Probing Light Sterile Neutrino at INO-ICAL over a wide Δm^2 range

[1]Tarak Thakore, [2]Moon Moon Devi, [3]Sanjib Kumar Agarwalla, [4]**Amol Dighe**
For the INO Collaboration
[1]IFIC (UV-CSIC), Spain; [2]TEZU, India; [3]IOP, India; [4]TIFR, India
[4]amol@theory.tifr.res.in

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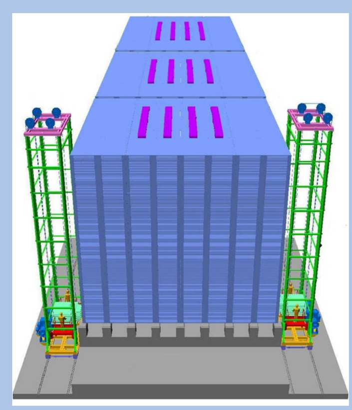
India-based Neutrino Observatory (INO)

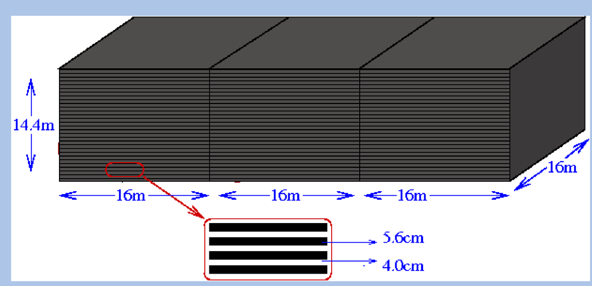
The INO underground facility will host a 50 kt magnetized **Iron CALorimeter (ICAL)** detector to study atmospheric neutrino oscillations.

- Proposed to be located in the Bodi West Hills in the South India.
- ~1 km rock cover in all directions to shield from cosmic muon background
- Primary goals : Identification of the neutrino mass ordering, precision measurements of atmospheric parameters, probes of non-standard physics like sterile neutrino, dark matter, magnetic monopoles, CPT violation, Non-Standard Interactions

The ICAL Detector



- 151 layers of 5.6 cm iron plates (interaction target) alternative with 150 layers of resistive plate chambers (RPCs, active detector elements)
- ~1.3 Tesla magnetic field to enable muon charge identification (distinguish ν from ν̄).
- Optimized to detect O(1-10) GeV muons with good energy, direction resolutions
- Energy of hadron showers may be reconstructed, albeit with a coarse resolution
- Oscillation physics sensitivity primarily from the ν_μ disappearance channel.



INO-ICAL White Paper : arXiv:1505.07380
Pramana 88 (2017) 79

Sterile Neutrinos

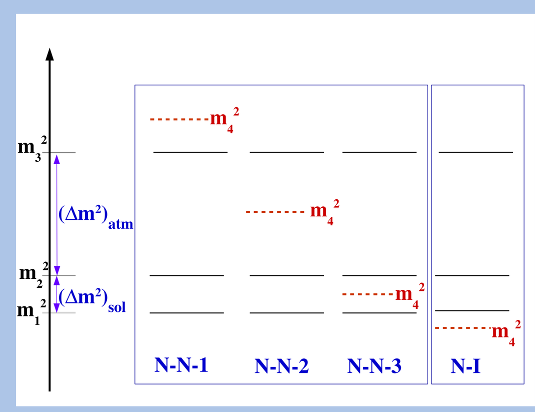
Mixing matrix with 4 neutrinos

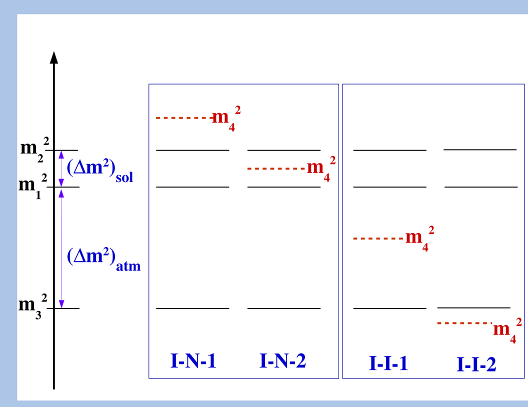
$$U \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} .$$

