論文の内容の要旨

Title of the Thesis:

Study of the Oscillation of Neutrinos and Anti-Neutrinos and of
Non-Standard Neutrino Interactions with the
Atmospheric Data in Super-Kamiokande

(スーパーカミオカンデの大気ニュートリノデータによる
ニュートリノと反ニュートリノ振動の研究と
非標準ニュートリノ相互作用の研究)

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In atmospheric neutrinos, there has been a long established deficit of muon neutrino events that enter from below the detector after traversing long distances. This phenomena has been well described by a theory called Neutrino Oscillations, which allows neutrinos to oscillate from one favour to another. The probability of these transitions is characterised by the ratio of the flight path of the neutrino to its energy, L/E. The L/E Analysis aims to accurately determine the oscillation parameters by reconstructing the L/E dependence of the flavour transitions (Fig. 1). It achieves this by selecting events with a high resolution in L/E.

Atmospheric neutrino experiments have typically measured oscillations with combined neutrino and anti-neutrino data. In recent years, accelerator experiments have been reversing the polarity of their focussing magnets, greatly increasing the anti-neutrino composition in their beams. Early oscillation analyses of this $\bar{\nu}$ data by MINOS (2011) resulted in a much larger Δm^2_{31} measurement than the established value for neutrinos. This lead to experiments checking if distinct anti-neutrino oscillation parameters can be measured by oscillating the $\bar{\nu}$ independently from the ν. In addition, Neutral-Current (NC) Non-Standard Interactions (NSI) of neutrinos with matter were proposed to explain the anomaly. In the years that followed, MINOS reported on ν and $\bar{\nu}$ oscillation parameters that were in agreement.

However, it is important to make independent checks of any physical phenomena, particularly with an experiment with a different scope of sensitivity. Super-Kamiokande (SK) covers a wider range of the parameter space with baselines extending from $\sim$10 km to over 10^4 km; and energies ranging from 30 MeV to 50 GeV in this analysis. These baselines traverse extensive amounts of matter, crossing the entire Earth and include the

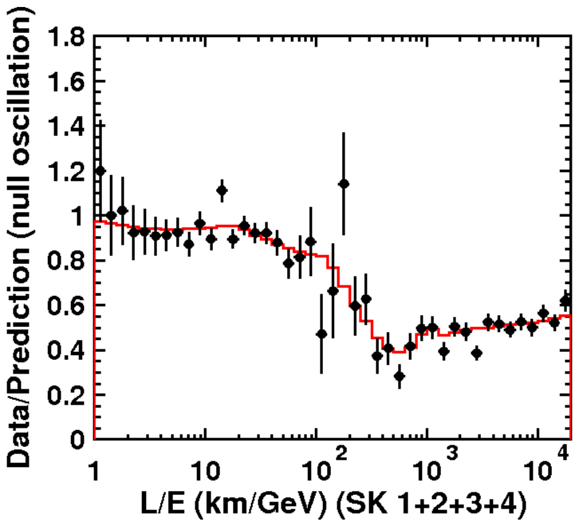

Figure 1: The characteristic shape of Neutrino Oscillations with varying L/E can be seen. The data points are from the standard 2-flavour L/E analysis, and the best-fit MC is shown in the solid red curve. Both have been divided by the null-observation hypothesis, with no observation a flat ratio of one would be expected. This analysis observes a signature “dip” at around $L/E \sim 500\,\text{km/GeV}$.

mantle and core. While SK cannot distinguish between ν and $\bar{\nu}$ on an event-by-event basis, it has the potential for discovery of unexpected effects and unparalleled sensitivity to matter effects, such as in NC NSI. In addition, there has been interest to check the CPT symmetry in neutrinos, rather than assuming it holds. Furthermore, the NSI analysis here provides an elegant model independent investigation in to the possibility of measuring new physics alongside Neutrino Oscillations.

In this thesis, both of these hypotheses have been investigated. After extending the Standard L/E Analysis to cover over 10 years of atmospheric neutrino data, further improvements were made to increase the sensitivity to $\bar{\nu}$ parameters and sub-dominant NSI. These included a separately binned second resolution sample to considerably increase the available statistics, and an improved χ^2 calculation with greater stability in bins with few events. The standard analysis was in 2-flavours, which was extended to a 3-flavour model and then again to include $\mu\tau$–sector NSI. Included in this thesis is the first L/E analysis performed with 3-flavour oscillations, and the first analysis of atmospheric neutrino data with 3-flavour oscillations and NSI in the $\mu\tau$–sector.

No distinction could be observed between the ν and $\bar{\nu}$ parameters, which can be seen by the overlapping regions of the green line and shaded green contour in the left of Fig. 2. The results were consistent with no observation of NSI, which can be seen by the green contour in the right of Fig. 2. The 90% C.L. limits on the NSI parameters were:

$$-1.97 \times 10^{-2} < \varepsilon_{\mu\tau} < 1.45 \times 10^{-2}, \text{ and}$$
$$-4.54 \times 10^{-2} < \varepsilon' \equiv (\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}) < 4.47 \times 10^{-2},$$

assuming a normalisation of neutrino NSI with down-quarks in the matter traversed and $\varepsilon_{\mu\mu} = \varepsilon_{e\tau} = 0$. With proper consideration of 3-flavour effects, and the best sensitivity to matter effects, these constraints are currently the best in the world. The oscillation

