PROCEEDINGS OF SCIENCE

The appearance of tau neutrinos in the flux of atmospheric neutrinos at Super-Kamiokande

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With an exposure of 484.2 kt·years collected from 1996-2020 at Super-Kamiokande (SK), the study of tau neutrino appearance from neutrino oscillations can enable us to test the robustness of the three-flavor oscillation paradigm. We present the latest analysis of tau neutrino detection in atmospheric neutrino flux where tau neutrino charged-current interactions are identified by employing a neural network. We observe an excess of 428 ± 92 tau neutrino like events, over the expected atmospheric neutrino background. The tau neutrino normalisation is estimated to be 1.36 ± 0.29. We exclude the absence of tau neutrino appearance at 4.8σ significance.

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1. Introduction

In the precision era of neutrino physics, phenomena like tau neutrino appearance from neutrino oscillations have become more accessible, allowing us to probe aspects of the three-flavor neutrino oscillation theory such as the unitarity of the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix, and to deepen our understanding of tau neutrinos themselves. Since the first direct observation of tau neutrinos in 2000 [1], studying these particles remains challenging. This proceeding presents Super-Kamiokande's approach to overcoming these challenges in its latest measurement of tau neutrino appearance.

2. Tau neutrino appearance at Super-Kamiokande

Detection of tau neutrino charged-current (CC) interactions require neutrino energies greater than a threshold of 3.5 GeV. The flux of atmospheric neutrinos, which are neutrinos produced in the atmosphere from the interactions of cosmic rays, exceeds the threshold by far. However, the tau neutrino composition of the flux is negligible for neutrino energies less than 100 GeV. Muon neutrinos in this flux traversing large distances of the order of the length of the earth, are known to oscillate to tau neutrinos [2]. Such tau neutrinos appearing from oscillation of the atmospheric neutrinos can then be detected at Super-Kamiokande (SK).

SK is a water Cherenkov detector located in Japan, and has been recording atmospheric neutrino data since 1996. The 50 kt cylindrical tank is optically divided into inner and outer regions, such that over 11000 photo-multiplier tubes line the wall of the inner detector. It was filled with ultra-pure water until 2019. We use data from this period. With an exposure (fiducial mass $\times$ livetime) of 484.2 kt·years, this is a significant increase over previous analyses from SK [3–5].

3. Methodology

The analysis incorporates neutrino interaction events, such that, nearly all the optical activity of the event is contained within the inner detector, with the minimum visible energy of 1.33 GeV, and the reconstructed neutrino vertex is atleast 1 m from the inner wall of the detector. Tau neutrino CC interactions constitute only 2% of this dataset, with an expectation of about 20 tau neutrino CC interactions per live-time year. The background comprises of muon and electron neutrino CC interactions and neutral-current (NC) interactions of all flavors. Due to the short lifetime of the tau lepton and the similarity of the resulting particle showers to background events, it is challenging to distinguish between signal and background.

To address this, we employ a neural network (NN) trained on Monte Carlo simulations, assuming the three-flavor paradigm with the oscillation parameters from the nominal model of the latest SK oscillation analysis [6]. We combine the cosine of the zenith angle, $\cos\theta$ (a measure of the direction in which the neutrinos arrive at the detector) with the NN output to construct two-dimensional probability density distributions, as shown in Figure 1.

Finally, the simulated background and signal distributions are fit to the observed data, to ascertain the tau neutrino normalisation, α, a scale factor that modulates the number of tau neutrino events observed in the dataset. We search for tau neutrinos by looking for an excess over the

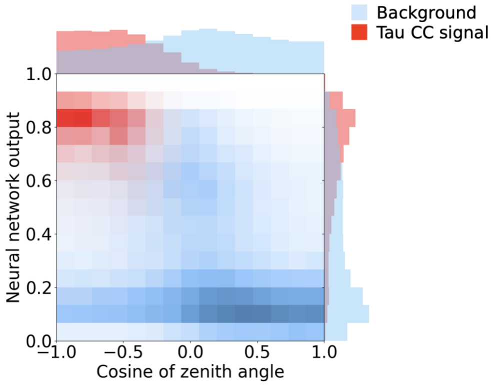

Figure 1: Simulated probability density distributions of the neural network (NN) output versus the cosine of the zenith angle for the signal of ν_τ CC interactions (red), and background events (blue). Signal events, which are upward-going, tend to cluster at higher NN output values.

background such that $\alpha = 1$ would indicate perfect agreement of the data with the three-flavor neutrino oscillation paradigm. $\alpha = 0$ in the case of no tau neutrino appearance.