We expect

$$|U_{e4}|^2, |U_{\mu4}|^2, |U_{\tau4}|^2 \ll 1; |U_{s4}|^2 \approx 1.$$

Possible 4ν Mass Ordering configurations





Matter effects inside the Earth's important for active-sterile neutrino oscillation probabilities. Effective matter potentials:

$$V_{es} = \sqrt{2}G_F(N_e - N_n/2) \quad \text{between } \nu_e \text{ and } \nu_s ,$$
$$V_{\mu s} = V_{\tau s} = -\sqrt{2}G_F N_n/2 \quad \text{between } \nu_{\mu/\tau} \text{ and } \nu_s$$

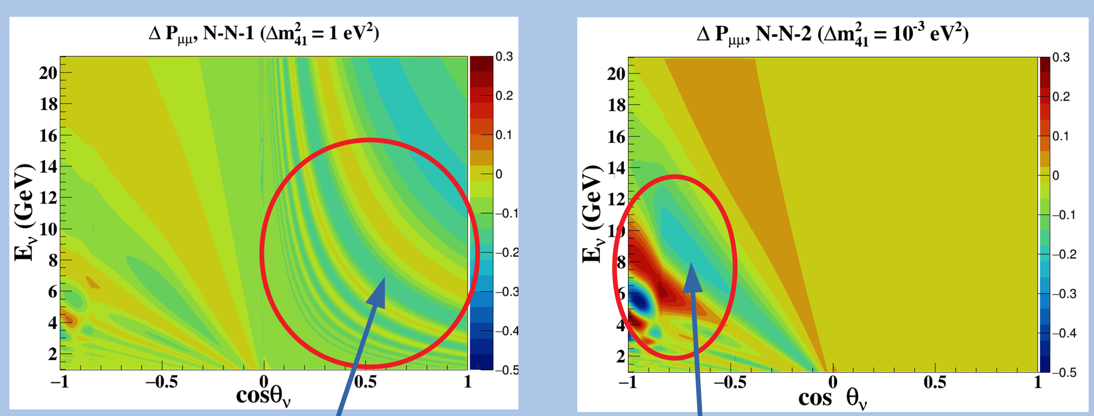
Our analysis spans a wide range,

$$10^{-5}\text{eV}^2 \le \Delta m^2_{41} \le 10^2\text{eV}^2.$$

Expect significant matter effects and interference effects for $|\Delta m^2_{41}| \sim |\Delta m^2_{31}|$, since for typical atmospheric neutrino energies, one has $|V_{es}| \sim |V_{\mu s}| \sim |\Delta m_{31}{}^2| / (2E_\nu)$.

