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A simulation study of tau events at the proposed ICAL in INO

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We present our results of tau neutrino events analysis at the Iron Calorimeter detector in the proposed India based Neutrino Observatory. The charged current ν_τ events at the detector cannot be separated from the neutral current events of all flavors. Hence, we have analyzed the combined charged current and neutral current events. The event samples were prepared with the NUANCE event generator. By simulating a data taking period of 10 years, we have shown that the detection capability for tau neutrino events is over 3 sigma confidence level. We performed the sensitivity study of ν_τ to the oscillation parameters θ_{23} and Δm^2_{32}. We also performed the combined analysis of ν_τ events and ν_μ events and that study shows that we can expect a significant improvement in sensitivity to the oscillation parameter θ_{23} and its octant, and a moderate improvement in Δm^2_{32} comparing to the standard muon analysis.

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1. Introduction

The proposed underground facility India-based Neutrino Observatory (INO) will house the magnetized Iron Calorimeter (ICAL) detector [1]. We present our results of simulation study of ν_τ events at this detector.

The primary and secondary interaction of cosmic rays with the Earth atmosphere produce atmospheric neutrinos. The flavor ratio among these neutrinos is $\nu_e{:}\nu_\mu{:}\nu_\tau = 1:2:3\times10^{-5}$ in the few GeV energy range. When these atmospheric neutrinos pass through the Earth before reaching the detector, neutrino flavor oscillations occur, and the flavor ratio would become closer to $1:1:1$ in the tens of GeV energy range. Hence there is a significant fraction of ν_τ in atmospheric neutrino flux in the upward direction.

The ν_τ interact via charged current (CC) interaction with the nucleons in the detector to produce charged τ leptons and hadrons (X) via $(\nu_\tau/\overline{\nu}_\tau)\,N \to (\tau^-/\tau^+)\,X$. The produced τ leptons will decay promptly, primarily into hadrons (H) as, $\tau^\pm \to (\overline{\nu}_\tau/\nu_\tau)\,H$, with a branching fraction of $\approx 66\%$. Therefore, the total visible hadronic energy produced by a CC - ν_τ interaction with the detector comes from the $(X+H)$ particles.

Neutral current (NC) interactions from all the flavors of neutrinos and antineutrinos also produce hadrons (X') in the detector, via

$$\nu_i\,N \to \nu_i\,X'\ ,\ \overline{\nu}_i\,N \to \overline{\nu}_i\,X'\ ;\quad i = e, \mu, \tau\ .$$

Hadrons $(X+H)$ from CC interactions of ν_τ and hadrons (X') from NC interactions of all neutrino flavors cannot be separated. However, the hadronic energy deposited in a τ event is much larger than the NC event initiated by neutrinos of similar energy. The NC events act as an inseparable background to the CC-tau events. Therefore we study the combined sample of all flavors of NC events and CC-tau events to look for the ν_τ signature.

2. Generation of CC-tau and NC events for ICAL

For the simulation study we use the NUANCE event generator [2] for the generation of the events. The atmospheric ν_τ flux arise from oscillation of both ν_μ and ν_e. Hence, the observed τ events at the detector are $N_{\mu\tau} + N_{e\tau}$.

We first generate the 'unoscillated' CC-tau events excluding the oscillation probability. They are later weighted with appropriate oscillation probability during the 'data' generation and analysis [3]. We use PMNS mixing matrix [4] and PREM profile for matter distribution inside the Earth [5] for calculating oscillation probabilities.

The background NC events are generated using same atmospheric neutrino fluxes and NC cross sections. GEANT4-based simulation toolkit was used for the response of hadrons in the detector. We performed the analysis for an exposure of 10 years assuming normal mass ordering. The events are shown in figure 1 as a function of total hadronic energy.

3. Numerical analysis and physics reach

A χ^2 analysis including well understood detector characteristics such as hadron energy and angle resolution etc.[6], was carried out. We have included the possible five systematic uncertainties

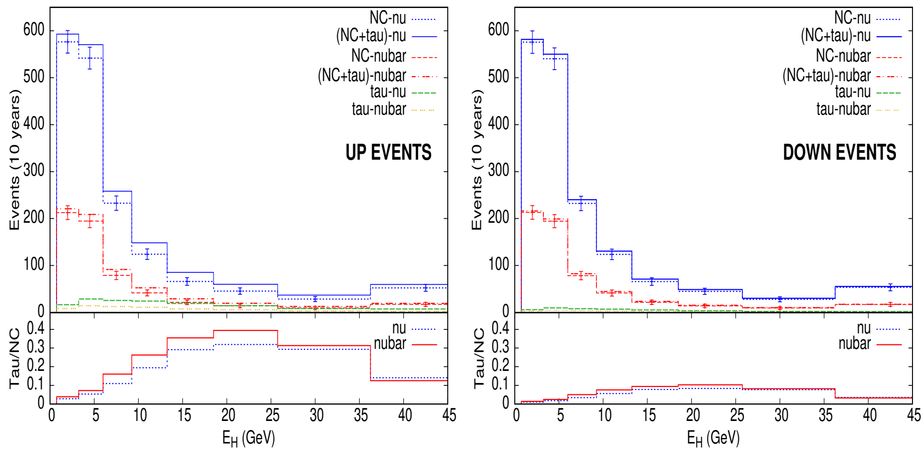

Figure 1: NC and CC-tau events in reconstructed E_{hadron} bins for upward going (UP) and downward going (DOWN) events and the ratio of the CC tau events to the NC events.

