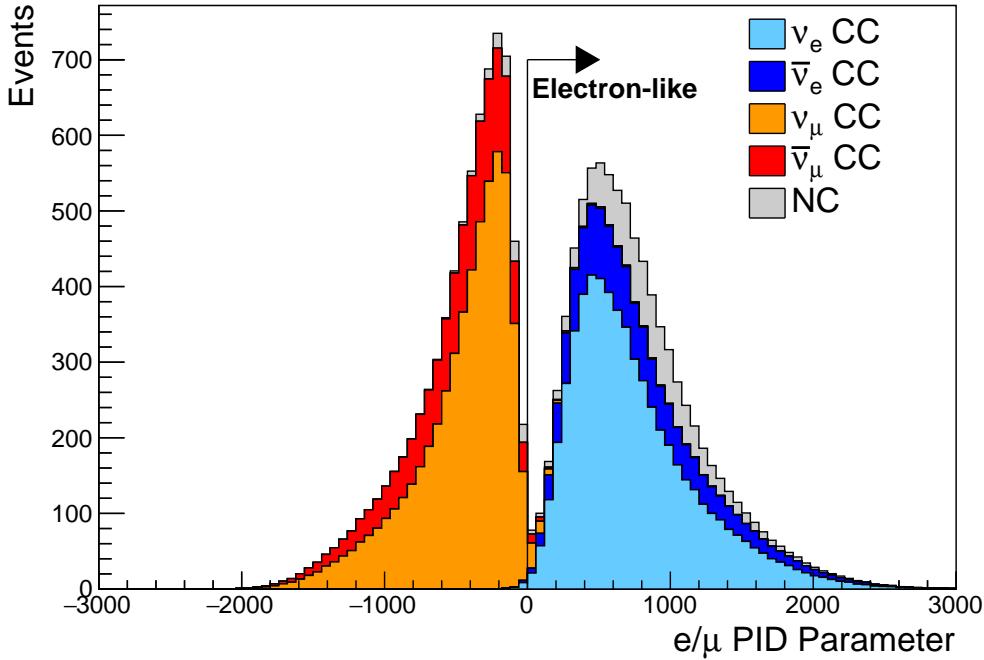


Figure 4.4: The electron/muon PID separation parameter for all sub-GeV single-ring events in SK-IV. The charged current (CC) component is broken down in four flavours of neutrino (ν_μ , $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$). Events with positive values of the parameter are determined to be electron-like.

¹⁴⁸⁷ parameters which are then fit in the same methodology as the standard single-ring
¹⁴⁸⁸ hypotheses.

¹⁴⁸⁹ Whilst low energy events are predominately single-ring events, higher energy
¹⁴⁹⁰ neutrino events can generate final states with multiple particles which generate
¹⁴⁹¹ Cherenkov photons. These “multi-ring” hypotheses are also considered in the `fitQun`
¹⁴⁹² algorithm. When calculating the charge likelihood density, the predicted charge
¹⁴⁹³ associated with each ring is calculated separately and then merged to calculate the
¹⁴⁹⁴ total accumulated charge on each PMT. Similarly, the time likelihood for the multi-ring
¹⁴⁹⁵ hypothesis is calculated assuming each ring is independent. Each track is time-ordered
¹⁴⁹⁶ based on the time of flight from the center of the track to the PMT and the direct light
¹⁴⁹⁷ from any ring incident on the PMT is assumed to arrive before any scattered light. To
¹⁴⁹⁸ reduce computational resources, the multi-ring fits only consider electron-like and

1499 charged pion-like rings as the pion fit can be used as a proxy for a muon fit due to
1500 their similar mass.

1501 Multi-ring fits proceed by proposing another ring to the previous fit and then
1502 fitting the parameters in the method described above. Typically, multi-ring fits have
1503 the largest likelihood because of the additional degrees of freedom introduced. Conse-
1504 quently, the additional ring is only added if the ratio of likelihoods passes a criterion,
1505 which is determined by Monte Carlo studies.

1506 As an example of how the reconstruction depends on the detector conditions, the
1507 author of this thesis assessed the quality of event reconstruction for SK-V data. The
1508 detector systematics invoked within the T2K-only oscillation analysis are determined
1509 using data to Monte Carlo comparisons using the SK-IV data [183]. Due to tank-open
1510 maintenance occurring between SK-IV and SK-V, the dark rate of each PMT was
1511 observed to increase in SK-V due to light exposure for a significant time during the
1512 repairs. This increase can be seen in Figure 4.5. Run-10 of the T2K experiment was
1513 conducted in the SK-V period, so the consistency of SK-IV and SK-V data needs to
1514 be studied to determine whether the SK-IV-defined systematics can be applied to the
1515 run-10 data. This comparison study was performed using the stopping muon data set
1516 for both the SK-IV and SK-V periods. This data sample is used due to the high rate of
1517 interactions ($O(200)$ events per hour) as well as having similar energies to muons from
1518 CCQE ν_μ interactions from beam interactions. The rate of cosmic muons does depend
1519 on the solar activity cycle [184] but has been neglected in this comparison study. This
1520 is because the shape of the distributions is most important for the purposes of being
1521 compared to the detector systematics. The SK-IV and SK-V data samples consist of
1522 2398.42 and 626.719 hours of data which equates to 686k and 192k events respectively.

1523 The predicted charge calculated in the `fitQun` charge likelihood prediction includes
1524 a contribution from the photoelectron emission due to dark noise. Therefore, the

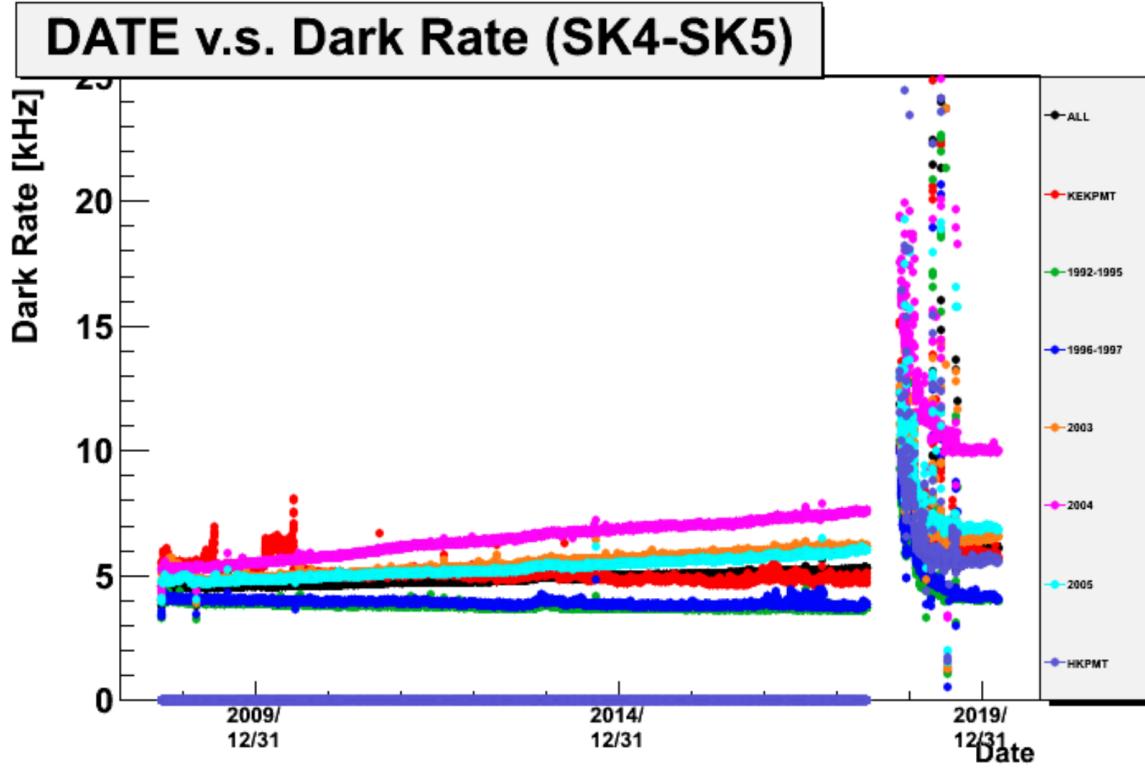


Figure 4.5: The variation of the measured dark rate as a function of date, broken down by PMT type. The SK-IV and SK-V periods span September 2008 to May 2018 and January 2019 to July 2020, respectively. The break in measurement in 2018 corresponds to the period of tank repair and refurbishment. Figure adapted from [183].

increase in the SK-V dark rate needs to be accounted for. In practice, the average dark rate in each SK period is calculated and used as an input in the reconstruction. This is calculated by averaging the dark rate per run for each period separately, using the calibration measurements detailed in subsection 2.1.2. The average dark rate from SK-IV and SK-V were found to be 4.57kHz and 6.30kHz, respectively. The associated charge with the muon and decay electron subevents are illustrated in Figure 4.6. The photoelectron emission from dark noise will be more noticeable for events that have lower energy. This is because this contribution becomes more comparable to the number of photoelectrons emitted from incident photons in low-energy events. This behaviour is observed in the data, where the charge deposited by the muon subevent

1535 is mostly unaffected by the increase in dark rate, whilst the charge associated with the
 1536 decay-electron is clearly affected.

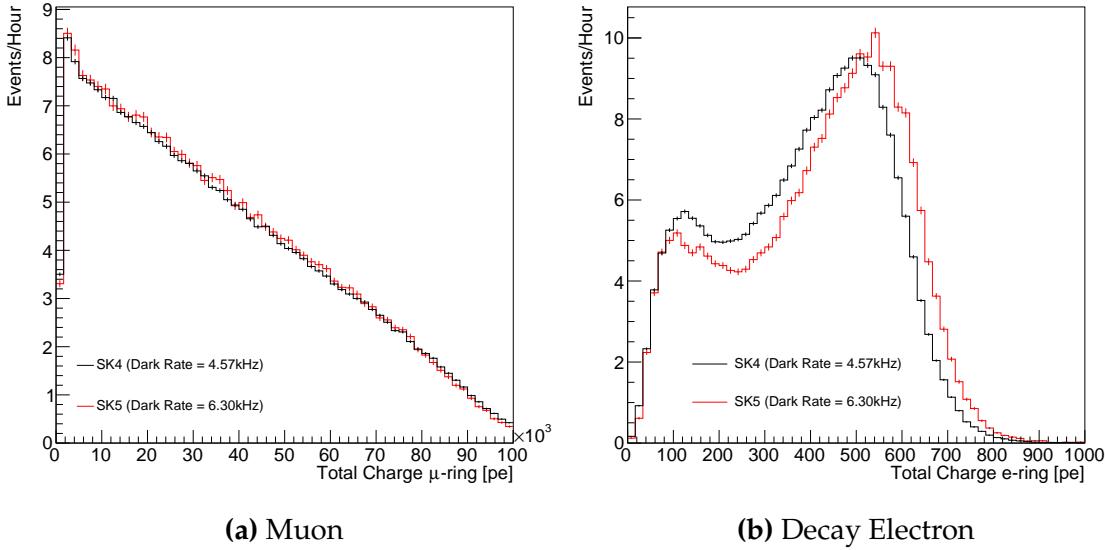


Figure 4.6: Comparison of the measured raw charge deposited per event from the stopping muon data samples between SK-IV (Blue) and SK-V (Red), split by the primary muon subevent and the associated decay electron subevent.

1537 The energy scale systematic for the SK-IV period was determined to be 2.1% [185].
 1538 It is defined to be equal to the difference between data and Monte Carlo prediction
 1539 in the stopping muon data sample. To determine the consistency of the SK-IV and
 1540 SK-V with respect to the energy scale systematic, the muon momentum distribution is
 1541 compared between the two SK periods. As the total number of Cherenkov photons
 1542 is integrated across the track length, the reconstructed momentum divided by track
 1543 length (or range) is compared between SK-IV and SK-V as illustrated in Figure 4.7.