Oscillograms for the $\nu_\mu \to \nu_\mu$ Channel

$$\Delta P_{\mu\mu} \equiv P_{\mu\mu}\ (4f) - P_{\mu\mu}\ (3f)$$

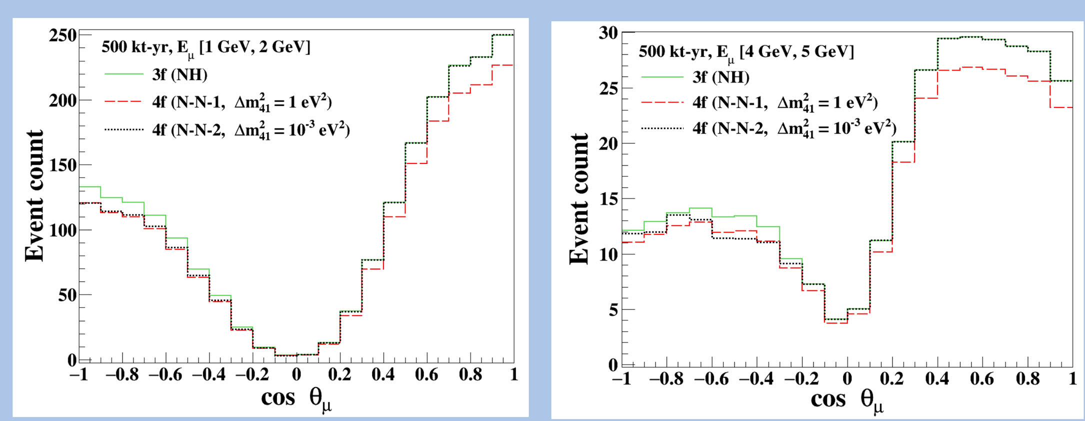


Fast oscillations, would be averaged out by finite detector resolutions

These features can be resolved by ICAL, leading to an enhanced sensitivity

Zenith Angle Distribution of Events

Suppression of muon event counts

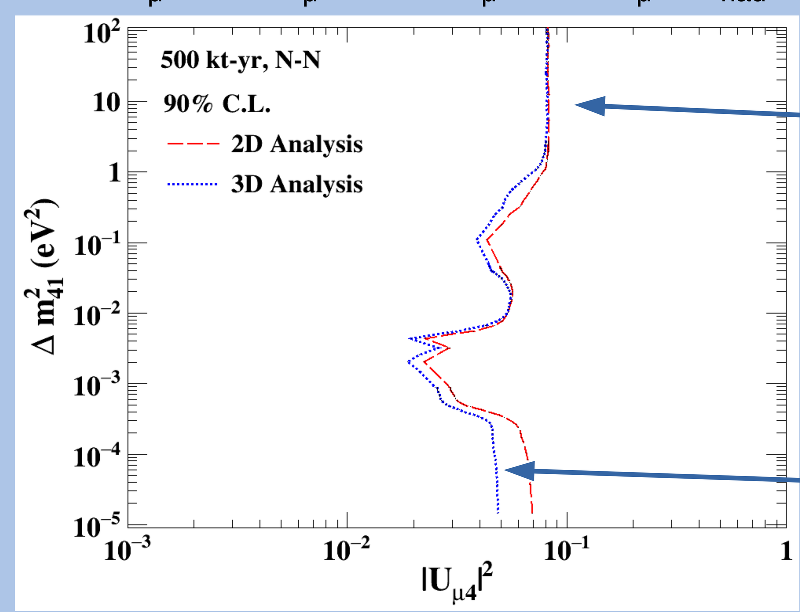


N-N-1 : Suppression of muon events for all zenith angles
N-N-2 : Non-trivial dependence of suppression on zenith angle

Benchmark Values: $|U_{e4}|^2 = 0.025, |U_{\mu4}|^2 = 0.05$

Importance of Hadron Energy Information

2D (E_μ, cos θ_μ), 3D (E_μ, cos θ_μ, E'_{had})

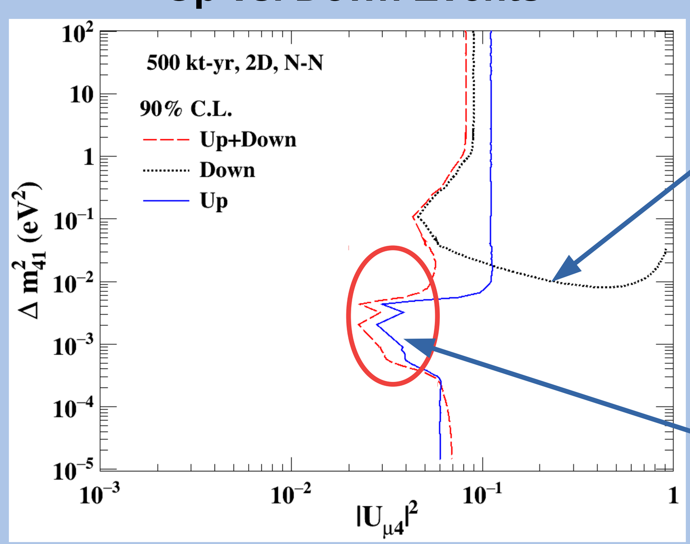


Information is mainly in the number of events, so E'_{had} not very useful

Information in the energy and angular spectra, so E'_{had} crucial

Factors affecting $|U_{\mu4}|^2$ Sensitivity

Up vs. Down Events



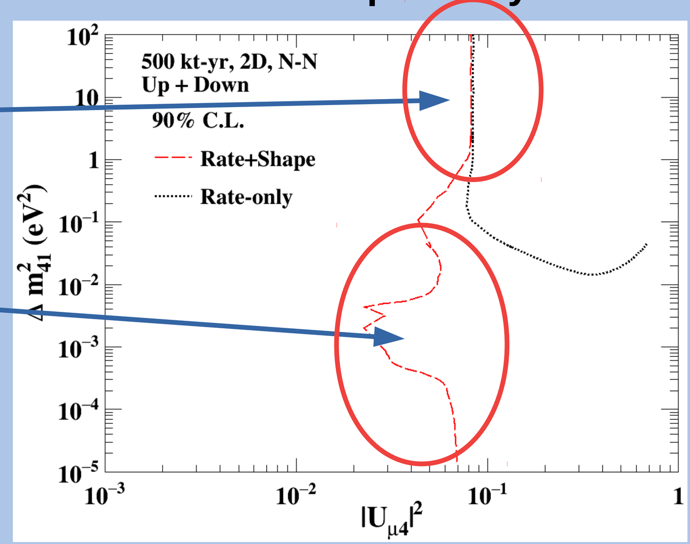
For $\Delta m^2_{41} < 10^{-2}$ eV², down-going neutrinos do not travel long enough for oscillations to develop.

