PROCEEDINGS OF SCIENCE

Tau Neutrino Appearance in the Flux of Atmospheric Neutrinos at the Super-Kamiokande Experiment

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The Super-Kamiokande experiment (Super-K) is a water Cherenkov detector noted for its discovery of the oscillation of atmospheric neutrinos. The dominant effect of the oscillation of muon neutrinos in the atmosphere is the appearance of tau neutrinos. Direct detection of ν_τ in the atmospheric neutrino flux would provide a clear confirmation of neutrino oscillations. The sub-dominant ν_μ oscillation mode, of ν_μ changing to ν_e, is studied at Super-K to determine mass ordering. Currently, ν_τ interactions form the biggest background to the mass ordering signal in the Super-K analysis. Machine learning techniques of neural networks are used at Super-K to segregate ν_τ charged-current interactions from the interactions of the atmospheric muon and electron neutrinos. 10% more events can be added to the analysis by expanding the fiducial volume of the detector. Studies on the Monte-Carlo simulations for a Super-K run period, between 2008 to 2018, suggest that we can expect improvements in the search for tau neutrinos and the suppression of mass-ordering backgrounds.

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1. Introduction

Interactions of cosmic rays with the Earth's atmosphere lead to the production of muon neutrinos and electron neutrinos, hereby referred to as atmospheric neutrinos. The intrinsic tau neutrino flux in the atmosphere, such as from the decays of D mesons, is negligible upto a few hundred GeV[1]. In the lower energy events, tau neutrinos are expected to appear mainly from the oscillation of muon neutrinos[2]. The tau neutrinos can be observed through charged current (CC) interactions, for which the neutrinos must have energies above the threshold of 3.5 GeV. However, the flux of atmospheric neutrinos above this threshold is low, and so, CC interactions of the oscillated tau neutrinos are rare. Super-Kamiokande (Super-K) is one of the experiments capable of detecting these oscillated tau neutrinos.

2. Super-Kamiokande

Super-K is a water Cherenkov detector, which consists of a cylindrical tank of diameter, 39.3 m, and height, 41.4 m, lined inside with photomultiplier tubes. Events in the detector are reconstructed by observing the Cherenkov rings of the charged particles produced in the detector. About one oscillated tau neutrino event is expected to be observed at Super-K per kiloton-year of detector exposure. Super-K rejected the hypothesis of no tau appearance with a significance level of 4.6 σ with data from 1998 to 2016[2].

The fiducial volume (FV) of a detector is the volume over which event reconstruction is considered for an analysis. The standard FV of 22.5 kT takes into account the events with the neutrino interaction vertex located upto 2m from the wall of the detector. Monte-Carlo (MC) studies discussed here are with 500 years of signal and background, each weighted to the Super-K live-time of about 9 years, corresponding to the SKIV run period (2008 to 2018). In line with the latest analysis of the oscillation of atmospheric neutrinos at Super-K[3], by reconstructing events even closer to the detector wall, upto 1 m, the expanded FV for this study is 27.2 kT. Although this is a 20% increase in fiducial mass, this study considers only those events for which nearly all of the neutrino energy is deposited inside the detector. This approach adds 10% more events to the analysis, thereby increasing the possible candidates of tau neutrinos that can be observed by Super-K.

3. Neural Network for Tau Neutrino Identification

Aside from its rarity, the observation of tau neutrino appearance is complicated by the short lifetime of the tau lepton ($\tau_\tau \sim 2.9 \times 10^{-13}$s). Tau lepton decays produce showers of charged secondary particles. While these events with multiple Cherenkov rings can be observed at SK, such multi-ring events are also produced by neutral current (NC) interactions of all flavours and CC interactions of ν_e and ν_μ at these energies, which comprise the background to the signal of ν_τ CC interactions. A feed forward neural network (NN) - a multi-layer perceptron consisting of seven inputs (Figure 1-A), and a single hidden layer - is used at Super-K to distinguish the ν_τ CC signal from the background. Events with an NN output above 0.5, as shown in Figure 1-B, are classified as ν_τ CC signal-like, resulting in a 72% signal selection efficiency in the standard FV. The performance of the NN in the expanded FV is similar. Tau neutrinos are selected with an efficiency of 74% in the expanded FV.

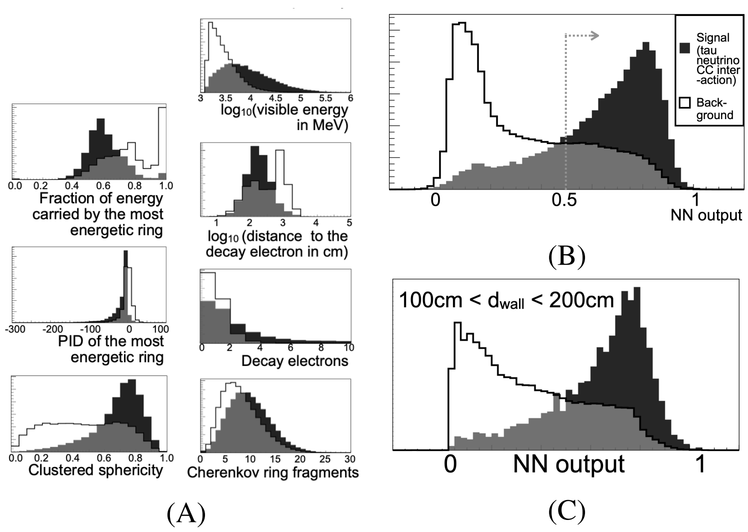

Figure 1: Distributions of the signal of ν_τ CC interactions, in black, has been normalised to the background, in white. (A) Inputs to the neural network (NN) for ν_τ identification. (B) NN output for the standard fiducial volume (FV) of the neutrino interaction vertex to the wall, $d_{wall} > 200$cm. Optimal cut point for selecting the ν_τ signal is set at 0.5 (gray dotted line). (C) NN output for the new events added from the FV expansion.

