Precision measurement of neutrino oscillation parameters at INO-ICAL Detector

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1 Introduction

Neutrino oscillation is now a well established fact and is a direct indication for physics beyond the standard model. Recent discovery of the relatively large value of third neutrino mixing angle θ_{13} from various experiments has heralded a new era in neutrino physics. But, still there are various unsolved mysteries related to neutrinos are present like what is the actual mass of the neutrinos, what is the value of Dirac δ_{CP} phase, measurement of neutrino mass hierarchy, etc. A large number of neutrino experiments are ongoing or proposed to resolve these mysteries. In the same stream India-based Neutrino Observatory (INO) [1] experiment has been proposed to be build in India with a large magnetised Iron CALorimeter (ICAL) detector. In this paper, we show the precision measurement analysis for ICAL detector using atmospheric muon neutrino (anti-neutrinos) oscillation events, generated through Monte Carlo NUANCE [2] event generator. The analysis has been performed for 10 year exposure of ICAL detector. Various resolutions and efficiencies obtained by the INO collaboration are implemented to reconstruct the neutrino energy and muon direction. A marginalised χ^2 analysis based on neutrino energy and muon zenith angle binning scheme has been performed to determine the sensitivity for the atmospheric neutrino mixing parameters ($\sin^2\theta_{23}$ and $|\Delta m^2_{32}|$).

2 The ICAL detector

The India-based Neutrino Observatory (INO) has been planned to set up an underground laboratory in India to study atmospheric neutrinos. INO will host a 50 kt magnetized Iron CALorimeter (ICAL) detector consists of total three modules, each of dimension 16 m x 16 m x 14.5 m. Total detector will be a stack of 151 horizontal layers of 5.6 cm thick iron slab interleaved within 4 cm gap for the active detector element. Glass Resistive Plate Chambers (RPCs) of dimension 2 m x 2 m will be used as active part of the detector. Atmospheric neutrino interaction with the iron target produces the muons along with shower of hadrons through a Charge-Current interaction process. ICAL detector will be able to detect muons using their long tracks and hadron showers hits produced by neutrino events. ICAL will have a unique capability to detect the charge of the produced muon through its magnetic field which is around 1.5 tesla and hence can determine the charge of neutrino. Since the neutrinos and anti-neutrinos interact differently with matter, the atmospheric neutrinos with large coverage of flight distance can reveal the mass hierarchy problem while passing through

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

Table 1: Oscillation parameters used for analysis.

earth matter. Thus, ICAL with atmospheric neutrino source have a potential to solve the unknown correct mass spectrum of neutrinos.

3 Analysis

3.1 Event generation and oscillation effect

The atmospheric neutrino events are generated with the available 3-dimensional neutrino flux provided by HONDA et.al. [3] using ICAL detector specifications. The atmospheric muon neutrinos (anti-neutrinos) interactions are simulated for 1000 years exposure of 50kt ICAL detector and then normalised to 10 years exposure to keep Monte Carlo fluctuations under control. Only Charge-Current (CC) interactions are considered for the present analysis. At first, each event is generated in the absence of oscillations and then the effect of oscillations are included using the Re-weighting algorithm similar to the method as described in earlier ICAL analyses [4, 5]. The current best fit values and errors in the oscillation parameters used for analysis are shown in Table 1. For each neutrino event of a given energy E_ν and zenith direction θ_z, oscillation probabilities are estimated in the framework of three flavor mixing taking Earth matter effects into account.

3.2 ICAL detector resolutions and the neutrino energy reconstruction

Reconstruction of the neutrino energy required the measurement of muon as well as hadron energy. Once we have the reconstructed muon and hadron energies, we directly add them together to get the final reconstructed neutrino energy. Muon and hadron energy resolutions have been obtained by the INO collaboration as a function of true energy E_{true} and direction $\cos\theta_{true}$ of the particle using a GEANT4 based code. Muons give clear track of hits inside the magnetised detector, therefore, the energy of muons can be reconstructed easily using a track fitting algorithm. It was observed that the muons energy reconstructed by ICAL detector follows Gaussian distribution for $E_\mu \geq 1$ GeV whereas it follows Landau distribution function for $E_\mu < 1$ GeV [7]. Hadrons deposited their energies in a shower like pattern. Total energy deposited by the hadron shower ($E'_{had} = E_\nu - E_\mu$) has been used to calibrate the detector response. It has been found that hadron hit patterns follow Vavilov distribution and the hadron energy resolution is then shown as function of E'_{had}. The details of INO resolution analysis can be found in [8, 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. Energies of hadron events are smeared using ICAL hadron resolution functions. Reconstructed neutrino energy is then taken as the sum of reconstructed muon and hadron energy. We have also taken care of muon's reconstruction and charge identification efficiencies as provided by INO collaboration in the present work.

