# Neutrino oscillation parameter determination at INO-ICAL using track and non-track hit information from GEANT (arXiv: 2111.14184)


Jaydeep Datta[1, 2, 4], Bana Singh[3, 5], S. Uma Sankar[3]

1. Homi Bhabha National Institute, Mumbai, India; 2. Saha Institute of Nuclear Physics, Kolkata, India; 3. Indian Institute of Technology, Bombay, Mumbai, India; 4.Université Libre de Bruxelles, Bruxelles, Belgium (Present address); 5. Indian Institute of Science Education and Research, Mohali, India (Present address)


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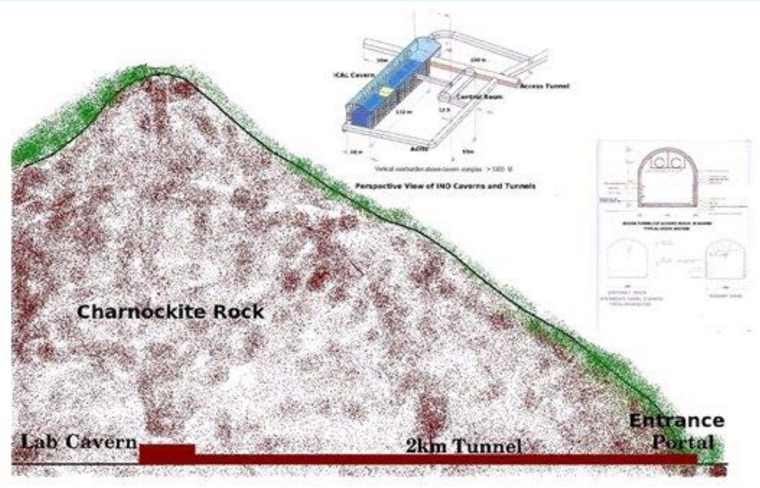
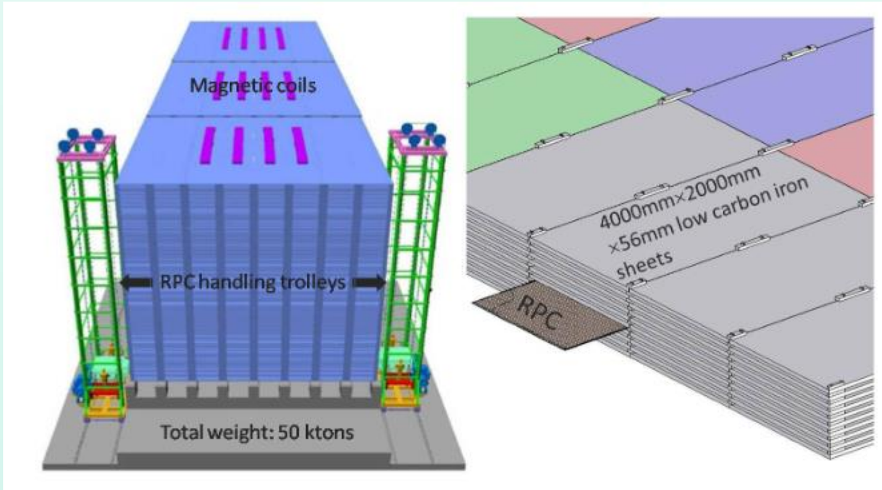
## ICAL @ INO



