Future atmospheric neutrino data from Super-Kamiokande

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Expected sensitivity of future atmospheric neutrino data from Super-Kamiokande on neutrino oscillation physics is discussed. We expect that the accuracy of the $\sin^2 2\theta_{23}$ measurement will be improved with (exposure time)$^{1/2}$. By analyzing high energy fully contained events, it could be possible to statistically demonstrate the existence of charged current ν_τ interactions at the 3 standard deviation level with a few more years of data. Subdominant $\nu_\mu \to \nu_e$ oscillations could be observed if θ_{13} is near the present limit. However, significantly more data will be required to observe a 3 standard deviation effect.

1. Introduction

Atmospheric neutrino data from Super-Kamiokande are explained by two flavor $\nu_\mu \to \nu_\tau$ oscillations with $\sin^2 2\theta_{23} > 0.88$ and $1.5 < \Delta m^2_{23} < 5 \times 10^{-3}\mathrm{eV}^2$ [1] [2]. In addition, Super-Kamiokande has studied high-energy and neutral-current-enriched atmospheric neutrino data and concluded that $\nu_\mu \to \nu_{sterile}$ oscillations can not explain the data at 99% C.L. [3] [2].

The mixing parameter, $\sin^2 2\theta_{23}$, is one of a fundamental parameters which could constrain theories beyond the standard model of the particle physics. Therefore, it is important to measure $\sin^2 2\theta_{23}$ accurately.

Although the present atmospheric neutrino data favor $\nu_\mu \to \nu_\tau$ rather than $\nu_\mu \to \nu_{sterile}$, evidence for charged current (CC) ν_τ events has not been observed yet. Assuming the best fit neutrino oscillation parameters, the expected event rate of CC ν_τ interactions is about 1 /kton·yr. It will be important to observe evidence for CC ν_τ interactions in the data.

If a three flavor oscillation scheme is considered, it is natural to expect subdominant $\nu_\mu \to \nu_e$ oscillations, i.e., non-zero θ_{13}. This effect could be observed as an excess of electron neutrino events in the upward-going direction. In this article, we discuss the sensitivity of future atmospheric neutrino data from Super-Kamiokande on these three topics.

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2. Measurement of $\sin^2 2\theta$

The atmospheric neutrino flux is accurately predicted to be up-down symmetric in the multi-GeV energy range, and $(up/down)_{Data}/(up/down)_{MC} \simeq 1-(\sin^2 2\theta_{23})/2$ to first approximation, assuming that there is no (full) oscillation effect for downward-(upward-)going neutrinos. Hence atmospheric neutrino data are useful for an accurate measurement of $\sin^2 2\theta_{23}$. Figure 1 shows the expected sensitivity of future Super-Kamiokande data to $\sin^2 2\theta_{23}$ and Δm^2_{23}. The expected accuracy of the $\sin^2 2\theta_{23}$ measurement will be improved with (exposure time)$^{1/2}$. The accuracy of the Δm^2_{23} measurement will also be improved. However, we have to be careful for Δm^2_{23}, because the Δm^2_{23} measurement can not be expressed by any simple formula in contrast to the case of $\sin^2 2\theta_{23}$. In fact, (Data/Monte Carlo) values in the horizontal direction as a function of the lepton energy are the most important for the Δm^2_{23} measurement. However, the flux prediction has relatively large uncertainties due partly to the three dimensional flux calculation effects [4]. The three dimensional flux calculations predict higher fluxes and shorter neutrino pass lengths near horizon.

The accuracy of the $\sin^2 2\theta_{23}$ can be improved

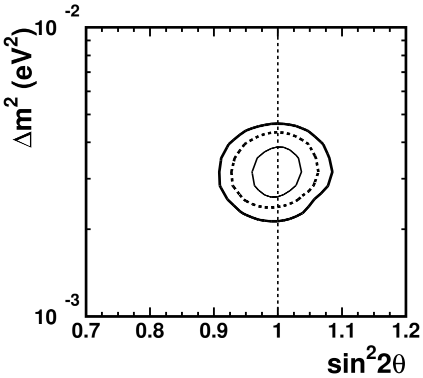

Figure 1. Expected sensitivity of future Super-Kamiokande data to $\sin^2 2\theta_{23}$ and Δm^2_{23}. Thick, dashed, and thin lines show the sensitivity for 5, 10 and 40 years of the data assuming $\sin^2 2\theta_{23}$ =1,00 and $\Delta m^2_{23} = 3 \times 10^{-3}$eV^2. Systematic errors from the present Super-Kamiokande analysis are assumed.

further by including multi-ring events in the oscillation analysis. It is relatively easy to select CC ν_μ events in the multi-ring sample. Reducing various systematic errors, including uncertainties in the flux prediction, is also very important.

