The INO-ICAL sensitivity to measure the difference between ν_μ and $\bar{\nu}_\mu$ mass-squared splittings

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Abstract

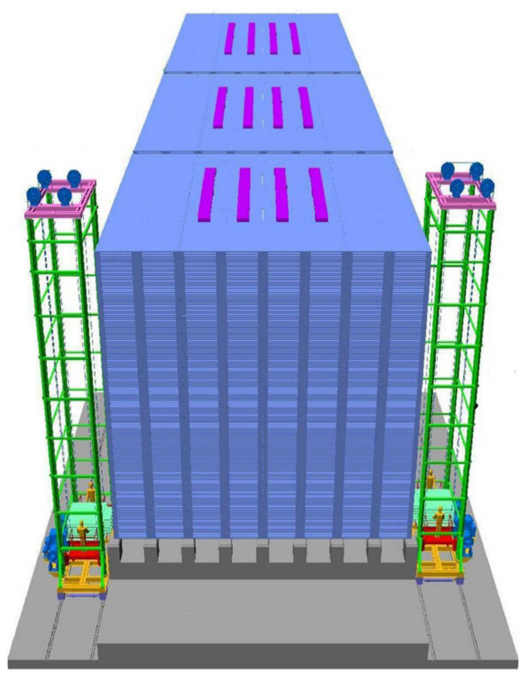
We present an experimental observation for the differences in the mass-squared splittings of atmospheric ν and $\bar{\nu}_\mu$ oscillations for the magnetised Iron Calorimeter (ICAL) detector at the India-based Neutrino Observatory (INO). The ICAL detector is enriched with an excellent charge-identification capability for neutrino and anti-neutrino detection on an event by event basis. A Charged-Current (CC) ν_μ and $\bar{\nu}_\mu$ interactions with the detector, assuming three flavor oscillations along with the inclusion of the Earth matter effect have been simulated for ten years exposure of the detector. The observed ν_μ and $\bar{\nu}_\mu$ events spectrum folded with realistic detector resolutions and efficiencies are separately binned to direction and energy bins, and a χ^2 is minimized with respect to each bin to find out the oscillation parameters for ν_μ and $\bar{\nu}_\mu$ independently. Assuming non-identical atmospheric oscillation parameters for neutrinos and antineutrinos, we estimate the detector sensitivity to confirm a non-zero difference in the mass-squared splittings ($|\Delta m^2_{32}| - |\Delta \overline{m}^2_{32}|$).

Introduction and Physics goals of INO:

- The INO-ICAL is unique in its ability to distinguish between Neutrino and anti-Neutrino by measuring the charge of secondary muons produced by the neutrino interaction with ICAL detector.
- India-based Neutrino Observatory is set to be with a modern Iron CALorimeter (ICAL) detector with the Resistive Plate Chamber (RPCs) as the active detector element.
- Unambiguous and more precise determination of oscillation parameters using atmospheric neutrinos.
- Study of matter effects through electric charge identification, that may lead to the determination of the unknown sign of one of the mass differences.
- Study of charge-conjugation and parity (CP) violation in the leptonic sector as well as possible charge-conjugation, parity, time-reversal (CPT) violation studies.
- Neutrino-less double beta decay, to determine whether neutrinos are Dirac or Majorana particles
- High-precision determination of the oscillation parameters when ICAL is (perhaps upgraded and) used in the future as a far-end detector for a long base-line neutrino oscillation experiment.

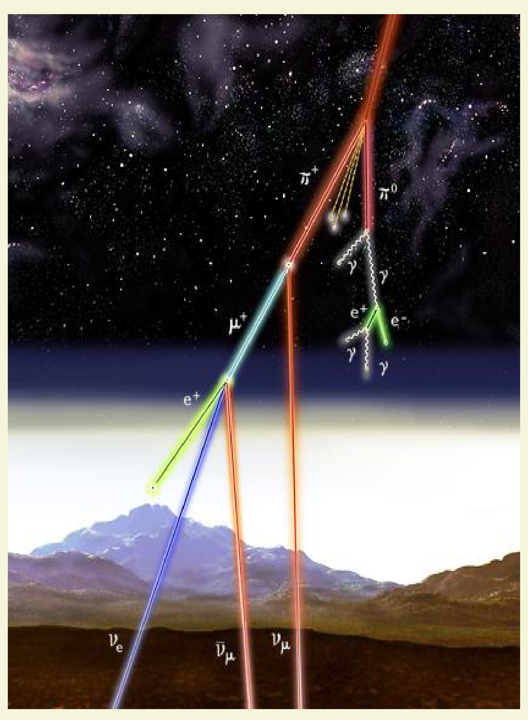
ICAL specifications:

