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Precision measurement of neutrino oscillation parameters @ INO-ICAL detector

Daljeet Kaur, Md. Naimuddin, Sanjeev Kumar
Department of Physics and Astrophysics, University of Delhi, India, 110007

Abstract

Atmospheric neutrino experiments have the potential to measure the neutrino mixing parameters and mass hierarchy through the observation of earth matter effects. The magnetised Iron CALorimeter detector (ICAL) at the India-based Neutrino Observatory (INO) is one of the best experiments to separate the ν_μ and $\bar{\nu}_\mu$ with its excellent charge identification capabilities. We show the oscillation sensitivity of ICAL detector for the precision measurement of atmospheric mixing parameters $|\Delta m^2_{32}|$ and $\sin^2\theta_{23}$. The Monte Carlo simulation for NUANCE generated atmospheric ν_μ and $\bar{\nu}_\mu$ events and a marginalised χ^2 analysis using realistic detector resolutions and efficiencies has been performed. We show the expected improvement in the precision measurement of these parameters using reconstructed neutrino energy (E_ν) and muon direction ($\cos\theta_\mu$) observables.

Keywords: INO, ICAL, neutrino oscillations

1. Introduction

The recently measured large third mixing angle θ_{13} [1] of PMNS mixing matrix [2, 3] has opened up various new opportunities in the neutrino physics sector. Measurement of correct neutrino mass hierarchy, octant of θ_{23} and determination of the CP violating phase δ_{CP} are still unknown puzzles. To explain these unknown mysteries, various experiments are ongoing and proposed. The India-based Neutrino Observatory (INO) [4] is one of the planned projects to study oscillations and flavor mixing of atmospheric neutrinos and will be located at Theni district in South India. Precision measurement of atmospheric mixing parameters and determination of neutrino mass hierarchy are the major goals of INO. A 50 kt magnetised Iron CALorimeter (ICAL) detector will be the main detector at INO where Resistive Plate Chamber (RPC) will be used as an active detector to trace the particle tracks in their passage through the detector. We have performed a χ^2 analysis for the precision measurement using the simulated neutrino data generated for the ICAL detector using NUANCE [5] neutrino generator. Here, we present INO-ICAL capability for measuring the atmospheric neutrino oscillation parameters $|\Delta m^2_{32}|$ and $\sin^2\theta_{23}$ using neutrino energy and muon direction as observables in presence of actual detector resolutions and efficiencies.

Email address: daljeet.kaur97@gmail.com (Daljeet Kaur)

2. Atmospheric ν_μ ($\bar{\nu}_\mu$) at ICAL

Interactions of atmospheric ν_μ ($\bar{\nu}_\mu$) with the ICAL produce charged muons and hadrons through Quasi-Elastic (QE), Resonance and Deep Inelastic Scattering (DIS) Charged-Current processes. Muons leave a long track inside the detector and can be identified through bending of the track in magnetic field whereas hadrons produce bunch of hits in form of shower. Energy and direction of muons can be reconstructed though the muon track and that of hadrons can be reconstructed by considering shower hits. The energy and direction resolutions are provided by the INO collaboration as a function of true energies and true directions of muons and hadrons [6, 7] based on GEANT4 detector [8] simulation. Since the muon direction reconstruction is well

Parameters	True values	Marginalisation range
$\sin^2(2\theta_{12})$	0.86	Fixed
$\sin^2(\theta_{23})$	0.5	0.4-0.6
$\sin^2(\theta_{13})$	0.03	0.02-0.04
$\Delta m^2_{21}(eV^2)$	7.6×10^{-5}	Fixed
$\Delta m^2_{32}(eV^2)$	2.4×10^{-3}	$(2.1\text{-}2.6) \times 10^{-3}$
δ_{CP}	0.0	Fixed

Table 1: Oscillation parameters with their best fit values and marginalisation range used in the analysis.

known for ICAL we have used the reconstructed muon directions in the final analysis. Hadron energy resolution has been obtained by taking shower hadron hits into account. To find the detector response, total energy deposited by the hadron shower ($E'_{had} = E_\nu - E_\mu$) has been used for calibration [7]. In the present analysis, muon energy and angular resolutions are implemented by smearing true muon energy and direction of each μ^+ and μ^- event using the ICAL muon resolution functions [6]. True hadron energies are smeared using ICAL hadron resolution functions [7]. The neutrino energy can be reconstructed from reconstructed muon and hadron energy. We use reconstructed neutrino energy as the sum of reconstructed muon and hadron energy and muon direction as observables for binned χ^2 analysis.