$\Delta\tilde{m}^2_{41} \sim \Delta\tilde{m}^2_{31}$: Features due to the interference between these two frequencies

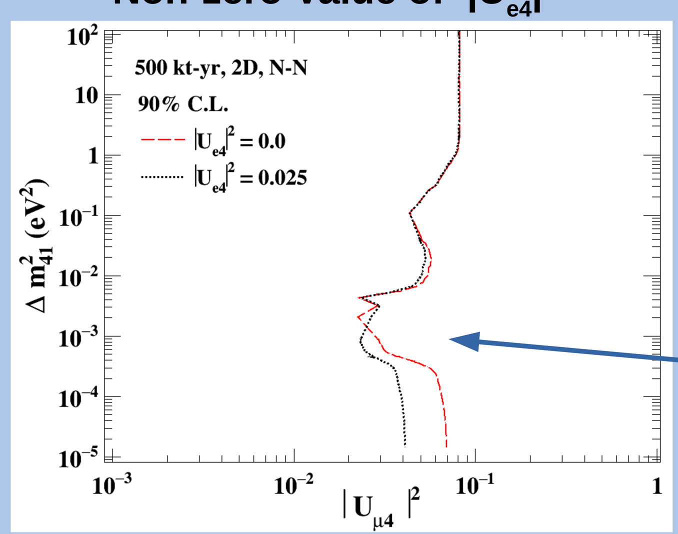
Rate vs. Shape Analysis

Only the averaged oscillation effects observable for $\Delta m^2_{41} \sim 1$ eV²

The muon energy and direction resolutions in ICAL enhance the sensitivity in this Δm^2_{41} regime.



