

1

2

3

4

5

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

6

Daniel Robert Clement Barrow

7

8

Magdalen College,
Oxford University

9

Version 1.1

10

A Dissertation Submitted to Oxford University
11 for the Degree of Doctor of Philosophy

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*

19 Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Nulla aliquet porttitor lacus luctus accumsan tortor posuere. Pulvinar neque laoreet suspendisse interdum. Sem viverra aliquet eget sit. Nunc sed velit dignissim sodales ut eu sem integer vitae. At erat pellentesque adipiscing commodo elit at imperdiet dui accumsan. Fames ac turpis egestas integer eget aliquet nibh. Scelerisque eu ultrices vitae auctor eu augue. Purus non enim praesent elementum facilisis leo vel. Sollicitudin nibh sit amet commodo. Vitae auctor eu augue ut. Vel quam elementum pulvinar etiam. A condimentum vitae sapien pellentesque habitant morbi tristique senectus. Viverra accumsan in nisl nisi scelerisque eu ultrices. Sed viverra ipsum nunc aliquet bibendum enim.

32 Declaration

33 This dissertation is the result of my own work, except where ex-
34 plicit reference is made to the work of others, and has not been sub-
35 mitted for another qualification to this or any other university. This
36 dissertation does not exceed the word limit for the respective Degree
37 Committee.

38 Daniel Robert Clement Barrow

39 ©The copyright of this thesis rests with the author and is made available under a Creative
40 Commons Attribution Non-Commercial No Derivatives licence. Researchers are free to copy,
41 distribute or transmit the thesis on the condition that they attribute it, that they do not use
42 it for commercial purposes and that they do not alter, transform or build upon it. For any
43 reuse or redistribution, researchers must make clear to others the licence terms of this work.

44

Acknowledgements

45 at pretium nibh ipsum. Eget nunc scelerisque viverra mauris in aliquam. Arcu vitae
46 elementum curabitur vitae nunc sed velit dignissim. Sed arcu non odio euismod lacinia
47 at quis risus sed. Vitae tempus quam pellentesque nec nam aliquam sem et tortor.
48 Viverra aliquet eget sit amet tellus cras adipiscing. Purus sit amet luctus venenatis
49 lectus magna. In aliquam sem fringilla ut morbi tincidunt augue. Fermentum dui
50 faucibus in ornare. Aliquam malesuada bibendum arcu vitae elementum curabitur
51 vitae nunc sed.

52 Ultricies leo integer malesuada nunc vel risus commodo. Tellus cras adipiscing
53 enim eu turpis egestas pretium. Dictumst quisque sagittis purus sit amet volutpat
54 consequat mauris nunc. Vitae congue mauris rhoncus aenean vel elit scelerisque
55 mauris pellentesque. Vel facilisis volutpat est velit egestas dui id ornare. Suscipit
56 adipiscing bibendum est ultricies. At in tellus integer feugiat scelerisque varius
57 morbi enim. Cras semper auctor neque vitae tempus. Commodo sed egestas egestas
58 fringilla phasellus faucibus. Cras pulvinar mattis nunc sed blandit. Pretium viverra
59 suspendisse potenti nullam ac tortor vitae. Purus sit amet volutpat consequat. Orci
60 sagittis eu volutpat odio facilisis mauris. Sit amet massa vitae tortor condimentum
61 lacinia quis. Commodo sed egestas egestas fringilla phasellus. Sed libero enim sed
62 faucibus turpis. Vitae tempus quam pellentesque nec.

63 Blandit massa enim nec dui. Viverra tellus in hac habitasse platea dictumst vestibulu-
64 lum. Bibendum enim facilisis gravida neque convallis. Sagittis nisl rhoncus mattis
65 rhoncus urna neque. Nisl rhoncus mattis rhoncus urna neque. Ac tortor vitae purus
66 faucibus ornare. Aenean sed adipiscing diam donec adipiscing tristique risus. Sapien
67 nec sagittis aliquam malesuada bibendum. Et leo duis ut diam quam nulla. Tellus
68 rutrum tellus pellentesque eu tincidunt tortor aliquam nulla facilisi.

Contents

| | | |
|----------|---|-----------|
| 1 | Introduction | 1 |
| 2 | Neutrino Oscillation Physics | 2 |
| 2.1 | Discovery of Neutrinos | 2 |
| 2.2 | Theory of Neutrino Oscillation | 4 |
| 2.2.1 | Three Flavour Oscillations | 4 |
| 2.2.2 | The MSW Effect | 8 |
| 2.3 | Neutrino Oscillation Measurements | 9 |
| 2.3.1 | Solar Neutrinos | 11 |
| 2.3.2 | Atmospheric Neutrinos | 13 |
| 2.3.3 | Accelerator Neutrinos | 16 |
| 2.3.4 | Reactor Neutrinos | 18 |
| 2.4 | Summary | 20 |
| 3 | T2K and SK Experiment Overview | 23 |
| 3.1 | The Super-Kamiokande Experiment | 23 |
| 3.1.1 | The SK Detector | 24 |
| 3.1.2 | Calibration | 28 |
| 3.1.3 | Data Acquisition and Triggering | 31 |
| 3.1.4 | Cherenkov Radiation | 33 |
| 3.2 | The Tokai to Kamioka Experiment | 35 |
| 3.2.1 | The Neutrino Beam | 37 |
| 3.2.2 | The Near Detector at 280m | 40 |
| 3.2.2.1 | Fine Grained Detectors | 43 |
| 3.2.2.2 | Time Projection Chambers | 44 |

| | | | |
|-----|----------|--|-----|
| 93 | 3.2.2.3 | π^0 Detector | 46 |
| 94 | 3.2.2.4 | Electromagnetic Calorimeter | 46 |
| 95 | 3.2.2.5 | Side Muon Range Detector | 48 |
| 96 | 3.2.3 | The Interactive Neutrino GRID | 48 |
| 97 | 4 | Bayesian Statistics and Markov Chain Monte Carlo Techniques | 50 |
| 98 | 4.1 | Bayesian Statistics | 51 |
| 99 | 4.2 | Monte Carlo Simulation | 52 |
| 100 | 4.2.1 | Markov Chain Monte Carlo | 53 |
| 101 | 4.2.2 | Metropolis-Hastings Algorithm | 56 |
| 102 | 4.2.3 | MCMC Optimisation | 58 |
| 103 | 4.3 | Understanding the MCMC Results | 61 |
| 104 | 4.3.1 | Marginalisation | 62 |
| 105 | 4.3.2 | Parameter Estimation and Credible Intervals | 63 |
| 106 | 4.3.3 | Bayesian Model Comparisons | 65 |
| 107 | 4.3.4 | Comparison of MCMC Output to Expectation | 66 |
| 108 | 5 | Simulation, Reconstruction, and Event Reduction | 68 |
| 109 | 5.1 | Simulation | 68 |
| 110 | 5.2 | Event Reconstruction at SK | 73 |
| 111 | 5.3 | Event Reduction at SK | 84 |
| 112 | 6 | Sample Selections and Systematics | 90 |
| 113 | 6.1 | Atmospheric Samples | 92 |
| 114 | 6.2 | Near Detector Beam Samples | 99 |
| 115 | 6.3 | Far Detector Beam Samples | 101 |
| 116 | 6.4 | Systematic Uncertainties | 107 |
| 117 | 6.4.1 | Beam Flux | 107 |
| 118 | 6.4.2 | Atmospheric Flux | 109 |

| | | | |
|-----|------------------------|--|------------|
| 119 | 6.4.3 | Neutrino Interaction | 110 |
| 120 | 6.4.4 | Near Detector | 116 |
| 121 | 6.4.5 | Far Detector | 118 |
| 122 | 6.4.5.1 | Beam Samples | 119 |
| 123 | 6.4.5.2 | Atmospheric Samples | 122 |
| 124 | 6.4.5.3 | Correlated Detector Model | 124 |
| 125 | 7 | Oscillation Probability Calculation | 131 |
| 126 | 7.1 | Overview | 132 |
| 127 | 7.2 | Treatment of Fast Oscillations | 140 |
| 128 | 7.3 | Calculation Engine | 146 |
| 129 | 7.4 | Matter Density Profile | 149 |
| 130 | 7.5 | Production Height Averaging | 155 |
| 131 | Bibliography | | 159 |
| 132 | List of Figures | | 171 |
| 133 | List of Tables | | 182 |

¹³⁵ **Chapter 1**

¹³⁶ **Introduction**

¹³⁷ **Chapter 2**

¹³⁸ **Neutrino Oscillation Physics**

¹³⁹ When first proposed, neutrinos were expected to be massless fermions that only in-
¹⁴⁰ teract through weak and gravitational forces. This meant they were very difficult to
¹⁴¹ detect as they can pass through significant amounts of matter without interacting. De-
¹⁴² spite this, experimental neutrino physics has developed with many different detection
¹⁴³ techniques and neutrino sources being used today. In direct tension with standard
¹⁴⁴ model physics, neutrinos have been determined to oscillate between different lepton
¹⁴⁵ flavours, requiring them to have mass.

¹⁴⁶ The observation techniques which lead to the discovery of the neutrino are doc-
¹⁴⁷ umented in section 2.1. The theory underpinning neutrino oscillation is described
¹⁴⁸ in section 2.2 and includes the approximations which can be made to simplify the
¹⁴⁹ understanding of neutrino oscillation in the two-flavour approximation. Past, current,
¹⁵⁰ and future neutrino experiments are detailed in section 2.3, including the reactor,
¹⁵¹ atmospheric, and long-baseline accelerator neutrino sources that have been used to
¹⁵² successfully constrain oscillation parameters. Finally, the current state of oscillation
¹⁵³ parameter measurements are summarised in section 2.4.

¹⁵⁴ **2.1 Discovery of Neutrinos**

¹⁵⁵ At the start of the 20th century, the electrons emitted from the β -decay of the nucleus
¹⁵⁶ were found to have a continuous energy spectrum [1,2]. This observation seemingly
¹⁵⁷ broke the energy conservation invoked within that period's nuclear models. Postulated

158 in 1930 by Pauli as the solution to this problem, the neutrino (originally termed
159 “neutron”) was theorized to be an electrically neutral spin-1/2 fermion with a mass of
160 the same order of magnitude as the electron [3]. This neutrino was to be emitted with
161 the electron in β -decay to alleviate the apparent breaking of energy conservation. As a
162 predecessor of today’s weak interaction model, Fermi’s theory of β -decay developed
163 the understanding by coupling the four constituent particles; electron, proton, neutron,
164 and neutrino, into a consistent model [4].

165 Whilst Pauli was not convinced of the ability to detect neutrinos, the first observa-
166 tions of the particle were made in the mid-1950s when neutrinos from a reactor were
167 observed via the inverse β -decay (IBD) process, $\bar{\nu}_e + p \rightarrow n + e^+$ [5, 6]. The detector
168 consisted of two parts: a neutrino interaction medium and a liquid scintillator. The
169 interaction medium was built from two water tanks. These were loaded with cadmium
170 chloride to allow increased efficiency of neutron capture. The positron emitted from
171 IBD annihilates, $e^+ + e^- \rightarrow 2\gamma$, generating a prompt signal and the neutron is captured
172 on the cadmium via $n + {}^{108}Cd \rightarrow {}^{109*}Cd \rightarrow {}^{109}Cd + \gamma$, producing a delayed signal. An
173 increase in the coincidence rate was observed when the reactor was operating which
174 was interpreted 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, generating
178 a π -dominated beam which then decayed via $\pi^\pm \rightarrow \mu^\pm + (\nu_\mu, \bar{\nu}_\mu)$, and the subsequent
179 interactions of the ν_μ were observed. As the subsequent interaction of the neutrino
180 generates muons rather than electrons, it was determined the ν_μ was fundamentally
181 different from ν_e . The final observation to be made was that of the ν_τ from the DONUT
182 experiment [8]. Three neutrinos seem the obvious solution as it mirrors the known
183 number of charged lepton (as they form weak isospin doublets) but there could be

¹⁸⁴ evidence of more. Several neutrino experiments have found anomalous results [9, 10]
¹⁸⁵ which could be attributed to sterile neutrinos. However, cosmological observations
¹⁸⁶ indicate the number of neutrino species $N_{eff} = 2.99 \pm 0.17$ [11], as measured from
¹⁸⁷ the cosmic microwave background power spectrum, and LEP measured 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.

¹⁹⁰ 2.2 Theory of Neutrino Oscillation

¹⁹¹ As direct evidence of beyond Standard Model physics, a neutrino generated with
¹⁹² lepton flavour α can change into a different lepton flavour β after propagating some
¹⁹³ distance. This phenomenon is called neutrino oscillation and requires that neutrinos
¹⁹⁴ must have a non-zero mass (as seen in subsection 2.2.1). This observation is direct
¹⁹⁵ evidence of beyond standard model physics. This behaviour has been characterised
¹⁹⁶ by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) [13–15] mixing matrix which
¹⁹⁷ describes how the flavour and mass of neutrinos are associated. This is analogous to
¹⁹⁸ the Cabibbo-Kobayashi-Maskawa (CKM) [16] matrix measured in quark physics.

¹⁹⁹ 2.2.1 Three Flavour Oscillations

²⁰⁰ The PMNS parameterisation defines three flavour eigenstates, ν_e , ν_μ and ν_τ (indexed
²⁰¹ ν_α), which are eigenstates of the weak interaction and three mass eigenstates, ν_1 , ν_2 and
²⁰² ν_3 (indexed ν_i). Each mass eigenstate is the superposition of all three flavour states,

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle. \quad (2.1)$$

203 Where U is the PMNS matrix which is unitary and connects the mass and flavour

204 eigenstates.

205 The weak interaction couples to flavour eigenstates so neutrinos interact with

206 leptons of the same flavour. The propagation of a neutrino flavour eigenstate, in a

207 vacuum, can be re-written as a plane-wave solution to the time-dependent Schrödinger

208 equation,

$$|\nu_\alpha(t)\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle e^{-i\phi_i}. \quad (2.2)$$

209 The probability of observing a neutrino of flavour eigenstate β from one which

210 originated as flavour α can be calculated as,

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \sum_{i,j} U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* e^{-i(\phi_j - \phi_i)} \quad (2.3)$$

211 The ϕ_i term can be expressed in terms of the energy, E_i , and magnitude of the

212 three momenta, p_i , of the neutrino, $\phi_i = E_i t - p_i x$ (t and x being time and position

213 coordinates). Therefore,

$$\phi_j - \phi_i = E_j t - E_i t - p_j x + p_i x. \quad (2.4)$$

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

$$p_i = \sqrt{E_i^2 - m_i^2} \approx E_i - \frac{m_i^2}{2E_i}. \quad (2.5)$$

215 Making the approximations that neutrinos are relativistic, the mass eigenstates
216 were created with the same energy and that $x = L$, where L is the distance traveled by
217 the neutrino, Equation 2.4 then becomes

$$\phi_j - \phi_i = \frac{\Delta m_{ij}^2 L}{2E}, \quad (2.6)$$

218 where $\Delta m_{ij}^2 = m_j^2 - m_i^2$. This, combined with further use of unitarity relations
219 results in Equation 2.3 becoming

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re \left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \right) \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E} \right) + (-) 2 \sum_{i>j} \Im \left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \right) \sin \left(\frac{\Delta m_{ij}^2 L}{2E} \right). \quad (2.7)$$

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

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

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric, Accelerator}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor, Accelerator}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Reactor, Solar}} \underbrace{\begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Majorana}}. \quad (2.8)$$

²²⁴ Where $s_{ij} = \sin(\theta_{ij})$ and $c_{ij} = \cos(\theta_{ij})$. The oscillation parameters are often
²²⁵ grouped; (1,2) as “solar”, (2,3) as “atmospheric” and (1,3) as “reactor”. Many
²²⁶ neutrino experiments aim to measure the PMNS parameters from a wide array of
²²⁷ origins, as is the purpose of this thesis.

²²⁸ The Majorana phase, $\alpha_{1,2}$, included within the fourth matrix in Equation 2.8 is only
²²⁹ included for completeness. For an oscillation analysis experiment, any terms contain-
²³⁰ ing this phase disappear due to taking the expectation value of the PMNS matrix.
²³¹ Measurements of these phases are typically performed by experiments searching for
²³² neutrino-less double β -decay [17].

²³³ A two flavour approximation can be obtained when one assumes the third mass
²³⁴ eigenstate is degenerate with another. As discussed in section 2.3, it is found that
²³⁵ $\Delta m_{21}^2 \ll |\Delta m_{31}^2|$. This results in the two flavour approximation being reasonable for
²³⁶ understanding the features of the oscillation. In this two flavour case, the mixing
²³⁷ matrix becomes,

$$U_{2 \text{ Flav.}} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix}. \quad (2.9)$$

²³⁸ This culminates in the oscillation probability,

$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\alpha) &= 1 - \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right), \\ P(\nu_\alpha \rightarrow \nu_\beta) &= \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right). \end{aligned} \quad (2.10)$$

²³⁹ Where $\alpha \neq \beta$. For a fixed neutrino energy, the oscillation probability is a sinusoidal
²⁴⁰ function depending upon the distance over which the neutrino propagates. The
²⁴¹ frequency and amplitude of oscillation are dependent upon $\Delta m^2/4E$ and $\sin^2 2\theta$,
²⁴² respectively. The oscillation probabilities presented thus far assume $c = 1$, where
²⁴³ c is the speed of light in vacuum. In more familiar units, the maximum oscillation
²⁴⁴ probability for a fixed value of θ is given at $L[km]/E[GeV] \sim 1.27/\Delta m^2$. It is this
²⁴⁵ calculation that determines the best L/E value for a given experiment to be designed
²⁴⁶ around for measurements of a specific value of Δm^2 .

²⁴⁷ 2.2.2 The MSW Effect

²⁴⁸ The theory of neutrino oscillation in a vacuum has been described in subsection 2.2.1.
²⁴⁹ However, the beam neutrinos and atmospheric neutrinos originating from below the
²⁵⁰ horizon propagate through matter in the Earth. The coherent scattering of neutrinos
²⁵¹ from a material target modifies the Hamiltonian of the system. This results in a change
²⁵² in the oscillation probability. Notably, charged current scattering ($\nu_e + e^- \rightarrow \nu_e + e^-$,
²⁵³ propagated by a W boson) only affects electron neutrinos whereas the neutral current
²⁵⁴ scattering ($\nu_l + l^- \rightarrow \nu_l + l^-$, propagated by a Z^0 boson) interacts through all neutrino
²⁵⁵ flavours equally. In the two-flavour approximation, the effective mixing parameter
²⁵⁶ becomes

$$\sin^2(2\theta) \rightarrow \sin^2(2\theta_m) = \frac{\sin^2(2\theta)}{(A/\Delta m^2 - \cos(2\theta))^2 + \sin^2(2\theta)}, \quad (2.11)$$

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

$$N_e = \frac{\Delta m^2 \cos(2\theta)}{2\sqrt{2}G_F E}. \quad (2.12)$$

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.

2.3 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

²⁷³ neutrino oscillation [24]. Since then, the field has seen a wide array of oscillation
²⁷⁴ measurements from a variety of neutrino sources. As seen in subsection 2.2.1, the
²⁷⁵ neutrino oscillation probability is dependent on the ratio of the propagation baseline, L ,
²⁷⁶ to the neutrino energy, E . It is this ratio that determines the type of neutrino oscillation
²⁷⁷ a particular experiment is sensitive to.

²⁷⁸ As illustrated in Figure 2.1, there are many neutrino sources that span a wide
²⁷⁹ range of energies. The least energetic neutrinos are from diffuse supernovae and
²⁸⁰ terrestrial neutrinos at $O(1)$ MeV whereas the most energetic neutrinos originate from
²⁸¹ atmospheric and galactic neutrinos of $> O(1)$ TeV.

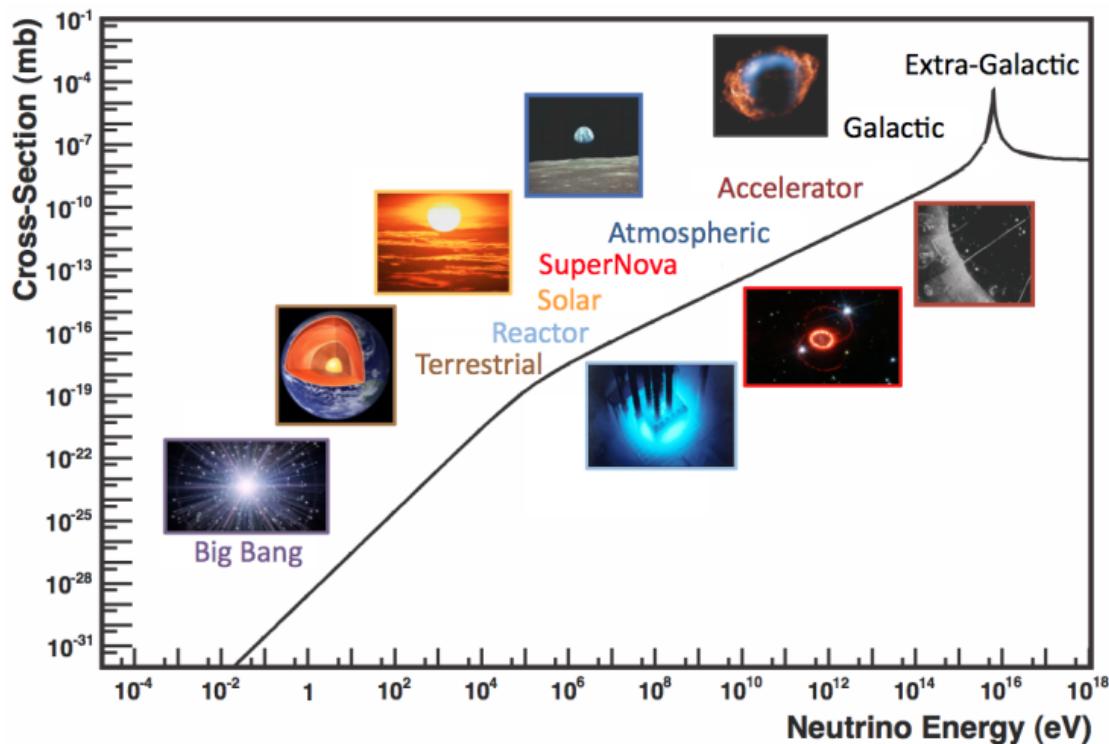


Figure 2.1: The cross-section of neutrinos from various natural and man-made sources as a function of neutrino energy. Taken from [25]

²⁸² 2.3.1 Solar Neutrinos

²⁸³ Solar neutrinos are emitted from fusion reaction chains at the center of the Sun. The
²⁸⁴ solar neutrino flux, given as a function of neutrino energy for different fusion and
²⁸⁵ decay chains, is illustrated in Figure 2.2. Whilst proton-proton fusion generates the
²⁸⁶ largest flux of neutrinos, the neutrinos are of low energy and are difficult to reconstruct
²⁸⁷ due to the IBD interaction threshold of 1.8MeV. Consequently, most experiments focus
²⁸⁸ on the neutrinos from the decay of 8B (via $^8B \rightarrow ^8Be^* + e^+ + \nu_e$), which are higher
²⁸⁹ energy.

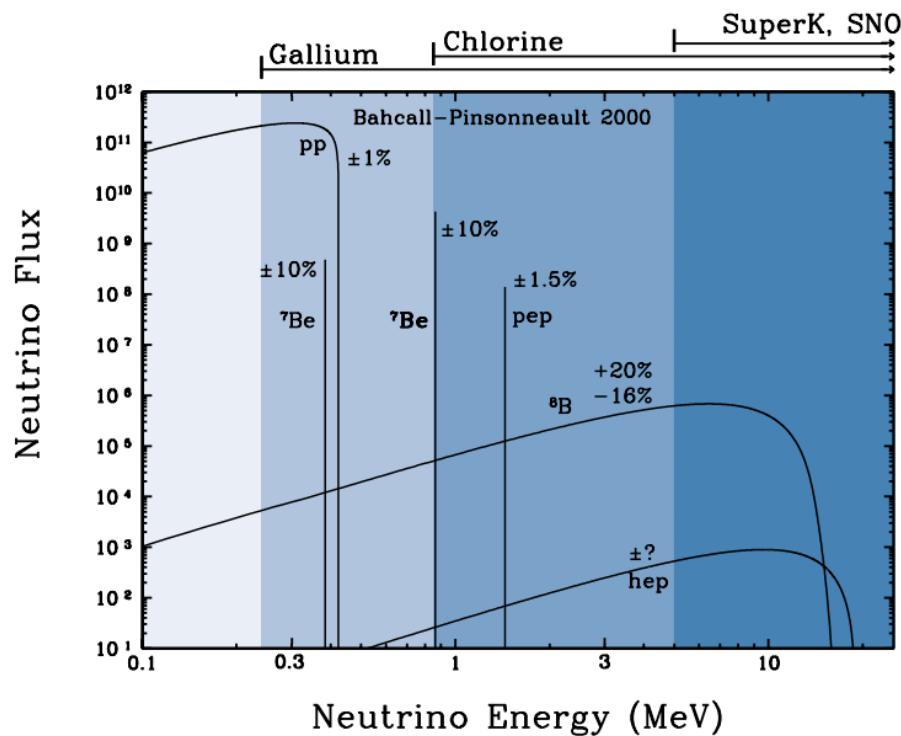
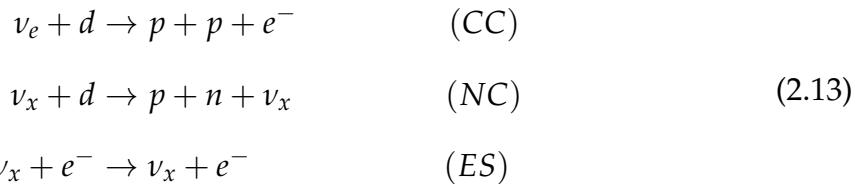


Figure 2.2: The solar neutrino flux as a function of neutrino energy for various fusion reactions and decay chains as predicted by the Standard Solar Model. Taken from [26].

²⁹⁰ The first measurements of solar neutrinos observed a significant reduction in the
²⁹¹ event rate compared to predictions from the Standard Solar Model [27, 28]. The
²⁹² proposed solution to this “solar neutrino problem” was $\nu_e \leftrightarrow \nu_\mu$ oscillations in a

²⁹³ precursory version of the PMNS model [29]. The Kamiokande [30], Gallex [31] and
²⁹⁴ Sage [32] experiments confirmed the ~ 0.5 factor deficit of solar neutrinos.

²⁹⁵ The conclusive solution to this problem was determined by the SNO collaboration
²⁹⁶ [33]. Using a deuterium water target to observe 8B neutrinos, the event rate of charged
²⁹⁷ current (CC), neutral current (NC), and elastic scattering (ES) interactions (Given in
²⁹⁸ Equation 2.13) was simultaneously measured. CC events can only occur for electron
²⁹⁹ neutrinos, whereas the NC channel is agnostic to neutrino flavour, and the ES reaction
³⁰⁰ has a slight excess sensitivity to electron neutrino interactions. This meant that there
³⁰¹ were direct measurements of the ν_e and ν_x neutrino flux. It was concluded that the
³⁰² CC and ES interaction rates were consistent with the deficit previously observed.
³⁰³ Most importantly, the NC reaction rate was only consistent with the others under the
³⁰⁴ hypothesis of flavour transformation.



³⁰⁵ Many experiments have since measured the neutrino flux of different interaction
³⁰⁶ chains within the sun [34–36]. The most recent measurement was that of CNO neutrinos
³⁰⁷ which were recently observed with 5σ significance by the Borexino collaboration.
³⁰⁸ Future neutrino experiments aim to further these spectroscopic measurements of
³⁰⁹ different fusion chains within the Sun [37–39]. Solar neutrinos act as an irreducible
³¹⁰ background for dark matter experiments like DARWIN but oscillation parameter
³¹¹ measurements can be made [40].

³¹² 2.3.2 Atmospheric Neutrinos

- ³¹³ The interactions of primary cosmic ray protons in Earth's upper atmosphere generate
³¹⁴ showers of energetic hadrons. These are mostly pions and kaons which when they
³¹⁵ decay produce a natural source of neutrinos spanning energies of MeV to TeV [41].
³¹⁶ The main decay is via

$$\begin{aligned}\pi^\pm &\rightarrow \mu^\pm + (\nu_\mu, \bar{\nu}_\mu) \\ \mu^\pm &\rightarrow e^\pm + (\nu_e, \bar{\nu}_e)\end{aligned}\tag{2.14}$$

³¹⁷ such that for a single pion decay, three neutrinos are typically produced. The
³¹⁸ atmospheric neutrino flux energy spectra as predicted by the Bartol [42], Honda
³¹⁹ [43–45], and FLUKA [46] models are illustrated in Figure 2.3. The flux distribution
³²⁰ peaks at an energy of $O(10)$ GeV. The uncertainties associated with these models
³²¹ are dominated by the hadronic production of kaon and pions as well as the primary
³²² cosmic flux.

³²³ Unlike long-baseline experiments which have a fixed baseline, the distance at-
³²⁴ mospheric neutrinos propagate is dependent upon the zenith angle at which they
³²⁵ interact. This is illustrated in Figure 2.4. Neutrinos that are generated directly above
³²⁶ the detector ($\cos(\theta) = 1.0$) have a baseline equivalent to the height of the atmosphere
³²⁷ whereas neutrinos that interact directly below the detector ($\cos(\theta) = -1.0$) have to
³²⁸ travel a length equal to the diameter of the Earth. This means atmospheric neutrinos
³²⁹ have a baseline that varies from $O(20)$ km to $O(6 \times 10^3)$ km. Any neutrino generated
³³⁰ at or below the horizon will be subject to matter effects as they propagate through the
³³¹ Earth.

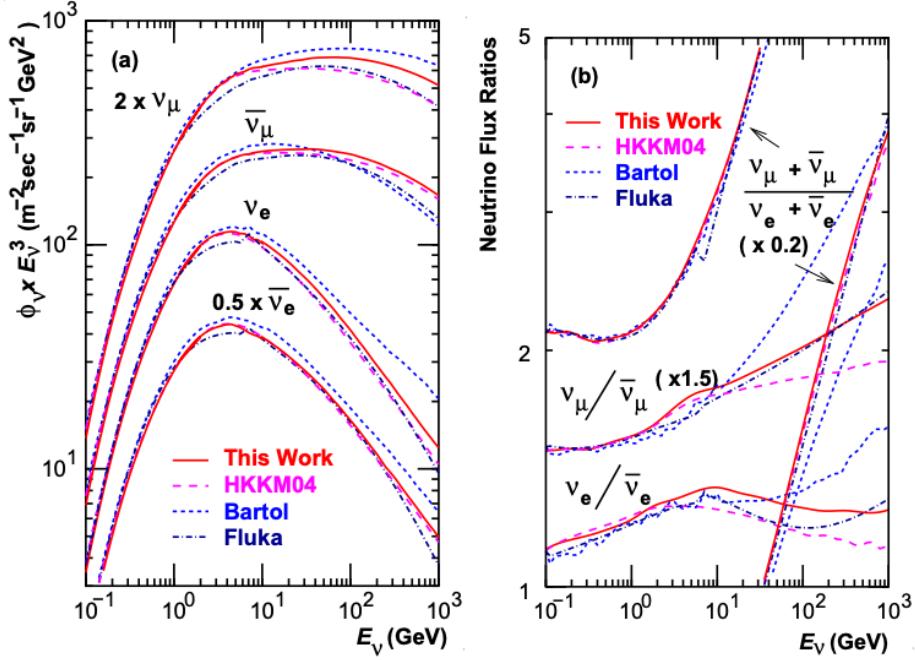


Figure 2.3: Left panel: The atmospheric neutrino flux for different neutrino flavours as a function of neutrino energy as predicted by the 2007 Honda model (“This work”) [43], the 2004 Honda model (“HKKM04”) [44], the Bartol model [42] and the FLUKA model [46]. Right panel: The ratio of the muon to electron neutrino flux as predicted by all the quoted models. Both figures taken from [43].

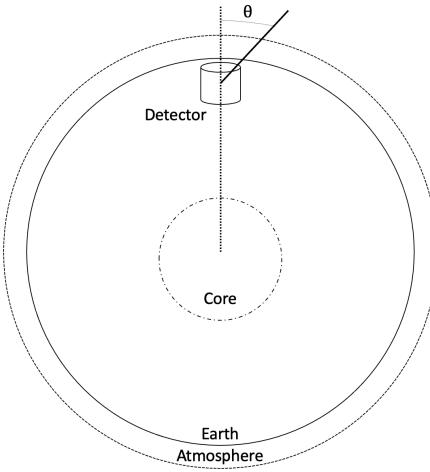


Figure 2.4: A diagram illustrating the definition of zenith angle as used in the Super Kamiokande experiment [47].

Figure 2.5 highlights the neutrino flux as a function of the zenith angle for different

slices of neutrino energy. For medium to high-energy neutrinos (and to a lesser degree

for low-energy neutrinos), the flux is approximately symmetric around $\cos(\theta) = 0$.

To the accuracy of this approximation, the systematic uncertainties associated with atmospheric flux for comparing upward-going and down-going neutrino cancels. This allows the down-going events, which are mostly insensitive to oscillation probabilities, to act as an unoscillated prediction (similar to a near detector in an accelerator neutrino experiment).

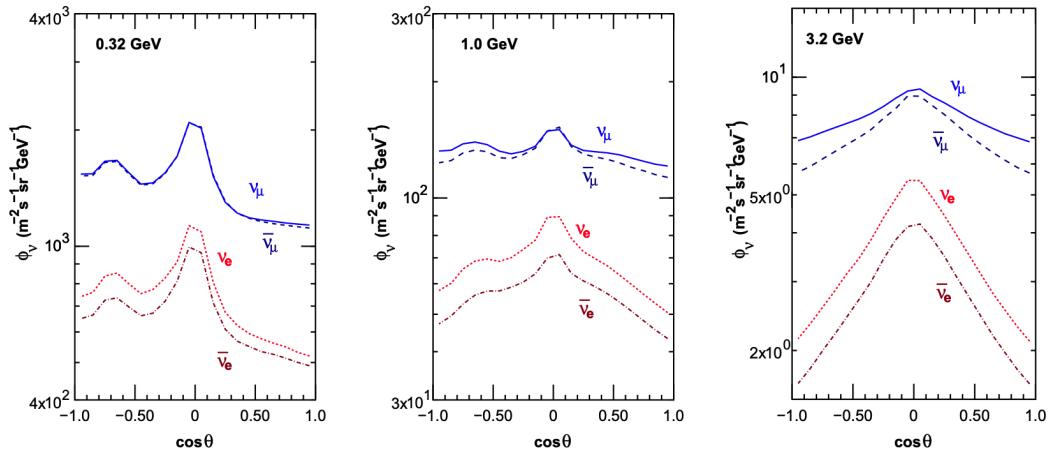


Figure 2.5: Prediction of $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$ fluxes as a function of zenith angle as calculated by the HKKM model [45]. The left, middle and right panels represent three values of neutrino energy, 0.32GeV, 1.0GeV and 3.2GeV respectively. Predictions for other models including Bartol [42], Honda [43] and FLUKA [46] are given in [47].

Precursory hints of atmospheric neutrinos were observed in the mid-1960s searching for $\nu_\mu + X \xrightarrow{(-)} X^* + \mu^\pm$ [48], although it was called an anomaly at the time of measurement. This was succeeded with the IMB-3 [49] and Kamiokande [50] experiments which measured the ratio of muon neutrinos compared to electron neutrinos $R(\nu_\mu/\nu_e)$. Both experiments were found to have a consistent deficit of muon neutrinos, 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 (SK) [47] extended this analysis by fitting oscillation parameters in $P(\nu_\mu \rightarrow \nu_\tau)$ which found best fit parameters $\sin^2(2\theta) > 0.92$ and $1.5 \times 10^{-3} < \Delta m^2 < 3.4 \times 10^{-3}$ eV 2 .

Since then, atmospheric neutrino experiments have been making precision measurements of the $\sin^2(\theta_{23})$ and Δm^2_{32} oscillation parameters. Atmospheric neutrino oscillation is dominated by $P(\nu_\mu \rightarrow \nu_\tau)$, where SK observed a 4.6σ discovery of ν_τ

³⁵¹ appearance [51]. Figure 2.6 illustrates the current estimates on the atmospheric mixing
³⁵² parameters from a wide range of atmospheric and accelerator neutrino observatories.

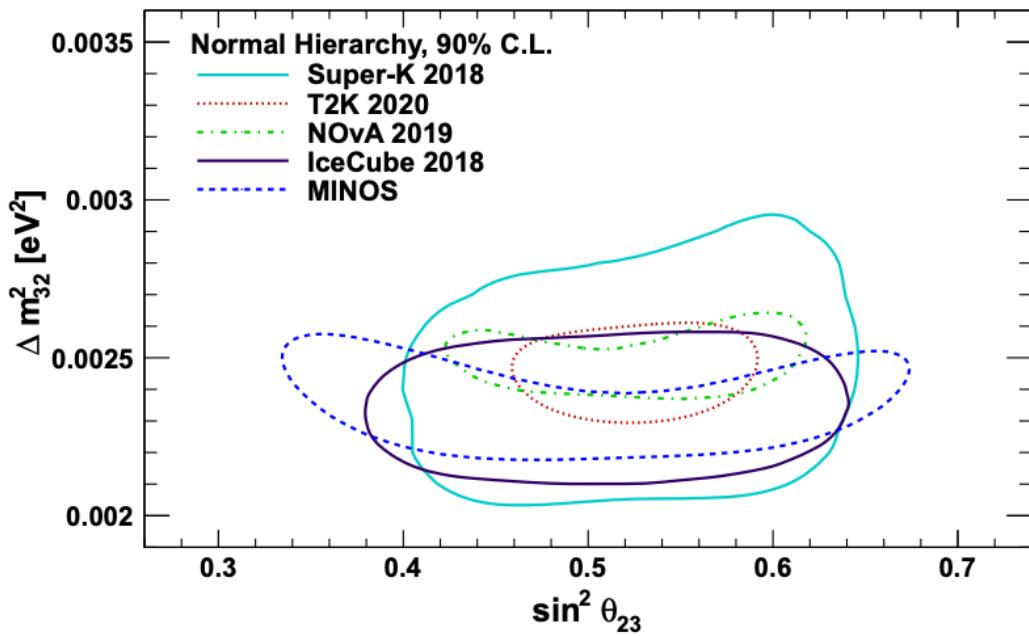


Figure 2.6: Constraints on the atmospheric oscillation parameters, $\sin^2(\theta_{23})$ and Δm_{32}^2 , from atmospheric and long baseline experiments: SK [52], T2K [53], NOvA [54], IceCube [55] and MINOS [56]. Figure taken from [57].

³⁵³ 2.3.3 Accelerator Neutrinos

³⁵⁴ The concept of using a man-made “neutrino beam” was first realised in 1962 [58].
³⁵⁵ Since then, many experiments have followed which all use the same fundamental
³⁵⁶ concepts. Typically, a proton beam is aimed at a target producing charged mesons that
³⁵⁷ decay to neutrinos. The mesons can be sign-selected by the use of magnetic focusing
³⁵⁸ horns to generate a neutrino or antineutrino beam. Pions are the primary meson that
³⁵⁹ decay and depending on the orientation of the magnetic field, a muon (anti-)neutrino
³⁶⁰ beam is generated via $\pi^+ \rightarrow \mu^+ + \nu_\mu$ or $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$. The decay of muons and
³⁶¹ kaons does result in an irreducible intrinsic electron neutrino background. In T2K,
³⁶² this background contamination is $O(< 1\%)$ [59]. There is also an approximately $\sim 5\%$

³⁶³ “wrong-sign” neutrino background of $\bar{\nu}_\mu$ generated via the same decays. As the beam is
³⁶⁴ generated by proton interactions (rather than anti-proton interactions), the wrong-sign
³⁶⁵ component in the antineutrino beam is larger when operating in neutrino mode.

³⁶⁶ Tuning the proton energy in the beam and using beam focusing techniques allows
³⁶⁷ the neutrino energy to be set to a value that maximises the disappearance oscillation
³⁶⁸ probability in the L/E term in Equation 2.10. This means that accelerator experiments
³⁶⁹ are typically more sensitive to the mixing parameters as compared to a natural neutrino
³⁷⁰ source. However, the disadvantage compared to atmospheric neutrino experiments is
³⁷¹ that the baseline has to be shorter due to the lower flux. Consequently, there is typically
³⁷² less sensitivity to matter effects and the ordering of the neutrino mass eigenstates.

³⁷³ A neutrino experiment measures

$$R(\vec{x}) = \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(\vec{x}) \times P(\nu_\alpha \rightarrow \nu_\beta), \quad (2.15)$$

³⁷⁴ where $R(\vec{x})$ is the event rate of neutrinos at position \vec{x} , $\Phi(E_\nu)$ is the flux of neutrinos
³⁷⁵ with energy E_ν , $\sigma(E_\nu)$ is the cross-section of the neutrino interaction and $\epsilon(\vec{x})$ is the
³⁷⁶ efficiency and resolution of the detector. In order to leverage the most out of an
³⁷⁷ accelerator neutrino experiment, the flux and cross-section systematics need to be
³⁷⁸ constrained. This is typically done via the use of a “near detector”, situated at a baseline
³⁷⁹ of $O(1)$ km. This detector observes the unoscillated neutrino flux and constrains the
³⁸⁰ parameters used within the flux and cross-section model.

³⁸¹ The first accelerator experiments to precisely measure oscillation parameters were
³⁸² MINOS [60] and K2K [61]. These experiments confirmed the ν_μ disappearance seen in
³⁸³ atmospheric neutrino experiments by finding consistent parameter values for $\sin^2(\theta_{23})$
³⁸⁴ and Δm_{23}^2 . The current generation of accelerator neutrino experiments, T2K and NO ν A

385 extended this field by observing $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and lead the sensitivity to atmospheric mix-
 386 ing parameters as seen in Figure 2.6 [62]. The two experiments differ in their peak
 387 neutrino energy, baseline, and detection technique. The NO ν A experiment is situated
 388 at a baseline of 810km from the NuMI beamline which delivers 2GeV neutrinos. The
 389 T2K neutrino beam is peaked around 0.6GeV and propagates 295km. The NO ν A
 390 experiment also uses functionally identical detectors (near and far) which allow the
 391 approximate cancellation of detector systematics whereas T2K uses a plastic scintil-
 392 lator technique at the near detector and a water Cherenkov far detector. The future
 393 generation experiments DUNE [63] and Hyper-Kamiokande [64] will succeed these
 394 experiments as the high-precision era of neutrino oscillation parameter measurements
 395 develops.

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

402 2.3.4 Reactor Neutrinos

403 As illustrated in the first discovery of neutrinos (section 2.1), nuclear reactors are a very
 404 useful man-made source of electron antineutrinos. For reactors that use low-enriched
 405 uranium ^{235}U as fuel, the antineutrino flux is dominated by the β -decay fission of ^{235}U ,
 406 ^{238}U , ^{239}Pu and ^{241}Pu [68] as illustrated in Figure 2.7.

407 Due to their low energy, reactor electron antineutrinos predominantly interact
 408 via the inverse β -decay (IBD) interaction. The typical signature contains two signals

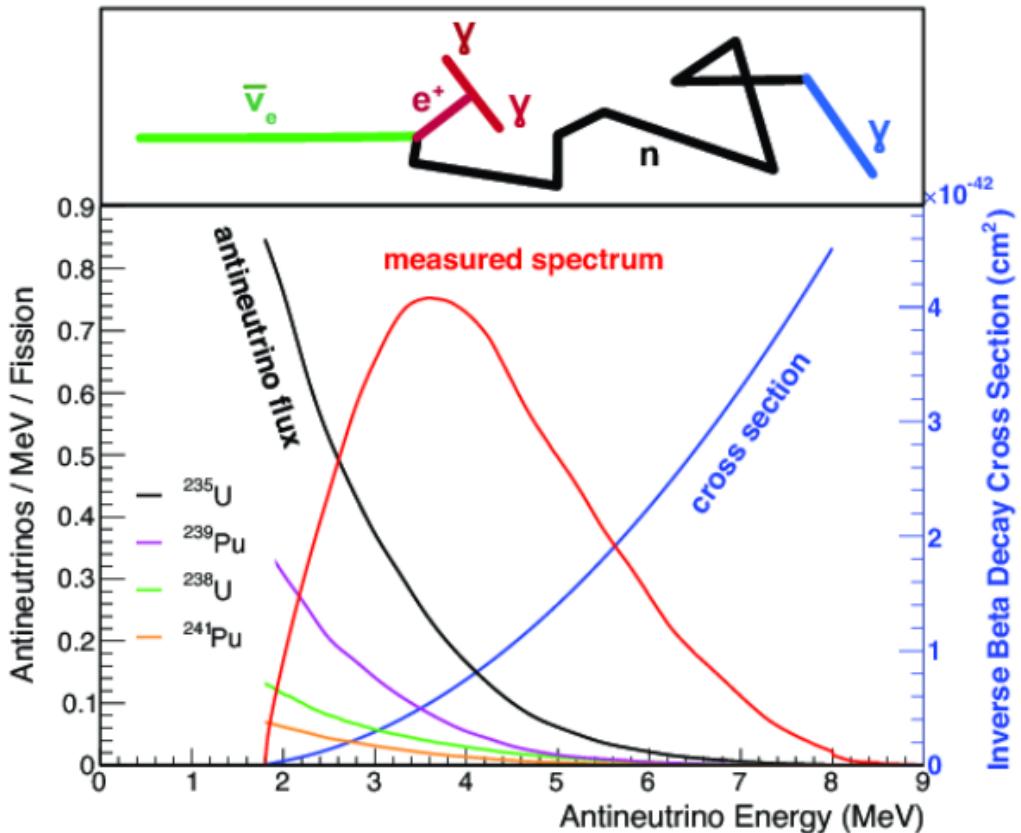


Figure 2.7: Reactor electron antineutrino fluxes for ^{235}U (Black), ^{238}U (Green), ^{239}Pu (Purple), and ^{241}Pu (Orange) isotopes. The inverse β -decay cross-section (Blue) and corresponding measurable neutrino spectrum (Red) are also given. Top panel: Schematic of Inverse β -decay interaction 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].

delayed by $O(200)\mu\text{s}$; firstly the prompt photons from positron annihilation, and secondly the photons emitted ($E_{tot}^\gamma = 2.2\text{MeV}$) from de-excitation after neutron capture on hydrogen. Searching for both signals improves the detector's ability to distinguish between background and signal events [70]. Recently, SK included gadolinium dopants into the ultra-pure water to increase the energy released from the photon cascade to $\sim 8\text{MeV}$ and reduce the time of the delayed signal to $\sim 28\mu\text{s}$.

There are many short baseline experiments ($L \sim O(1)\text{km}$) that have measured the $\sin^2(\theta_{13})$ and Δm_{23}^2 oscillation parameters. Daya Bay [71], RENO [72] and Double Chooz [73] have all provided precise measurements, with the first discovery of a

418 non-zero θ_{13} made by Daya Bay and RENO (and complemented by T2K [73]). The
419 constraints on $\sin^2(\theta_{13})$ by the reactor experiments lead the field and are often used as
420 external inputs to accelerator neutrino experiments to improve their sensitivity to δ_{CP}
421 and mass hierarchy determination. JUNO-TAO [74], a small collaboration within the
422 larger JUNO experiment, is a next-generation reactor experiment that aims to precisely
423 measure the isotopic antineutrino yields from the different fission chains. Alongside
424 this, it aims to explain the ‘5MeV excess’ [75–77] by conducting a search for sterile
425 neutrinos with a mass scale of around 1eV.

426 Kamland [78] is the only experiment to have observed reactor neutrinos using a
427 long baseline (flux weighted averaged baseline of $L \sim 180\text{km}$) which allows it to have
428 sensitivity to Δm_{12}^2 . Combined with the SK solar neutrino experiment, the combined
429 analysis puts the most stringent constraint on Δm_{12}^2 [79].

430 2.4 Summary

431 Since observing the first evidence of neutrino oscillations in the late 1990’s, numerous
432 measurements of the mixing parameters have been made. Many experiments use
433 neutrinos as a tool for discovery of new physics (diffuse supernova background,
434 neutrinoless double beta decay and others) so the PMNS parameters are summarised
435 in the Particle Data Group (PDG) review tables. The analysis presented in this thesis
436 focuses on the 2020 T2K oscillation analysis presented in [80] where the 2018 PDG
437 constraints [81] were used. These constraints are outlined in Table 2.1.

438 The $\sin^2(\theta_{13})$ measurement stems from the electron antineutrino disappearance,
439 $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$, and is take as the average best-fit from the combination of Daya Bay,
440 Reno and Double Chooz. It is often used as a prior uncertainty within other neu-
441 trino oscillation experiments, typically termed the reactor constraint. The $\sin^2(\theta_{12})$

| 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 2.1: 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.

parameter is predominantly measured through electron neutrino disappearance, $P(\nu_e \rightarrow \nu_{\mu,\tau})$, in solar neutrino experiments. The long-baseline reactor neutrino experiment Kamland also has sensitivity to this parameter and is used in a joint fit to solar data from SNO and SK, using the reactor constraint. Measurements of $\sin^2(\theta_{23})$ are made by long-baseline and atmospheric neutrino experiments. The PDG value is a joint fit of T2K, NOvA, MINOS and IceCube DeepCore experiments. The latest T2K-only measurement, provided at Neutrino2020 and is the basis of this thesis, is given as $\sin^2(\theta_{23}) = 0.546^{+0.024}_{-0.046}$ [80]. The PDG constraint on Δm_{12}^2 is provided by the KamLAND experiment using solar and geoneutrino data. This measurement utilised a $\sin^2(\theta_{13})$ constraint from accelerator (T2K, MINOS) and reactor neutrino (Daya Bay, RENO, Double Chooz) experiments. Accelerator measurements make some of the most stringent constraints on Δm_{23}^2 although atmospheric experiments have more sensitivity to the mass hierarchy determination. The PDG performs a joint fit of accelerator and atmospheric data, in both normal and inverted hierarchy separately. The 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]. The value of δ_{CP} is largely undetermined. CP-conserving values of 0 and π were

458 rejected with $\sim 2\sigma$ intervals, as published in Nature, although more recent analysis
459 have reduced the rejection intervals to 90%. Since the 2018 PDG publication, there has
460 been a new measurement of $\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$ [82], alongside updated
461 Δm_{23}^2 and $\sin^2(\theta_{23})$ measurements.