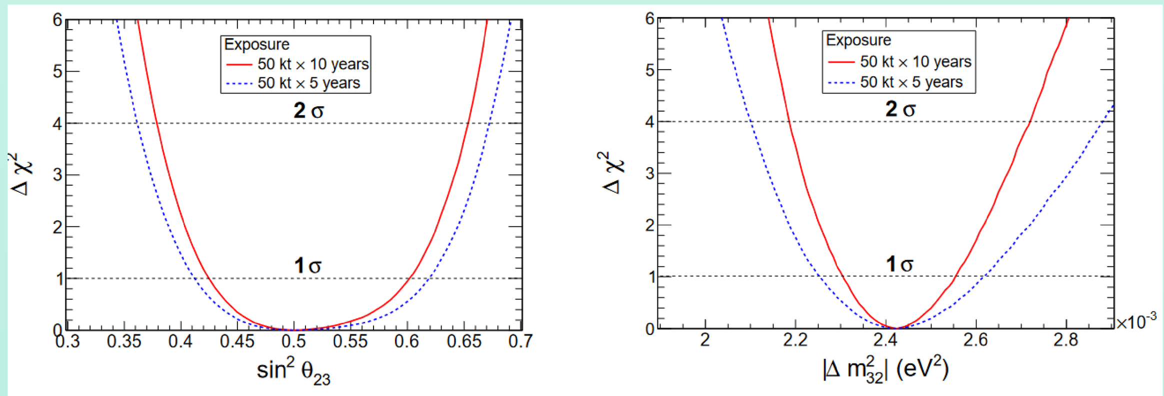

India-based Neutrino Observatory (INO) [1], an underground neutrino research facility.



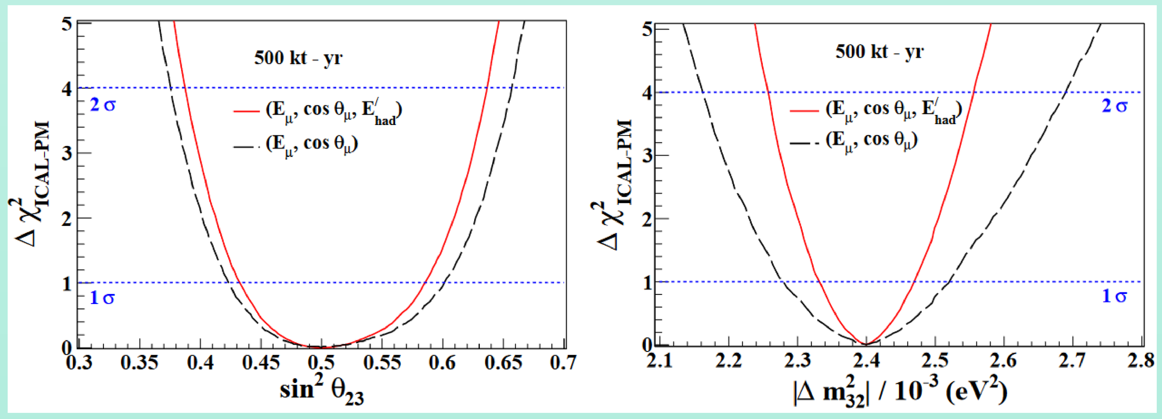

The ICAL detector

The ICAL detector will be
- A 50 kilo-ton magnetized iron calorimeter.
- Nearly 30000 Resistive Plate Chambers (RPCs) as its active detector component.
- Have the unique capability to measure the zenith angle dependence of atmospheric neutrino and anti-neutrino flux.

