# Tau Neutrino Events at ICAL Detector in INO and Their Sensitivity to Oscillation Parameter Theta23

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## Introduction

One of the primary goal of ICAL (magnetized Iron Calorimeter) detector which will be located in India Based Neutrino Observatory is more precise determination of neutrino oscillation parameters. In atmospheric neutrino flux, without oscillation the ratio $\nu_\mu : \nu_e$ is $2 : 1$. Neutrino oscillation produces tau neutrino ($\nu_\tau$) in the atmospheric flux. Due to large $\theta_{23}$, many $\nu_\mu \leftrightarrow \nu_\tau$ oscillations occur. After oscillations, $\nu_\mu : \nu_e : \nu_\tau$ is $1 : 1 : 1$. This results the fact that there are large number of $\nu_\tau$ in the atmospheric neutrino flux. As a result of charged-current (CC) interactions of $\nu_\tau$ with the iron in ICAL detector, $\tau$ leptons are produced. Although these events are kinematically suppressed due to the large mass of the $\tau$, they are significant due to the large fluxes.

The produced $\tau$ leptons will predominantly decay into hadrons ($\sim$ 67% of times).

$$\nu_\tau N \rightarrow \tau^- \mathbf{X}$$

The produced $\tau^-$ further decay as,

- $\tau^- \rightarrow e^- \nu_e \nu_\tau \;\sim 17\%$
- $\tau^- \rightarrow \mu^- \nu_\mu \nu_\tau \;\sim 17\%$
- $\tau^- \rightarrow \nu_\tau \mathbf{X} \;\sim 64\%$

Hence there is huge hadron energy (**X**), which will add to Neutral current events (**N**).

$$\nu_i \mathbf{N} \rightarrow \nu_i \mathbf{N} \quad i = e, \mu, \tau.$$

These events will therefore imitate neutral current (NC) events with no charged leptons in the final state. Hence to precisely determine the number of tau events, the NC background must be calculated precisely. Due to large mass of the $\tau$, the relevant hadron energies are greater than 3.5 GeV, i.e. predominantly in Deep inelastic scattering. Sometimes Charged Current (CC) electrons are misidentified as hadrons.

$$\nu_e N \rightarrow e^- \mathbf{X}$$

Hence if we know NC background this also can be seperated.

## Neutrino event generator in DIS region

- We have calculated the deep inelastic cross section for NC events and numerically computerd the event rate with Honda atmospheric neutrino fluxes for ICAL.
- We have written a C-based program for the event generation. This generates Monte Carlo type events by using a random number generator weighted by the fluxes and cross sections.
- At low energy ($E < 3$ GeV), there are additional contributions from quasi-elastic and resonance NC cross-sections. However, in the energy range of interest for tau production, the cross sections are dominated by Deep Inelastic Scattering processes. Hence we have considered Deep Inelastic Scattering region at present for the calculation here.
- The generator has been validated against the NUANCE neutrino generator, which in addition can also account for final state interactions.

## Comparing electron events with nuance

We have calculated the NC electron events from cross section calculation and honda flux and ploted in energy bins. Data in the curve is nuance electron events in DIS for comparision.