462 Throughout this thesis, several sample spectra predictions and contours are pre-
463 sented which require oscillation parameters to be assumed. Table 2.2 defines two sets
464 of oscillation parameters, with “Asimov A” set being close to the preferred values
465 from a previous T2K-only fit [83] and “Asimov B” being CP-conserving and further
466 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 2.2: Reference values of the neutrino oscillation parameters for two different oscillation parameter sets.

467 **Chapter 3**

468 **T2K and SK Experiment Overview**

469 As the successor of the Kamiokande experiment, the Super-Kamiokande (SK) collabora-
470 ration has been leading atmospheric neutrino oscillation analyses for over two decades.
471 The detector has provided some of the strongest constraints on proton decay and the
472 first precise measurements of the Δm_{23}^2 and $\sin^2(\theta_{23})$ neutrino oscillation parameters.
473 The ability of the detector to low-energy neutrino events has been significantly im-
474 proved with the recent gadolinium doping of the ultra-pure water target. The history,
475 detection technique, and operation of the SK detector is described in section 3.1.

476 The Tokai-to-Kamioka (T2K) experiment was one of the first long-baseline ex-
477 periments to use both neutrino and antineutrino beams to precisely measure the
478 charge parity violation within the neutrino sector. With the SK detector observing
479 the oscillated neutrino flux, the T2K experiment observed the first hints of a non-zero
480 $\sin^2(\theta_{13})$ measurement and continues to lead the field with the constraints it provides
481 on $\sin^2(\theta_{13})$, $\sin^2(\theta_{23})$, Δm_{23}^2 and δ_{CP} . The techniques which T2K uses in gener-
482 ating its neutrino beam as well as the near-detector used to constrain the flux and
483 cross-section parameters used in this analysis are documented in section 3.2.

484 **3.1 The Super-Kamiokande Experiment**

485 The SK experiment began taking data in 1996 [84] and has had many modifications
486 throughout its lifespan. There have been seven defined periods of data taking as
487 noted in Table 3.1. Data taking began in SK-I which ran for five years. Between the

488 SK-I and SK-II periods, a significant proportion of the PMTs were damaged during
 489 maintenance. Those that survived were equally distributed throughout the detector
 490 in the SK-II era, which resulted in a reduced photo-coverage. From SK-III onwards,
 491 repairs to the detector meant the full suite of PMTs was operational. Before the
 492 start of SK-IV, the data acquisition and electronic systems were upgraded. Between
 493 SK-IV and SK-V, a significant effort was placed into tank open maintenance and
 494 repair/replacement of defective PMTs, a task for which the author of this thesis was
 495 required. Consequently, the detector conditions were significantly different between
 496 the two operational periods. SK-VI saw the start of the 0.01% gadolinium doped water.
 497 SK-VII, which started during the writing of this thesis, has increased the gadolinium
 498 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 3.1: 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.

499 3.1.1 The SK Detector

500 The basic structure of the Super-Kamiokande (SK) detector is a cylindrical tank with a
 501 diameter 39.3m and height 41.1m filled with ultrapure water [86]. A diagram of the
 502 significant components of the SK detector is given in Figure 3.1. The SK detector is
 503 situated in the Kamioka mine in Gifu, Japan. The mine is underground with roughly
 504 1km rock overburden (2.7km water equivalent overburden) [87]. At this depth, the

505 rate of cosmic ray muons is significantly decreased to a value of $\sim 2\text{Hz}$. The top of
 506 the tank is covered with stainless steel which is designed as a working platform for
 507 maintenance, calibration, and location for high voltage and data acquisition electronics.

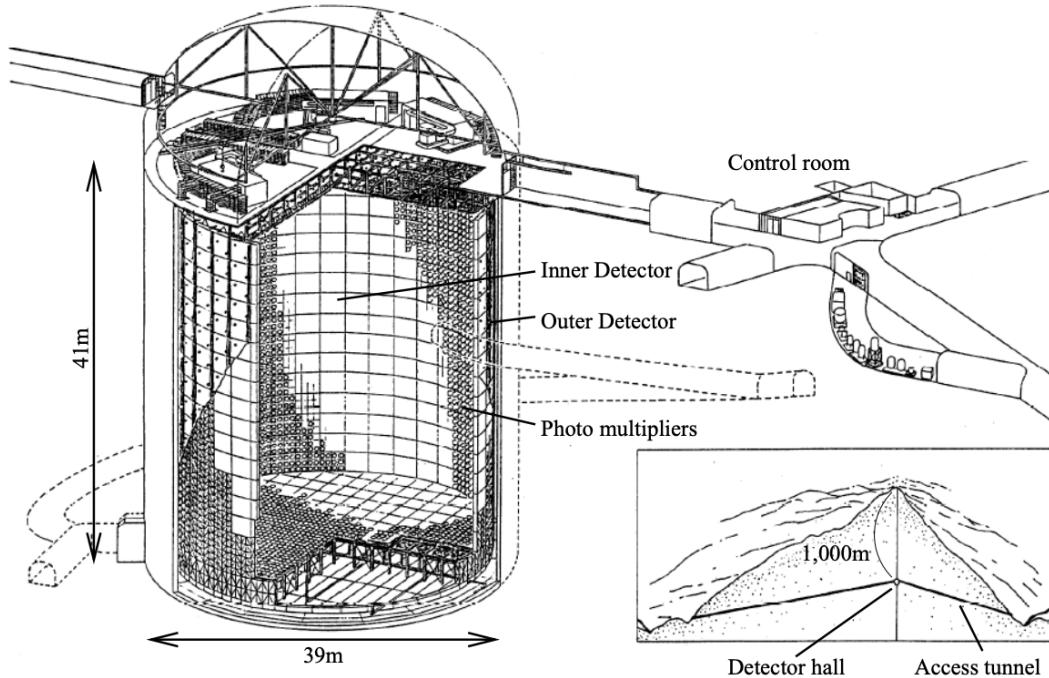


Figure 3.1: A schematic diagram of the Super-Kamiokande Detector. Taken from [88].

508 A smaller cylindrical structure (36.2m diameter, 33.8m height) is situated inside the
 509 tank, with an approximate 2m gap between this structure and the outer tank wall. The
 510 purpose of this structure is to support the photomultiplier tubes (PMTs). The volume
 511 inside and outside the support structure is referred to as the inner detector (ID) and
 512 outer detector (OD), respectively. In the SK-IV era, the ID and OD are instrumented
 513 by 11,129 50cm and 1,885 20cm PMTs respectively [86]. The ID contains a 32kton
 514 mass of water. Many analyses performed at SK use a “fiducial volume” defined by the
 515 volume of water inside the ID excluding some distance to the ID wall. This reduces the
 516 volume of the detector which is sensitive to neutrino events but reduces radioactive
 517 backgrounds and allows for better reconstruction performance. The nominal fiducial

518 volume is defined as the area contained inside 2m from the ID wall for a total of
519 22.5kton water [89].

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

529 In the SK-IV data-taking period, the photocathode coverage of the detector, or the
530 fraction of the ID wall instrumented with PMTs, is $\sim 40\%$ [87]. The PMTs have a
531 quantum efficiency (the ratio of detected electrons to incident photons) of $\sim 21\%$ for
532 photons with wavelengths of $360\text{nm} < \lambda < 390\text{nm}$. The proportion of photoelectrons
533 that produce a signal in the dynode of a PMT, termed the collection efficiency, is
534 $> 70\%$ [87]. The PMTs used within SK are most sensitive to photons with wavelength
535 $300\text{nm} \leq \lambda \leq 600\text{nm}$ [87]. One disadvantage of using PMTs as the detection media
536 is that the Earth's geomagnetic field can modify its response. Therefore, a set of
537 compensation coils is built around the inner surface of the detector to mitigate this
538 effect [90].

539 As mentioned, the SK detector is filled with ultrapure water, which in a perfect
540 world would contain no impurities. However, bacteria and organic compounds can
541 significantly degrade the water quality. This decreases the attenuation length, which
542 reduces the total number of photons that hit a PMT. To combat this, a sophisticated
543 water treatment system has been developed [87, 91]. UV lights, mechanical filters,

544 and membrane degasifiers are used to reduce the bacteria, suspended particulates,
545 and radioactive materials from the water. The flow of water within the tank is also
546 critical as it can remove stagnant bacterial growth or build-up of dust on the surfaces
547 within the tank. Gravity drifts impurities in the water towards the bottom of the
548 tank which, if left uncontrolled, can create asymmetric water conditions between
549 the top and bottom of the tank. Typically, the water entering the tank is cooled
550 below the ambient temperature of the tank to control convection and inhibit bacteria
551 growth. Furthermore, the rate of dark noise hits within PMTs is sensitive to the PMT
552 temperature [92] so controlling the temperature gradients within the tank is beneficial
553 for stable measurements.

554 SK-VI is the first phase of the SK experiment to use gadolinium dopants within
555 the ultrapure water [85]. As such, the SK water system had to be replaced to avoid
556 removing the gadolinium concentrate from the ultrapure water [93]. For an inverse
557 β -decay (IBD) interaction in a water target, the emitted neutron is thermally captured
558 on hydrogen. This process releases 2.2MeV γ rays which are difficult to detect as
559 the resulting Compton scattered electrons are very close to the Cherenkov threshold,
560 limiting the number of photons produced. Thermal capture of neutrons on gadolin-
561 ium generates γ rays with higher energy (8MeV [70]) meaning they are more easily
562 detected. SK-VI has 0.01% Gd loading (0.02% gadolinium sulphate by mass) which
563 causes \approx 50% of neutrons emitted by IBD to be captured on gadolinium [94, 95].
564 Whilst predominantly useful for low energy analyses, Gd loading allows better $\nu/\bar{\nu}$
565 separation for atmospheric neutrino event selections [96]. Efforts are currently in place
566 to increase the gadolinium concentrate to 0.03% for \approx 75% neutron capture efficiency
567 on gadolinium [97]. The final stage of loading targets 0.1% concentrate.

568 3.1.2 Calibration

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

576 Before installation, 420 PMTs were calibrated to have identical charge responses
577 and then distributed throughout the tank in a cross-shape pattern (As illustrated by
578 Figure 3.2). These are used as a standardised measure for the rest of the PMTs installed
579 at similar geometric positions within SK to be calibrated against. To perform this
580 calibration, a xenon lamp is located at the center of the SK tank which flashes uniform
581 light at 1Hz. This allows for geometrical effects, water quality variation, and timing
582 effects to be measured in-situ throughout normal data-taking periods.

583 When specifically performing calibration of the detector (in out-of-data taking
584 mode), the water in the tank was circulated to avoid top/bottom asymmetric water
585 quality. Any non-uniformity within the tank significantly affects the PMT hit proba-
586 bility through scattering or absorption. This becomes a dominant effect for the very
587 low-intensity light sources discussed later which are designed such that only one
588 photon is incident upon a given PMT.

589 The “gain” of a PMT is defined as the ratio of the total charge of the signal produced
590 compared to the charge of photoelectrons emitted by the photocathodes within the
591 PMT. To calibrate the signal of each PMT, the “relative” and “absolute” gain values are

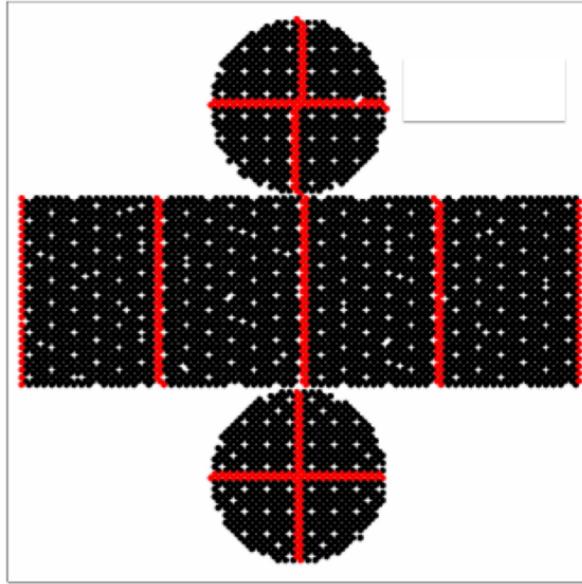


Figure 3.2: The location of “standard PMTs” (red) inside the SK detector. Taken from [86].

592 measured. The relative gain is the variation of gain among each of the PMTs whereas
 593 the absolute gain is the average gain of all PMTs.

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

$$\begin{aligned} Q_{obs}(i) &\propto I_H \times f(i) \times \epsilon(i) \times G(i), \\ N_{obs}(i) &\propto I_L \times f(i) \times \epsilon(i), \end{aligned} \tag{3.1}$$

601 Where I_H and I_L is the intensity of the high and low flashes, $f(i)$ is the acceptance
 602 efficiency of the i^{th} PMT, $\epsilon(i)$ is the product of the quantum and collection efficiency

603 of the i^{th} PMT and $G(i)$ is the gain of the i^{th} PMT. The relative gain for each PMT can
 604 determined by taking the ratio of these quantities.

605 The absolute gain calibration is performed by observing fixed energy γ -rays of
 606 $E_{\gamma} \sim 9\text{MeV}$ emitted isotropically from neutron capture on a NiCf source situated at
 607 the center of the detector. This generates a photon yield of about 0.004 photoelec-
 608 trons/PMT/event, meaning that $> 99\%$ of PMT signals are generated from single
 609 photoelectrons. A charge distribution is generated by performing this calibration over
 610 all PMTs, and the average value of this distribution is taken to be the absolute gain
 611 value.

612 As mentioned in subsection 3.1.1, the average quantum and collection efficiency
 613 for the SK detector is $\sim 21\%$ and $> 70\%$ respectively. However, these values do differ
 614 between each PMT and need to be calibrated accordingly. Consequently, the NiCf
 615 source is also used to calibrate the “quantum \times collection” efficiency (denoted “QE”)
 616 value of each PMT. The NiCf low-intensity source is used as the PMT hit probability
 617 is proportional to the QE ($N_{\text{obs}}(i) \propto \epsilon(i)$ in Equation 3.1). A Monte Carlo prediction
 618 which includes photon absorption, scattering, and reflection is made to estimate the
 619 number of photons incident on each PMT and the ratio of the number of predicted
 620 to observed hits is calculated. The difference is attributed to the QE efficiency of that
 621 PMT. This technique is extended to calculate the relative QE efficiency by normalizing
 622 the average of all PMTs which removes the dependence on the light intensity.

623 Due to differing cable lengths and readout electronics, the timing response between
 624 a photon hitting the PMT and the signal being captured by the data acquisition can be
 625 different between each PMT. Due to threshold triggers (Described in subsection 3.1.3),
 626 the time at which a pulse reaches a threshold is dependent upon the size of the pulse.
 627 This is known as the ‘time-walk’ effect and also needs to be accounted for in each PMT.
 628 To calibrate the timing response, a pulse of light with width 0.2ns is emitted into the

629 detector through a diffuser. Two-dimensional distributions of time and pulse height
630 (or charge) are made for each PMT and are used to calibrate the timing response. This
631 is performed in-situ during data taking with the light source pulsing at 0.03Hz.

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

636 Dark noise is the phenomenon where a PMT registers a pulse that is consistent
637 with a single photoelectron emitted from photon detection despite the PMT being in
638 complete darkness. This is predominately caused by two processes. Firstly there is
639 intrinsic dark noise which is where photoelectrons gain enough thermal energy to be
640 emitted from the photocathode, and secondly, the radioactive decay of contaminants
641 inside the structure of the PMT. Typical dark noise rate for PMTs used within SK are
642 $O(3)$ kHz [87]. This is lower than the expected number of photons generated for a ‘high
643 energy event’ (As described in subsection 3.1.4) but instability in this value can cause
644 biases in reconstruction. Dark noise is related to the gain of a PMT and is calibrated
645 using hits inside a time window recorded before an event trigger [98].

646 3.1.3 Data Acquisition and Triggering

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

651 Before the SK-IV period started, the existing front-end electronics were replaced
652 with “QTC-Based Electrons with Ethernet, QBEE” systems [101]. When the QBEE

observes a signal above a 1/4 photoelectron threshold, the charge-to-time (QTC) converter generates a rectangular pulse. The start of the rectangular pulse indicates the time at which the analog photoelectron signal was received and the width of the pulse indicates the total charge integrated throughout the signal. This is then digitized by time-to-digital converters and sent to the “front-end” PCs. The digitized signal from every QBEE is then chronologically ordered and sent to the “merger” PCs. It is the merger PCs that apply the software trigger. Any triggered events are passed to the “organizer” PC. This sorts the data stream of multiple merger PCs into chronologically ordered events which are then saved to disk. The schematic of data flow from PMTs to disk is illustrated in Figure 3.3.

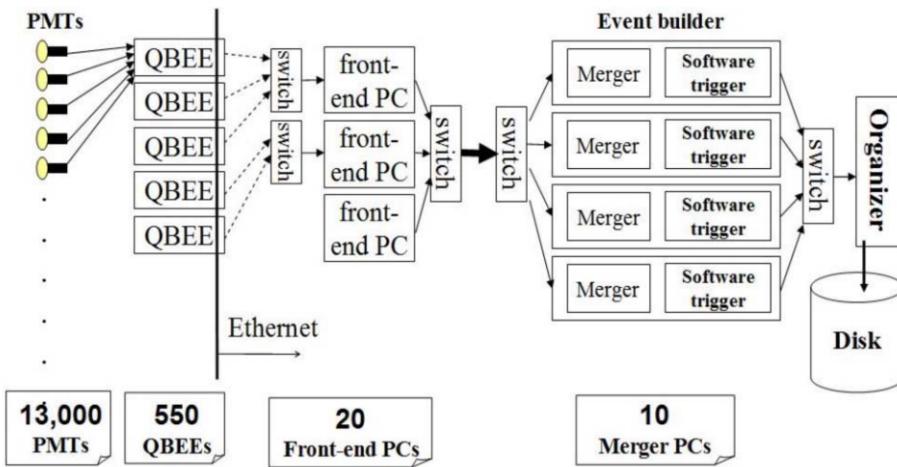


Figure 3.3: Schematic view of the data flow through the data acquisition and online system. Taken from [102].

The software trigger (described in [103]) operates by determining the number of PMT hits within a 200ns sliding window, N_{200} . This window coincides with the maximum time that a Cherenkov photon would take to traverse the length of the SK tank [100]. For lower energy events that generate fewer photons, this technique is useful for eliminating background processes like dark noise and radioactive decay which would be expected to separate in time. When the value of N_{200} exceeds some threshold, a software trigger is issued. There are several trigger thresholds used within

the SK-IV period which are detailed in Table 3.2. If one of these thresholds is met, the PMT hits within an extended time window are also read out and saved to disk. In the special case of an event that exceeds the SHE trigger but does not exceed the OD trigger, the AFT trigger looks for delayed coincidences of 2.2MeV gamma rays emitted from neutron capture in a $535\mu\text{s}$ window after the SHE trigger. A similar but more complex “Wideband Intelligent Trigger (WIT)” has been deployed and is described 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 3.2: 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.

3.1.4 Cherenkov Radiation

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

$$\cos(\theta) = \frac{1}{\beta n}. \quad (3.2)$$

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

$$P_{thres} = \frac{m}{\sqrt{n^2 - 1}} \quad (3.3)$$

For water, where $n = 1.33$, the Cherenkov threshold momentum and energy for various particles are given in Table 3.3. In contrast, γ -rays are detected indirectly via the combination of photons generated by Compton scattering and pair production. The threshold for detection in the SK detector is typically higher than the threshold for photon production. This is due to the fact that the attenuation of photons in the water means that typically $\sim 75\%$ of Cherenkov photons reach the ID PMTs. Then the collection and quantum efficiencies described in subsection 3.1.1 result in the number 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 3.3: The threshold momentum and energy for a particle to generate Cherenkov light in ultrapure water, as calculated in Equation 3.2 in ultrapure water which has refractive index $n = 1.33$.

The Frank-Tamm equation [106] describes the relationship between the number of Cherenkov photons generated per unit length, dN/dx , the wavelength of the photons generated, λ , and the relativistic velocity of the charged particle,

$$\frac{d^2N}{dxd\lambda} = 2\pi\alpha \left(1 - \frac{1}{n^2\beta^2}\right) \frac{1}{\lambda^2}. \quad (3.4)$$

where α is the fine structure constant. For a 100MeV momentum electron, approximately 330 photons will be produced per centimeter in the $300\text{nm} \leq \lambda \leq 700\text{nm}$ region which the ID PMTs are most sensitive to [87].

3.2 The Tokai to Kamioka Experiment

The Tokai to Kamioka (T2K) experiment is a long-baseline neutrino oscillation experiment located in Japan. Proposed in the early 2000s [107, 108] to replace K2K [109], T2K was designed to observe electron neutrino appearance whilst precisely measuring the oscillation parameters associated with muon neutrino disappearance [110]. The experiment consists of a neutrino beam generated at the Japan Proton Accelerator Research Complex (J-PARC), a suite of near detectors situated 280m from the beam target, and the Super Kamiokande far detector positioned at a 295km baseline. The cross-section view of the T2K experiment is drawn in Figure 3.4.

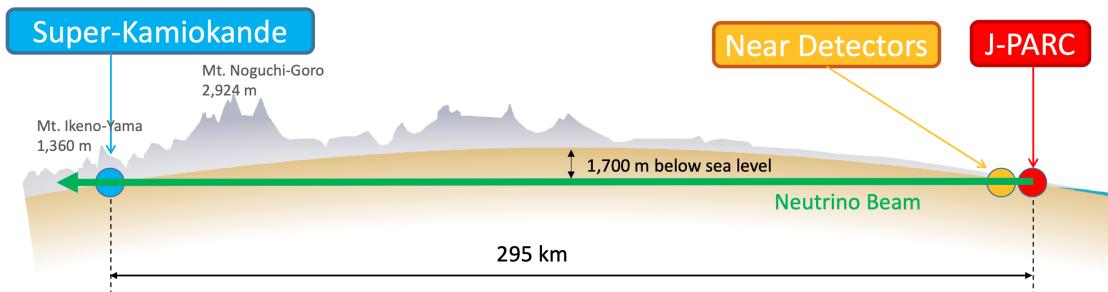


Figure 3.4: The cross-section view of the Tokai to Kamioka experiment illustrating the beam generation facility at J-PARC, the near detector situated at a baseline of 280m and the Super Kamiokande far detector situated 295km from the beam target.

The T2K collaboration makes world-leading measurements of the $\sin^2(\theta_{23})$, Δm_{23}^2 , and δ_{CP} oscillation parameters. Improvements in the precision and accuracy of parameter estimates are still being made by including new data samples and developing the models which describe the neutrino interactions and detector responses [111]. Electron neutrino appearance was first observed at T2K in 2014 [112] with 7.3σ significance.

The near detectors provide constraints on the beam flux and cross-section model parameters used within the oscillation analysis by observing the unoscillated neutrino beam. There are a host of detectors situated in the near detector hall (As illustrated in Figure 3.5): ND280 (subsection 3.2.2), INGRID (subsection 3.2.3), NINJA [113], WAGASCI [114], and Baby-MIND [115]. The latter three are not currently used within the oscillation analysis presented within this thesis.

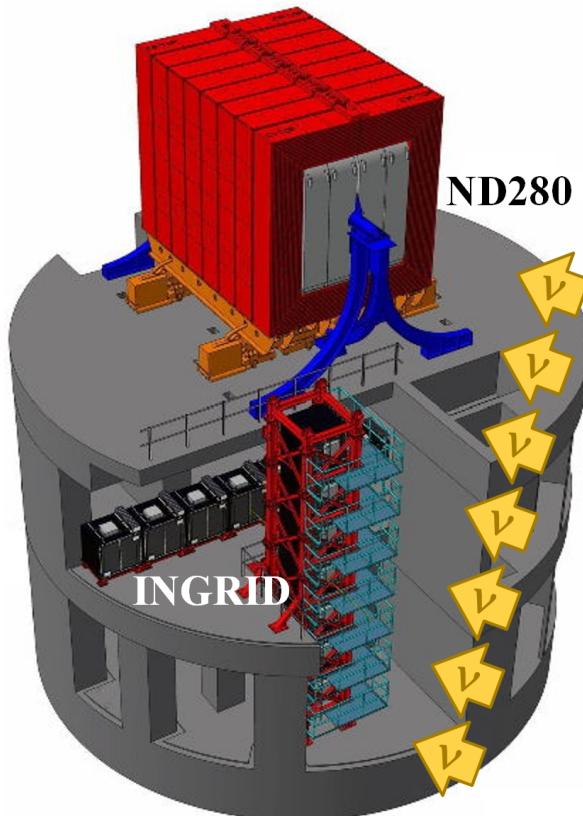


Figure 3.5: The near detector suite for the T2K experiment showing the ND280 and INGRID detectors. The distance between the detectors and the beam target is 280m.

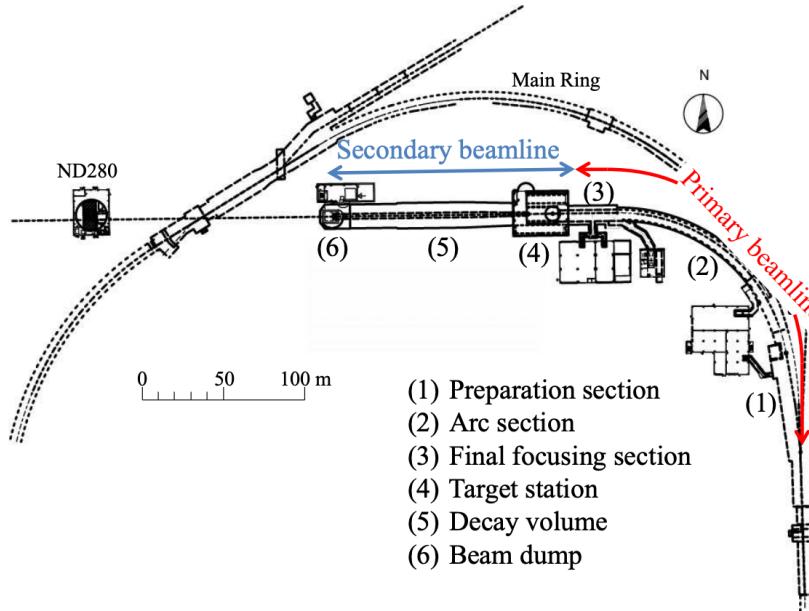
Whilst this thesis presents the ND280 in terms of its purpose for the oscillation analysis, the detector can also make many cross-section measurements at neutrino energies of $O(1)$ GeV for the different targets within the detector [116, 117]. These measurements are of equal importance as they can lead the way in determining the model parameters used in the interaction models for the future high-precision era of neutrino physics.

DB: Discuss BANFF, PTheta, MaCh3 and covariance

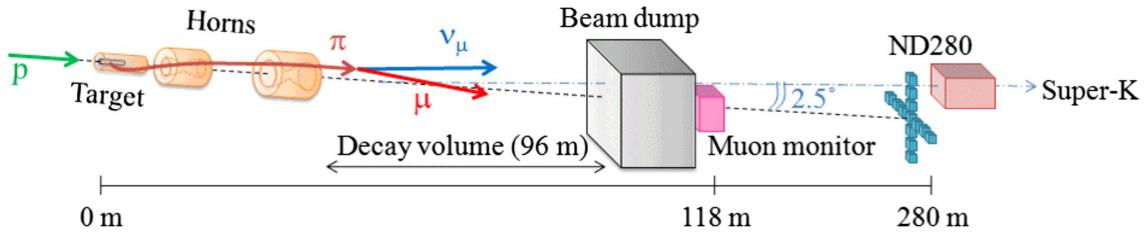
3.2.1 The Neutrino Beam

The neutrino beam used within the T2K experiment is described in [59, 118] and summarised below. The accelerating facility at J-PARC is composed of two sections; the primary and secondary beamlines. Figure 3.6 illustrates a schematic of the beamline, focusing mostly on the components of the secondary beamline. The primary beamline has three accelerators that progressively accelerate protons; a linear accelerator, a rapid-cycling synchrotron, and the main-ring (MR) synchrotron. Once fully accelerated by the MR, the protons have a kinetic energy of 30GeV. Eight bunches of these protons, separated by 500ns, are extracted per “spill” from the MR and directed towards a graphite target (a rod of length 91.4cm and diameter 2.6cm). Spills are extracted at 0.5Hz with $\sim 3 \times 10^{14}$ protons contained per spill.

The secondary beamline consists of three main components: the target station, the decay volume, and the beam dump. The target station is comprised of the target, beam monitors, and three magnetic focusing horns. The proton beam interacts with the graphite target to form a secondary beam of mostly pions and kaons. The secondary beam travels through a 96m long decay volume, generating neutrinos through the following decays [59],



(a) Primary and secondary beamline



(b) Secondary beamline

Figure 3.6: 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].

$$\begin{array}{ll}
 \pi^+ \rightarrow \mu^+ + \nu_\mu & \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \\
 K^+ \rightarrow \mu^+ + \nu_\mu & K^- \rightarrow \mu^- + \bar{\nu}_\mu \\
 \rightarrow \pi^0 + e^+ + \nu_e & \rightarrow \pi^0 + e^- + \bar{\nu}_e \\
 \rightarrow \pi^0 + \mu^+ + \nu_\mu & \rightarrow \pi^0 + \mu^- + \bar{\nu}_\mu \\
 K_L^0 \rightarrow \pi^- + e^+ + \nu_e & K_L^0 \rightarrow \pi^+ + e^- + \bar{\nu}_e \\
 \rightarrow \pi^- + \mu^+ + \nu_\mu & \rightarrow \pi^+ + \mu^- + \bar{\nu}_\mu \\
 \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e & \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e
 \end{array}$$

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

Figure 3.7 illustrates the different contributions to the FHC and RHC neutrino flux.

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

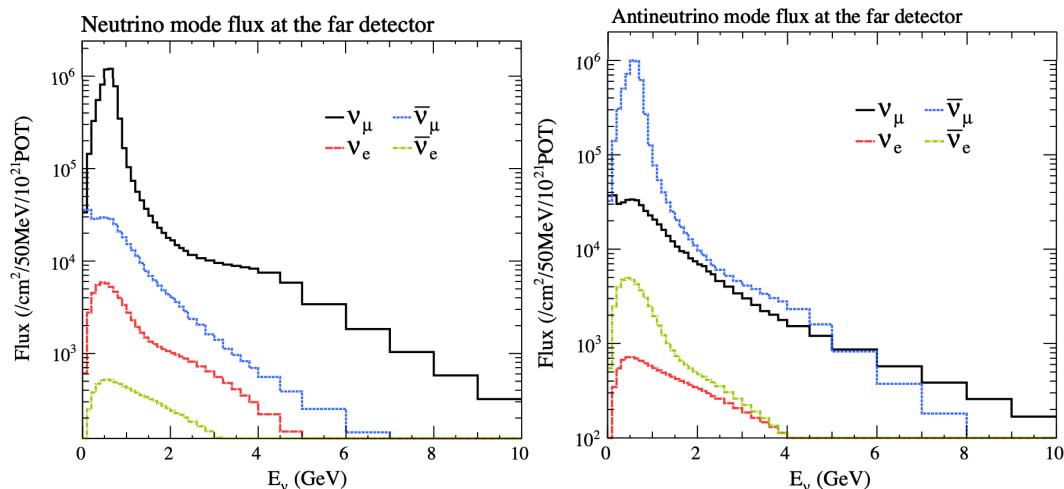


Figure 3.7: The Monte Carlo prediction of the energy spectrum for each flavour of neutrino (ν_e , $\bar{\nu}_e$, ν_μ and $\bar{\nu}_\mu$) in the neutrino dominated beam FHC mode (Left) and antineutrino dominated beam RHC mode (Right) expected at SK. Taken from [120].

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

⁷⁵⁸ penetrating muons to determine the beam direction and intensity which is used to
⁷⁵⁹ constrain some of the beam flux systematics within the analysis [119, 121].

⁷⁶⁰ The T2K experiment uses an off-axis beam to narrow the neutrino energy distribution.
⁷⁶¹ This was the first implementation of this technique in a long-baseline neutrino
⁷⁶² oscillation experiment after its original proposal [122]. Pion decay, $\pi \rightarrow \mu + \nu_\mu$, is a
⁷⁶³ two-body decay. Consequently, the neutrino energy, E_ν , can be determined based on
⁷⁶⁴ the pion energy, E_π , and the angle at which the neutrino is emitted, θ ,

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

⁷⁶⁵ where m_π and m_μ are the mass of the pion and muon respectively. For a fixed
⁷⁶⁶ energy pion, the neutrino energy distribution is dependent upon the angle at which the
⁷⁶⁷ neutrinos are observed from the initial pion beam direction. For the 295km baseline at
⁷⁶⁸ T2K, $E_\nu = 0.6\text{GeV}$ maximises the electron neutrino appearance probability, $P(\nu_\mu \rightarrow \nu_e)$,
⁷⁶⁹ whilst minimising the muon disappearance probability, $P(\nu_\mu \rightarrow \nu_\mu)$. Figure 3.8
⁷⁷⁰ illustrates the neutrino energy distribution for a range of off-axis angles, as well as the
⁷⁷¹ oscillation probabilities most relevant to T2K.

⁷⁷² 3.2.2 The Near Detector at 280m

⁷⁷³ Whilst all the near detectors are situated in the same “pit” located at 280m from the
⁷⁷⁴ beamline, the “ND280” detector is the off-axis detector which is situated at the same
⁷⁷⁵ off-axis angle as the Super-Kamiokande far detector. It has two primary functions;
⁷⁷⁶ firstly it measures the neutrino flux and secondly it counts the event rates of different
⁷⁷⁷ types of neutrino interactions. Both of these constrain the flux and cross-section

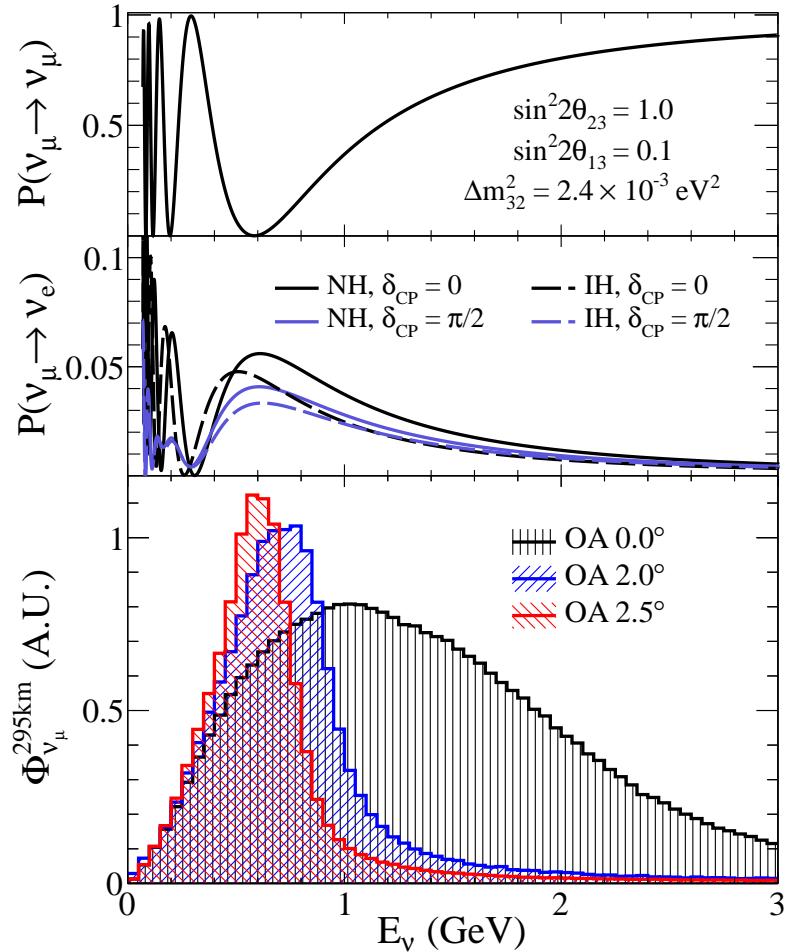


Figure 3.8: Top panel: T2K muon neutrino disappearance probability as a function of neutrino energy. Middle panel: T2K electron neutrino appearance probability as a function of neutrino energy. Bottom panel: The neutrino flux distribution for three different off-axis angles (Arbitrary units) as a function of neutrino energy.

systematics invoked within the model for a more accurate prediction of the expected event rate at the far detector.

As illustrated in Figure 3.9, the ND280 detector consists of several sub-detectors. The most important part of the detector for this analysis is the tracker region. This is comprised of two time projection chambers (TPCs) sandwiched between three fine grain detectors (FGDs). The FGDs contain both hydrocarbon plastics and water targets for neutrino interactions and provide track reconstruction near the interaction vertex. The emitted charged particles can then propagate into the TPCs which provide particle identification and momentum reconstruction. The FGDs and TPCs are

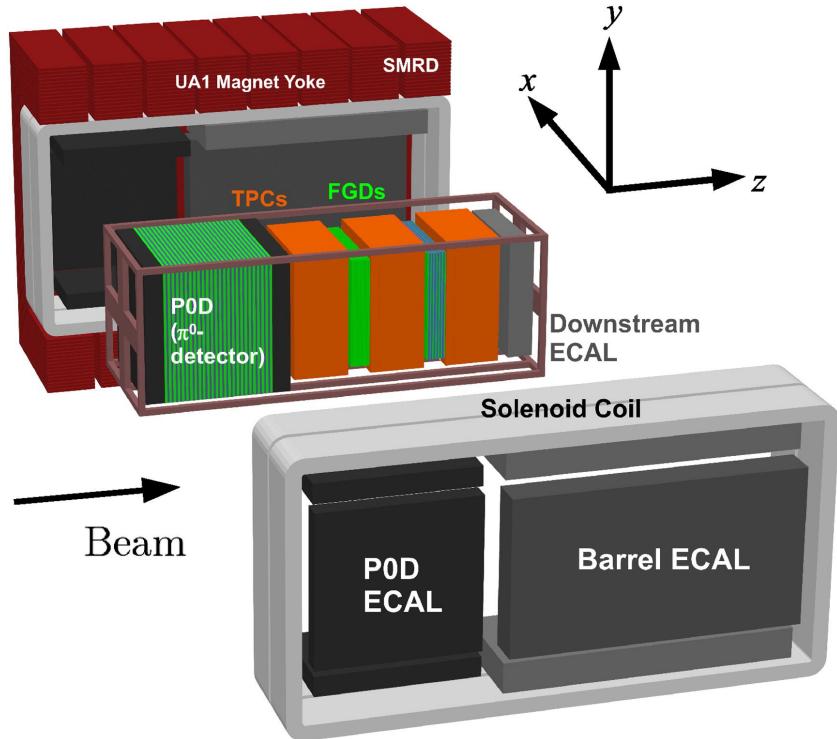


Figure 3.9: The components of the ND280 detector. The neutrino beam travels from left to right. Taken from [118].

787 further described in subsubsection 3.2.2.1 and subsubsection 3.2.2.2 respectively. The
 788 electromagnetic calorimeter (ECAL) encapsulates the tracker region alongside the π^0
 789 detector (P0D). The ECAL measures the deposited energy from photons emitted from
 790 interactions within the FGD. The P0D constrains the cross-section of neutral current
 791 interactions which generate neutral pions, which is one of the largest backgrounds in
 792 the electron neutrino appearance oscillation channel. The P0D and ECAL detectors
 793 are detailed in subsubsection 3.2.2.3 and subsubsection 3.2.2.4 respectively. The entire
 794 detector is located within a large yoke magnet which produces a 0.2T magnetic field.
 795 This design of the magnet also includes a scintillating detector called the side muon
 796 range detector (SMRD) which is used to track high-angle muons as well as acting as a
 797 cosmic veto. The SMRD is described in subsubsection 3.2.2.5.

798 3.2.2.1 Fine Grained Detectors

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

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

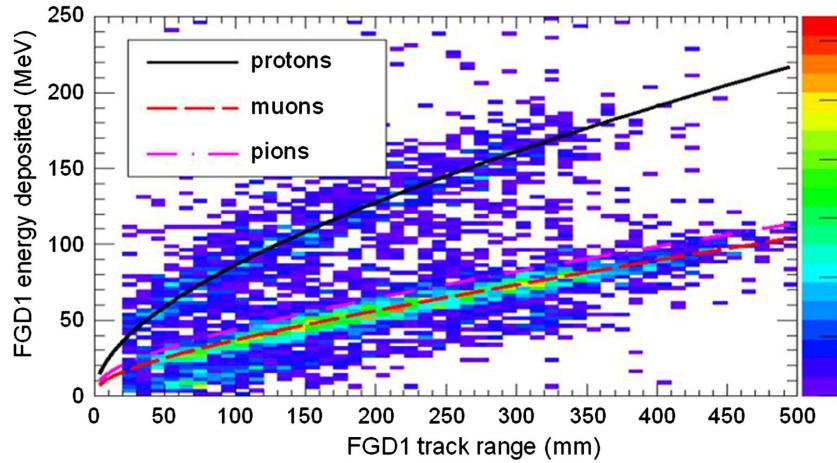


Figure 3.10: Comparison of data to Monte Carlo prediction of integrated deposited energy as a function of track length for particles that stopped in FGD1. Taken from [123].

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 3.10.

3.2.2.2 Time Projection Chambers

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

Each TPC module consists of two gas-tight boxes, as shown in Figure 3.11, which are made of non-magnetic material. The outer box is filled with CO₂ which acts as an electrical insulator between the inner box and the ground. The inner box forms the field cage which produces a uniform electric drift field of $\sim 275\text{V/cm}$ and is filled with an argon gas mixture. Charged particles moving through this gas mixture ionize the gas and the ionised charge is drifted towards micromegas detectors which measure the ionization charge. The time and position information in the readout allows a three-dimensional image of the neutrino interaction.

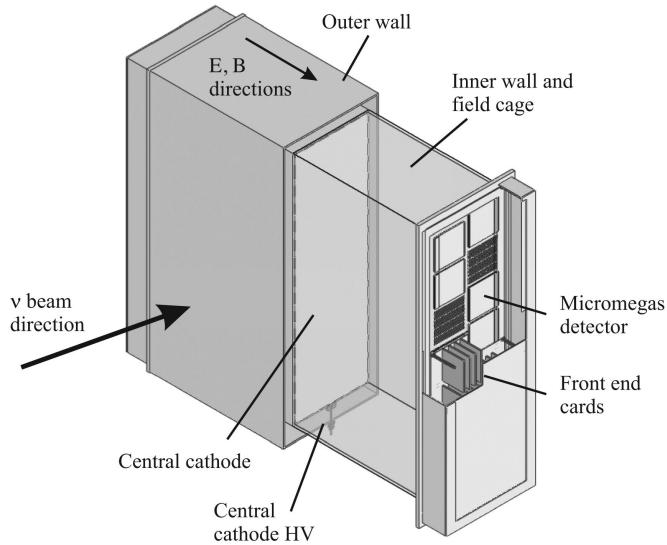
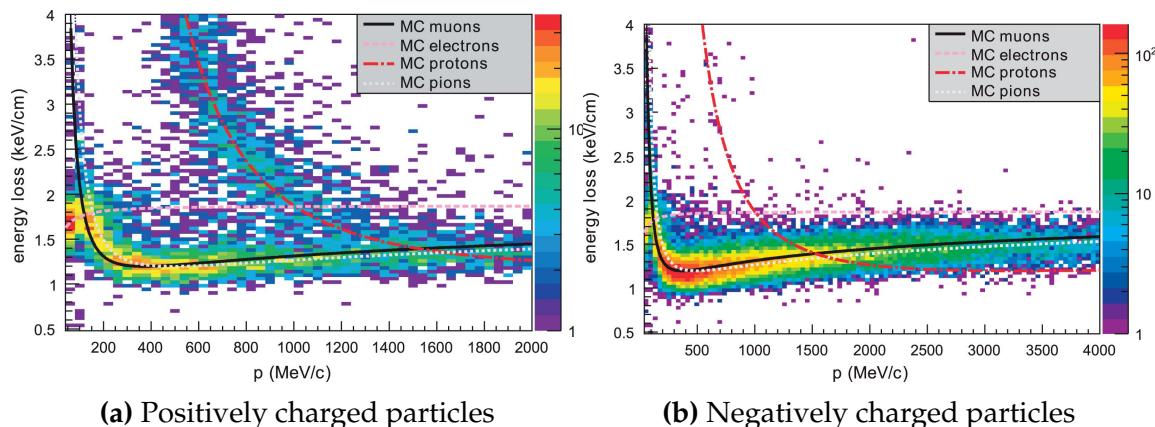


Figure 3.11: Schematic design of a Time Projection Chamber detector. Taken from [124].

The particle identification of tracks that pass through the TPCs is performed using

dE/dx measurements. Figure 3.12 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.



(a) Positively charged particles

(b) Negatively charged particles

Figure 3.12: 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].

⁸⁴⁴ 3.2.2.3 π^0 Detector

⁸⁴⁵ If one of the γ -rays from a $\pi^0 \rightarrow 2\gamma$ decay is missed at the far detector, the recon-
⁸⁴⁶ struction will determine that event to be a charge current ν_e -like event. This is one of
⁸⁴⁷ the main backgrounds hindering the electron neutrino appearance searches. The π^0
⁸⁴⁸ detector (P0D) measures the cross-section of the neutral current induced neutral pion
⁸⁴⁹ production on a water target to constrain this background.

⁸⁵⁰ The P0D is a cube of approximately 2.5m length consisting of layers of scintillating
⁸⁵¹ bars, brass and lead sheets, and water bags as illustrated in Figure 3.13. Two electro-
⁸⁵² magnetic calorimeters are positioned at the most upstream and most downstream
⁸⁵³ position in the sub-detector and the water target is situated in between them. The
⁸⁵⁴ scintillator layers are built from two triangular bars orientated in opposite directions
⁸⁵⁵ to form a rectangular layer. Each triangular scintillator bar is threaded with optical
⁸⁵⁶ fiber which is read out by MPPCs. The high-Z brass and lead regions produce electron
⁸⁵⁷ showers from the photons emitted in π^0 decay.

⁸⁵⁸ The sub-detector can generate measurements of NC1 π^0 cross-sections on a water
⁸⁵⁹ target by measuring the event rate both with and without the water target, with the
⁸⁶⁰ cross-section on a water target being determined as the difference. The total active
⁸⁶¹ mass is 16.1 tonnes when filled with water and 13.3 tonnes when empty.

⁸⁶² 3.2.2.4 Electromagnetic Calorimeter

⁸⁶³ The electromagnetic calorimeter [126] (ECal) encapsulates the P0D and tracking sub-
⁸⁶⁴ detectors. Its primary purpose is to aid π^0 reconstruction from any interaction in
⁸⁶⁵ the tracker. To do this, it measures the energy and direction of photon showers from
⁸⁶⁶ $\pi^0 \rightarrow 2\gamma$ decay. It can also distinguish pion and muon tracks depending on the shape
⁸⁶⁷ of the photon shower deposited.

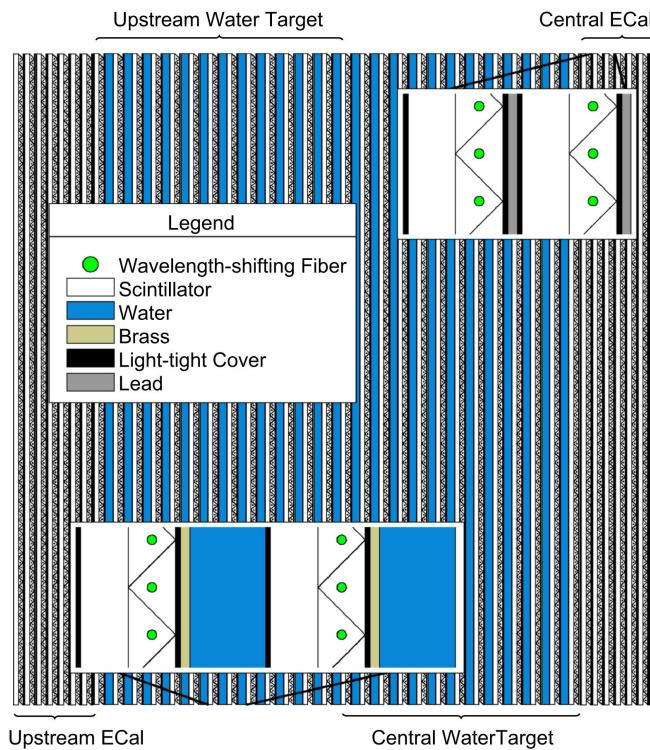


Figure 3.13: A schematic of the P0D side-view. Taken from [125].

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

Each ECal is constructed of multiple layers of scintillating bars sandwiched between lead sheets. The scintillating bars are threaded with optical fiber and read out by MPPCs. Each sequential layer of the scintillator is orientated perpendicular to the previous which allows a three dimensional event reconstruction. The target mass

882 of the P0D ECal, barrel ECal, and downstream ECal are 1.50, 4.80 and 6.62 tonnes
883 respectively.

884 **3.2.2.5 Side Muon Range Detector**

885 As illustrated in Figure 3.9, the ECal, FGDs, P0D, and TPCs are enclosed within the
886 UA1 magnet. Originally designed for the NOMAD [127] experiment and reconditioned
887 for use in the T2K experiment [128], the UA1 magnet provides a uniform horizontal
888 magnetic field of 0.2T with an uncertainty of 2×10^{-4} T.

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

892 **3.2.3 The Interactive Neutrino GRID**

893 The Interactive Neutrino GRID (INGRID) detector is situated within the same “pit” as
894 the other near detectors. It is aligned with the beam in the “on-axis” position and mea-
895 sures the beam direction, spread, and intensity. The detector was originally designed
896 with 16 identical modules [118] (two modules have since been decommissioned) and a
897 “proton” module. The design of the detector is cross-shaped with length and height
898 10m × 10m as illustrated in Figure 3.14.

899 Each module is composed of iron sheets interlaced with eleven tracking scintillator
900 planes for a total target mass of 7.1 tonnes per module. The scintillator design is an X-Y
901 pattern of 24 bars in both orientations, where each bar contains wave-length shifting
902 fibers which are connected to multi-pixel photon counters (MPPCs). Each module is
903 encapsulated inside veto planes to aid the rejection of charged particles entering the
904 module.