We also account for 54 sources of systematic uncertainties from the modelling of the atmospheric neutrino flux, neutrino interactions, oscillation parameters, detector response and event reconstruction. Details of the NN and the analysis procedure have been presented in [5] and [7].

4. Results

From toy MC studies, we infer that the expected uncertainty in the tau neutrino normalisation at SK is 18% when the systematic uncertainties are discounted. On accounting for the systematics, the expected uncertainty is 28%. When systematics are considered one at a time and assumed to be independent of each other, i.e. correlations between the systematics are ignored, the measurement is seen to be most sensitive to the uncertainty in the ratio of expected NC to CC events, followed by the systematics involved in the calculation of the deep inelastic scattering (DIS) cross-sections; the expected uncertainty in tau neutrino normalisation being 24% and 22% respectively.

On considering the relevant systematic uncertainties simultaneously while fitting the signal and background simulations to the data, we estimated the tau neutrino normalisation to be $\alpha = 1.36 \pm 0.29$ and observed 428 ± 92 tau neutrino CC events. The data agrees well with expectations, as illustrated in Figure 2. We reject the absence of tau neutrino appearance with a significance of 4.8σ.

We find that the global estimates of tau neutrino normalisation, summarised in Figure 3, are consistent within 2σ, and do not deviate significantly from the three-flavor oscillation paradigm. To possibly rule out the unitarity of the PMNS matrix from tau neutrino appearance measurements, we require such future measurements to be more precise.

5. Conclusions and way forward

It is clear from Figure 4, that an increase in the exposure at SK has led to a pronounced increase in the precision of estimating tau neutrino normalisation. In the latest results, we analysed the

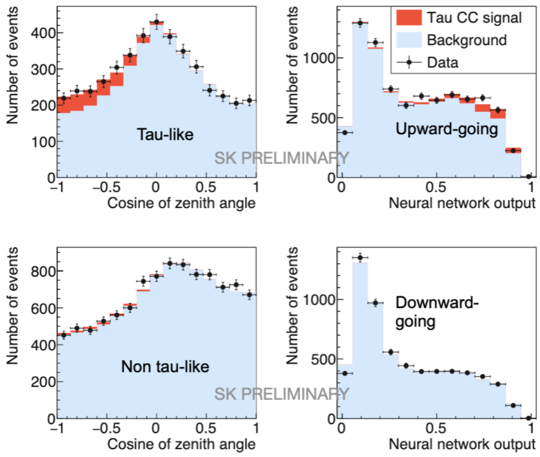

Figure 2: Distribution of the signal of ν_τ CC interactions (red) and background (blue) events from the MC simulations fit to the data (black dots) with respect to the neural network (NN) output and the cosine of the zenith angle. Tau-like events are those with NN output greater than 0.54.

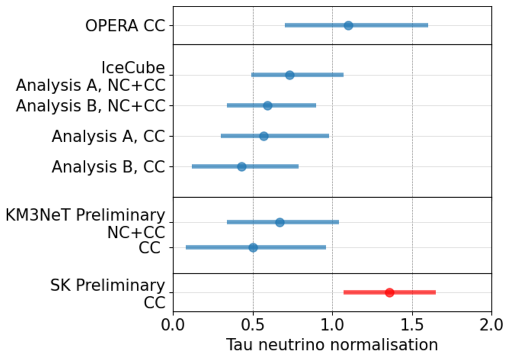

Figure 3: SK result compared to the latest results for the tau neutrino normalisation (dots) and 68% confidence interval (error bars) from other experiments: OPERA [8], IceCube [9] and KM3NeT [10].

data from 27.2 kt fiducial mass of SK. The upcoming water Cherenkov detector facility of Hyper-Kamiokande (HK) would start collecting data in 2027. With its significantly larger fiducial mass of 185 kt and an exposure projected to reach 5.6 Mt·y over 30 years, HK will provide much higher statistics, potentially bringing the uncertainty of tau neutrino normalisation down to 8% [11].

To increase the precision further, we consider the pulls for the systematic uncertainties in this analysis, shown in Figure 5. These pinpoint areas like the modelling of the neutrino flux in the horizontal ($0 < \cos\theta < 0.1$) and vertical ($0.9 < \cos\theta < 1$) directions, DIS interactions, and single pion production, where improvements could reduce plausible systematic biases in future results from SK and HK.

