PROCEEDINGS OF SCIENCE

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

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We present the latest results on the appearance of tau neutrinos from neutrino oscillations in the flux of atmospheric neutrinos recorded at Super-Kamiokande. The dataset is for a live-time of 6511.3 days recorded from 1996 to 2020, and accounts for all of the pure-water runs at Super-Kamiokande. The exposure of the detector is 484.2 kT-years. 428 ± 92 oscillated tau neutrino events have been observed. The measured tau neutrino normalisation is 1.36 ± 0.29. We exclude the hypothesis of no tau neutrino appearance with a significance of 4.8σ.

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1. Tau neutrino appearance at Super-Kamiokande

Super-Kamiokande (Super-K) is a water Cherenkov detector that has been collecting data on neutrinos since 1996. It was one of the experiments that first reported on the discovery of neutrino oscillations by confirming a deficit in the expected number of muon neutrinos in the atmosphere created due to cosmic rays [6]. This flux of atmospheric neutrinos comprises of muon and electron neutrinos, up to neutrino energies of about 100 GeV, and is nearly isotropic [8].

The deficit in the muon neutrino flux can be explained by the three-flavor neutrino oscillation paradigm, which predicts that on travelling large distances, such as those of $\sim 13,000$ km through the Earth, muon neutrinos would oscillate predominantly to tau neutrinos. Detecting the oscillated tau neutrinos, thus, is an additional confirmation of the theory of neutrino oscillations. These measurements of tau neutrino appearance help set bounds on the unitary of the 3×3 PMNS matrix which governs the neutrino oscillations, for which the tau neutrino row is the least constrained [5].

Until 2020, Super-K was filled with ultra-pure water. It is for this period, of a live-time of 6511.3 days, that we report on the latest measurement of the appearance of tau neutrinos from neutrino oscillations in the flux of atmospheric neutrinos at Super-K.

2. Measurement of tau neutrino appearance at Super-Kamiokande

Located 1km underground in the Mozumi Mine, the Super-K detector consists of a 41.4m high and 39.3m wide cylindrical tank. It is lined with about $11,000$ photo-multiplier tubes (PMTs). When a neutrino interaction produces charged particles with energies above their respective Cherenkov thresholds, PMTs detect the Cherenkov radiation. The event can be reconstructed from the positions, timings and energy of the signals recorded by the PMTs.

At Super-K, we expect to observe one event per unit kT.year exposure due to charged current (CC) interactions of the oscillated tau neutrinos. In our analysis, we considered only events for which the Cherenkov light from the particle tracks subsided inside the aforementioned tank, produced minimum 1.33 GeV visible energy (the average ν_τ energy is about 15 GeV) and had a neutrino interaction vertex reconstructed at least at a 1 m distance from the inner wall of the detector. The last cut results in a fiducial mass of 27.2 kT of the detector. Therefore, for the data collected between 1996-2020, the exposure of 484.2 kT.years. Compared to the last Super-K analysis on tau neutrino appearance [9], this is a 48% increase in the exposure. The increased statistics are on account of additional live-time of roughly 3 years and the expansion of the fiducial mass which in the last analysis was 22.5 kT [12].

The resultant sample is one where only 2% of all events recorded were be expected to be due to ν_τ CC interactions. The rest was background from the neutral current interactions of all neutrino flavors and CC interactions of ν_e and ν_μ in the atmospheric neutrino flux. The limited statistics of the oscillated ν_τ CC events is further complicated by difficulty in detecting the lepton associated. ν_τ CC interaction produces tau, which with its lifetime of 10^{-13} s, cannot be directly reconstructed at Super-K. Particle showers from semi-leptonic decays of tau are nearly identical to those produced by the background and hence, it is not possible to classify the ν_τ CC signal from the background on an event-by-event basis. So instead, we turned to statistically separating the two.

We trained a neural network (NN), detailed in [9] and tested on the expanded fiducial volume in [10], on the Monte-Carlo (MC) predictions. The NN output assigns the ν_τ CC signal with values close to 1 and the background with values close to 0, as shown in Figure 1. Since we expect only the atmospheric neutrinos that arrive at the detector from below to oscillate to tau neutrinos, we make considerations also on the direction of the incoming neutrino relative to the vertical axis of the detector given by the cosine of the zenith angle. We construct two-dimensional probability density functions (PDFs), f_s, for the signal and f_b, background, with the NN output and cosine of the zenith angle.