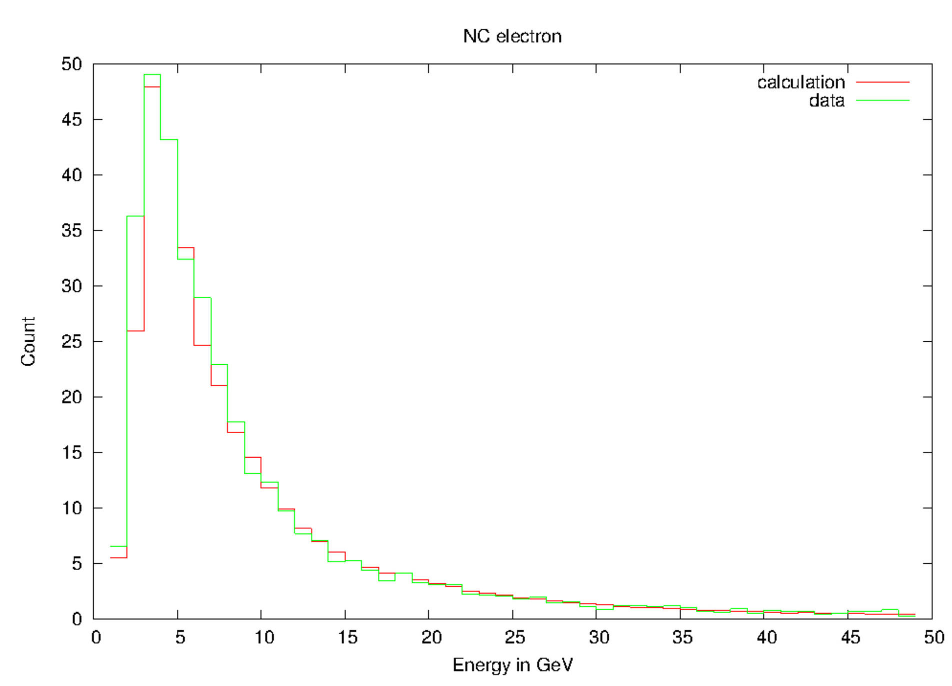


**Figure 1:** electron neutral current events

## Comparing muon events with nuance

We have calculated the NC muon events from cross section calculation and honda flux and ploted in energy bins. Data in the curve is nuance muon events in DIS for comparision.

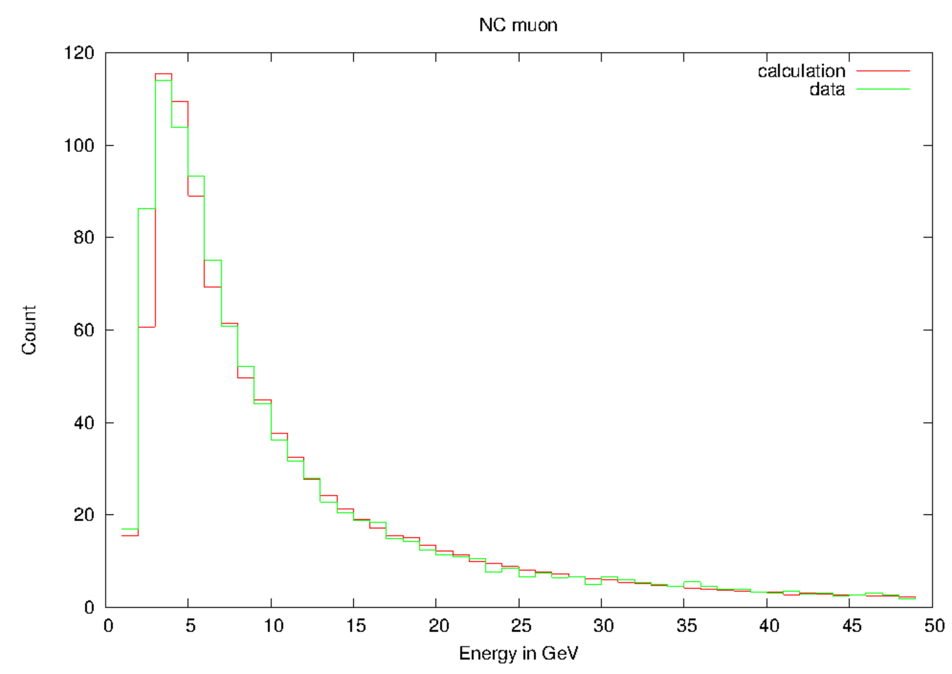


**Figure 2:** muon neutral current events

## Tau events generation

- tau events are produced from oscillation of muon and electron type neutrino passes through the earth and reach the detector. These are UP events. Therefore almost all the tau events are CC up events.
- While generating these events we have applied costheta cut of 70 degrees. i.e. the events above $\pm 70 degrees$ were allowed.
- We have also applied detector efficiency of 0.95 for the observation of hadron energy.

## Optimizing the bins

- We have generated the neutral current events and charged current events using our generator and seperated them into upgoing and downgoing events based on the costheta.
- Since the detector observes the hadron energy from these events, we cannot differentiate tau and taubar.
- In order to overcome the fluctuation in data we calculate true chisqare as follows: Data= Total CC events + NC events for 5 years
- For Theory part we generate CC and NC events for 500 years and rescale them to 5 years.

$$Chisqr_{true} = \sum_i (Data - Theory)^2 / Data$$

- We optimize our bins according to the lowest $Chisqr_{true}$ value.
- In order tofind the correct $Chisqr$ for tau events we will subtract this $Chisqr_{true}$ from our calculation.