- Dimension :$16m \times 16m \times 14.5m$ (for one module)
- Absorber material : Iron (5.6 cm thick plates)
- Active Detector : Resistive Plate Chambers
- Total No. of layers : 150
- Magnetic field : 1.5 Tesla
- Total Mass : 50k Tons
- Location : Bodi Hills,Tamilnadu, India



Neutrino Interactions:

- Cosmic rays from galactic sources interact with Earth's atmosphere continuously producing pions and kaons which are the main source of atmospheric neutrinos.
- Neutrinos interact in the detector through Charge Current (CC) and Neutral Current (NC) interactions.
- ICAL detector at INO is sensitive to atmospheric neutrinos and anti-neutrinos. Neutrino interaction within the detector results in the production of muons and hadrons.
- Muons can be identified and reconstructed using their tracks in the magnetized detector and hadrons can be calibrated with their shower hits in the detector.
- Energy and angle of neutrino/anti-neutrino can be reconstructed using the information of muons and hadrons.



Oscillation Parameters and their marginalisation range

True values and marginalization range of the used oscillation parameters are listed in the below table:

Neutrino/anti-neutrino oscillation parameters		
Oscillation Parameters	(ν) True values	Marginalization range
$\sin^2(2\theta_{12})$	0.86	Fixed
$\sin^2(\theta_{23})$	varied	0.3-0.7
$\sin^2(\theta_{13})$	0.0234	Fixed
$\Delta m^2(sol.in eV^2)$	7.6×10^{-5}	Fixed
$\Delta m^2(Atm.in eV^2)$	varied	$(2.0\text{-}3.0)\times10^{-3}(3\sigma)$
δ_{CP}	0.0	Fixed

Analysis:

- Non-identical atmospheric oscillation parameters for neutrinos and antineutrinos are considered.
- All the four atmospheric oscillation parameters i.e. $|\Delta m^2_{32}|$, $|\Delta\overline{m}^2_{32}|$, θ_{23} and $\overline{\theta}_{23}$ are varied within their marginalization range.
- Using the results of the four parameters analysis, we study the prospects of the scenario when both the differences ($|\Delta m^2_{32}|-|\Delta\overline{m}^2_{32}|$) and ($\sin^2\theta_{23}$-$\sin^2\overline{\theta}_{23}$) are non-zero.
- Extracted a two oscillation parameters plot from Four oscillation parameter fit data to show the comparison with MINOS result.

Event Generation and Event Selection:

- We use the atmospheric neutrino data which was obtained by HONDA et.al. 3-D neutrino flux with ICAL detector specifications using NUANCE event generation.
- Unoscillated neutrino/anti-neutrino events are generated for 1000 years of exposure of ICAL and it scaled to 10 years of ICAL running for estimation of sensitivity.

Detector's Resolutions and Efficiency:

- Reconstruction and charge identification efficiencies (Obtained by INO) are implemented.
- Muon energy resolutions and hadron energy resolutions are implemented.
- Only the Muon angle resolution has been used for the analysis.

Energy and Direction Binning:

- 20 muon energy bins ranging from 0.8 GeV to 12.8 GeV
- 20 muon direction bins($\cos\theta$ bins ranging from -1 to +1)
- 5 hadron bins ranging from 0.0 GeV to 15.0 GeV
- Binning is done in similar way for neutrinos and anti-neutrinos with $20 \times 20 \times 5 = 2000$ bins with optimised bin size.
- Random number smearing is applied both for expected and observed events.