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

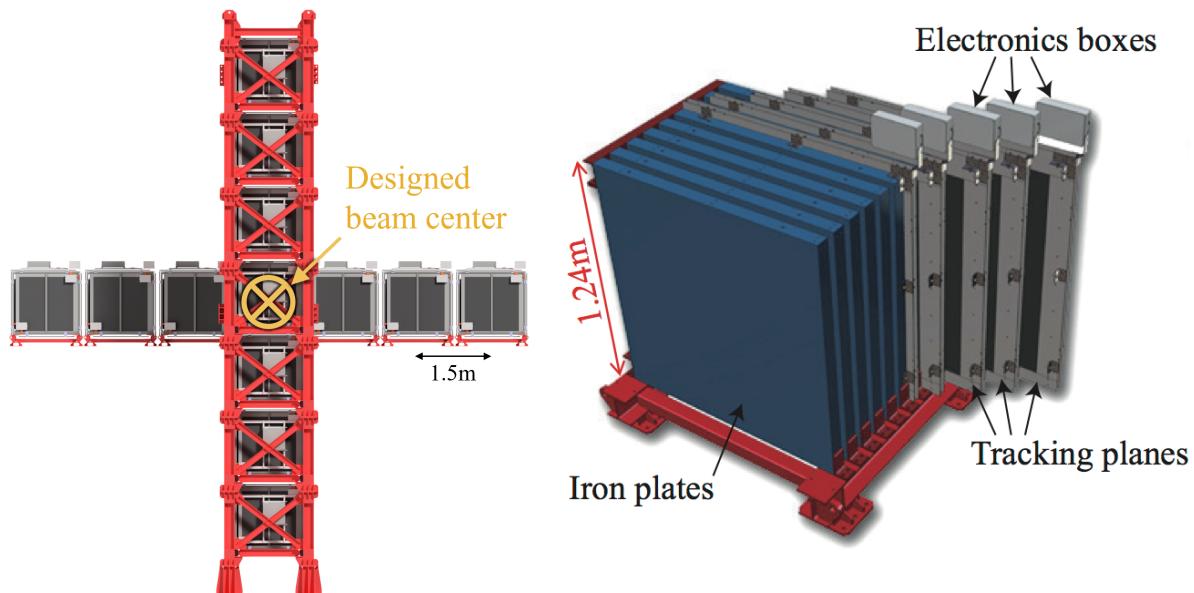


Figure 3.14: Left panel: The Interactive Neutrino GRID on-axis Detector. 14 modules are arranged in a cross-shape configuration, with the center modules being directly aligned with the on-axis beam. Right panel: The layout of a single module of the INGRID detector. Both figures are recreated from [118].

911 The INGRID detector can measure the beam direction to an uncertainty of 0.4mrad
 912 and the beam center within a resolution of 10cm [118]. The beam direction in both the
 913 vertical and horizontal directions is discussed in [130] and it is found to be in good
 914 agreement with the MUMON monitor described in subsection 3.2.1.

915 **Chapter 4**

916 **Bayesian Statistics and Markov Chain**
917 **Monte Carlo Techniques**

918 This thesis presents a Bayesian oscillation analysis. To extract the oscillation parameters,
919 a Markov Chain Monte Carlo (MCMC) method is used. This chapter explains
920 the theory of how parameter estimates can be determined using this technique and
921 condenses the material found in the literature [131–134].

922 The oscillation parameter determination presented within this thesis is built upon
923 a simultaneous fit to neutrino beam data in the near detector, beam data at SK and
924 atmospheric data at SK. In total, there are four oscillation parameters of interest
925 ($\sin^2(\theta_{23})$, $\sin^2(\theta_{13})$, Δm_{23}^2 , and δ_{CP}), two oscillation parameters to which this study
926 will not be sensitive ($\sin^2(\theta_{12})$, Δm_{12}^2) and many nuisance parameters that control the
927 systematic uncertainty models invoked within this study.

928 The MCMC technique generates a multi-dimensional probability distribution across
929 all of the model parameters used in the fit. To determine the parameter estimate of a
930 single parameter, this multi-dimensional object is integrated over all other parameters.
931 This process is called Marginalisation and is further described in subsection 4.3.1.
932 Monte Carlo techniques approximate the probability distribution of each parameter
933 within the limit of generating infinite samples. As ever, generating a large number of
934 samples is time and resource-dependent. Therefore, an MCMC technique is utilised
935 within this analysis to reduce the required number of steps to sufficiently sample the
936 parameter space. This technique is described in further detail in subsection 4.2.1.

⁹³⁷ 4.1 Bayesian Statistics

⁹³⁸ Bayesian inference treats observable data, D , and model parameters, $\vec{\theta}$, on equal
⁹³⁹ footing such that a probability model of both data and parameters is required. This is
⁹⁴⁰ the joint probability distribution $P(D, \vec{\theta})$ and can be described by the prior distribution
⁹⁴¹ for model parameters $P(\vec{\theta})$ and the likelihood of the data given the model parameters
⁹⁴² $P(D|\vec{\theta})$,

$$P(D, \vec{\theta}) = P(D|\vec{\theta})P(\vec{\theta}). \quad (4.1)$$

⁹⁴³ The prior distribution, $P(\vec{\theta})$, describes all previous knowledge about the parameters
⁹⁴⁴ within the model. For example, if the risk of developing health problems is known
⁹⁴⁵ to increase with age, the prior distribution would describe the increase. For the
⁹⁴⁶ purpose of this analysis, the prior distribution is typically the best-fit values taken
⁹⁴⁷ from external data measurements with a Gaussian uncertainty. The prior distribution
⁹⁴⁸ can also contain correlations between model parameters. In an analysis using Monte
⁹⁴⁹ Carlo techniques, the likelihood of measuring some data assuming some set of model
⁹⁵⁰ parameters is calculated by comparing the Monte Carlo prediction generated at that
⁹⁵¹ particular set of model parameters to the data.

⁹⁵² It is parameter estimation that is important for this analysis and as such, we apply
⁹⁵³ Bayes' theorem [135] to calculate the probability for each parameter to have a certain
⁹⁵⁴ value given the observed data, $P(\vec{\theta}|D)$, which is known as the posterior distribution
⁹⁵⁵ (often termed the posterior). This can be expressed as

$$P(\vec{\theta}|D) = \frac{P(D|\vec{\theta})P(\vec{\theta})}{\int P(D|\vec{\theta})P(\vec{\theta})d\vec{\theta}}. \quad (4.2)$$

956 The denominator in Equation 4.2 is the integral of the joint probability distribution

957 over all values of all parameters used within the fit. For brevity, we say that the
958 posterior distribution is

$$P(\vec{\theta}|D) \propto P(D|\vec{\theta})P(\vec{\theta}). \quad (4.3)$$

959 In subsection 4.3.1, we see that for the cases used within this analysis, it is reason-
960 able to know the posterior to some normalisation constant.

961 4.2 Monte Carlo Simulation

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

966 An example that uses Monte Carlo techniques is to calculate the area underneath
967 a curve. For example, take the problem of calculating the area under a straight line
968 with gradient $M = 0.4$ and intercept $C = 1.0$. Analytically, one can calculate the area
969 under the line is equal to 30 units for $0 \leq x \leq 10$. Using Monte Carlo techniques,
970 one can calculate the area under this line by throwing many random values for the x
971 and y components of each sample and then calculating whether that point falls below

the line. The area can then be calculated by the ratio of points below the line to the total number of samples thrown multiplied by the total area in which samples were scattered. The study is shown in Figure 4.1 highlights this technique and finds the area under the curve to be 29.9 compared to an analytical solution of 30.0. The deviation of the numerical to analytical solution can be attributed to the number of samples used in the study. The accuracy of the approximation in which the properties of the Monte Carlo samples replicate those of the desired distribution is dependent on the number of samples used. Replicating this study with a differing number of Monte Carlo samples used in each study (As shown in Figure 4.2) highlights how the Monte Carlo techniques are only accurate within the limit of a high number of samples.

Whilst the above example has an analytical solution, these techniques are just as applicable to complex solutions. Clearly, any numerical solution is only as useful as its efficiency. As discussed, the accuracy of the Monte Carlo technique is dependent upon the number of samples generated to approximate the properties of the distribution. Furthermore, if the positions at which the samples are evaluated are not ‘cleverly’ picked, the efficiency of the Monte Carlo technique significantly drops. Given the example in Figure 4.1, if the region in which the samples are scattered significantly extends passed the region of interest, many calculations will be calculated but do not add to the ability of the Monte Carlo technique to achieve the correct result. For instance, any sample evaluated at a $y \geq 5$ could be removed without affecting the final result. This does bring in an aspect of the ‘chicken and egg’ problem in that to achieve efficient sampling, one needs to know the distribution beforehand.

4.2.1 Markov Chain Monte Carlo

This analysis utilises a multi-dimensional probability distribution, with some dimensions being significantly more constrained than others. This could be from prior

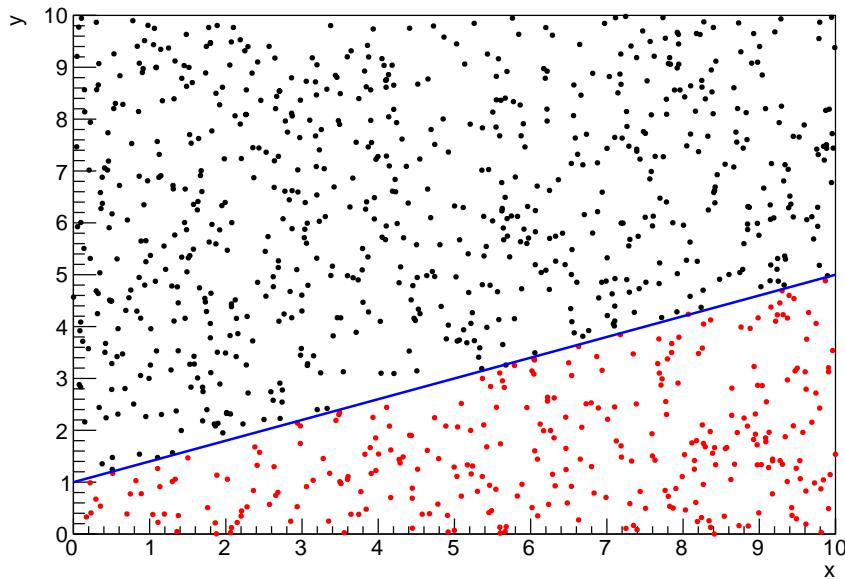


Figure 4.1: Example of using Monte Carlo techniques to find the area under the blue line. The gradient and intercept of the line are 0.4 and 1.0 respectively. The area found to be under the curve using one thousand samples is 29.9 units.

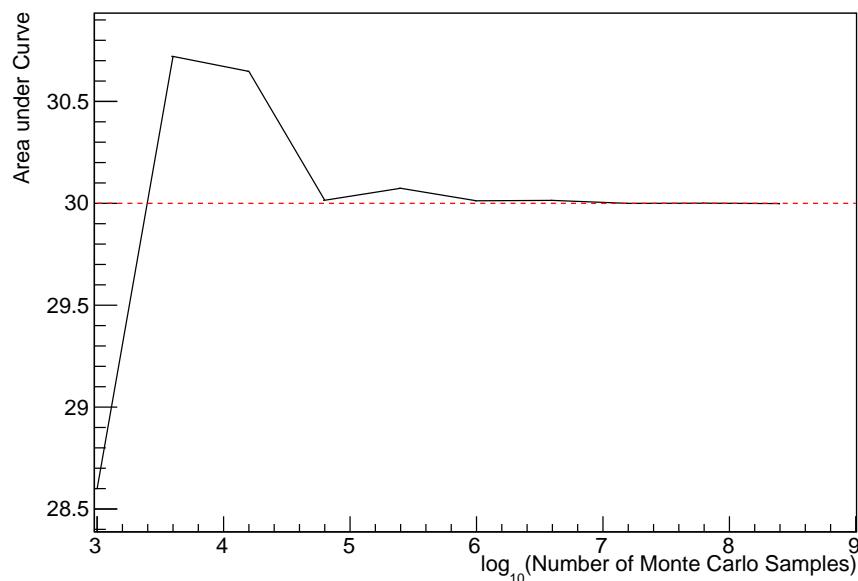


Figure 4.2: The area under a line of gradient 0.4 and intercept 1.0 for the range $0 \leq x \leq 10$ as calculated using Monte Carlo techniques as a function of the number of samples used in each repetition. The analytical solution to the area is 30 units as given by the red line.

knowledge of parameter distributions from external data or un-physical regions in 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 further history of the chain (\vec{x}_0, \vec{x}_1 , etc.). However, in solving the multi-dimensionality of the fit used within this analysis, each step becomes correlated with several of the steps preceding itself. This behaviour is further explained in subsection 4.2.3. Providing the MCMC chain is well optimised, it will begin to converge towards a unique stationary distribution. The period between the chain's initial starting point and the convergence to the unique stationary distribution is colloquially known as the burn-in period. This is discussed further in subsection 4.2.3. Once the chain reaches the stationary distribution, all points sampled after that point will look like samples from that distribution.

1021 Further details of the theories underpinning MCMC techniques are discussed
 1022 in [132] but can be summarised by the requirement that the chain satisfies the three
 1023 ‘regularity conditions’:

- 1024 • Irreducibility: From every position in the parameter space \vec{x} , there must exist a
 1025 non-zero probability for every other position in the parameter space to be reached.
- 1026 • Recurrence: Once the chain arrives at the stationary distribution, every step fol-
 1027 lowing from that position must be samples from the same stationary distribution.
- 1028 • Aperiodicity: The chain must not repeat the same sequence of steps at any point
 1029 throughout the sampling period.

1030 The output of the chain after burn-in (ie. the sampled points after the chain
 1031 has reached the stationary distribution) can be used to approximate the posterior
 1032 distribution and model parameters $\vec{\theta}$. To achieve the requirement that the unique
 1033 stationary distribution found by the chain be the posterior distribution, one can use
 1034 the Metropolis-Hastings algorithm. This guides the stochastic process depending on
 1035 the likelihood of the current proposed step compared to that of the previous step.
 1036 Implementation and other details of this technique are discussed in subsection 4.2.2.

1037 4.2.2 Metropolis-Hastings Algorithm

1038 As a requirement for MCMCs, the Markov chain implemented in this technique must
 1039 have a unique stationary distribution that is equivalent to the posterior distribution.
 1040 To ensure this requirement and that the regularity conditions are met, this analysis
 1041 utilises the Metropolis-Hastings (MH) algorithm [136,137]. For the i^{th} step in the chain,
 1042 the MH algorithm determines the position in the parameter space to which the chain
 1043 moves to based on the current step, \vec{x}_i , and the proposed step, \vec{y}_{i+1} . The proposed step
 1044 is randomly selected from some proposal function $f(\vec{x}_{i+1} | \vec{x}_i)$, which depends solely

1045 on the current step (ie. not the further history of the chain). The next step in the chain
 1046 \vec{x}_{i+1} can be either the current step or the proposed step determined by whether the
 1047 proposed step is accepted or rejected. To decide if the proposed step is selected, the
 1048 acceptance probability, $\alpha(\vec{x}_i, \vec{y}_i)$, is calculated as

$$\alpha(\vec{x}_i, \vec{y}_{i+1}) = \min \left(1, \frac{P(\vec{y}_{i+1}|D)f(\vec{x}_i|\vec{y}_{i+1})}{P(\vec{x}_i|D)f(\vec{y}_{i+1}|\vec{x}_i)} \right). \quad (4.4)$$

1049 Where $P(\vec{y}_{i+1}|D)$ is the posterior distribution as introduced in section 4.1. To
 1050 simplify this calculation, the proposal function is required to be symmetric such that
 1051 $f(\vec{x}_i|\vec{y}_{i+1}) = f(\vec{y}_{i+1}|\vec{x}_i)$. In practice, a multi-variate Gaussian distribution is used to
 1052 throw parameter proposals from. This reduces Equation 4.4 to

$$\alpha(\vec{x}_i, \vec{y}_{i+1}) = \min \left(1, \frac{P(\vec{y}_{i+1}|D)}{P(\vec{x}_i|D)} \right). \quad (4.5)$$

1053 After calculating this quantity, a random number, β , is generated uniformly be-
 1054 tween 0 and 1. If $\beta \leq \alpha(\vec{x}_i, \vec{y}_{i+1})$, the proposed step is accepted. Otherwise, the chain
 1055 sets the next step equal to the current step and this procedure is repeated. This can be
 1056 interpreted as if the posterior probability of the proposed step is greater than that of
 1057 the current step, ($P(\vec{y}_{i+1}|D) \geq P(\vec{x}_i|D)$), the proposed step will always be accepted.
 1058 If the opposite is true, ($P(\vec{y}_{i+1}|D) \leq P(\vec{x}_i|D)$), the proposed step will be accepted
 1059 with probability $P(\vec{x}_i|D)/P(\vec{y}_{i+1}|D)$. This ensures that the Markov chain does not get
 1060 trapped in any local minima in the potentially non-Gaussian posterior distribution.
 1061 The outcome of this technique is that the density of steps taken in a discrete region is
 1062 directly proportional to the probability density in that region.

¹⁰⁶³ 4.2.3 MCMC Optimisation

¹⁰⁶⁴ As discussed in subsection 4.2.2, the proposal function invoked within the MH algo-
¹⁰⁶⁵ rithm can take any form and the chain will still converge to the stationary distribution.
¹⁰⁶⁶ At each set of proposed parameter values, a prediction of the same spectra has to be
¹⁰⁶⁷ generated which requires significant computational resources. Therefore, the number
¹⁰⁶⁸ of steps taken before the unique stationary distribution is found should be minimised
¹⁰⁶⁹ as only steps after convergence add information to the oscillation analysis. Further-
¹⁰⁷⁰ more, the chain should entirely cover the allowable parameter space to ensure that all
¹⁰⁷¹ values have been considered. Tuning the distance that the proposal function jumps
¹⁰⁷² between steps on a parameter-by-parameter basis can both minimise the length of the
¹⁰⁷³ burn-in period and ensure that the correlation between step \vec{x}_i and \vec{x}_j is sufficiently
¹⁰⁷⁴ small.

¹⁰⁷⁵ The effect of changing the width of the proposal function is highlighted in Figure 4.3.
¹⁰⁷⁶ Three scenarios, each with the same underlying stationary distribution (A Gaussian of
¹⁰⁷⁷ width 1.0 and mean 0.), are presented. The only difference between the three scenarios
¹⁰⁷⁸ is the width of the proposal function, colloquially known as the ‘step size σ ’. Each
¹⁰⁷⁹ scenario starts at an initial parameter value of 10.0 which would be considered an
¹⁰⁸⁰ extreme variation. For the case where $\sigma = 0.1$, it is clear to see that the chain takes
¹⁰⁸¹ a long time to reach the expected region of the parameter. This indicates that this
¹⁰⁸² chain would have a large burn-in period and does not converge to the stationary
¹⁰⁸³ distribution until step ~ 500 . Furthermore, whilst the chain does move towards the
¹⁰⁸⁴ expected region, each step is significantly correlated with the previous. Considering
¹⁰⁸⁵ the case where $\sigma = 5.0$, the chain approaches the expected parameter region almost
¹⁰⁸⁶ instantly meaning that the burn-in period is not significant. However, there are clearly
¹⁰⁸⁷ large regions of steps where the chain does not move. This is likely due to the chain
¹⁰⁸⁸ proposing steps in the tails of the distribution which have a low probability of being

1089 accepted. Consequently, this chain would take a significant number of steps to fully
 1090 span the allowable parameter region. For the final scenario, where $\sigma = 0.5$, you can see
 1091 a relatively small burn-in period of approximately 100 steps. Once the chain reaches
 1092 the stationary distribution, it moves throughout the expected region of parameter
 1093 values many times, sufficiently sampling the full parameter region. This example is a
 1094 single parameter varying across a continuous distribution and does not fully reflect
 1095 the difficulties in the many-hundred multi-variate parameter distribution used within
 1096 this analysis. However, it does give a conceptual idea of the importance of selecting
 1097 the proposal function and associated step size.

1098 As discussed, step size tuning directly correlates to the average step acceptance
 1099 rate. If the step size is too small, many steps will be accepted but the chain moves
 1100 slowly. If the opposite is true, many steps will be rejected as the chain proposes steps
 1101 in the tails of the distribution. Discussion in [138] suggests that the ‘ideal’ acceptance
 1102 rate of a high dimension MCMC chain should be approximately $\sim 25\%$. An “ideal”
 1103 step size [138] of

$$\sigma = \frac{2.4}{N_p}, \quad (4.6)$$

1104 where N_p is the number of parameters included in the MCMC fit. However, the
 1105 complex correlations between systematics mean that some parameters have to be hand
 1106 tuned and many efforts have been taken to select a set of parameter-by-parameter step
 1107 sizes to approximately reach the ideal acceptance rate.

1108 Figure 4.3 highlights the likelihood as calculated by the fit in [DB: Link to AsimovA](#)
 1109 **Sensitivity Section** as a function of the number of steps in each chain. In practice,
 1110 many independent MCMC chains are run simultaneously to parallelise the task of

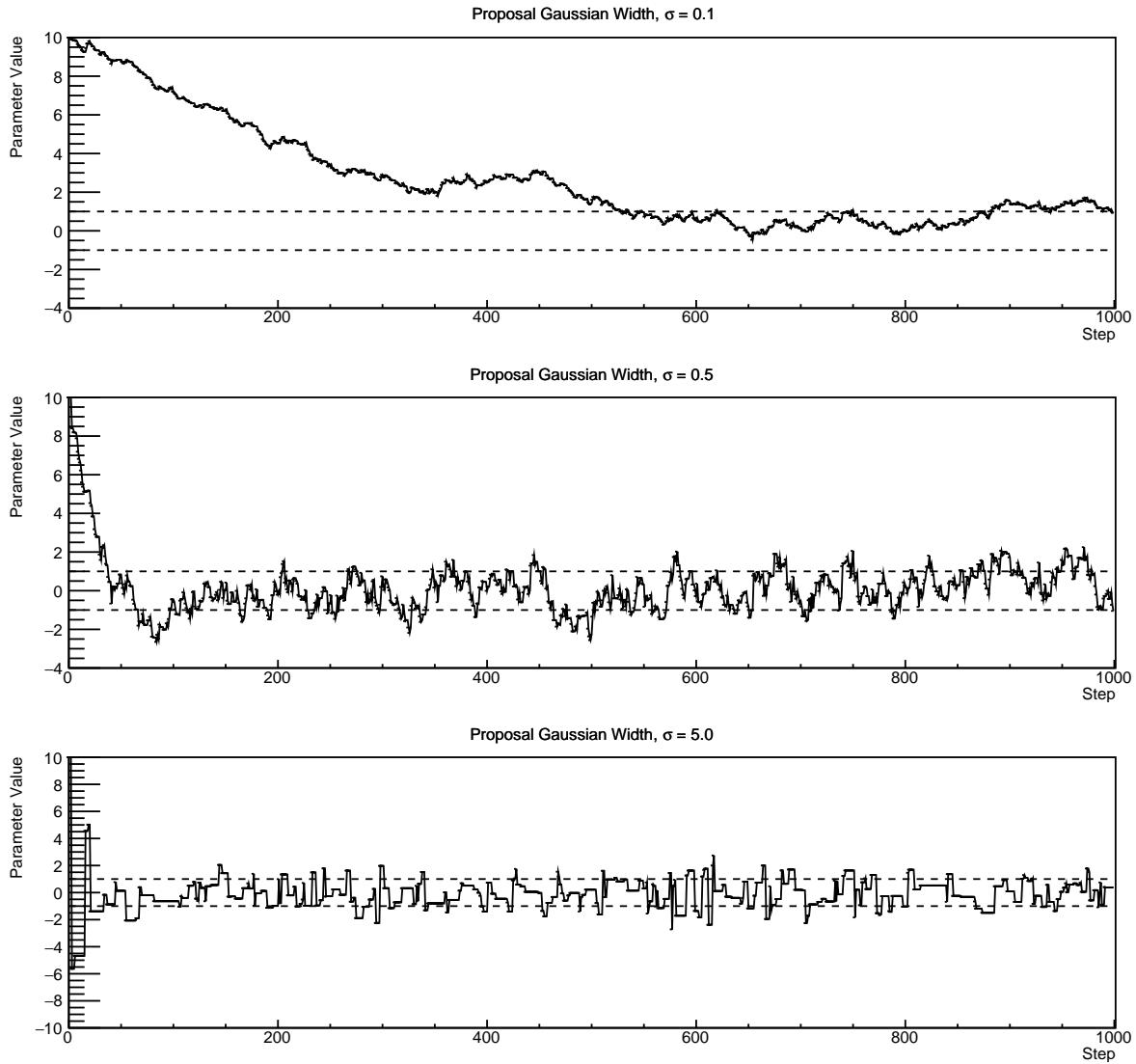


Figure 4.3: Three MCMC chains, each with a stationary distribution equal to a Gaussian centered at 0 and width 1 (As indicated by the black dotted lines). All of the chains use a Gaussian proposal function but have different widths (or ‘step size σ ’). The top panel has $\sigma = 0.1$, middle panel has $\sigma = 0.5$ and the bottom panel has $\sigma = 5.0$.

1111 performing the fit. This figure overlays the distribution found in each chain. As seen,
 1112 the likelihood decreases from its initial value and converges towards a stationary
 1113 distribution after $\sim 1 \times 10^5$ steps.

1114 Multiple configurations of this analysis have been performed throughout this thesis
 1115 where different samples or systematics have been used. For all of these configurations,
 1116 it was found that a burnin period of 1×10^5 was sufficient in all cases.

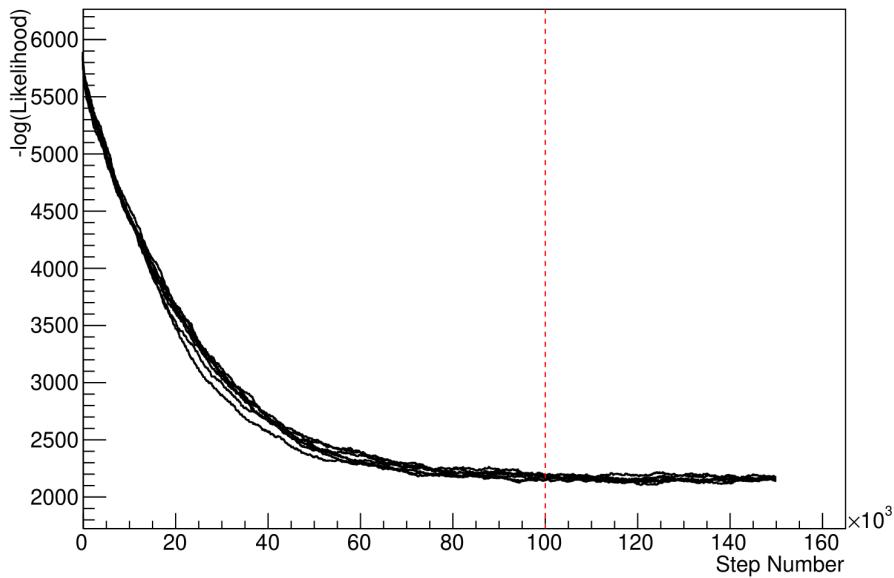


Figure 4.4: The log-likelihood from the fit detailed in DB: [Link to AsimovA Sensitivity Section](#) as a function of the number of steps accumulated in each fit. Many independent MCMC chains were run in parallel and overlaid on this plot. The red line indicates the 1×10^5 step burn-in period after which the log-likelihood becomes stable.

1117 4.3 Understanding the MCMC Results

1118 The previous sections have described how to generate the posterior probability distri-
1119 bution using Bayesian MCMC techniques. However, this analysis focuses on oscillation
1120 parameter determination. The posterior distribution output from the chain is a high
1121 dimension object, with as many dimensions as there are parameters included in the os-
1122 cillation analysis. However, this multi-dimensional object is difficult to conceptualize
1123 so parameter estimations are often presented in one or two-dimensional projections
1124 of this probability distribution. To do this, we invoke the marginalisation technique
1125 highlighted in subsection 4.3.1.

¹¹²⁶ 4.3.1 Marginalisation

¹¹²⁷ The output of the MCMC chain is a highly dimensional probability distribution
¹¹²⁸ which is very difficult to interpret. From the standpoint of an oscillation analysis
¹¹²⁹ experiment, the one or two-dimensional ‘projections’ of the oscillation parameters of
¹¹³⁰ interest are most relevant. Despite this, the best fit values and uncertainties on the
¹¹³¹ oscillation parameters of interest should correctly encapsulate the correlations to the
¹¹³² other systematic uncertainties (colloquially called ‘nuisance’ parameters). For this joint
¹¹³³ beam and atmospheric analysis, the oscillation parameters of interest are $\sin^2(\theta_{23})$,
¹¹³⁴ $\sin^2(\theta_{13})$, Δm_{23}^2 , and δ_{CP} . All other parameters (Including the oscillation parameter
¹¹³⁵ this fit is insensitive to) are deemed nuisance parameters. To generate these projections,
¹¹³⁶ we rely upon integrating the posterior distribution over all nuisance parameters. This
¹¹³⁷ is called marginalisation. A simple example of this technique is to imagine the scenario
¹¹³⁸ where two coins are flipped. To determine the probability that the first coin returned
¹¹³⁹ a ‘head’, the exact result of the second coin flip is disregarded and simply integrated
¹¹⁴⁰ over. For the parameters of interest, $\vec{\theta}_i$, we can calculate the marginalised posterior by
¹¹⁴¹ integrating over the nuisance parameters, $\vec{\theta}_n$. In this case, Equation 4.2 becomes

$$P(\vec{\theta}_i|D) = \frac{\int P(D|\vec{\theta}_i, \vec{\theta}_n)P(\vec{\theta}_i, \vec{\theta}_n)d\vec{\theta}_n}{\int P(D|\vec{\theta})P(\vec{\theta})d\vec{\theta}} \quad (4.7)$$

¹¹⁴² Where $P(\vec{\theta}_i, \vec{\theta}_n)$ encodes the prior knowledge about the uncertainty and correlations
¹¹⁴³ between the parameters of interest and the nuisance parameters. In practice, this
¹¹⁴⁴ is simply taking the one or two-dimensional projection of the multi-dimensional
¹¹⁴⁵ probability distribution.

Whilst in principle an easy solution to a complex problem, correlations between the interesting and nuisance parameters can bias the marginalised results. A similar effect is found when the parameters being marginalised over have non-Gaussian probability distributions. For example, Figure 4.5 highlights the marginalisation bias in the probability distribution found for a parameter when requiring a correlated parameter to have a positive parameter value. Due to the complex nature of this oscillation parameter fit presented in this thesis, there are correlations occurring between the oscillation parameters of interest and the other nuisance parameters included in the fit.

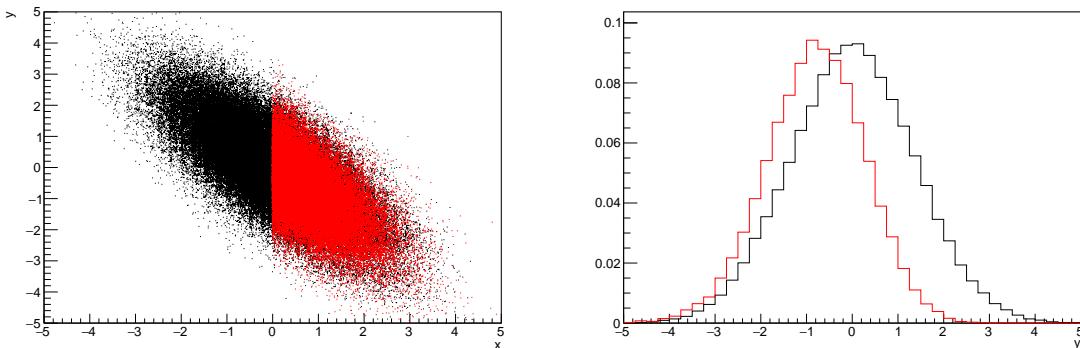


Figure 4.5: Left: The two dimensional probability distribution for two correlated parameters x and y . The red distribution shows the two dimensional probability distribution when $0 \leq x \leq 5$. Right: The marginalised probability distribution for the y parameter found when requiring the x to be bound between $-5 \leq x \leq 5$ and $0 \leq x \leq 5$ for the black and red distribution, respectively.

4.3.2 Parameter Estimation and Credible Intervals

The purpose of this analysis is to determine the best fit values for the oscillation parameters that the beam and atmospheric samples are sensitive to: $\sin^2(\theta_{23})$, $\sin^2(\theta_{13})$, Δm_{23}^2 , and δ_{CP} . Typically, the results presented take the form of one or two-dimension marginalised probability distributions for the appearance ($\sin^2(\theta_{13})$ and δ_{CP}) and disappearance ($\sin^2(\theta_{23})$ and Δm_{23}^2) parameters. The posterior probability density

₁₁₆₁ taken from the output MCMC chain is binned in these parameters. The parameter
₁₁₆₂ best-fit point is then taken to be the value that has the highest posterior probability.
₁₁₆₃ This is performed in both one and two-dimensional projections.

₁₁₆₄ However, the single best-fit point in a given parameter is not of much use on its
₁₁₆₅ own. We would also like to determine the uncertainty, or credible interval, on that
₁₁₆₆ best-fit point. The definition of the 1σ credible interval is that we have 68% belief that
₁₁₆₇ the parameter is within those bounds. For a more generalised definition, the credible
₁₁₆₈ interval is the region, R , of the posterior distribution that contains a specific fraction of
₁₁₆₉ the total probability, such that

$$\int_R P(\theta|D)d\theta = \alpha \quad (4.8)$$

₁₁₇₀ Where θ is the parameter on which we calculate the credible interval. This technique
₁₁₇₁ then calculates the $\alpha \times 100\%$ credible interval.

₁₁₇₂ In practice, this analysis uses the highest posterior density (HPD) credible intervals
₁₁₇₃ which are calculated through the following method. First, the probability distribution
₁₁₇₄ is area-normalised such that it has an integrated area equal to 1.0. The bins of proba-
₁₁₇₅ bility are then summed from the highest to lowest until the sum exceeds the 1σ level
₁₁₇₆ (0.68 in this example). This process is repeated for a range of credible intervals, notably
₁₁₇₇ the 1σ , 2σ and 3σ along with other levels where the critical values for each level can
₁₁₇₈ be found in [139]. This process can be repeated for the two-dimensional probability
₁₁₇₉ distributions by creating two-dimensional contours of credible intervals rather than a
₁₁₈₀ one-dimensional result.

¹¹⁸¹ 4.3.3 Bayesian Model Comparisons

¹¹⁸² Due to the matter resonance, this analysis has some sensitivity to the mass hierarchy
¹¹⁸³ of neutrino states (whether Δm_{23}^2 is positive or negative) and the octant of $\sin^2(\theta_{23})$
¹¹⁸⁴ . The Bayesian approach utilised within this analysis gives an intuitive method of
¹¹⁸⁵ model comparison by determining which hypothesis is most favourable. Taking the
¹¹⁸⁶ ratio of Equation 4.3 for the two hypotheses of normal hierarchy, NH , and inverted
¹¹⁸⁷ hierarchy, IH , gives

$$\frac{P(\vec{\theta}_{NH}|D)}{P(\vec{\theta}_{IH}|D)} = \frac{P(D|\vec{\theta}_{NH})}{P(D|\vec{\theta}_{IH})} \times \frac{P(\vec{\theta}_{NH})}{P(\vec{\theta}_{IH})}. \quad (4.9)$$

¹¹⁸⁸ The middle term defines the Bayes factor which is a data-driven interpretation of
¹¹⁸⁹ how strong the data prefers one hierarchy to the other. For this analysis, equal priors
¹¹⁹⁰ on both mass hierarchy hypotheses are chosen ($P(\vec{\theta}_{NH}) = P(\vec{\theta}_{IH}) = 0.5$). In practice,
¹¹⁹¹ the MCMC chain proposes a value of $|\Delta m_{23}^2|$ and then applies a 50% probability
¹¹⁹² that the value is sign flipped. Consequently, the Bayes factor can be calculated from
¹¹⁹³ the ratio of the probability density in either hypothesis. This equates to counting the
¹¹⁹⁴ number of steps taken in the normal and inverted hierarchies and taking the ratio. The
¹¹⁹⁵ same approach can be taken to compare the upper octant (UO) compared to the lower
¹¹⁹⁶ octant (LO) hypothesis of $\sin^2(\theta_{23})$.

¹¹⁹⁷ Whilst the value of the Bayes factor should always be shown, the Jeffreys scale [140]
¹¹⁹⁸ (highlighted in Table 4.1) gives an indication of the strength of preference for one model
¹¹⁹⁹ compared to the other. Other interpretations of the strength of preference of a model
¹²⁰⁰ 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 4.1: 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.

1201 4.3.4 Comparison of MCMC Output to Expectation

1202 To ensure the fit is performing well, a best-fit spectrum is produced using the pos-
 1203 terior probability distribution and compared with the data, allowing easy by-eye
 1204 comparisons to be made. A simple method of doing this is to perform a comparison
 1205 in the fitting parameters (For instance, the reconstructed neutrino energy and lepton
 1206 direction for T2K far detector beam samples) of the spectra generated by the MCMC
 1207 chain to ‘data’. This ‘data’ could be true data or some variation of Monte Carlo predic-
 1208 tion. This allows easy comparison of the MCMC probability distribution to the data.
 1209 To perform this, N steps from the post burn-in MCMC chain are randomly selected
 1210 (Where for all plots of this style in this thesis, $N = 3000$). From these, the Monte Carlo
 1211 prediction at each step is generated by reweighting the model parameters to the values
 1212 specified at that step. Due to the probability density being directly correlated with
 1213 the density of steps in a certain region, parameter values close to the best fit value are
 1214 most likely to be selected.

1215 In practice, for each bin of the fitting parameters has a probability distribution
 1216 of event rates, with one entry per sampled MCMC step. This distribution is binned
 1217 where the bin with the highest probability is selected as the mean and an error on

1218 the width of this probability distribution is calculated using the approach highlighted
1219 in subsection 4.3.2. Consequently, the best fit distribution in the fit parameter is not
1220 necessarily that which would be attained by reweighting the Monte Carlo prediction
1221 to the most probable parameter values.

1222 A similar study can be performed to illustrate the freedom of the model parameter
1223 space prior to the fit. This can be done by throwing parameter values from the prior
1224 uncertainty of each parameter. This becomes troublesome for parameters with no
1225 prior uncertainty as the range is technically infinite. Where applicable solutions to
1226 remove these have been addressed.

1227 **Chapter 5**

1228 **Simulation, Reconstruction, and Event
Reduction**

1230 As a crucial part of the oscillation analysis, an accurate prediction of the expected
1231 neutrino spectrum at the far detector is required. This includes modeling the flux
1232 generation, neutrino interactions, and detector effects. All of the simulation packages
1233 required to do this are briefly described in section 5.1. The reconstruction of neutrino
1234 events inside the far detector, including the `fitQun` algorithm, is documented in
1235 section 5.2. This also includes data quality checks of the SK-V data which the author
1236 performed for the T2K oscillation analysis presented at Neutrino 2020 [80]. Finally,
1237 section 5.3 describes the steps taken in the SK detector to trigger on events of interest
1238 whilst removing the comparatively large rate of cosmic ray muon events.

1239 **5.1 Simulation**

1240 In order to generate a Monte Carlo prediction of the expected event rate at the far
1241 detector, all the processes in the beam and atmospheric flux, neutrino interaction, and
1242 detector need to be modeled. Each of these parts is individually modeled and each of
1243 them is detailed below.

1244 The beamline simulation consists of three distinct parts: the initial hadron inter-
1245 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 3.7.

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 2.3 and Figure 2.5, 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 5.1, 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).

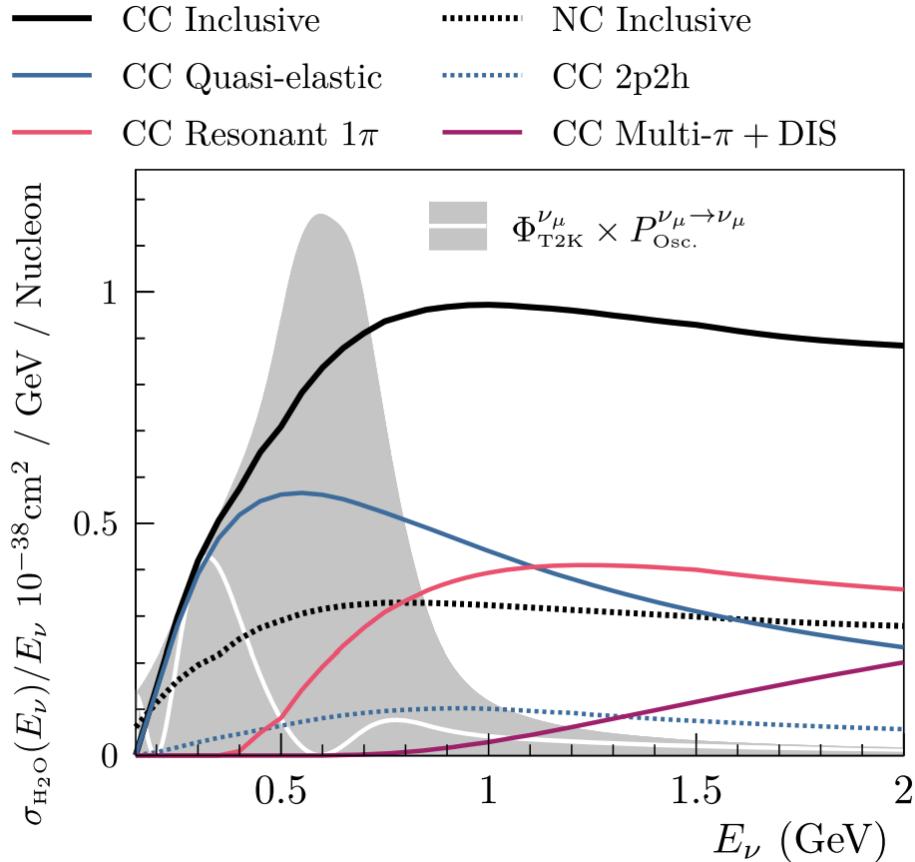


Figure 5.1: The NEUT prediction of the ν_μ -H₂O cross-section overlaid on the T2K ν_μ flux. The charged current (black, solid) and neutral current (black, dashed) inclusive, charged current quasi-elastic (blue, solid), charged current 2p2h (blue, dashed), charged current single pion production (pink), and charged current multi- π and DIS (Purple) cross-sections are illustrated. Figure taken from [159].

1299 For neutrinos of energy $O(1)\text{GeV}$, PROD interactions become dominant. These
 1300 predominantly produce charged and neutral pions although γ , kaon, and η production
 1301 is also considered. To simulate these interactions, the Berger-Sehgal [166] model is
 1302 implemented within NEUT. It simulates the excitation of a nucleon from a neutrino
 1303 interaction, production of an intermediate baryon, and the consequential decay to a
 1304 single meson or γ . Pions can also be produced through COH interactions, which occur
 1305 when the incoming neutrino interacts with the entire oxygen nuclei target leaving a
 1306 single pion outside of the nucleus. NEUT utilises the Berger-Sehgal [167] model to
 1307 simulate these COH interactions.

1308 DIS and multi- π producing interactions become the most dominant for energies
1309 $> O(5)\text{GeV}$. PYTHIA [168] is used to simulate any interaction with invariant mass,
1310 $W > 2\text{GeV}/c^2$, which produces at least one meson. For any interaction which produces
1311 at least two mesons but has $W < 2\text{GeV}/c^2$, the Bronner model is invoked [169].
1312 Both of these models use Parton distribution functions based on the Bodek-Yang
1313 model [170–172].

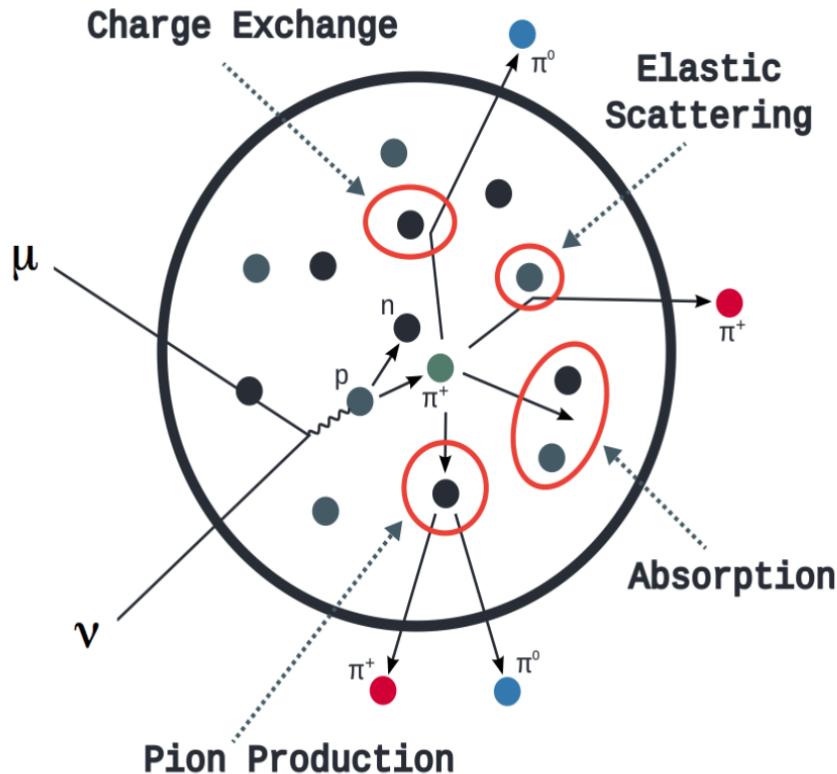


Figure 5.2: Illustration of the various processes which a pion can undergo before exiting the nucleus. Taken from [173].

1314 Any pion which is produced within the nucleus can re-interact through final state
1315 interactions before it exits, as illustrated by the scattering, absorption, production, and
1316 exchange interactions in Figure 5.2. These re-interactions alter the observable particles
1317 within the detector. For instance, if the charged pion from a CC PROD interaction is
1318 absorbed, the observables would mimic a CC QE interaction. To simulate these effects,

1319 NEUT uses a semi-classical intranuclear cascade model [159]. This cascade functions by
1320 stepping the pion through the nucleus in fixed-length steps equivalent to $dx = R_N/100$,
1321 where R_N is the radius of the nucleus. At each step, the simulation allows the pion
1322 to interact through scattering, charged exchange, absorption, or production with an
1323 interaction-dependent probability calculated from a fit to external data [174]. This
1324 cascade continues until the pion is absorbed or exits the nucleus.

1325 Once the final state particle kinematics have been determined from NEUT, they
1326 are passed into the detector simulation. The near detectors, ND280 and INGRID, are
1327 simulated using a GEANT4 package [118,175] to simulate the detector geometry, particle
1328 tracking, and energy deposition. The response of the detectors is simulated using
1329 the elecSim package [118]. The far detector simulation is based upon the original
1330 Kamiokande experiment software which uses the GEANT3-based SKDETSIM [118,176]
1331 package. This controls the interactions of particles in the water as well as Cherenkov
1332 light production. The water quality and PMT calibration measurements detailed in
1333 subsection 3.1.2 are also used within this simulation to make accurate predictions of
1334 the detector response.

1335 5.2 Event Reconstruction at SK

1336 Any above Cherenkov threshold event which occurs in SK will be recorded by the
1337 PMT array, where each PMT records the time and accumulated charge. This recorded
1338 information is shown in event displays similar to those illustrated in Figure 5.3. To
1339 be useful for physics analyses, this series of PMT hit information needs to be recon-
1340 structed to determine the particle's identity and kinematics (or track parameters):
1341 four-vertex, direction, and momenta. This is because the charge and timing distribu-
1342 tion of photons generated by a particular particle in an event is dependent upon its

1343 initial kinematics. The concept of distinguishing electron and muon events is from the
 1344 “fuzziness” of the ring. Muons are heavier and less affected by scattering or showering
 1345 meaning they typically produce “crisp” rings. Electrons are more likely to interact
 1346 via electromagnetic showering or scattering which results in larger variations of their
 1347 direction from the initial direction. Consequently, electrons typically produce “fuzzier”
 1348 rings compared to muons.

1349 For the purposes of this analysis, the `fiTQun` reconstruction algorithm is utilised.
 1350 Its core function is to compare a prediction of the accumulated charge and timing
 1351 distribution from each PMT, generated for a particular particle identity and track
 1352 parameters, to that observed in the neutrino event. It determines the preferred values
 1353 by minimising a likelihood function which includes information from PMTs which
 1354 were hit and those that were not hit. The `fiTQun` algorithm improves upon the APFit
 1355 reconstruction algorithm which has been used for many previous SK analyses. APFit
 1356 fits the vertex from timing information and then fits the momentum and direction
 1357 of the particle from PMT hits within a 43 deg Cherenkov cone (which assumes an
 1358 ultra-relativistic particle). It then fits the particle identity once the track parameters
 1359 have been fit. Conversely, `fiTQun` performs a simultaneous fit of particle kinematics
 1360 and identity, improving both the accuracy of the fit parameters and the rejection of
 1361 neutral current π^0 events [177,178]. The `fiTQun` algorithm is based on the key concepts
 1362 of the MiniBooNE reconstruction algorithm [179] and is described in [180] which is
 1363 summarised below.