1544 The consistency between these distributions has been computed in two ways.
 1545 Firstly, a Gaussian is fit to each distribution separately. The mean of which is found to
 1546 be $(2.272 \pm 0.003)\text{MeV/cm}$ and $(2.267 \pm 0.006)\text{MeV/cm}$ for SK-IV and SK-V respec-
 1547 tively. The ratio of these is equal to 1.002 ± 0.003 . The mean of the Gaussian fits are
 1548 consistent with the expected stopping power of a minimum ionising muon for a target

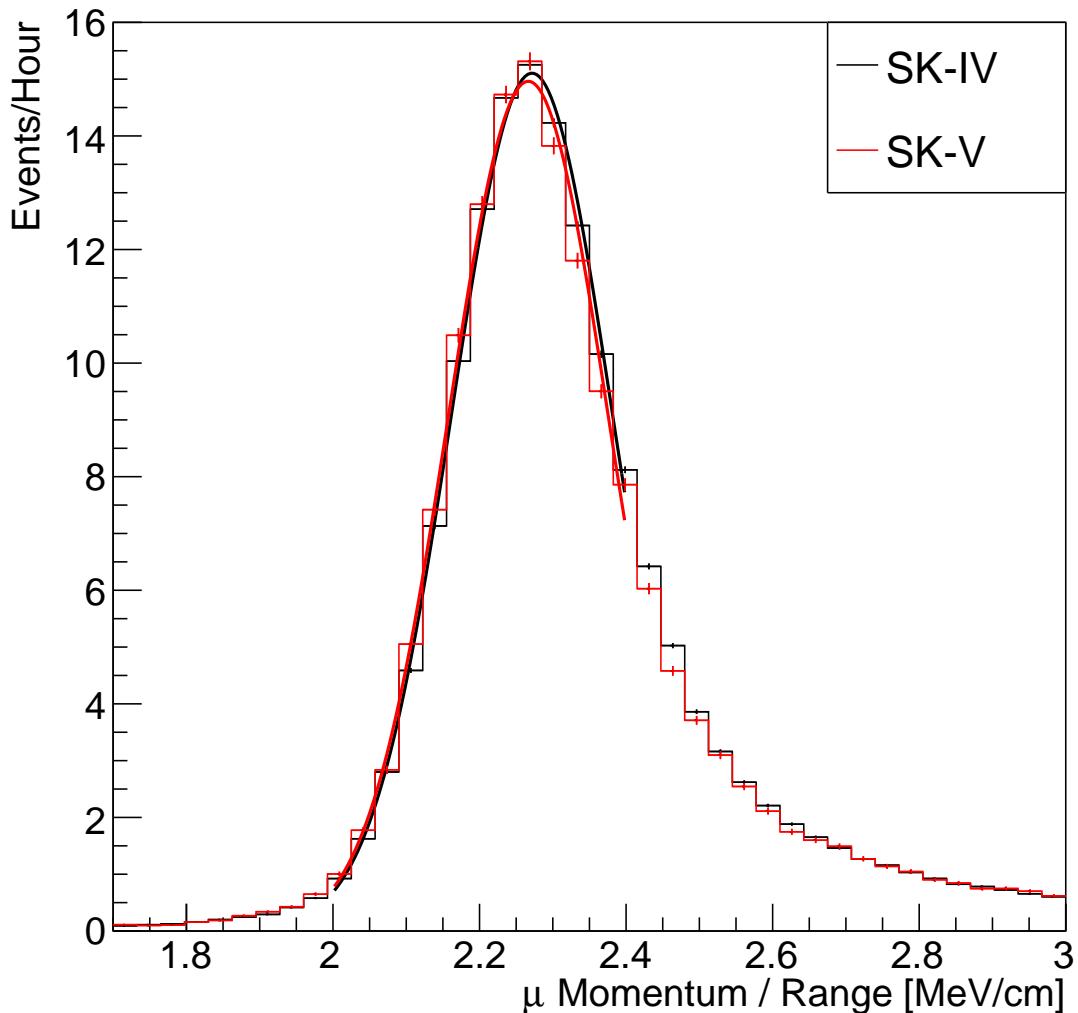


Figure 4.7: The distribution of the reconstructed momentum from the muon ring divided by the distance between the reconstructed muon and decay electron vertices as found in the stopping muon data sets of SK-IV (Black) and SK-IV (Red). Only events with one tagged decay electron are considered. A Gaussian fit is considered in the range [2.0, 2.4] MeV/cm and illustrated as the solid curve.

material (water) with $Z/A \sim 0.5$ [186]. The second consistency check is performed by introducing a nuisance parameter, α , which modifies the SK-V distribution. The value of α which minimises the χ^2 value between the SK-IV and SK-V is determined by scanning across a range of values. This is repeated by applying the nuisance parameter as both a multiplicative factor and an additive shift. The χ^2 distributions for different values of α is illustrated in Figure 4.8. The values which minimise the χ^2 are found to

- ₁₅₅₅ be 0.0052 and 1.0024 for the additive and multiplicative implementations, respectively.
₁₅₅₆ No evidence of shifts larger than the 2.1% uncertainty on the energy scale systematic
₁₅₅₇ has been found in the reconstructed momentum distribution of SK-IV and SK-V.

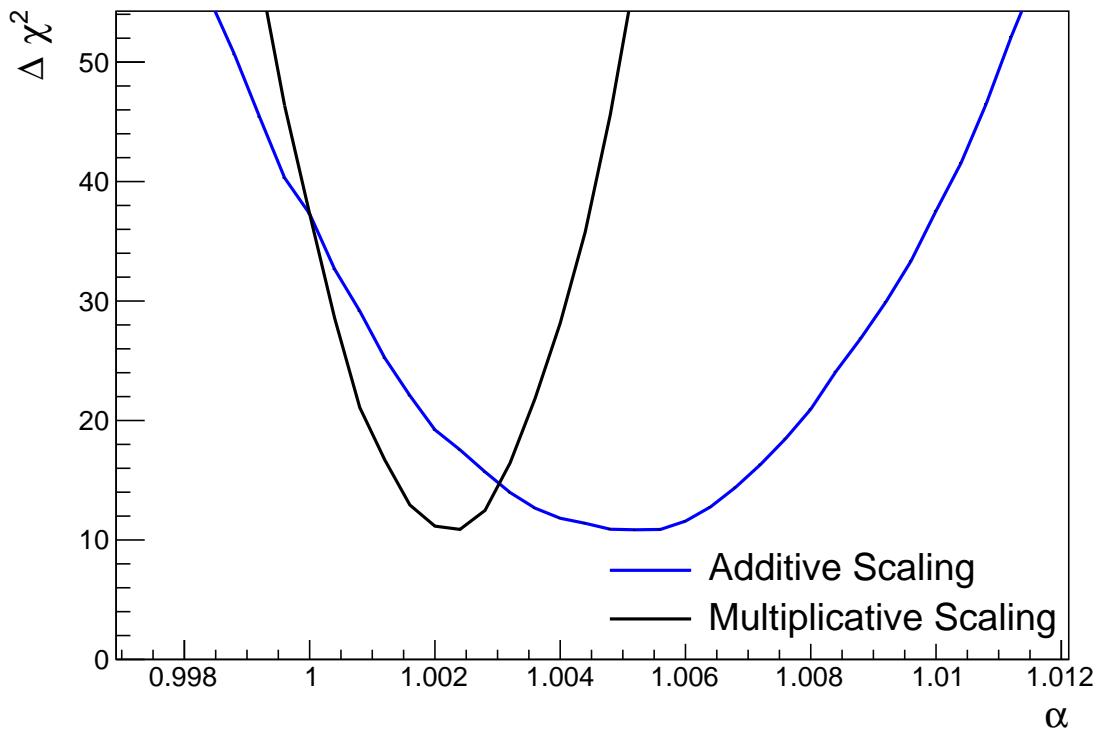


Figure 4.8: The χ^2 difference between the SK-IV and SK-V reconstructed muon momentum divided by range when the SK-V is modified by the scaling parameter α . Both additive (Blue) and multiplicative (Black) scaling factors have been considered. In practice, the additive scaling factor actually uses the value of $(\alpha - 1.0)$ but is illustrated like this so the results can be shown on the same axis range.

₁₅₅₈ 4.3 Event Reduction at SK

- ₁₅₅₉ Atmospheric neutrino events observed in the SK detector are categorised into three
₁₅₆₀ different types of samples: fully contained (FC), partially contained (PC) and up-
₁₅₆₁ going muon (Up- μ), using PMT hit signatures in the inner and outer detector (ID
₁₅₆₂ and OD, respectively). To identify FC neutrino events, it is required that the neutrino

1563 interacts inside the fiducial volume of the ID such that no significant OD activity is
 1564 observed. For this analysis, an event is defined to be in the fiducial volume providing
 1565 the event vertex is at least 0.5m away from the ID walls. PC events have the same
 1566 ID requirements but can have a larger signal present inside the OD. Typically these
 1567 events are higher energy muon interactions that penetrate the ID walls. The Up- μ
 1568 sample contains events where muons are created from neutrino interactions in the
 1569 OD water or rock below the tank. They then propagate upwards through the detector.
 1570 The reason downward-going muons generated from neutrino interactions above the
 1571 tank are neglected is due to the difficulty in separating their signature from the cosmic
 1572 muon shower background. The sample categories are visually depicted in Figure 4.9.

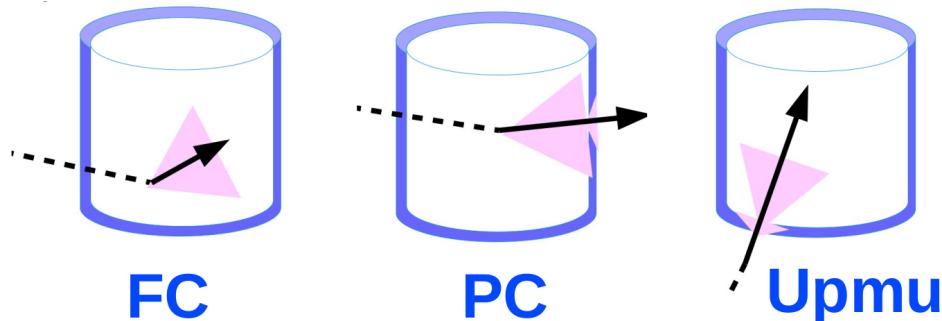


Figure 4.9: A depiction of the topology patterns for fully-contained (FC), partially-contained (PC) and up-going muon (Up- μ) samples included in this analysis.

1573 Based on the event characteristics, as defined by the `fitQun` event reconstruction
 1574 software, the FC events are categorised by

- 1575 • **Visible Energy:** equal to the sum of the reconstructed kinetic energy above the
 1576 Cerenkov threshold for all rings present in the event. The purpose is to separate
 1577 events into sub-GeV and multi-GeV categories.
- 1578 • **Number of observed Cerenkov rings.** The purpose is to separate single-ring and
 1579 multi-ring events, where single-ring events predominantly consist of quasi-elastic
 1580 interactions and multi-ring events are typically resonant pion production or deep
 1581 inelastic scattering events.

- **Particle identification parameter of the most energetic ring:** A value determined from the maximum likelihood value based on `fitQun`'s electron, muon, or pion hypothesis. The purpose is to separate electron-like and muon-like events.
- **Number of decay electrons:** The purpose is to separate quasi-elastic events (which have one decay electron emitted from the muon decay) and resonant pion production events (which have two decay electrons emitted from the muon and pion).

The PC and Up- μ categories are broken down into “through-going” and “stopping” samples depending on whether the muon left the detector. This is because the stopping events deposit the entire energy of the interaction into the detector, resulting in better reconstruction. The energy of events that exit the detector has to be estimated which introduces much larger systematic uncertainties. Through-going Up- μ samples are further broken down by whether any hadronic showering was observed in the event which typically indicates DIS interactions. The expected neutrino energy for the different categories is given in Figure 4.10. FC sub-GeV and multi-GeV events peak around 0.7GeV and 3GeV respectively, with slightly different peak energies for $\nu_x \rightarrow \nu_e$ and $\nu_x \rightarrow \nu_\mu$ oscillation channels. PC and Up- μ are almost entirely comprised of $\nu_x \rightarrow \nu_\mu$ events and peak around 7GeV and 100GeV, respectively.

In normal data-taking operations, the SK detector observes many background events alongside the beam and atmospheric neutrino signal events of physics interest. Cosmic ray muons and flasher events, which are the spontaneous discharge of a given PMT, contribute the largest amount of background events in the energy range relevant to any analysis searching for neutrino events. Lower energy analyses like DSNB searches are also subject to radioactive backgrounds [187]. Therefore the data recorded is reduced with the aim of removing these background events. The reduction process is detailed in [47, 89] and briefly summarised below.

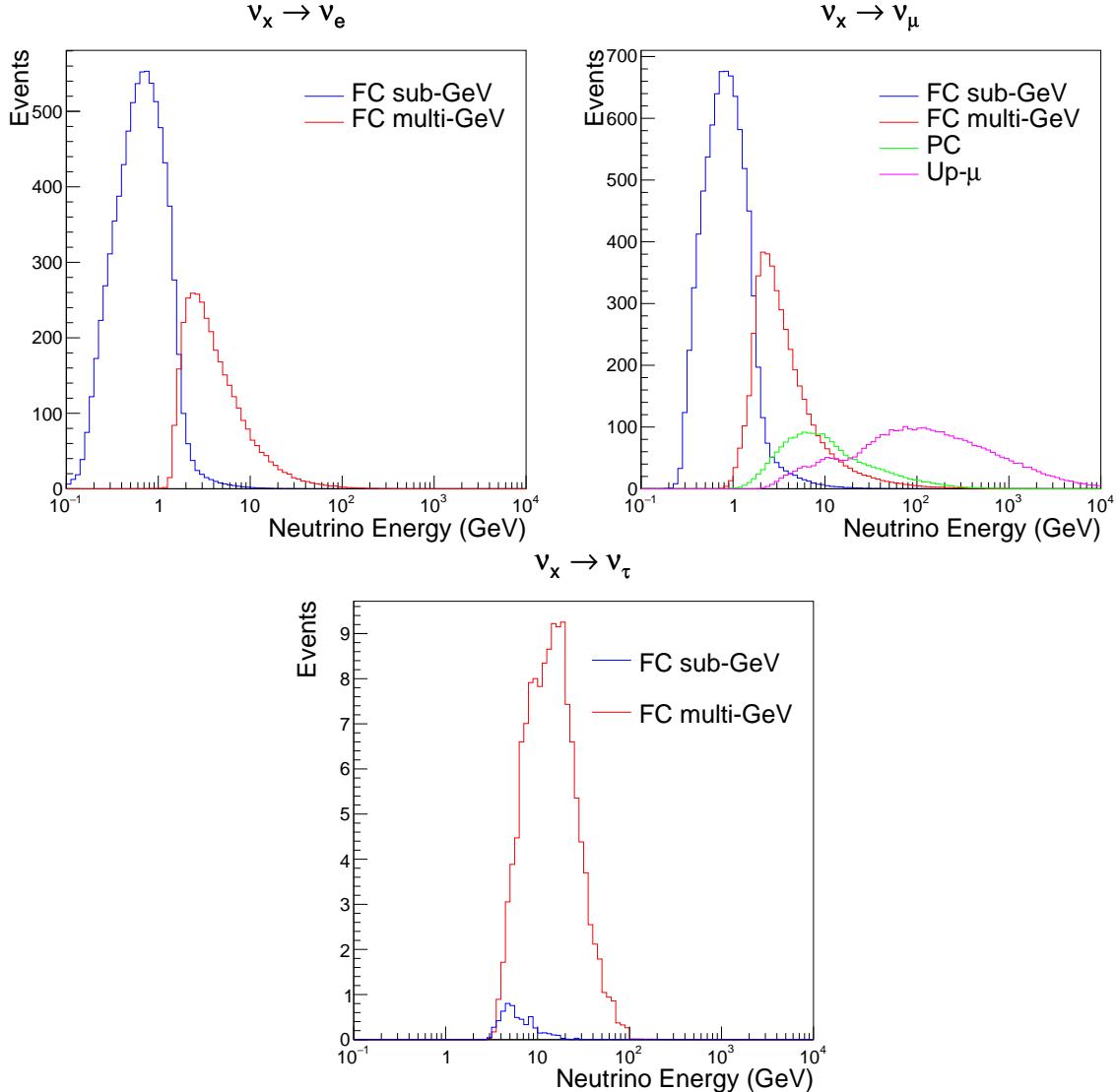


Figure 4.10: The predicted neutrino flux of the fully contained (FC) sub-GeV and multi-GeV, partially contained (PC), and upward-going muon (Up- μ) events. The prediction is broken down by the $\nu_x \rightarrow \nu_e$ prediction (top left), $\nu_x \rightarrow \nu_\mu$ prediction (top right) and $\nu_x \rightarrow \nu_\tau$ prediction (bottom). All systematic dials are set to their nominal values and the Asimov A oscillation parameters are assumed.