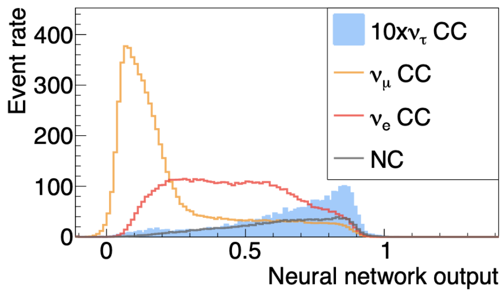

Figure 1: The neural network (NN) output, with the signal of ν_τ CC interactions, in blue. The optimum threshold above which the NN most efficiently rejects the background, while accepting the signal, is at 0.54. Selecting events above the threshold leads to the mis-classification of 13% of the total ν_μ CC background (in yellow), 37% of the ν_e CC (in red) and 70% of the NC background (in gray). Therefore, events are not filtered solely on the basis on the NN output in the tau neutrino appearance study.

We performed an extended maximum likelihood fit, designed on RooFit [11], where we reduced our uncertainty on the estimated parameters by using the information that the number of events observed, N_{obs} follows a Poisson distribution with the mean of $N_b + \alpha N_s$, where $N_{b(s)}$ is the expected number of background (ν_τ CC signal) events [4], modulated by scale factor, α, which we refer to as the tau neutrino normalisation. This is our parameter of interest.

The absence of tau neutrino appearance is characterised by $\alpha = 0$. $\alpha = 1$ means perfect agreement of the data with our prediction which considers the three-flavor neutrino oscillation paradigm. The nominal model assumes normal neutrino mass ordering, the same oscillation parameters as [12] and draws the neutrino interaction models from NEUT 5.4.0.1 [7]. We take into account 54 systematic uncertainties related to the modelling of the atmospheric neutrino flux, neutrino interactions, oscillation parameters, detector response and event reconstruction. For an ith systematic uncertainty in our model, parameterised by ϵ_i, we construct a PDF, f_i, similar to that of $f_{s/b}$, with the distributions for the change in the event rates for $\pm 1\sigma$ change in the ith systematic uncertainty. N_i denotes the total change in expected number of background and signal due to the ith ith systematic uncertainty. We maximise a likelihood function,

$$\mathcal{L}(\alpha; \epsilon_i) = \frac{e^{-\mathcal{N}}}{N_{\text{obs}}!} \mathcal{N}^{N_{\text{obs}}} \prod_{j=1}^{N_{\text{obs}}} (N_b f_b + \alpha N_s f_s + \sum_{i=1}^{54} \epsilon_i N_i f_i), \tag{1}$$

where $\mathcal{N} = N_b + \alpha N_s + \sum_{i=1}^{m} \epsilon_i N_i$. Each ϵ_i has a Gaussian constraint, of mean 0 and standard deviation 1, in the fit.

3. Latest Super-Kamiokande results

We performed toy MC studies to gauge the sensitivity of the measurement of the tau neutrino normalisation, α. By setting $\epsilon_i = 0$, i.e. without considering the systematic uncertainties, Super-K can measure α, with a precision of 18%. The precision of measuring α on simultaneously fitting all the systematic uncertainties is 28%. The dominant sources of systematic uncertainties in the measurement are of the ratio of expected NC to CC events, and those in the calculation of the deep inelastic scattering cross-sections.

The results of fitting the model to the data, are shown in Figures 3 and 2. The event rates after the fit for the ν_τ CC interactions clearly accounts the difference between the distributions of the data and background. The observed number of tau neutrino events is 428 ± 92. We estimated tau neutrino normalisation to be $\alpha = 1.36 \pm 0.29$. This excludes the hypothesis of no tau neutrino appearance with a significance of 4.8σ.

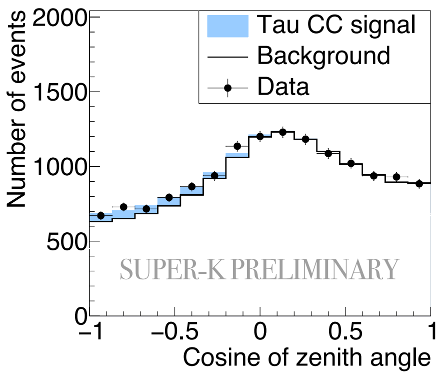

Figure 2: Event rates of the atmospheric neutrinos observed for an exposure of 484.2 kT.years at Super-Kamiokande, as a function of the cosine of the zenith angle. The excess in the data over the background-only Monte-Carlo (black histogram) is due to the oscillated tau neutrinos (in blue).

4. Conclusion and future prospects

We have measured the appearance of tau neutrinos through neutrino oscillations from the flux of the atmospheric neutrinos recorded at an exposure of 484.2 kT.years at Super-K. With the new result from Super-K, the global efforts of measuring tau neutrino appearance characterised by the tau neutrino normalisation have been summarised in Figure 4. The global measurements are consistent within 2σ.