3. Analysis

We simulate 1000 year unoscillated neutrino data generated from NUANCE neutrino generator using Honda et al. 3D flux [9]. Only the Charged-Current events are considered for the analysis. The inclusion of the oscillation effect have been incorporated using a re-weighting algorithm as mentioned in Refs. [10, 11]. Best fit values of the oscillation parameters used in the analysis with their 3σ marginalisation range are listed in Table 1. Events are selected in the 3-flavor neutrino mixing framework assuming normal hierarchy is true. The oscillation re-weighted events with detector resolutions and efficiencies folded in, are binned into neutrino energy and muon direction for the estimation of χ^2. The data is divided neutrino energy (E_ν) bins in the range of 0.8-10.8 GeV. We used 15 bins in the range 0.8-5.8 GeV with bin size of 0.33 GeV and from 5.8-10.8 GeV, 5 bins with bin size of 1 GeV. 20 $\cos\theta_\mu$ direction bins are used in the range [-1, 1]. Same binning for both ν_μ and $\bar{\nu}_\mu$ events have been used. The bin size for the analysis has been optimised such that each bin contains at least one event. Finally, we scale the data for 10 years to minimising the statistical fluctuations. The definition of atmospheric mass square splitting as $|\Delta m^2_{eff}|$ following Ref [11] has been considered for the analysis. We have used the poissonian definition of χ^2 given as

$$\chi^2(\nu_\mu = \sum_{min} 2N^{th'}_{ij}(\nu_\mu) - 2N^{ex}_{i,j}(\nu_\mu) + 2N^{ex}_{i,j}(\nu_\mu) \ln\left(\frac{N^{ex}_{i,j}(\nu_\mu)}{N^{th'}_{i,j}(\nu_\mu)}\right) + \sum_k \zeta_k^2, \quad (1)$$

where

$$N^{th'}_{ij}(\nu_\mu) = N^{th}_{i,j}(\nu_\mu)\left(1 + \sum_k \pi^k_{ij}\zeta_k\right). \quad (2)$$

In Eq.(1), N^{ex}_{ij} is the observed number of the ν_μ events in the i^{th} E_ν & j^{th} $\cos\theta_\mu$ bin generated using true values of the oscillation parameters as listed in Table 1. In Eq. (2), N^{th}_{ij} is the number of theoretically predicted events generated by varying oscillation parameters without including systematic errors, $N^{th'}_{ij}$ shows shifted events spectrum due to different systematic uncertainties, π^k_{ij} is the systematic shift bin due to k^{th} systematic error.

A total five systematic uncertainties are considered for our analysis; these are 20% overall flux normalisation uncertainty, 10% cross-section uncertainty, 5% uncertainty on the zenith angle dependence of the flux, 5% energy dependent tilt error and 5% overall statistical uncertainty. All the systematic uncertainties are applied using the method of “pulls” as described in [10, 12]. ζ_k is the univariate pull variable corresponding to the π^k_{ij} uncertainty. An expression similar to Eq. (1) can be obtained for $\chi^2(\bar{\nu}_\mu)$ using reconstructed μ^+ event samples. We have calculated $\chi^2(\nu_\mu)$ and $\chi^2(\bar{\nu}_\mu)$ separately and then these two are added to get total χ^2_{total} as

$$\chi^2_{\text{total}} = \chi^2(\nu_\mu) + \chi^2(\bar{\nu}_\mu). \quad (3)$$

We impose a 10% prior while marginalising over $\sin^2\theta_{13}$ as

$$\chi^2_{\text{ICAL}} = \chi^2_{\text{total}} + \left(\frac{\sin^2\theta_{13}(true) - \sin^2\theta_{13}}{\sigma_{\sin^2\theta_{13}}}\right)^2. \quad (4)$$

Finally, in order to obtain the experimental sensitivity for θ_{23} and $|\Delta m^2_{32}|$, we minimise the χ^2_{ICAL} function by varying oscillation parameters within their allowed ranges over all systematic uncertainties. The precision on the oscillation parameters can be defined as:

$$Precision = \frac{P_{\max} - P_{\min}}{P_{\max} + P_{\min}}, \quad (5)$$

where $P_{\max}$ and $P_{\min}$ are the maximum and minimum values of the concerned oscillation parameters at the given confidence level.