1364 An event in SK can consist of multiple particles. For example, a charge current
 1365 muon neutrino interaction can generate two particles that have the potential of gen-
 1366 erating Cherenkov photons: the primary muon, and the secondary decay-electron
 1367 from the muon. To ensure both subevents are reconstructed separately, each event is
 1368 divided into time clusters which are called “subevents”. The number of subevents is

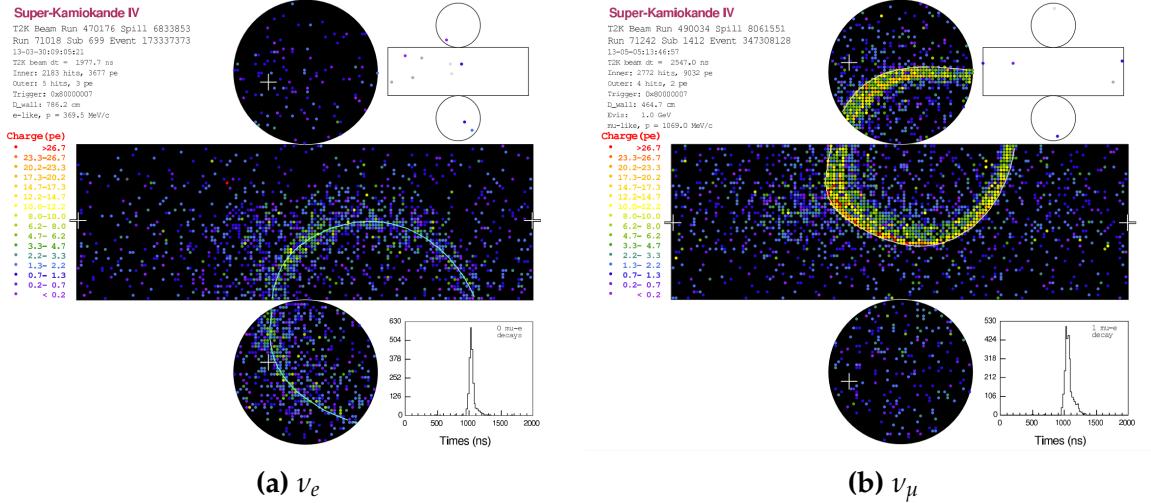


Figure 5.3: Event displays from Super Kamiokande illustrating the “crisp” ring from a muon and the typically “fuzzy” electron ring. Each pixel represents a PMT and the color scheme denotes the accumulated charge deposited on that PMT. Figures taken from [181].

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 ,

$$G(\vec{x}, t) = \sum_i^{\text{hit PMTs}} \exp \left(-\frac{1}{2} \left(\frac{T_{Res}^i(\vec{x}, t)}{\sigma} \right)^2 \right) \quad (5.1)$$

where

$$T_{Res}^i(\vec{x}, t) = t^i - t - |R_{PMT}^i - \vec{x}| / c_n \quad (5.2)$$

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,

$$L(\Gamma, \vec{\theta}) = \prod_j^{\text{unhit}} P_j(\text{unhit}|\Gamma, \vec{\theta}) \prod_i^{\text{hit}} \{1 - P_i(\text{unhit}|\Gamma, \vec{\theta})\} f_q(q_i|\Gamma, \vec{\theta}) f_t(t_i|\Gamma, \vec{\theta}), \quad (5.3)$$

1397 where $\vec{\theta}$ defines the track parameters; vertex position, direction vector and mo-
 1398 ments, and Γ represents the particle hypothesis. $P_i(\text{unhit}|\Gamma, \vec{\theta})$ defines the probability
 1399 of the i^{th} tube to not register a hit given the track parameters and particle hypothesis.
 1400 The charge likelihood, $f_q(q_i|\Gamma, \vec{\theta})$, and time likelihood, $f_t(t_i|\Gamma, \vec{\theta})$, represent the prob-
 1401 ability density function of observing charge q_i and time t_i on the i^{th} PMT given the
 1402 specified track parameters and particle hypothesis.

1403 As the generation and propagation of the optical photons are independent of the
 1404 PMT and electronics response, it is natural to split the calculation into two. Firstly,
 1405 the expected number of photoelectrons (or predicted charge), $\mu_i = \mu_i(\vec{\theta}, \Gamma)$, at the i^{th}
 1406 PMT is calculated. This value is then substituted into the likelihood function. This
 1407 allows the charge likelihood density $f_q(q_i|\mu_i)$ and unhit probability $P_i(\text{unhit}|\mu_i)$ to be
 1408 expressed via quantities that are only dependent on the response of the PMT.

1409 The predicted charge is calculated based on contributions from both the direct
 1410 light and the scattered light. The direct light contribution is determined based on the
 1411 integration of the Cherenkov photon profile along the track. PMT angular acceptance,
 1412 water quality, and calibration measurements discussed in subsection 3.1.2 are included
 1413 to accurately predict the charge probability density at each PMT. The scattered light
 1414 is calculated in a similar way, although it includes a scattering function that depends
 1415 on the vertex of the particle and the position of the PMT. The charge likelihood is
 1416 calculated by comparing the prediction to the observed charge in the PMT.

1417 The time likelihood is approximated to depend on the vertex \vec{x} , direction \vec{d} , and
 1418 time t of the track parameters as well as the particle hypothesis. The expected time
 1419 for PMT hits is calculated by assuming unscattered photons being emitted from the
 1420 midpoint of the track, S_{mid} ,

$$t_{exp}^i = t + S_{mid}/c + |R_{PMT}^i - \vec{x} - S_{mid}\vec{d}|/c_n, \quad (5.4)$$

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 5.4.

DB: Mentiton Pi0 rejection and mu/pip separation cuts

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

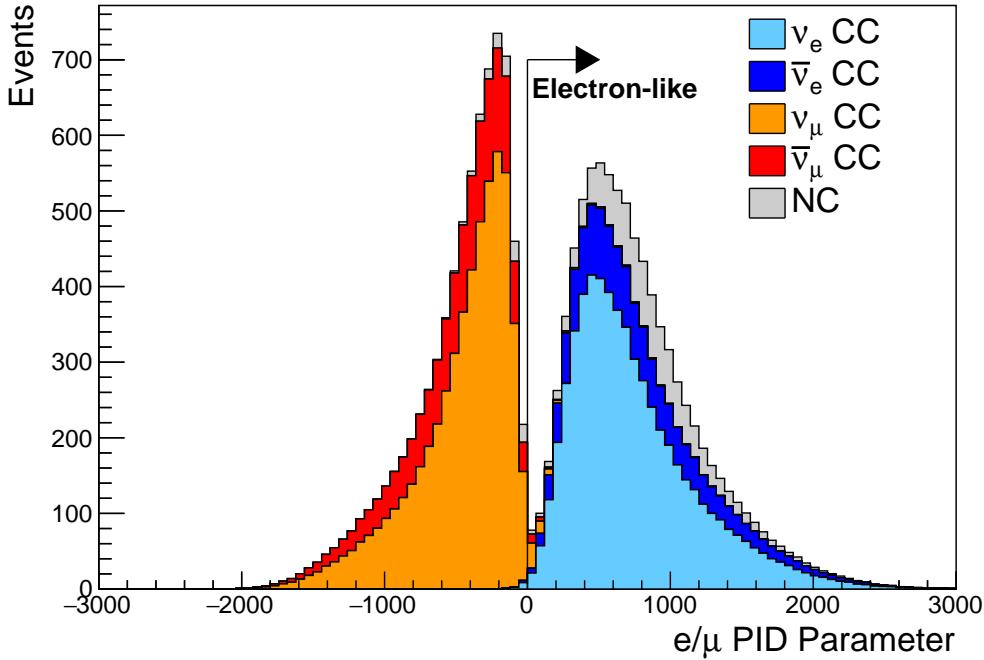


Figure 5.4: The electron/muon PID separation parameter for all sub-GeV single-ring events in SK-IV. The charged current (CC) component is broken down in four flavours of neutrino (ν_μ , $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$). Events with positive values of the parameter are determined to be electron-like.

¹⁴⁴³ conversion length, direction, and momenta of each photon are also considered as track
¹⁴⁴⁴ parameters which are then fit in the same methodology as the standard single-ring
¹⁴⁴⁵ hypotheses.

¹⁴⁴⁶ Whilst low energy events are predominately single-ring events, higher energy
¹⁴⁴⁷ neutrino events can generate final states with multiple particles which generate
¹⁴⁴⁸ Cherenkov photons. These “multi-ring” hypotheses are also considered in the `fitQun`
¹⁴⁴⁹ algorithm. When calculating the charge likelihood density, the predicted charge
¹⁴⁵⁰ associated with each ring is calculated separately and then merged to calculate the
¹⁴⁵¹ total accumulated charge on each PMT. Similarly, the time likelihood for the multi-ring
¹⁴⁵² hypothesis is calculated assuming each ring is independent. Each track is time-ordered
¹⁴⁵³ based on the time of flight from the center of the track to the PMT and the direct light
¹⁴⁵⁴ from any ring incident on the PMT is assumed to arrive before any scattered light. To

reduce computational resources, the multi-ring fits only consider electron-like and charged pion-like rings as the pion fit can be used as a proxy for a muon fit due to their similar mass.

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

As an example of how the reconstruction depends on the detector conditions, the author of this thesis assessed the quality of event reconstruction for SK-V data. The detector systematics invoked within the T2K-only oscillation analysis are determined using data to Monte Carlo comparisons using the SK-IV data [183]. Due to tank-open maintenance occurring between SK-IV and SK-V, the dark rate of each PMT was observed to increase in SK-V due to light exposure for a significant time during the repairs. This increase can be seen in Figure 5.5. Run-10 of the T2K experiment was conducted in the SK-V period, so the consistency of SK-IV and SK-V data needs to be studied to determine whether the SK-IV-defined systematics can be applied to the run-10 data. This comparison study was performed using the stopping muon data set for both the SK-IV and SK-V periods. This data sample is used due to the high rate of interactions ($O(200)$ events per hour) as well as having similar energies to muons from CCQE ν_μ interactions from beam interactions. The rate of cosmic muons does depend on the solar activity cycle [184] but has been neglected in this comparison study. This is because the shape of the distributions is most important for the purposes of being compared to the detector systematics. The SK-IV and SK-V data samples consist of 2398.42 and 626.719 hours of data which equates to 686k and 192k events respectively.

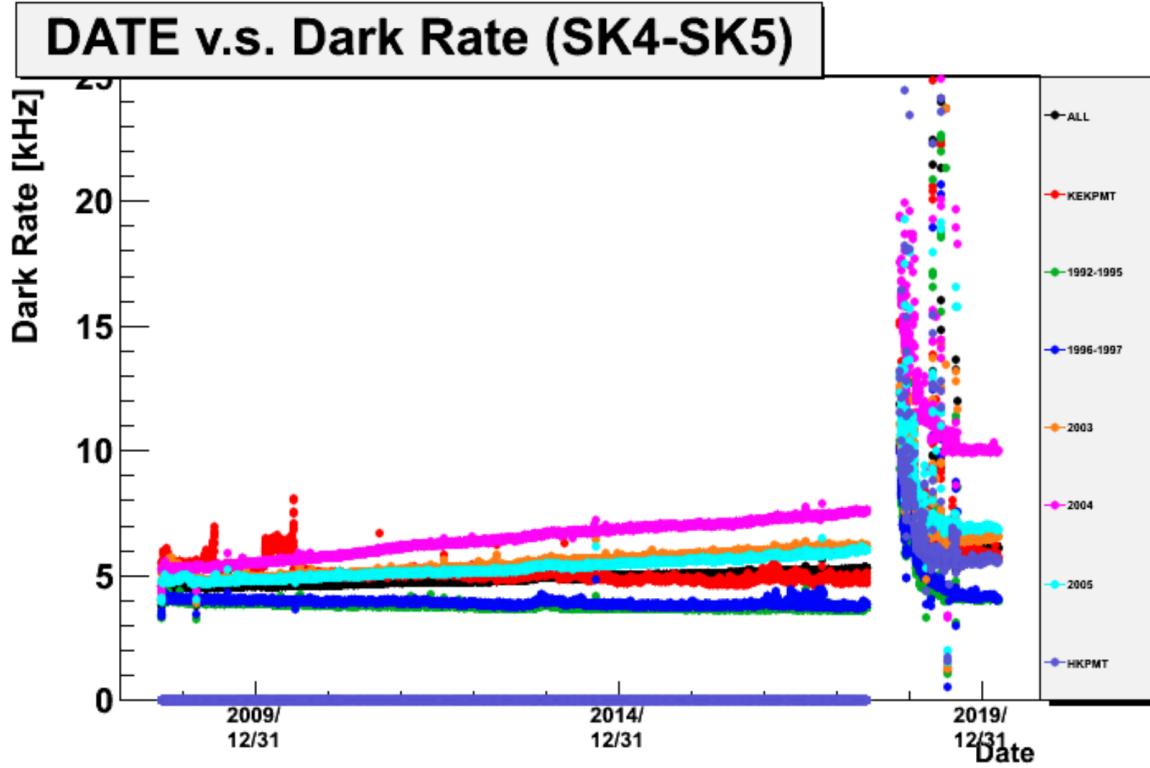


Figure 5.5: The variation of the measured dark rate as a function of date, broken down by PMT type. The SK-IV and SK-V periods span September 2008 to May 2018 and January 2019 to July 2020, respectively. The break in measurement in 2018 corresponds to the period of tank repair and refurbishment. Figure adapted from [183].

The predicted charge calculated in the `fitQun` charge likelihood prediction includes a contribution from the photoelectron emission due to dark noise. Therefore, the 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 3.1.2. 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 5.6. 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

1491 behaviour is observed in the data, where the charge deposited by the muon subevent
 1492 is mostly unaffected by the increase in dark rate, whilst the charge associated with the
 1493 decay-electron is clearly affected.

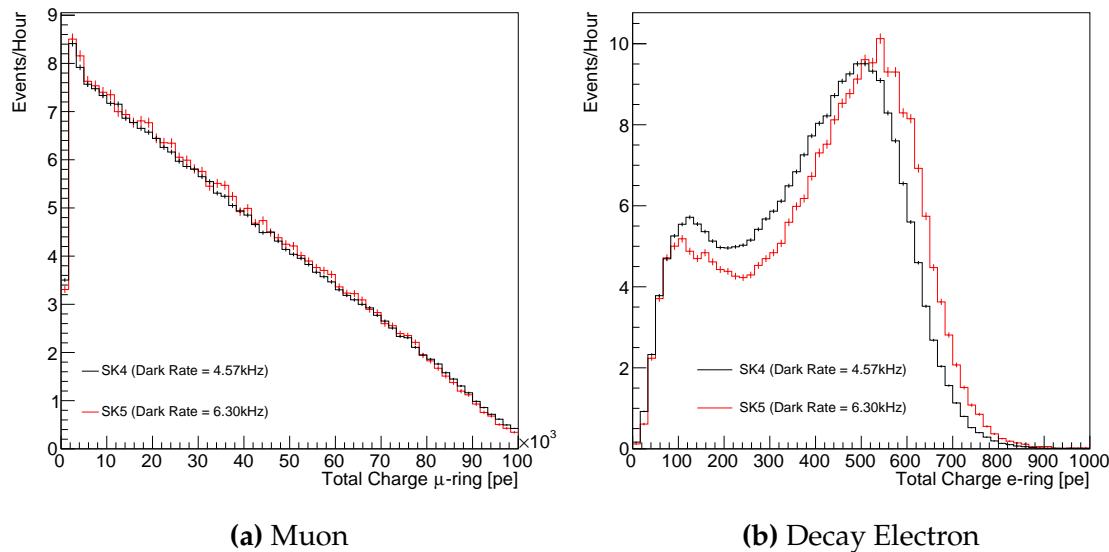


Figure 5.6: Comparison of the measured raw charge deposited per event from the stopping muon data samples between SK-IV (Blue) and SK-V (Red), split by the primary muon subevent and the associated decay electron subevent.

1494 The energy scale systematic for the SK-IV period was determined to be 2.1% [185].
 1495 It is defined to be equal to the difference between data and Monte Carlo prediction
 1496 in the stopping muon data sample. To determine the consistency of the SK-IV and
 1497 SK-V with respect to the energy scale systematic, the muon momentum distribution is
 1498 compared between the two SK periods. As the total number of Cherenkov photons
 1499 is integrated across the track length, the reconstructed momentum divided by track
 1500 length (or range) is compared between SK-IV and SK-V as illustrated in Figure 5.7.

1501 The consistency between these distributions has been computed in two ways.
 1502 Firstly, a Gaussian is fit to each distribution separately. The mean of which is found to
 1503 be $(2.272 \pm 0.003)\text{MeV/cm}$ and $(2.267 \pm 0.006)\text{MeV/cm}$ for SK-IV and SK-V respectively. The ratio of these is equal to 1.002 ± 0.003 . The mean of the Gaussian fits are

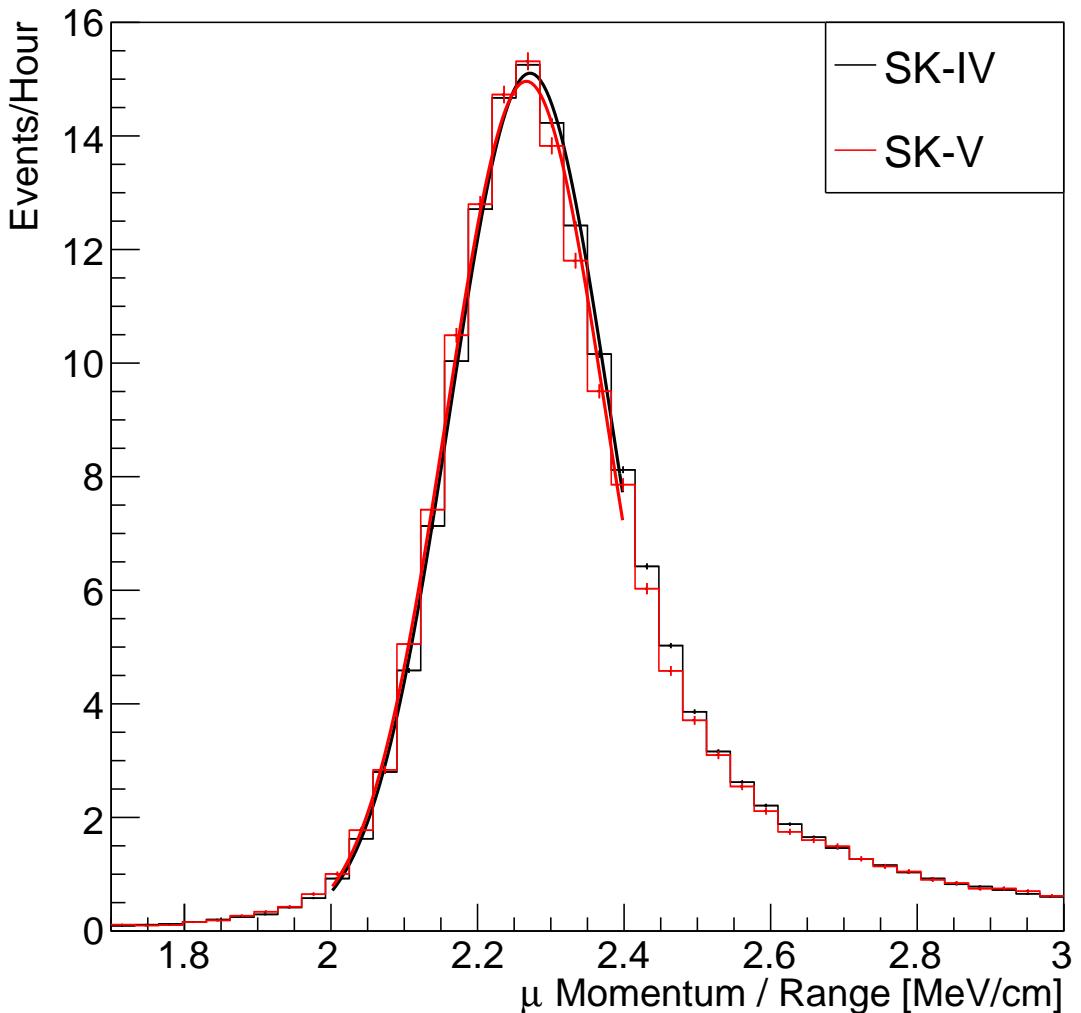


Figure 5.7: The distribution of the reconstructed momentum from the muon ring divided by the distance between the reconstructed muon and decay electron vertices as found in the stopping muon data sets of SK-IV (Black) and SK-IV (Red). Only events with one tagged decay electron are considered. A Gaussian fit is considered in the range [2.0, 2.4] MeV/cm and illustrated as the solid curve.

consistent with the expected stopping power of a minimum ionising muon for a target 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

₁₅₁₁ values of α is illustrated in Figure 5.8. The values which minimise the χ^2 are found to
₁₅₁₂ be 0.0052 and 1.0024 for the additive and multiplicative implementations, respectively.
₁₅₁₃ No evidence of shifts larger than the 2.1% uncertainty on the energy scale systematic
₁₅₁₄ has been found in the reconstructed momentum distribution of SK-IV and SK-V.

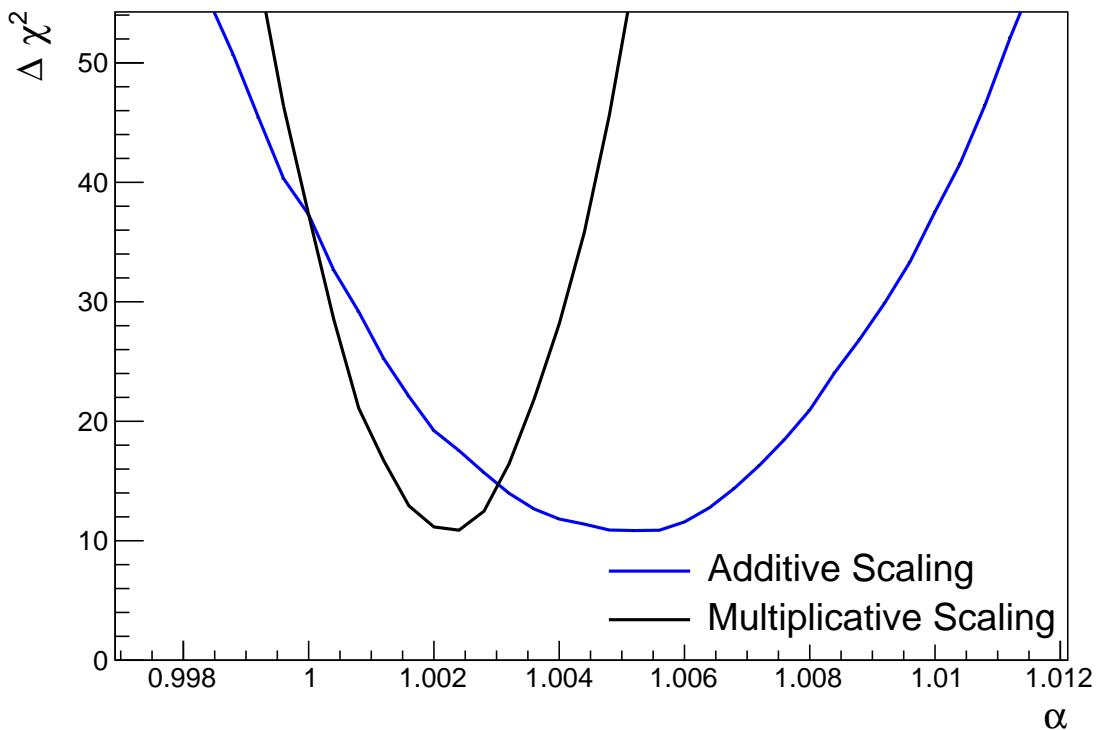


Figure 5.8: The χ^2 difference between the SK-IV and SK-V reconstructed muon momentum divided by range when the SK-V is modified by the scaling parameter α . Both additive (Blue) and multiplicative (Black) scaling factors have been considered. In practice, the additive scaling factor actually uses the value of $(\alpha - 1.0)$ but is illustrated like this so the results can be shown on the same axis range.

₁₅₁₅ 5.3 Event Reduction at SK

₁₅₁₆ Atmospheric neutrino events observed in the SK detector are categorised into three
₁₅₁₇ different types of samples: fully contained (FC), partially contained (PC) and up-
₁₅₁₈ going muon ($\text{Up-}\mu$), using PMT hit signatures in the inner and outer detector (ID

and OD, respectively). To identify FC neutrino events, it is required that the neutrino interacts inside the fiducial volume of the ID such that no significant OD activity is observed. For this analysis, an event is defined to be in the fiducial volume providing the event vertex is at least 0.5m away from the ID walls. PC events have the same ID requirements but can have a larger signal present inside the OD. Typically these events are higher energy muon interactions that penetrate the ID walls. The Up- μ sample contains events where muons are created from neutrino interactions in the OD water or rock below the tank. They then propagate upwards through the detector. The reason downward-going muons generated from neutrino interactions above the tank are neglected is due to the difficulty in separating their signature from the cosmic muon shower background. The sample categories are visually depicted in Figure 5.9.

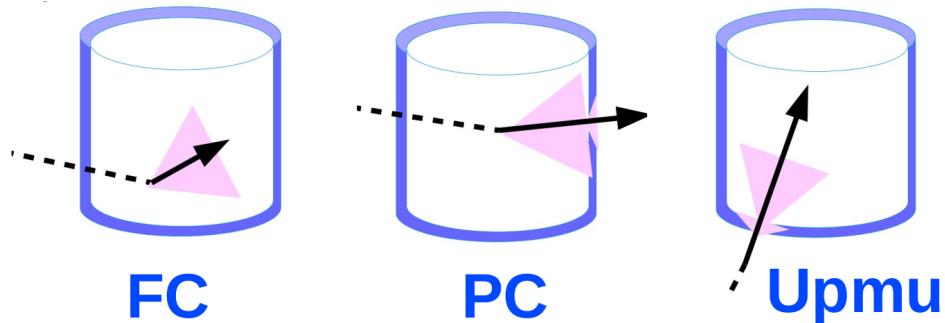


Figure 5.9: A depiction of the topology patterns for fully-contained (FC), partially-contained (PC) and up-going muon (Up- μ) samples included in this analysis.

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

- **Visible Energy:** equal to the sum of the reconstructed kinetic energy above the Cerenkov threshold for all rings present in the event. The purpose is to separate events into sub-GeV and multi-GeV categories.
- **Number of observed Cerenkov rings.** The purpose is to separate single-ring and multi-ring events, where single-ring events predominantly consist of quasi-elastic

interactions and multi-ring events are typically resonant pion production or deep 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 5.10. 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

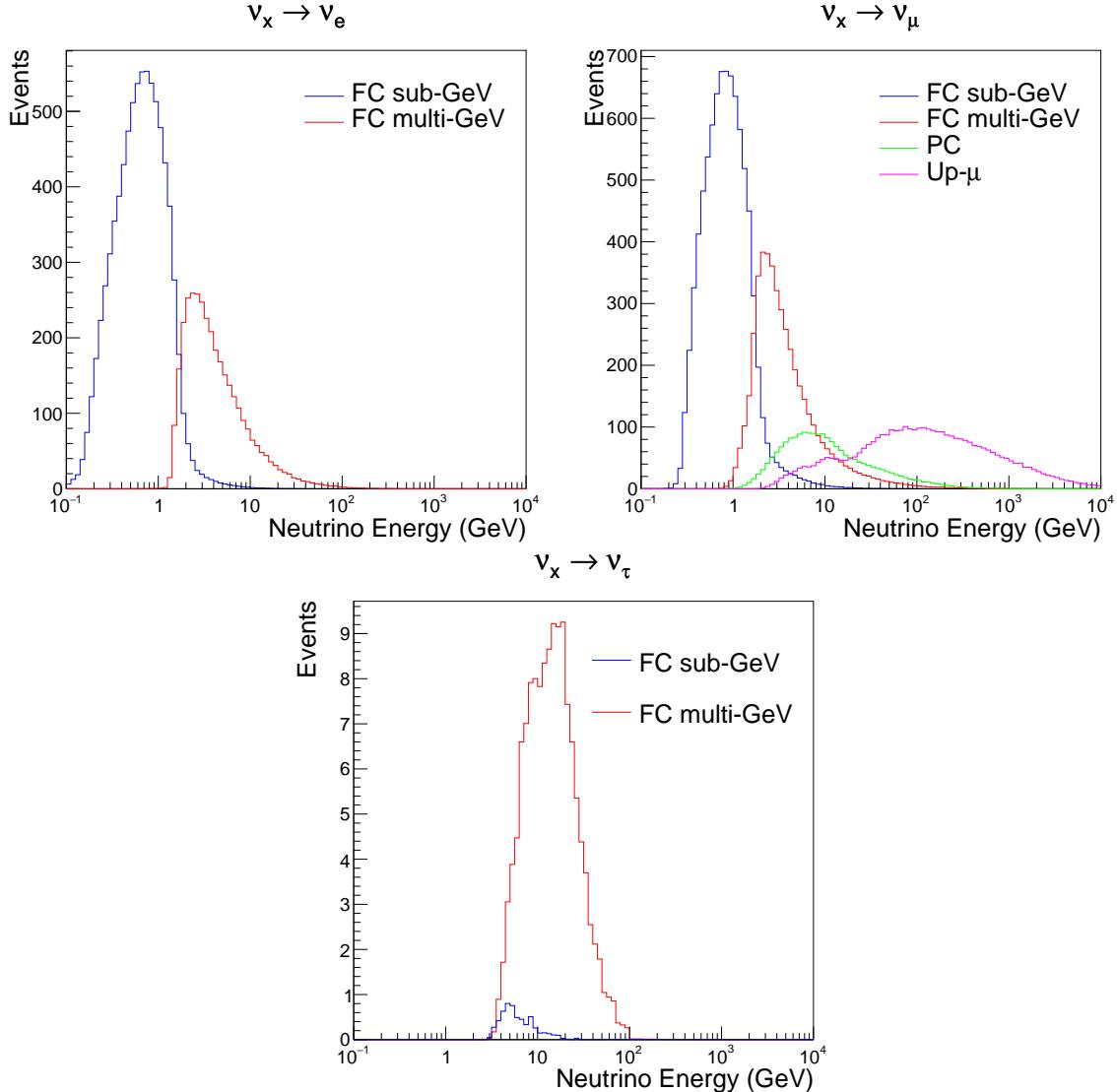


Figure 5.10: The predicted neutrino flux of the fully contained (FC) sub-GeV and multi-GeV, partially contained (PC), and upward-going muon (Up- μ) events. The prediction is broken down by the $\nu_x \rightarrow \nu_e$ prediction (top left), $\nu_x \rightarrow \nu_\mu$ prediction (top right) and $\nu_x \rightarrow \nu_\tau$ prediction (bottom). All systematic dials are set to their nominal values and the Asimov A oscillation parameters are assumed.

is reduced with the aim of removing these background events. The reduction process

is detailed in [47, 89] and briefly summarised below.

The first two steps in the FC reconstruction remove the majority of cosmic ray

muons by requiring a significant amount of ID activity compared to that measured in

the OD. Events that pass this cut are typically very high momentum muons or events

that leave very little activity in the OD. Consequently, a third reduction step is then

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

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

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

1595 Due to the lower energy beam neutrinos, the T2K samples are not dependent
 1596 upon the visible energy neutrino as the range of neutrino energies are smaller than
 1597 that found in atmospheric neutrinos. Furthermore, the 2020 T2K-only oscillation
 1598 analysis only considers events which contain a single ring. Similar to atmospheric
 1599 event selection, the number of decay electrons is used as a proxy for distinguishing
 1600 CCQE and CCRES events. The expected neutrino energy, broken down by number of
 1601 decay electrons, is given in Figure 5.11.

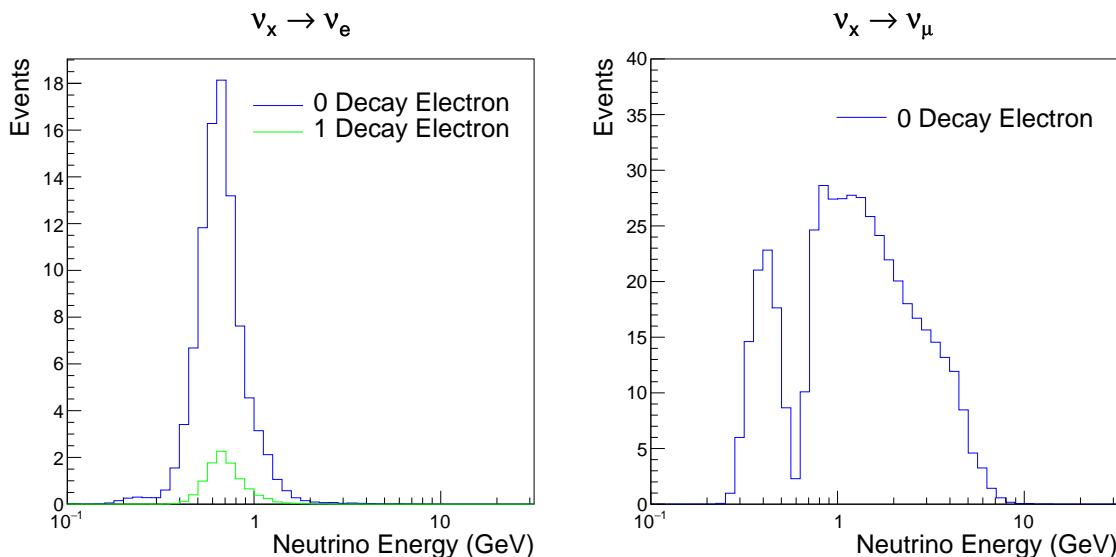


Figure 5.11: The predicted neutrino flux of the beam neutrinos, illustrated as a function of neutrino energy. The predictions are broken down by the number of decay electrons associated with the particular events. All systematic dials are set to their nominal values and the Asimov A oscillation parameters are assumed.

₁₆₀₂ **Chapter 6**

₁₆₀₃ **Sample Selections and Systematics**

₁₆₀₄ The oscillation analysis presented within this thesis is built upon a simultaneous
₁₆₀₅ fit to atmospheric data at SK, neutrino beam data in the near detector and beam
₁₆₀₆ data measured at SK. The definitions of these samples are documented in section 6.1,
₁₆₀₇ section 6.2, and section 6.3, respectively. The data collected and used within this
₁₆₀₈ analysis is detailed in Table 6.1. The near and far detector data corresponds to T2K
₁₆₀₉ runs 2-9 and runs 1-10, respectively. The accumulated POT and beam power for runs
₁₆₁₀ 1 – 10 is illustrated in Figure 6.1.

| Data Type | Total |
|-------------------|---------------------------|
| Near Detector FHC | 1.15×10^{21} POT |
| Near Detector RHC | 8.34×10^{20} POT |
| Far Detector FHC | 1.97×10^{21} POT |
| Far Detector RHC | 1.63×10^{21} POT |
| Atmospheric SK-IV | 3244.4 days |

Table 6.1: The amount of data collected in each detector used within this analysis. The data collected at the near and far detector, for both neutrino beam (FHC) and antineutrino beam (RHC), is measured as the amount of protons on target (POT).

₁₆₁₁ The difference in POT recorded at the near and far detector is due to the difference
₁₆₁₂ in downtime of the respective detector. The SK detector is very stable with almost 100%
₁₆₁₃ of data recorded during beam operation. Due to various technical and operational
₁₆₁₄ issues, the downtime of the near detector is significantly higher due to its more
₁₆₁₅ complex design and operating requirements.

1616 The systematic parameters invoked within the flux, detector, and interaction models
 1617 used within this analysis are documented in section 6.4. The standard configuration of
 1618 the joint beam and atmospheric data fit utilises far detector systematics provided in
 1619 the official inputs from the two experiments. Additionally, a correlated detector model
 1620 which fits the parameters used in sample selections to data has been developed and
 1621 documented in subsection 6.4.5.

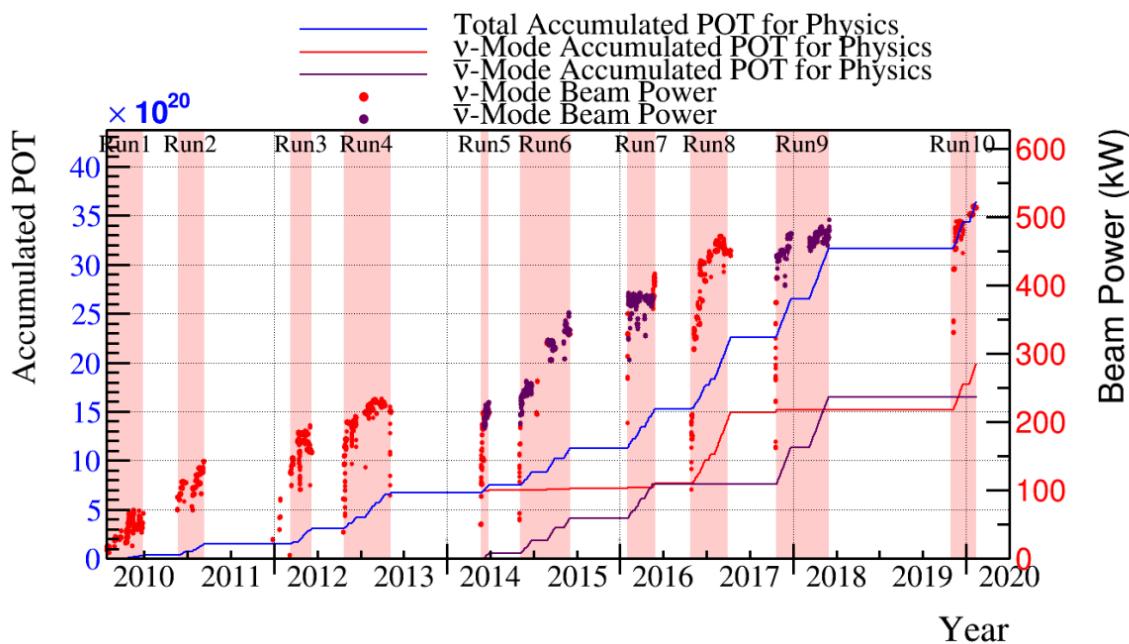


Figure 6.1: The accumulated beam data, measured as the number of protons on target (POT). The total data (blue) is given which comprises of the neutrino beam (red) and antineutrino (purple) components. The beam power for neutrino and antineutrino beams is given as the markers using the same colourscheme. The timescale runs from Run 1 which started in January 2010 until Run 10 which ended in February 2020. The ratio of accumulated data in neutrino and antineutrino beam is 54.7% : 45.3%.

1622 6.1 Atmospheric Samples

1623 The atmospheric event selection follows the official SK-IV analysis presented in [89]
1624 and is documented below. The Monte Carlo prediction used within this analysis
1625 corresponds to 500 years worth of neutrino events, which is scaledx down to match
1626 the SK-IV livetime of 3244.4 days.

1627 The fully contained (FC), partially contained (PC), and upward going muon events
1628 ($\text{up-}\mu$) which pass the reduction cuts discussed in section 5.3 are further broken down
1629 into different samples based on reconstruction information. This section details the
1630 samples used within the oscillation analysis, alongside the chosen binning and final
1631 spectra used within the fit.

1632 In general, the FC events are first separated by the visible energy deposited within
1633 the detector. This is calculated as the sum of the reconstructed kinetic energy above the
1634 Cerenkov threshold for all rings present in the event. Events are separated by whether
1635 they were above or below $E_{\text{vis}} = 1.33\text{GeV}$. This separates “subGeV” and “multiGeV”
1636 events. Typically, lower energy events consist of charge current quasi-elastic (CCQE)
1637 interactions which are simpler to reconstruct resulting in smaller systematic uncertain-
1638 ties. Events are further separated by the number of rings associated with the event
1639 due to similar reasoning. As the oscillation probability is dependent upon the flavour
1640 of neutrino, electron and muon events are separated using a similar likelihood method
1641 to that discussed in section 5.2. To reduce computational resources required for the
1642 reconstruction, only electron and pion hypotheses are considered so this separation cut
1643 depends on the ratio of the electron to pion likelihoods. Finally, the number of decay
1644 electrons is also used to classify events. As charged current resonant pion production
1645 (CCRES) generates a final-state pion that decays to an electron, electron-like events
1646 with one decay electron or muon-like events with two decay electrons must have

₁₆₄₇ contained a pion in the final state. Consequently, the number of decay electrons is used
₁₆₄₈ to target CCQE and CCRES interaction modes. FC subGeV events are then separated
₁₆₄₉ into the samples listed in Table 6.2.

| Index | Sample |
|-------|---|
| 0 | SubGeV-e-like-0dcy Single ring e -like events with zero decay electrons |
| 1 | SubGeV-e-like-1dcy Single ring e -like events with one or more decay electrons |
| 2 | SubGeV-mulike-0dcy Single ring μ -like events with zero decay electrons |
| 3 | SubGeV-mulike-1dcy Single ring μ -like events with one decay electrons |
| 4 | SubGeV-mulike-2dcy Single ring μ -like events with two or more decay electrons |
| 5 | SubGeV-pi0like Two e -like ring events with zero decay electrons and reconstructed π^0 mass $85 \leq m_{\pi^0} < 215\text{MeV}$ |

Table 6.2: The fully contained subGeV samples used within this oscillation analysis. Both the sample name and description are given.

₁₆₅₀ In addition to the cuts discussed above, multiGeV samples also have additional cuts
₁₆₅₁ to separate samples which target neutrino and antineutrino separation. As discussed
₁₆₅₂ in section 7.1, the matter resonance only occurs for neutrinos in normal hierarchy and
₁₆₅₃ antineutrinos in inverse mass hierarchy so having flavour-enriched samples aids in
₁₆₅₄ the determination of the mass hierarchy. For a CCRES interaction,

$$\begin{aligned}
 \bar{\nu}_e + N &\rightarrow e^+ + N' + \pi^-, \\
 \nu_e + N &\rightarrow e^- + N' + \pi^+ \\
 &\quad \downarrow \mu^+ + \nu_\mu \\
 &\quad \downarrow e^+ + \nu_e + \bar{\nu}_\mu.
 \end{aligned} \tag{6.1}$$

1655 Where the π^- emitted from a $\bar{\nu}_e$ interaction is more likely to be absorbed within
 1656 the oxygen nucleus [190] compared to the π^+ from ν_e interactions. Consequently, the
 1657 number of tagged decay electrons associated with an event gives an indication of
 1658 whether the interaction was due to a neutrino or antineutrino: zero for $\bar{\nu}_e$ events, and
 1659 one or more for ν_e events. The ability to separate neutrino from antineutrino events is
 1660 illustrated in Table 6.4, where the MultiGeV-*elike-nue* has 78% purity enhancement
 1661 of neutrino events with only 7% antineutrino background in that sample.

1662 This relatively simple discriminator works reasonably well for single-ring events.
 1663 However, this is not the case for multi-ring events. A multi-GeV multi-ring separation
 1664 (MME) likelihood cut which specifically targets multiGeV multiRing electron-like
 1665 events was introduced in [191, 192]. Four observables are used within this likelihood
 1666 cut: the number of decay electrons, the maximum distance between the vertex of the
 1667 neutrino and the decay electrons, the energy deposited by the leading energy ring,
 1668 and the reconstructed particle identification of that highest energy ring. The last three
 1669 variables are selected based on typical event kinematics comparing CC ν_e events to the
 1670 CC ν_μ and NC backgrounds. Typically, more energy is carried by the hadronic system
 1671 in these background interactions and the distance cut targets the decay of muons from
 1672 CC ν_μ , which tend to travel further than the pions from CC ν_e interactions.

1673 Neutrino and antineutrino events are then separated by a second likelihood method
 1674 ($\nu/\bar{\nu}$ separation) detailed in [52]. This uses the number of decay electrons, the number

| Index | Sample |
|-------|--|
| 0 | MultiGeV- <i>e</i> like-nue Single ring <i>e</i> -like events with zero decay electrons |
| 1 | MultiGeV- <i>e</i> like-nuebar Single ring <i>e</i> -like events with one or more decay electrons |
| 2 | MultiGeV- <i>μ</i> like Single ring <i>μ</i> -like events |
| 3 | MultiRing- <i>e</i> like-nue Two or more ring events with leading energy <i>e</i> -like ring and passed both MME and $\nu/\bar{\nu}$ separation likelihood cuts |
| 4 | MultiRing- <i>e</i> like-nuebar Two or more ring events with leading energy <i>e</i> -like ring and passed MME and failed $\nu/\bar{\nu}$ separation likelihood cuts |
| 5 | MultiRing- <i>μ</i> like Two or more ring events with leading energy <i>μ</i> -like ring and only requires $E_{vis} > 0.6\text{GeV}$ |
| 6 | MultiRing-Other1 Two or more ring events with leading energy <i>e</i> -like ring and failed the MME likelihood cut |

Table 6.3: The fully contained multiGeV samples used within this oscillation analysis. Both the sample name and description are given.

1675 of reconstructed rings, and the event’s transverse momentum. As discussed above,
 1676 positively charged pions from neutrino interactions are less likely to be absorbed. For
 1677 this high-energy sample, the majority of those pions will be above the Cherenkov
 1678 threshold which results in more rings compared to an antineutrino interaction. The
 1679 angular distribution also tends to be more forward peaked in antineutrino interactions.
 1680 The FC multiGeV sample definitions are detailed in Table 6.3.

1681 The PC and up- μ events are split by the amount of energy deposited within the
 1682 outer detector, into “stopping” and “through-going” samples. If an event leaves the
 1683 detector, the energy it takes with it has to be estimated which increases the systematic
 1684 uncertainty compared to events entirely contained within the inner detector. The

through-going up- μ are further separated by the presence of any electromagnetic showering in the event, as the assumption of non-showering muon does not give reliable reconstruction for these types of events [47]. In total, 13 FC, 2 PC, and 3 up- μ atmospheric samples are included within this analysis.

| Sample | $CC\nu_e$ | $CC\bar{\nu}_e$ | $CC(\nu_\mu + \bar{\nu}_\mu)$ | $CC(\nu_\tau + \bar{\nu}_\tau)$ | NC |
|---------------------------|-----------|-----------------|-------------------------------|---------------------------------|-------|
| SubGeV-elselike-0dcy | 72.17 | 23.3 | 0.724 | 0.033 | 3.77 |
| SubGeV-elselike-1dcy | 86.81 | 1.773 | 7.002 | 0.062 | 4.351 |
| SubGeV-mulike-0dcy | 1.003 | 0.380 | 90.07 | 0.036 | 8.511 |
| SubGeV-mulike-1dcy | 0.023 | 0. | 98.46 | 0.029 | 1.484 |
| SubGeV-mulike-2dcy | 0.012 | 0. | 99.25 | 0.030 | 0.711 |
| SubGeV-pi0like | 6.923 | 2.368 | 0.928 | 0.011 | 89.77 |
| MultiGeV-elselike-nue | 78.18 | 7.041 | 3.439 | 1.886 | 9.451 |
| MultiGeV-elselike-nuebar | 56.68 | 37.81 | 0.174 | 0.614 | 4.718 |
| MultiGeV-mulike | 0.024 | 0.005 | 99.67 | 0.245 | 0.058 |
| MultiRing-elselike-nue | 59.32 | 12.39 | 4.906 | 3.385 | 20 |
| MultiRing-elselike-nuebar | 52.39 | 31.03 | 1.854 | 1.585 | 13.14 |
| MultiRing-mulike | 0.673 | 0.080 | 97.33 | 0.342 | 1.578 |
| MultiRingOther-1 | 27.98 | 2.366 | 34.93 | 4.946 | 29.78 |
| PCStop | 8.216 | 3.118 | 84.45 | 0. | 4.214 |
| PCThr | 0.564 | 0.207 | 98.65 | 0. | 0.576 |
| UpStop-mu | 0.829 | 0.370 | 98.51 | 0. | 0.289 |
| UpThruNonShower-mu | 0.206 | 0.073 | 99.62 | 0. | 0.103 |
| UpThruShower-mu | 0.128 | 0.054 | 99.69 | 0. | 0.132 |

Table 6.4: The purity of each atmospheric sample used within this analysis, broken down by charged current (CC) and neutral current (NC) interactions and which neutrino flavour interacted within the detector. The pre-fit dial values and Asimov A oscillation parameter sets are assumed. Electron neutrino and antineutrino events are separated to illustrate the ability of the separation likelihood cuts used within the sample selections.

The atmospheric samples are binned in reconstructed lepton momentum and direction, as given by Table 6.5. The distribution of the reconstructed lepton momentum (for samples that only have one bin reconstructed zenith angle) and reconstructed direction for each atmospheric sample used within this analysis is illustrated in Figure 6.2.