## Tau events over NC background

- We have generated the neutral current events and charged current events using our generator and seperated them into upgoing and downgoing events.
- Since the detector observes the hadron energy from these events, we cannot differentiate tau and taubar. Hence we will take the particle and antiparticle in the same footing.
- We have plotted the seperated Up NC events and Down NC events along with the CC Up events.

In our analysis for 5 years we have calculated the chisqr as follows: Data is the generated 5 years of CC and NC events. Theory is the rescaled 5 years of NC events from 500 years data. The plot shows the excess of tau events over the NC background. The $Chisqr_{calculated}$ for the given plot is 23.4 and the $Chisqr_{true}$ is 3.48.

$$Chisqr_{Actual} = Chisqr_{calculated} - Chisqr_{true}$$

Therefore we conclude the precence of tau events in this analysis with over $4\sigma$ confidence.

## Tau events over NC background

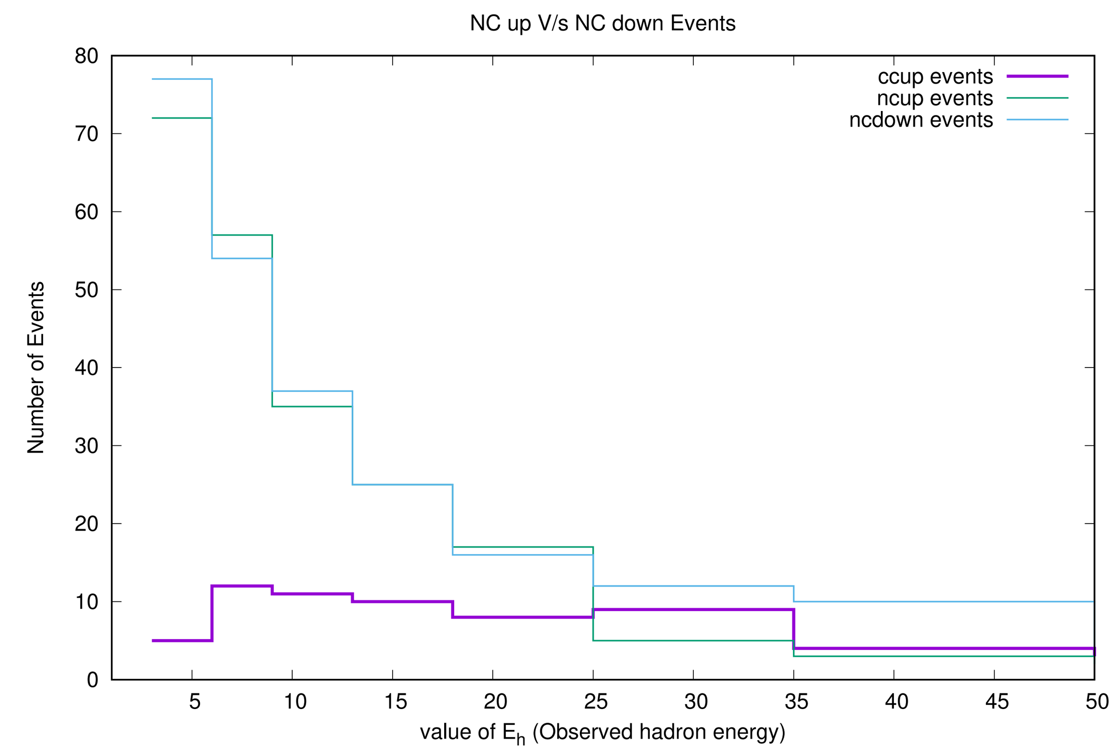


**Figure 3:** Tau events along with NC up and NC down events

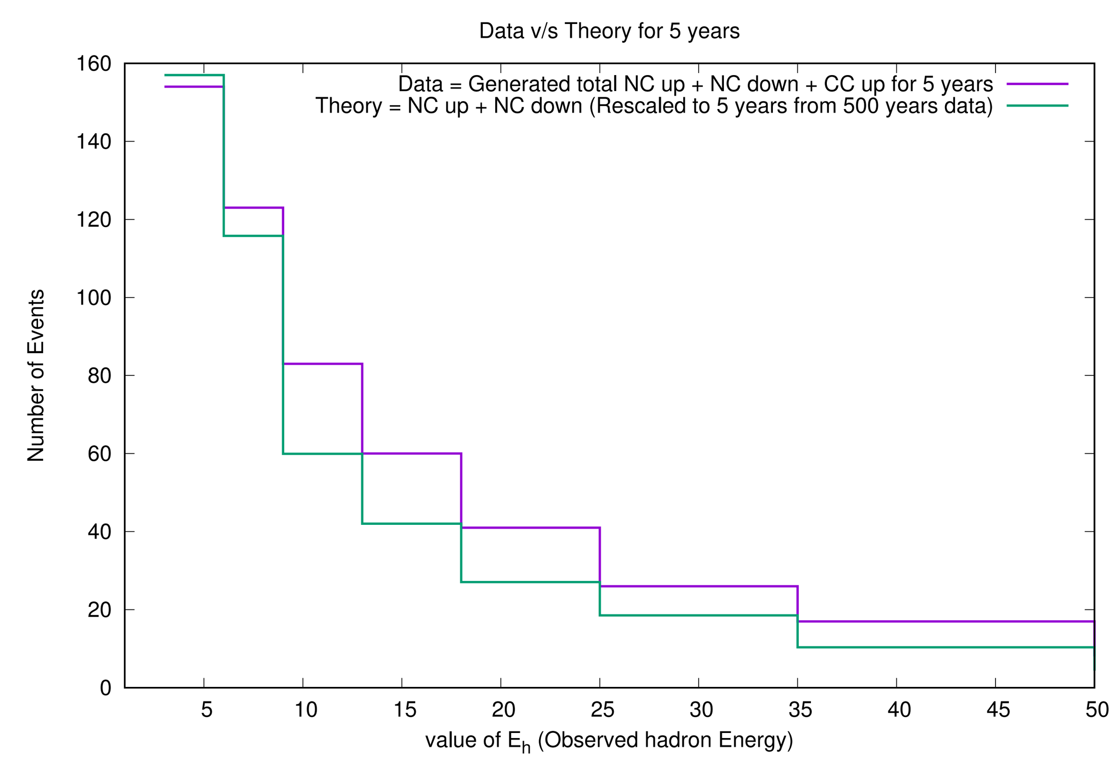