1608 The first two steps in the FC reconstruction remove the majority of cosmic ray
 1609 muons by requiring a significant amount of ID activity compared to that measured in
 1610 the OD. Events that pass this cut are typically very high momentum muons or events
 1611 that leave very little activity in the OD. Consequently, a third reduction step is then
 1612 applied to select cosmic-ray muons that pass the initial reduction step. A purpose-built
 1613 cosmic muon fitter is used to determine the entrance (or exit) position of the muon and

1614 a cut is applied to OD activity contained within 8m of this position. Flasher events are
 1615 removed in the fourth reduction step which is based on the close proximity of PMT
 1616 hits surrounding the PMT producing the flash. Events that pass all these reduction
 1617 steps are reconstructed with the APFit algorithm. The fifth step of the reduction uses
 1618 information from the more precise fitter to repeat the previous two steps with tighter
 1619 cuts. Muons below the Cherenkov threshold can not generate optical photons in the
 1620 ID but the associated decay electron can due to its lower mass. These are the types of
 1621 events targeted in the fifth reduction step. The final cuts require the event vertex to be
 1622 within the fiducial volume (0.5m from the wall although the nominal distance is 2.0m),
 1623 visible energy $E_{vis} > 30\text{MeV}$ and fewer than 16 hits within the higher energy OD
 1624 cluster. The culmination of the fully contained reduction results in 8.09 events/day in
 1625 the nominal fiducial volume [188]. The uncertainty in the reconstruction is calculated
 1626 by comparing Monte Carlo prediction to data. The largest discrepancy is found to be
 1627 1.3% in the fourth reduction step.

1628 The PC and Up- μ events are processed through their own reduction processes
 1629 detailed in [47]. Both of these samples are reconstructed with the APFit algorithm
 1630 rather than fitQun. This is because the efficiency of reconstructing events that leave
 1631 the detector has not been sufficiently studied for reliable systematic uncertainties. The
 1632 PC and Up- μ samples attain events at approximately 0.66 and 1.44 events/day.

1633 Events due to beam neutrinos undergo the same reduction steps as FC events and
 1634 are then subject to further cuts [189]. The GPS system which links the timing between
 1635 the beam facility and SK needs to be operating correctly and there should be no activity
 1636 within the detector in the previous $100\mu\text{s}$ before the trigger. The events then need to
 1637 triggered between $-2\mu\text{s}$ and $10\mu\text{s}$ of the expected spill timing.

1638

Chapter 5

1639

Oscillation Probability Calculation

1640 It is important to understand how and where the sensitivity to the oscillation pa-
1641 rameters comes from for both atmospheric and beam samples. An overview of how
1642 these samples observe changes in δ_{CP} , Δm_{23}^2 , and $\sin^2(\theta_{23})$ is given in section 5.1. It
1643 also explains the additional complexities involved when performing an atmospheric
1644 neutrino analysis as compared to a beam-only analysis.

1645 Without additional techniques, atmospheric sub-GeV upward-going neutrinos
1646 ($E_\nu < 1.33\text{GeV}, \cos(\theta_Z) < 0.$) can artificially inflate the sensitivity to δ_{CP} due to the
1647 quickly varying oscillation probability in this region. Therefore, a “sub-sampling”
1648 approach has been developed to reduce these biases ensuring accurate and reliable
1649 sensitivity measurements. This technique ensures that small-scale unresolvable fea-
1650 tures of the oscillation probability have been averaged over whilst the large-scale
1651 features in the oscillation probability are unaffected. The documentation and valida-
1652 tion of this technique are found in section 5.2. The oscillation probability calculation is
1653 computationally intensive due to the large number of matrix multiplications needed.
1654 Consequently, the CUDAProb3 implementation choice made within the fitting frame-
1655 work, as detailed in section 5.3, ensures that the analysis can be done in a timely
1656 manner.

1657 Whilst the beam neutrinos are assumed to propagate through a constant density
1658 slab of material, the density variations through the Earth result in more complex
1659 oscillation patterns. Furthermore, the uncertainty in the electron density can modify
1660 the oscillation probability for the denser core layers of the Earth. The model of the

1661 Earth used within this analysis is detailed in section 5.4. This includes information
 1662 about the official SK-only methodology as well as improvements that can be made
 1663 to remove some of the approximations made in that analysis. Another complexity of
 1664 atmospheric neutrinos oscillation studies is that the height of production in the atmo-
 1665 sphere is not known on an event-by-event basis. An analytical averaging technique
 1666 that approximates the uncertainty of the oscillation probability has been followed,
 1667 with the author of this thesis being responsible for the implementation and validation.
 1668 This implementation of an external technique is illustrated in section 5.5.

1669 5.1 Overview

1670 The analysis presented within this thesis focuses on the determination of oscillation
 1671 parameters from atmospheric and beam neutrinos. Whilst subject to the same oscil-
 1672 lation formalism, the way in which the two samples have sensitivity to the different
 1673 oscillation parameters differs quite significantly.

1674 Atmospheric neutrinos have a varying baseline, or “path length”, L , such that
 1675 the distance each neutrino travels before interacting is dependent upon the zenith
 1676 angle, θ_Z . As primary cosmic rays can interact anywhere between the Earth’s surface
 1677 and $\sim 50\text{km}$ above that, the height, h , in the atmosphere at which the neutrino was
 1678 generated also affects the path length,

$$L = \sqrt{(R_E + h)^2 - R_E^2 (1 - \cos^2(\theta_Z))} - R_E \cos(\theta_Z). \quad (5.1)$$

1679 Where $R_E = 6,371\text{km}$ is the Earth’s radius. Consequently, the oscillation probabil-
 1680 ity is dependent upon two parameters, $\cos(\theta_Z)$ and E_ν .

1681 The oscillation probability used within this analysis is based on [21]. The neutrino
1682 wavefunction in the vacuum Hamiltonian evolves in each layer of constant matter
1683 density via

$$i\frac{d\psi_j(t)}{dt} = \frac{m_j^2}{2E_\nu}\psi_j(t) - \sum_k \sqrt{2}G_F N_e U_{ej} U_{ke}^\dagger \psi_k(t), \quad (5.2)$$

1684 where m_j^2 is the square of the j^{th} vacuum eigenstate mass, E_ν is the neutrino
1685 energy, G_F is Fermi's constant, N_e is the electron number density and U is the PMNS
1686 matrix. The transformation $N_e \rightarrow -N_e$ and $\delta_{CP} \rightarrow -\delta_{CP}$ is applied for antineutrino
1687 propagation. Thus, a model of the Earth's density is required for atmospheric neutrino
1688 propagation. Following the official SK-only methodology [190], this analysis uses the
1689 Preliminary Reference Earth Model (PREM) [191]. This model provides piecewise cubic
1690 polynomials as a function of the Earth's radius which results in the density profile
1691 illustrated in Figure 5.1. As discussed, the propagator requires layers of constant
1692 density. The SK methodology approximates the PREM model by using four layers of
1693 constant density [190]. The details of these layers are detailed in Table 5.1.

| Layer | Outer Radius [km] | Density [g/cm ³] | Chemical composition (Z/A) |
|-----------------|-------------------|------------------------------|----------------------------|
| Inner Core | 1220 | 13 | 0.468 ± 0.029 |
| Outer Core | 3480 | 11.3 | 0.468 ± 0.029 |
| Lower Mantle | 5701 | 5.0 | 0.496 |
| Transition Zone | 6371 | 3.3 | 0.496 |

Table 5.1: Description of the four layers of the Earth invoked within the constant density approximation of the PREM model [191].

1694 The atmospheric neutrino oscillation probabilities can be presented as two dimensional
1695 “oscillograms” as illustrated in Figure 5.2. The distinct discontinuities, as a

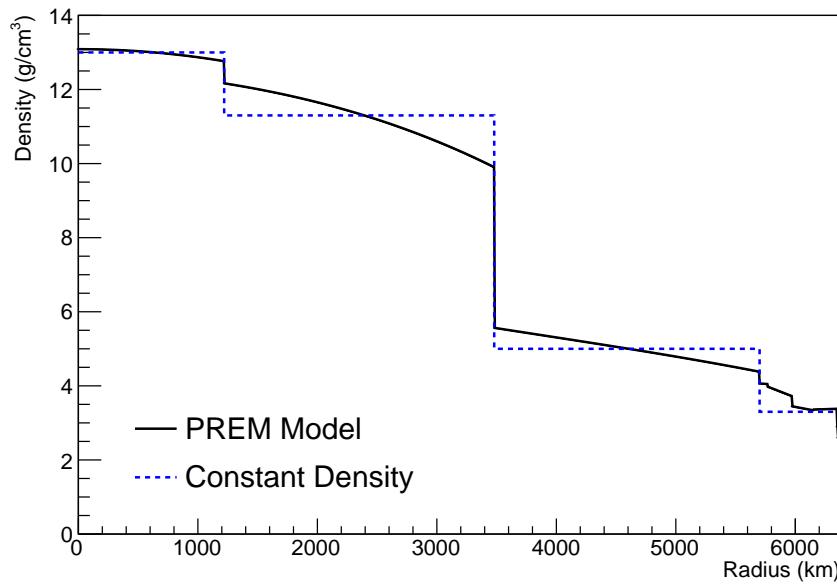


Figure 5.1: The density of the Earth given as a function of the radius, as given by the PREM model (Black), and the constant density four-layer approximation (Blue), as used in the official SK-only analysis.

function of $\cos(\theta_Z)$, are due to the discrete change in density invoked within the PREM model.

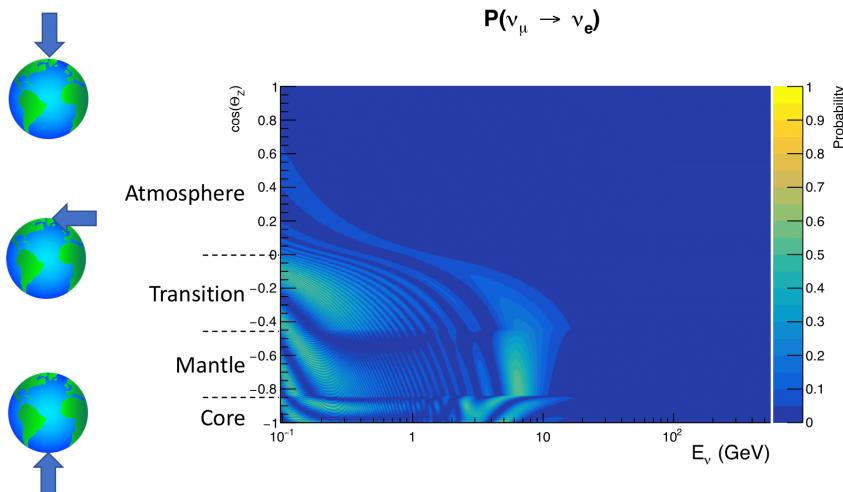


Figure 5.2: An “oscillogram” that depicts the $P(\nu_\mu \rightarrow \nu_e)$ oscillation probability as a function of neutrino energy and cosine of the zenith angle. The zenith angle is defined such that $\cos(\theta_Z) = 1.0$ represents neutrinos that travel from directly above the detector. The four-layer constant density PREM model approximation is used and Asimov A oscillation parameters are assumed (Table 1.2).

Atmospheric neutrinos do have sensitivity to δ_{CP} through a normalisation term. Figure 5.3 illustrates the difference in oscillation probability between CP-conserving ($\delta_{CP} = 0.$) and a CP-violating ($\delta_{CP} = -1.601$) value taken from Asimov A oscillation parameter set (Table 1.2). The result is a complicated oscillation pattern in the appearance probability for sub-GeV upgoing neutrinos. The detector does not have sufficient resolution to resolve these individual patterns so the sensitivity to δ_{CP} for atmospheric neutrinos comes via the overall normalisation of these events.