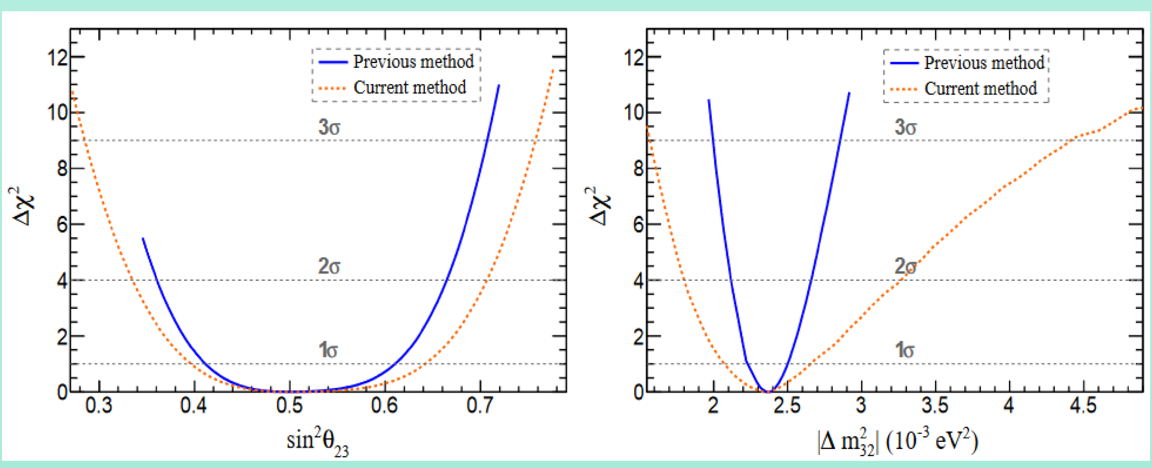
## Motivation & scope of work



Initial studies [2] to estimate INO reach to oscillation parameters was carried out using smeared MC data and only muon kinematical variables.



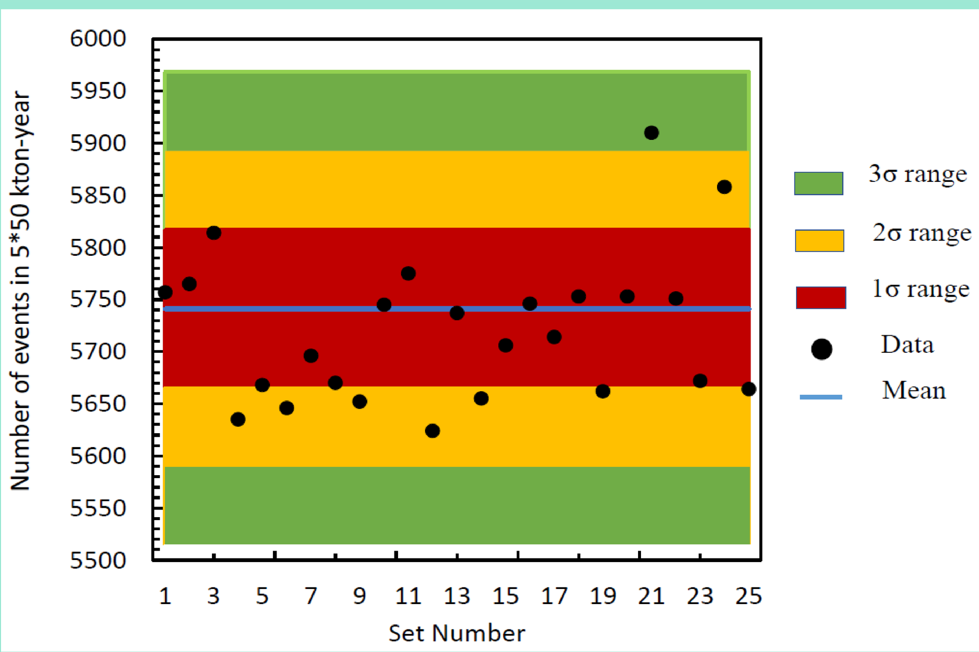
Later [3] showed that inclusion of hadron information along with muon kinematical variables improves the precision.



In recent work [4], Rebin et al. used the complete reconstruction software of ICAL to find its reach without using the hadron information.

**This work**
- **Uses event by event reconstruction output**
- **Incorporates statistical fluctuation**
- **Includes hadron information**

## Methodology




Fluctuation observed in the 5 year data set

- Generated 50 *500 kton-years un-oscillated atmospheric neutrino data using Kamioka flux and NUANCE event generator
- GEANT4 based detector simulation software
- C++ based reconstruction code used to reconstruct event by event
- Only $\nu_\mu/\overline{\nu_\mu}$ CC events with at least one reconstructed track

- The whole data set divided in two parts, five years and 495 years.
- The 5-year event set is oscillated using the input oscillation parameters $\sin^2\theta_{23}$ = 0.5 and $|\Delta m^2_{31}|$ = 2.32 * $10^{-3}$ eV$^2$, denoted data
- The 495-year event set oscillated using $|\Delta m^2_{31}|$ = [0.9, 5.1] * $10^{-3}$ eV$^2$, $\sin^2\theta_{23}$ = [0,1] denoted theory.
- Other oscillation parameters fixed at global best fit values [6].