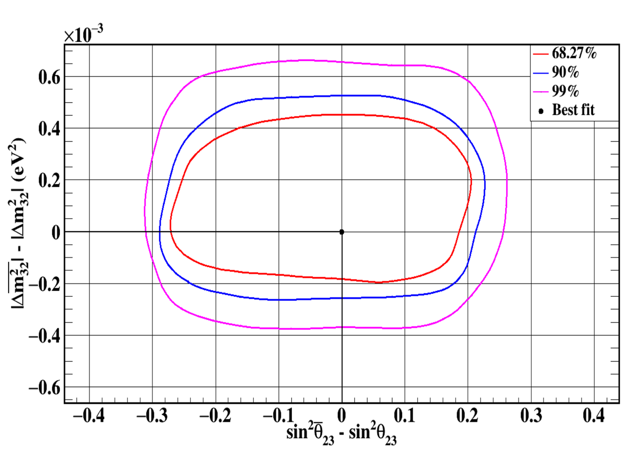
Systematic Errors:

- A 20% error on atmospheric neutrino flux normalization, a 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 have been implemented without correlation.

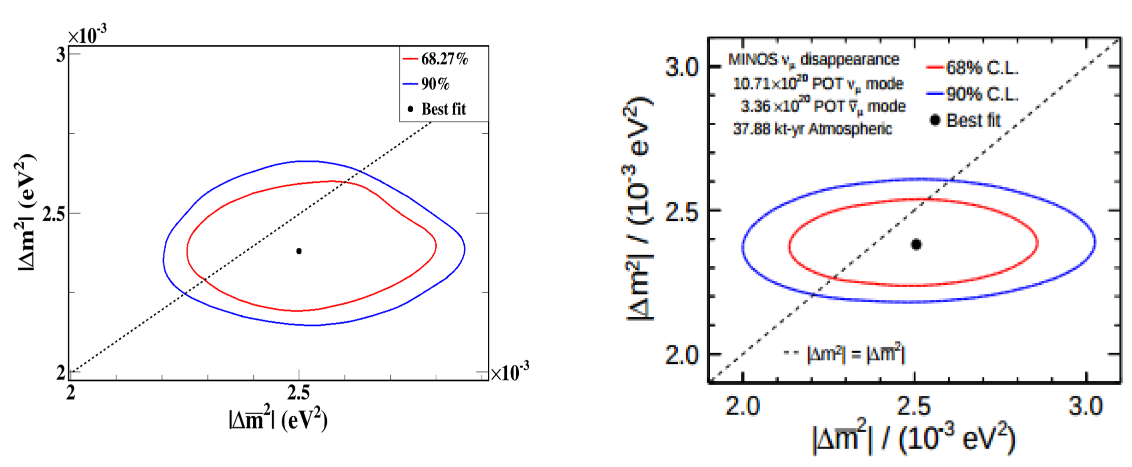
χ^2 analysis:

- Poisson χ^2 function with method of pulls is used.
- χ^2 has been calculated for neutrino and anti-neutrino seoparately.
- χ^2_{total}=χ^2_ν + $\chi^2\bar{\nu}$