The presence of matter means that the effect δ_{CP} has on the oscillation probability is not equal between neutrinos and antineutrinos, which would be expected when propagating through a vacuum. This is further extenuated by the fact that SK can not distinguish neutrinos and antineutrinos well and that the cross-section neutrino interaction is larger than that for antineutrinos. Finally, sample selections (discussed in DB: [Link to selection chapter](#)) targeting different neutrino interaction modes result in an imbalance in the percentage of neutrinos to anti-neutrinos. This is because negatively charged pions from antineutrino interactions are more likely to be captured by a nucleus compared to a positively charged pion. All of these effects lead to a difference in the number of neutrinos detected compared to antineutrinos. This changes how the δ_{CP} normalisation term is observed, resulting in a very complex sensitivity to δ_{CP} .

Atmospheric neutrinos are subject to matter effects as they travel through the dense matter in the Earth. The vacuum and matter oscillation probabilities for $P(\nu_e \rightarrow \nu_e)$ and $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ are presented in Figure 5.4, where the PREM model has been assumed. The oscillation probability for both neutrinos and antineutrinos is affected in the presence of matter. However, the resonance effects around $O(5)$ GeV only occur for neutrinos in normal mass hierarchy and antineutrinos in inverse mass hierarchy. The

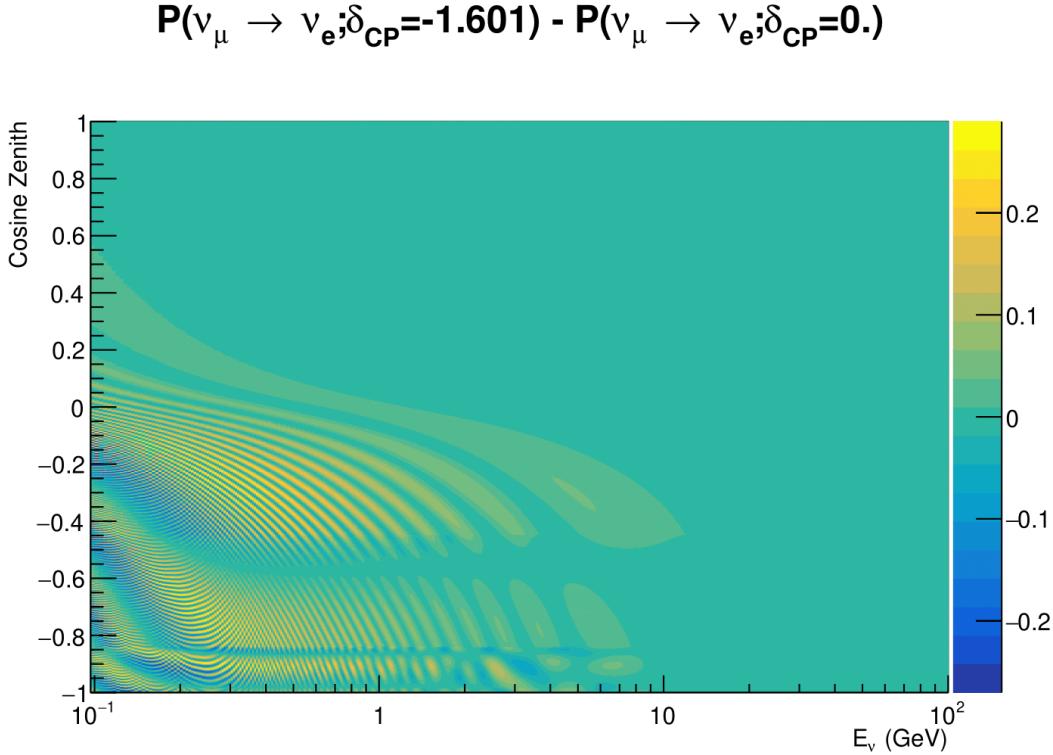


Figure 5.3: The effect of δ_{CP} for atmospheric neutrinos given in terms of the neutrino energy and zenith angle. This oscillogram compares the $P(\nu_\mu \rightarrow \nu_e)$ oscillation probability for a CP conserving ($\delta_{CP} = 0.0$) and a CP violating ($\delta_{CP} = -1.601$) value taken from the Asimov A parameter set. The other oscillation parameters assume the Asimov A oscillation parameter set given in Table 1.2.

1723 exact position and amplitude of the resonance depend on $\sin^2(\theta_{23})$ meaning that the
 1724 atmospheric neutrinos have sensitivity to $\sin^2(\theta_{23})$.

1725 As the T2K beam flux is centered at the first oscillation maximum ($E_\nu = 0.6\text{GeV}$),
 1726 the sensitivity to δ_{CP} is predominantly observed as a change in the event-rate of e-like
 1727 samples in $\nu/\bar{\nu}$ modes. Figure 5.5 illustrates the $P(\nu_\mu \rightarrow \nu_e)$ oscillation probability
 1728 for a range of δ_{CP} values. A circular modulation of the first oscillation peak (in both
 1729 magnitude and position) is observed when varying throughout the allowable values
 1730 of δ_{CP} . The CP-conserving values of $\delta_{CP} = 0, \pi$ have a lower(higher) oscillation
 1731 maximum than the CP-violating values of $\delta_{CP} = -\pi/2(\delta_{CP} = \pi/2)$. A sub-dominant

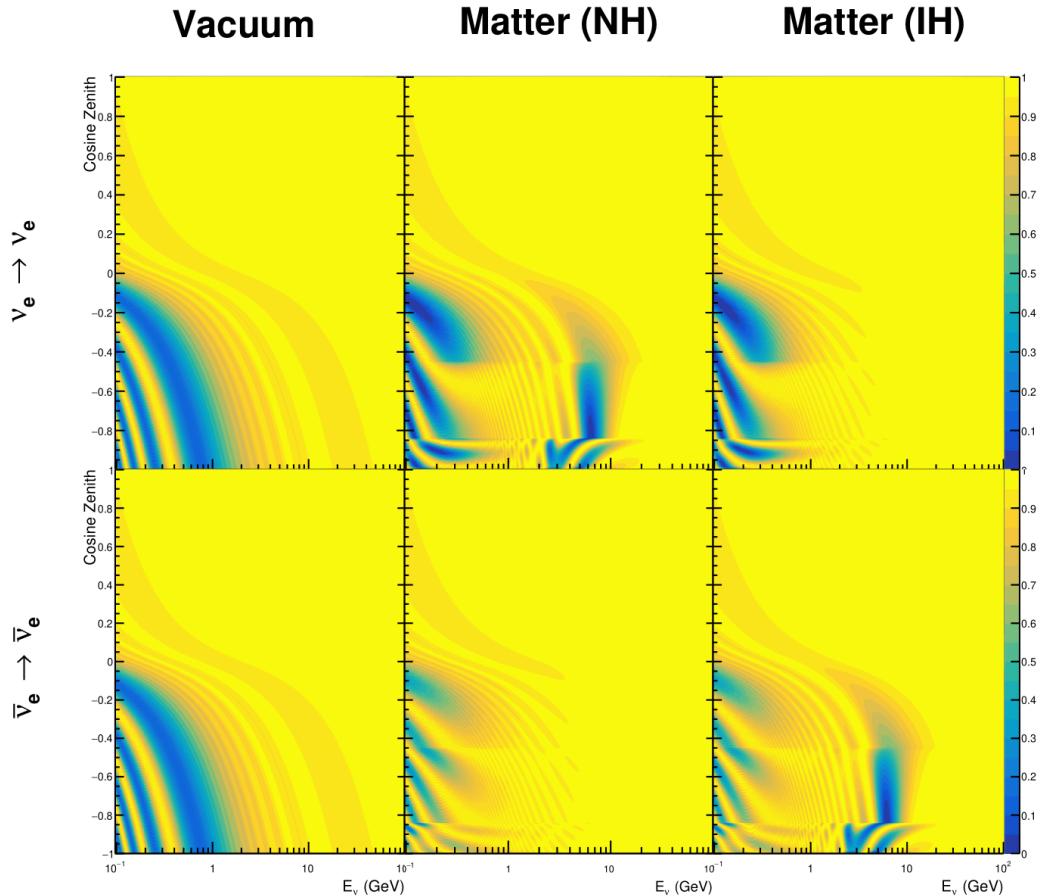


Figure 5.4: An illustration of the matter-induced effects on the oscillation probability, given as a function of neutrino energy and zenith angle. The top row of panels gives the $P(\nu_e \rightarrow \nu_e)$ oscillation probability and the bottom row illustrates the $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ oscillation probability. The left column highlights the oscillation probability in a vacuum, whereas the middle and right column represents the oscillation probabilities when the four-layer fixed density PREM model is assumed. All oscillation probabilities assume the “Asimov A” set given in Table 1.2, but importantly, the right column sets an inverted mass hierarchy. The “matter resonance” effects at $E_\nu \sim 5\text{GeV}$ can be seen in the $P(\nu_e \rightarrow \nu_e)$ for normal mass hierarchy and $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ for inverted hierarchy.

₁₇₃₂ shift in the energy of the oscillation peak is also present to aid in separating the two

₁₇₃₃ CP-conserving values of δ_{CP} .

₁₇₃₄ T2K’s sensitivity to the $\sin^2(\theta_{23})$ and Δm_{23}^2 is observed as a shape-based variation

₁₇₃₅ of the muon-like samples, as illustrated in Figure 5.5. The value of Δm_{32}^2 laterally shifts

₁₇₃₆ the position of the oscillation dip (around $E_\nu \sim 0.6\text{GeV}$) in the $P(\nu_\mu \rightarrow \nu_\mu)$ oscillation

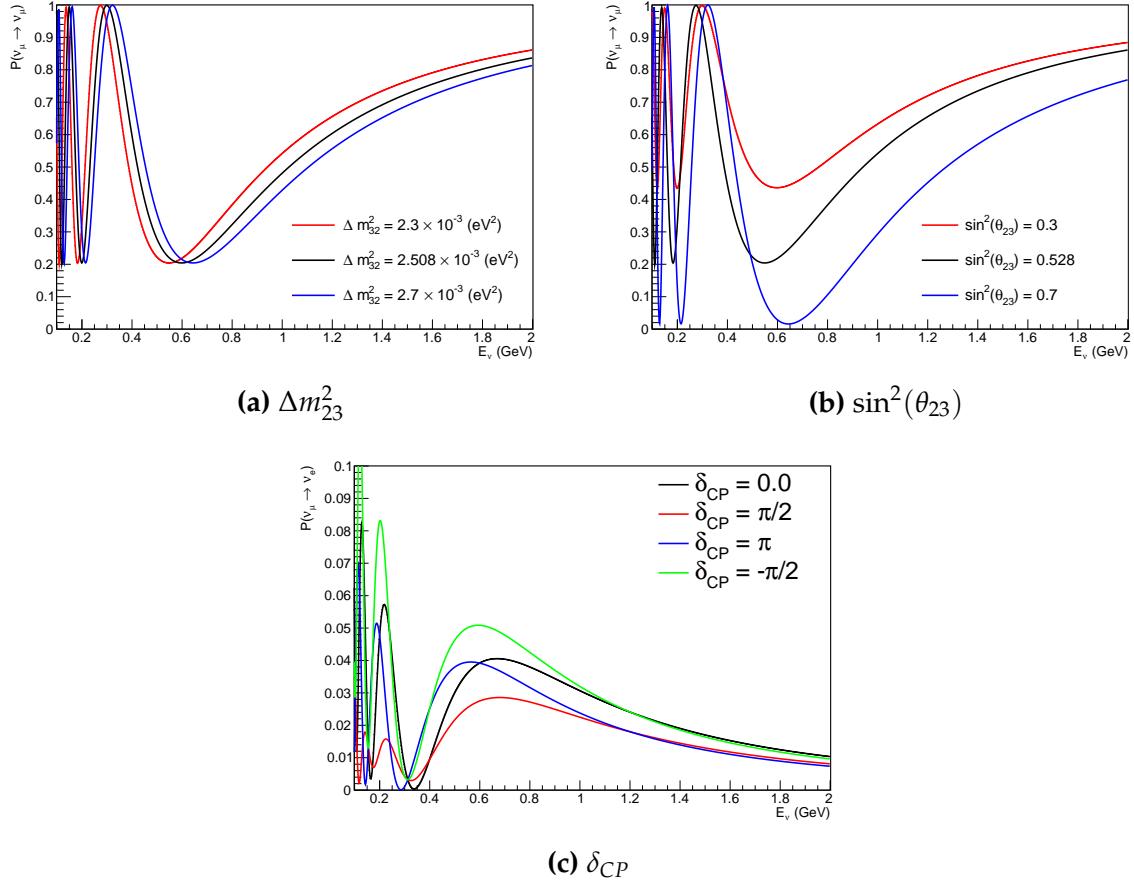


Figure 5.5: The oscillation probability for beam neutrino events given as a function of neutrino energy. All oscillation parameters assume the “Asimov A” set given in Table 1.2 unless otherwise stated. Each panel represents a change in one of the oscillation parameters whilst keeping the remaining parameters fixed.

probability. A variation of $\sin^2(\theta_{23})$ is predominantly observed as a vertical shift of the oscillation dip with second-order horizontal shifts being due to matter effects. The beam neutrinos have limited sensitivity to matter effects due to the relatively shorter baseline as well as the Earth’s mantle being a relatively low-density material (as compared to the Earth’s core). For some values of δ_{CP} , the degeneracy in the number of e-like events allows the mass hierarchy to be resolved. This leads to a δ_{CP} -dependent mass hierarchy sensitivity which can be seen in Figure 5.6.