**Figure 4:** CC events as excess of NC events

## Sensitivity to oscillation parameter theta23

In order to find the sensitivity to the oscillation, we estimate the $chisqr_{true}$ value for different oscillation parameter theta23 values. The results show good sensitivity to theta23 in the tau events.

| THETA23 (in degrees) | TRUE CHISQUARE |
|---|---|
| 20 | 11.48 |
| 25 | 8.1 |
| 30 | 5.7 |
| 35 | 4.3 |
| 40 | 3.66 |
| 45 | 3.48 |
| 50 | 3.63 |
| 55 | 4.24 |
| 60 | 5.61 |
| 65 | 8.01 |
| 70 | 11.45 |

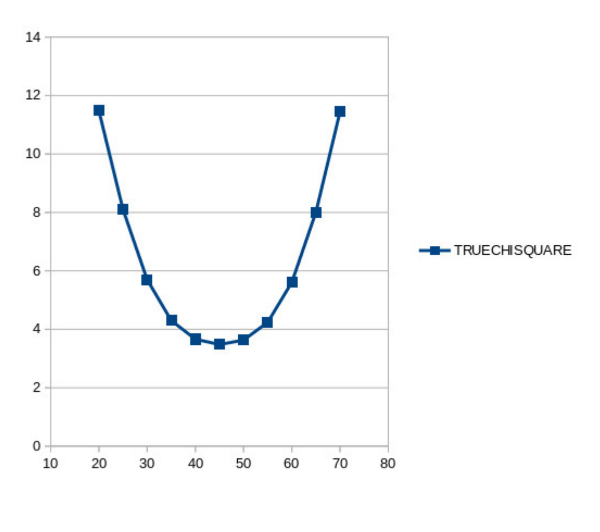


**Figure 5:** Sensitivity to theta23

## Conclusion

We have presented our event generator which generates neutrino events in Deep inelastic scattering region for both CC and NC. We presented our novel way of identifying tau events over NC background. We have also presented the sensitivity to oscillation parameter theta23, in the generated events. Although the tau events are less in number, we have the sensitivity to oscillation parameter. This can further be enhanced by combining with muon events, which are large in number.

## References

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