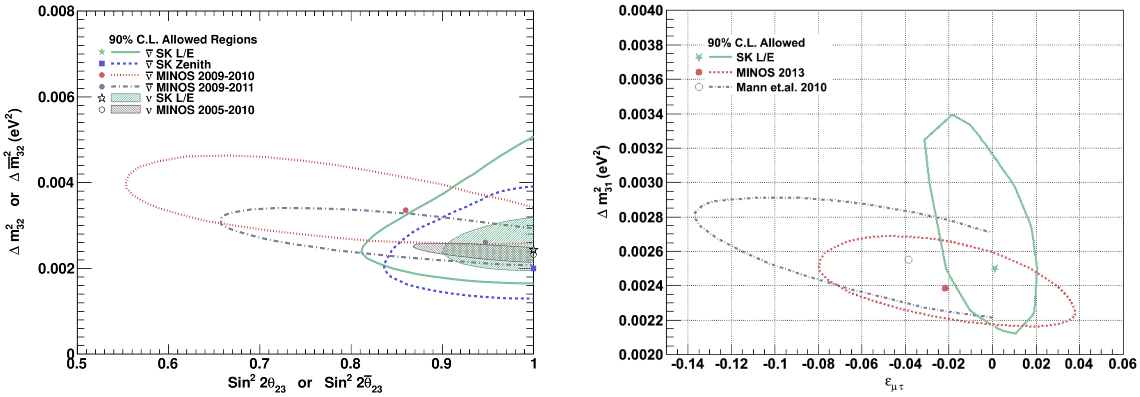

Figure 2: Comparisons of various ν and $\bar{\nu}$ oscillation parameter measurements at the 90% C.L. on the left, and comparisons of NSI measurements on the $\varepsilon_{\mu\tau} \times \Delta m^2_{31}$ parameter space on the right. (Left) The dotted red contour shows the first $\bar{\nu}$ result from MINOS in 2011, which was distinct from the ν data in the shaded grey region (updated $\bar{\nu}$ result in the dash-dotted grey contour). The L/E $\bar{\nu}$ contour is drawn in the green solid line, the Zenith measurement in dashed blue. The L/E ν region has been overlaid in the shaded green contour. All results now overlapping. (Right) L/E shown in solid green; a 2010 NSI phenomenological study of MINOS distributions by Mann et.al. in dash-dotted grey; and a 2013 MINOS NSI measurement of data in dashed red. The L/E region is much more confined in $\varepsilon_{\mu\tau}$, and takes a steeper angle through the parameter space.

parameters measured in the 3-flavour L/E analysis for Normal (Inverted) Hierarchy were:

$$\sin^2\theta_{23} = 0.55^{+0.07}_{-0.13}\left(0.54^{+0.07}_{-0.12}\right), \text{ and}$$
$$\Delta m^2_{31} = 2.60^{+0.22}_{-0.21}\left(2.45^{+0.25}_{-0.16}\right) \times 10^{-3}\,\text{eV}^2.$$

The data showed no preference between Normal and Inverted Hierarchy.

The thesis begins in Chapter 1 with an introduction including a brief overview of the neutrino history, a look at atmospheric neutrinos as the data source of this thesis, followed by an overview of the theory of Neutrino Oscillations and Non-Standard Neutrino Interactions (NSI). The chapter closes with an overview of relevant NSI results in the literature. Chapter 2 then provides a comprehensive look at the experimental results, over 40 years, supporting neutrino oscillations. The literature review covers several classes of experiments: Solar, Atmospheric, Reactor, and Accelerator neutrino experiments. As well as a quick look at future experiments in the field.

The next couple of chapters give an overview of the Super-Kamiokande experiment. This includes details about the detector in Chapter 3; details of the simulation from the atmospheric neutrino flux to detector simulation in Chapter 4; and detector calibrations in Chapter 5. Data reduction from the raw recorded events down to neutrino events is discussed in Chapter 6; and the reconstruction of physical variables from the charge and timing data from the PMTs is explained in Chapter 7.

The following chapters cover the various analyses carried out for this thesis. The

Standard 2-flavour L/E Analysis and its update to cover over 10 years of data is covered in Chapter 8. Every analysis in this thesis depends on the reconstruction of these L/E distributions, so Chapter 8 is important and relevant to each of the other analyses. In Chapter 9, details of the various improvements to the analysis to increase sensitivity to anti-neutrino parameters (as well as other sub-dominant effects) are written. The neutrino and anti-neutrino parameters were measured independently using the L/E distributions and no discrepancy was found.

The L/E Analysis was updated to a 3-flavour model, discussed in Chapter 10, and both the Normal and Inverted Neutrino Mass Hierarchy hypotheses were analysed. No discrepancy between these scenarios was observed. The single-angle parameter, $\sin^2\theta_{23}$, was scanned, but no distinct octant could be determined. However, the bestfit values for both hierarchies were slightly greater than 0.5. The analysis was then extended to incorporate a 3-flavour oscillation and NSI model, to investigate NSI in the $\mu\tau$–sector, which is described in Chapter 11. The Δm^2_{31} dependence on $\varepsilon_{\mu\tau}$ was observed. However, the results were consistent with no observation of NSI and Neutrino Oscillations were found to be robust even in the presence of NSI. Finally, the results are collected and summarised in the Conclusion in Chapter 12.