## References


1. "Physics potential of the ICAL detector at the India-based Neutrino Observatory (INO)" A. Kumar et al, *Pramana - J Phys* 88, 79 (2017)
2. "The Reach of INO for Atmospheric Neutrino Oscillation Parameters", T. Thakore et al. JHEP, (58) 2013.
3. "Enhancing sensitivity to neutrino parameters at INO combining muon and hadron information", M. Devi et al. JHEP, (189) 2014
4. "Study of neutrino oscillation parameters at the INO-ICAL detector using event-by-event reconstruction", Rebin et al. EPJC (295) 2019
5. "Neutrino oscillation parameter determination at INO-ICAL using track and non-track hit information from GEANT", J. Datta et al. arXiv: 2111.14184
6. "Global analysis of three-flavour neutrino oscillations: synergies and tensions in the determination of $\theta_{23}$, $\delta_{CP}$, and the mass ordering" I. Esteban et al. JHEP (106) 2019


## Acknowledgement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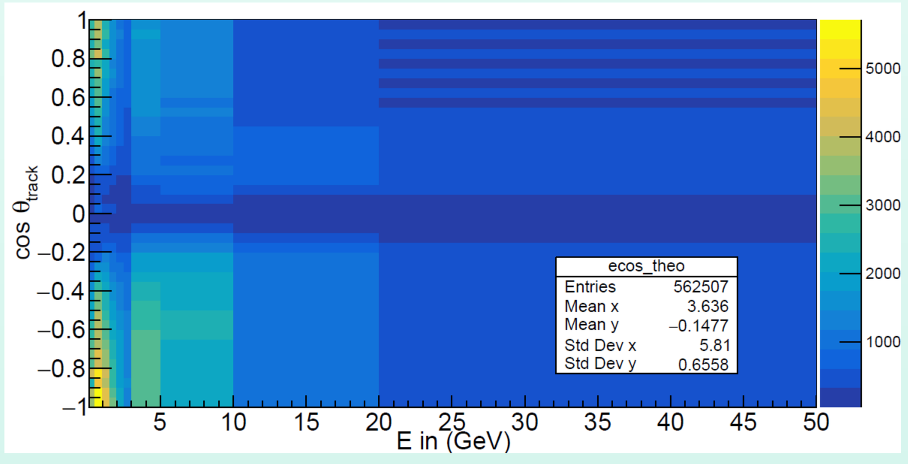
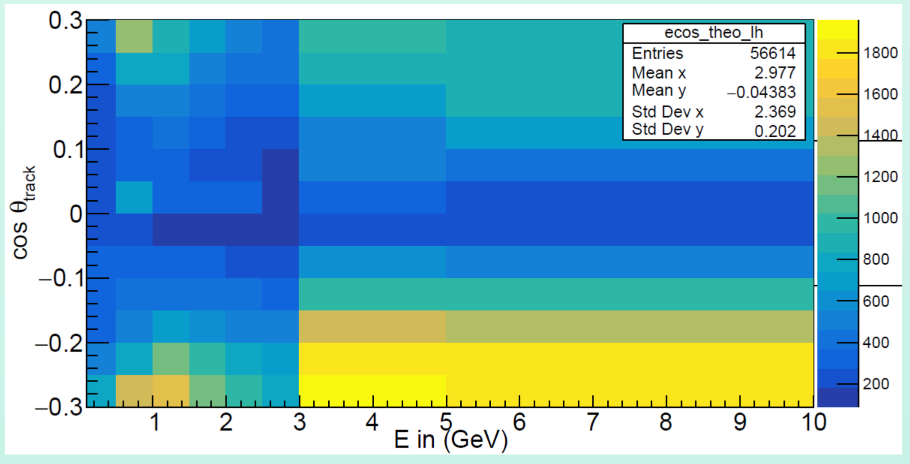
## Analysis methods and variables