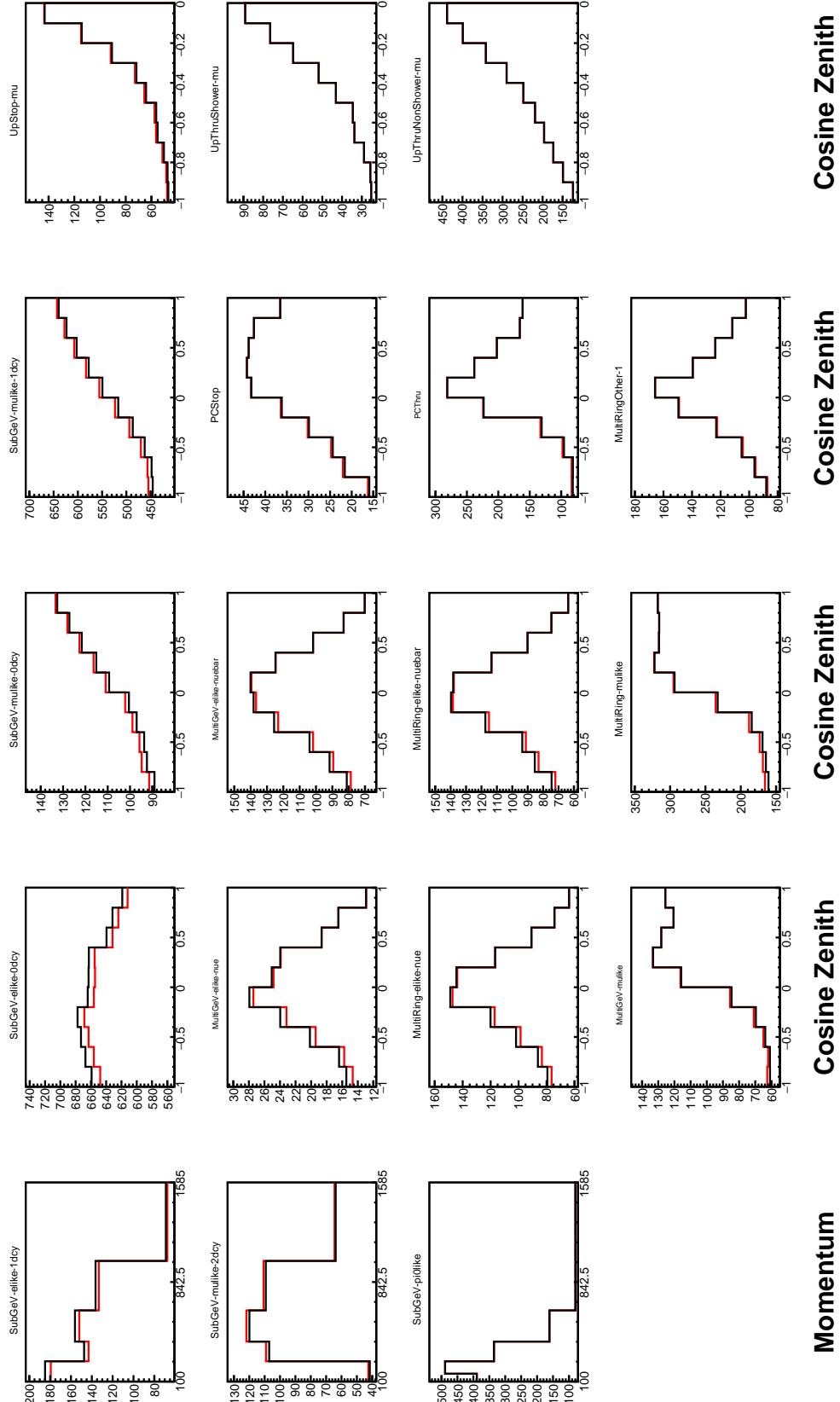


Figure 6.2: Comparison of the SK-IV atmospheric samples between predictions made with the Asimov A (Black) and Asimov B (Red) oscillation parameter sets, given in Table 2.2. The subGeV samples CCRES and π^0 -like samples are given in their reconstructed lepton momentum. All other samples are presented in their reconstructed zenith angle projection.

| Sample | $\cos(\theta_Z)$ Bins | Momentum Bin Edges ($\log_{10}(P)$ MeV) |
|---------------------------------|-----------------------|--|
| SubGeV- <i>elike</i> -0dcy | 10 | 2.0, 2.4, 2.6, 2.8, 3.0, 3.2 |
| SubGeV- <i>elike</i> -1dcy | 1 | 2.0, 2.4, 2.6, 2.8, 3.0, 3.2 |
| SubGeV- <i>mulike</i> -0dcy | 10 | 2.0, 2.4, 2.6, 2.8, 3.0, 3.2 |
| SubGeV- <i>mulike</i> -1dcy | 10 | 2.0, 2.4, 2.6, 2.8, 3.0, 3.2 |
| SubGeV- <i>mulike</i> -2dcy | 1 | 2.0, 2.4, 2.6, 2.8, 3.0, 3.2 |
| SubGeV- <i>pi0like</i> | 1 | 2.0, 2.2, 2.4, 2.6, 2.8, 3.2 |
| MultiGeV- <i>elike</i> -nue | 10 | 3.0, 3.4, 3.7, 4.0, 5.0 |
| MultiGeV- <i>elike</i> -nuebar | 10 | 3.0, 3.4, 3.7, 4.0, 5.0 |
| MultiGeV- <i>mulike</i> | 10 | 3.0, 3.4, 5.0 |
| MultiRing- <i>elike</i> -nue | 10 | 3.0, 3.4, 3.7, 5.0 |
| MultiRing- <i>elike</i> -nuebar | 10 | 3.0, 3.4, 3.7, 5.0 |
| MultiRing- <i>mulike</i> | 10 | 2.0, 3.124, 3.4, 3.7, 5.0 |
| MultiRing- <i>Other1</i> | 10 | 3.0, 3.4, 3.7, 4.0, 5.0 |
| PC-Stop | 10 | 2.0, 3.4, 5.0 |
| PC-Through | 10 | 2.0, 3.124, 3.4, 3.7, 5.0 |
| Upmu-Stop | 10 | 3.2, 3.4, 3.7, 8.0 |
| Upmu-Through-Showering | 10 | 2.0, 8.0 |
| Upmu-Through-NonShowering | 10 | 2.0, 8.0 |

Table 6.5: The reconstructed cosine zenith and lepton momentum binning assigned to the atmospheric samples. The “ $\cos(\theta_Z)$ Bins” column illustrates the number of bins uniformly distributed over the $-1.0 \leq \cos(\theta_Z) \leq 1.0$ region for fully and partially contained samples and $-1.0 \leq \cos(\theta_Z) \leq 0.0$ region for up- μ samples.

¹⁶⁹³ 6.2 Near Detector Beam Samples

¹⁶⁹⁴ The near detector sample selections are documented in detail within [193] and sum-
¹⁶⁹⁵ marised below. Samples are selected based upon the particular Fine Grained Detector
¹⁶⁹⁶ (FGD) (see subsection 3.2.2) the neutrino interacted within as well as the operating
¹⁶⁹⁷ mode of the beam. For more substantial constraints on cross-section model parameters,
¹⁶⁹⁸ wrong-sign neutrino samples are also considered when the beam is operating in RHC
¹⁶⁹⁹ (antineutrino) mode. Samples from the wrong-sign component of the FHC beam mode
¹⁷⁰⁰ are not included as they are statistically insignificant compared to those already listed.

¹⁷⁰¹ Before being assigned a sample, all events must undergo CC-inclusive cuts, as
¹⁷⁰² defined in DB: TN212.

- ¹⁷⁰³ • Event Timing: The DAQ must be operational and the event must occur within
¹⁷⁰⁴ the expected time window
- ¹⁷⁰⁵ • TPC Requirement: The track path must intercept one or more TPCs
- ¹⁷⁰⁶ • Fiducial volume: The event must originate from within a fiducial volume
- ¹⁷⁰⁷ • Upstream Background: Remove reconstruction failures occurring from muons
¹⁷⁰⁸ that originate upstream of the FGDs by requiring no high-momentum tracks
¹⁷⁰⁹ within 150mm of the candidate vertex. Additionally, events that occur within the
¹⁷¹⁰ downstream FGD are vetoed if a secondary track starts within the upstream FGD
- ¹⁷¹¹ • Broken track removal: All candidates where the muon candidate is broken in two
¹⁷¹² tracks are removed
- ¹⁷¹³ • Muon PID: Measurements of dE/dx in a TPC are used to distinguish muon-like
¹⁷¹⁴ events using a likelihood cut

₁₇₁₅ In addition to these cuts, the RHC neutrino events also have to undergo the following cuts to aid in the separation of neutrino and antineutrino DB: TN246:

- ₁₇₁₇ • TPC Requirement: The track path must intercept TPC2
- ₁₇₁₈ • Positive Track: The highest momentum track must be positive
- ₁₇₁₉ • TPC1 Veto: Remove any events originating upstream of TPC1

₁₇₂₀ Once all CC-inclusive events have been determined, they are further segregated
₁₇₂₁ into sub-samples that target the constraints on interaction modes most relevant at the
₁₇₂₂ far detector. These are CC0 π , CC1 π , and CCOther, which target CCQE, CCRES, and
₁₇₂₃ other CC background interactions. They are defined with the following cuts:

- ₁₇₂₄ • ν_μ CC0 π Selection: No electrons in TPC and no charged pions or decay electrons
₁₇₂₅ within the TPC or FGD
- ₁₇₂₆ • ν_μ CC1 π Selection: Exactly one charged pion in either the TPC or FGD,
₁₇₂₇ where the number of charged pions in the FGD is equal to the number of decay
₁₇₂₈ electrons
- ₁₇₂₉ • ν_μ CCOther Selection: All events which are not classified into the above two
₁₇₃₀ selections. These contain neutral pion and multiple charged pion events.

₁₇₃₁ Counting the three selections for each FGD in neutrino (FHC) and anti-neutrino
₁₇₃₂ (RHC) running, including the wrong-sign background in RHC, 18 near detector samples
₁₇₃₃ are used within this analysis. These samples are binned in reconstructed lepton
₁₇₃₄ momentum (illustrated in Figure 6.3) and direction with respect to the beam. The
₁₇₃₅ binning is chosen such that each event has at least 20 Monte Carlo events in each bin.
₁₇₃₆ This is to ensure that the bins are coarse enough to ensure the reduction of statistical
₁₇₃₇ errors, whilst also being fine enough to sample the high-resolution peak regions. The
₁₇₃₈ binning and choice of non-uniform binning are detailed in [194].

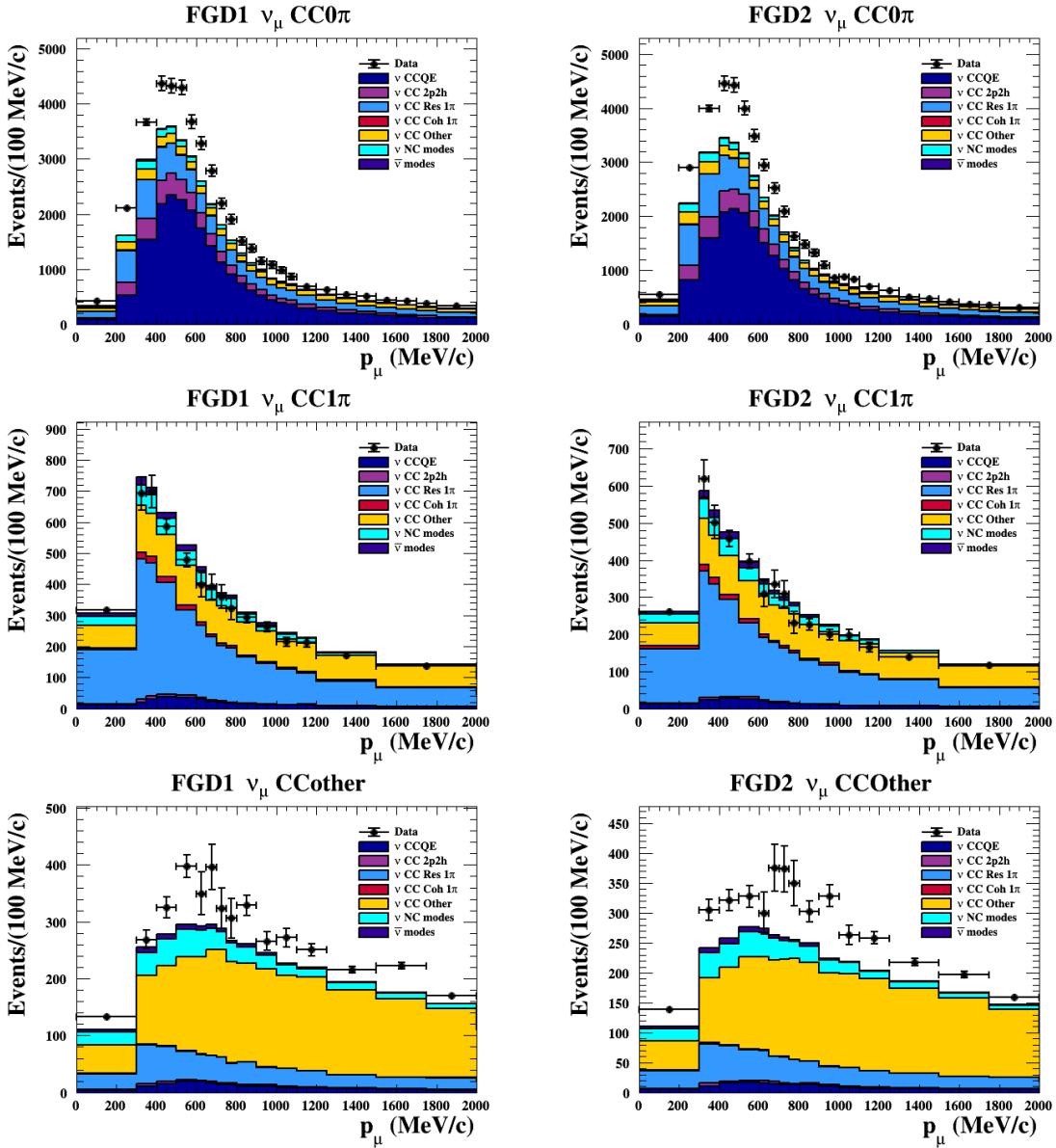


Figure 6.3: The nominal Monte Carlo predictions for the FGD1 and FGD2 samples in neutrino beam mode (FHC), broken down into the $CC\nu_\mu 0\pi$, $CC\nu_\mu 1\pi$ and $CC\nu_\mu$ Other categories. Figures taken from [193].

1739 6.3 Far Detector Beam Samples

1740 The beam neutrino events which occur at the SK detector, which pass the reduction cuts
 1741 detailed in section 5.3, are separated depending on whether the beam was operating
 1742 in neutrino or antineutrino mode. The events are then segregated into three separate
 1743 samples: electron-like (1Re), muon-like (1R μ), and CC1 π^+ -like which are observed

1744 as electron-like events with an associated decay electron. As discussed in section 6.1,
 1745 positively charged pions from emitted from neutrino interactions are less likely to
 1746 be absorbed by oxygen nuclei and thus are more likely to produce events that are
 1747 observed with an associated decay electron. Consequently, the CC1 π^+ -like sample is
 1748 only selected when the beam is operating in FHC-neutrino mode. Therefore, five beam
 1749 samples measured at SK are used in this analysis. As the T2K oscillation analysis has
 1750 evolved over the years and the selections changed, the sample names are suffixed with
 1751 2020 to indicate they are the samples used within the 2020 T2K oscillation analysis.

1752 The fiducial volume definition for beam samples is slightly different from that used
 1753 within the atmospheric samples. It uses both the distance to the closest wall (d_{Wall})
 1754 and the distance to the wall along the trajectory of the particle (t_{Wall}). This allows
 1755 events that originate close to the wall but are facing into the tank to be included within
 1756 the analysis, which would have otherwise been removed. The exact cut values for both
 1757 d_{Wall} and t_{Wall} are different for each of the three types of sample and optimised
 1758 based on T2K sensitivity to δ_{CP} [195, 196].

1759 **1Re event selection** For an event to be classified as a 1Re-like, the event must follow:

- 1760 • Fully-contained and within $d_{\text{Wall}} > 80\text{cm}$ and $t_{\text{Wall}} > 170\text{cm}$
- 1761 • Total of one ring which is reconstructed as electron-like with reconstructed mo-
1762 mentum $P_e > 100\text{MeV}$
- 1763 • Zero decay electrons are associated with the event
- 1764 • Passes π^0 rejection cut discussed in section 5.2

1765 The zero decay electron cut specifically targets CCQE interactions and the π^0
 1766 rejection cut it designed to remove neutral current π^0 background events as they can
 1767 be easily reconstructed as 1Re events without this cut.

¹⁷⁶⁸ **CC1 π^+ event selection** This event selection is very similar to that of the 1Re sample.
¹⁷⁶⁹ The only difference is that the `dWall` and `toWall` criteria are shifted to $> 50\text{cm}$ and
¹⁷⁷⁰ $> 270\text{cm}$, respectively. Furthermore, exactly one decay electron is required from the
¹⁷⁷¹ π^+ decay.

¹⁷⁷² **1R μ event selection** A 1Re-like event is determined by the following cuts:

- ¹⁷⁷³ • Fully-contained and within `dWall` $> 50\text{cm}$ and `toWall` $> 250\text{cm}$
- ¹⁷⁷⁴ • Total of one ring which is reconstructed as muon-like with reconstructed momen-
¹⁷⁷⁵ tum $P_\mu > 200\text{MeV}$
- ¹⁷⁷⁶ • Fewer than two decay electrons are associated with the event
- ¹⁷⁷⁷ • Passes π^+ rejection cut discussed in section 5.2

¹⁷⁷⁸ As pions and muons have similar masses, the Cherenkov rings they generate have
¹⁷⁷⁹ similar opening angles. Consequently, to select muons, the events have to pass the π^+
¹⁷⁸⁰ rejection cut which is specifically optimised to separate the two types of events.

¹⁷⁸¹ All of these samples are binned in reconstructed neutrino energy. This is possible as
¹⁷⁸² the direction from the source is known extremely well, unlike atmospheric neutrinos.
¹⁷⁸³ This value is calculated for the 1Re and 1R μ samples assuming CCQE interactions,

$$E_\nu^{rec} = \frac{(M_N - V_{nuc})E_l - m_l^2/2 + M_N V_{nuc} - V_{nuc}^2/2 + (M_P^2 + M_N^2)/2}{M_N - V_{nuc} - E_l + P_l \cos(\theta_{beam})} \quad (6.2)$$

¹⁷⁸⁴ Where M_N , M_P and m_l are the masses of the neutron, proton and outgoing lepton,
¹⁷⁸⁵ respectively. $V_{nuc} = 27\text{MeV}$ is the binding energy of the oxygen nuclei, θ_{beam} is the
¹⁷⁸⁶ angle between the beam and the direction of the outgoing lepton, and E_l and P_l are
¹⁷⁸⁷ the energy and momentum of that outgoing lepton.

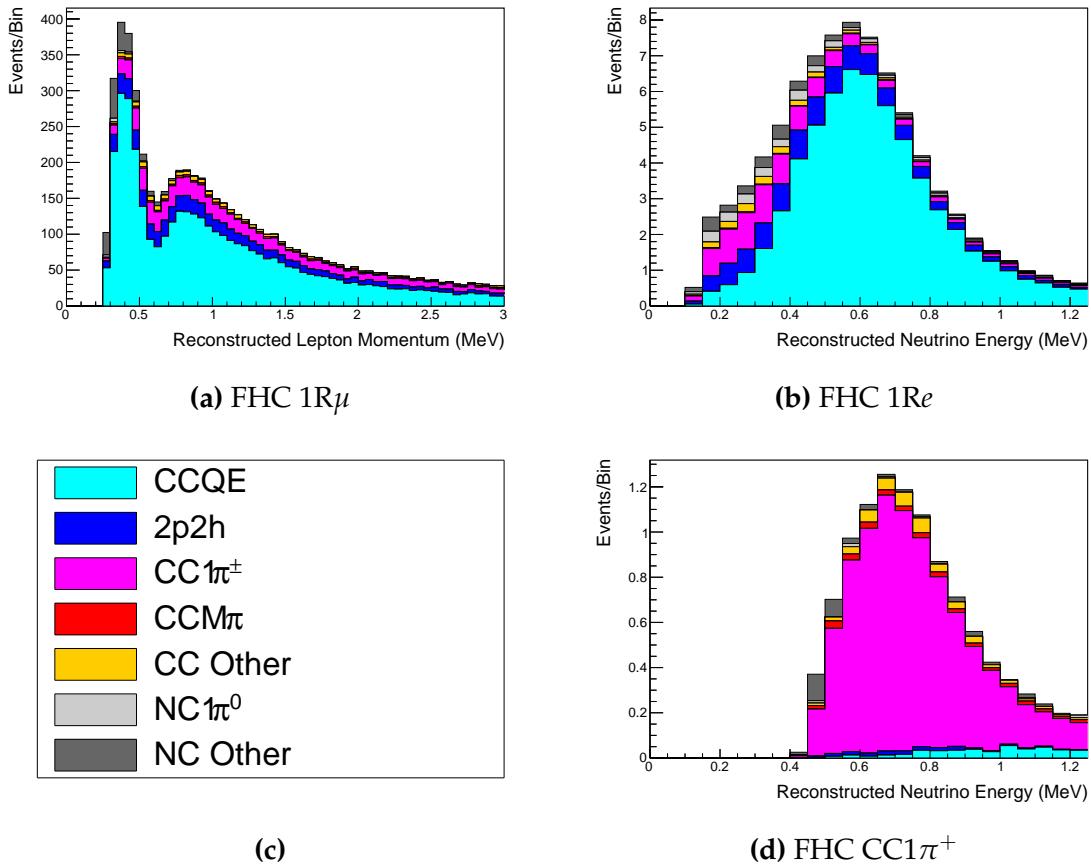


Figure 6.4: The reconstructed neutrino energy, as defined by Equation 6.2 and Equation 6.3, for the 1R μ , 1Re and CC1 π^+ samples. The generated dial values and Asimov A oscillation parameter sets are assumed. These samples are the FHC mode samples. For ease of viewing, the 1R μ sample only shows the $0. \leq E_\nu^{rec} < 3.0\text{GeV}$ but the binning extends out to 30.0GeV.

1788 The reconstructed neutrino energy of the CC1 π^+ events is modified to include the
 1789 delta resonance resonantly produced within the interaction,

$$E_\nu^{rec} = \frac{2M_N E_l + M_{\Delta^{++}}^2 - M_N^2 - m_l^2}{2(M_N - E_l + P_l \cos(\theta_{beam}))} \quad (6.3)$$

1790 Where $M_{\Delta^{++}}$ is the mass of the delta baryon. Binding energy effects are not
 1791 considered due to the two-body process with the delta baryon is assumed.

1792 The reconstructed neutrino energy for the FHC samples is illustrated in Figure 6.4.
1793 This is the binning used within the analysis. As expected, the $1R\mu$ and $1Re$ are heavily
1794 dominated by CCQE interactions, with smaller contributions from 2p2h meson ex-
1795 change and resonant pion production interactions. The $CC1\pi^+$ sample predominantly
1796 consists of charged current resonant pion production interactions. The $1Re$ and $CC1\pi^+$
1797 samples are also binned by the angle between the neutrino beam and the reconstructed
1798 lepton momentum. This is to aid in charged current and neutral current separation
1799 as indicated in Figure 6.5. This is because the neutral current backgrounds are pre-
1800 dominantly due to π^0 -decays, where the opening angle of the two gammas alongside
1801 the different final state kinematics produces a slightly broader angular distribution
1802 compared to the final state particles originating from charged current ν_e interactions.

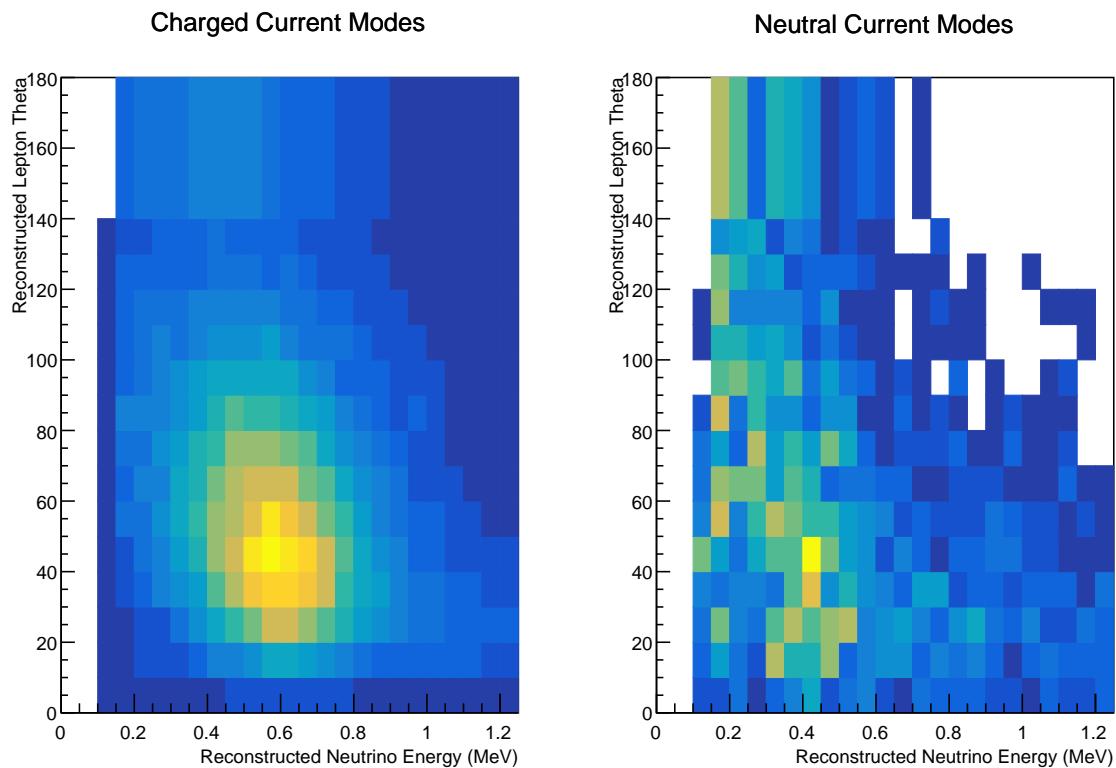


Figure 6.5: The distribution of the angle between the neutrino beam direction and the reconstructed final state lepton, for the FHC neutrino mode beam one ring electron sample. The distribution is broken down by neutrino interaction mode into charged current (left) and neutral current (right) components. The pre-fit systematic dial values and Asimov A oscillation parameter sets are assumed.

¹⁸⁰³ 6.4 Systematic Uncertainties

¹⁸⁰⁴ The systematics for this analysis are split into groups, or blocks, depending on their
¹⁸⁰⁵ purpose. They consist of flux uncertainties, neutrino-matter interaction systematics,
¹⁸⁰⁶ and detector efficiencies. There are also uncertainties on the oscillation parameters
¹⁸⁰⁷ which this analysis will not be sensitive to, Δm_{12}^2 and $\sin^2(\theta_{12})$. As described in
¹⁸⁰⁸ chapter 4, each model parameter used within this analysis requires a prior uncertainty.
¹⁸⁰⁹ This is provided via separate covariance matrices for each block. The covariance
¹⁸¹⁰ matrices can include prior correlations between parameters within a single block, but
¹⁸¹¹ the separate treatment means prior uncertainties can not be included for parameters
¹⁸¹² in different groups. Alternatively, some parameters have no reasonably motivated
¹⁸¹³ uncertainties. These parameters are assigned flat priors which do not change the
¹⁸¹⁴ likelihood penalty. The flux, neutrino interaction, and detector modeling have already
¹⁸¹⁵ been discussed in section 5.1. The uncertainties invoked within these models are
¹⁸¹⁶ described below.

¹⁸¹⁷ 6.4.1 Beam Flux

¹⁸¹⁸ The neutrino beam flux systematics is based upon our uncertainty in the modeling of
¹⁸¹⁹ the components of the beam. This includes the hadron production model and their re-
¹⁸²⁰ interactions, the shape, intensity, and alignment of the beam with respect to the target,
¹⁸²¹ and the uniformity of the magnetic field produced by the horn, alongside other effects.
¹⁸²² The uncertainty, as a function of neutrino energy, is illustrated in Figure 6.6 which
¹⁸²³ includes the total uncertainty as well as the individual components. The uncertainty
¹⁸²⁴ for events below, and much higher than, the peak neutrino energy is dominated by
¹⁸²⁵ hadron production and re-interaction systematics. The beam profile and alignment of
¹⁸²⁶ the proton beam dominate the systematic uncertainty for events with $E_\nu \sim 1\text{GeV}$.

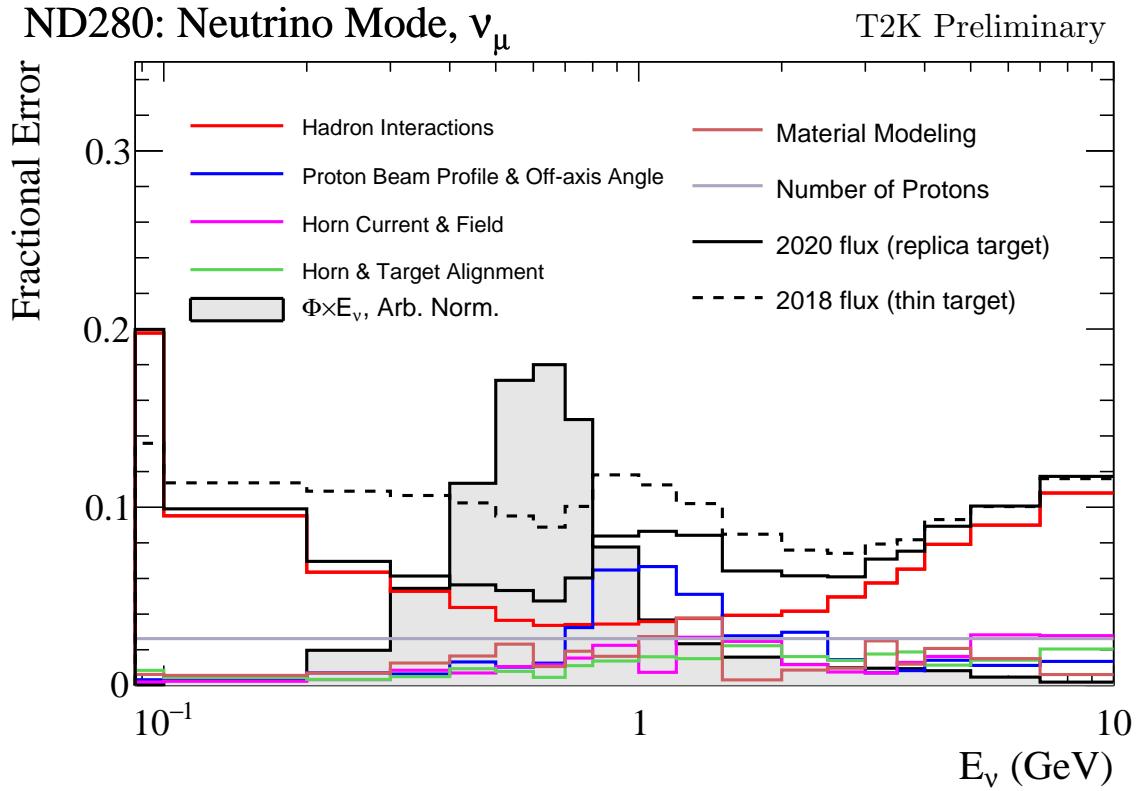


Figure 6.6: The total uncertainty evaluated on the near detector ν_μ flux prediction constrained by the replica-target data, illustrated as a function of neutrino energy. The solid(dashed) line indicates the uncertainty used within this analysis(the T2K 2018 analysis). The solid histogram indicates the neutrino flux as a function of energy. Figure taken from [197].

1827 The beam flux uncertainties are described by one hundred parameters. They are
 1828 split between both ND280 and SK detectors and binned by neutrino flavour: ν_μ , $\bar{\nu}_\mu$, ν_e
 1829 and $\bar{\nu}_e$. The response is then broken down as a function of neutrino energy. The bin
 1830 density in the neutrino energy is the same for the FHC- ν_μ and RHC- $\bar{\nu}_\mu$, and narrows
 1831 for neutrino energies close to the oscillation maxima of $E_\nu = 0.6\text{GeV}$. This binning is
 1832 specified in Table 6.6. All of these systematic uncertainties are applied as normalisation
 1833 parameters with Gaussian priors centered at 1.0 and error specified from a covariance
 1834 matrix provided by the T2K beam group.

| Neutrino Flavour | Sign | Neutrino Energy Bin Edges (GeV) |
|------------------|-------|--|
| μ | Right | 0., 0.4, 0.5, 0.6, 0.7, 1., 1.5, 2.5, 3.5, 5., 7., 30. |
| μ | Wrong | 0., 0.7, 1., 1.5, 2.5, 30. |
| e | Right | 0., 0.5, 0.7, 0.8, 1.5, 2.5, 4., 30. |
| e | Wrong | 0., 2.5, 30. |

Table 6.6: The neutrino energy binning for the different neutrino flavours. “Right” sign indicates neutrinos in the FHC beam and antineutrinos in the RHC beam mode. “Wrong” sign indicates antineutrinos in the FHC beam and neutrinos in the RHC beam mode. The binning of the detector response is identical for the FHC and RHC modes as well as at ND280 and SK.

1835 6.4.2 Atmospheric Flux

1836 The atmospheric neutrino flux is modeled by the HKKM model, however, 16 system-
 1837 atic uncertainties are applied to control the normalisation of each neutrino flavour,
 1838 energy, and direction. All of the parameters are given Gaussian priors centered at 0
 1839 and width 1.. They are summarised below:

- 1840 • **Absolute Normalisation:** The overall normalisation of each neutrino flavour is
 1841 controlled by two independent systematic uncertainties, for $E_\nu < 1\text{GeV}$ and $E_\nu >$
 1842 1GeV , respectively. This is driven mostly by hadronic interaction uncertainties for
 1843 the production of pions and kaons [43]. The strength of the response is dependent
 1844 upon the neutrino energy.
- 1845 • **Relative Normalisation:** Uncertainties on the ratio of $(\nu_\mu + \bar{\nu}_\mu) / (\nu_e + \bar{\nu}_e)$ are
 1846 controlled by the difference between the HKKM model [43], FLUKA [46] and
 1847 Bartol models [42]. Three independent parameters are applied in the energy
 1848 ranges: $E_\nu < 1\text{GeV}$, $1\text{GeV} < E_\nu < 10\text{GeV}$, and $E_\nu > 10\text{GeV}$.
- 1849 • **$\nu/\bar{\nu}$ Normalisation:** The uncertainties in the π^+/π^- (and kaon equivalent) pro-
 1850 duce uncertainties in the flux of $\nu/\bar{\nu}$. The response is applied in the same way as
 1851 the relative normalisation parameters.

- **Up/Down and Vertical/Horizontal Ratio:** Similar to the above two systematics, the difference between the HKKM, FLUKA, and Bartol model predictions, as a function of $\cos(\theta_Z)$, is used to control the normalisation of events as a function of zenith angle.
 - **K/π Ratio:** Higher energy neutrinos ($E_\nu < 10\text{GeV}$) become dependent upon kaon decay as the dominant source of neutrinos. Measurements of the ratio of K/π [198] are used to control the systematic uncertainty of the expected ratio of pion and kaon production.
 - **Solar Activity:** As the 11-year solar cycle can affect the Earth's magnetic field, the flux of primary cosmic rays is modulated across the same period. The uncertainty is calculated by taking a ± 1 year variation, equating to a 10% uncertainty for the SK-IV period.
 - **Atmospheric Density:** The height of the interaction of the primary cosmic rays is dependent upon the atmospheric density. The HKKM assumes the US standard 1976 [153] profile. This systematic controls the uncertainty in that model.
- Updates to the HKKM and Bartol models are underway to use a similar tuning technique to that used in the beam flux predictions. After those updates, it may be possible to include correlations in the hadron production uncertainty systematics for beam and atmospheric flux predictions.

6.4.3 Neutrino Interaction

The neutrino interactions which occur within all the detectors are modeled by NEUT. The two independent oscillation analyses, T2K beam only and the SK atmospheric only, have developed separate interaction models. The T2K-only analysis uses the systematics model defined in [199] and the SK-only analysis uses the uncertainties

1876 detailed in [52]. To leverage the most sensitivity out of this joint beam and atmospheric
1877 analysis, a correlated interaction model has been defined. Where applicable, these
1878 correlations allow the systematic uncertainties applied to the atmospheric samples to
1879 be constrained by measurements of the near detector in the beam experiment leading
1880 to stronger sensitivity to oscillation parameters as compared to an uncorrelated model.
1881 An in-depth discussion of the reasoning and validity of enforcing correlations is
1882 documented in [200] and briefly summarised below.

1883 The low energy T2K systematic model has a more sophisticated treatment of CCQE,
1884 CCMEC, and CCRES uncertainties which is due to the purpose-made cross-section
1885 measurements made by the near detector. Furthermore, extensive testing of this model
1886 has been performed by the working group responsible for this model [199]. However,
1887 it is not designed for the high-energy atmospheric events illustrated in Figure 5.10.
1888 Therefore the high energy systematic model from the SK-only analysis is implemented
1889 for the relevant multiGeV samples. The CCQE systematic parameters invoked within
1890 the SK high energy model are actually contained within T2K’s CCQE model. Conse-
1891 quently, the more sophisticated CCQE and CCMEC T2K model parameters have been
1892 incorporated into the high energy model but are uncorrelated from the low energy
1893 counterparts. This results in a more complete model but without any constraint from
1894 the near detector measurements.

1895 The high energy systematic model includes parameters developed from compar-
1896 isons of Nieves and Rein-Seghal models which affect CCRES interactions, comparisons
1897 of the GRV98 and CKMT models which control DIS interactions, and hadron multipli-
1898 city measurements which modulate the normalisation of $CCN\pi$ events. The uncertainty
1899 of the ν_τ cross-section is particularly large and is controlled by a 25% normalisation
1900 uncertainty. These parameters are applied via normalisation or shape parameters.
1901 The former linearly scales the weight of all affected Monte-Carlo events, whereas the

latter can increase or decrease a particular event's weight depending on its neutrino energy and mode of interaction. The response of the shape parameters are defined by third-order polynomial splines which return a weight for a particular neutrino energy. In total, 17 normalisation and 15 shape parameters are included in the more sophisticated high-energy model.

Figure 6.7 indicates the predicted neutrino energy distribution for both beam and subGeV atmospheric samples, and Figure 6.8 illustrates the fractional contribution of the different interaction modes per sample. There is clearly significant overlap in neutrino energy between the subGeV atmospheric and beam samples, allowing similar kinematics in the final state particles. Comparing beam samples with zero decay electrons and atmospheric electron-like(muon-like) samples with zero(zero or one) decay electrons, there is a very similar contribution of CCQE, CC 2p2h, and CC1 π^\pm interactions. The samples which target CC1 π^\pm interactions, FHC 1Re1de beam sample and atmospheric electron-like(muon-like) samples with one(two) decay electrons, also consist of very similar mode interactions. As a consequence of the similarity in energy and mode contributions, correlating the systematic model between the beam and subGeV atmospheric samples ensures that this analysis attains the largest sensitivity to oscillation parameters while still ensuring neutrino interaction systematics are correctly accounted for. Due to its sophisticated CCQE model, the T2K systematic model was chosen as the basis of the correlated model.

The T2K uncertainty model is applied in a similar methodology to the SK model parameters. It consists of 19 shape parameters applied via third-order polynomial splines and 24 normalisation parameters. Four additional parameters, which model the uncertainty in the binding energy, are applied in a way to shift the momentum of the lepton emitted from a nucleus. The majority of these parameters are assigned a Gaussian prior uncertainty. Those that have no theoretical reasoning, or those which

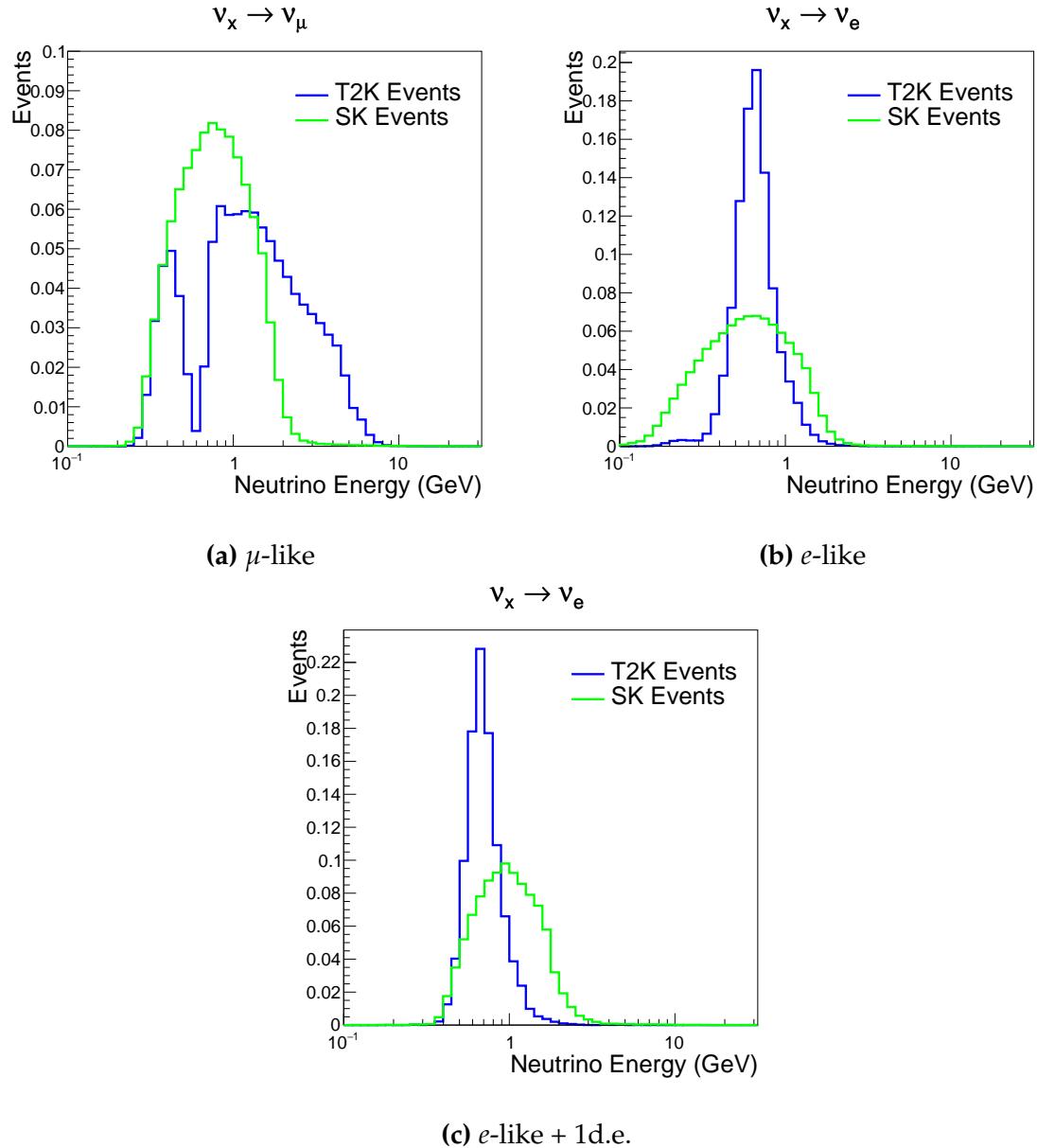


Figure 6.7: The prediction neutrino energy distribution for subGeV atmospheric and beam samples, given for muon-like samples FHC+RHC 1R μ beam samples compared to the subGeV μ -like 0+1 decay electrons (d.e.) atmospheric samples, electron-like 0d.e. samples FHC+RHC 1Re beam samples compared to the subGeV e -like 1d.e. sample, and electron-like 1d.e. sample FHC1Re1de beam sample compared to the subGeV e -like 1d.e. atmospheric sample.

have not been fit to external data, are assigned a flat prior which does not affect the penalty term. The CCQE model parameters were tuned to MiniBooNE [201] and MINER ν A [202] measurements and CCRES model parameters are tuned to ANL and BNL experiments [203].

| | CC QE | CC 2p2h | CC $1\pi^\pm$ | CC $M\pi$ | CC Other | NC π^0 | NC $1\pi^\pm$ | NC $M\pi$ | NC Coh. | NC Other |
|----------------------|-------------|-------------|---------------|-------------|-------------|-------------|---------------|-------------|-------------|-------------|
| FHC 1R+1d.e. e-like | 0.04 | 0.02 | 0.83 | 0.03 | 0.04 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 |
| RHC 1R e-like | 0.62 | 0.12 | 0.11 | 0.01 | 0.02 | 0.06 | 0.01 | 0.01 | 0.01 | 0.04 |
| FHC 1R e-like | 0.68 | 0.12 | 0.10 | 0.00 | 0.02 | 0.04 | 0.01 | 0.00 | 0.00 | 0.02 |
| RHC 1R μ -like | 0.62 | 0.13 | 0.17 | 0.02 | 0.03 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 |
| FHC 1R μ -like | 0.62 | 0.12 | 0.16 | 0.02 | 0.03 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 |
| S.G. π^0 -like | 0.05 | 0.01 | 0.02 | 0.00 | 0.01 | 0.68 | 0.06 | 0.07 | 0.06 | 0.04 |
| S.G. μ -like 2de | 0.04 | 0.01 | 0.80 | 0.10 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| S.G. μ -like 1de | 0.72 | 0.11 | 0.12 | 0.01 | 0.02 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| S.G. μ -like 0de | 0.68 | 0.11 | 0.10 | 0.01 | 0.02 | 0.01 | 0.05 | 0.01 | 0.00 | 0.02 |
| S.G. e-like 1de | 0.05 | 0.01 | 0.75 | 0.10 | 0.05 | 0.00 | 0.01 | 0.02 | 0.00 | 0.01 |
| S.G. e-like 0de | 0.73 | 0.11 | 0.10 | 0.01 | 0.02 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 |

Figure 6.8: The interaction mode contribution of each sample given as a fraction of the total event rate in that sample. All systematic dials are set to their nominal values and the Asimov A oscillation parameters are assumed. The Charged Current (CC) modes are broken into quasi-elastic (QE), meson exchange (2p2h), resonant charged pion production ($1\pi^\pm$), multi-pion production ($M\pi$), and other interaction categories. Neutral Current (NC) interaction modes are given in interaction mode categories: π^0 production, resonant charged pion production, multi-pion production, and others.

1932 There are three particular tunes of the T2K low energy cross section model typically
 1933 considered. Firstly, the “generated” tune which is the set of dial values with which
 1934 the Monte Carlo was generated. Secondly, the set of dial values which are taken
 1935 from external data measurements and used as inputs. These are the “pre-fit” dial
 1936 values. The reason these two sets of dial values are different is that the external data
 1937 measurements are continually updated but it is very computationally intensive to
 1938 regenerate a Monte Carlo prediction after each update. Consequently, the pre-fit and
 1939 generated dial values differ. The final tune is the “post-fit” or “post-BANFF” dial
 1940 values. These are the values taken from a fit to the beam near detector data. This fit is

1941 performed by two independent fitting frameworks, MaCh3 and BANFF, which ensures
1942 reliable measurements. The output of each fitter is converted into a covariance matrix
1943 to describe the error and correlations between all the cross-section parameters. This is
1944 then propagated to the far-detector oscillation analysis group for use in the P-Theta
1945 fitting framework. As MaCh3 can perform a near detector fit, it is included within
1946 the simultaneous fit of the far-detector beam and atmospheric oscillation analysis.
1947 This is because this technique does not require any assumption of Gaussian posterior
1948 distributions which is required in the covariance matrix methodology.

1949 On top of the combination of the SK and T2K interaction models, several other
1950 parameters have been specifically developed for the joint oscillation analysis. As
1951 the majority of the atmospheric samples' δ_{CP} sensitivity comes from the normali-
1952 sation of subGeV electron-like events, an additional dial that models an alternative
1953 Continous Random Phase Approximation (CRPA) nuclear ground state has been im-
1954 plemented [200]. As the near detector can not sufficiently constrain the model, this
1955 dial approximates the event weights if a CRPA model had been assumed rather than a
1956 spectral function. This dial only effects ν_e and $\bar{\nu}_e$ and is applied as a shape parameter.

1957 Further additions to the model have been included due to the subGeV π^0 atmo-
1958 spheric sample. This particularly targets charged current and neutral current π^0
1959 producing interactions to constrain the systematic uncertainties. However, there
1960 is no analogous sample in the T2K beam-only analysis so no significant effort has
1961 been placed into building a sufficient uncertainty model. Therefore, an uncertainty
1962 that affects neutral current resonant π^0 production is incorporated in this analysis.
1963 Comparisons of NEUT's NC resonant pion production predictions have been made
1964 to MiniBooNE [204] data and a consistent 16% to 21% underprediction is observed.
1965 Consequently, a conservative 30% normalisation is invoked.

1966 Events which originate from above the detector and travel downward are very
 1967 insensitive to oscillation parameters and act similar to the near detector within an
 1968 accelerator experiment (Details are illustrated in chapter 7). Consequently, the applica-
 1969 tion of the T2K low energy cross section and the effect of the near detector constraint
 1970 on the atmospheric samples can be studied through these events, without biasing
 1971 the results from oscillation effects. The downward going predictives are illustrated
 1972 in Figure 6.9. For samples that target CCQE interactions (electron-like with 0 decay
 1973 electrons and muon-like with 0 or 1 decay electrons), the application of the near
 1974 detector constraint is well within statistical fluctuation of the down-going data and
 1975 no significant tension is observed between the data and the Monte Carlo prediction
 1976 with the T2K near detector constraint. This is not the case for samples with target
 1977 CCRES interactions (electron-like with 1 decay electron and muon-like with 2 decay
 1978 electrons). The electron-like data is consistent with the constrained prediction at higher
 1979 reconstructed momenta but diverges at lower momentum, whereas the muon-like
 1980 sample is under-predicted throughout the range of momenta. To combat this disagree-
 1981 ment, an additional cross-section systematic dial, specifically designed to inflate the
 1982 low pion momentum systematics was developed in [200]. This is a shape parameter
 1983 implemented through a splined response.

