Tau Neutrino Studies at ICAL Detector in INO

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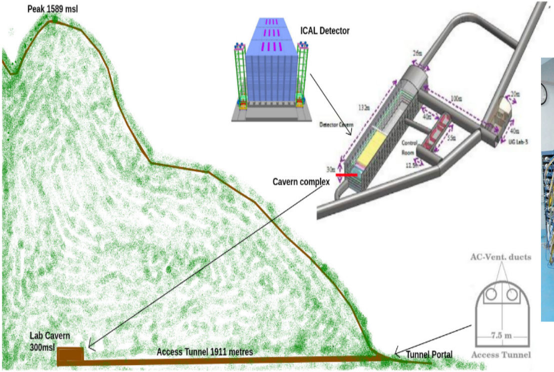
Outline

1. ν_τ events at INO
2. Generation of CC-tau and NC events in ICAL
3. Numerical analysis and physics reach
   - Best fit approach
   - Sensitivity to the presence of tau events
   - Sensitivity to the oscillation parameters
4. Combined study of tau events and standard muon events
5. Conclusion

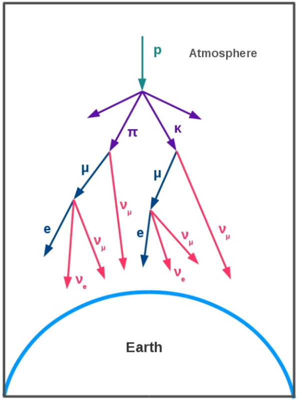
Iron Calorimeter Detector (ICAL) at India-based Neutrino Observatory (INO) and miniICAL Detector



Schematic of mountain showing horizontal tunnel, its cross sectional view, caverns and ICAL

Atmospheric neutrino flux

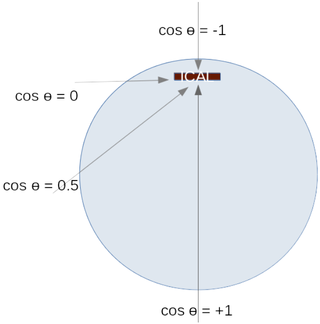
- Atmospheric neutrinos are produced from the primary and secondary interactions of cosmic rays with Earth's atmosphere.
- The ratio of ν_e:ν_μ:ν_τ in atmospheric neutrinos is approximately $1 : 2 : \sim 10^{-5}$ in the few GeV energy range.

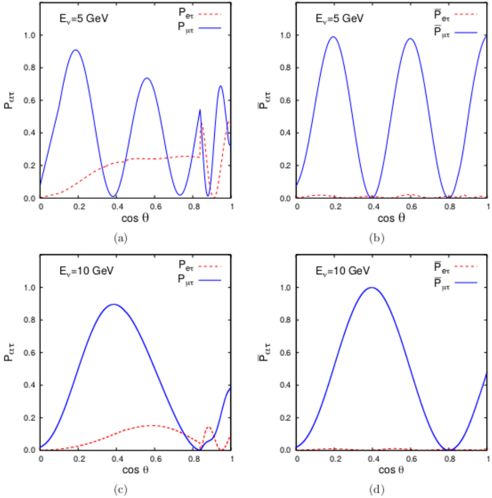


Atmospheric ν_τ

- When these atmospheric neutrinos pass through the Earth to reach the detector, neutrino flavour oscillations occur, and the flavor ratio is closer to $1:1:1$ in few 10s of GeV energy range.
- The atmospheric neutrino fluxes contain a significant fraction of ν_τ in the upward direction.

Atmospheric ν_τ - Oscillation probabilities





Interaction of ν_τ with ICAL

ν_τ interacting via charged current (CC) with the nucleons in the detector produces charged τ leptons and hadrons (X) via

$$\nu_\tau N \to \tau^- X \; ; \qquad \overline{\nu}_\tau N \to \tau^+ X \; ,$$

The τ leptons will decay promptly, primarily into hadrons (H).

$$\begin{aligned} \tau^- &\to e^- \bar{\nu}_e \nu_\tau & \sim \quad & 17\% \; , \\ \tau^- &\to \mu^- \bar{\nu}_\mu \nu_\tau & \sim \quad & 17\% \; , \\ \tau^- &\to \nu_\tau H & \sim \quad & 66\% \; , \end{aligned}$$

(and similar fractions for τ^+ as well).

Hence, the total hadron energy from CC: ($X + H$).