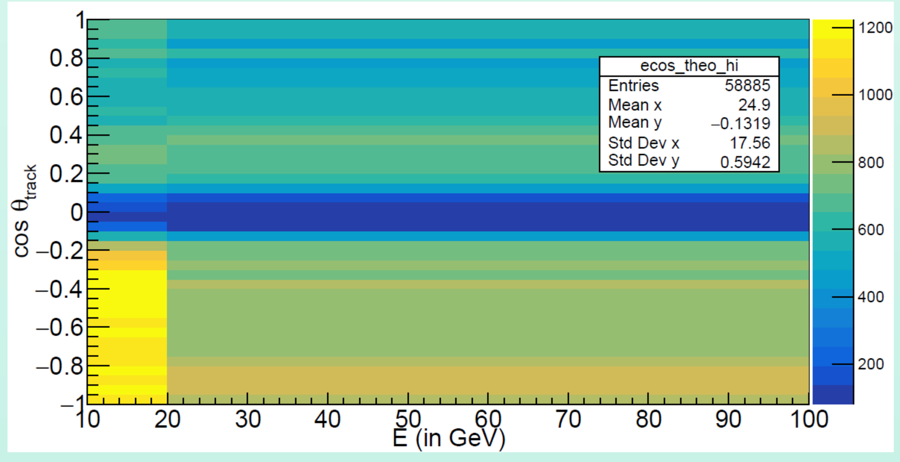
Event spectra for 2 variable analysis method.

- For 2-variable analysis, events binned in E and $cos\theta_{track}$, the energy and direction of the longest reconstructed track.
- For 3-variable analysis, variables are

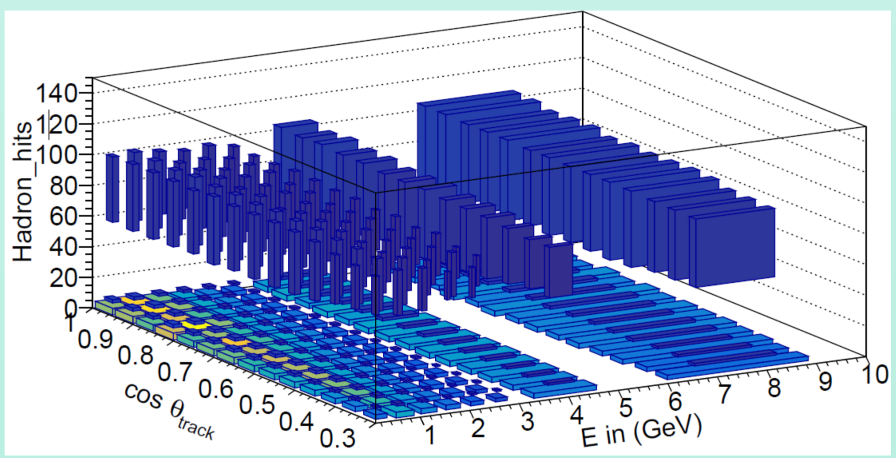
a) E = |Track momenta| for single track event
b) E = $\sum|Track\ momenta|$ for multi-track events
c) $cos\theta_{track}$ = Direction of the longest track
d) The number of hadron hits binned in (0,4), (5,10), (>10)



