Improving the hierarchy sensitivity of ICAL using neural network

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Abstract. Atmospheric neutrino experiments can determine the neutrino mass hierarchy for any value of $\delta_{CP}$. The Iron Calorimeter (ICAL) detector at the India-based Neutrino Observatory can distinguish between the charged current interactions of $\nu_\mu$ and $\bar{\nu}_\mu$ by determining the charge of the produced muon. Hence it is particularly well suited to determine the hierarchy. The hierarchy signature is more prominent in neutrinos with energy of a few GeV and with pathlength of a few thousand kilometers, i.e. neutrinos whose direction is not close to horizontal. We use adaptive neural networks to identify such events with good efficiency and good purity. The hierarchy sensitivity, calculated from these selected events, is above $3\sigma$ level.

1. Introduction

India-based Neutrino Observatory (INO) [1] is an upcoming experimental facility which will house the Iron Calorimeter (ICAL) neutrino detector to study atmospheric neutrino interactions. It is a magnetised detector, comprising of resistive plate chambers (RPCs) as the active detector elements, weighing 50 kton in total. Owing to its capability of distinguishing the $\mu^+$ from the $\mu^-$, ICAL is most suitable to determine the ordering of the neutrino mass hierarchy. In the following study, we aim to improve this sensitivity [1] with the use of the neural network techniques [2].

2. Physics Motivation

The plots of the muon neutrino survival probability $P_{\mu\mu}$ for atmospheric neutrinos, as a function of neutrino energy, are shown in figure 1 for various different values of $\cos \theta_z$, where $\theta_z$ is the zenith angle. Hence, for the purpose of hierarchy determination, $\nu_\mu$CC events in the vertical cone with $E_\nu >$ few GeV should be considered as the signal events and all other events should be termed background. It is imperative to develop a procedure by which it is possible to select the signal events with high efficiency and purity. We develop such a procedure based on artificial neural network, and determine the hierarchy discrimination sensitivity with full detector simulation.

3. Simulations

Using NUANCE, we have generated 500 years of ICAL data in the energy range $E_\nu = \{0.1, 100\}$ GeV, under the assumption of no oscillations (NOOSC). The data consists of all types of interactions of all the three neutrino flavours. The generated events are then propagated in
ICAL using a Geant4 simulation of the detector. The pattern of hits thus generated are used to first identify the muon track, and then reconstruct its energy $E_\mu$ and the cosine of its zenith angle $\cos \theta_\mu$ [3]. We use the oscillation parameters as in [1], to generate the Normal Hierarchy (NH) and the Inverted Hierarchy (IH) dataset.

4. Effective Selection Parameters

We first select only those events with hits in more than five layers ($L > 5$). This lower limit on the number of layers is chosen to optimize the reconstruction efficiency of the muon tracks. This cut also eliminates most of the background due to the non-$\nu_\mu$CC events. About 90% of the events selected after this cut are $\nu_\mu$CC events [4]. We want the neural network to select signal events with high efficiency and good purity. We need to choose appropriate input variables for the neural network to achieve this aim. We consider the following variables.

- Hits: This roughly refers to the number of strips receiving the pulse during an event. Low energy neutrino events give less number of hits compared to the high energy events.
- Layers: It is the number of layers in ICAL, which has received one or more hits in an event.
- Maximum Horizontal Spread: The energetic but near horizontal muons have a larger spread on the horizontal plane than the vertical (or near-vertical) events.
- Singlets: It is the number of layers in an event that contain a single hit. A signal event is expected to contain more singlets than the low energy or the horizontal $\nu_\mu$CC events.
- Triplets: It is the number of 3 consecutive layers with single hits in an event. A signal event with a long muon track is expected to contain at least one such triplet.

5. Application of Neural Network Analysis

We employ tools for multi variate analysis (TMVA) for our signal selection [5]. A selection based on neural network techniques, TMlpANN [5], with these parameters as inputs, can select the signal events efficiently as shown in figure 2 and table 1.

![Figure 2. Neural network response to the signal vs. background discrimination. Signal defined: $E_\nu > 2$ GeV and $|\cos \theta| > 0.2$.](image)

| Value of ANNcut | 0.5 | 0.6 | 0.7 | 0.8 |
|-----------------|-----|-----|-----|-----|
| Efficiency %    | 73  | 64  | 55  | 46  |
| Purity %        | 85  | 89  | 93  | 96  |

Table 1. Efficiency and purity of signal events chosen by the placing ANNcuts (explained in following text) for the NH dataset of 500 years, assuming the signal events to be $E_\nu = \{2,100\}$ GeV, $|\cos \theta| > 0.2$ and number of layers>5.
A subset of the NOOSC sample is used to train the neural network. The trained neural network is then applied on the NH and the IH datasets. A probability value (i.e. “response” as in figure 2) is assigned to each event, and we choose our signal events by placing cuts on this value (called ANNcuts as in table 1).

6. Calculation of Mass Hierarchy Discrimination Sensitivity

After a detailed study we finally chose to define our signal as $E_{\nu} = \{2, 100\}$ GeV and $|\cos \theta| > 0.2$. Therefore, the background comprises of all the rest of the $\nu_{\mu}$CC events. For the selected signal-like events, the muon energy $E_{\mu}$ and its direction $\cos \theta_{\mu}$ are reconstructed. The events are sorted into bins of the reconstructed $E_{\mu}$ and $\cos \theta_{\mu}$.

We found the following 10 $E_{\mu}$ bins to be optimal: (0, 2), (2, 3), (3, 4), (4, 5), (5, 6), (6, 7.5), (7.5, 9), (9, 11), (11, 14) and (14, 17) GeV. The binning is done separately for $\mu^{-}$ and $\mu^{+}$ events. The chosen $\cos \theta_{\mu}$ binwidths, different for different $E_{\mu}$ ranges, are listed in table 2.

| $E_{\mu}$ range | $\cos \theta_{\mu}$ range | $\cos \theta_{\mu}$ binwidth |
|-----------------|---------------------------|-----------------------------|
| 0-6 GeV         | (1-0.8, 0.8-0.2, 0.2-0)   | (0.01, 0.02, 0.1)           |
| 6-17 GeV        | (1-0.2, 0.2-0)            | (0.01, 0.1)                 |

Table 2. The $\cos \theta_{\mu}$ binwidths chosen in different energy and $\cos \theta_{\mu}$ ranges.

The NH and the IH data of the upward going events were binned according to the scheme described above. We compute the $\Delta \chi^{2}$ between these two data sets using the Poissonian definition and scale it by 50 to obtain $\Delta \chi^{2}$ for a ten year exposure. We obtained a maximum $\Delta \chi^{2} = 10.2 \approx 10$ for an ANN probability cut of 0.7.

7. Conclusion

We have used a neural network to identify high energy $\nu_{\mu}$CC events in the vertical direction. We defined the signal events to be those with $E_{\nu} > 2$ GeV and $|\cos \theta| > 0.2$. With an ANNcut of 0.7, the neural network is able to select such events with an efficiency of 55% and a purity of 93%. We obtained a hierarchy discrimination $\Delta \chi^{2}$ of 10 for a 10 year exposure. Marginalisation and equal systematic uncertainties for neutrinos and anti-neutrinos do not reduce this value. If we assume that the systematic uncertainties for neutrinos and anti-neutrinos are unrelated, it reduces to 9.5.

In conclusion, ICAL@INO can determine the ordering of the neutrino mass hierarchy at better than 3 $\sigma$ sensitivity with an exposure of 10 years.

References
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