1984 6.4.4 Near Detector

1985 The systematics applied due to uncertainties arising from the response of the near
 1986 detector is contained within 574 normalisation parameters binned in momentum and
 1987 angle, $P_\mu \text{ ad } \cos(\theta_\mu)$, of the final-state muon. These are applied via a covariance
 1988 matrix with each parameter being assigned a Gaussian prior from that covariance
 1989 matrix. These normalisation parameters are built from underlying systematics, e.g.
 1990 pion secondary interaction systematics, which are randomly thrown and the variation

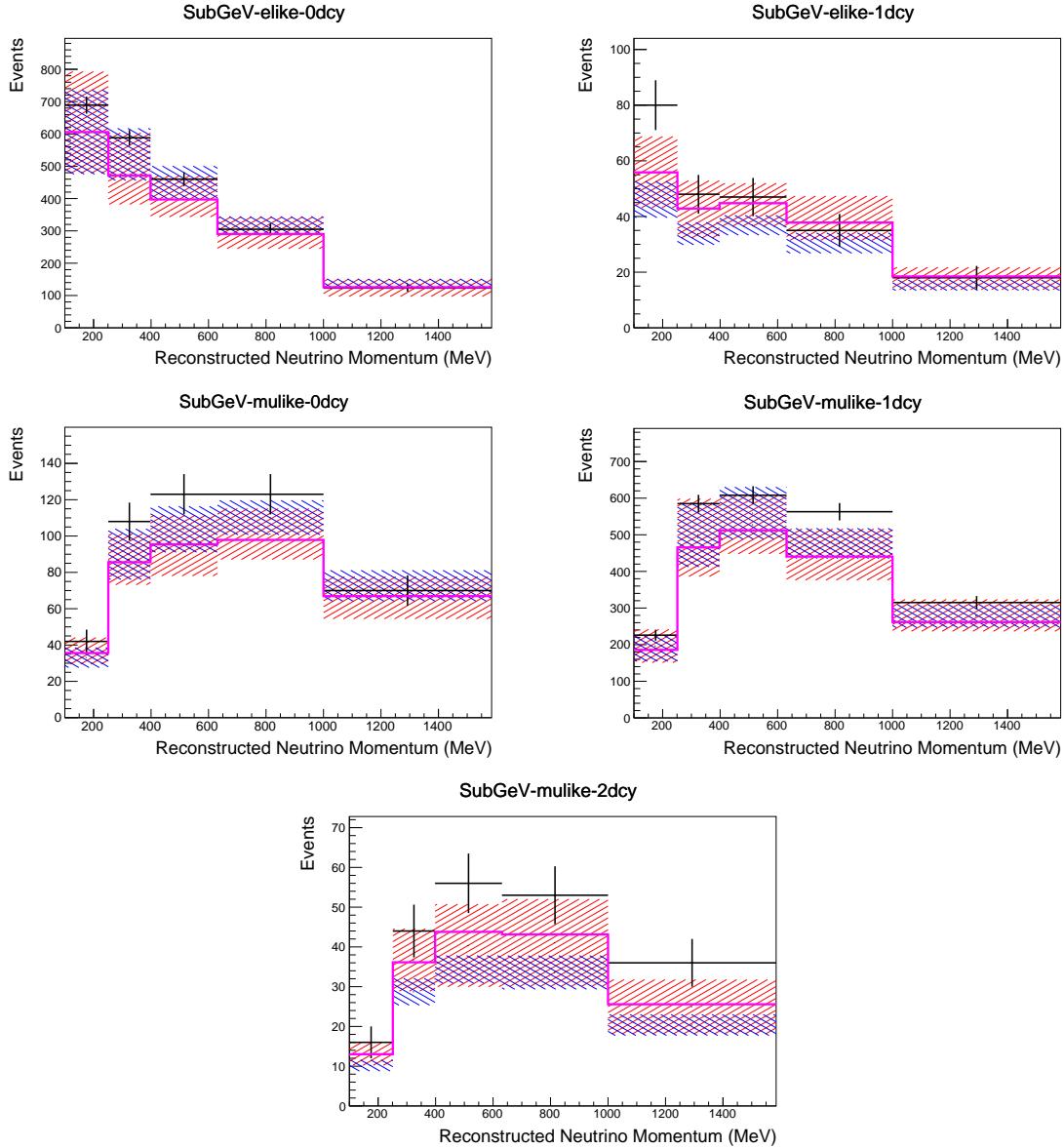


Figure 6.9: Down-going atmospheric subGeV single-ring samples comparing the mean and error of the pre-fit and post-fit Monte Carlo predictions in red and blue, respectively. The magenta histogram illustrates the Monte Carlo prediction using the generated dial values. The black points illustrate the down-going data with statistical errors given. The mean and errors of the Monte Carlo predictions are calculated by the techniques documented in subsection 4.3.4. The cross-section and atmospheric flux parameters are either thrown from their pre-fit uncertainties (denoted pre-fit band), or the cross section dial values are randomly sampled from a MCMC chain whilst the atmospheric flux parameters are thrown from their pre-fit distributions (denoted post-fit band).

¹⁹⁹¹ in each $P_\mu \times \cos(\theta_\mu)$ bin is determined. This is performed 2000 times and a covariance matrix response is created. This allows significant correlations between FGD1 and

1993 FGD2 samples, as well as adjacent bins. Statistical uncertainties are accounted for by
1994 including fluctuations of each event's weight from a Poisson distribution.

1995 Similar to the cross-section systematics, MaCh3 and BANFF are used to constrain
1996 the uncertainty of these systematics through independent validations. Each fitter
1997 generates a post-fit covariance matrix which is compared and passed to the far-detector
1998 oscillation analysis working group. However, as the analysis presented within this
1999 thesis uses the MaCh3 framework, a joint oscillation analysis fit of all three sets of
2000 samples is performed. From the T2K-only perspective, this joint analysis including
2001 atmospheric samples allows additional constraints on the systematic uncertainties
2002 where correlations have been invoked.

2003 **6.4.5 Far Detector**

2004 Two configurations of the far detector systematic model implementation have been
2005 considered. Firstly, the far detector systematic uncertainties for beam and atmospheric
2006 samples are taken from their respective analysis inputs, denoted "official inputs" anal-
2007 ysis. Consequently, no correlations are assumed between the beam and atmospheric
2008 samples. The generation of the beam- and atmospheric-specific inputs are documented
2009 in subsubsection 6.4.5.1 and subsubsection 6.4.5.2 for the beam and atmospheric sam-
2010 ples, respectively. Secondly, a correlated detector model has been considered. Here, the
2011 distribution of parameters used for applying event cuts (e.g. electron-muon separation)
2012 is modified within the fit, following a similar methodology to the beam far detector
2013 systematics model implementation. However, it has been designed to ensure that the
2014 atmospheric data is not double-counted, which would be the case for the official-inputs
2015 analysis. This alternative implementation is detailed in subsubsection 6.4.5.3.

2016 6.4.5.1 Beam Samples

2017 There are 45 systematics which describes the response of the far detector, specifically for
 2018 beam sample neutrino events. 44 of these parameters are normalisation parameters and
 2019 are split by the interaction mode, true neutrino flavour, reconstructed neutrino energy,
 2020 and sample which they affect. The final parameter is the energy scale uncertainty. It is
 2021 applied as a multiplicative factor to the reconstructed neutrino energy. The value of
 2022 the systematic is taken from Monte Carlo to data differences illustrated in [185]. The
 2023 normalisation parameters are assigned a Gaussian error centralised at 1.0 and a width
 2024 taken from the covariance matrix. A detailed breakdown of the following procedure is
 2025 found in [195]. To build the covariance matrix, a fit is performed on atmospheric data
 2026 which has been selected using beam sample selection cuts. The variable which defines
 2027 each cut, L (e.g. the electron-muon PID parameter) is assigned a smear, α , and shift, β
 2028 parameter such that,

$$L_j^i \rightarrow \bar{L}_j^i = \alpha_j^i L + \beta_j^i \quad (6.4)$$

2029 Where L_j^i (\bar{L}_j^i) correspond to nominal(varied) PID cut parameters given in Table 6.7.
 2030 The shift and smear parameters are binned by final-state topology, j , where the binning
 2031 is given in Table 6.8. This approach is used to allow the cut parameter distributions to
 2032 be modified within the fit which allows better data to Monte Carlo agreement.

2033 Beyond the uncertainty on the PID cut criteria, the mis-modeling of π^0 events is also
 2034 considered. If one of the two rings from a π^0 event is missed, this will be reconstructed
 2035 as a $CC\nu_e$ event. This is one of the largest systematics hindering the electron neutrino
 2036 appearance analyses. Consequently, a systematic has been introduced to constrain
 2037 the mis-modeling of π^0 events in SK. To evaluate this systematic uncertainty, a set of

| Cut Variable | Parameter Name |
|--------------|---|
| 0 | <code>fitQun e/μ PID</code> |
| 1 | <code>fitQun e/π⁰ PID</code> |
| 2 | <code>fitQun μ/π PID</code> |
| 3 | <code>fitQun Ring-Counting Parameter</code> |

Table 6.7: List of cut variables that are included within the shift/smear fit documented in [195].

| Category | Description |
|-----------------------|---|
| 1e | Only one electron above Cherenkov threshold in the final state |
| 1μ | Only one muon above Cherenkov threshold in the final state |
| 1e+other | One electron and one or more other charged particles above Cherenkov threshold in the final state |
| 1μ+other | One muon and one or more other charged particles above Cherenkov threshold in the final state |
| 1π ⁰ | Only one π ⁰ in the final state |
| 1π [±] or 1p | Only one hadron (typically charged pion or proton) in the final state |
| Other | Any other final state |

Table 6.8: Reconstructed event topology categories on which the SK detector systematics [195] are based.

“hybrid- π^0 samples is constructed. These events are built by overlaying one electron-like ring from the SK atmospheric neutrino samples or decay electron ring from a stopping cosmic ray muon with one simulated photon ring. Both rings are chosen so that momenta and opening angle follow the decay kinematics of NC π^0 events from the T2K-MC. Hybrid- π^0 Monte Carlo samples with both rings from the SK Monte Carlo are produced to compare with the hybrid- π^0 data samples and the difference in the fraction of events that pass the ν_e selection criteria is used to assign the systematic error. In order to investigate any data to Monte Carlo differences that may originate from either the higher energy ring or lower energy ring, two samples are built; a sample in which the electron constitutes the higher energy ring from the π^0 decay called the primary sample and another one in which it constitutes the lower energy

2049 ring called the secondary sample. The standard T2K ν_e `fiTQun` event selection criteria
2050 are used to select events.

2051 Final contributions to the covariance matrix are determined by supplementary
2052 uncertainties attained by comparing stopping muon data to Monte Carlo prediction,
2053 as first introduced in section 5.2. The efficiency of tagging decay electrons is estimated
2054 by the stopping muon data/Monte Carlo differences by comparing the number of
2055 one decay electron events to the number of events with one or fewer decay electrons.
2056 The rate at which fake decay electrons are reconstructed by `fiTQun` is estimated in a
2057 similar way with the only difference being the ratio compares the number of two decay
2058 electron events to the number of events with one or two reconstructed decay electrons.
2059 The two sources of systematics are added in quadrature weighted by the number of
2060 events with one true decay electron yielding a 0.2% systematic uncertainty. The muon
2061 misidentification rate is estimated by comparing the number of electron-like events
2062 which have one decay electron to the total number of events with one decay electron.
2063 This systematic is estimated as a 30% effect in the rate of muon misidentification.
2064 A fiducial volume systematic of $\pm 2.5\text{cm}$ which corresponds to a 0.5% shift in the
2065 normalisation of events. Additional normalisation uncertainties based on neutrino
2066 flavour and interaction mode are also defined in [183, 205, 206].

2067 This covariance matrix is then added in quadrature with two other covariance ma-
2068 trices. These are matrices that describe the uncertainties due to secondary interactions
2069 which modify the final state kinematics and the photo-nucleon interactions. These
2070 are generated by studying the effect of each sample's event rates when considering
2071 variations of the underlying parameters.

2072 **6.4.5.2 Atmospheric Samples**

2073 The systematic parameters which control the detector systematics are split into two
2074 sub-groups. Those which are related to particle identification and ring counting
2075 systematics and those which are related to calibration measurements.

2076 The particle identification systematics consist of five parameters. The ring sepa-
2077 ration systematic enforces an anti-correlated response between the single-ring and
2078 multi-ring samples. This is implemented as a fractional increase/decrease in the over-
2079 all normalisation of each sample, depending on the distance to the nearest wall from an
2080 event's vertex. The coefficients of the normalisation are estimated prior to the fit and
2081 depend on the atmospheric sample. The single-ring and multi-ring PID systematics
2082 encode the detector's ability to separate electron-like and muon-like events and are
2083 implemented in an identical way to the ring separation systematic.

2084 The multi-ring electron-like separation systematics encode the ability of the detector
2085 to separate neutrino from anti-neutrino events. As an important systematic in the mass
2086 hierarchy determination, this systematic controls the relative normalisation's of the ν_e
2087 and $\bar{\nu}_e$ enriched samples. A two-stage approach is implemented in the event selection
2088 and a systematic is implemented for both stages. The first stage in the event selection
2089 is to confirm that the most energetic ring, which is required to be electron-like, is from
2090 the neutrino interaction rather than a pion decay from any hadronic system present
2091 in the event. The second stage of separation uses a likelihood-based cut to separate
2092 $\nu_e/\bar{\nu}_e$ events. This takes the typical properties of ν_e scattering events into account;
2093 e.g. less forward-going, with larger energy fractions in the hadronic system. These
2094 parameters are implemented via normalisation parameters which vary the event rate
2095 of each multi-ring sample, whilst ensuring the total event rate is conserved.

2096 There are 22 systematics related to calibration measurements, including effects
2097 from backgrounds, reduction, and showering effects. They are documented in [89] and
2098 briefly summarised in Table 6.9. They are applied via normalisation parameters, with
2099 the separation systematics requiring the conservation of event rate across all samples.

Table 6.9: Sources of systematic errors specified within the grouped into the “calibration” systematics model.

| Index | Description |
|-------|--|
| 0 | Partially contained reduction |
| 1 | Fully contained reduction |
| 2 | Separation of fully contained and partially contained events |
| 3 | Separation of stopping and through-going partially contained events in top of detector |
| 4 | Separation of stopping and through-going partially contained events in barrel of detector |
| 5 | Separation of stopping and through-going partially contained events in bottom of detector |
| 6 | Background due to cosmic rays |
| 7 | Background due to flasher events |
| 8 | Vertex systematic moving events into and out of fiducial volume |
| 9 | Upward going muon event reduction |
| 10 | Separation of stopping and through-going in upward going muon events |
| 11 | Energy systematic in upward going muon events |
| 12 | Reconstruction of the path length of upward going muon events |
| 13 | Separation of showering and non-showering upward going muon events |
| 14 | Background of stopping upward going muon events |
| 15 | Background of non-showering through-going upward going muon events |
| 16 | Background of showering through-going upward going muon events |
| 17 | Efficiency of tagging two rings from π^0 decay |
| 18 | Efficiency of decay electron tagging |
| 19 | Background from downgoing cosmic muons |
| 20 | Asymmetry of energy deposition in tank |
| 21 | Energy scale deposition |

2100 **6.4.5.3 Correlated Detector Model**

2101 A complete uncertainty model of the SK detector would be able to determine the
2102 systematic shift on the sample spectra for a variation of the underlying parameters, e.g.
2103 PMT angular acceptance. However, this is computationally intensive, requiring Monte
2104 Carlo predictions to be made for each plausible variation. Consequently, an effective
2105 parameter model has been utilised for a correlated detector model. This follows from
2106 the T2K-only model implementation documented in subsubsection 6.4.5.1. The T2K-
2107 only implementation can not be used for atmospheric sample systematics because it
2108 is built upon a fit to atmospheric data. Consequently, an implementation where the
2109 cut distributions (given in Table 6.7) from both beam and atmospheric samples are fit,
2110 whilst simultaneously fitting for oscillation parameters. The fit to the cut variables
2111 performs a shape-only fit to ensure that no double-counting occurs.

2112 The correlated detector model utilises the same smear and shift parameters doc-
2113 umented in subsubsection 6.4.5.1, split by final state topology. This splitting is done
2114 because the detector will respond differently to events that have one or multiple rings.
2115 For example, the detector will be able to distinguish single-ring events better than
2116 two overlapping ring events, resulting in smaller systematic uncertainty for one-ring
2117 events compared to two-ring events. Furthermore, the shift and smear parameters
2118 are split by visible energy deposited within the tank has been included, with bin-
2119 ning specified in Table 6.10. This is because atmospheric events are categorised by
2120 subGeV and multiGeV events based on visible energy, so this splitting is required
2121 when correlating the systematic model for beam and atmospheric events. Alongside
2122 the technical requirement, higher energy events will be better reconstructed due to
2123 fractionally less noise within the detector. Consequently, this analysis correlates the
2124 detector systematics between the far-detector beam and subGeV atmospheric samples

2125 due to their similar energies and interaction types. As a result of the inclusion of
2126 visible energy binning, Equation 6.4 becomes

$$L_{jk}^i \rightarrow \bar{L}_{jk}^i = \alpha_{jk}^i L + \beta_{jk}^i, \quad (6.5)$$

2127 where k is the visible energy bin. The multi-GeV, multi-ring, PC, and Up- μ samples
2128 will be subject to the ATMPD particle identification systematics implementation as
2129 described in subsubsection 6.4.5.2 rather than using this correlated detector model.
2130 The calibration systematics also described in the aforementioned chapter still apply to
2131 all atmospheric samples.

| Index | Range (MeV) |
|-------|---------------------|
| 0 | $30 \geq x > 300$ |
| 1 | $300 \geq x > 700$ |
| 2 | $700 \geq x > 1330$ |
| 3 | $1330 \geq x$ |

Table 6.10: Reconstructed event topology categories on which the SK detector systematics are based

2132 The implementation of this systematic model takes the events reconstructed values
2133 of the cut parameters, modifies them by the particular shift and smear parameter for
2134 that event, and then re-applies event selection. This invokes event migration, which is
2135 a new feature incorporated into the MaCh3 framework which is only achievable due
2136 to the event-by-event reweighting scheme.

2137 Particular care has to be taken when varying the ring counting parameter. This
2138 is because the number of rings is a finite value (one-ring, two-rings, etc.) which
2139 can not be continuously varied. Consequently a ring counting parameter, RC_i , is
2140 calculated for the i^{th} event, following the definition in [207]. The likelihood from

2141 all considered one-ring ($1R$) and two-ring ($2R$) fits are compared to determine the
2142 preferred hypothesis. This is done by searching for the minimum log-likelihoods,
2143 $\log(L_{1R})$ and $\log(L_{2R})$. The difference is computed as $\Delta_{LLH} = \log(L_{1R}) - \log(L_{2R})$.
2144 The ring counting parameter is then defined as,

$$RC_i = \text{sgn}(\Delta_{LLH} - C_{Thres}) \times \sqrt{|\Delta_{LLH} - C_{Thres}|}, \quad (6.6)$$

2145 where $C_{Thres} = 150.0 - 0.6 \times P_{2R}$, and P_{2R} is the momentum of the preferred two-
2146 ring hypothesis, and $\text{sgn}(x) = x/|x|$. The coefficients used within the definition of
2147 C_{Thres} are calculated based on Monte Carlo studies. This ring counting parameter
2148 corresponds to an intermediate likelihood value used within the `fitQun` algorithm
2149 to decide the number of rings associated with a particular event. However, fake-ring
2150 merging algorithms are applied after this likelihood value is used to determine the
2151 number of rings associated with an event. Consequently, this ring counting parameter
2152 does not always exactly correspond to the number of reconstructed rings. This can be
2153 seen in Figure 6.10.

2154 As the `fitQun` algorithm does not provide a likelihood value after the fake-ring
2155 algorithms have been applied, the ring counting parameter distribution is connected to
2156 the final number of reconstructed rings through “maps”. These are two-dimensional
2157 distributions linking the ring counting parameter and the final number of recon-
2158 structed rings. An example is illustrated in Figure 6.11. In principle, the `fitQun`
2159 reconstruction algorithm should be re-run after the variation in the ring counting
2160 parameter. However, this is not computationally viable. Therefore the “maps” are
2161 used as a reweighting template.

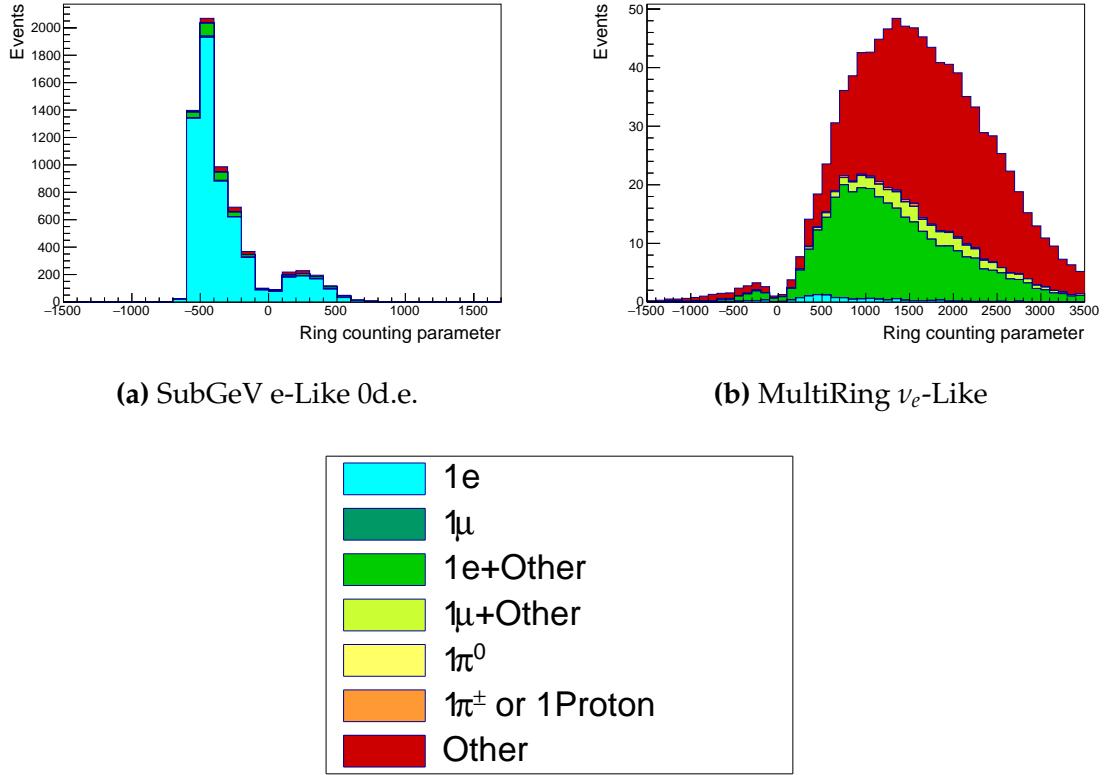


Figure 6.10: The ring counting parameter, as defined in Equation 6.6, for the subGeV electron-like zero decay electron and multi-ring ν_e -like samples.

The maps are split by final state topology and true neutrino flavour and all fiTQun-reconstructed Monte Carlo events are used to fill them. To ensure the conservation of event rate, the maps are normalised such that the total event rate across all number of reconstructed rings is equal to one. Prior to the fit, an event's nominal weight is calculated as $W(N_{Rings}^i, L_{jk}^i)$, where N_{Rings}^i is the reconstructed number of rings for the i^{th} event and $W(x, y)$ is the bin content in the associated map for x number of rings and ring counting parameter L . Then during the fit, the value of $R = W(N_{Rings}^i, \bar{L}_{jk}^i)/W(N_{Rings}^i, L_{jk}^i)$ is calculated as the ring-counting weight for the i^{th} event. This is the only cut variable that uses a reweighting scheme rather than event migration.

The π^0 systematics introduced in subsection 6.4.4 were expected to be applied via a covariance matrix. As this alternative technique performs a simultaneous fit

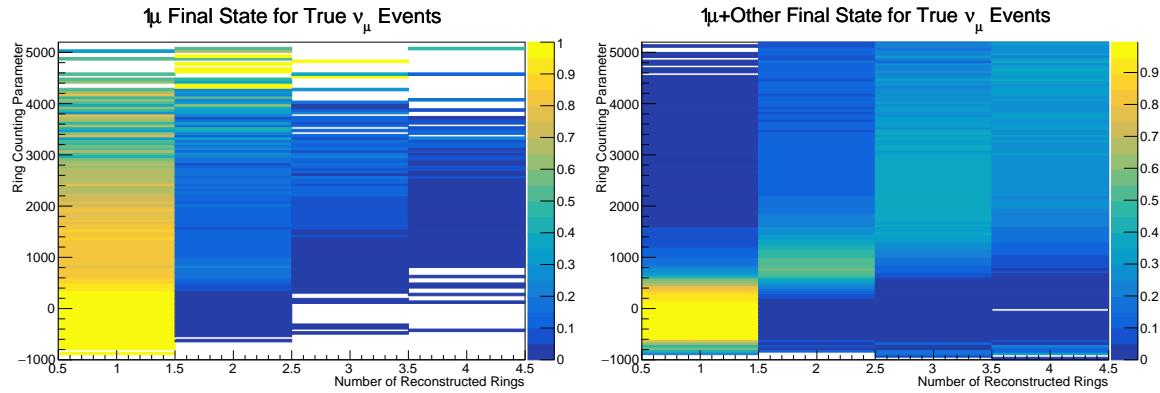


Figure 6.11: The ring counting parameter, defined in Equation 6.6, as a function of the number of reconstructed rings as found by the `fitQun` algorithm. Left: true ν_μ events with only one muon above the Cherenkov threshold in the final state. Right: true ν_μ events with one muon and at least one other charged particle above the Cherenkov threshold in the final state.

2174 between detector distributions and oscillation parameters, the implementation of the
 2175 π^0 systematics has been modified. In practice, the inputs from the hybrid π^0 sample
 2176 is included via the use of “ χ^2 maps”, which are two dimensional histograms in α
 2177 and β parameters over some range. Illustrative examples of the χ^2 maps are given
 2178 in Figure 6.12. Due to their nature, the shift and smear parameters are typically very
 2179 correlated.

2180 The maps are filled through the χ^2 comparison of the hybrid π^0 Monte Carlo and
 2181 data in the particle identification parameters documented in Table 6.7. The Monte
 2182 Carlo distribution is modified with the α and β scaling, whilst cross-section and flux
 2183 nuisance parameters are thrown from their prior uncertainties, and the χ^2 between
 2184 the scaled Monte Carlo and data is calculated and the relevant point in the χ^2 map is
 2185 filled. Then in the fit, the likelihood penalty term is found for the particular particle
 2186 identification parameter by using the value of the relevant χ^2 map for the α and β
 2187 parameter at that step in the MCMC fit. For this fit, only $1\pi^0$ final state topology shift
 2188 and smear parameters use the hybrid $\pi^0 \chi^2$ prior uncertainty.

2189 Similarly, the supplementary systematics which are added into the covariance from
 2190 stopping muon and decay electron studies need to be included. A new framework

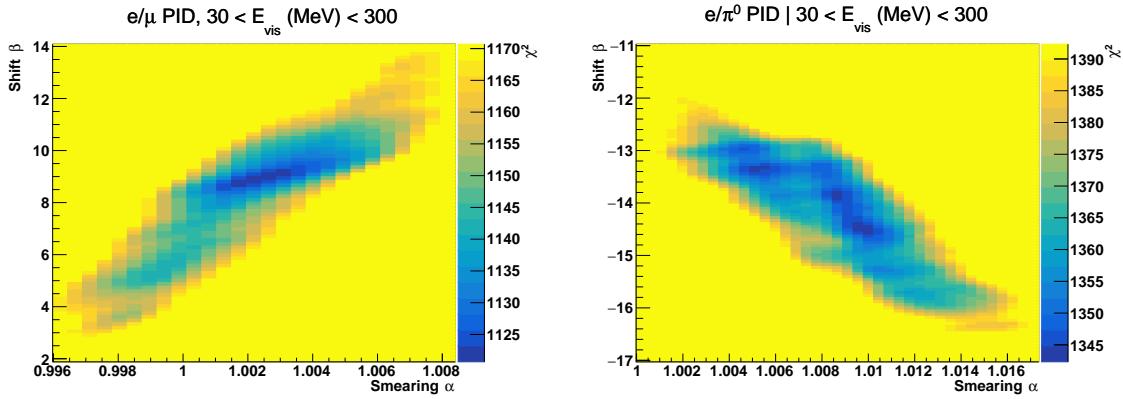


Figure 6.12: The χ^2 between the hybrid- π^0 Monte Carlo and data samples, as a function of smear (α) and shift (β) parameters, for events which have $1\pi^0$ final state topology. Left: Electron-muon separation PID parameter for events with $30 \geq E_{vis}(\text{MeV}) < 300$. Right: Electron- π^0 separation PID parameter for events with $30 \geq E_{vis}(\text{MeV}) < 300$.

[208] was built in tandem with the T2K-SK working group [183] so the additional parameters can be incorporated into the MaCh3 framework. These are applied as normalisation parameters, depending on the particular interaction mode, number of tagged decay electrons, and whether the primary particle generated Cherenkov light. They are assigned Gaussian uncertainties with widths described by a covariance matrix.

Finally, the secondary interaction and photo-nuclear effects need to be accounted for in this detector model. In the T2K-only analysis, a covariance matrix was built to describe the response of the samples to variations of these parameters which was then added in quadrature to the detector covariance matrix. However, this technique can not be applied in the correlated detector model. Consequently, a binned response of each of the secondary interaction systematic parameters and the photo-nuclear response was generated and included through splined shape parameters, similar to the application of shape parameters in the cross-section model (see subsection 6.4.3).

There are a total of 224 α_{jk}^i and β_{jk}^i parameters, of which 32 have prior constraints from the hybrid π^0 samples.

2207 One final complexity of this correlated detector model is that the two sets of sam-
 2208 ples, beam and subGeV atmospheric, use slightly different parameters to distinguish
 2209 electron and muon-like events. The beam-only events use the $\log(L_e/L_\mu)$ whereas
 2210 the atmospheric samples use $\log(L_e/L_\pi)$, where L_X is the likelihood for hypothesis X.
 2211 This is because the beam-only fits use single-ring `fitQun` fitting techniques, whereas
 2212 multi-ring fits are applied to the atmospheric samples where only the electron and
 2213 pion hypothesis are considered. As discussed in section 5.2, the pion hypothesis is
 2214 a very good approximation of the muon hypothesis due to their similar mass. The
 2215 correlation between the two likelihood ratios is illustrated in Figure 6.13. A very
 2216 strong correlation is clearly shown. Consequently, using the same shift and smear
 2217 parameters correlated between the beam and subGeV atmospheric samples is a good
 2218 approximation.

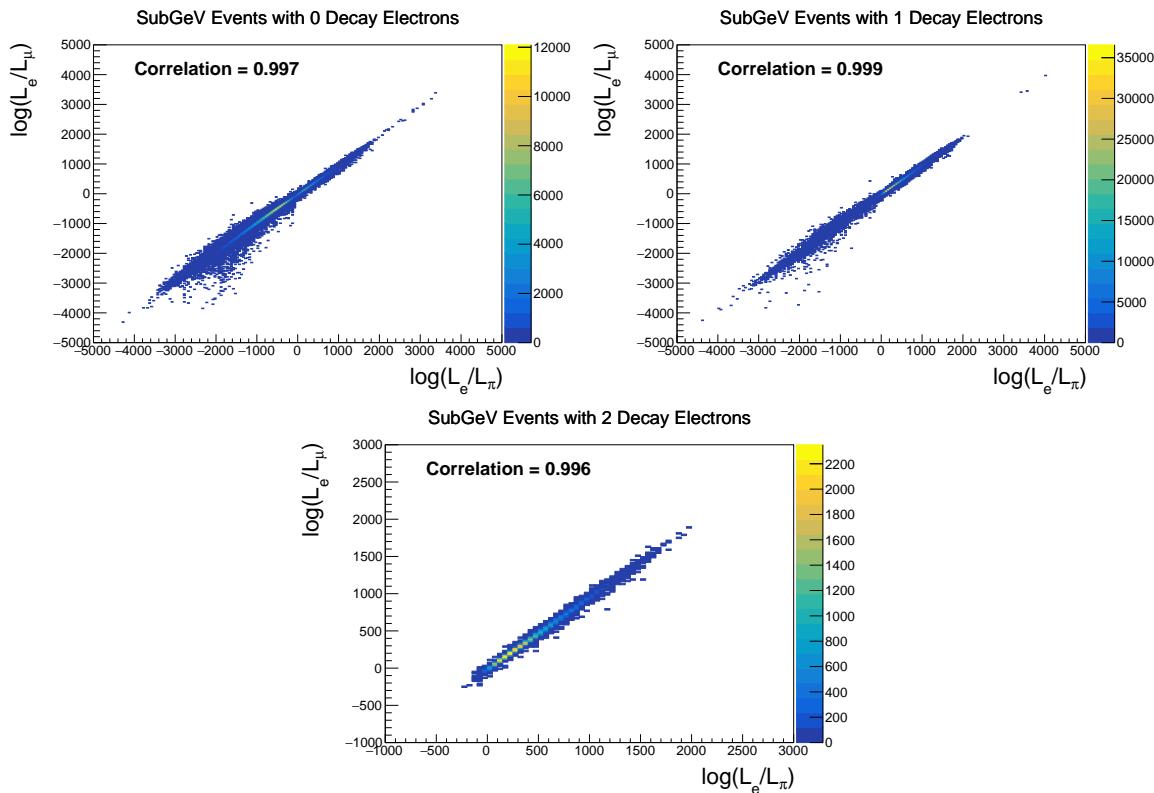


Figure 6.13: The distribution of $\log(L_e/L_\mu)$ compared to $\log(L_e/L_\pi)$ for subGeV events with zero (top left), one (top right) or two (bottom) decay electrons. The correlation in the distribution is calculated as 0.997, 0.999 and 0.996, respectively.

2219

Chapter 7

2220

Oscillation Probability Calculation

2221 It is important to understand how and where the sensitivity to the oscillation pa-
2222 rameters comes from for both atmospheric and beam samples. An overview of how
2223 these samples observe changes in δ_{CP} , Δm_{23}^2 , and $\sin^2(\theta_{23})$ is given in section 7.1. It
2224 also explains the additional complexities involved when performing an atmospheric
2225 neutrino analysis as compared to a beam-only analysis.

2226 Without additional techniques, atmospheric sub-GeV upward-going neutrinos
2227 ($E_\nu < 1.33\text{GeV}, \cos(\theta_Z) < 0.$) can artificially inflate the sensitivity to δ_{CP} due to the
2228 quickly varying oscillation probability in this region. Therefore, a “sub-sampling”
2229 approach has been developed to reduce these biases ensuring accurate and reliable
2230 sensitivity measurements. This technique ensures that small-scale unresolvable fea-
2231 tures of the oscillation probability have been averaged over whilst the large-scale
2232 features in the oscillation probability are unaffected. The documentation and valida-
2233 tion of this technique are found in section 7.2. The oscillation probability calculation is
2234 computationally intensive due to the large number of matrix multiplications needed.
2235 Consequently, the CUDAProb3 implementation choice made within the fitting frame-
2236 work, as detailed in section 7.3, ensures that the analysis can be done in a timely
2237 manner.

2238 Whilst the beam neutrinos are assumed to propagate through a constant density
2239 slab of material, the density variations through the Earth result in more complex
2240 oscillation patterns. Furthermore, the uncertainty in the electron density can modify
2241 the oscillation probability for the denser core layers of the Earth. The model of the

2242 Earth used within this analysis is detailed in section 7.4. This includes information
 2243 about the official SK-only methodology as well as improvements that can be made
 2244 to remove some of the approximations made in that analysis. Another complexity of
 2245 atmospheric neutrinos oscillation studies is that the height of production in the atmo-
 2246 sphere is not known on an event-by-event basis. An analytical averaging technique
 2247 that approximates the uncertainty of the oscillation probability has been followed,
 2248 with the author of this thesis being responsible for the implementation and validation.
 2249 This implementation of an external technique is illustrated in section 7.5.

2250 7.1 Overview

2251 DB: Should this be moved into an earlier chapter? The selections chapter references
 2252 the matter resonance which has not yet been explained at that point

2253 The analysis presented within this thesis focuses on the determination of oscillation
 2254 parameters from atmospheric and beam neutrinos. Whilst subject to the same oscil-
 2255 lation formalism, the way in which the two samples have sensitivity to the different
 2256 oscillation parameters differs quite significantly.

2257 Atmospheric neutrinos have a varying baseline, or “path length”, L , such that
 2258 the distance each neutrino travels before interacting is dependent upon the zenith
 2259 angle, θ_Z . As primary cosmic rays can interact anywhere between the Earth’s surface
 2260 and $\sim 50\text{km}$ above that, the height, h , in the atmosphere at which the neutrino was
 2261 generated also affects the path length,

$$L = \sqrt{(R_E + h)^2 - R_E^2 (1 - \cos^2(\theta_Z))} - R_E \cos(\theta_Z). \quad (7.1)$$

2262 Where $R_E = 6,371\text{km}$ is the Earth's radius. Consequently, the oscillation probabil-
2263 ity is dependent upon two parameters, $\cos(\theta_Z)$ and E_ν .

2264 The oscillation probability used within this analysis is based on [21]. The neutrino
2265 wavefunction in the vacuum Hamiltonian evolves in each layer of constant matter
2266 density via

$$i \frac{d\psi_j(t)}{dt} = \frac{m_j^2}{2E_\nu} \psi_j(t) - \sum_k \sqrt{2} G_F N_e U_{ej} U_{ke}^\dagger \psi_k(t), \quad (7.2)$$

2267 where m_j^2 is the square of the j^{th} vacuum eigenstate mass, E_ν is the neutrino
2268 energy, G_F is Fermi's constant, N_e is the electron number density and U is the PMNS
2269 matrix. The transformation $N_e \rightarrow -N_e$ and $\delta_{CP} \rightarrow -\delta_{CP}$ is applied for antineutrino
2270 propagation. Thus, a model of the Earth's density is required for atmospheric neutrino
2271 propagation. Following the official SK-only methodology [209], this analysis uses the
2272 Preliminary Reference Earth Model (PREM) [210]. This model provides piecewise cubic
2273 polynomials as a function of the Earth's radius which results in the density profile
2274 illustrated in Figure 7.1. As discussed, the propagator requires layers of constant
2275 density. The SK methodology approximates the PREM model by using four layers of
2276 constant density [209]. The details of these layers are detailed in Table 7.1.

| 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 7.1: Description of the four layers of the Earth invoked within the constant density approximation of the PREM model [210].

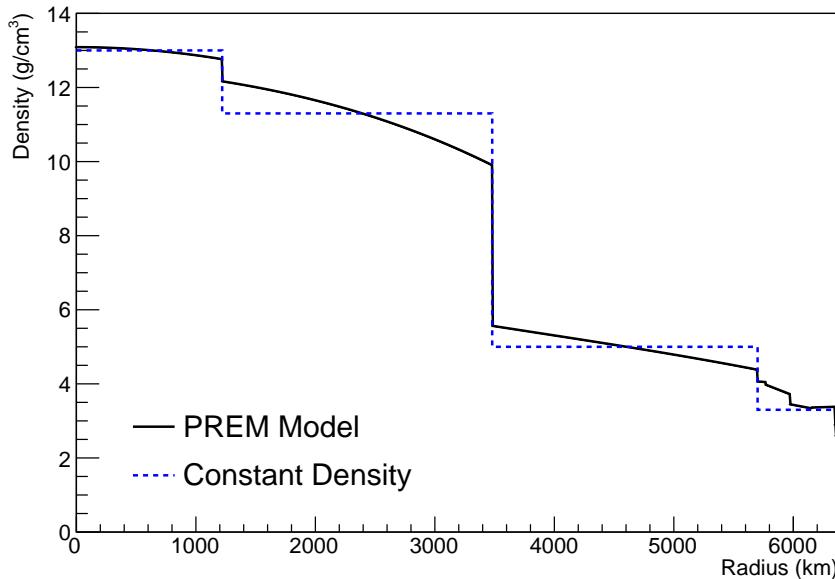


Figure 7.1: The density of the Earth given as a function of the radius, as given by the PREM model (Black), and the constant density four-layer approximation (Blue), as used in the official SK-only analysis.

2277 The atmospheric neutrino oscillation probabilities can be presented as two dimen-
 2278 sional “oscillograms” as illustrated in Figure 7.2. The distinct discontinuities, as a
 2279 function of $\cos(\theta_Z)$, are due to the discrete change in density invoked within the PREM
 2280 model.

2281 Atmospheric neutrinos do have sensitivity to δ_{CP} through a normalisation term.
 2282 Figure 7.3 illustrates the difference in oscillation probability between CP-conserving
 2283 ($\delta_{CP} = 0$) and a CP-violating ($\delta_{CP} = -1.601$) value taken from Asimov A oscillation
 2284 parameter set (Table 2.2). The result is a complicated oscillation pattern in the appear-
 2285 ance probability for sub-GeV upgoing neutrinos. The detector does not have sufficient
 2286 resolution to resolve these individual patterns so the sensitivity to δ_{CP} for atmospheric
 2287 neutrinos comes via the overall normalisation of these events.

2288 The presence of matter means that the effect δ_{CP} has on the oscillation probability
 2289 is not equal between neutrinos and antineutrinos, which would be expected when
 2290 propagating through a vacuum. This is further extenuated by the fact that SK can

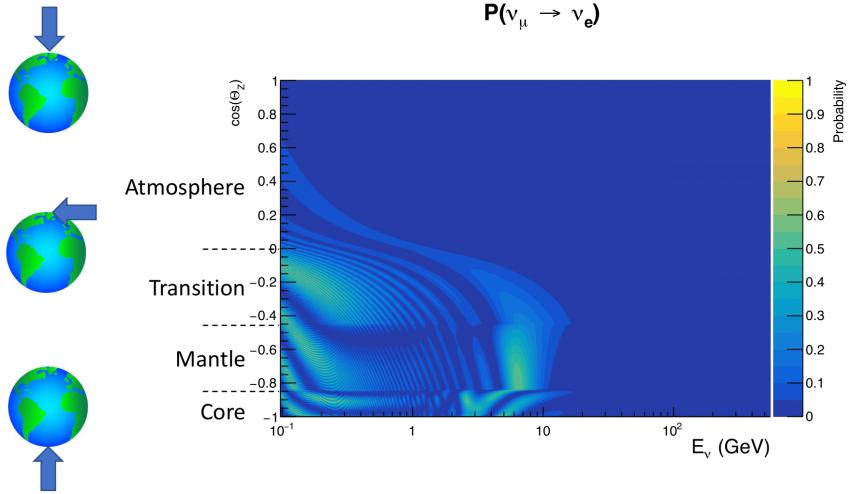


Figure 7.2: An “oscillogram” that depicts the $P(\nu_\mu \rightarrow \nu_e)$ oscillation probability as a function of neutrino energy and cosine of the zenith angle. The zenith angle is defined such that $\cos(\theta_Z) = 1.0$ represents neutrinos that travel from directly above the detector. The four-layer constant density PREM model approximation is used and Asimov A oscillation parameters are assumed (Table 2.2).

2291 not distinguish neutrinos and antineutrinos well and that the cross-section neutrino
 2292 interaction is larger than that for antineutrinos. Finally, sample selections (discussed
 2293 in section 6.1) targeting different neutrino interaction modes result in an imbalance
 2294 in the percentage of neutrinos to anti-neutrinos. This is because negatively charged
 2295 pions from antineutrino interactions are more likely to be captured by a nucleus
 2296 compared to a positively charged pion. All of these effects lead to a difference in the
 2297 number of neutrinos detected compared to antineutrinos. This changes how the δ_{CP}
 2298 normalisation term is observed, resulting in a very complex sensitivity to δ_{CP} .

2299 Atmospheric neutrinos are subject to matter effects as they travel through the dense
 2300 matter in the Earth. The vacuum and matter oscillation probabilities for $P(\nu_e \rightarrow \nu_e)$
 2301 and $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ are presented in Figure 7.4, where the PREM model has been assumed.
 2302 The oscillation probability for both neutrinos and antineutrinos is affected in the
 2303 presence of matter. However, the resonance effects around $O(5)\text{GeV}$ only occur for
 2304 neutrinos in normal mass hierarchy and antineutrinos in inverse mass hierarchy. The

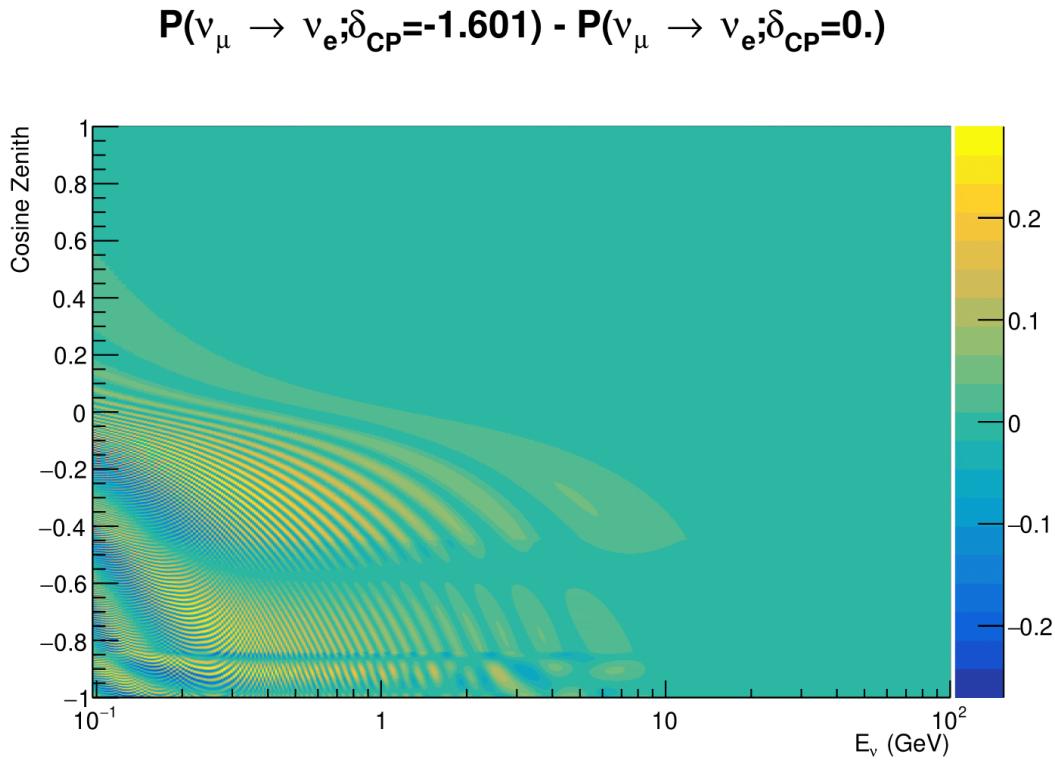


Figure 7.3: The effect of δ_{CP} for atmospheric neutrinos given in terms of the neutrino energy and zenith angle. This oscillogram compares the $P(\nu_\mu \rightarrow \nu_e)$ oscillation probability for a CP conserving ($\delta_{CP} = 0.0$) and a CP violating ($\delta_{CP} = -1.601$) value taken from the Asimov A parameter set. The other oscillation parameters assume the Asimov A oscillation parameter set given in Table 2.2.

2305 exact position and amplitude of the resonance depend on $\sin^2(\theta_{23})$ meaning that the
 2306 atmospheric neutrinos have sensitivity to $\sin^2(\theta_{23})$.

2307 As the T2K beam flux is centered at the first oscillation maximum ($E_\nu = 0.6\text{GeV}$),
 2308 the sensitivity to δ_{CP} is predominantly observed as a change in the event-rate of e-like
 2309 samples in $\nu/\bar{\nu}$ modes. Figure 7.5 illustrates the $P(\nu_\mu \rightarrow \nu_e)$ oscillation probability
 2310 for a range of δ_{CP} values. A circular modulation of the first oscillation peak (in both
 2311 magnitude and position) is observed when varying throughout the allowable values
 2312 of δ_{CP} . The CP-conserving values of $\delta_{CP} = 0, \pi$ have a lower(higher) oscillation
 2313 maximum than the CP-violating values of $\delta_{CP} = -\pi/2 (\delta_{CP} = \pi/2)$. A sub-dominant

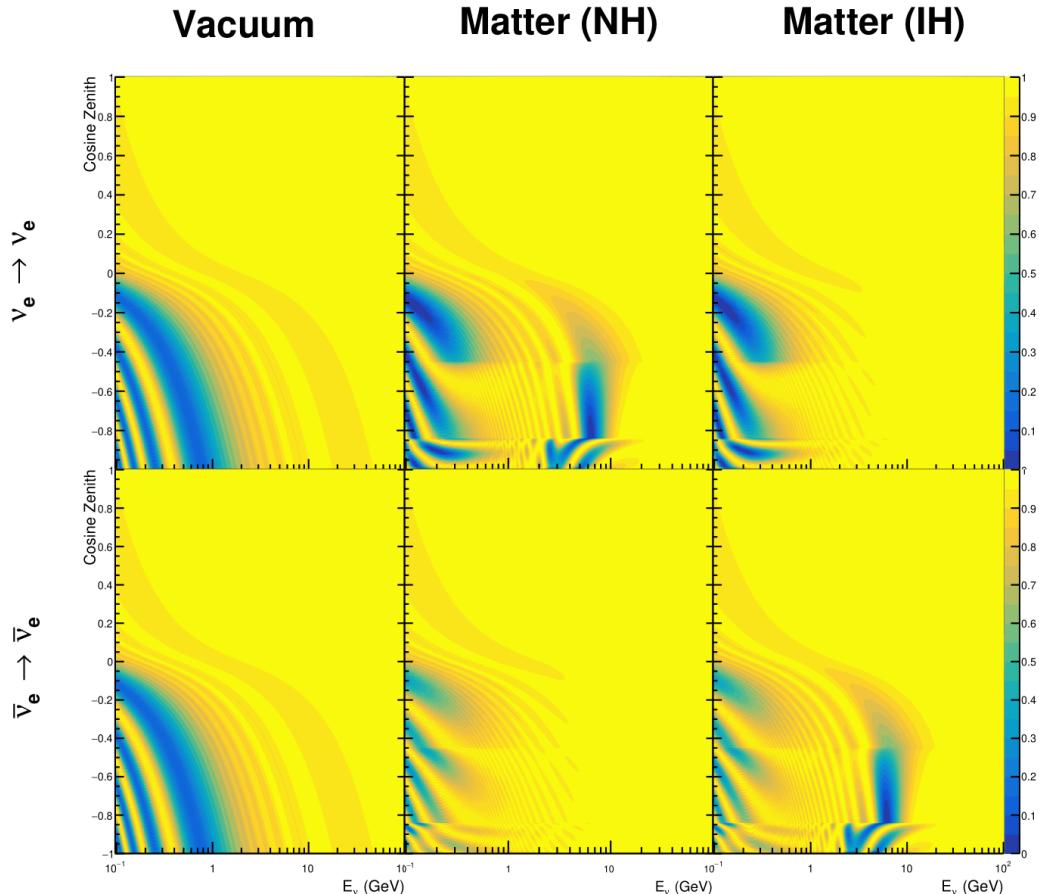


Figure 7.4: An illustration of the matter-induced effects on the oscillation probability, given as a function of neutrino energy and zenith angle. The top row of panels gives the $P(\nu_e \rightarrow \nu_e)$ oscillation probability and the bottom row illustrates the $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ 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 2.2, 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.

²³¹⁴ shift in the energy of the oscillation peak is also present to aid in separating the two

²³¹⁵ CP-conserving values of δ_{CP} .