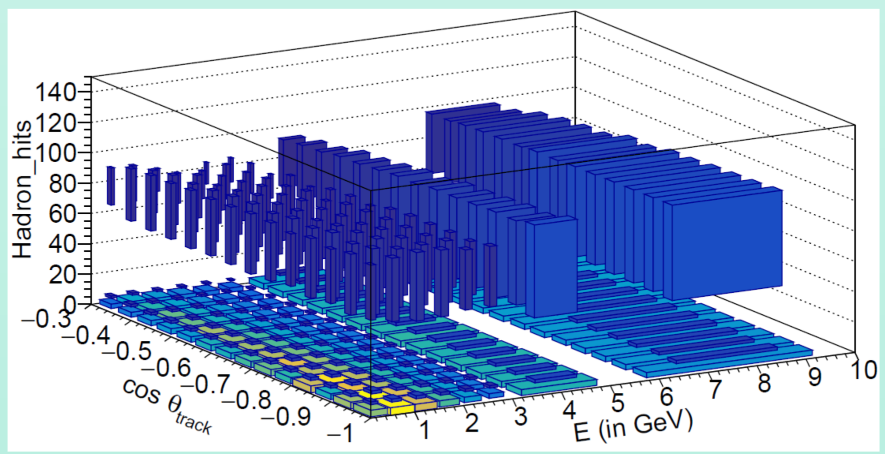
Low energy, horizontal events with E > 10 GeV and $|cos\theta_{track}|$< 0.3



