Search for charged current tau neutrino appearance in Super-Kamiokande

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Abstract

An appearance search for tau neutrinos is performed in the Super-Kamiokande experiment. If the observed muon neutrino oscillation is to tau neutrinos, it should be possible to detect charged current tau neutrino interactions in Super-Kamiokande. A statistical separation based on kinematic variables is used to enhance a sample of tau-like events. Results using the SK-I data set are presented.

1. Introduction

In previous papers[1], the Super-Kamiokande(Super-K) group reported evidence for neutrino oscillation with atmospheric neutrinos. The data shows a strong zenith angle dependent disappearance for muon neutrinos, and no such deficit for electron neutrinos. The data could also be explained by $\nu_\mu \leftrightarrow \nu_\tau$ two flavor neutrino oscillation and the allowed oscillation parameters are estimated to be $1.6 \times 10^{-3} < \Delta m^2 < 3.9 \times 10^{-3}\mathrm{eV}^2$ and $\sin^2 2\theta > 0.92$. Also this disappearance could be explained by oscillation to sterile neutrinos (ν_s) but this pure $\nu_\mu \leftrightarrow \nu_s$ oscillation scenario have already been excluded at more than 99% confidence level[2,3,4,5]. Therefore the appearance signal of tau neutrino charged current interactions should be observed in Super-K.

2. The atmospheric neutrino sample

Super-K is a water Cherenkov detector located 2700 meter water-equivalent underground in Kamioka Mine. The detector contains 50 kiloton of ultra-pure water in a cylindrical stainless steel tank. The water is separated into two regions. 11146 50 cm PMTs are installed in the inner detector region and 1885 20 cm PMTs are installed in the outer detector region. The fiducial volume of the detector for the atmospheric neutrino analysis is 22.5 kilotons. Details of the detector are explained in Ref. [6].

Neutrino events interacting with the water in the detector are observed as fully-contained or partially-contained events according to the amount of outer-

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detector activity. The vertex position, number of Cherenkov rings, particle directions and momentum are reconstructed, and the particle type of each Cherenkov ring is identified as e-like or μ-like. Moreover, fully contained events are subdivided into sub-GeV events and multi-GeV events according to their visible energies which are less or more than 1.33 GeV. A total of 1489 days of atmospheric neutrino data were used to this analysis. During this period, 772 single-ring e-like events, 664 single-ring μ-like events and 1532 multi-ring events are collected in the fully contained multi-GeV sample.

3. Tau appearance searches

In this study, the number of tau leptons produced by the tau neutrino interaction in the Super-K detector will be estimated. However the tau production threshold is ≈ 3.4 GeV and most atmospheric neutrinos have less energy than this threshold, around 86 charged current tau neutrino interactions are expected in Super-K, assuming two flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with the bestfit oscillation parameters.

We performed an appearance search for charged current tau neutrinos. Since the characteristics of a tau lepton are the short lifetime and its many decay products, the directly identification of a tau lepton in Super-K is difficult. Therefore the analysis is based on the statistical differences between charged current tau neutrinos and other interactions. The differences appeared in the energy spectrum, the number of charged pions in the final state, the fraction of lepton energy with respect to neutrino energy and so on. We have done three different analyses to enrich charged current tau neutrino interactions.

The first method is a likelihood method using parameters such as visible energy, number of rings, number of decay electrons and so on. These parameters are estimated by the standard Super-K event reconstruction tools described in section 2. This analysis has 44% efficiency to detect tau neutrino interactions in the fiducial volume.

The second method is a neural network method. The neural network selects tau neutrino interactions based on event variables which are similar to the first method. This analysis has 55% efficiency to detect tau neutrino interactions in the fiducial volume.

The third method is a likelihood analysis based on energy flow variables. This analysis uses the difference between a tau decay and a non-tau production event. A tau produced near threshold will decay more isotropically, while a non-tau production events will have remaining parent neutrino momentum and the resulting particles will tend to be produced in one direction. Several energy flow parameters are defined and the analysis is carried out based on the minimum likelihood method.