Whilst all oscillation channels should be included for completeness, the computational resources required to run a fit are limited and any reasonable approximations

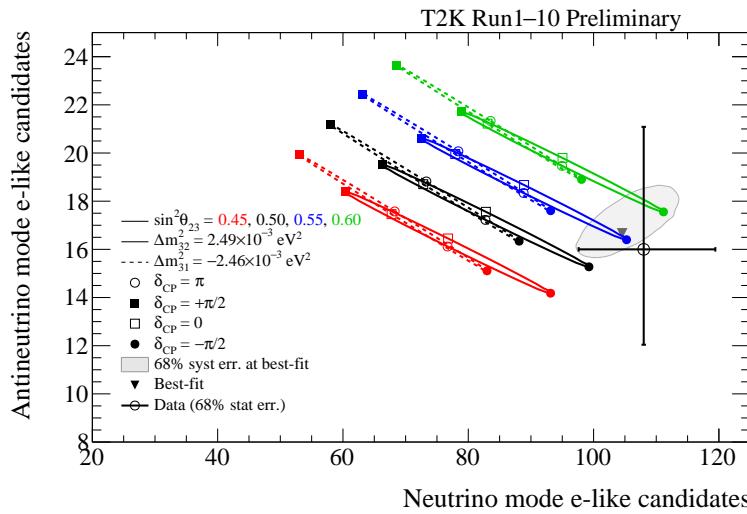


Figure 5.6: The number of electron-like events in the FHC and RHC operating mode of the beam, as a function of the oscillation probabilities. Both normal hierarchy (Solid) and inverse hierarchy (Dashed) values of Δm_{23}^2 are given.

1746 which reduce the number of oscillation probability calculations that need to be made
 1747 should be applied. The $\nu_e \rightarrow \nu_{e,\mu,\tau}$ (and antineutrino equivalent) oscillations can be
 1748 ignored for beam neutrinos as the $\nu_e/\bar{\nu}_e$ fluxes are approximately two orders of magni-
 1749 tude smaller than the corresponding $\nu_\mu/\bar{\nu}_\mu$ flux. Furthermore, as the peak neutrino
 1750 energy of the beam is well below the threshold for charged current tau production
 1751 ($E_\nu = 3.5\text{GeV}$ [51], only a small proportion of the neutrinos produced in the beam have
 1752 the required energy. For the few neutrinos that have sufficient energy, the oscillation
 1753 probability is very small due to the short baseline. Whilst these approximations can
 1754 be made for the beam neutrinos, the atmospheric flux of ν_e is of the same order of
 1755 magnitude as the ν_μ flux and the energy distribution of atmospheric neutrinos extends
 1756 well above the tau production threshold.

¹⁷⁵⁷ 5.2 Treatment of Fast Oscillations

¹⁷⁵⁸ As shown in Figure 5.7, atmospheric neutrino oscillations have a significantly more
¹⁷⁵⁹ complex structure for upgoing neutrinos with energy below 1GeV. This is because the
¹⁷⁶⁰ L/E dependence of the oscillation probability in this region induces rapid variations
¹⁷⁶¹ for small changes in L or E . As discussed in section 5.1, this is also the region in which
¹⁷⁶² atmospheric neutrinos have sensitivity to δ_{CP} . In practice, the direction of the neutrino
¹⁷⁶³ is inferred from the direction of the final state particles traveling in the detector, which
¹⁷⁶⁴ can be poor for low-energy neutrino interactions. This creates a distinct difference
¹⁷⁶⁵ from the beam neutrinos where the position of the source is very precisely known.

¹⁷⁶⁶ As a consequence of the unresolvable structure, an average oscillation probability
¹⁷⁶⁷ is observed in the subGeV upgoing region. This creates a computational problem; A
¹⁷⁶⁸ significantly large amount of Monte Carlo statistics would be required to accurately
¹⁷⁶⁹ predict the number of events if Monte Carlo averaging was the only technique used.
¹⁷⁷⁰ This section describes the ‘sub-sampling’ approach developed for this analysis and
¹⁷⁷¹ compares it to the methodology used within the SK-only analysis.

¹⁷⁷² The official SK-only analysis uses the osc3++ oscillation parameter fitter [190].
¹⁷⁷³ To perform the fast oscillation averaging, it uses a ‘nearest-neighbour’ technique.
¹⁷⁷⁴ For a given neutrino event, the nearest twenty neighbours in reconstructed lepton
¹⁷⁷⁵ momentum and zenith angle are found and a distribution of their neutrino energies is
¹⁷⁷⁶ built. The RMS, σ , of this distribution is then used to compute an average oscillation
¹⁷⁷⁷ probability for the given neutrino Monte Carlo event.

¹⁷⁷⁸ For the i^{th} event, the oscillation weight is calculated as

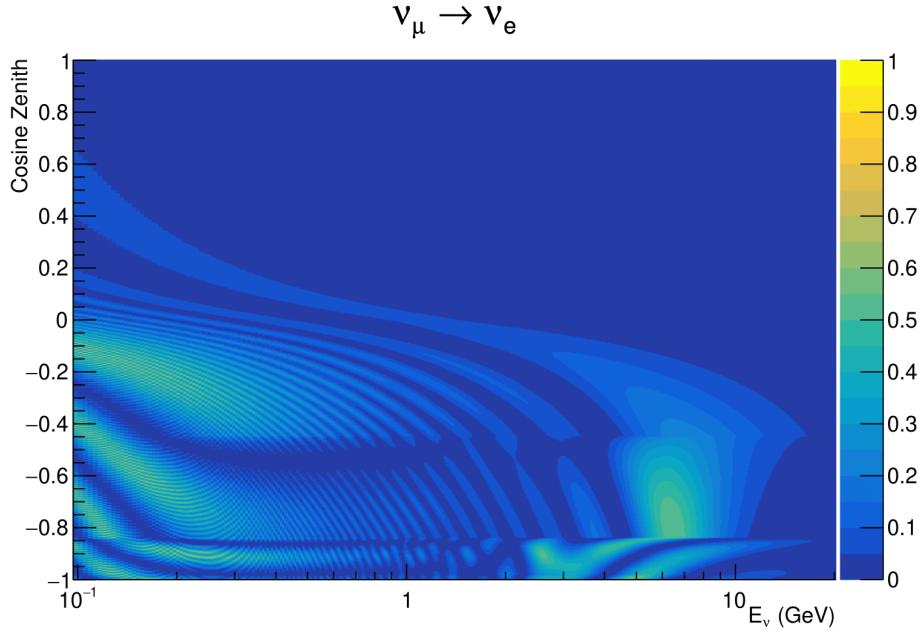


Figure 5.7: The oscillation probability $P(\nu_\mu \rightarrow \nu_e)$, given as a function of neutrino energy and zenith angle, which highlights an example of the “fast” oscillations in the sub-GeV upgoing region.

$$W_i = \frac{1}{5}P(E_i, \bar{L}_i) + \frac{1}{5} \sum_{\beta=-1,-0.5,0.5,1} P(E_i + \beta\sigma_i, L_\beta), \quad (5.3)$$

where $P(E, L)$ is the oscillation probability calculation for neutrino energy E and path length L and the two path lengths, \bar{L}_i and L_β are discussed below. All of the oscillation probability calculations are performed with a fixed zenith angle such that the same density profile is used.

The uncertainty in the production height is controlled by using an “average” production height, \bar{L}_i , which represents the average path length computed using twenty production heights taken from the Honda flux model’s prediction [45]. For a given event, the production heights are sampled in steps of 5% of their cumulative distribution function. L_β values are similarly calculated but instead use different combinations of four production heights,

$$\begin{aligned}
 L_{-1.0} &= \frac{1}{4}L(45, 50, 55, 60), \\
 L_{-0.5} &= \frac{1}{4}L(35, 40, 65, 70), \\
 L_{+0.5} &= \frac{1}{4}L(25, 30, 75, 68), \\
 L_{+1.0} &= \frac{1}{4}L(15, 20, 85, 89).
 \end{aligned} \tag{5.4}$$

1789 This averaging technique works because of the inference between the zenith angle
 1790 and the reconstructed direction of final state particles in the detector. For low-energy
 1791 neutrinos, where the resolution of the true neutrino direction is poor, σ_i will be large,
 1792 resulting in significant averaging effects. Contrary to this, the inferred direction of
 1793 high-energy neutrinos will be much closer to the true value, meaning that σ_i will be
 1794 smaller, culminating in small averaging effects.

1795 In practice, this technique is performed before the fit in order to deal with the
 1796 computational cost. This is possible as the Osc3++ framework uses binned oscillation
 1797 parameters rather than continuous so the oscillation parameters used in the fit are
 1798 known prior to run-time. The framework used in this analysis uses continuous
 1799 oscillation parameters, and due to the MCMC fitting technique, there is no way to
 1800 know which oscillation parameter values will be selected *a priori*. Therefore, the
 1801 oscillation parameter calculation has to be performed at run-time. Computing five
 1802 oscillation probabilities per event would require far too many computational resources
 1803 to be viable. Therefore SK technique can not be used within this analysis. However,
 1804 the concept of the averaging technique can be taken from it.

1805 To perform a similar averaging as the SK analysis, a sub-sampling approach using
 1806 binned oscillograms has been devised. The technique can be explained by considering
 1807 a “fine” and “coarse” oscillogram. The fine oscillograms are used to define the array of

1808 $\cos(\theta_Z)$ and E_ν used in the oscillation engine. The coarse oscillograms cover the same
1809 phase-space but have fewer bins, where the value of a particular coarse bin is taken
1810 as the linear average (flat prior in E_ν and $\cos(\theta_Z)$) of all fine bins which falls into it.
1811 The coarse oscillogram is then used for determining the oscillation weight for a given
1812 event. The binning which is used to calculate the oscillation probabilities, known as
1813 the ‘fine’ binning, has $N \times N$ subdivisions per coarse bin. Figure 5.8 illustrates the
1814 $N = 2$ example where the assigned value to a coarse bin is the average of the four fine
1815 bins which fall in that coarse bin. Whilst the coarse bin edges do not have to be linear
1816 on either axis, the sub-division of the fine bins is linear over the range of a coarse bin.

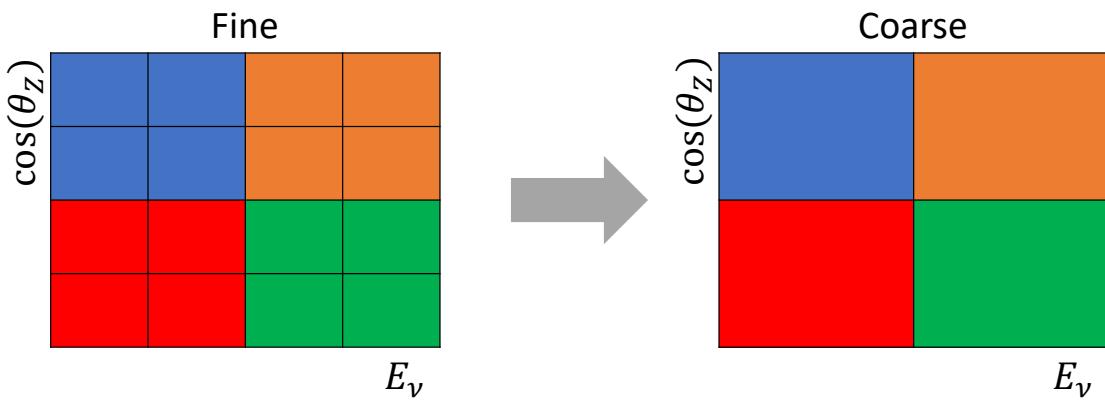


Figure 5.8: Illustration of the averaging procedure for $N = 2$. The oscillation probabilities calculated on the finer left binning are averaged to obtain the oscillation probabilities in the coarser right binning. These averaged oscillation probabilities with the coarser binning are then applied to each event during the fit.

1817 The coarse binning is defined with 67×52 bins in true neutrino energy \times cosine
1818 zenith. It is picked to be identical to that provided in [192]. In general, the binning is
1819 logarithmically spaced in neutrino energy but has some hand-picked bin edges. Firstly,
1820 the bin density around the matter resonance is smoothly increased around the matter
1821 resonance region. This is to avoid smearing this region which can be well sampled by
1822 the Monte Carlo. Secondly, bin edges are selected to hit $0.4, 0.6, 1, 10, 30, 50, 100\text{GeV}$.
1823 This is to ensure that the Coulomb correction systematic and the atmospheric flux
1824 systematics definitions in neutrino energy can be hit. The cosine zenith binning is

approximately linearly spaced across the allowable range but the values of layer transitions are hit precisely: -0.8376 (core-mantle) and -0.4464 (mantle/transition zone). Bins are spread further apart for downgoing events as this is a region unaffected by the fast oscillation wavelengths and reduces the total number of calculations required to perform the calculation.

The choice of N is justified based on two studies. Firstly, the variation of event rates of each sample is studied as a function of N . For a given set of oscillation parameters thrown from the PDG prior constraints (detailed in Table 1.1), the oscillation probabilities are calculated using a given value of N . Each sample is re-weighted and the event rate is stored. The value of N is scanned from 1, which corresponds to no averaging, to 24, which corresponds to the largest computationally viable subdivision binning. The event rate of each sample at large N is expected to converge to a stationary value due to the fine binning fully sampling the small-scale structure. Figure 5.9 illustrates this behaviour for the SubGeV_elike_0dcy sample for 30 different throws of the oscillation parameters.