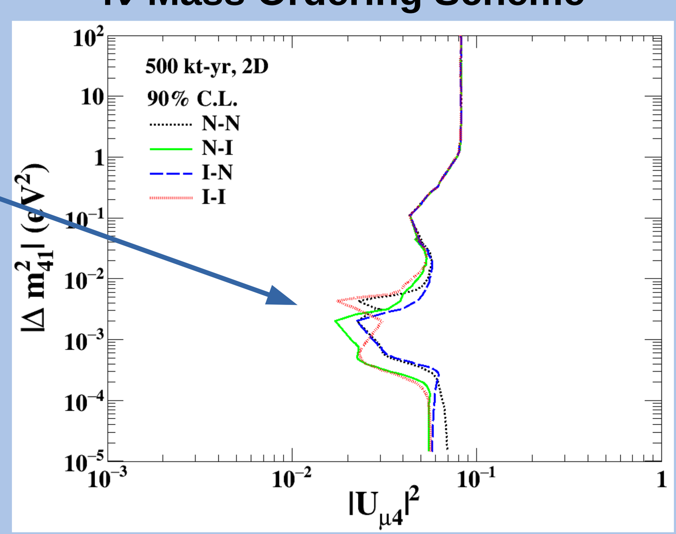
Non-zero Value of $|U_{e4}|^2$



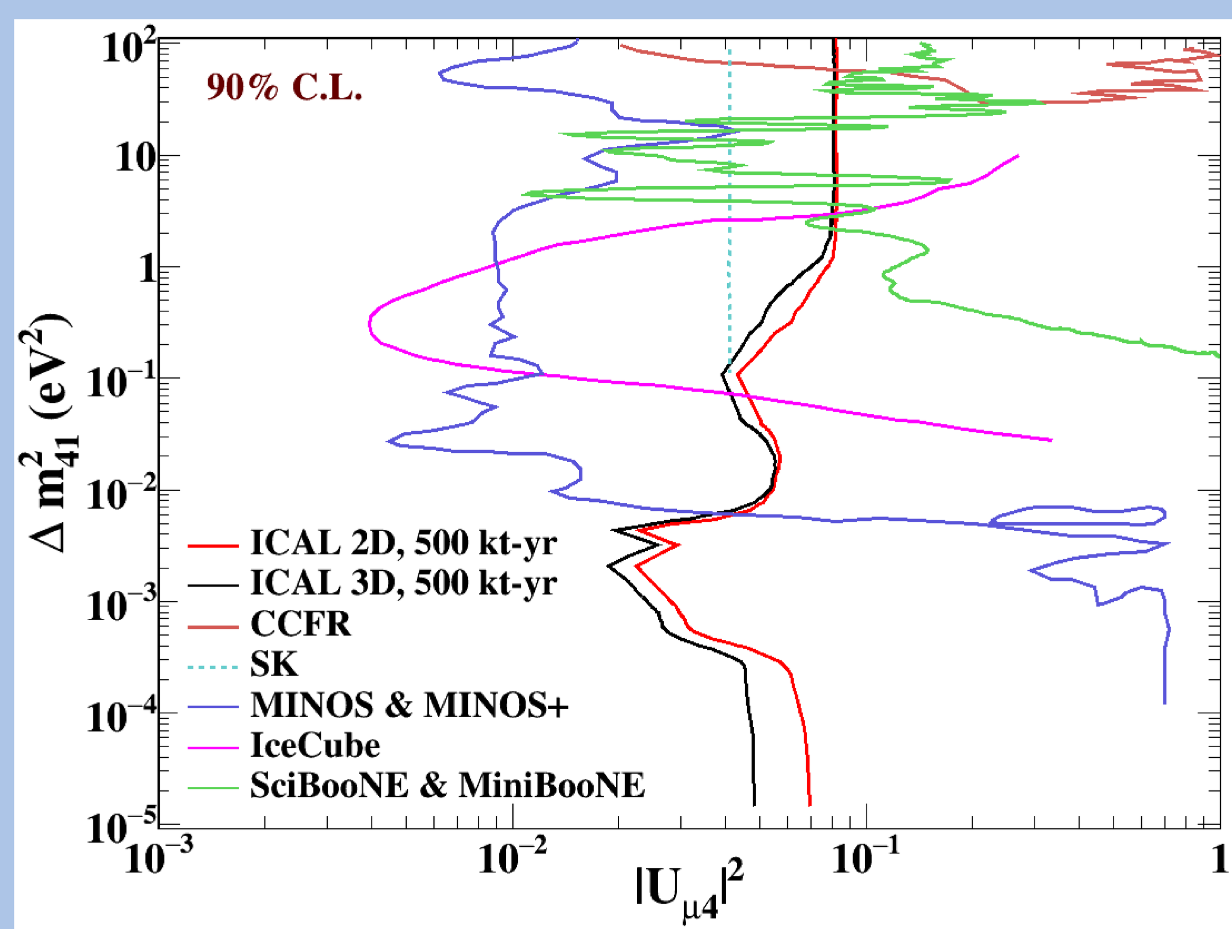
The most conservative sensitivity estimate on $|U_{\mu4}|^2$ are those with $|U_{e4}|^2 = 0$.

4ν Mass Ordering Scheme

The sensitivity to $|U_{\mu4}|^2$ depends only mildly on the 4ν mass ordering scheme.