²³¹⁶ T2K’s sensitivity to the $\sin^2(\theta_{23})$ and Δm_{23}^2 is observed as a shape-based variation

²³¹⁷ of the muon-like samples, as illustrated in Figure 7.5. The value of Δm_{32}^2 laterally shifts

²³¹⁸ the position of the oscillation dip (around $E_\nu \sim 0.6\text{GeV}$) in the $P(\nu_\mu \rightarrow \nu_\mu)$ oscillation

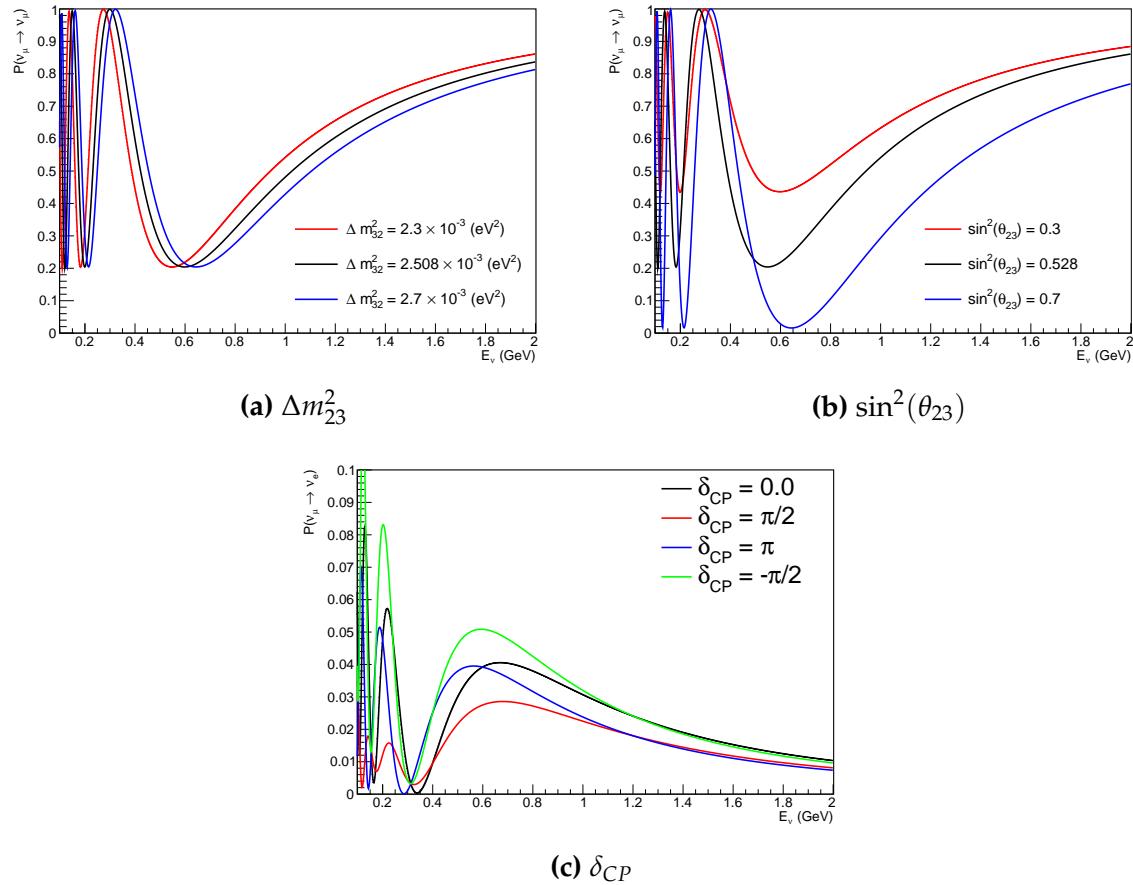


Figure 7.5: The oscillation probability for beam neutrino events given as a function of neutrino energy. All oscillation parameters assume the “Asimov A” set given in Table 2.2 unless otherwise stated. Each panel represents a change in one of the oscillation parameters whilst keeping the remaining parameters 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 7.6.

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

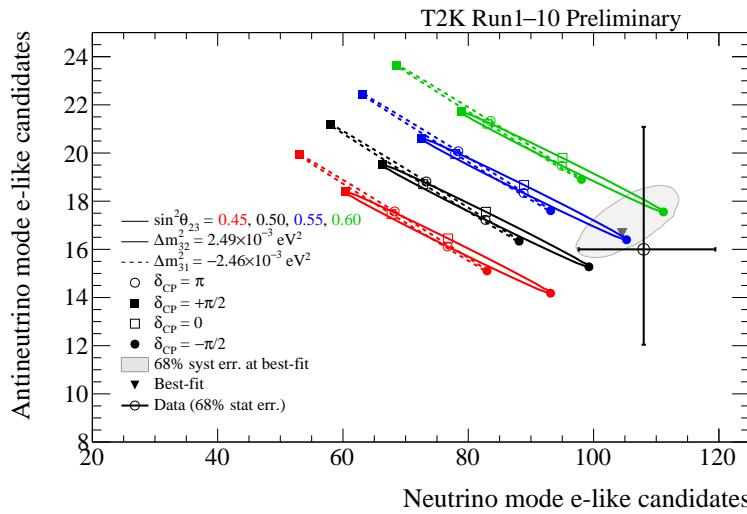


Figure 7.6: The number of electron-like events in the FHC and RHC operating mode of the beam, as a function of the oscillation probabilities. Both normal hierarchy (Solid) and inverse hierarchy (Dashed) values of Δm_{23}^2 are given.

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

2339 7.2 Treatment of Fast Oscillations

2340 As shown in Figure 7.7, atmospheric neutrino oscillations have a significantly more
2341 complex structure for upgoing neutrinos with energy below 1GeV. This is because the
2342 L/E dependence of the oscillation probability in this region induces rapid variations
2343 for small changes in L or E . As discussed in section 7.1, this is also the region in which
2344 atmospheric neutrinos have sensitivity to δ_{CP} . In practice, the direction of the neutrino
2345 is inferred from the direction of the final state particles traveling in the detector, which
2346 can be poor for low-energy neutrino interactions. This creates a distinct difference
2347 from the beam neutrinos where the position of the source is very precisely known.

2348 As a consequence of the unresolvable structure, an average oscillation probability
2349 is observed in the subGeV upgoing region. This creates a computational problem; A
2350 significantly large amount of Monte Carlo statistics would be required to accurately
2351 predict the number of events if Monte Carlo averaging was the only technique used.
2352 This section describes the ‘sub-sampling’ approach developed for this analysis and
2353 compares it to the methodology used within the SK-only analysis.

2354 The official SK-only analysis uses the osc3++ oscillation parameter fitter [209].
2355 To perform the fast oscillation averaging, it uses a ‘nearest-neighbour’ technique.
2356 For a given neutrino event, the nearest twenty neighbours in reconstructed lepton
2357 momentum and zenith angle are found and a distribution of their neutrino energies is
2358 built. The RMS, σ , of this distribution is then used to compute an average oscillation
2359 probability for the given neutrino Monte Carlo event.

2360 For the i^{th} event, the oscillation weight is calculated as

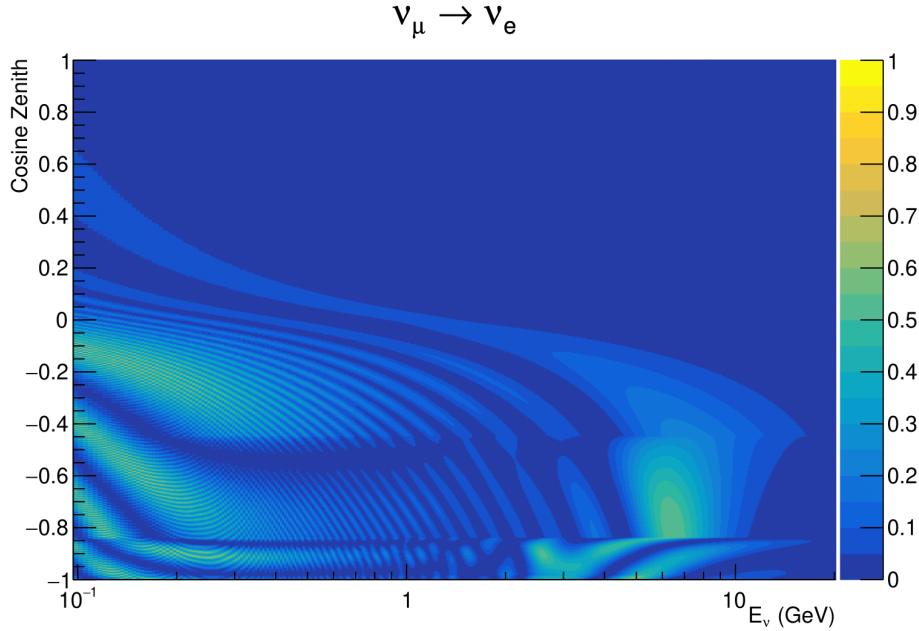


Figure 7.7: The oscillation probability $P(\nu_\mu \rightarrow \nu_e)$, given as a function of neutrino energy and zenith angle, which highlights an example of the “fast” oscillations in the sub-GeV upgoing region.

$$W_i = \frac{1}{5}P(E_i, \bar{L}_i) + \frac{1}{5} \sum_{\beta=-1,-0.5,0.5,1} P(E_i + \beta\sigma_i, L_\beta), \quad (7.3)$$

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,

$$\begin{aligned}
 L_{-1.0} &= \frac{1}{4}L(45, 50, 55, 60), \\
 L_{-0.5} &= \frac{1}{4}L(35, 40, 65, 70), \\
 L_{+0.5} &= \frac{1}{4}L(25, 30, 75, 68), \\
 L_{+1.0} &= \frac{1}{4}L(15, 20, 85, 89).
 \end{aligned} \tag{7.4}$$

2371 This averaging technique works because of the inference between the zenith angle
 2372 and the reconstructed direction of final state particles in the detector. For low-energy
 2373 neutrinos, where the resolution of the true neutrino direction is poor, σ_i will be large,
 2374 resulting in significant averaging effects. Contrary to this, the inferred direction of
 2375 high-energy neutrinos will be much closer to the true value, meaning that σ_i will be
 2376 smaller, culminating in small averaging effects.

2377 In practice, this technique is performed before the fit in order to deal with the
 2378 computational cost. This is possible as the Osc3++ framework uses binned oscillation
 2379 parameters rather than continuous so the oscillation parameters used in the fit are
 2380 known prior to run-time. The framework used in this analysis uses continuous
 2381 oscillation parameters, and due to the MCMC fitting technique, there is no way to
 2382 know which oscillation parameter values will be selected *a priori*. Therefore, the
 2383 oscillation parameter calculation has to be performed at run-time. Computing five
 2384 oscillation probabilities per event would require far too many computational resources
 2385 to be viable. Therefore SK technique can not be used within this analysis. However,
 2386 the concept of the averaging technique can be taken from it.

2387 To perform a similar averaging as the SK analysis, a sub-sampling approach using
 2388 binned oscillograms has been devised. The technique can be explained by considering
 2389 a “fine” and “coarse” oscillogram. The fine oscillograms are used to define the array of

2390 $\cos(\theta_Z)$ and E_ν used in the oscillation engine. The coarse oscillograms cover the same
2391 phase-space but have fewer bins, where the value of a particular coarse bin is taken
2392 as the linear average (flat prior in E_ν and $\cos(\theta_Z)$) of all fine bins which falls into it.
2393 The coarse oscillogram is then used for determining the oscillation weight for a given
2394 event. The binning which is used to calculate the oscillation probabilities, known as
2395 the ‘fine’ binning, has $N \times N$ subdivisions per coarse bin. Figure 7.8 illustrates the
2396 $N = 2$ example where the assigned value to a coarse bin is the average of the four fine
2397 bins which fall in that coarse bin. Whilst the coarse bin edges do not have to be linear
2398 on either axis, the sub-division of the fine bins is linear over the range of a coarse bin.

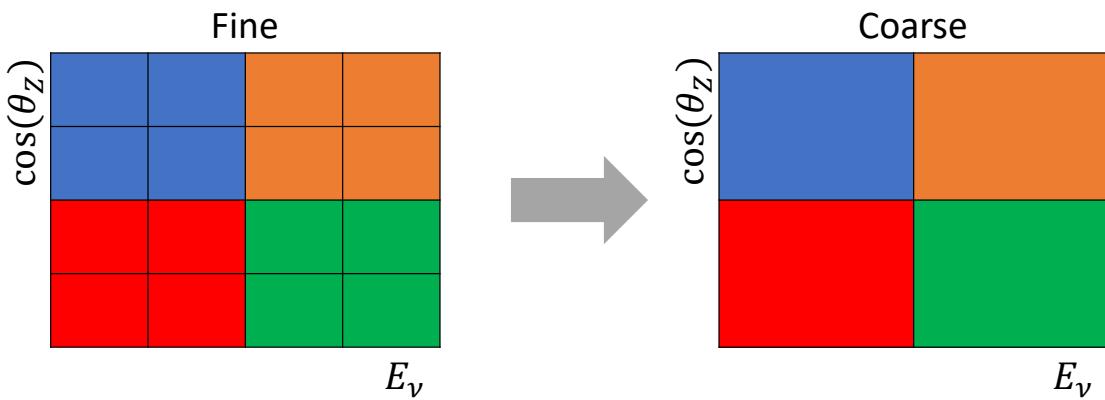


Figure 7.8: Illustration of the averaging procedure for $N = 2$. The oscillation probabilities calculated on the finer left binning are averaged to obtain the oscillation probabilities in the coarser right binning. These averaged oscillation probabilities with the coarser binning are then applied to each event during the fit.

2399 The coarse binning is defined with 67×52 bins in true neutrino energy \times cosine
2400 zenith. It is picked to be identical to that provided in [211]. In general, the binning is
2401 logarithmically spaced in neutrino energy but has some hand-picked bin edges. Firstly,
2402 the bin density around the matter resonance is smoothly increased around the matter
2403 resonance region. This is to avoid smearing this region which can be well sampled by
2404 the Monte Carlo. Secondly, bin edges are selected to hit $0.4, 0.6, 1, 10, 30, 50, 100\text{GeV}$.
2405 This is to ensure that the Coulomb correction systematic and the atmospheric flux
2406 systematics definitions in neutrino energy can be hit. The cosine zenith binning is

2407 approximately linearly spaced across the allowable range but the values of layer
2408 transitions are hit precisely: -0.8376 (core-mantle) and -0.4464 (mantle/transition
2409 zone). Bins are spread further apart for downgoing events as this is a region unaffected
2410 by the fast oscillation wavelengths and reduces the total number of calculations
2411 required to perform the calculation.

2412 The choice of N is justified based on two studies. Firstly, the variation of event rates
2413 of each sample is studied as a function of N . For a given set of oscillation parameters
2414 thrown from the PDG prior constraints (detailed in Table 2.1), the oscillation probabili-
2415 ties are calculated using a given value of N . Each sample is re-weighted and the event
2416 rate is stored. The value of N is scanned from 1, which corresponds to no averaging, to
2417 24, which corresponds to the largest computationally viable subdivision binning. The
2418 event rate of each sample at large N is expected to converge to a stationary value due
2419 to the fine binning fully sampling the small-scale structure. Figure 7.9 illustrates this
2420 behaviour for the SubGeV_elike_0dcy sample for 30 different throws of the oscillation
2421 parameters.

2422 Denoting the event rate for one sample for a given throw t at each N by λ_t^N , the
2423 average over all considered N values ($\bar{\lambda}_t = \frac{1}{24} \sum_{N=1}^{24} \lambda_t^N$) is computed. The variance in
2424 the event rate at each N is then calculated as

$$\text{Var}[\lambda^N] = \frac{1}{N_{\text{throws}}} \sum_{t=1}^{N_{\text{throws}}} (\lambda_t^N - \bar{\lambda}_t)^2 - \left[\frac{1}{N_{\text{throws}}} \sum_{t=1}^{N_{\text{throws}}} (\lambda_t^N - \bar{\lambda}_t) \right]^2. \quad (7.5)$$

2425 The aim of the study is to find the lowest value of N such that this variance is
2426 below 0.001. This is the typical threshold used by T2K fitters to validate systematic
2427 implementation so has been set as the same criteria. The results of this study for
2428 each atmospheric sample used within this thesis are illustrated in Figure 7.10 for

SubGeV-elike-0dcy

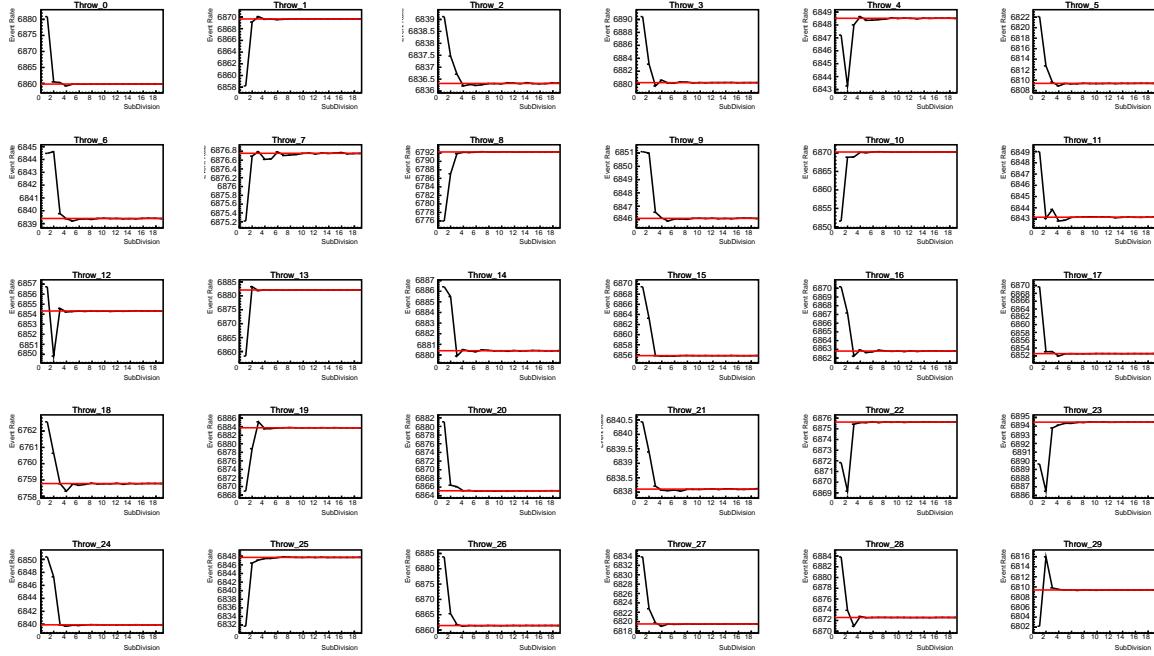


Figure 7.9: Event rate of the SubGeV_elike_0dcy sample as a function of the number of subdivisions per coarse bin. Each subplot represents the event rate of the sample at a different oscillation parameter set thrown from the PDG priors detailed in Table 2.1. The red line in each subplot represents the mean of the event rate over the different values of sub-divisions for that particular oscillation parameter throw.

2429 2000 throws of the oscillation parameters. As can be seen, the variance is below
 2430 the threshold at $N = 10$, and is driven primarily by the SubGeV_mulike_1dcy and
 2431 SubGeV_elike_0dcy samples.

2432 The second study to determine the value of N is as follows. The likelihood for each
 2433 sample is computed against an Asimov data set created with Asimov A oscillation
 2434 parameters (Table 2.2). Following Equation 7.5, the variance of the log-likelihood over
 2435 all considered N is computed. The results are shown in Figure 7.11.

2436 A choice of $N = 10$ sub-divisions per coarse bin has a variance in both event rate
 2437 and log-likelihood residuals less than the required threshold of 0.001. The largest
 2438 value of the likelihood variance is of order 10^{-7} , corresponding to an error on the log-

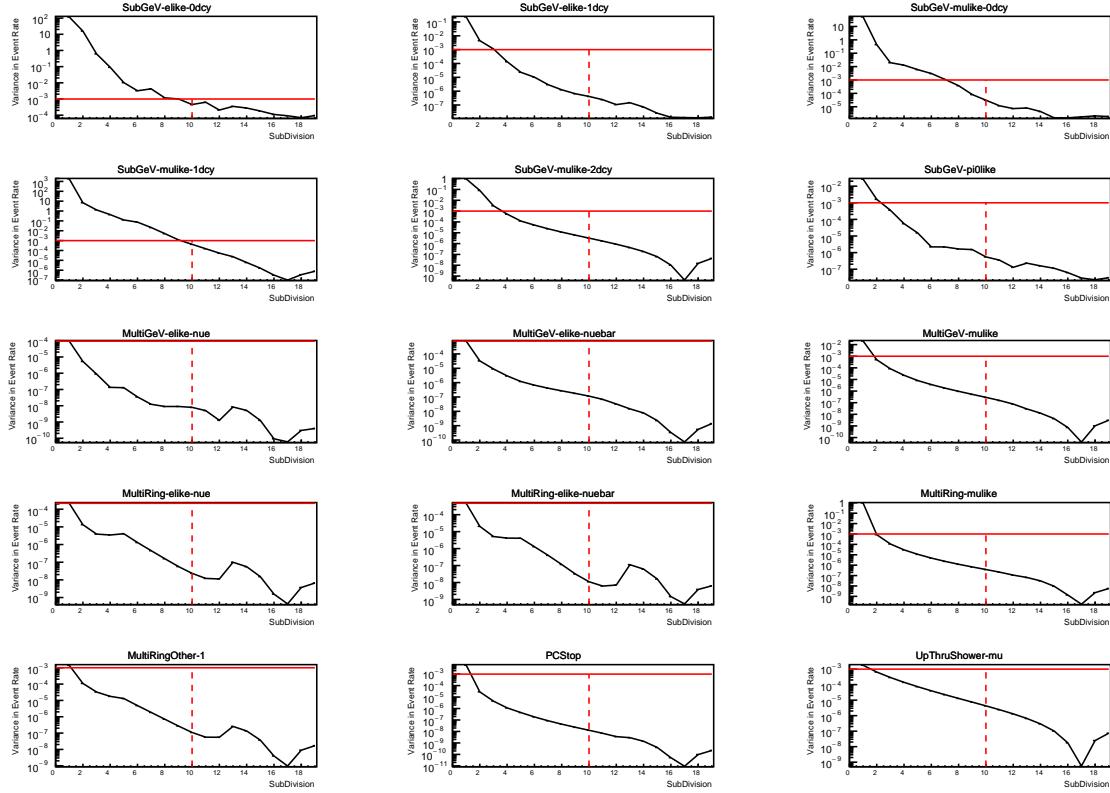


Figure 7.10: Variance of event rate for each atmospheric sample as a function of the number of sub-divisions per coarse bin. The solid red line indicates the 0.1% threshold and the dashed red line indicates the variance at a sub-division $N = 10$.

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

Figure 7.12 illustrates the effect of the smearing using $N = 10$. The fast oscillations in the sub-GeV upgoing region have been replaced with a normalisation effect whilst the large matter resonance structure remains.

7.3 Calculation Engine

As previously discussed in section 7.2, the calculation of oscillation probabilities is performed at run-time due to utilising continuous oscillation parameters. Consequently, the time per calculation is crucial for fit performance. The initial fitting framework

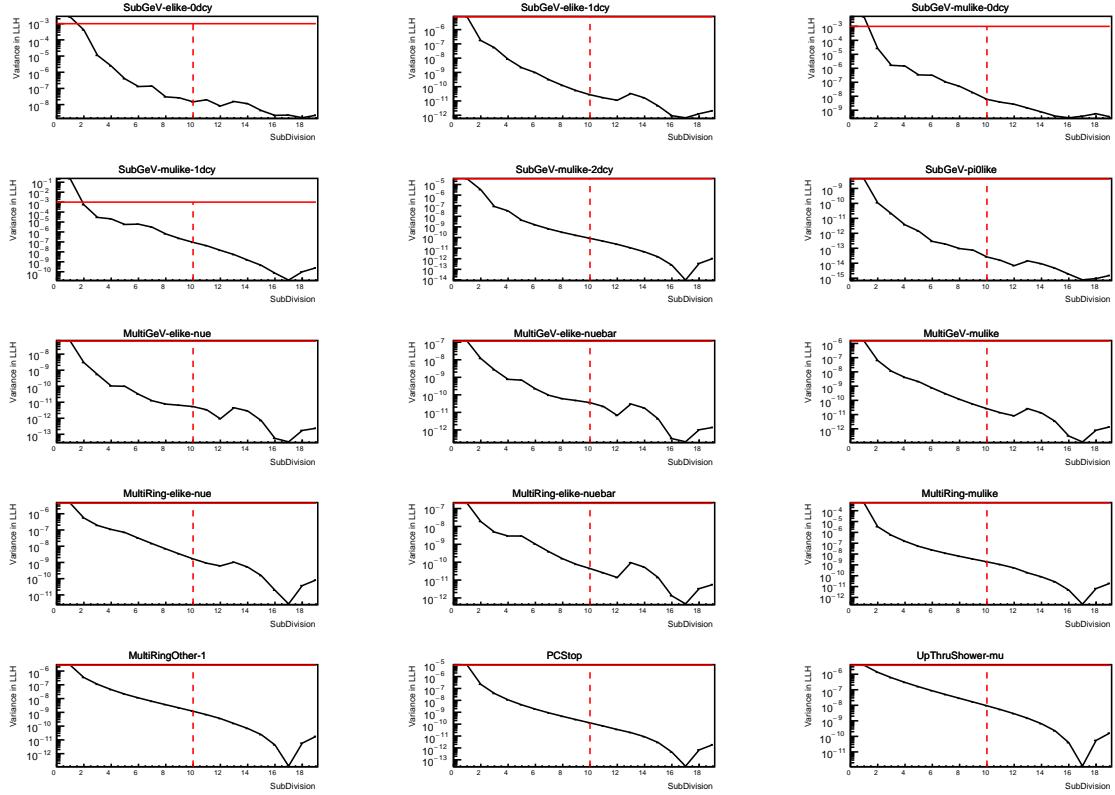


Figure 7.11: Variance of sample likelihood, when compared to ‘Asimov data’ set at Asimov A, for each atmospheric sample as a function of the number of sub-divisions per coarse bin. The solid red line indicates the 0.1% threshold and the dashed red line is a graphical indication of the variance at a sub-division $N = 10$.

used for this analysis was developed with ProbGPU [212]. This is a GPU-only implementation of the prob3 engine [213]. 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 [214], 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

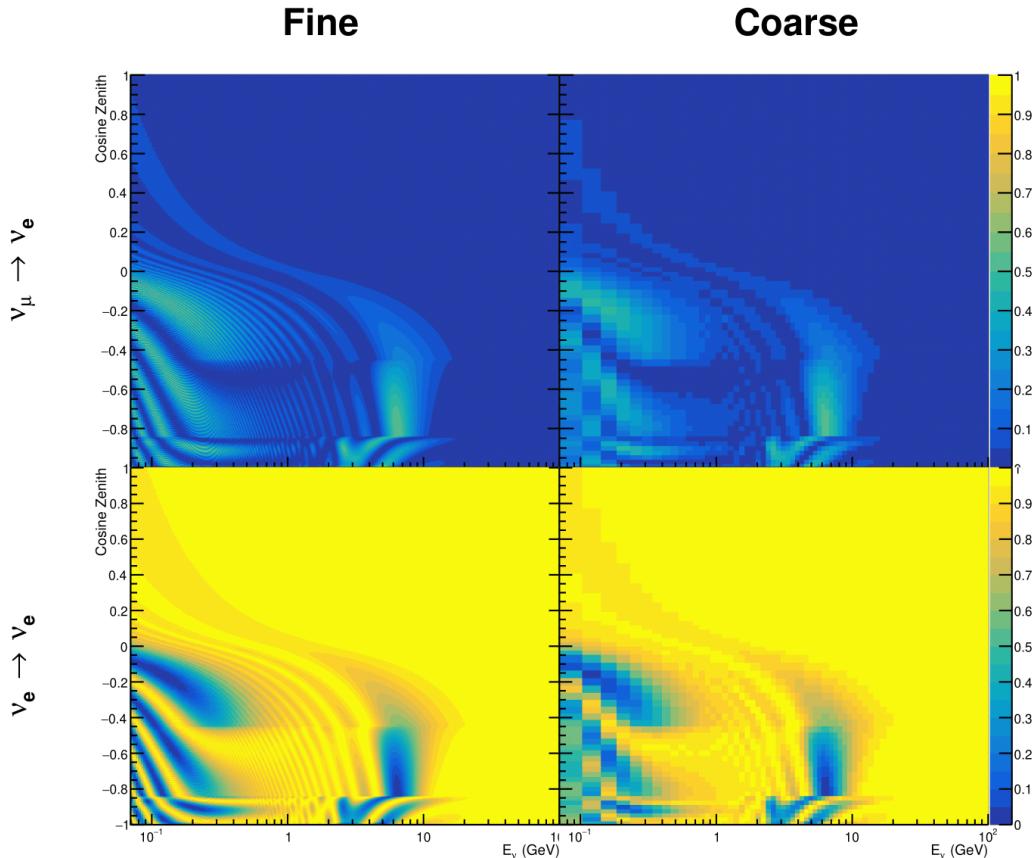


Figure 7.12: The oscillation probability, $P(\nu_\mu \rightarrow \nu_e)$ (top row) and $P(\nu_e \rightarrow \nu_e)$ (bottom row), given as a function of neutrino energy and zenith angle. The left column gives the “fine” binning used to calculate the oscillation probabilities and the right column illustrates 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 7.10 and Figure 7.11.

2459 GPUs can do, so being able to eliminate this significantly reduces the time required
 2460 for calculation. This can be seen in Figure 7.13, where the GPU implementation of
 2461 CUDAProb3 is approximately three times faster than the ProbGPU engine.

2462 Another significant advantage of CUDAProb3 is that it contains a CPU multithreaded
 2463 implementation which is not possible with the ProbGPU or prob3 engines. This elimi-
 2464 nates the requirement for GPU resources when submitting jobs to batch systems. As
 2465 illustrated in Figure 7.13, the calculation speed depends on the number of available

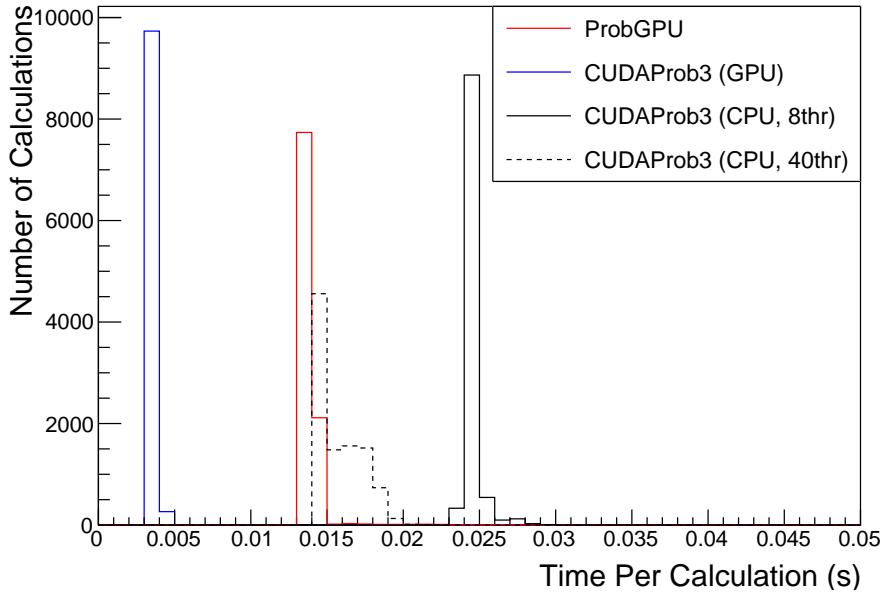


Figure 7.13: The calculation time taken to both calculate the oscillation probabilities and fill the “coarse” oscillograms, following the technique given in section 7.2, for the CUDAProb3 and ProbGPU (Red) calculation engines. CUDAProb3 has both a GPU (Blue) and CPU (Black) implementation, where the 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.

2466 threads. Using 8 threads (which is typical of the batch systems being used) is ap-
 2467 proximately twice as slow as the ProbGPU engine implementation, but would allow
 2468 the fitting framework to be run on many more resources. This fact is utilised for any
 2469 SK-only fits but GPU resources are required for any fits which include beam samples
 2470 due to the ProbGPU requirement. Based on the benefits shown by the implementa-
 2471 tion in this section, efforts are being placed into including linear propagation for beam
 2472 neutrino propagation into the engine [215].

2473 7.4 Matter Density Profile

2474 For an experiment observing atmospheric neutrinos propagating through the Earth, a
 2475 model of the Earth’s density profile is required. The model used within this analysis is

the Preliminary Reference Earth Model (PREM) [210], as illustrated in Figure 7.1. As discussed in section 7.1, the propagator used within the calculation engine requires constant density layers. To follow the official SK-only analysis [209], the average density of each layer has been taken from the PREM model. Table 7.1 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 [216]. 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 [217]. This value is assigned a Gaussian error with a standard deviation equivalent to the difference in chemical composition in core and mantle layers. Figure 7.14 illustrates the effect of moving from the $Z/A = 0.5$ method which is used in the official SK-only analysis [209] 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 [218].

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.

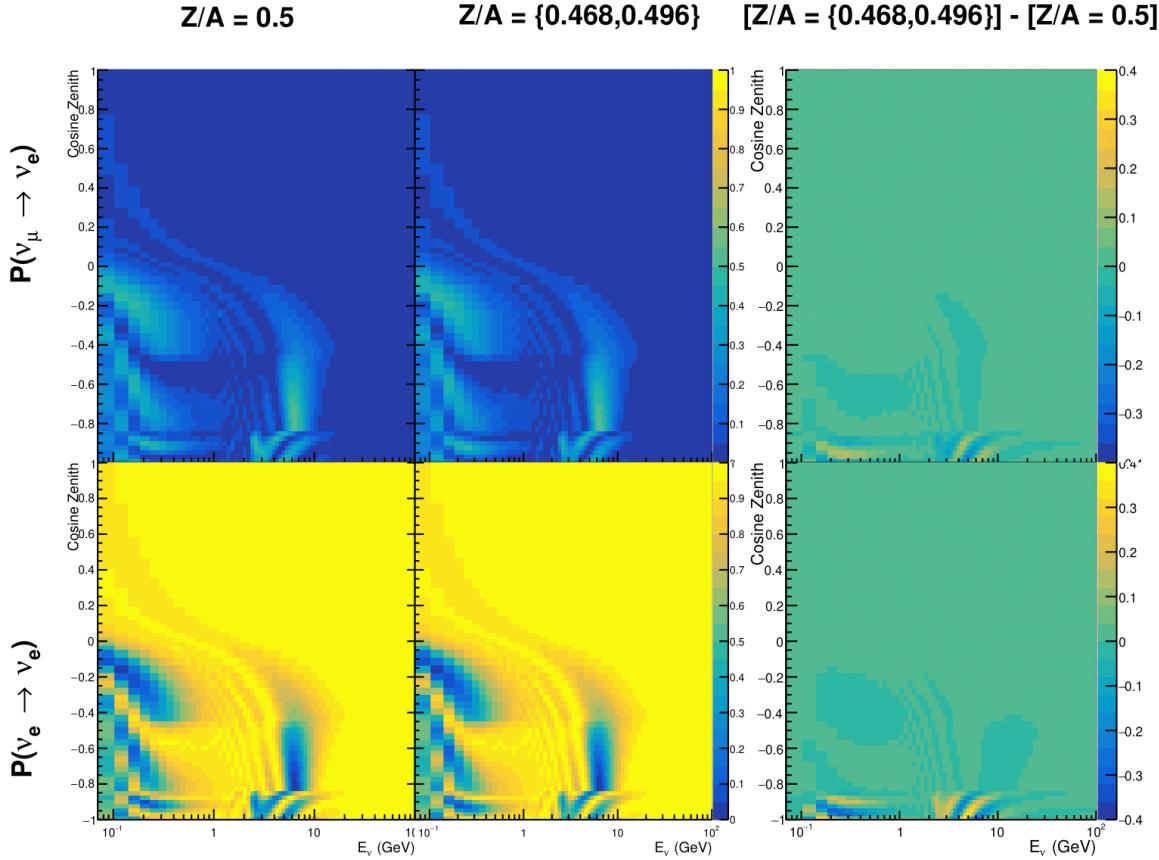


Figure 7.14: The oscillation probability, $P(\nu_\mu \rightarrow \nu_e)$ (top row) and $P(\nu_e \rightarrow \nu_e)$ (bottom row), given as a function of neutrino energy and zenith angle. The left column gives probabilities where the constant $Z/A = 0.5$ approximation which is used in the official SK-only analysis. The middle column gives the probabilities where $Z/A = [0.468, 0.498]$ values are used, as given in Table 7.1. The right column illustrates the difference in oscillation probability between the two different techniques.

2502 To achieve this, the average density, $\langle \rho \rangle_i$, in the i^{th} layer, is calculated as the density,
 2503 $\rho(t)$, integrated over the track a given $\cos(\theta_Z)$,

$$\langle \rho \rangle_i = \frac{1}{t_{i+1} - t_i} \int_{t_i}^{t_{i+1}} \rho(t) dt \quad (7.6)$$

2504 where t_i are the intersection points between each layer and t is the path length of
 2505 the trajectory across the layer.

2506 The oscillation probability calculation speed is approximately linear in the number
 2507 of layers invoked within the Earth model. Therefore a four-layer model is still utilized
 2508 with the only difference to the official SK-only analysis being that the four-layer model
 2509 used for each value of $\cos(\theta_Z)$ is different. Following the method outlined in [219],
 2510 a four-layer piecewise quadratic polynomial is fit to the PREM model for the four
 2511 layers defined in Table 7.1. This fit was not performed by the author of the thesis
 2512 and is documented in [211]. The coefficients of the quadratic fit to each layer are
 2513 given in Table 7.2 with the final distribution illustrated in Figure 7.15. The quadratic
 2514 approximation is clearly much closer to the PREM model as compared to the constant
 2515 density approximation.

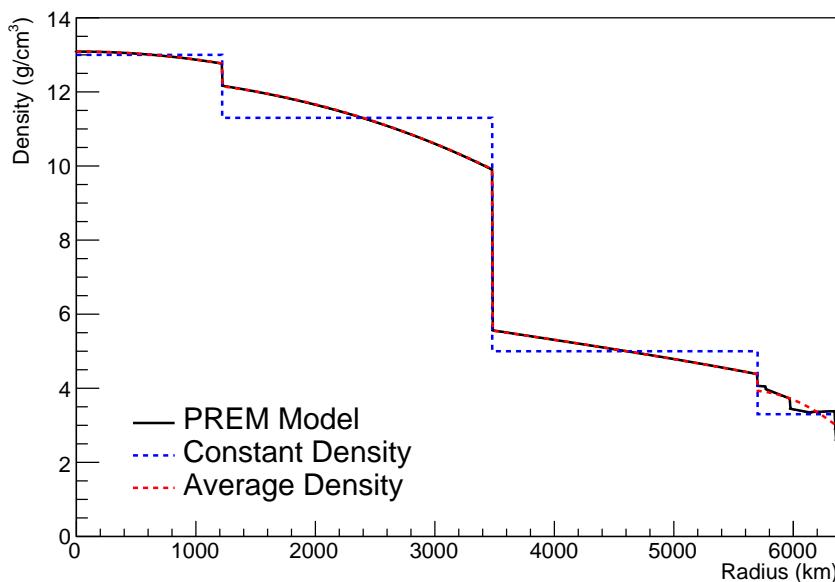


Figure 7.15: The density of the Earth given as a function of the radius, as given by the PREM model (Black), the constant density four-layer approximation (Blue), as used in the official SK-only analysis, and the quadratic approximation of the PREM model (Red).

| 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 7.2: 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 [211], where $x = R/R_{Earth}$.

2516 The effect of using the quadratic density per $\cos(\theta_Z)$ model is highlighted in
 2517 Figure 7.16. The slight discontinuity in the oscillation probability around $\cos(\theta_Z) \sim -$
 2518 0.45 in the fixed density model, which is due to the transition to mantle layer boundary,
 2519 has been reduced. This is expected as the difference in the density across this boundary
 2520 is significantly smaller in the quadratic density model as compared to the constant
 2521 density model. Whilst the difference in density across the other layer transitions
 2522 is reduced, there is still a significant difference. This means the discontinuities in
 2523 the oscillation probabilities remain but are significantly reduced. However, as the
 2524 quadratic density approximation matches the PREM model well in this region, these
 2525 discontinuities are due to the Earth model rather than an artifact of the oscillation
 2526 calculation.

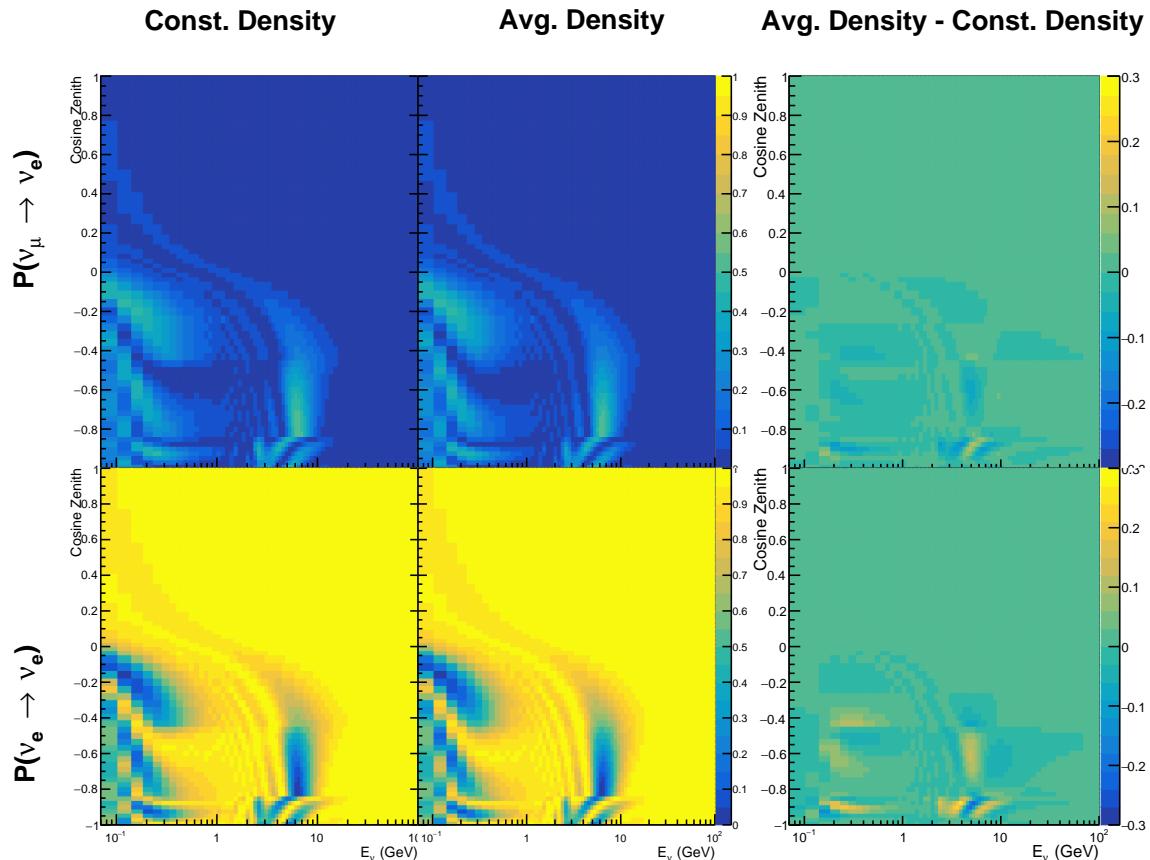


Figure 7.16: The oscillation probability, $P(\nu_\mu \rightarrow \nu_e)$ (top row) and $P(\nu_e \rightarrow \nu_\mu)$ (bottom row), given as a function of neutrino energy and zenith angle. The left column gives probabilities where the four-layer constant density approximation is used. The middle column 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.

²⁵²⁷ 7.5 Production Height Averaging

²⁵²⁸ As discussed in section 7.1, the height at which the cosmic ray flux interacts in the
²⁵²⁹ atmosphere is not known on an event-by-event basis. The production height can vary
²⁵³⁰ from the Earth’s surface to $\sim 50\text{km}$ above that. The SK-only analysis methodology
²⁵³¹ (described in section 7.2) for including the uncertainty on the production height is
²⁵³² to include variations from the Honda model when pre-calculating the oscillation
²⁵³³ probabilities prior to the fit. This technique is not possible for this analysis which
²⁵³⁴ uses continuous oscillation parameters that can not be known prior to the fit. Conse-
²⁵³⁵ quently, an analytical averaging technique was developed in [211]. The author of this
²⁵³⁶ thesis was not responsible for the derivation of the technique but has performed the
²⁵³⁷ implementation and validation of the technique for this analysis alone.

²⁵³⁸ Using the 20 production heights per Monte Carlo neutrino event, provided as 5%
²⁵³⁹ percentiles from the Honda flux model, a production height distribution $p_j(h|E_\nu, \cos\theta_Z)$
²⁵⁴⁰ is built for each neutrino flavour $j = \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$. In practice, a histogram is filled with
²⁵⁴¹ 20 evenly spaced bins in production height h between 0 and 50km. The neutrino energy
²⁵⁴² and cosine zenith binning of the histogram is the same as that provided in section 7.2.
²⁵⁴³ The average production height, $\bar{h} = \int dh \frac{1}{4} \sum_j p_j(h|E_\nu, \cos(\theta_Z))$, is calculated. The
²⁵⁴⁴ production height binning of this histogram is then translated into $\delta t(h) = t(\bar{h}) - t(h)$,
²⁵⁴⁵ where $t(h)$ is the distance travelled along the trajectory.

²⁵⁴⁶ For the i^{th} traversed layer, the transition amplitude, $D_i(t_{i+1}, t_i)$, is computed. The
²⁵⁴⁷ time-ordered product of these is then used as the overall transition amplitude via

$$A(t_{n+1}, t_0) = D_n(t_{n+1}, t_n) \dots D_1(t_2, t_1) D_0(t_1, t_0), \quad (7.7)$$

2548

where,

$$\begin{aligned} D_n(t_{n+1}, t_n) &= \exp[-iH_n(t_{n+1} - t_n)] \\ &= \sum_{k=1}^3 C_k \exp[ia_k(t_{n+1} - t_n)] \end{aligned} \quad (7.8)$$

2549

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

2550 The 0^{th} layer is the propagation through the atmosphere and is the only term that
 2551 depends on the production height. Using the substitution $t_0 = t(\bar{h}) - \delta t(h)$, it can be
 2552 shown that

$$D_0(t_1, t_0) = D_0(t_1, \bar{h})D_0(\delta t). \quad (7.9)$$

2553

Thus Equation 7.7 becomes

$$\begin{aligned} A(t_{n+1}, t_0) &= D_n(t_{n+1}, t_n) \dots D_1(t_2, t_1) D_0(t_1, \bar{h}) D(\delta t) \\ &= A(t_{n+1}, \bar{h}) \sum_{k=1}^3 C_k \exp[ia_k \delta t], \\ &= \sum_{k=1}^3 B_k \exp[ia_k \delta t]. \end{aligned} \quad (7.10)$$

2554

The oscillation probability averaged over production height is then calculated as

$$\begin{aligned}
 \bar{P}(\nu_j \rightarrow \nu_i) &= \int d(\delta t) p_j(\delta t | E_\nu, \cos \theta_Z) P(\nu_j \rightarrow \nu_i) \\
 &= \int d(\delta t) p_j(\delta t | E_\nu, \cos \theta_Z) A(t_{n+1}, t_0) A^*(t_{n+1}, t_0) \\
 &= \sum_{km} (B_k)_{ij} (B_m)_{ij}^* \int d(\delta t) p_j(\delta t | E_\nu, \cos \theta_Z) \exp[i(a_k - a_m)\delta t]
 \end{aligned} \tag{7.11}$$

2555 In practice, implementation in CUDAProb3 [214] is relatively straightforward as
 2556 the majority of these terms are already calculated in the standard oscillation calculation.
 2557 Figure 7.17 illustrates the results of the production height averaging. As expected,
 2558 the main effect is observed in the low-energy downward-going and horizontal-going
 2559 events. Upward-going events have to travel the radius of the Earth, $R_E = 6371\text{km}$,
 2560 where the production height uncertainty is a small fraction of the total path length.

2561

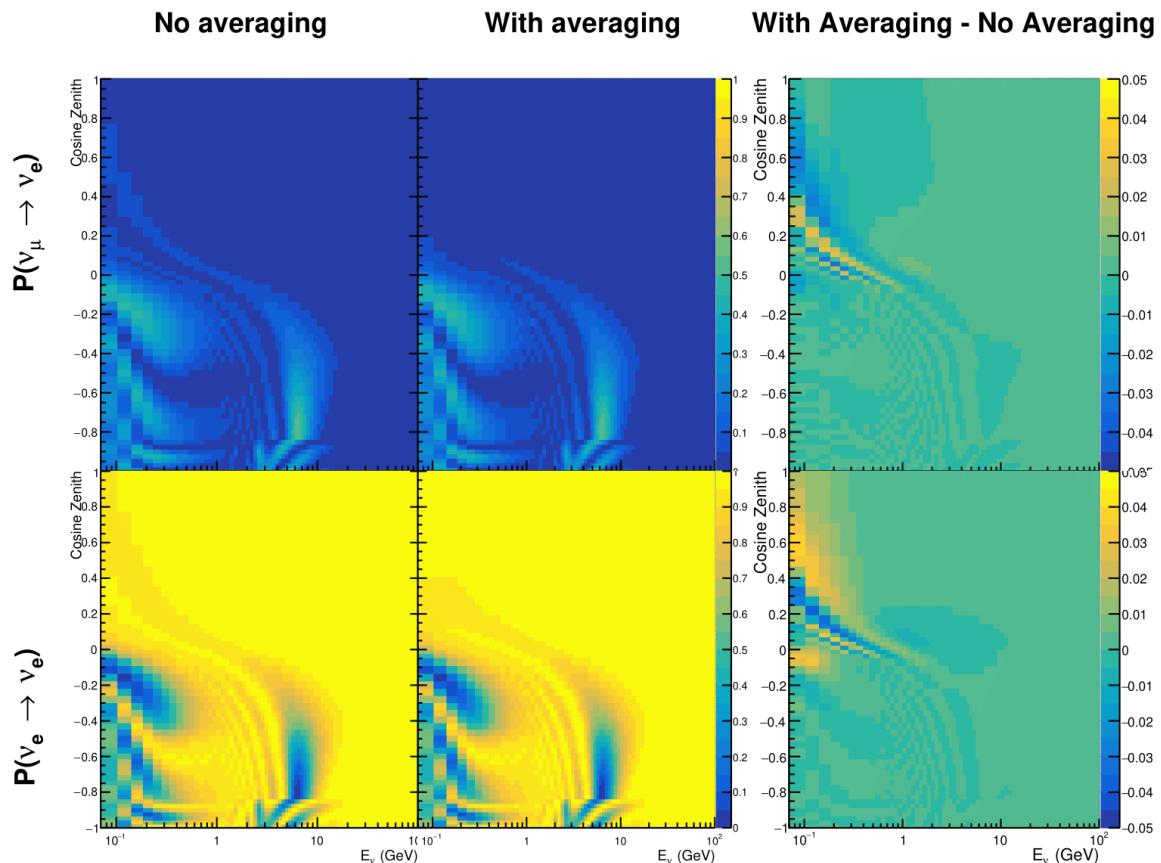


Figure 7.17: The oscillation probability, $P(\nu_\mu \rightarrow \nu_e)$ (top row) and $P(\nu_e \rightarrow \nu_\mu)$ (bottom row), given as a function of neutrino energy and zenith angle. The left column gives probabilities where a fixed production height of 25km is used. The middle column gives the probabilities where the production height is analytically averaged. The right column illustrates the difference in oscillation probability between the two different techniques.

