INO-ICAL detector sensitivity for the measurement of atmospheric neutrino mixing parameters

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Neutrino oscillation physics is now enriched with various compelling evidences of neutrino oscillations and their masses from several experiments but measurement of correct neutrino mass hierarchy, octant of θ_{23} and determination of value CP violating phase δ_{CP} are still unknown puzzles. The recently measured substantially large third mixing angle θ_{13} from the reactor experiments [1, 2] has opened up new opportunities in the neutrino physics sector [3, 4]. Atmospheric neutrino experiments have potential to explain these unknown mysteries through their wide coverage of baseline and with energies in the range from MeV to TeV. The magnetised Iron CALorimeter detector (ICAL) at India-based Neutrino Observatory (INO) [5] is a proposed atmospheric neutrino experiment, located at Theni district in South India. The main goals of INO experiment is to measure the correct neutrino mass hierarchy and the precise measurement of neutrino mixing parameters through the observation of atmospheric ν_μ and $\bar{\nu}_\mu$ events. A 50 kton 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 on their passage through the detector. The unique feature of ICAL is to separate the atmospheric ν_μ and $\bar{\nu}_\mu$ with its excellent charge identification capabilities. We have performed a χ^2 analysis for the precision measurement using the simulated neutrino data generated for the ICAL detector using NUANCE [6] 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.

Interaction of atmospheric neutrinos with the detector produce associative lepton and hadrons through Quasi-Elastic (QE), Single pion production (Resonance) and Deep Inelastic scattering (DIS) processes. Muons are produced due to Charged Current interactions of muon neutrinos ant anti-neutrinos while single pion along with one lepton produced due to resonance interactions. Hadrons are produced due to deep inelastic scattering (DIS) at high energies. Muons create a long track on their passage through detector and their charge and momenta can be identified through the track bending and curvature in presence of magnetic field whereas hadrons produce bunch of hits in form of shower. The energy and direction resolutions of muons and hadrons based on GEANT4 detector [8] simulation are provided by the INO collaboration as a function of their true energies and true directions [7, 9]. Since the muon direction reconstruction is well known for ICAL we have used the reconstructed muon directions in the final analysis. 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 [7]. True hadron energies are smeared using ICAL hadron resolution functions [9].

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.

For the analysis, we simulate 1000 year unoscillated NUANCE data generated using Honda et al. 3D flux [10]. The implementation of oscillation effects to these unoscillated data have been done using a well known re-weighting algorithm as presented in earlier ICAL analyses [11, 12]. We use the fixed values of solar mixing parameters $\sin^2(2\theta_{12}) = 0.86$, $\Delta m^2_{21} = 7.6 \times 10^{-5} eV^2$ and $\delta_{cp} = 0$ where as the atmospheric mixing parameters are marginalised within their 3σ range with the best fit values $\sin^2(\theta_{23}) = 0.5$ and $\Delta m^2_{32} = 2.4 \times 10^{-3} eV^2$. Here, we assume normal hierarchy is true. The oscillation re-weighted events with detector resolutions and efficiencies are then binned into neutrino energy and muon direction. The data is divided into neutrino energy bins in the range of 0.8 - 10.8 GeV. We use 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 of -1 to 1. Finally, for χ^2 estimation, the data has been scaled down for 10 years of exposure to minimising the statistical fluctuations. The definition of atmospheric mass square splitting as $|\Delta m^2_{eff}|$ following the Ref. [12] has been considered for the analysis. We have used the poissonian definition of χ^2 given as

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

where

$$N_{ij}^{th'}(\nu_\mu) = N_{i,j}^{th}(\nu_\mu) \left(1 + \sum_k \pi_{ij}^k \zeta_k \right). \tag{2}$$

In Eq.(1), N_{ij}^{ex} is the observed number of the ν_μ events in i^{th} E_ν and j^{th} $\cos\theta_\mu$ bin generated using true values of the oscillation parameters. In Eq.(2), N_{ij}^{th} is the number of theoretically predicted events generated by varying oscillation parameters without including systematic errors, $N_{ij}^{th'}$ shows shifted events spectrum due to different systematic uncertainties, π_{ij}^k is the systematic shift 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 [11, 13]. ζ_k is the univariate pull variable corresponding to the π_{ij}^k 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

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

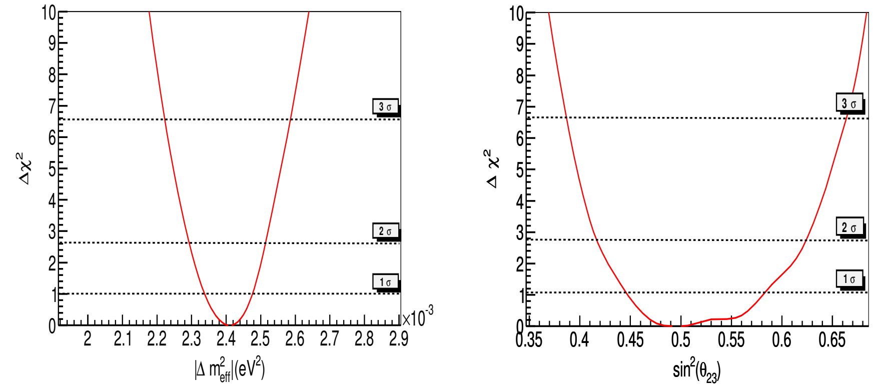
We impose a 10% prior while marginalising over $\sin^2\theta_{13}$ as

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

Finally, in order to obtain the experimental sensitivity for θ_{23} and $|\Delta m^2_{eff}|$, 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:

$$Precision = \frac{P_{max} - P_{min}}{P_{max} + P_{min}}, \tag{5}$$

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



(a)

(b)

Figure 1: (a) $\Delta\chi^2$ as a function of $|\Delta m^2_{32}|$ (b) $\Delta\chi^2$ as a function of $\sin^2\theta_{23}$.

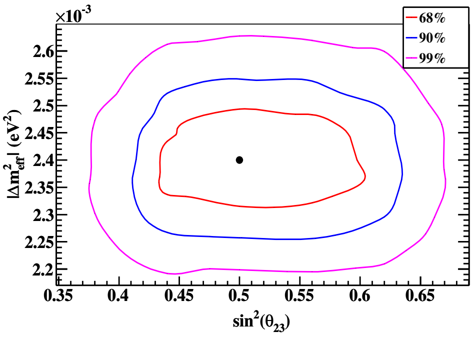


Figure 2: Contour plot for 68%, 90% and 99% confidence level for 10 years exposure of ICAL detector

The sensitivity for the measurement of test parameters $|\Delta m^2_{eff}|$ and for $\sin^2\theta_{23}$ at 1σ, 2σ and 3σ confidence intervals are shown in Figure 1(a) and Figure 1(b) respectively. The final contour plots in $|\Delta m^2_{eff}|$ and $\sin^2\theta_{23}$ plane assuming $\Delta\chi^2_{ical} = \chi^2_{min} + m$ has been obtained, where χ^2_{min} is the minimum value of χ^2_{ical} 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. The $(|\Delta m^2_{eff}|, \sin^2\theta_{23})$ contour plot is shown in Figure 2. We find that for 10 years of exposure of ICAL detector with detector resolutions and efficiencies, INO-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 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 with muon energy and muon direction observables [11].

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