Denoting the event rate for one sample for a given throw t at each N by λ_t^N , the average over all considered N values ($\bar{\lambda}_t = \frac{1}{24} \sum_{N=1}^{24} \lambda_t^N$) is computed. The variance in the event rate at each N is then calculated as

$$\text{Var}[\lambda^N] = \frac{1}{N_{\text{throws}}} \sum_{t=1}^{N_{\text{throws}}} (\lambda_t^N - \bar{\lambda}_t)^2 - \left[\frac{1}{N_{\text{throws}}} \sum_{t=1}^{N_{\text{throws}}} (\lambda_t^N - \bar{\lambda}_t) \right]^2. \quad (5.5)$$

The aim of the study is to find the lowest value of N such that this variance is below 0.001. This is the typical threshold used by T2K fitters to validate systematic implementation so has been set as the same criteria. The results of this study for each atmospheric sample used within this thesis are illustrated in Figure 5.10 for

SubGeV-elike-0dcy

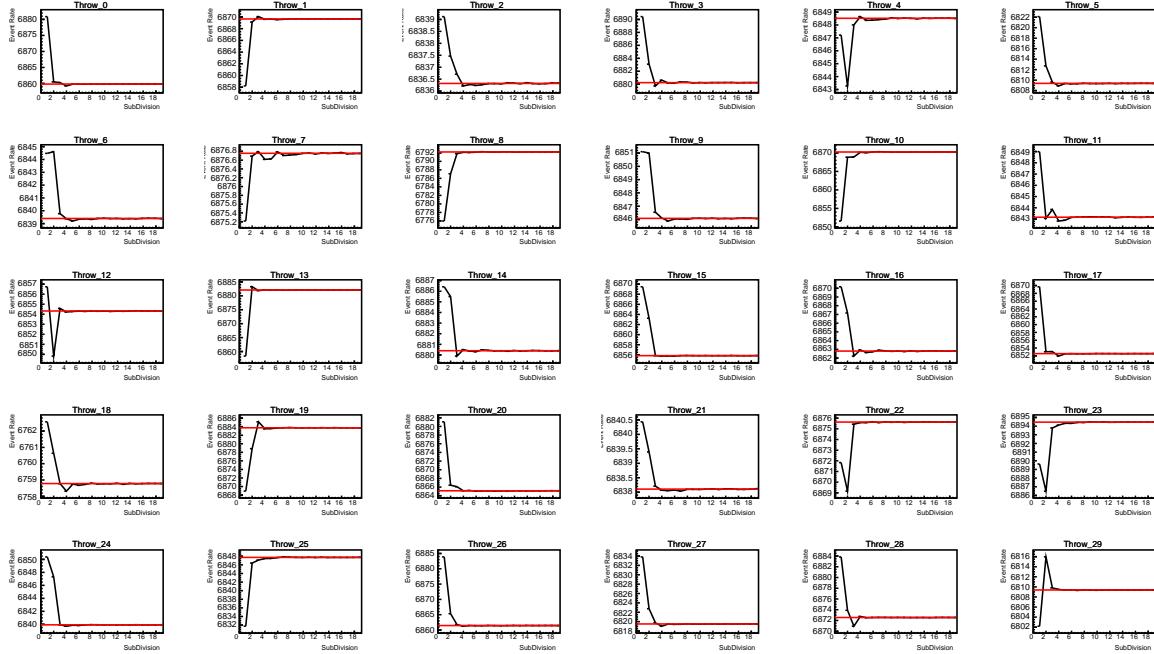


Figure 5.9: Event rate of the SubGeV_elike_0dcy sample as a function of the number of subdivisions per coarse bin. Each subplot represents the event rate of the sample at a different oscillation parameter set thrown from the PDG priors detailed in Table 1.1. The red line in each subplot represents the mean of the event rate over the different values of sub-divisions for that particular oscillation parameter throw.

1847 2000 throws of the oscillation parameters. As can be seen, the variance is below
 1848 the threshold at $N = 10$, and is driven primarily by the SubGeV_mulike_1dcy and
 1849 SubGeV_elike_0dcy samples.

1850 The second study to determine the value of N is as follows. The likelihood for each
 1851 sample is computed against an Asimov data set created with Asimov A oscillation
 1852 parameters (Table 1.2). Following Equation 5.5, the variance of the log-likelihood over
 1853 all considered N is computed. The results are shown in Figure 5.11.

1854 A choice of $N = 10$ sub-divisions per coarse bin has a variance in both event rate
 1855 and log-likelihood residuals less than the required threshold of 0.001. The largest
 1856 value of the likelihood variance is of order 10^{-7} , corresponding to an error on the log-

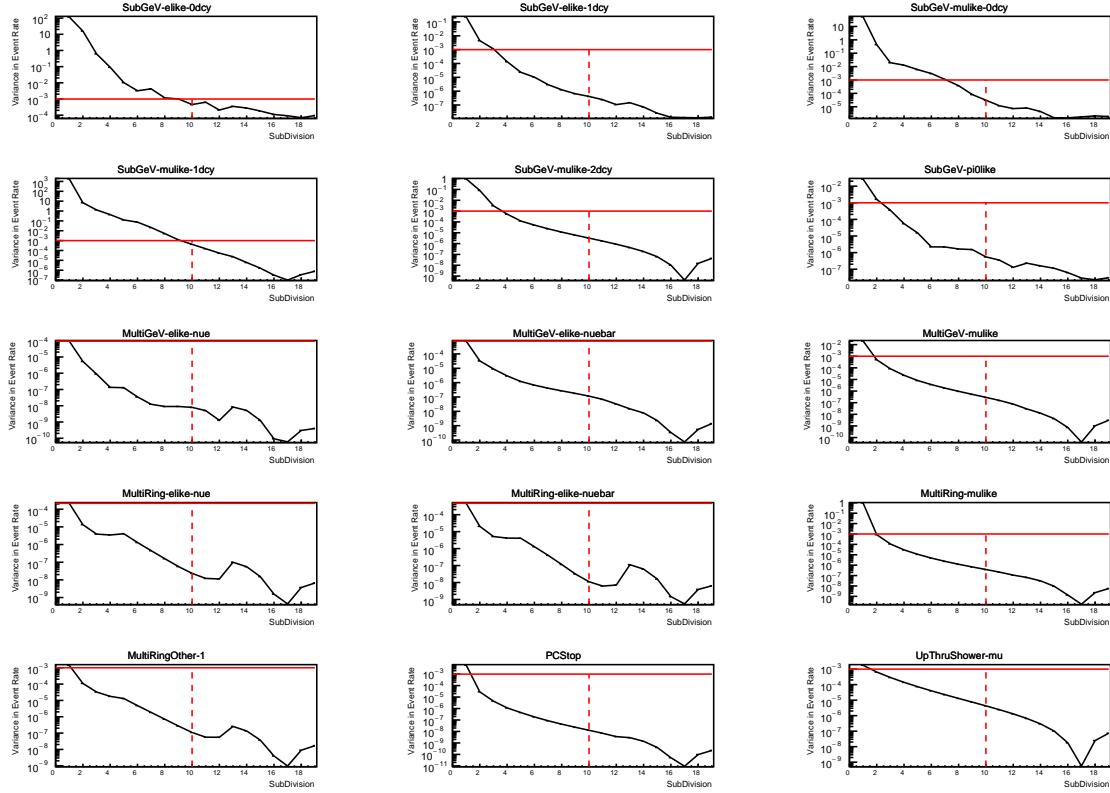


Figure 5.10: Variance of event rate for each atmospheric sample as a function of the number of sub-divisions per coarse bin. The solid red line indicates the 0.1% threshold and the dashed red line indicates the variance at a sub-division $N = 10$.

1857 likelihood of about 3×10^{-4} which is small enough to be negligible for the oscillation
 1858 analysis.

1859 Figure 5.12 illustrates the effect of the smearing using $N = 10$. The fast oscillations
 1860 in the sub-GeV upgoing region have been replaced with a normalisation effect whilst
 1861 the large matter resonance structure remains.

1862 5.3 Calculation Engine

1863 As previously discussed in section 5.2, the calculation of oscillation probabilities is per-
 1864 formed at run-time due to utilising continuous oscillation parameters. Consequently,
 1865 the time per calculation is crucial for fit performance. The initial fitting framework

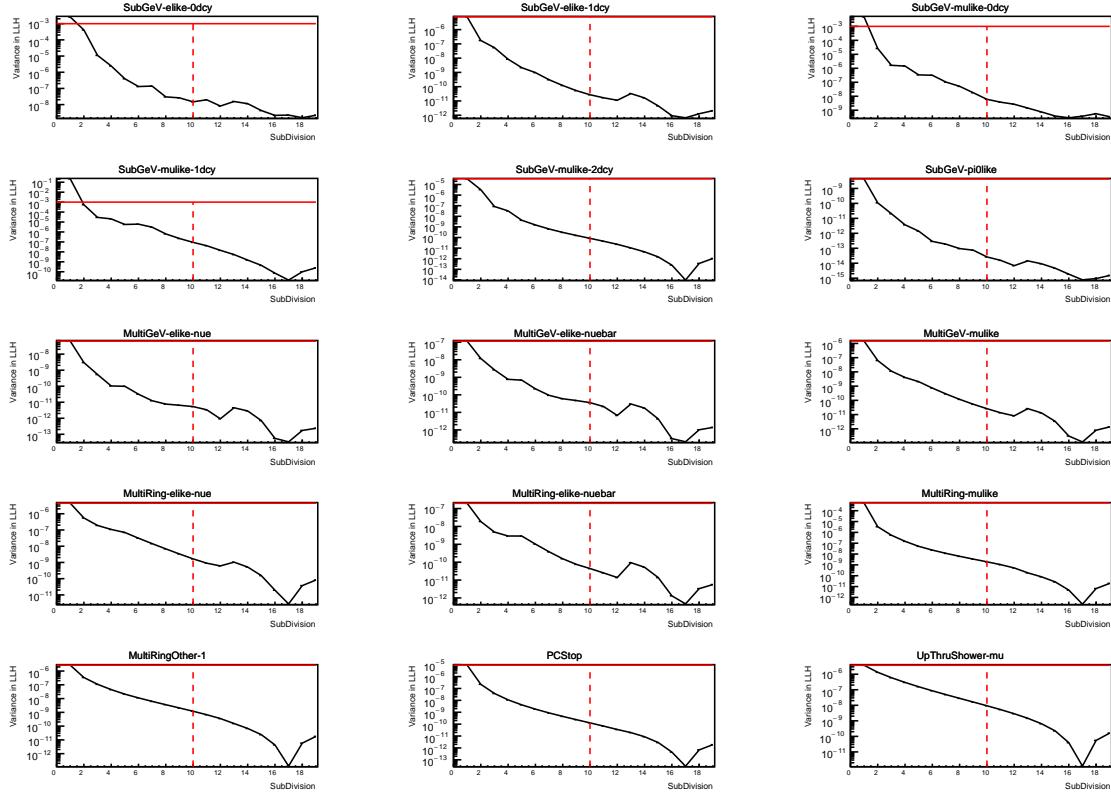


Figure 5.11: Variance of sample likelihood, when compared to ‘Asimov data’ set at Asimov A, for each atmospheric sample as a function of the number of sub-divisions per coarse bin. The solid red line indicates the 0.1% threshold and the dashed red line is a graphical indication of the variance at a sub-division $N = 10$.

used for this analysis was developed with ProbGPU [193]. This is a GPU-only implementation of the prob3 engine [194]. It is primarily designed for neutrino propagation in a beam experiment (single layer of constant density) with the atmospheric propagation code not being used prior to the analysis in this thesis.