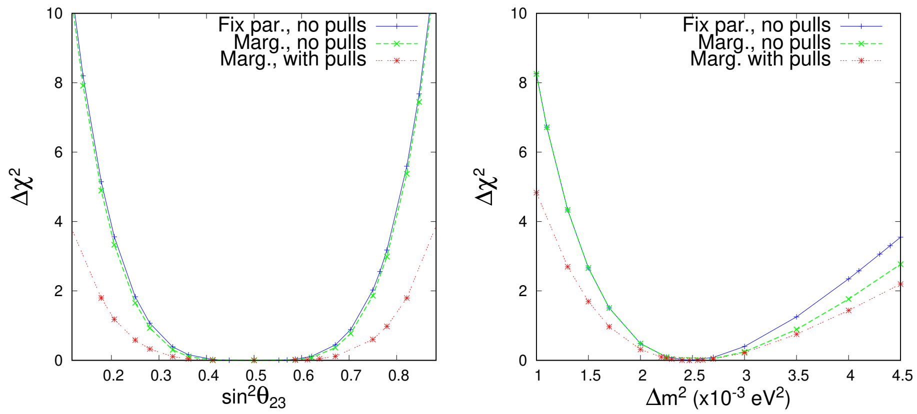

Figure 2: Sensitivity of ν_τ to the oscillation parameters $\sin^2\theta_{23}$ and Δm^2

in the analysis, which are error in tilt, zenith angle dependency, flux normalization, cross section and detector response. The sensitivity to the presence of ν_τ events was determined to be at the level of 3.6 σ confidence. The effect on sensitivity to $sin^2\theta_{23}$ and Δm^2_{32} is shown in figure 2.

4. Combined study of tau events and "standard" muon events

We have performed the combined analysis of ν_τ events and ν_μ events and the results are shown in figure 3. This analysis improves the sensitivity to the oscillation parameter θ_{23} and its octant over standard muon analysis [1]. The improvement due to the combined analysis in Δm^2_{32} is moderate, instead. Figure 4 shows the improvement in sensitivity to the octant of θ_{23}, especially where the true value is in the first octant.

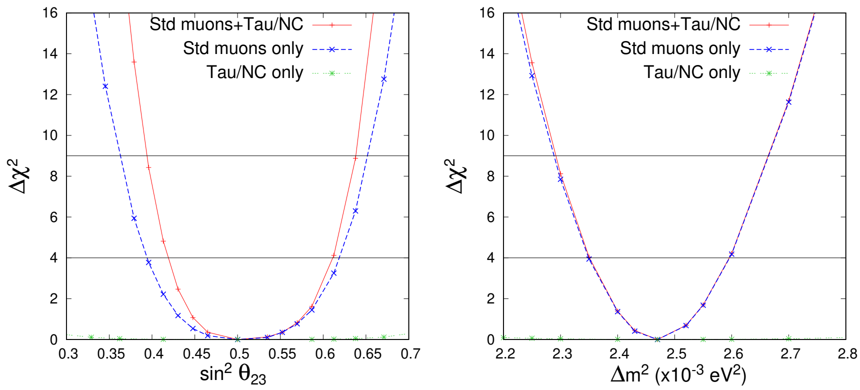

Figure 3: Sensitivity to $\sin^2\theta_{23}$ and Δm^2 in combined analysis of standard muon and tau events.

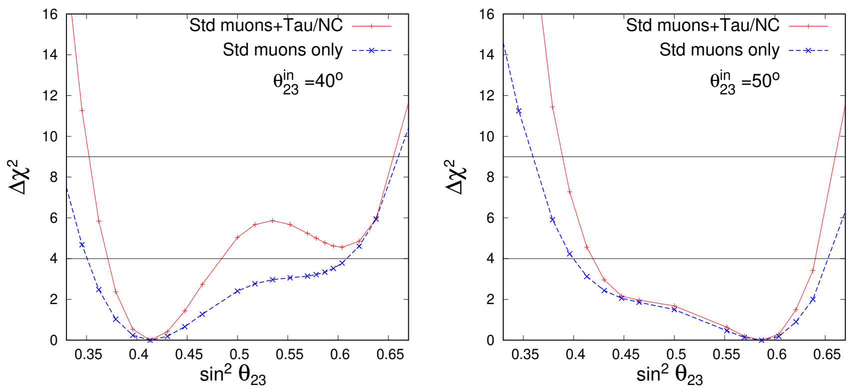

Figure 4: Sensitivity to the octant of $\sin^2\theta_{23}$ for input values in the (a) lower 40° and (b) upper 50°.

5. Conclusion

We have presented our analysis of ν_τ events at the ICAL detector in INO and shown that their presence can be detected at more than 3σ confidence level for 10 years period with systematics. The study calculated the sensitivity of ν_τ events to the oscillation parameter θ_{23} and Δm^2_{32}. We have shown that the combined analysis of ν_μ and ν_τ events improves the precision of the measurement of $\sin^2\theta_{23}$ and its octant significantly and Δm^2_{32} moderately over a standard muon analysis.

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