3. Charged current ν_τ interactions

The threshold energy of a CC ν_τ event is about 3.5 GeV. Typical CC ν_τ events have higher visible energy and higher pion multiplicity. In addition, since the leptonic branching ratio of τ is about 35%, typical CC ν_τ events have no energetic lepton in the final state. However, the difference in the event pattern between the CC ν_τ and other events is relatively small in the Super-Kamiokande detector. Therefore, several information are combined to select CC ν_τ candidates by a maximum likelihood method. In studies that are in progress in Super-Kamiokande, we start with a set of basic cuts and then use the maximum likelihood method to improve the signal to noise ratio. Finally we argue the zenith-angle distribution, since CC ν_τ events should be observed only in the upward going direction. Two examples of the present Monte Carlo (MC) studies are shown in Figure 2. In both plots, the expected CC ν_τ signal is about a 2 standard deviation level

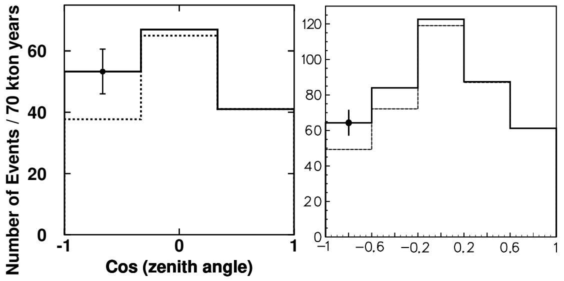

Figure 2. Expected sensitivity to CC ν_τ events. Very preliminary MC results from two different studies are shown. Solid and dotted histograms show expectations for $\nu_\mu \to \nu_\tau$ with and without CC ν_τ interactions, respectively. In both analyses, similar sets of primary cuts (a visible energy cut and a requirement that the most energetic particle must be e-like) are applied to the MC data. Then a maximum likelihood method is used. Various information obtained from an event, such as number of Cherenkov rings, number of electrons from muon decays, energy-flow constraints, and visible energy, are used as inputs to the likelihood function.

for 1144 days of data. Therefore, with a few more years of data, it could be possible to observe a 3 standard deviation effect.

4. Sensitivity to non-zero θ_{13}

A non-zero θ_{13} effect could be observed as an excess of electron neutrinos in the upward-going directions. However, for a original flux ratio (i.e., the flux ratio at the production point), ν_μ/ν_e, of 2/1 and for a near maximal $\sin^2 2\theta_{23}$, a non-zero θ_{13} effect is almost invisible. The only realistic way to observe a non-zero θ_{13} is through a matter resonance effect in the high energy range [5]. For Δm^2 of $3{\times}10^{-3}$eV^2, the resonance could occur for neutrinos with their energies around 10 GeV. Figure 3 (top) shows a $\nu_e \leftrightarrow \nu_\mu$ oscillation probability as a function of the neutrino energy and zenith angle. A clear resonance effect is seen for upward-going neutrinos near 10 GeV.

There are several experimental difficulties. One is the low neutrino flux near 10 GeV. The other is the fact that a majority of the interactions are deep inelastic interactions. Therefore, it might

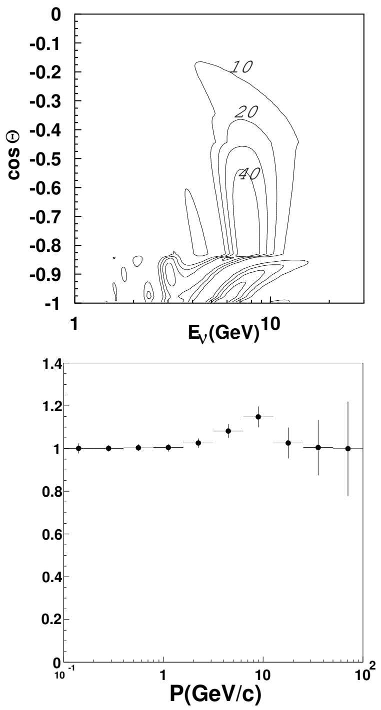

Figure 3. Top: $\nu_e \leftrightarrow \nu_\mu$ oscillation probability as a function of the neutrino energy and zenith angle. Numbers in the figure shows the probability in %. Bottom: Expected excess of single+multi-ring e-like events due to non-zero θ_{13} for the upward going direction ($\cos\Theta < -0.2$) and as a function of E_{vis}. 0.9Mton·yr exposure is assumed. In both plots, $\sin^2\theta_{23}$ =0.5 (maximal mixing), $\Delta m^2 = 3 \times 10^{-3}\text{eV}^2$, and $\sin^2\theta_{13}$ =0.026 are assumed.

necessary to use events with multi-particle final states in this analysis to improve the statistics. In contrast to CC ν_μ events, it is not easy separate CC ν_e and NC (+ a fraction of CC ν_μ) events. We will also use the maximum likelihood method for selecting CC ν_e events. A preliminary study suggests that a CC ν_e purity of about 75% can be achieved with almost the same statistics as the single-ring sample for E_{vis} >3 GeV.

Figure 3 (bottom) shows the excess of single+multi-ring e-like events as a function of E_{vis} for the upward going direction. The assumed detector exposure is 0.9Mton·yr (40yrs of the exposure of the Super-Kamiokande detector). In this figure, $\sin^2\theta_{13} = 0.026$ (CHOOZ limit [6]) is assumed. A signal of more than 4 standard deviations could be seen. However, if the true $\sin^2\theta_{13}$ is 0.005, the expected signal is less than a two sigma effect for this exposure time. Therefore, we conclude that the signal could be observed if the true θ_{13} is close to the present limit and if the statistics of the events are improved significantly.

5. Summary

Future atmospheric neutrino data from Super-Kamiokande will contribute further to the neutrino oscillation physics. The accuracy of the $\sin^2 2\theta$ measurement will be improved with (exposure time)$^{1/2}$. By a careful analysis of the high energy fully contained events, it could be possible to statistically demonstrate the existence of CC ν_τ interactions at the 3 standard deviation level with a few more years of data. A non-zero θ_{13} could be observed only if θ_{13} is near the CHOOZ limit. However, even in this case, significantly more data will be required to observe a 3 standard deviation effect.

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