3.3 χ^2 Analysis

The oscillation parameters determining the atmospheric neutrinos are extracted by χ^2 analysis. The re-weighted events with detector resolutions and efficiencies folded in, are binned into reconstructed neutrino energy and muon direction for the estimation of χ^2. The data has been divided into total 10 equal neutrino energy bins in the range of 0.8 - 10.8 GeV with bin width of 1 GeV. A total of 20 $\cos\theta_\mu$ direction bins in the range of -1 to 1, with equal bin width has been chosen. The above mentioned binning scheme is applied for both ν_μ and $\bar{\nu}_\mu$ events. Here, We use the reference of maximal mixing i.e. $\sin^2\theta_{23} = 0.5$. The atmospheric mass square splitting are related to the other oscillation parameters, so for the precision study we have defined it as Δm^2_{eff}, which can be written as follows

$$\Delta m^2_{eff} = \Delta m^2_{32} - (\cos^2\theta_{12} - \cos\delta_{CP}\sin\theta_{32}\sin 2\theta_{12}\tan\theta_{23})\Delta m^2_{21}. \quad (1)$$

The other oscillation parameters (θ_{12}, Δm^2_{21} and δ_{CP}) are kept fixed both for observed and predicted events as the marginalisation over these parameters has negligible effects on the analysis results. In the present analysis we have implemented five systematic uncertainties, which are a 20 % error on atmospheric neutrino flux normalisation, 10% error on neutrino cross-section, an overall 5% statistical error, a 5% uncertainty due to zenith angle dependence of the fluxes and an energy dependent tilt error as applied in earlier ICAL analyses [4, 5]. All mentioned systematic uncertainties are applied using the method of "pulls" as outline in Ref.[9]. In the analysis framework, due to the fine binning, some bins have very small number of entries. Therefore, we have used the poissonian definition of χ^2 given as

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

where

$$N^{th'}_{ij}(\nu_\mu) = N^{th}_{i,j}(\nu_\mu)\left(1 + \sum_k \pi^k_{ij}\zeta_k\right). \quad (3)$$

In Eq. (2), N^{ex}_{ij} are the observed number of reconstructed μ^- events generated using true values of the oscillation parameters as listed in Table 1 in i^{th} neutrino energy bin and $j^{th}\cos\theta_\mu$ bin. In Eq. (3), N^{th}_{ij} are the number of theoretically predicted events generated by varying oscillation parameters, $N^{th'}_{ij}$ shows modified events spectrum due to different systematic uncertainties, π^k_{ij} is the systematic shift in the events of i^{th} neutrino energy bin and $j^{th}\cos\theta_\mu$ bin due to k^{th} systematic error. ζ_k is the univariate pull variable corresponding to the π^k_{ij} uncertainty. The similar expression for $\chi^2(\bar{\nu}_\mu)$ can be obtained 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

$$\chi^2_{total} = \chi^2(\nu_\mu) + \chi^2(\bar{\nu}_\mu). \quad (4)$$

Since the value of θ_{13} is now known to several Gaussian standard deviations (σ), so we use a 10% deviation from the true value of $\sin^2\theta_{13}$ as a prior to marginalise over $\sin^2\theta_{13}$ as

$$\chi^2_{ino} = \chi^2_{total} + \left(\frac{\sin^2\theta_{13}(true) - \sin^2\theta_{13}}{\sigma_{\sin^2\theta_{13}}}\right)^2. \tag{5}$$

Finally, we minimise the χ^2_{ino} function by varying oscillation parameters within their allowed ranges over all systematic uncertainties.

4 Results

We have derived the measurement contours of the atmospheric oscillation parameters in 3 flavor mixing using earth matter effect. The two dimensional confidence region of the oscillation parameters ($|\Delta m^2_{eff}|$, $\sin^2\theta_{23}$) are determined from $\Delta\chi^2_{total}$ around the best fit. The resultant region is shown in Figure 1. We have obtained these contour plots assuming $\Delta\chi^2_{total} = \chi^2_{min} + m$, where χ^2_{min} is the minimum value of χ^2_{total} for each set of oscillation parameters and values of m are taken as 2.30, 4.61 and 9.21 corresponds to 68%, 90% and 99% confidence levels respectively. Figure 2 depicts the one dimensional plot for the measurement of test parameter $\sin^2\theta_{23}$ (right) at fixed $|\Delta m^2_{eff}| = 2.4 \times 10^{-3}$ (eV^2) and for the $|\Delta m^2_{eff}|$ at fixed $\sin^2\theta_{23} = 0.5$ (left) at 1 σ, 2 σ and 3σ levels for one parameter estimation.