Results

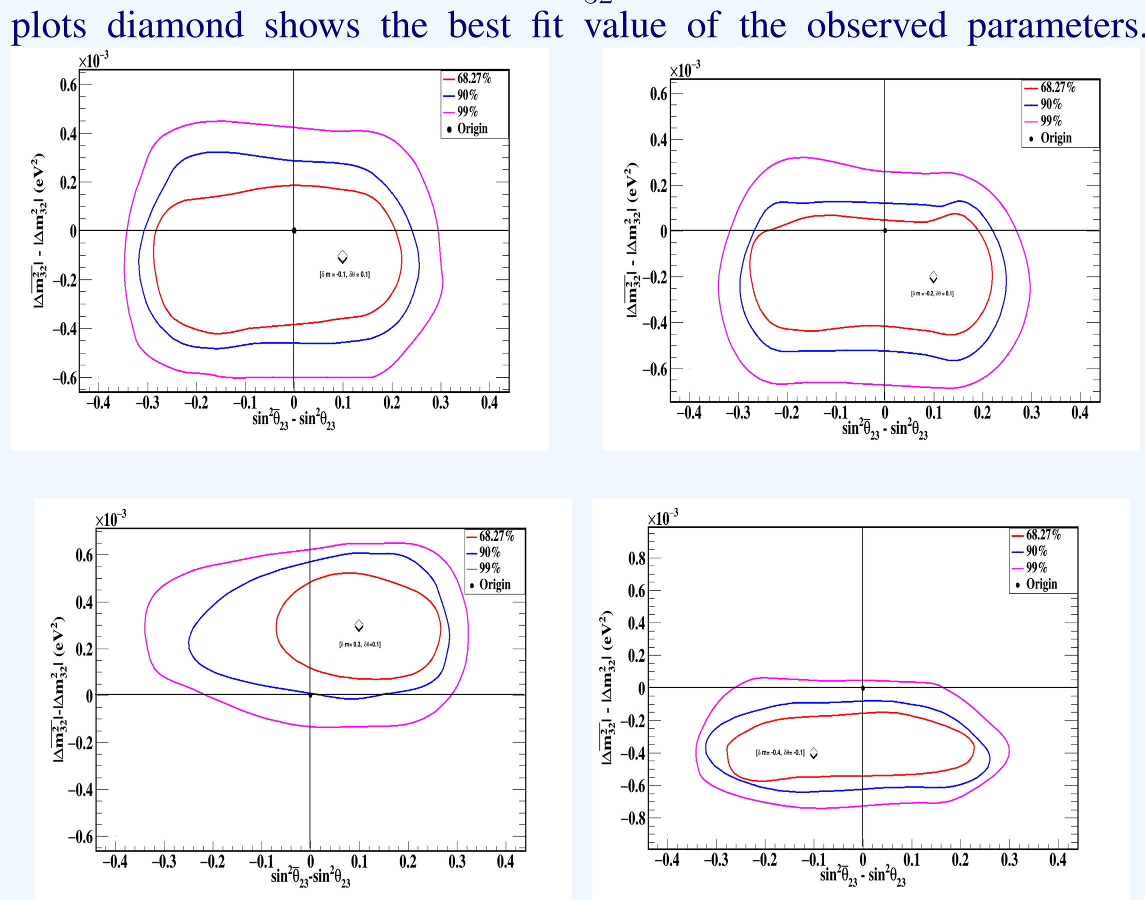


The ICAL sensitivity on ($\delta_m = |\Delta\overline{m}^2_{32}| - |\Delta m^2_{32}|$) and ($\delta_\theta = \sin^2\overline{\theta}_{23} - \sin^2\theta_{23}$) plane at 68%, 90% and 99% confidence levels. Origin is the point where, neutrino and antineutrino parameters are identical. Here, $|\Delta m^2_{32}|$=$2.38\times10^{-3}(eV^2)$, $|\Delta\overline{m}^2_{32}|$=$2.5\times10^{-3}(eV^2)$ such that the difference ($|\Delta\overline{m}^2_{32}| - |\Delta m^2_{32}| = 0.12$), and $\sin^2\theta_{23}$= $\sin^2\overline{\theta}_{23}$=0.5 such that ($\sin^2\overline{\theta}_{23} - \sin^2\theta_{23} = 0$).