4. Tau Neutrino Appearance and Mass-Ordering

The observation of tau neutrino events in the atmosphere, in the energy range 3.5 GeV to 100 GeV, would be a clear confirmation of the dominant oscillation channel of muon neutrinos changing to tau neutrinos. Such muon neutrinos travel a distance through the Earth before hitting the detector. The angle made by the neutrino travel direction with the vertical axis of the detector, known as the zenith angle, θ, is defined such that these muon neutrinos have $\cos\theta < 0$. An ability to identify tau neutrinos also aids the process of observing the sub-dominant channel of muon neutrinos in the atmosphere oscillating to electron neutrinos. Due to matter effects, for normal (inverted) ordering,

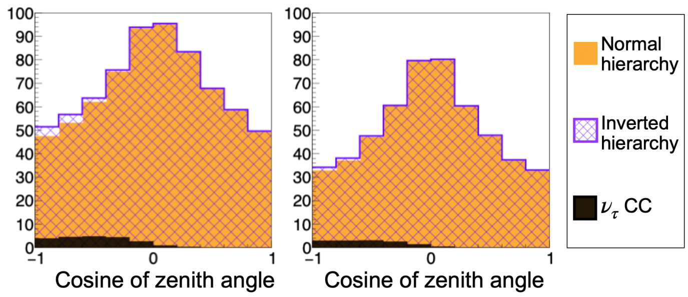

Figure 2: Electron neutrino (left) and antineutrino (right) multi-ring multi-GeV samples expected at Super-K, as a distribution of the cosine of the zenith angle, θ, under the normal (orange) and inverted (purple) neutrino mass-ordering assumption. In the region of $\cos\theta < 0$, there is the possible matter effect related resonance sensitive to the mass-ordering and the ν_τ CC interactions which obscures the resonance signal.

a resonance of ν_e ($\bar{\nu}_e$) appearance from the oscillation of muon neutrinos is expected in the multi-GeV neutrinos with $\cos\theta < 0$[4]. In the atmospheric neutrino oscillation analysis at Super-K, ν_τ appearance contaminates these samples, as shown in Figure 2. Therefore, constraining ν_τ CC

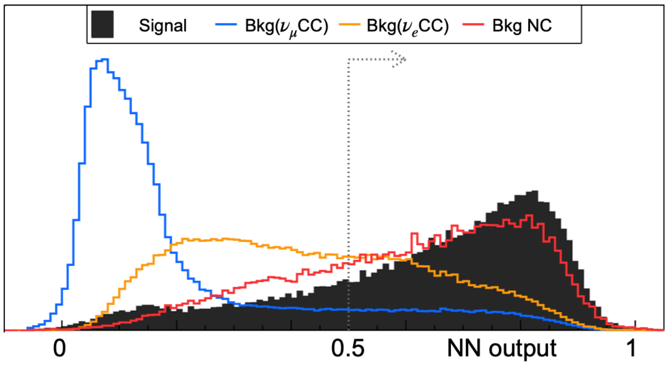

Figure 3: NN output distributions of the ν_τ CC interactions signal (black), and background - ν_e CC interactions (blue), ν_μ CC interactions (orange), and NC interactions (red). The optimal cut threshold is denoted by the gray dotted line, events above this cut are classified as tau-like.

background in the multi-GeV e-like samples would improve the constraints on the study of neutrino mass-ordering.

5. Results and Further Work

These MC studies showed that NN for tau neutrino identification performs well in the expanded FV. 22% of the background is misidentified as tau-like. Figure 3 shows that the most misclassified background (about 70%) is that of NC interactions. On average, more neutrons are expected to be produced in the NC interactions than in the ν_τ CC interactions. We expect that adding NN inputs related to neutron captures may help reject NC backgrounds. This approach will benefit from the increased neutron tagging efficiency of Super-K after the SK-Gd[5] upgrade in 2019, in which the ultra-pure water of Super-K was doped with Gadolinium, an element with high neutron capture cross-section. We expect that the processing of the data from the latest Super-K periods, combined with the higher neutron tagging efficiency achievable with the SK-Gd upgrade, can lead to improved ν_τ CC cross-section measurement and mass-ordering result at Super-K.

References

[1] L. Pasquali and M. Reno, *Tau neutrino fluxes from atmospheric charm*, *Physical Review D* **59** (1999) 093003.

[2] Z. Li et al., *Measurement of the tau neutrino cross section in atmospheric neutrino oscillations with Super-Kamiokande*, *Physical Review D* **98** (2018) .

[3] M. Posiadala-Zezula, *Atmospheric Neutrino Oscillations with the Super-Kamiokande detector*, *this proceedings* (2022) .

[4] K. Abe et al., *Atmospheric neutrino oscillation analysis with external constraints in Super-Kamiokande I-IV*, *Physical Review D* **97** (2018) 072001.

[5] K. Abe et al., *First Gadolinium loading to Super-Kamiokande*, *Nuclear Instruments and Methods in Physics Research Section A* **1027** (2022) 166248.

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