Neutral current background

Neutral Current (NC) interactions from all flavours of neutrinos and antineutrinos also produce hadrons (X')

$$\nu_i N \to \nu_i X' \ , \ \overline{\nu}_i N \to \overline{\nu}_i X' \ ; \quad i = e, \mu, \tau \ .$$

- Hadrons $(X + H)$ from CC interactions of ν_τ and hadrons (X') from NC interactions of all neutrino flavours, cannot be separated.
- Therefore, the NC events act as an inseparable background to the CC-tau events.
- Hence, we study the combined sample of all NC and CC-tau events.

Generation of CC-tau and NC events in ICAL

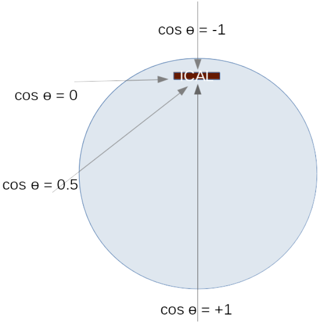
- We use NUANCE event generator.
- We generate "Unoscillated" CC-tau events (assuming ν_μ and ν_e atmospheric fluxes and the CC-tau cross sections) excluding the oscillation probability.
- These unoscillated events are weighted with the oscillation probability during "data" generation and analysis.
  - We use PMNS mixing matrix and PREM profile for matter distribution inside the Earth during the probability calculation.
  - We assume normal mass ordering and performed the analysis for 10 years.
- Similarly NC events are generated using same atmospheric neutrino fluxes and NC cross sections.

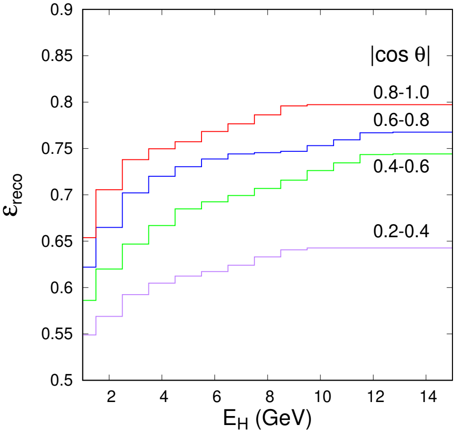
Neutrino oscillation parameters and their 3σ range used

Parameter	Value	3σ Range
$\sin^2\theta_{12}$	0.304	fixed
$\sin^2\theta_{13}$	.0222	$.0203 \leftrightarrow .0241$
$\sin^2\theta_{23}$	0.5	$.381 \leftrightarrow .615$
$\Delta m^2_{21}(\times 10^{-5} eV^2)$	7.42	fixed
$\Delta m^2 \times 10^{-3} eV^2)$	2.47	$2.395 \leftrightarrow 2.564$
$\delta_{CP}(^\circ)$	0.0	fixed

Table: 3σ ranges of neutrino oscillation parameters. $\Delta m^2 \equiv m_3^2 - \left(m_2^2 + m_1^2\right)/2$.

Reconstruction efficiency of hadrons





Pull method

$$\chi^2 = \min_{\xi_k} \sum_{i=1}^{N_E} \sum_{j=1}^{N_{cos\theta}} 2\left(\left(T^{ij} - D^{ij}\right) - D^{ij} \ln\left(\frac{T^{ij}}{D^{ij}}\right)\right) + \sum_{k=1}^{N_k} \xi_k^2$$

- $D^{ij} = [D^{ij}_{\tau,+} + D^{ij}_{\tau,-} + D^{ij}_{NC,+} + D^{ij}_{NC,-}]$: CC-tau + NC events.
- T^{ij} is No. of predicted theory events (generated using a various set of oscillation parameters).

$$\begin{aligned} T^{ij} &= T^{ij}_{+} + T^{ij}_{-} \ , \\ \text{where } T^{ij}_{\pm} &= T^{ij,0}_{\pm}\left(1 + \sum_{k=1}^{N_k} \pi^{ij}_{k,\pm}\xi_{k,\pm}\right) \end{aligned} \quad (1)$$

$T^{ij,0}_{\pm}$ are events without systematic errors

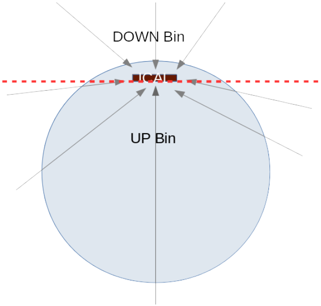
- $\xi_k^2 \equiv \xi_{k,-}^2 + \xi_{k,+}^2$ includes the penalty from each pull parameter for neutrino and anti-neutrino events.