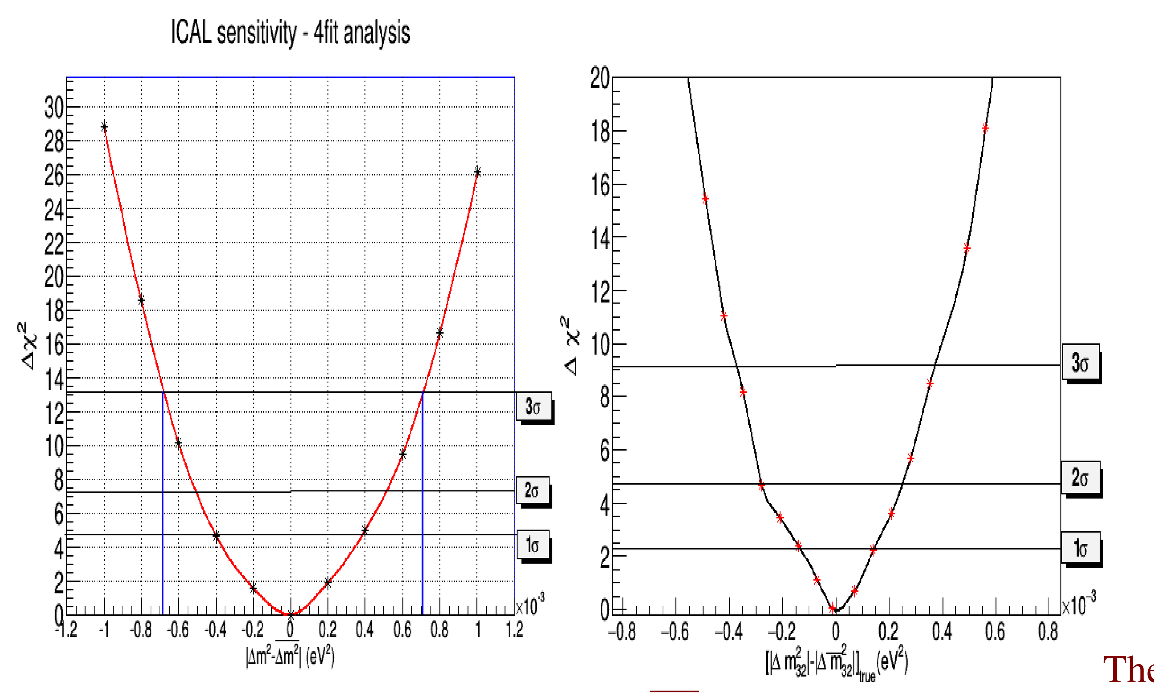


The 68% and 90% confidence level contours on the $|\Delta m^2_{32}|$ and $|\Delta\overline{m}^2_{32}|$ parameter space. Right shows the sensitivity obtained by MINOS experiment using combined beamline and atmospheric data. Left shows the sensitivity of the ICAL experiment using atmospheric data only.

Contour plots at 68%, 90% and 99% C.L. for different true values of $|\Delta m^2_{32}|$, $|\Delta\overline{m}^2_{32}|$, $\sin^2\theta_{23}$ and $\sin^2\overline{\theta}_{23}$ as shown in table below. Here, X-axis corresponds to the differences of $\sin^2\theta_{23}$ and $\sin^2\overline{\theta}_{23}$ and Y-axis corresponds to differences in $|\Delta m^2_{32}|$ and $|\Delta\overline{m}^2_{32}|$ values. In these plots diamond shows the best fit value of the observed parameters.



Set No.	$|\Delta m^2_{32}|(eV^2)$	$|\Delta\overline{m}^2_{32}|(eV^2)$	$\sin^2\theta_{23}$	$\sin^2\overline{\theta}_{23}$	$\delta_m(eV^2)$	δ_θ
Set-1	2.6×10^{-3}	2.5×10^{-3}	0.5	0.6	-0.1×10^{-3}	0.1
Set-2	2.6×10^{-3}	2.4×10^{-3}	0.5	0.6	-0.2×10^{-3}	0.1
Set-3	2.2×10^{-3}	2.5×10^{-3}	0.4	0.5	0.3×10^{-3}	0.1
Set-4	2.4×10^{-3}	2.0×10^{-3}	0.5	0.4	-0.4×10^{-3}	-0.1



The INO-ICAL sensitivity for $(|\Delta m^2_{32}| - |\Delta\overline{m}^2_{32}|)_{True}(eV^2)$ at 1σ, 2σ and 3σ confidence levels using four oscillation parameter fit technique (Left) and with two oscillation parameter fit (Right).

Conclusion:

1. Keeping ICAL's good charge-identification feature in mind, neutrino and antineutrino oscillations parameters can be measured separately.
2. With fixed true values for non-identical oscillation parameters of ν_μ and $\bar{\nu}_\mu$, we measured the sensitivity of ICAL detector for difference in oscillation parameters of ν_μ and $\bar{\nu}_\mu$.
3. An extraction of two parameter fit from the four-fit plot has been shown for a comparitive study with the MINOS experiment
4. The ICAL sensitivity for neutrinos mass-squared splitting is almost comparable to that of MINOS while the ICAL is more sensitive for the anti-neutrinos mass-squared splittings (12.87 % at 90 % CL) compared to MINOS (20 % at 90 % CL), by using the atmospheric events only.
5. With the variation of true as well as observed values, ICAL can rule out the null hypothesis of $|\Delta m^2_{32}| = |\Delta\overline{m}^2_{32}|$ at more than 3σ level if the difference of true values of $|\Delta m^2_{32}| - |\Delta\overline{m}^2_{32}| \geq +0.7\times10^{-3}eV^2$ or $|\Delta m^2_{32}| - |\Delta\overline{m}^2_{32}| \leq -0.7\times10^{-3}eV^2$.

References:

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