When comparing the Super-K result from 2018, we see that with increased statistics, our result is more consistent with the three-flavor neutrino oscillation paradigm than before. In future analysis at Super-K with increased statistics, better modelling and new measurements of neutrino cross-sections, and improvements in the tau neutrino identification process, we expect higher precision in measuring the tau neutrino normalisation.

In 2027, Hyper-Kamiokande (Hyper-K), a new 186.5 kT fiducial mass detector will start taking data. Hyper-K would have an exposure of 5.6 MT.y in 30 years of data taking, and we expect that this would reduce the uncertainty on measurement of tau neutrino normalisation down to 8% [2].

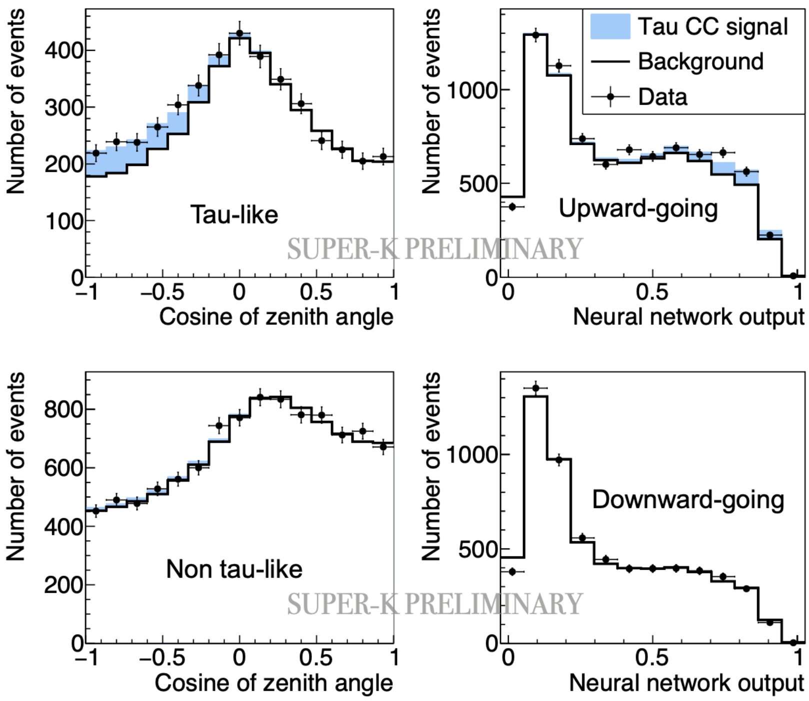

Figure 3: Event rates for the atmospheric neutrinos observed for an exposure of 484.2 kT.years at Super-Kamiokande, as a function of the cosine of the zenith angle and the neural network (NN) output of Figure 1. Top: Tau-like (NN output>0.54) and upward-going samples (cosine of zenith angle <0.2) show that the fitted Monte-Carlo (MC) for the oscillated tau neutrinos (in blue) accounts well for the deficit between the data (black points) and the atmospheric neutrino background MC (black histogram). Bottom: In the non tau-like and downward-going samples, where we do not expect oscillated tau neutrinos, we see good agreement between the background-only MC and the data.

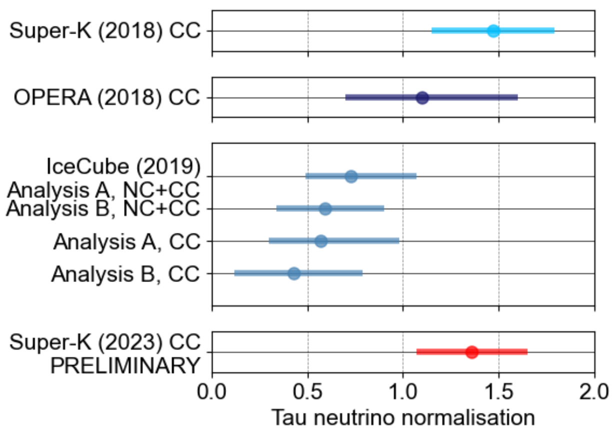

Figure 4: Results for the tau neutrino normalisation (dots) and 68% confidence interval (error bars), from Super-K (the 2018 [9] and latest 2023 analysis), OPERA [3], and IceCube [1], for the tau charged current (CC) interactions. IceCube also reported on the tau neutrino normalisation for all (neutral current and charged current, NC+CC) tau neutrino interactions.

5. Acknowledgements

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