While improved simulations and increased statistics will benefit tau neutrino appearance studies, efforts are also underway to improve the machine learning based identification of tau neutrinos and defining a dedicated tau neutrino sample for the oscillation analysis at SK. This could enhance the mass-ordering sensitivity of the experiment, by constraining the uncertainty in tau neutrino cross-section of the analysis.

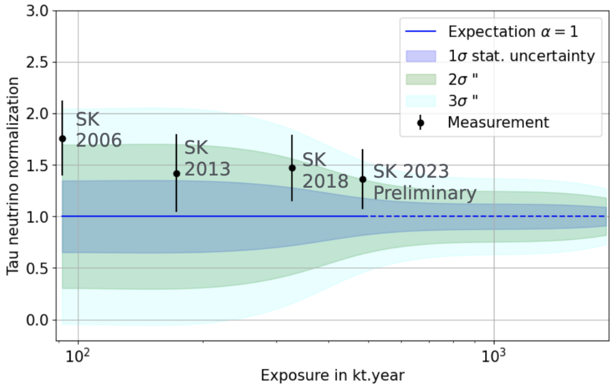

Figure 4: Tau neutrino normalisation measurements, from [3–5] and this analysis as a function of detector exposure in kt·years. The blue horizontal line corresponds to the expected tau neutrino normalisation ($\alpha = 1$), while shaded regions indicate the 1σ (blue), 2σ (green), and 3σ (light blue) confidence intervals.

Acknowledgments

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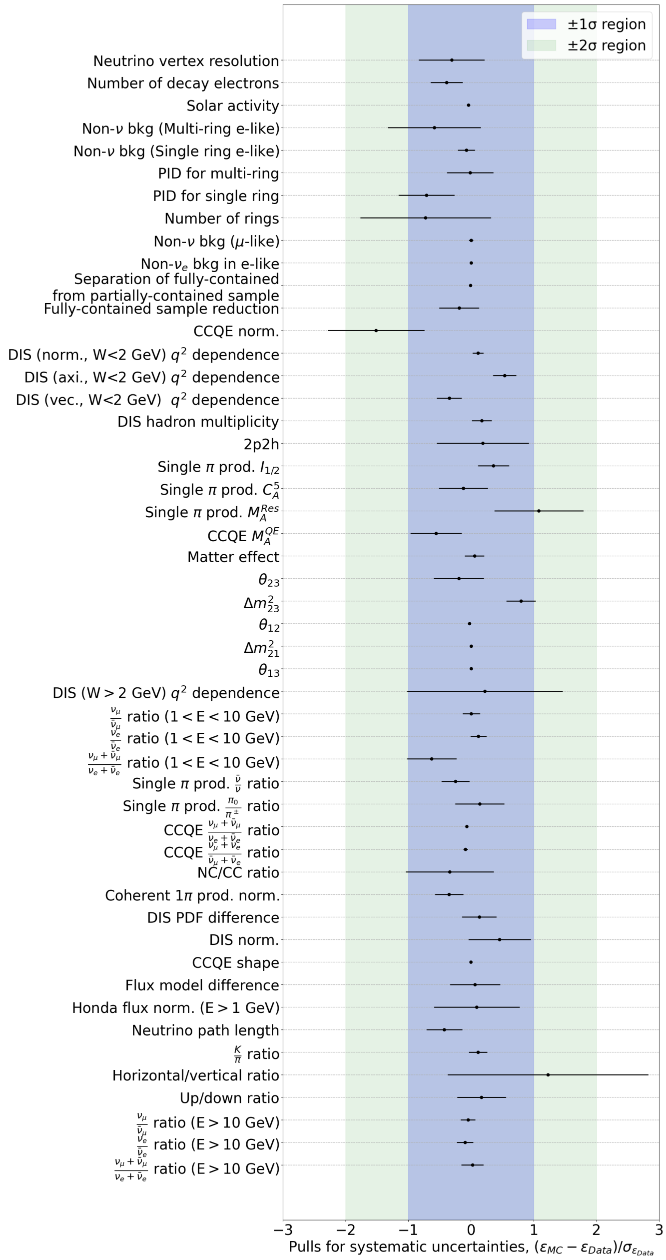

Figure 5: Pulls for the different sources of systematic uncertainties, showing the impact of uncertainties on the tau normalisation measurement. The shaded blue (green) region represents the $\pm 1\sigma$ ($\pm 2\sigma$) range. Most uncertainties have pulls close to 0 and are considered likely to be well-modelled.

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