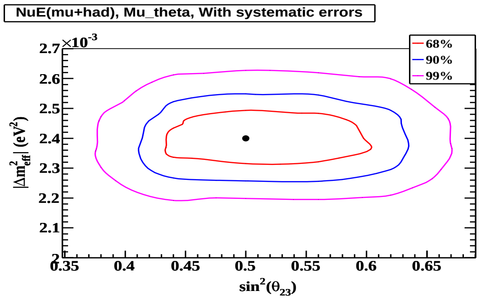

Figure 1: Contour plot for 68%, 90% and 99% confidence level for 10 years exposure of ICAL detector.

The precision on the oscillation parameters can be defined as:

$$Precision = \frac{P_{max} - P_{min}}{P_{max} + P_{min}}, \tag{6}$$

where P_{max} and P_{min} are the maximum and minimum values of the concerned oscillation parameters at the given confidence level. The current study shows that ICAL is capable of measuring the atmospheric mixing angle $\sin^2\theta_{23}$ with a precision of 16%, 21% and 28% at 68%, 90% and 99% confidence levels respectively. The atmospheric mass square splitting $|\Delta m^2_{eff}|$ can be measured with a precision of 3.75%, 6% and 9% at 68%, 90% and 99% confidence levels respectively.

5 Conclusions

We have studied the ICAL detector capability for the precise measurement of atmospheric neutrino oscillation parameters using neutrino energy and muon angle observables. A Monte

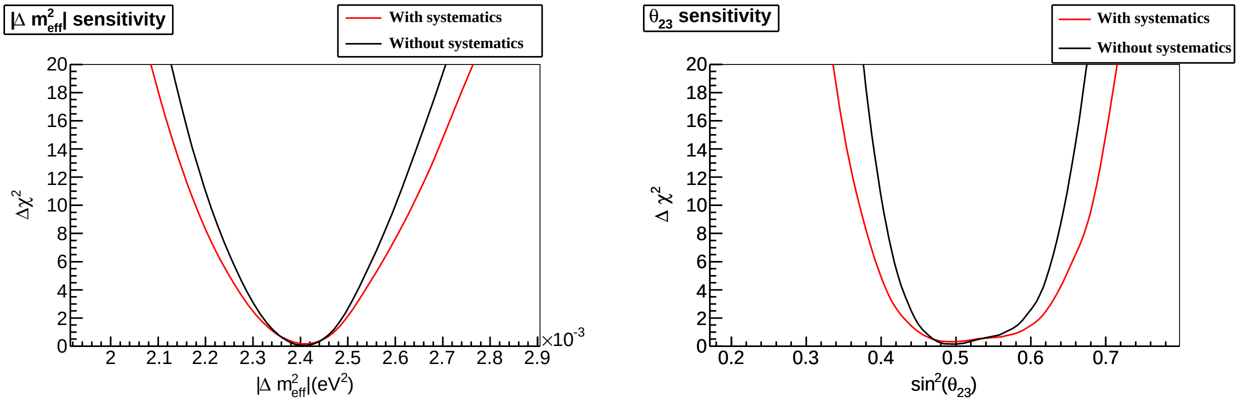

Figure 2: $\Delta\chi^2$ as a function of test values of the $|\Delta m^2_{eff}|$ (left) and $\Delta\chi^2$ as a function of test values of $\sin^2\theta_{23}$ (right).

Carlo simulation using NUANCE generated neutrino data for 10 years exposure of ICAL detector has been carried out. Finally, a marginalised χ^2 analysis in bins of neutrino energy and muon angle using realistic detector resolutions for measurement of $\sin^2\theta_{23}$ and $|\Delta m^2_{eff}|$. On comparing these results with the we find that there is an improvement of 6% and 16% on the precision measurement of $\sin^2\theta_{23}$ and $|\Delta m^2_{eff}|$ parameters respectively using neutrino energy, muon angle observables over muon energy, muon angle analysis [4]. Results presented here can further be improved using improved resolutions of ICAL and with fine energy and direction binning. Moreover, this study shows that the ICAL experiment has the capability of using hadron information to further improve the measurement of oscillation parameters.

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