4. Results & Conclusions

We have studied the INO-ICAL detector capability for the precision measurement of atmospheric neutrino oscillation parameters using neutrino energy and muon angle observables. We obtain the contour plots assuming $\Delta\chi^2_{\rm ICAL} = \chi^2_{\rm min} + m$, where $\chi^2_{\rm min}$ is the minimum value of $\chi^2_{\rm ICAL}$ for each set of oscillation parameters and values of m are taken as 2.30, 4.61 and 9.21 corresponding to 68%, 90% and 99% confidence levels. The ($|\Delta m^2_{\rm eff}|$, $\sin^2\theta_{23}$) contour plot is shown in Figure 1. Figure 2 and Figure 3 depict the one dimensional sensitivity at 1σ, 2σ and 3σ levels for $|\Delta m^2_{\rm eff}|$ and $\sin^2\theta_{23}$ respectively. We find that ICAL is able to measure $|\Delta m^2_{32}|$ and $\sin^2\theta_{23}$ with a precision of 4.15% and 16% at 1σ confidence level for 10 years of exposure with the given detector resolutions and efficiencies, using neutrino energy and muon direction binning. Present results show an imrovement of 18.62% and 5% on the precision of $|\Delta m^2_{32}|$ and $\sin^2\theta_{23}$ over the earlier ICAL analysis using muon energy and muon direction observables [10].

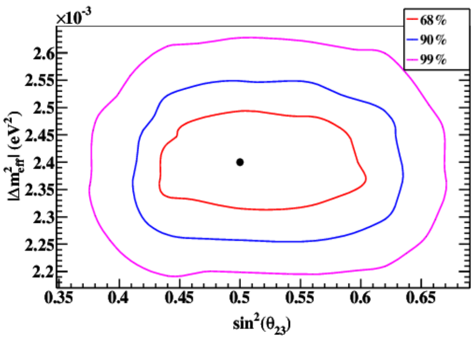

Figure 1: Contour plot for 68%, 90% and 99% confidence level for 10 years exposure of ICAL detector.

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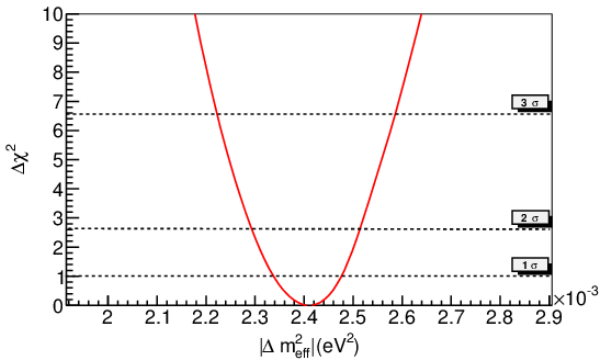

Figure 2: $\Delta\chi^2$ as a function of test values of $|\Delta m^2_{\rm eff}|$.

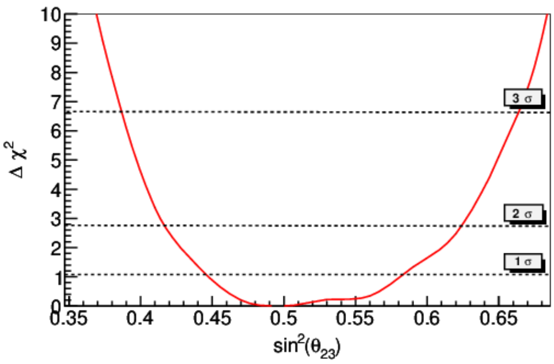

Figure 3: $\Delta\chi^2$ as a function of test values of the $\sin^2\theta_{23}$.

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