After testing the methods using the MC data, these analyses were applied to the atmospheric neutrino data set. Tau neutrino events are expected to appear as upward going events for the current Δm^2 allowed region explained in section 1. Therefore charged current tau neutrino events should be observed as the excess of upward-going events in the zenith angle distribution. The tau likelihood distributions for upward going event data and MC by the likelihood method are shown in Fig 1. The points show the data. The solid line shows the MC assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with the appearance signal of tau neutrino charged current interactions. The dashed line shows the MC assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillations without the appearance signal of charged current tau neutrino interactions. Tau like events are defined as likelihood > 1 for single-ring events and likelihood > 0 for multi-ring events.

The zenith angle distribution for the tau neutrino enriched sample has fitted by a combination of atmospheric electron neutrino and muon neutrino events taking into account oscillations and the expected tau neutrino charged current events resulting from oscillations. Fig. 2 shows the zenith angle distribution for the tau neutrino enriched sample from a likelihood analysis with the best fit result of the fitting. The points show the zenith angle distribution of the data. The solid line shows zenith angle distribution of the best fit. The dashed line shows the zenith angle distribution assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillations without the appearance signal of tau neutrino charged current interactions.

The results of there analyses are summarized in table 1. The MC predicts 86 charged current tau neutrino events. The three analyses are highly correlated with each other, and therefore cannot be combined in an independent way to increase the significance.

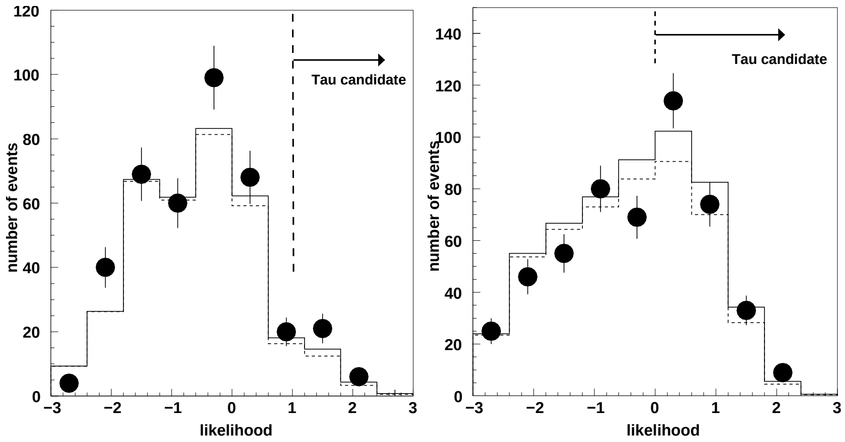

Fig. 1. Tau likelihood distributions for data(point) and simulation(line). Left figure shows single-ring events and right figure shows multi-ring events

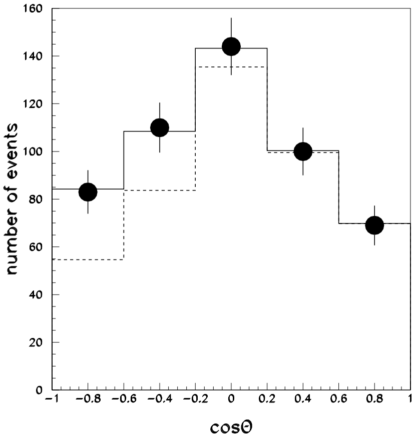

Fig. 2. Zenith angle distribution for tau candidate events. The result of a fit to the number of atmospheric ν_e and ν_μ events including oscillations and the expected ν_τ events are shown by histograms.

Table 1. Summary of the three tau analysis results. Their selection efficiencies for tau events and the number of observed tau events are shown.

Method	ϵ_τ	number of observed events
Likelihood	44%	$145 \pm 44(stat.)^{+11}_{-16}(sys.)$
Neural net	55%	$99 \pm 39(stat.)^{+13}_{-21}(sys.)$
Energy flow	32%	$135^{+47}_{-44}(stat. + sys.)$

4. Summary

Searches for the tau appearance associated with $\nu_\mu \leftrightarrow \nu_\tau$ oscillations are performed using three methods. These results of these three methods and the MC expectation agree well within the statistical error and the data are consistent with $\nu_\mu \leftrightarrow \nu_\tau$ oscillation in the Super-K detector.

5. References

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