Systematic uncertainities

Pull (π)	Description	Error
π_{tilt}	Tilt error	5%
π_{zenith}	Zenith angle dependence	5%
π_{norm}	Flux normalization	20%
π_{σ}	Cross section	10%
π_{D}	Detector response	5%

Hardron energy bins and Zenith angle bins

Bin	Energy (GeV)	Bin width (GeV)
1	1–3	2
2	3–6	3
3	6–9	3
4	9–13	4
5	13–18	5
6	18–25	7
7	25–35	10
8	35–50	15



Measure of sensitivity - $\Delta\chi^2$

$$\Delta\chi^2 = \chi^2(\text{input}) - \chi^2(\text{par}) \ , \tag{2}$$

- χ^2(input) is the minimum χ^2 obtained when the theory events are calculated with the same value of the parameter as its input value.
- χ^2(par) is the minimum χ^2 obtained when a different theory value of the parameter is used.

Program to invert large matrices

- As part of systematics calculation, we have developed a program 'Invertor' for fast invertion large matrices.
- It is general purpose program written in C to calculate inversion of matrices analytically.
- As example, inversion of matrices of order 100, 1000 are computed in 6ms and 5.24s respectively in Intel i7 6700 CPU, 8GB RAM machine (Common modern computer).

Sensitivity to the presence of ν_τ

Presence of CC tau events over NC background

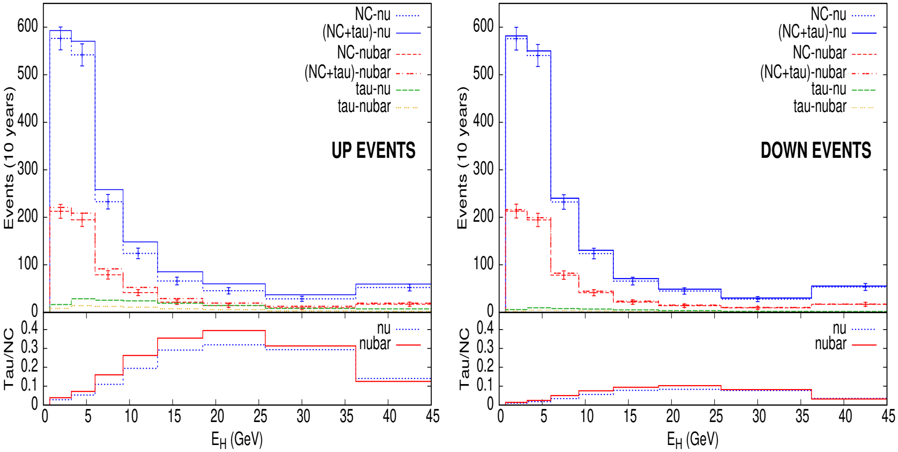


Figure: NC and CC-tau events in reconstructed E_{hadron} bins and the ratio of the CC tau events to the NC events.

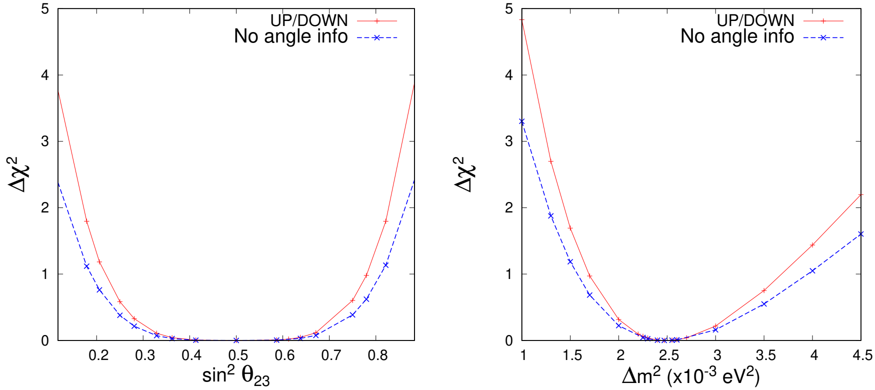
Sensitivity to the presence of tau events

