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A Search for Tau Appearance in Atmospheric Neutrinos with Super-Kamiokande

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A search for the appearance of tau neutrino charged-current interactions has been performed using all the atmospheric neutrino data from the Super-Kamiokande-I experiment. The evidence for atmospheric neutrino oscillations, in which $\nu_\mu \leftrightarrow \nu_\tau$ is dominant, has been already presented. A tau neutrino enriched sample is selected by a statistical analysis method with a set of variables based on kinematics of tau decay. The zenith angle distribution of the sample is fitted with a combination of the expected tau neturino signals resulting from oscillations and the predicted atmospheric neutrino background events including oscillations. SK-I atmospheric neutrino data for 1489 days of exposure find a best fit tau signal of 145 ± 48 (stat.) $^{+9.4}_{-36.2}$ (sys.) and are consistent with the tau neutrino appearance.

1. Introduction

Atmospheric neutrino oscillations, in which $\nu_\mu \leftrightarrow \nu_\tau$ oscillations is favored, have been confirmed by several recent experiments [1, 2, 3]. The Super-Kamiokande atmospheric neutrino data also favor such oscillations [1, 4, 5] and have excluded $\nu_\mu \leftrightarrow \nu_{sterile}$ oscillations at more than the 99% confidence level [6] and some other exotic hypotheses have been disfavored [4]. However, ν_τ appearance has not yet been observed although the most favored senario for the observed zenith angle dependent deficit of muon neutrinos, i.e. ν_μ disappearance, has been $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. Therefore, an unambiguous confirmation of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations would be the observation of tau appearance resulting from tau neutrino charged-current interactions.

2. The Atmospheric neutrino data in Super-Kamiokande-I

Super-Kamiokande (SK) is a cylindrical 50-kton water Cherenkov detector, with a rock overburden of 2700 m water equivalent located in Gifu, Japan. The detector is optically isolated into two regions. The inner detector (ID) has 11,146 50cm photomultiplier tubes (PMT) to monitor the ID fiducial volume of 22.5 kilotons. The outer detector (OD) has 1885 20cm PMTs facing outward and vetoes cosmic ray muons. Details of the detector, calibrations, and data reduction can be found in Refs.[5, 7]. Super-Kamiokande-I (SK-I) has accumulated a total of 1489 days (92 kton-yr) of exposure of atmospheric neutrino data from May, 1996 to July, 2001. The atmospheric neutrino events are classified as fully-contained (FC), partially-contained (PC) events, and upward-going muons as described in Ref. [5]. In the present analysis, only fully-contained (FC) atmospheric neutrino data were used.

3. Search for tau appearance

The energy threshold of tau lepton production in ν_τ charged-current (CC) interactions is approximately 3.5 GeV, which is higher than most of atmospheric neutrino interactions in SK. Assuming two flavor maximal mixing in $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, we estimate that approximately one ν_τ CC event to occur in the SK detector per kiloton-year of exposure, or about 20 events/year. This corresponds to approximately a total of 79 events

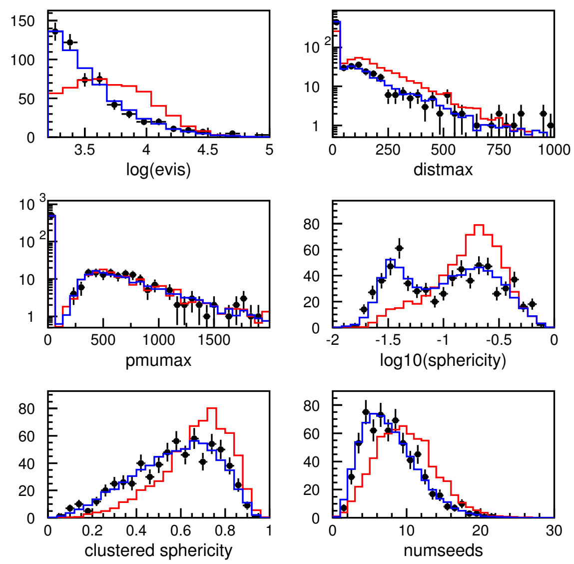

Figure 1. The distributions of variables in the likelihood function for only downward-going data, tau MC, and background MC events. All of the distribution are normalized arbitrarily.