Another engine, CUDAProb3 [195], has been implemented within the fitting framework used in this analysis. It has been specifically optimised for atmospheric neutrino oscillation calculation so does not contain the code to replace the beam oscillation calculation. The engine utilises object-orientated techniques as compared to the functional implementation of ProbGPU. This allows the energy and cosine zenith arrays to be kept on GPU memory, rather than having to load these arrays onto GPU memory for each calculation. General memory interfacing is one of the slowest tasks which

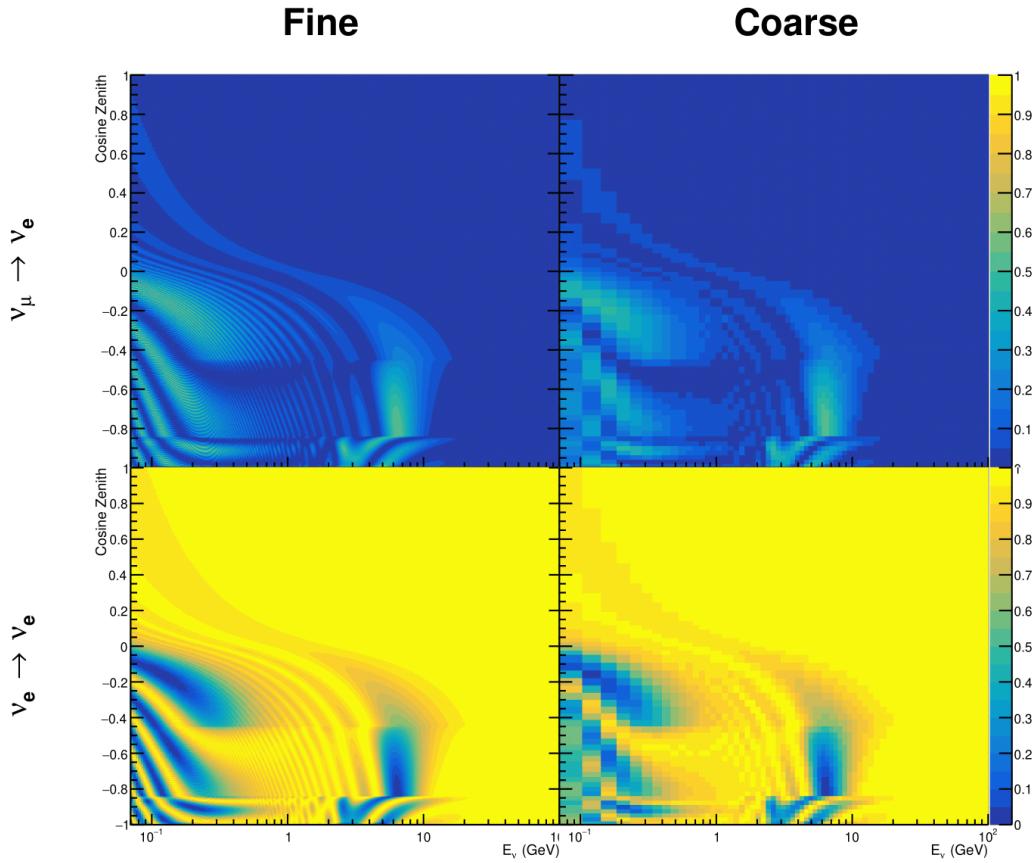


Figure 5.12: The oscillation probability, $P(\nu_\mu \rightarrow \nu_e)$ (top row) and $P(\nu_e \rightarrow \nu_e)$ (bottom row), given as a function of neutrino energy and zenith angle. The left column gives the “fine” binning used to calculate the oscillation probabilities and the right column illustrates the “coarse” binning used to reweight the Monte Carlo events. The fine binning choice is given with $N = 10$, which was determined to be below the threshold from Figure 5.10 and Figure 5.11.

1877 GPUs can do, so being able to eliminate this significantly reduces the time required
 1878 for calculation. This can be seen in Figure 5.13, where the GPU implementation of
 1879 CUDAProb3 is approximately three times faster than the ProbGPU engine.

1880 Another significant advantage of CUDAProb3 is that it contains a CPU multithreaded
 1881 implementation which is not possible with the ProbGPU or prob3 engines. This elimi-
 1882 nates the requirement for GPU resources when submitting jobs to batch systems. As
 1883 illustrated in Figure 5.13, the calculation speed depends on the number of available

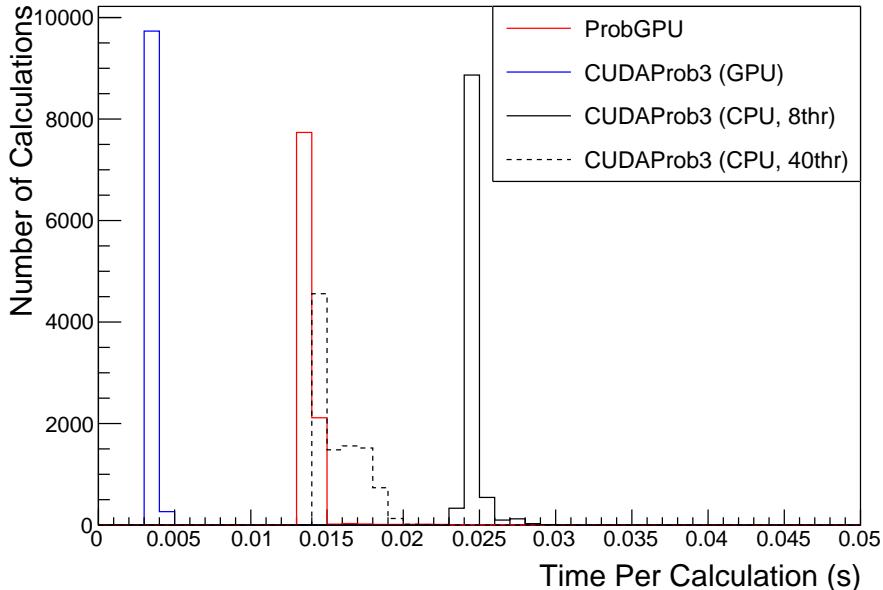


Figure 5.13: The calculation time taken to both calculate the oscillation probabilities and fill the “coarse” oscillograms, following the technique given in section 5.2, for the CUDAProb3 and ProbGPU (Red) calculation engines. CUDAProb3 has both a GPU (Blue) and CPU (Black) implementation, where the CPU implementation is multithreaded. Therefore, 8-threads (solid) and 40-threads (dashed) configurations have been tested. Prob3, which is a CPU single-thread implementation has a mean step time of 1.142s.

1884 threads. Using 8 threads (which is typical of the batch systems being used) is ap-
 1885 proximately twice as slow as the ProbGPU engine implementation, but would allow
 1886 the fitting framework to be run on many more resources. This fact is utilised for any
 1887 SK-only fits but GPU resources are required for any fits which include beam samples
 1888 due to the ProbGPU requirement. Based on the benefits shown by the implementation
 1889 in this section, efforts are being placed into including linear propagation for beam
 1890 neutrino propagation into the engine [196].

1891 5.4 Matter Density Profile

1892 For an experiment observing atmospheric neutrinos propagating through the Earth, a
 1893 model of the Earth’s density profile is required. The model used within this analysis is

the Preliminary Reference Earth Model (PREM) [191], as illustrated in Figure 5.1. As discussed in section 5.1, the propagator used within the calculation engine requires constant density layers. To follow the official SK-only analysis [190], the average density of each layer has been taken from the PREM model. Table 5.1 documents the density and radii of the layers used within this approximation. The density measurements provided in the PREM model are provided in terms of mass density, whereas neutrino oscillations are sensitive to the electron number density. This value can be computed as the product of the chemical composition, or the Z/A value, and the mass density of each layer. Currently, the only way to calculate the chemical composition value for layers close to the Earth's core is through neutrino oscillations.

The chemical composition of the upper layers of the Earth's Mantle and the Transition zone is well known due to it being predominantly pyrolite which has a chemical composition value of 0.496 [197]. The components of the Earth's core region are less well known. Consequently, the chemical composition dial for the core layers is set to a value of 0.468, as calculated in [198]. This value is assigned a Gaussian error with a standard deviation equivalent to the difference in chemical composition in core and mantle layers. Figure 5.14 illustrates the effect of moving from the $Z/A = 0.5$ method which is used in the official SK-only analysis [190] to these more precise values.

The beam oscillation probability in this thesis uses a baseline of 295km, density 2.6g/cm^3 , and chemical composition 0.5 as is done by the official T2K-only analysis [199].

Whilst the propagator requires a fixed density layer model of the Earth, the density only has to be fixed for a specific $E_\nu \times \cos(\theta_Z)$ bin in a given layer. As the density is a function of radius, which is a function of the direction in which a neutrino propagates, a better approximation of the PREM model can be made if a $\cos(\theta_Z)$ -specific density is calculated.

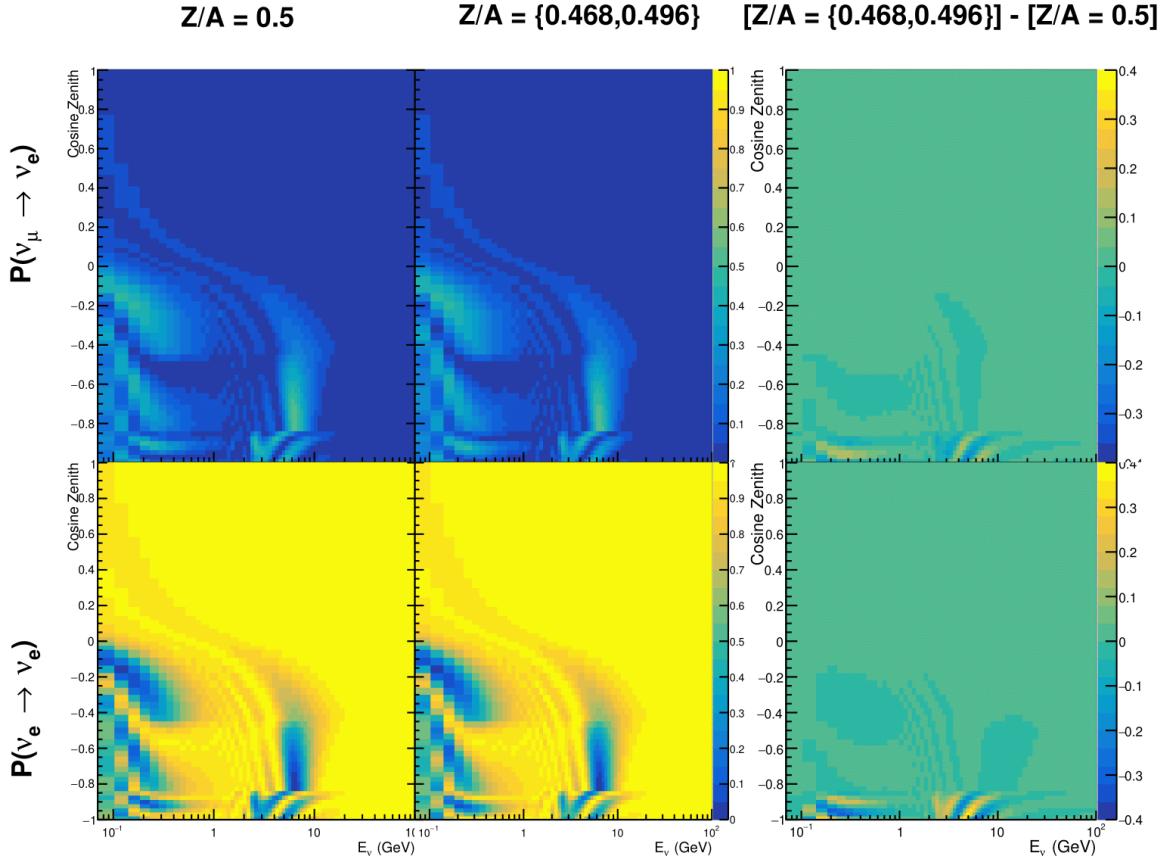


Figure 5.14: The oscillation probability, $P(\nu_\mu \rightarrow \nu_e)$ (top row) and $P(\nu_e \rightarrow \nu_e)$ (bottom row), given as a function of neutrino energy and zenith angle. The left column gives probabilities where the constant $Z/A = 0.5$ approximation which is used in the official SK-only analysis. The middle column gives the probabilities where $Z/A = [0.468, 0.498]$ values are used, as given in Table 5.1. The right column illustrates the difference in oscillation probability between the two different techniques.

1920 To achieve this, the average density, $\langle \rho \rangle_i$, in the i^{th} layer, is calculated as the density,
 1921 $\rho(t)$, integrated over the track a given $\cos(\theta_Z)$,

$$\langle \rho \rangle_i = \frac{1}{t_{i+1} - t_i} \int_{t_i}^{t_{i+1}} \rho(t) dt \quad (5.6)$$

1922 where t_i are the intersection points between each layer and t is the path length of
 1923 the trajectory across the layer.

1924 The oscillation probability calculation speed is approximately linear in the number
 1925 of layers invoked within the Earth model. Therefore a four-layer model is still utilized
 1926 with the only difference to the official SK-only analysis being that the four-layer model
 1927 used for each value of $\cos(\theta_Z)$ is different. Following the method outlined in [200],
 1928 a four-layer piecewise quadratic polynomial is fit to the PREM model for the four
 1929 layers defined in Table 5.1. This fit was not performed by the author of the thesis
 1930 and is documented in [192]. The coefficients of the quadratic fit to each layer are
 1931 given in Table 5.2 with the final distribution illustrated in Figure 5.15. The quadratic
 1932 approximation is clearly much closer to the PREM model as compared to the constant
 1933 density approximation.

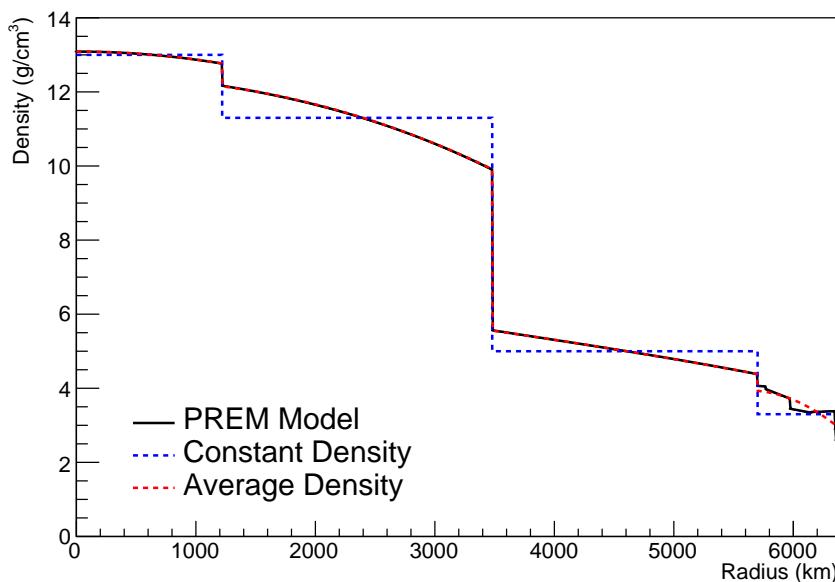


Figure 5.15: The density of the Earth given as a function of the radius, as given by the PREM model (Black), the constant density four-layer approximation (Blue), as used in the official SK-only analysis, and the quadratic approximation of the PREM model (Red).

| Layer | Outer Radius [km] | Density [g/cm ³] |
|-----------------|-------------------|-------------------------------|
| Inner Core | 1220 | $13.09 - 8.84x^2$ |
| Outer Core | 3480 | $12.31 + 1.09x - 10.02x^2$ |
| Lower Mantle | 5701 | $6.78 - 1.56x - 1.25x^2$ |
| Transition Zone | 6371 | $-50.42 + 123.33x - 69.95x^2$ |

Table 5.2: The quadratic polynomial fits to the PREM model for four assumed layers of the PREM model. The fit to calculate the coefficients is given in [192], where $x = R/R_{Earth}$.