Angular Bins	Including Systematics	$\Delta\chi^2$	$\sigma = \sqrt{\Delta\chi^2}$
2	No	35.34	5.95
2	Yes	13.06	3.61
2	Yes* (0.7)	14.95	3.87
2	Yes* (0.5)	16.46	4.06
1	No	27.50	5.24
1	Yes	7.90	2.81

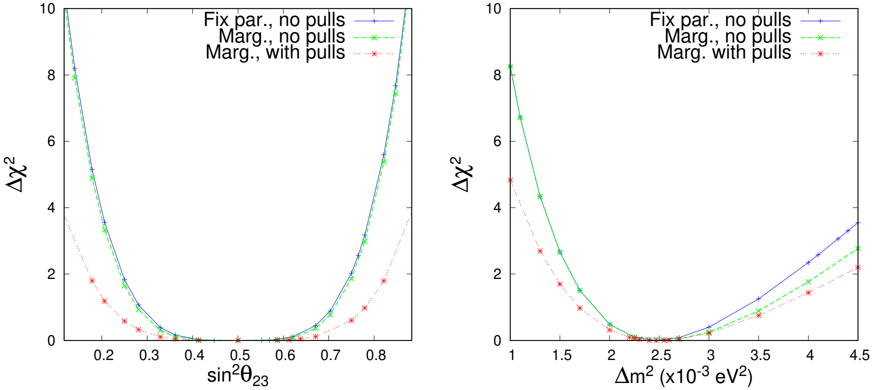
(* The effects of a reduction in tilt and zenith angle uncertainties to 70% and 50%)

Sensitivity of ν_τ events to the oscillation parameters θ_{23} and Δm^2

Effect of zenith angle bins

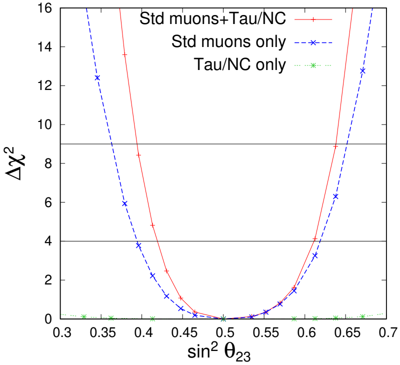


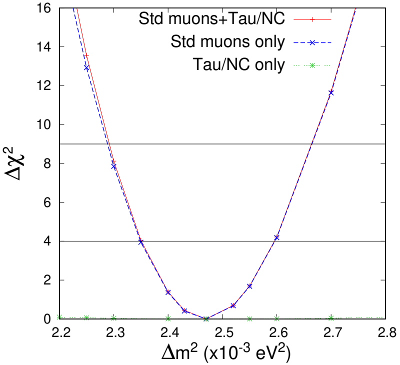
Sensitivity of ν_τ events to $\sin^2\theta_{23}$ and Δm^2



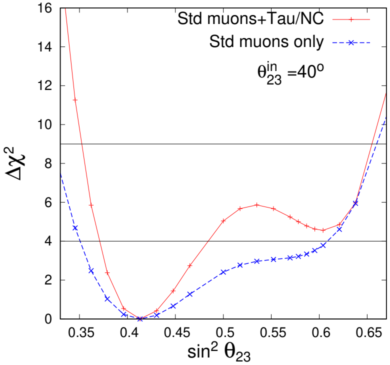
Combined analysis of standard muon events and tau events

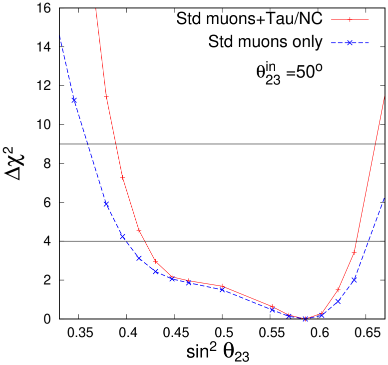
Sensitivity to oscillation parameters in combined analysis





Sensitivity to the octant of $\sin^2\theta_{23}$ in combined analysis





Conclusion

- The presence of ν_τ events at the ICAL detector in INO is closer to 4σ for 10 years period with systematics.
- ν_τ events have sensitivity to the oscillation parameter θ_{23} and $|\Delta m^2|$.
- Combined analysis of ν_μ and ν_τ events improves the precision measurement of $\sin^2\theta_{23}$ and its *octant* significantly and Δm^2 moderately.

For further reading: arXiv:2203.09863 [hep-ph]
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THANK YOU