in the SK-I data set. Since tau lepton is the heaviest particle in this energy region, the event shape of tau decay has a more spherical topology compared to atmospheric neutrino background events, mainly deep-inelastic scattering events with multiple pions produced, of which the shape is more forward due to momentum of a parent neutrino. However, SK is not suited to identify tau leptons directly due to the short lifetime of tau leptons and the high multiplicity of tau decay. Hence, we have employed the statistical analysis methods, likelihood and neural network analyzes, to distinguish tau-like events from atmospheric neutrino backgrounds. We use a Monte Carlo (MC) simulation to model the atmospheric neutrino and tau neutrino predictions in SK [5]. In tau MC, the polarization of tau leptons was implemented based on the calculation by Hagiwara *et al.* [8]. Also, tau leptons in the MC simulation decay using the tau decay library, TAUOLA [9].

We have applied basic tau selection criteria to reduce the backgrounds as follows: (1) FC events: fiducial volume (2m from the ID PMT surface) and no activity in OD region, (2) visible energy, E_{vis},> 1.33 GeV (multi-GeV events), and (3) most energetic ring is e-like (showering events). We then have constructed a likelihood function using six variables based on kinematics of tau decay to discriminate tau signals from backgrounds, which are (1) visible energy, (2) maximum distance between the primary and electron vertex from muon decay, (3) maximum momentum for μ-like ring, (4) the number of possible rings, (5) sphericity in the rest frame, and (6) clustered sphericity in the center of mass frame. The first 4 variables are reconstructed by SK starndard analysis tools and the last two variables are event shape variables obtained by energy flow analysis. Figure 1 shows the distribution of each variable for data, tau, atmospheric backgrounds only for downward-going events with an arbitrary normalization. Downward-going ν_μ have short path length and even with sufficient energy, the probability to oscillate into tau neutrinos is very small. Therefore, the downward-going data do not contain tau events and the agreement of downward-going data and background MC indicates the validity of our MC. Figure 1 also shows the difference between signal and background events. The distributions of the constructed

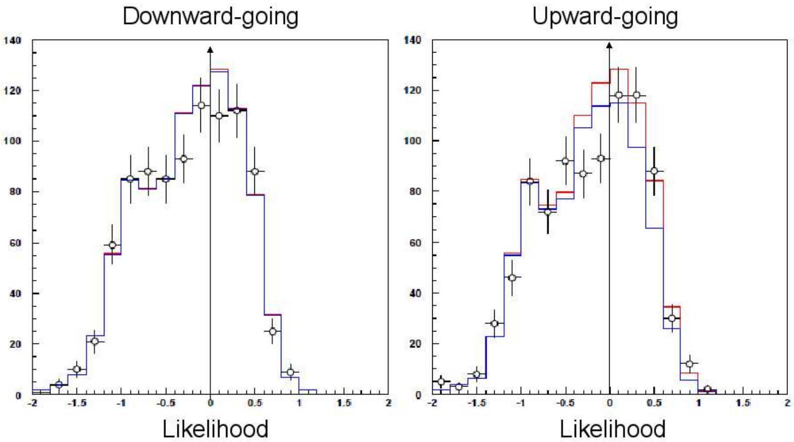

Figure 2. The tau likelihood distributions for downward-going (left) and upward-going (right) events are shown. L $>$ 0.0 is tau-like. The data are plotted by open circles, ν_e and ν_μ MC events are plotted by blue line, and ν_e and ν_μ MC with expected ν_τ events are plotted by red line.

likelihood function for downward-going and upward-going events are shown in Figure 2. The likelihood (L) $>$ 0.0 is tau-like.