2562 **Bibliography**

- 2563 [1] J. Chadwick, Verhandl. Dtsc. Phys. Ges. **16**, 383 (1914).
- 2564 [2] C. D. Ellis and W. A. Wooster, Proc. R. Soc. Lond. A Math. Phys. Sci. **117**, 109
2565 (1927).
- 2566 [3] W. Pauli, Phys. Today **31N9**, 27 (1978).
- 2567 [4] E. Fermi, Z. Phys. **88**, 161 (1934).
- 2568 [5] F. Reines and C. L. Cowan, Phys. Rev. **92**, 830 (1953).
- 2569 [6] C. L. Cowan, F. Reines, F. B. Harrison, H. W. Kruse, and A. D. McGuire, Science
2570 **124**, 103 (1956), <http://science.sciencemag.org/content/124/3212/103.full.pdf>.
- 2571 [7] G. Danby *et al.*, Phys. Rev. Lett. **9**, 36 (1962).
- 2572 [8] K. Kodama *et al.*, Physics Letters B **504**, 218 (2001).
- 2573 [9] LSND, A. Aguilar-Arevalo *et al.*, Phys. Rev. **D64**, 112007 (2001), hep-ex/0104049.
- 2574 [10] MiniBooNE Collaboration, A. A. Aguilar-Arevalo *et al.*, Phys. Rev. Lett. **110**,
2575 161801 (2013).
- 2576 [11] Planck Collaboration *et al.*, aap **641** (2020).
- 2577 [12] The ALEPH Collaboration, The Delphi Collaboration, The L3 Collaboration, The
2578 SLD Collaboration, The LEP Electroweak Working Group, The SLD Electroweak
2579 and Heavy Flavour Groups, J. A. Bagger *et al.*, Physics Reports **427**, 257 (2006).
- 2580 [13] B. Pontecorvo, Sov. Phys. JETP **26**, 984 (1968), [Zh. Eksp. Teor. Fiz. 53, 1717 (1967)].
- 2581 [14] B. Pontecorvo, Sov. Phys. JETP **7**, 172 (1958), [Zh. Eksp. Teor. Fiz. 34, 247 (1957)].
- 2582 [15] M. Kobayashi and T. Maskawa, Progress of Theoretical Physics **49**, 652 (1973).
- 2583 [16] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963).
- 2584 [17] A. M. and, Journal of Physics: Conference Series **587**, 012030 (2015).
- 2585 [18] A. Y. Smirnov, (2003).
- 2586 [19] S. Mikheyev and A. Smirnov, Soviet Journal of Nuclear Physics **42**, 913 (1985).

- 2587 [20] L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978).
- 2588 [21] V. D. Barger, K. Whisnant, S. Pakvasa, and R. J. N. Phillips, Phys. Rev. D **22**, 2718
2589 (1980).
- 2590 [22] The Super-Kamiokande Collaboration, Y. Ashie *et al.*, Phys. Rev. Lett. **93**, 101801
2591 (2004).
- 2592 [23] SNO Collaboration, Q. R. Ahmad *et al.*, Phys. Rev. Lett. **89**, 011301 (2002).
- 2593 [24] 2015 Nobel prize in Physics as listed by Nobelprize.org, [https://www.](https://www.nobelprize.org/nobel_prizes/physics/laureates/2015/)
2594 [nobelprize.org/nobel_prizes/physics/laureates/2015/](https://www.nobelprize.org/nobel_prizes/physics/laureates/2015/), Accessed: 22-06-
2595 2022.
- 2596 [25] J. A. Formaggio and G. P. Zeller, Rev. Mod. Phys. **84**, 1307 (2012), 1305.7513.
- 2597 [26] A. Bellerive, Int. J. Mod. Phys. A **19**, 1167 (2004).
- 2598 [27] R. Davis, D. S. Harmer, and K. C. Hoffman, Phys. Rev. Lett. **20**, 1205 (1968).
- 2599 [28] N. Vinyoles *et al.*, Astrophys. J. **835**, 202 (2017).
- 2600 [29] V. Gribov and B. Pontecorvo, Phys. Lett. B **28**, 493 (1969).
- 2601 [30] K. S. Hirata *et al.*, Phys. Rev. Lett. **63**, 16 (1989).
- 2602 [31] W. Hampel *et al.*, Phys. Lett. B **447**, 127 (1999).
- 2603 [32] SAGE Collaboration, J. N. Abdurashitov *et al.*, Phys. Rev. C **60**, 055801 (1999).
- 2604 [33] Q. R. Ahmad *et al.*, Phys. Rev. Lett. **89** (2002).
- 2605 [34] Borexino Collaboration, Nature **562**, 505 (2018).
- 2606 [35] B. Aharmim *et al.*, Astrophys. J. **653**, 1545 (2006).
- 2607 [36] M. Agostini *et al.*, (2020).
- 2608 [37] S. Andringa *et al.*, Adv. High Energy Phys. **2016**, 1 (2016).
- 2609 [38] J. F. Beacom *et al.*, Chin. phys. C **41**, 023002 (2017).
- 2610 [39] F. An *et al.*, J. Phys. G Nucl. Part. Phys. **43**, 030401 (2016).
- 2611 [40] J. Aalbers *et al.*, (2020), 2006.03114.
- 2612 [41] T. K. Gaisser and M. Honda, (2002).

- 2613 [42] G. D. Barr, T. K. Gaisser, P. Lipari, S. Robbins, and T. Stanev, Physical Review D
2614 **70** (2004).
- 2615 [43] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa, and T. Sanuki, Physical Review
2616 D **75** (2007).
- 2617 [44] M. Honda, T. Kajita, K. Kasahara, and S. Midorikawa, Phys. Rev. D **70**, 043008
2618 (2004).
- 2619 [45] M. Honda, T. Kajita, K. Kasahara, and S. Midorikawa, Phys. Rev. D **83**, 123001
2620 (2011).
- 2621 [46] A. Fasso, A. Ferrari, P. R. Sala, and J. Ranft, (2001).
- 2622 [47] Y. Ashie *et al.*, Physical Review D **71** (2005).
- 2623 [48] F. Reines *et al.*, Phys. Rev. Lett. **15**, 429 (1965).
- 2624 [49] D. Casper *et al.*, Phys. Rev. Lett. **66**, 2561 (1991).
- 2625 [50] K. S. Hirata *et al.*, Phys. Lett. B **280**, 146 (1992).
- 2626 [51] Z. Li *et al.*, Physical Review D **98** (2018).
- 2627 [52] Kamiokande Collaboration *et al.*, (2017).
- 2628 [53] T2K Collaboration, Nature **580**, 339 (2020).
- 2629 [54] M. A. Acero *et al.*, Phys. Rev. Lett. **123**, 151803 (2019).
- 2630 [55] M. G. Aartsen *et al.*, Phys. Rev. Lett. **120** (2018).
- 2631 [56] P. Adamson *et al.*, Phys. Rev. Lett. **112** (2014).
- 2632 [57] M. S. Athar *et al.*, Progress in Particle and Nuclear Physics **124**, 103947 (2022).
- 2633 [58] G. Danby *et al.*, Phys. Rev. Lett. **9**, 36 (1962).
- 2634 [59] K. Abe *et al.*, Physical Review D **87** (2013).
- 2635 [60] MINOS Collaboration, D. G. Michael *et al.*, Phys. Rev. Lett. **97**, 191801 (2006).
- 2636 [61] G. Danby *et al.*, Phys. Rev. Lett. **9**, 36 (1962).
- 2637 [62] NOvA Collaboration, M. A. Acero *et al.*, Phys. Rev. Lett. **123**, 151803 (2019).
- 2638 [63] B. Abi, R. Acciarri, M. A. Acero, and G. e. a. Adamov, Eur. Phys. J. C Part. Fields

- 2639 **80** (2020).
- 2640 [64] Hyper-Kamiokande Proto-Collaboration *et al.*, Prog. Theor. Exp. Phys. **2015**,
2641 53C02 (2015).
- 2642 [65] C. Blanco, D. Hooper, and P. Machado, Physical Review D **101** (2020).
- 2643 [66] MicroBooNE Collaboration *et al.*, Search for an Excess of Electron Neutrino
2644 Interactions in MicroBooNE Using Multiple Final State Topologies, 2021.
- 2645 [67] KARMEN Collaboration, B. Armbruster *et al.*, Phys. Rev. D **65**, 112001 (2002).
- 2646 [68] S.-B. Kim, T. Lasserre, and Y. Wang, Adv. High Energy Phys. **2013**, 1 (2013).
- 2647 [69] M. Sajjad Athar *et al.*, Prog. Part. Nucl. Phys. **124**, 103947 (2022), 2111.07586.
- 2648 [70] K. Abe *et al.*, Nucl. Instrum. Methods Phys. Res. A **1027**, 166248 (2022).
- 2649 [71] F. P. An *et al.*, Phys. Rev. Lett. **108**, 171803 (2012).
- 2650 [72] RENO Collaboration, J. K. Ahn *et al.*, Phys. Rev. Lett. **108**, 191802 (2012).
- 2651 [73] Double Chooz Collaboration, Y. Abe *et al.*, Phys. Rev. Lett. **108**, 131801 (2012).
- 2652 [74] J. Collaboration *et al.*, TAO Conceptual Design Report: A Precision Measurement
2653 of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution, 2020,
2654 2005.08745.
- 2655 [75] for the RENO Collaboration, New results from RENO and the 5 MeV excess,
2656 AIP Publishing LLC, 2015.
- 2657 [76] Y. Abe *et al.*, Journal of High Energy Physics **2014** (2014).
- 2658 [77] Daya Bay Collaboration, D. Adey *et al.*, Phys. Rev. Lett. **123**, 111801 (2019).
- 2659 [78] M. P. Decowski, Nucl. Phys. B. **908**, 52 (2016).
- 2660 [79] The KamLAND Collaboration, A. Gando *et al.*, Phys. Rev. D **83**, 052002 (2011).
- 2661 [80] P. Dunne, Latest Neutrino oscillation results from T2K, 2020.
- 2662 [81] M. Tanabashi *et al.*, Phys. Rev. D. **98** (2018).
- 2663 [82] Particle Data Group, R. L. Workman and Others, PTEP **2022**, 083C01 (2022).
- 2664 [83] T2K Collaboration, K. Abe *et al.*, Phys. Rev. Lett. **112**, 181801 (2014).

- [84] Y. Fukuda *et al.*, Phys. Rev. Lett. **81**, 1562 (1998).
- [85] Linyan Wan, (2022).
- [86] K. Abe *et al.*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **737**, 253 (2014).
- [87] S. Fukuda *et al.*, Nucl. Instrum. Methods Phys. Res. A **501**, 418 (2003).
- [88] Y. Itow *et al.*, (2001).
- [89] M. Jiang *et al.*, Prog. Theor. Exp. Phys. **2019** (2019).
- [90] S. Fukuda *et al.*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **501**, 418 (2003), <http://www.sciencedirect.com/science/article/pii/S016890020300425X>.
- [91] Y. Nakano *et al.*, Nucl. Instrum. Methods Phys. Res. A **977**, 164297 (2020).
- [92] Hamamatsu, Hamamatsu Photonics Photomultiplier Tubes Handbook.
- [93] K. Abe *et al.*, Nucl. Instrum. Methods Phys. Res. A **1027**, 166248 (2022).
- [94] J. F. Beacom and M. R. Vagins, Phys. Rev. Lett. **93**, 171101 (2004).
- [95] L. Marti *et al.*, Nucl. Instrum. Methods Phys. Res. A **959**, 163549 (2020).
- [96] L. Marti *et al.*, (2019).
- [97] M. Vagins, Solar/DSNB Neutrino_SK-Gd, 2022.
- [98] J. Focht, PhD thesis, Massachusetts Institute of Technology, 2004.
- [99] T. Tanimori *et al.*, IEEE Transactions on Nuclear Science **36**, 497 (1989).
- [100] Super-Kamiokande Collaboration, J. Hosaka *et al.*, Phys. Rev. D **73**, 112001 (2006).
- [101] H. Nishino *et al.*, Nucl. Instrum. Methods Phys. Res. A **610**, 710 (2009).
- [102] S. Yamada *et al.*, IEEE Transactions on Nuclear Science **57**, 428 (2010).
- [103] S. Yamada, Y. Hayato, Y. Obayashi, and M. Shiozawa, New online system without hardware trigger for the Super-Kamiokande experiment, in *2007 IEEE Nuclear Science Symposium Conference Record*, IEEE, 2007.

- 2692 [104] G. Carminati, Phys. Procedia **61**, 666 (2015).
- 2693 [105] P. A. Čerenkov, Phys. Rev. **52**, 378 (1937).
- 2694 [106] I. Frank and I. Tamm, Coherent visible radiation of fast electrons passing
2695 through matter, in *Selected Papers*, pp. 29–35, Springer Berlin Heidelberg, Berlin,
2696 Heidelberg, 1991.
- 2697 [107] The T2K Collaboration, KEK Proposal (2001),
2698 <http://neutrino.kek.jp/jhfnu/loi/loi.v2.030528.pdf>.
- 2699 [108] Y. Itow *et al.*, (2001), hep-ex/0106019.
- 2700 [109] The K2K Collaboration and S. H. Ahn, (2001), hep-ex/0103001.
- 2701 [110] The T2K Collaboration, KEK Proposal (2006), http://j-parc.jp/researcher/Hadron/en/pac_0606/pdf/p11-Nishikawa.pdf.
- 2702 [111] C. Bronner, Accelerator Neutrino I_Recent results from T2K, 2022.
- 2703 [112] T2K Collaboration, K. Abe *et al.*, Phys. Rev. Lett. **112**, 061802 (2014),
2704 <https://link.aps.org/doi/10.1103/PhysRevLett.112.061802>.
- 2705 [113] NINJA Collaboration, T. Fukuda *et al.*, Proposal for precise measurement of
2706 neutrino-water cross-section in NINJA physics run, Proposal for J-PARC and
2707 KEK, 2017.
- 2708 [114] T. Ovsiannikova *et al.*, Physics of Particles and Nuclei **48**, 1014 (2017),
2709 <https://doi.org/10.1134/S1063779617060478>.
- 2710 [115] M. Antonova *et al.*, Journal of Instrumentation **12**, C07028 (2017),
2711 <http://stacks.iop.org/1748-0221/12/i=07/a=C07028>.
- 2712 [116] The T2K Collaboration, K. Abe *et al.*, Phys. Rev. D **102**, 012007 (2020).
- 2713 [117] K. Abe *et al.*, Progress of Theoretical and Experimental Physics **2021** (2021).
- 2714 [118] The T2K Collaboration, K. Abe *et al.*, Nuclear Instruments
2715 and Methods in Physics Research Section A: Accelerators, Spectrometers,
2716 Detectors and Associated Equipment **659**, 106 (2011),
2717 <http://www.sciencedirect.com/science/article/pii/S0168900211011910>.
- 2718 [119] K. Matsuoka *et al.*, Nuclear Instruments and Methods in Physics Research Section
2719 A: Accelerators, Spectrometers, Detectors and Associated Equipment **624**, 591
- 2720

- 2721 (2010), <http://www.sciencedirect.com/science/article/pii/S016890021002098X>.
- 2722 [120] K. Abe *et al.*, Phys. Rev. D. **103** (2021).
- 2723 [121] T. Vladisavljevic, *Predicting the T2K neutrino flux and measuring oscillation parameters* Springer theses, 1 ed. (Springer Nature, Cham, Switzerland, 2020).
- 2725 [122] D. Beavis, A. Carroll, and I. Chiang, (1995).
- 2726 [123] P.-A. Amaudruz *et al.*, Nuclear Instruments and Methods in Physics Research
2727 Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
2728 **696**, 1 (2012).
- 2729 [124] N. Abgrall *et al.*, Nuclear Instruments and Methods in Physics Research Section
2730 A: Accelerators, Spectrometers, Detectors and Associated Equipment **637**, 25
2731 (2011).
- 2732 [125] S. Assylbekov *et al.*, Nuclear Instruments and Methods in Physics Research
2733 Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
2734 **686**, 48 (2012).
- 2735 [126] D. Allan *et al.*, Journal of Instrumentation **8**, P10019 (2013).
- 2736 [127] F. Vannucci, Advances in High Energy Physics **2014**, 1 (2014).
- 2737 [128] UA1 magnet sets off for a second new life, 2022.
- 2738 [129] S. Aoki *et al.*, Nuclear Instruments and Methods in Physics Research Section
2739 A: Accelerators, Spectrometers, Detectors and Associated Equipment **698**, 135
2740 (2013).
- 2741 [130] K. Suzuki *et al.*, Progress of Theoretical and Experimental Physics **2015**, 53C01
2742 (2015).
- 2743 [131] S. Brooks, A. Gelman, G. L. Jones, and X.-L. Meng, *Handbook of Markov Chain
2744 Monte Carlo* (CRC Press, 2011).
- 2745 [132] W. R. Gilks, S. Richardson, and D. J. Spiegelhalter, *Markov Chain Monte Carlo in
2746 Practice* (Chapman & Hall/CRC Interdisciplinary Statistics, 1995).
- 2747 [133] C. Wret, *Minimising systematic uncertainties in the T2K experiment using near-
2748 detector and external data*, PhD thesis, Imperial College London, 2018.
- 2749 [134] K. E. Duffy, *Measurement of the Neutrino Oscillation Parameters $\sin^2 \theta_{23}$, Δm_{32}^2 ,*

- 2750 $\sin^2 \theta_{13}$, and δ_{CP} in Neutrino and Antineutrino Oscillation at T2K, PhD thesis, Oriel
2751 College, University of Oxford, 2016.
- 2752 [135] T. Bayes, Rev. Phil. Trans. Roy. Soc. Lond. **53**, 370 (1764).
- 2753 [136] N. Metropolis, A. W. Rosenbluth, M. N. Rosenbluth, A. H. Teller, and E. Teller,
2754 Journal of Chemical Physics **21** (1970).
- 2755 [137] W. K. Hastings, Biometrika **57** (1970).
- 2756 [138] J. Dunkley, M. Bucher, P. G. Ferreira, K. Moodley, and C. Skordis, Mon. Not. R.
2757 Astron. Soc. **356**, 925 (2005).
- 2758 [139] Particle Data Group *et al.*, Prog. Theor. Exp. Phys. **2020** (2020).
- 2759 [140] H. Jeffreys, *The Theory of Probability* Oxford Classic Texts in the Physical Sciences
2760 (, 1939).
- 2761 [141] R. E. Kass and A. E. Raftery, J. Am. Stat. Assoc. **90**, 773 (1995).
- 2762 [142] T. Böhlen *et al.*, Nuclear Data Sheets **120**, 211 (2014),
2763 <http://www.sciencedirect.com/science/article/pii/S0090375214005018>.
- 2764 [143] R. Brun *et al.*, GEANT: Detector Description and Simulation Tool; Oct 1994 CERN
2765 Program Library (CERN, Geneva, 1993), <http://cds.cern.ch/record/1082634>,
2766 Long Writeup W5013.
- 2767 [144] T2K Collaboration, K. Abe *et al.*, Phys. Rev. D **87**, 012001 (2013).
- 2768 [145] C. Zeitnitz and T. Gabriel, Nuclear Instruments and Methods in
2769 Physics Research Section A: Accelerators, Spectrometers,
2770 Detectors and Associated Equipment **349**, 106 (1994),
2771 <http://www.sciencedirect.com/science/article/pii/0168900294906130>.
- 2772 [146] A. Fiorentini *et al.*, T2K Technical Note **217** (2017).
- 2773 [147] N. Abgrall *et al.*, Physical Review C **84** (2011).
- 2774 [148] N. Abgrall *et al.*, Physical Review C **85** (2012).
- 2775 [149] N. Abgrall *et al.*, Nuclear Instruments and Methods in Physics Research Section
2776 A: Accelerators, Spectrometers, Detectors and Associated Equipment **701**, 99
2777 (2013), <http://www.sciencedirect.com/science/article/pii/S016890021201234X>.

- 2778 [150] HARP Collaboration, M. Apollonio *et al.*, Phys. Rev. C **80**, 035208 (2009),
2779 <https://link.aps.org/doi/10.1103/PhysRevC.80.035208>.
- 2780 [151] B. Blau *et al.*, Nuclear Physics B - Proceedings Supplements **113**, 125 (2002).
- 2781 [152] S. Haino *et al.*, Physics Letters B **594**, 35 (2004).
- 2782 [153] NASA, U.S. Standard Atmosphere, 1976, 1976.
- 2783 [154] S. Roesler, R. Engel, and J. Ranft, The Monte Carlo Event Generator DPMJET-III,
2784 in *Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and*
2785 *Applications*, pp. 1033–1038, Springer Berlin Heidelberg, 2001.
- 2786 [155] K. Niita *et al.*, Radiation Measurements **41**, 1080 (2006).
- 2787 [156] T. Sanuki *et al.*, Physics Letters B **541**, 234 (2002).
- 2788 [157] P. Achard *et al.*, Physics Letters B **598**, 15 (2004).
- 2789 [158] K. Sato, Atmospheric Neutrino_Reviews on neutrino fluxes (low E atm nu),
2790 2022.
- 2791 [159] Y. Hayato and L. Pickering, The European Physical Journal Special Topics **230**,
2792 4469 (2021).
- 2793 [160] Y. Hayato, Acta Physica Polonica B **40** (2009).
- 2794 [161] C. L. Smith, Physics Reports **3**, 261 (1972),
2795 <http://www.sciencedirect.com/science/article/pii/0370157372900105>.
- 2796 [162] O. Benhar, A. Fabrocini, and S. Fantoni, Nuclear Physics A **497**, 423 (1989).
- 2797 [163] R. Bradford, A. Bodek, H. Budd, and J. Arrington, Nuclear
2798 Physics B - Proceedings Supplements **159**, 127 (2006),
2799 <http://www.sciencedirect.com/science/article/pii/S0920563206005184>,
2800 Proceedings of the 4th International Workshop on Neutrino-Nucleus Interac-
2801 tions in the Few-GeV Region.
- 2802 [164] A. A. Aguilar-Arevalo *et al.*, Physical Review D **81** (2010).
- 2803 [165] R. Gran, J. Nieves, F. Sanchez, and M. J. V. Vacas, Phys. Rev. D **88**, 113007 (2013),
2804 <https://link.aps.org/doi/10.1103/PhysRevD.88.113007>.
- 2805 [166] C. Berger and L. M. Sehgal, Phys. Rev. D **76**, 113004 (2007).

- 2806 [167] C. Berger and L. M. Sehgal, Phys. Rev. D **79**, 053003 (2009),
2807 <https://link.aps.org/doi/10.1103/PhysRevD.79.053003>.
- 2808 [168] T. Sjöstrand, Computer Physics Communications **82**, 74 (1994).
- 2809 [169] C. Bronner and M. Hartz, Tuning of the Charged Hadrons Multiplicities for Deep
2810 Inelastic Interactions in NEUT, in *Proceedings of the 10th International Workshop on*
2811 *Neutrino-Nucleus Interactions in Few-GeV Region (NuInt15)*, Journal of the Physical
2812 Society of Japan, 2016.
- 2813 [170] M. Glück, E. Reya, and A. Vogt, The European Physical Journal C **5**, 461 (1998).
- 2814 [171] A. Bodek and U.-k. Yang, Axial and Vector Structure Functions for Electron- and
2815 Neutrino- Nucleon Scattering Cross Sections at all Q^2 using Effective Leading
2816 order Parton Distribution Functions, 2010.
- 2817 [172] A. Bodek and U.-K. Yang, (2010).
- 2818 [173] S. Gollapinni, (2016).
- 2819 [174] E. S. P. Guerra *et al.*, Phys. Rev. D **99**, 052007 (2019).
- 2820 [175] GEANT4, S. Agostinelli *et al.*, Nucl. Instrum. Meth. **A506**, 250 (2003).
- 2821 [176] R. Brun, F. Bruyant, M. Maire, A. C. McPherson, and P. Zanarini, (1987).
- 2822 [177] K. Abe *et al.*, Physical Review Letters **121** (2018).
- 2823 [178] K. Abe *et al.*, Physical Review D **91** (2015).
- 2824 [179] R. Patterson *et al.*, Nuclear Instruments and Methods in Physics Research Section
2825 A: Accelerators, Spectrometers, Detectors and Associated Equipment **608**, 206
2826 (2009).
- 2827 [180] e. a. S. Berkman, T2K Technical Note **146** (2013).
- 2828 [181] e. a. A. Himmel, T2K Technical Note **219** (2015).
- 2829 [182] F. a. James, (1998), CERN Program Library Long Writeups.
- 2830 [183] e. a. D. Barrow, T2K Technical Note **326** (2020).
- 2831 [184] A. Maghrabi, A. Aldosari, and M. Almutairi, Advances in Space Research **68**,
2832 2941 (2021).

- 2833 [185] Super-Kamiokande Collaboration, K. Abe *et al.*, Phys. Rev. D **97**, 072001 (2018),
2834 <https://link.aps.org/doi/10.1103/PhysRevD.97.072001>.
- 2835 [186] Particle Data Group, J. Beringer *et al.*, Phys. Rev. D **86**, 010001 (2012).
- 2836 [187] Y. N. and, Journal of Physics: Conference Series **888**, 012191 (2017).
- 2837 [188] M. Jiang, *Study of the neutrino mass hierarchy with the atmospheric neutrino data*
2838 *collected in Super-Kamiokande IV*, PhD thesis, Kyoto University, 2019.
- 2839 [189] S. N. K. Iyogi and Y. Obayashi., T2K Technical Note **027** (2011).
- 2840 [190] LeeKaPik, *Study of the neutrino mass hierarchy with the atmospheric neutrino data*
2841 *observed in Super-Kamiokande*, PhD thesis, Tokyo University, 2012.
- 2842 [191] The Super-Kamiokande Collaboration, R. Wendell *et al.*, Phys. Rev. D **81**, 092004
2843 (2010).
- 2844 [192] Super-Kamiokande Collaboration, J. Hosaka *et al.*, Phys. Rev. D **74**, 032002
2845 (2006).
- 2846 [193] L. M. et al, T2K Technical Note **395** (2020).
- 2847 [194] W. Parker, *Constraining Systematic Uncertainties at T2K using Near Detector Data*,
2848 PhD thesis, Royal Holloway University of London, 2020.
- 2849 [195] J. Misset, T2K Technical Note **318** (2017).
- 2850 [196] X. Li and M. Wilking, T2K Technical Note **319** (2017).
- 2851 [197] e. a. Tomislav Vladisavljevic, T2K Technical Note **354** (2020).
- 2852 [198] G. Ambrosini *et al.*, Phys. Lett. B **420**, 225 (1998).
- 2853 [199] e. a. Edward Atkin, T2K Technical Note **344** (2019).
- 2854 [200] e. a. D. Barrow, T2K Technical Note **422** (2022).
- 2855 [201] MiniBooNE Collaboration, A. A. Aguilar-Arevalo *et al.*, Phys. Rev. D **81**, 092005
2856 (2010), <https://link.aps.org/doi/10.1103/PhysRevD.81.092005>.
- 2857 [202] MINERvA Collaboration, L. Fields *et al.*, Phys. Rev. Lett. **111**, 022501 (2013),
2858 <https://link.aps.org/doi/10.1103/PhysRevLett.111.022501>.
- 2859 [203] C. Wilkinson, P. Rodrigues, S. Cartwright, L. Thomp-

- 2860 son, and K. McFarland, Phys. Rev. D **90**, 112017 (2014),
2861 <https://link.aps.org/doi/10.1103/PhysRevD.90.112017>.
- 2862 [204] The MiniBooNE Collaboration, A. A. Aguilar-Arevalo *et al.*, Phys. Rev. D **81**,
2863 013005 (2010), <https://link.aps.org/doi/10.1103/PhysRevD.81.013005>.
- 2864 [205] P. de Perio and J. Imber, T2K Technical Note **186** (2014).
- 2865 [206] P. de Perio and J. Imber, T2K Technical Note **107** (2012).
- 2866 [207] S. Tobayama, *An Analysis of the Oscillation of Atmospheric Neutrinos*, PhD thesis,
2867 British Columbia U., 2016.
- 2868 [208] C. V. Daniel Barrow, T2K-SK Detector Matrix Uncertainties - MaCh3 In-
2869 tegration, <https://git.t2k.org/t2k-sk/t2ksk-detcovmat/-/tree/feature/MaCh3Integration>, Accessed: 22-06-2022.
- 2871 [209] R. Wendell, *Three Flavor Oscillation Analysis of Atmospheric Neutrinos in Super-*
2872 *Kamiokande*, PhD thesis, University of North Carolina, 2008.
- 2873 [210] A. M. Dziewonski and D. L. Anderson, Phys. Earth Planet. Inter. **25**, 297 (1981).
- 2874 [211] e. a. D. Barrow, T2K Technical Note **425** (2022).
- 2875 [212] R. G. Calland, A. C. Kaboth, and D. Payne, **9**, P04016 (2014).
- 2876 [213] R. Wendell, <http://www.phy.duke.edu/raw22/public/Prob3++/>.
- 2877 [214] F. Kallenborn, C. Hundt, S. Böser, and B. Schmidt, Computer Physics Communi-
2878 cations **234**, 235 (2019).
- 2879 [215] L. Warsame, MaCh3 Analysis Progress.
- 2880 [216] S. Bourret, J. A. B. Coelho, and V. V. E. and, Journal of Physics: Conference Series
2881 **888**, 012114 (2017).
- 2882 [217] C. Rott, A. Taketa, and D. Bose, Scientific Reports **5** (2015).
- 2883 [218] K. Hagiwara, N. Okamura, and K. ichi Senda, Journal of High Energy Physics
2884 **2011** (2011).
- 2885 [219] D. Typinski, Earth Gravity, <http://www.typnet.net/Essays/EarthGravGraphics/EarthGrav.pdf>, Accessed: 24-06-2022.

2887 **List of Figures**

| | | | |
|---------------------|-----|---|----|
| <small>2888</small> | 2.1 | The cross-section of neutrinos from various natural and man-made sources as a function of neutrino energy. Taken from [25] | 10 |
| <small>2889</small> | | | |
| <small>2890</small> | 2.2 | 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]. | 11 |
| <small>2891</small> | | | |
| <small>2892</small> | | | |
| <small>2893</small> | 2.3 | 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]. | 14 |
| <small>2894</small> | | | |
| <small>2895</small> | | | |
| <small>2896</small> | | | |
| <small>2897</small> | | | |
| <small>2898</small> | | | |
| <small>2899</small> | 2.4 | A diagram illustrating the definition of zenith angle as used in the Super Kamiokande experiment [47]. | 14 |
| <small>2900</small> | | | |
| <small>2901</small> | 2.5 | Prediction of $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$ 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]. | 15 |
| <small>2902</small> | | | |
| <small>2903</small> | | | |
| <small>2904</small> | | | |
| <small>2905</small> | | | |
| <small>2906</small> | 2.6 | Constraints on the atmospheric oscillation parameters, $\sin^2(\theta_{23})$ and Δm_{23}^2 , from atmospheric and long baseline experiments: SK [52], T2K [53], NO ν A [54], IceCube [55] and MINOS [56]. Figure taken from [57]. | 16 |
| <small>2907</small> | | | |
| <small>2908</small> | | | |
| <small>2909</small> | 2.7 | 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]. | 19 |
| <small>2910</small> | | | |
| <small>2911</small> | | | |
| <small>2912</small> | | | |
| <small>2913</small> | | | |
| <small>2914</small> | | | |
| <small>2915</small> | 3.1 | A schematic diagram of the Super-Kamiokande Detector. Taken from [88]. | 25 |

| | | |
|------|--|----|
| 2916 | 3.2 The location of “standard PMTs” (red) inside the SK detector. Taken from [86]. | 29 |
| 2917 | | |
| 2918 | 3.3 Schematic view of the data flow through the data acquisition and online system. Taken from [102]. | 32 |
| 2919 | | |
| 2920 | 3.4 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. | 35 |
| 2921 | | |
| 2922 | | |
| 2923 | | |
| 2924 | 3.5 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. | 36 |
| 2925 | | |
| 2926 | | |
| 2927 | 3.6 Top panel: Bird’s eye view of the most relevant part of primary and sec- ondary beamline used within the T2K experiment. The primary beam- line 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]. | 38 |
| 2928 | | |
| 2929 | | |
| 2930 | | |
| 2931 | | |
| 2932 | | |
| 2933 | | |
| 2934 | 3.7 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]. | 39 |
| 2935 | | |
| 2936 | | |
| 2937 | | |
| 2938 | 3.8 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. | 41 |
| 2939 | | |
| 2940 | | |
| 2941 | | |
| 2942 | | |
| 2943 | 3.9 The components of the ND280 detector. The neutrino beam travels from left to right. Taken from [118]. | 42 |
| 2944 | | |
| 2945 | 3.10 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]. | 44 |
| 2946 | | |
| 2947 | | |

| | | |
|------|--|----|
| 2948 | 3.11 Schematic design of a Time Projection Chamber detector. Taken from [124]. | 45 |
| 2949 | 3.12 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]. | 45 |
| 2950 | | |
| 2951 | | |
| 2952 | 3.13 A schematic of the P0D side-view. Taken from [125]. | 47 |
| 2953 | 3.14 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]. | 49 |
| 2954 | | |
| 2955 | | |
| 2956 | | |
| 2957 | | |
| 2958 | 4.1 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. | 54 |
| 2959 | | |
| 2960 | | |
| 2961 | | |
| 2962 | 4.2 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. | 54 |
| 2963 | | |
| 2964 | | |
| 2965 | | |
| 2966 | 4.3 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 $\sigma = 5.0$. | 60 |
| 2967 | | |
| 2968 | | |
| 2969 | | |
| 2970 | | |
| 2971 | 4.4 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. | 61 |
| 2972 | | |
| 2973 | | |
| 2974 | | |
| 2975 | | |

| | | |
|---------------|--|----|
| 2976 4.5 | 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 $-5 \leq x \leq 5$ and $0 \leq x \leq 5$ for the black and red distribution, respectively. | 63 |
| 2982 5.1 | The NEUT prediction of the ν_μ -H ₂ O 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]. | 71 |
| 2988 5.2 | Illustration of the various processes which a pion can undergo before exiting the nucleus. Taken from [173]. | 72 |
| 2990 5.3 | Event displays from Super Kamiokande illustrating the “crisp” ring from a muon and the typically “fuzzier” electron ring. Each pixel represents a PMT and the color scheme denotes the accumulated charge deposited on that PMT. Figures taken from [181]. | 75 |
| 2994 5.4 | 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. . . | 79 |
| 2998 5.5 | 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]. | 81 |
| 3003 5.6 | 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. | 82 |

| | | |
|------|---|----|
| 3007 | 5.7 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. | 83 |
| 3013 | 5.8 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. | 84 |
| 3019 | 5.9 A depiction of the topology patterns for fully-contained (FC), partially-contained (PC) and up-going muon (Up- μ) samples included in this analysis. | 85 |
| 3022 | 5.10 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. | 87 |
| 3028 | 5.11 The predicted neutrino flux of the beam neutrinos, illustrated as a function of neutrino energy. The predictions are broken down by the number of decay electrons associated with the particular events. All systematic dials are set to their nominal values and the Asimov A oscillation parameters are assumed. | 89 |

| | | | |
|------|-----|--|-----|
| 3033 | 6.1 | The accumulated beam data, measured as the number of protons on target (POT). The total data (blue) is given which comprises of the neutrino beam (red) and antineutrino (purple) components. The beam power for neutrino and antineutrino beams is given as the markers using the same colourscheme. The timescale runs from Run 1 which started in January 2010 until Run 10 which ended in February 2020. The ratio of accumulated data in neutrino and antineutrino beam is 54.7% : 45.3%. | 91 |
| 3041 | 6.2 | Comparison of the SK-IV atmospheric samples between predictions made with the Asimov A (Black) and Asimov B (Red) oscillation parameter sets, given in Table 2.2. The subGeV samples CCRES and π^0 -like samples are given in their reconstructed lepton momentum. All other samples are presented in their reconstructed zenith angle projection. . . | 97 |
| 3046 | 6.3 | The nominal Monte Carlo predictions for the FGD1 and FGD2 samples in neutrino beam mode (FHC), broken down into the $CC\nu_\mu 0\pi$, $CC\nu_\mu 1\pi$ and $CC\nu_\mu$ Other categories. Figures taken from [193]. | 101 |
| 3049 | 6.4 | The reconstructed neutrino energy, as defined by Equation 6.2 and Equation 6.3, for the $1R\mu$, $1Re$ and $CC1\pi^+$ samples. The generated dial values and Asimov A oscillation parameter sets are assumed. These samples are the FHC mode samples. For ease of viewing, the $1R\mu$ sample only shows the $0. \leq E_\nu^{rec} < 3.0\text{GeV}$ but the binning extends out to 30.0GeV | 104 |
| 3055 | 6.5 | The distribution of the angle between the neutrino beam direction and the reconstructed final state lepton, for the FHC neutrino mode beam one ring electron sample. The distribution is broken down by neutrino interaction mode into charged current (left) and neutral current (right) components. The pre-fit systematic dial values and Asimov A oscillation parameter sets are assumed. | 106 |
| 3061 | 6.6 | The total uncertainty evaluated on the near detector ν_μ flux prediction constrained by the replica-target data, illustrated as a function of neutrino energy. The solid(dashed) line indicates the uncertainty used within this analysis(the T2K 2018 analysis). The solid histogram indicates the neutrino flux as a function of energy. Figure taken from [197]. | 108 |

- 3066 6.7 The prediction neutrino energy distribution for subGeV atmospheric
3067 and beam samples, given for muon-like samples FHC+RHC 1R μ beam
3068 samples compared to the subGeV μ -like 0+1 decay electrons (d.e.) at-
3069 mospheric samples, electron-like 0d.e. samples FHC+RHC 1Re beam
3070 samples compared to the subGeV e -like 1d.e. sample, and electron-like
3071 1d.e. sample FHC1Re1de beam sample compared to the subGeV e -like
3072 1d.e. atmospheric sample. 113
- 3073 6.8 The interaction mode contribution of each sample given as a fraction
3074 of the total event rate in that sample. All systematic dials are set to
3075 their nominal values and the Asimov A oscillation parameters are as-
3076 sumed. The Charged Current (CC) modes are broken into quasi-elastic
3077 (QE), meson exchange (2p2h), resonant charged pion production ($1\pi^\pm$),
3078 multi-pion production ($M\pi$), and other interaction categories. Neutral
3079 Current (NC) interaction modes are given in interaction mode cate-
3080 gories: π^0 production, resonant charged pion production, multi-pion
3081 production, and others. 114
- 3082 6.9 Down-going atmospheric subGeV single-ring samples comparing the
3083 mean and error of the pre-fit and post-fit Monte Carlo predictions in
3084 red and blue, respectively. The magenta histogram illustrates the Monte
3085 Carlo prediction using the generated dial values. The black points illus-
3086 trate the down-going data with statistical errors given. The mean and
3087 errors of the Monte Carlo predictions are calculated by the techniques
3088 documented in subsection 4.3.4. The cross-section and atmospheric flux
3089 parameters are either thrown from their pre-fit uncertainties (denoted
3090 pre-fit band), or the cross section dial values are randomly sampled
3091 from a MCMC chain whilst the atmospheric flux parameters are thrown
3092 from their pre-fit distributions (denoted post-fit band). 117
- 3093 6.10 The ring counting parameter, as defined in Equation 6.6, for the subGeV
3094 electron-like zero decay electron and multi-ring ν_e -like samples. 127
- 3095 6.11 The ring counting parameter, defined in Equation 6.6, as a function of
3096 the number of reconstructed rings as found by the `fitQun` algorithm.
3097 Left: true ν_μ events with only one muon above the Cherenkov threshold
3098 in the final state. Right: true ν_μ events with one muon and at least one
3099 other charged particle above the Cherenkov threshold in the final state. 128

| | | |
|------|--|-----|
| 3100 | 6.12 The χ^2 between the hybrid- π^0 Monte Carlo and data samples, as a function of smear (α) and shift (β) parameters, for events which have $1\pi^0$ final state topology. Left: Electron-muon separation PID parameter for events with $30 \geq E_{vis}(MeV) < 300$. Right: Electron- π^0 separation PID parameter for events with $30 \geq E_{vis}(MeV) < 300$ | 129 |
| 3105 | 6.13 The distribution of $\log(L_e/L_\mu)$ compared to $\log(L_e/L_\pi)$ for subGeV events with zero (top left), one (top right) or two (bottom) decay electrons. The correlation in the distribution is calculated as 0.997, 0.999 and 0.996, respectively. | 130 |
| 3109 | 7.1 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. | 134 |
| 3112 | 7.2 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 2.2). | 135 |
| 3118 | 7.3 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 2.2. | 136 |

| | |
|---|-----|
| 3124 7.4 An illustration of the matter-induced effects on the oscillation probabil- | |
| 3125 ity, given as a function of neutrino energy and zenith angle. The top row | |
| 3126 of panels gives the $P(\nu_e \rightarrow \nu_e)$ oscillation probability and the bottom | |
| 3127 row illustrates the $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ oscillation probability. The left column | |
| 3128 highlights the oscillation probability in a vacuum, whereas the middle | |
| 3129 and right column represents the oscillation probabilities when the four- | |
| 3130 layer fixed density PREM model is assumed. All oscillation probabilities | |
| 3131 assume the “Asimov A” set given in Table 2.2, but importantly, the right | |
| 3132 column sets an inverted mass hierarchy. The “matter resonance” effects | |
| 3133 at $E_\nu \sim 5\text{GeV}$ can be seen in the $P(\nu_e \rightarrow \nu_e)$ for normal mass hierarchy | |
| 3134 and $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ for inverted hierarchy. | 137 |
| 3135 7.5 The oscillation probability for beam neutrino events given as a function | |
| 3136 of neutrino energy. All oscillation parameters assume the “Asimov A” | |
| 3137 set given in Table 2.2 unless otherwise stated. Each panel represents a | |
| 3138 change in one of the oscillation parameters whilst keeping the remaining | |
| 3139 parameters fixed. | 138 |
| 3140 7.6 The number of electron-like events in the FHC and RHC operating | |
| 3141 mode of the beam, as a function of the oscillation probabilities. Both | |
| 3142 normal hierarchy (Solid) and inverse hierarchy (Dashed) values of | |
| 3143 Δm_{23}^2 are given. | 139 |
| 3144 7.7 The oscillation probability $P(\nu_\mu \rightarrow \nu_e)$, given as a function of neutrino | |
| 3145 energy and zenith angle, which highlights an example of the “fast” | |
| 3146 oscillations in the sub-GeV upgoing region. | 141 |
| 3147 7.8 Illustration of the averaging procedure for $N = 2$. The oscillation | |
| 3148 probabilities calculated on the finer left binning are averaged to obtain | |
| 3149 the oscillation probabilities in the coarser right binning. These averaged | |
| 3150 oscillation probabilities with the coarser binning are then applied to | |
| 3151 each event during the fit. | 143 |
| 3152 7.9 Event rate of the SubGeV_elike_0dcy sample as a function of the num- | |
| 3153 ber of sub-divisions per coarse bin. Each subplot represents the event | |
| 3154 rate of the sample at a different oscillation parameter set thrown from | |
| 3155 the PDG priors detailed in Table 2.1. The red line in each subplot | |
| 3156 represents the mean of the event rate over the different values of sub- | |
| 3157 divisions for that particular oscillation parameter throw. | 145 |

| | | |
|------|---|-----|
| 3158 | 7.10 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 $N = 10$ | 146 |
| 3162 | 7.11 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 $N = 10$ | 147 |
| 3167 | 7.12 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 7.10 and Figure 7.11. | 148 |
| 3174 | 7.13 The calculation time taken to both calculate the oscillation probabilities and fill the “coarse” oscillograms, following the technique given in section 7.2, 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. | 149 |
| 3182 | 7.14 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 7.1. The right column illustrates the difference in oscillation probability between the two different techniques. | 151 |

- 3189 7.15 The density of the Earth given as a function of the radius, as given by
3190 the PREM model (Black), the constant density four-layer approxima-
3191 tion (Blue), as used in the official SK-only analysis, and the quadratic
3192 approximation of the PREM model (Red). 152
- 3193 7.16 The oscillation probability, $P(\nu_\mu \rightarrow \nu_e)$ (top row) and $P(\nu_e \rightarrow \nu_e)$ (bot-
3194 tom row), given as a function of neutrino energy and zenith angle. The
3195 left column gives probabilities where the four-layer constant density ap-
3196 proximation is used. The middle column gives the probabilities where
3197 the density is integrated over the trajectory, using the quadratic PREM
3198 approximation, for each $\cos(\theta_Z)$ is used. The right column illustrates the
3199 difference in oscillation probability between the two different techniques. 154
- 3200 7.17 The oscillation probability, $P(\nu_\mu \rightarrow \nu_e)$ (top row) and $P(\nu_e \rightarrow \nu_e)$ (bot-
3201 tom row), given as a function of neutrino energy and zenith angle. The
3202 left column gives probabilities where a fixed production height of 25km
3203 is used. The middle column gives the probabilities where the produc-
3204 tion height is analytically averaged. The right column illustrates the
3205 difference in oscillation probability between the two different techniques. 158

3206 List of Tables

| | | | |
|---------------------|-----|---|------------------------|
| <small>3207</small> | 2.1 | 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. | <small>3208</small> 21 |
| <small>3209</small> | | | |
| <small>3210</small> | | | |
| <small>3211</small> | 2.2 | Reference values of the neutrino oscillation parameters for two different oscillation parameter sets. | <small>3212</small> 22 |
| <small>3213</small> | | | |
| <small>3214</small> | | | |
| <small>3215</small> | 3.1 | The various SK periods and respective live-time. The SK-VI live-time is calculated until 1 st April 2022. SK-VII started during the writing of this thesis. | <small>3216</small> 24 |
| <small>3217</small> | | | |
| <small>3218</small> | | | |
| <small>3219</small> | 3.2 | 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. | <small>3220</small> 33 |
| <small>3221</small> | | | |
| <small>3222</small> | 3.3 | The threshold momentum and energy for a particle to generate Cherenkov light in ultrapure water, as calculated in Equation 3.2 in ultrapure water which has refractive index $n = 1.33$ | <small>3223</small> 34 |
| <small>3224</small> | | | |
| <small>3225</small> | | | |
| <small>3226</small> | 4.1 | 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. | <small>3227</small> 66 |
| <small>3228</small> | | | |
| <small>3229</small> | | | |
| <small>3230</small> | 6.1 | The amount of data collected in each detector used within this analysis. The data collected at the near and far detector, for both neutrino beam (FHC) and antineutrino beam (RHC), is measured as the amount of protons on target (POT). | <small>3231</small> 90 |
| <small>3232</small> | | | |
| <small>3233</small> | 6.2 | The fully contained subGeV samples used within this oscillation analysis. Both the sample name and description are given. | <small>3234</small> 93 |

| | | | |
|------|------|---|-----|
| 3233 | 6.3 | The fully contained multiGeV samples used within this oscillation analysis. Both the sample name and description are given. | 95 |
| 3234 | | | |
| 3235 | 6.4 | The purity of each atmospheric sample used within this analysis, broken down by charged current (CC) and neutral current (NC) interactions and which neutrino flavour interacted within the detector. The pre-fit dial values and Asimov A oscillation parameter sets are assumed. Electron neutrino and antineutrino events are separated to illustrate the ability of the separation likelihood cuts used within the sample selections. | 96 |
| 3236 | | | |
| 3237 | | | |
| 3238 | | | |
| 3239 | | | |
| 3240 | | | |
| 3241 | 6.5 | The reconstructed cosine zenith and lepton momentum binning assigned to the atmospheric samples. The “ $\cos(\theta_Z)$ Bins” column illustrates the number of bins uniformly distributed over the $-1.0 \leq \cos(\theta_Z) \leq 1.0$ region for fully and partially contained samples and $-1.0 \leq \cos(\theta_Z) \leq 0.0$ region for up- μ samples. | 98 |
| 3242 | | | |
| 3243 | | | |
| 3244 | | | |
| 3245 | | | |
| 3246 | 6.6 | The neutrino energy binning for the different neutrino flavours. “Right” sign indicates neutrinos in the FHC beam and antineutrinos in the RHC beam mode. “Wrong” sign indicates antineutrinos in the FHC beam and neutrinos in the RHC beam mode. The binning of the detector response is identical for the FHC and RHC modes as well as at ND280 and SK. | 109 |
| 3247 | | | |
| 3248 | | | |
| 3249 | | | |
| 3250 | | | |
| 3251 | | | |
| 3252 | 6.7 | List of cut variables that are included within the shift/smear fit documented in [195]. | 120 |
| 3253 | | | |
| 3254 | 6.8 | Reconstructed event topology categories on which the SK detector systematics [195] are based. | 120 |
| 3255 | | | |
| 3256 | 6.9 | Sources of systematic errors specified within the grouped into the “calibration” systematics model. | 123 |
| 3257 | | | |
| 3258 | 6.10 | Reconstructed event topology categories on which the SK detector systematics are based | 125 |
| 3259 | | | |
| 3260 | 7.1 | Description of the four layers of the Earth invoked within the constant density approximation of the PREM model [210]. | 133 |
| 3261 | | | |

| | | |
|------|--|-----|
| 3262 | 7.2 The quadratic polynomial fits to the PREM model for four assumed | |
| 3263 | layers of the PREM model. The fit to calculate the coefficients is given | |
| 3264 | in [211], where $x = R/R_{Earth}$ | 153 |