High energy, vertical and horizontal events with E > 10 GeV

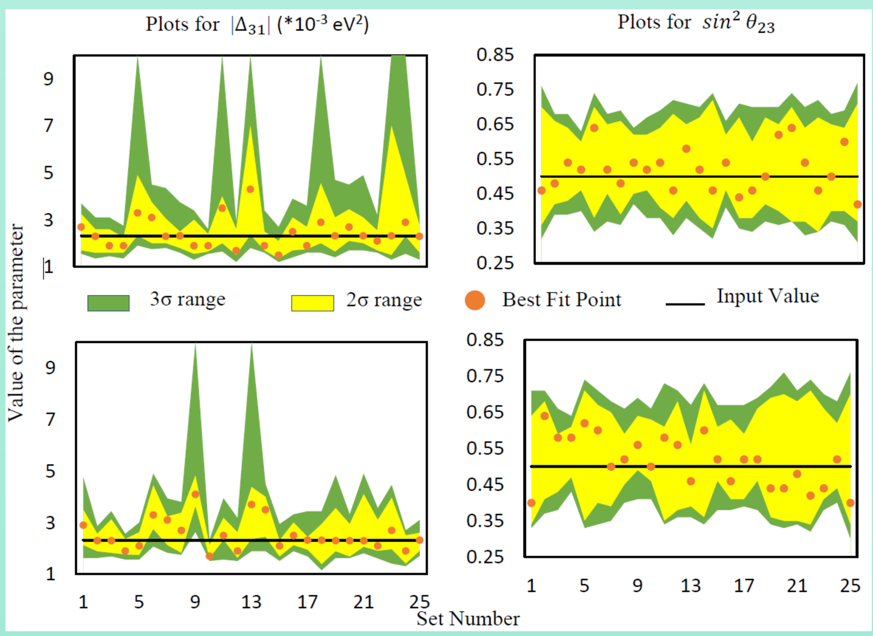


Low energy, upward going events with E<10 GeV and $cos\theta_{track}$>0.3

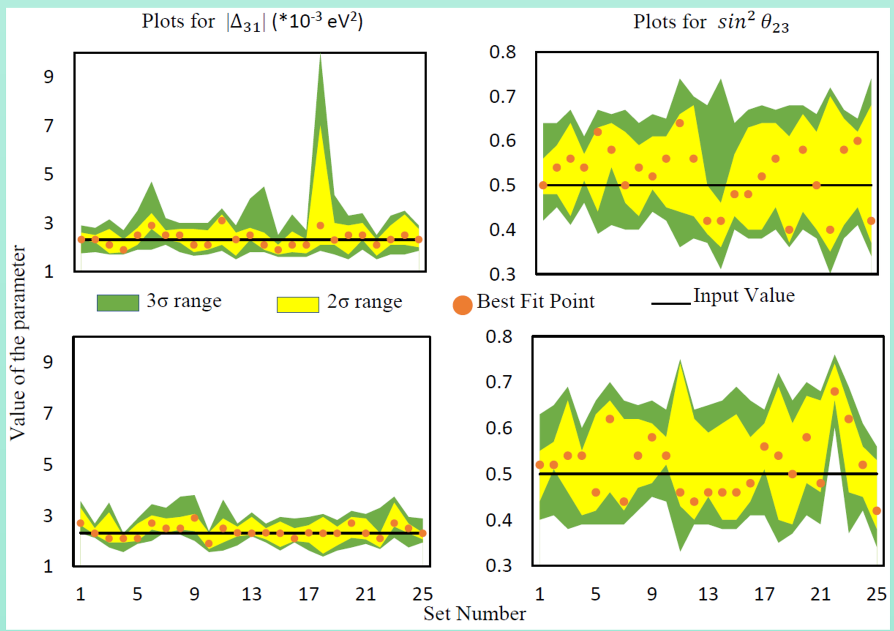


Low energy, downward going events with E < 10 GeV and $cos\theta_{track}$ < 0.3

## Results and conclusions



Results for 5-year exposure time [5]. Top: 2-variable, Bottom: 3-variable



Results for 10-year exposure time [5]. Top: 2-variable, Bottom: 3-variable

| Analysis Method | $\sin^2\theta_{23}$ | | | $\|\Delta_{31}\|$ ($*10^{-3}$ eV$^2$ ) | | |
|---|---|---|---|---|---|---|
| | Best fit point | 2σ range | 3σ range | Best fit point | 2σ range | 3σ range |
| 2-variable, 5 years | 0.52 | 0.26 (0.40-0.66) | 0.34 (0.36-0.70) | 2.43 | 1.63 (1.80-3.43) | 3.60 (1.53-5.13) |
| 2-variable, 10 years | 0.52 | 0.19 (0.43-0.62) | 0.28 (0.39-0.67) | 2.35 | 0.91 (2.01-2.92) | 1.80 (1.74-3.54) |
| 3-variable, 5 years | 0.51 | 0.25 (0.40-0.65) | 0.34 (0.36-0.70) | 2.53 | 1.20 (1.99-3.19) | 2.46 (1.67-4.13) |
| 3-variable, 10 years | 0.52 | 0.17 (0.45-0.62) | 0.26 (0.40-0.66) | 2.33 | 0.68 (2.09-2.77) | 1.22 (1.86-3.08) |
| Rebin et. al. | 0.496 | 0.38 (0.34-0.72) | 0.48 (0.29-0.77) | 2.32 | 2.03 (1.68-3.71) | 4.07 (1.40-5.47) |

**Table 1:** Comparison between different analysis methods

| Analysis Method | $\sin^2\theta_{23}$ | | | $\|\Delta_{31}\|$ ($*10^{-3}$ eV$^2$ ) | | |
|---|---|---|---|---|---|---|
| | Best fit point | 2σ range | 3σ range | Best fit point | 2σ range | 3σ range |
| Without Charge ID | 0.52 | 0.26 (0.40-0.66) | 0.34 (0.36-0.70) | 2.43 | 1.63 (1.80-3.43) | 3.60 (1.53-5.13) |
| With Charge ID | 0.54 | 0.24 (0.42-0.66) | 0.33 (0.37-0.70) | 2.56 | 1.29 (1.93-3.22) | 3.06 (1.63-4.69) |

**Table 2:** Comparison of result for analysis methods including charge ID and without charge ID.

- The 2σ and 3σ ranges of $|\Delta m^2_{31}|$ from the 3-variable analysis improves by a factor of 1.5 compared to the 2-variable analysis.
- No such improvement was noticed for the $\sin^2\theta_{23}$.
- The finer bin size of $cos\theta_{track}$ in our analysis improved the precision in $|\Delta m^2_{31}|$ measurement than the reported result in [4].
- Increase in exposure time improves the results.
- The charge ID capability of ICAL has negligible effect on improving precision.