The zenith angle distribution of the ν_τ enriched sample, after applying all the tau selection criteria including L>0, is fitted with a combination of the expected tau neutrino signals resulting from oscillations and the predicted atmospheric neutrino backgrounds with oscillations as shown in Figure 3. The normalizations for tau and background predictions are set to be free parameters. As can be seen, the data distribution agrees better with the prediction including tau appearance estimated by MC. The excess of tau-like events is observed in upward-going events as expected. The efficiency for detecting tau events is 44%. After correcting for the efficiency, we obtain 145 ± 48 (stat.) $^{+9.4}_{-36.2}$ (sys.) τ events in the SK-I atmospheric neutrino data sample.

Various systematic uncertainties are considered here and the more detailed description of systematic uncertainties is described in Ref. [5]. All of the error terms are re-evaluated for tau appearance analysis. The uncertainty in the tau cross-section gives a large contribution of $\pm$ 25%. The asymmetric systematic uncertainty comes from $\sin^2\theta_{13}$ since for non-zero θ_{13} we expect to see multi-GeV electrons in upward-going events, which become backgrounds for tau signals. The uncertainty due to $\sin^2\theta_{13}$ was estimated using the limit obtain by the CHOOZ reactor neutrino experiment [10].

Similarly, we have used neural network to distinguish tau signals from backgrounds with the same set of variables. The zenith angle distribution of neural network analysis is shown in Figure 3. Both results are consistent and summarized in Table 1.

Table 1. Summary of two statistical analysis results. Their selection efficiencies for tau events, the number of observed tau events, and the number of expected tau events are shown.

Method	ϵ_τ	Number of observed τ events	Number of expected τ events
Likelihood	44%	$145 \pm 48(stat.)^{+9.4}_{-36.2}(sys.)$	$79 \pm 31(stat.)$
Neural Net	36%	$152 \pm 47(stat.)^{+12.0}_{-27.3}(sys.)$	$79 \pm 31(stat.)$

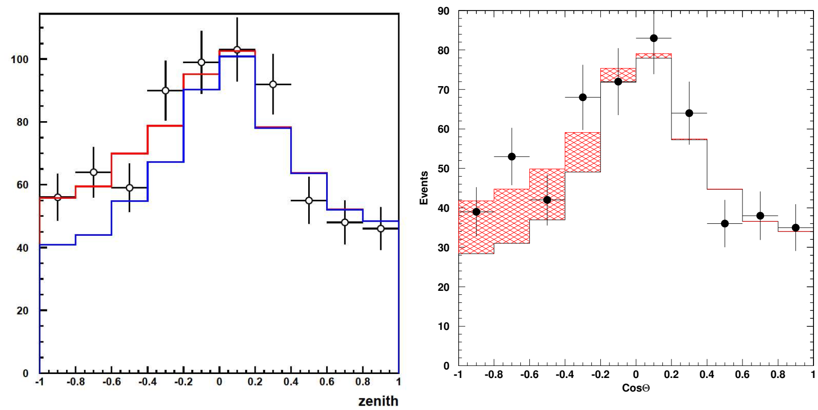

Figure 3. The zenith angle distributions of likelihood (left) and neural network (right) are shown. The ν_τ enriched sample is fitted after all of ν_τ selection criteria are applied. On the left-hand plot, the red line shows the best fit including ν_τ events and the blue line shows the backgrounds from ν_e and ν_μ. On the right-hand plot, the shaded area is an excess of tau-like events.

4. Conclusions

The search for the appearance of tau neutrino charged-current interactions has been carried out using atmospheric neutrino data observed in Super-Kamiokande I. The tau excess events were observed in upward-going directions. The results and the MC expectation agree well, and SK-I atmospheric neutrino data are consistent with $\nu_\mu \leftrightarrow \nu_\tau$ oscillations.

5. Acknowledgements

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