The effect of using the quadratic density per $\cos(\theta_Z)$ model is highlighted in Figure 5.16. The slight discontinuity in the oscillation probability around $\cos(\theta_Z) \sim -0.45$ in the fixed density model, which is due to the transition to mantle layer boundary, has been reduced. This is expected as the difference in the density across this boundary is significantly smaller in the quadratic density model as compared to the constant density model. Whilst the difference in density across the other layer transitions is reduced, there is still a significant difference. This means the discontinuities in the oscillation probabilities remain but are significantly reduced. However, as the quadratic density approximation matches the PREM model well in this region, these discontinuities are due to the Earth model rather than an artifact of the oscillation calculation.

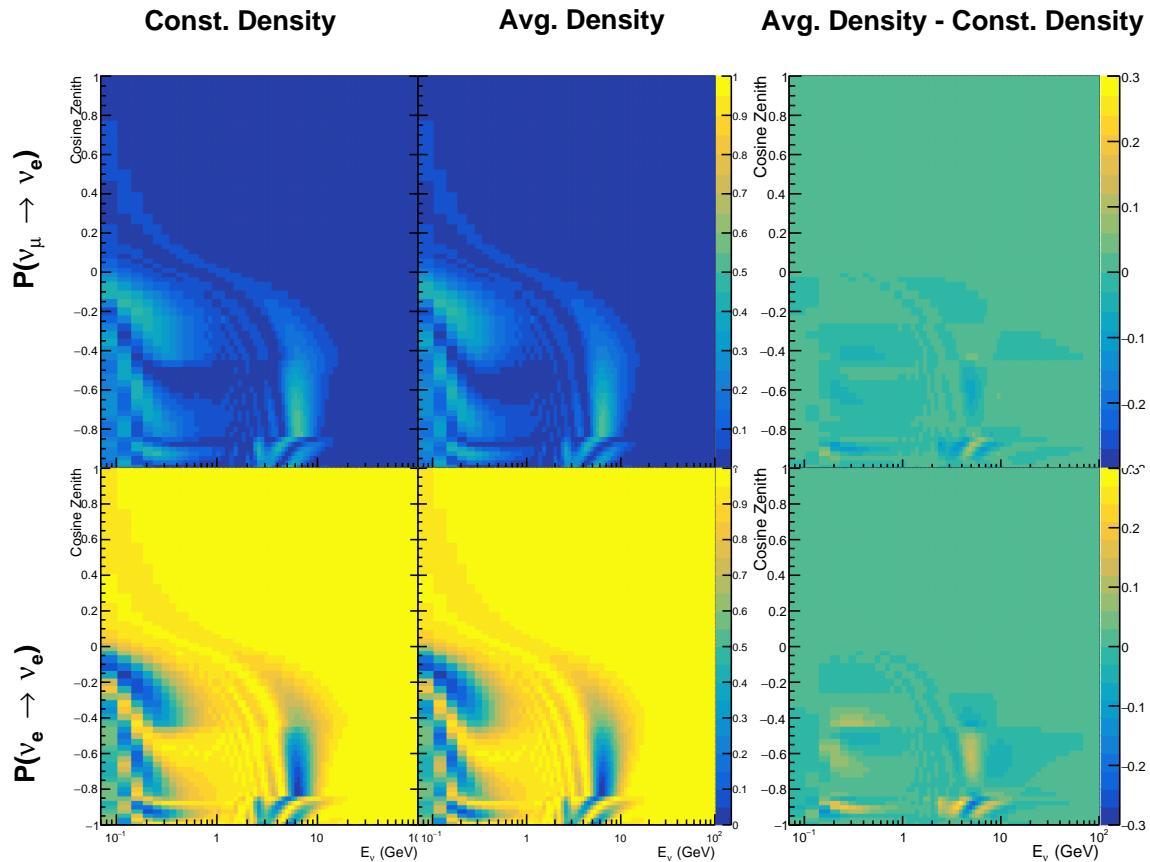


Figure 5.16: The oscillation probability, $P(\nu_\mu \rightarrow \nu_e)$ (top row) and $P(\nu_e \rightarrow \nu_\mu)$ (bottom row), given as a function of neutrino energy and zenith angle. The left column gives probabilities where the four-layer constant density approximation is used. The middle column gives the probabilities where the density is integrated over the trajectory, using the quadratic PREM approximation, for each $\cos(\theta_Z)$ is used. The right column illustrates the difference in oscillation probability between the two different techniques.

¹⁹⁴⁵ 5.5 Production Height Averaging

¹⁹⁴⁶ As discussed in section 5.1, the height at which the cosmic ray flux interacts in the
¹⁹⁴⁷ atmosphere is not known on an event-by-event basis. The production height can vary
¹⁹⁴⁸ from the Earth's surface to $\sim 50\text{km}$ above that. The SK-only analysis methodology
¹⁹⁴⁹ (described in section 5.2) for including the uncertainty on the production height is
¹⁹⁵⁰ to include variations from the Honda model when pre-calculating the oscillation
¹⁹⁵¹ probabilities prior to the fit. This technique is not possible for this analysis which
¹⁹⁵² uses continuous oscillation parameters that can not be known prior to the fit. Conse-
¹⁹⁵³ quently, an analytical averaging technique was developed in [192]. The author of this
¹⁹⁵⁴ thesis was not responsible for the derivation of the technique but has performed the
¹⁹⁵⁵ implementation and validation of the technique for this analysis alone.

¹⁹⁵⁶ Using the 20 production heights per Monte Carlo neutrino event, provided as 5%
¹⁹⁵⁷ percentiles from the Honda flux model, a production height distribution $p_j(h|E_\nu, \cos\theta_Z)$
¹⁹⁵⁸ is built for each neutrino flavour $j = \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$. In practice, a histogram is filled with
¹⁹⁵⁹ 20 evenly spaced bins in production height h between 0 and 50km. The neutrino energy
¹⁹⁶⁰ and cosine zenith binning of the histogram is the same as that provided in section 5.2.
¹⁹⁶¹ The average production height, $\bar{h} = \int dh \frac{1}{4} \sum_j p_j(h|E_\nu, \cos(\theta_Z))$, is calculated. The
¹⁹⁶² production height binning of this histogram is then translated into $\delta t(h) = t(\bar{h}) - t(h)$,
¹⁹⁶³ where $t(h)$ is the distance travelled along the trajectory.

¹⁹⁶⁴ For the i^{th} traversed layer, the transition amplitude, $D_i(t_{i+1}, t_i)$, is computed. The
¹⁹⁶⁵ time-ordered product of these is then used as the overall transition amplitude via

$$A(t_{n+1}, t_0) = D_n(t_{n+1}, t_n) \dots D_1(t_2, t_1) D_0(t_1, t_0), \quad (5.7)$$

1966

where,

$$\begin{aligned} D_n(t_{n+1}, t_n) &= \exp[-iH_n(t_{n+1} - t_n)] \\ &= \sum_{k=1}^3 C_k \exp[ia_k(t_{n+1} - t_n)] \end{aligned} \quad (5.8)$$

1967 is expressed as a diagonalised time-dependent solution to the Schrodinger equation.

1968 The 0^{th} layer is the propagation through the atmosphere and is the only term that
 1969 depends on the production height. Using the substitution $t_0 = t(\bar{h}) - \delta t(h)$, it can be
 1970 shown that

$$D_0(t_1, t_0) = D_0(t_1, \bar{h})D_0(\delta t). \quad (5.9)$$

1971 Thus Equation 5.7 becomes

$$\begin{aligned} A(t_{n+1}, t_0) &= D_n(t_{n+1}, t_n) \dots D_1(t_2, t_1)D_0(t_1, \bar{h})D(\delta t) \\ &= A(t_{n+1}, \bar{h}) \sum_{k=1}^3 C_k \exp[ia_k \delta t], \\ &= \sum_{k=1}^3 B_k \exp[ia_k \delta t]. \end{aligned} \quad (5.10)$$

1972 The oscillation probability averaged over production height is then calculated as

$$\begin{aligned}
 \bar{P}(\nu_j \rightarrow \nu_i) &= \int d(\delta t) p_j(\delta t | E_\nu, \cos \theta_Z) P(\nu_j \rightarrow \nu_i) \\
 &= \int d(\delta t) p_j(\delta t | E_\nu, \cos \theta_Z) A(t_{n+1}, t_0) A^*(t_{n+1}, t_0) \\
 &= \sum_{km} (B_k)_{ij} (B_m)_{ij}^* \int d(\delta t) p_j(\delta t | E_\nu, \cos \theta_Z) \exp[i(a_k - a_m)\delta t]
 \end{aligned} \tag{5.11}$$

1973 In practice, implementation in CUDAProb3 [195] is relatively straightforward as
 1974 the majority of these terms are already calculated in the standard oscillation calculation.
 1975 Figure 5.17 illustrates the results of the production height averaging. As expected,
 1976 the main effect is observed in the low-energy downward-going and horizontal-going
 1977 events. Upward-going events have to travel the radius of the Earth, $R_E = 6371\text{km}$,
 1978 where the production height uncertainty is a small fraction of the total path length.

1979

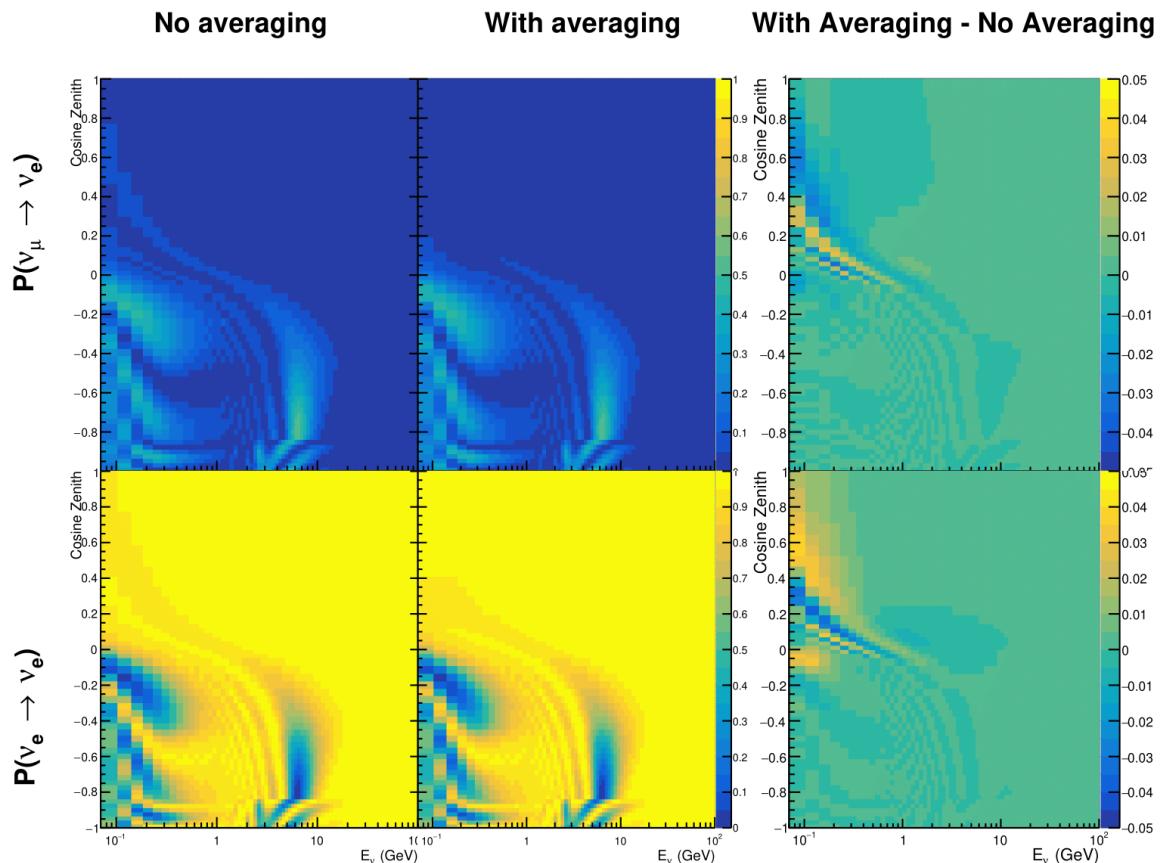


Figure 5.17: The oscillation probability, $P(\nu_\mu \rightarrow \nu_e)$ (top row) and $P(\nu_e \rightarrow \nu_\mu)$ (bottom row), given as a function of neutrino energy and zenith angle. The left column gives probabilities where a fixed production height of 25km is used. The middle column gives the probabilities where the production height is analytically averaged. The right column illustrates the difference in oscillation probability between the two different techniques.

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