Comparison of the ICAL $|U_{\mu4}|^2$ Sensitivity with Current Limits

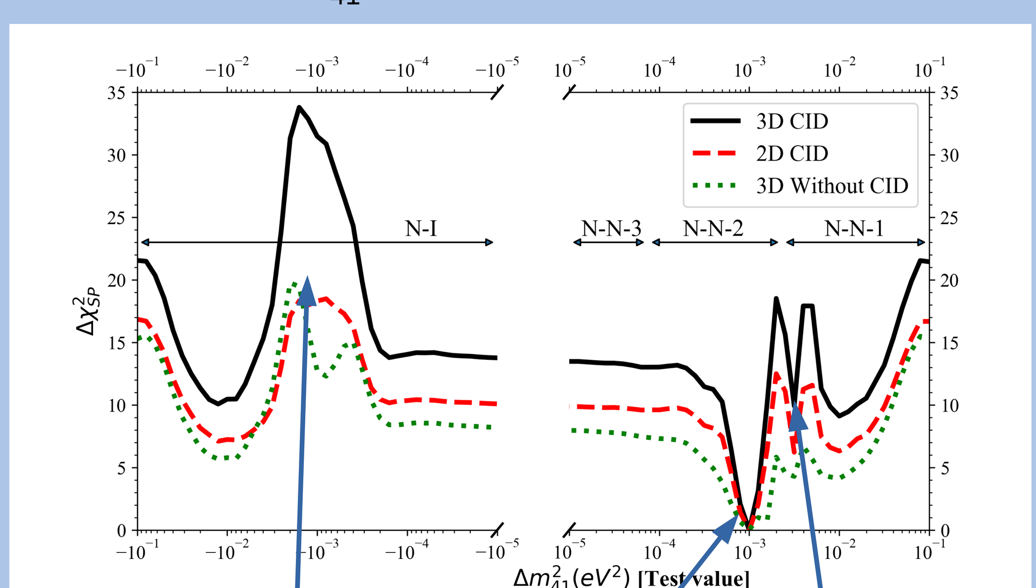


ICAL can improve upon the current limits on $|U_{\mu4}|^2$ for $\Delta m^2_{41} \sim 10^{-3}$ eV² and all the way down to 10^{-5} eV².

Determining magnitude and sign of Δm^2_{41} (if sterile neutrinos exist)

Precision measurement of $|\Delta m^2_{41}|$

Δm^2_{41} (true) = +10⁻³ eV² (N-N-2)



Exposure: 500 kt-year

Strongly disfavored due to the (absence of) MSW resonance

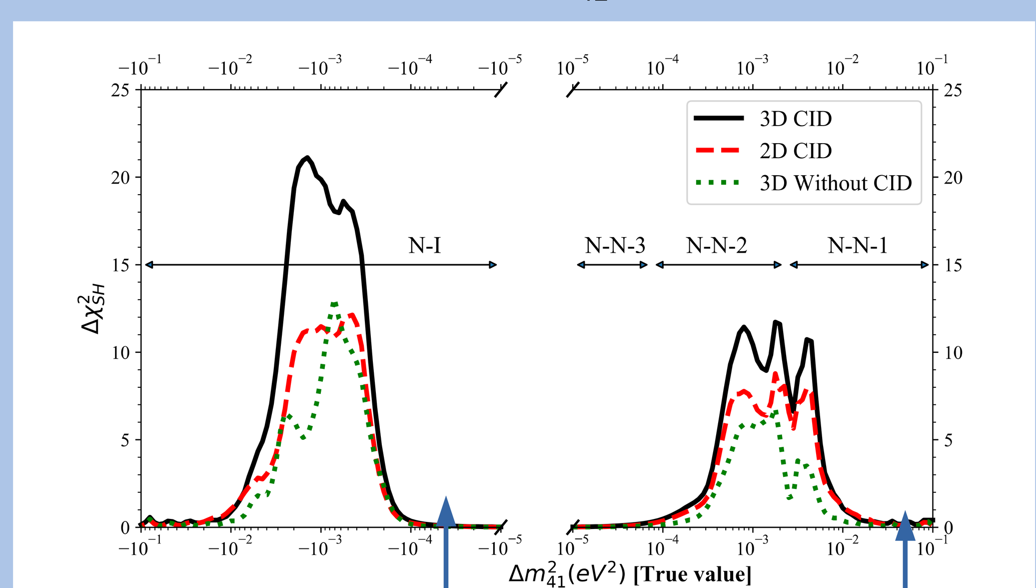
True Value

Interference effect between $\Delta\tilde{m}^2_{41} \sim \Delta\tilde{m}^2_{31}$

- **When the true scenario is N-N-2 it is possible to rule out N-N-1,N-N-3 and N-I.**

Sign of Δm^2_{41}

Marginalized over all Δm^2_{41} of the wrong sign



Too small $|\Delta m^2_{41}|$

Negligible matter effects

- **Sensitivity to sign of Δm^2_{41} for $|\Delta m^2_{41}|$ in (0.5 – 5) x10⁻³ eV²**
- **Hadron energy information (3D analysis) and charge identification (CID) crucial**

Benchmark values : best fits for 3ν parmeters, $\Delta m^2_{31} > 0, |U_{e4}|^2 = 0.025, |U_{\mu4}|^2 = 0.05, |U_{\tau4}|^2 = 0.00$, vanishing CP phases

Concluding Remarks

- ICAL (and atmospheric neturino experiments in general) sensitive to a wide range of Δm^2_{41}, even as low as 10^{-5} eV².
- ICAL sensitivity to the magnitude and sign of Δm^2_{41} is maximum in the range (0.5 – 5) x 10⁻³ eV²
- Spectral information (zenith angle distribution), hadron energy information(3D analysis) and charge identification (CID) crucial