Neutrino Experiments—The India-based Neutrino Observatory

D. Indumathi

The Institute of Mathematical Sciences, Chennai

indu@imsc.res.in

Anomalies 2021, Hyderabad (virtual talk)

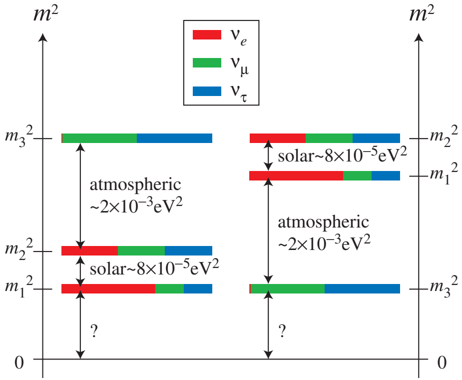
November 11, 2021

Overview

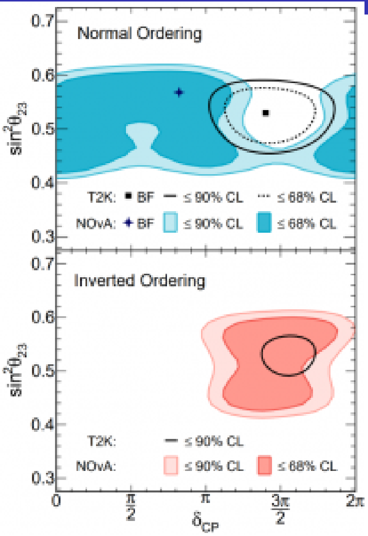
1. Neutrino Experiments, Status in Brief
   - Accelerator and Atmospheric Neutrinos only
2. ICAL at INO
   - On the way to ICAL: Experimental Status
   - With ICAL, in the future: Physics Potential

A Schematic of Neutrino Properties

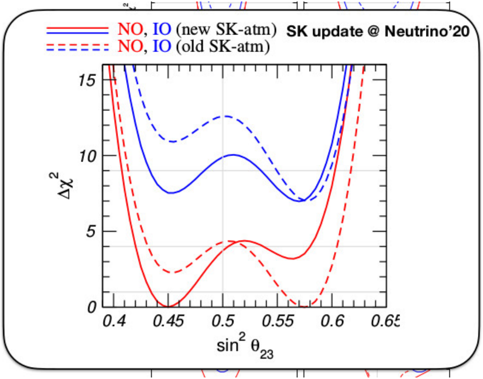
- Neutrino masses are not well-known. Oscillation studies only determine mass-squared differences: $\Delta m^2_{ij} = m^2_i - m^2_j$ and mixing angles θ_{ij}.
- $\Delta m^2_{21} \sim 0.8 \times 10^{-4}$ eV^2 ;
  $|\Delta m^2_{32}| \sim 2.0 \times 10^{-3}$ eV^2
  $\sum_i m_i < 0.7$–2 eV.
- $\theta_{12} \sim 34^\circ$
  $\theta_{23} \sim 45^\circ$: octant?
  $\theta_{13} \sim 8.5^\circ$;
  $\Rightarrow$ CP violation possible
- δ_{CP} =?:
  diff. between interaction of ν, $\overline{\nu}$ with matter
- INO being built in this context



Current Status

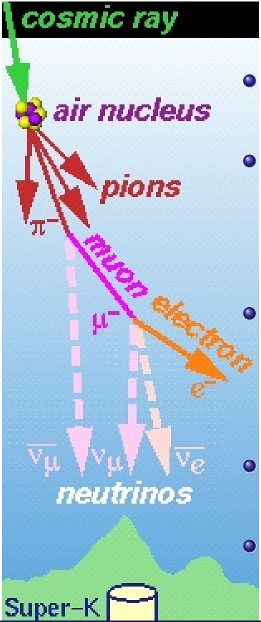


- Accl'r T2K and NOνA data
- Atmospheric SK data



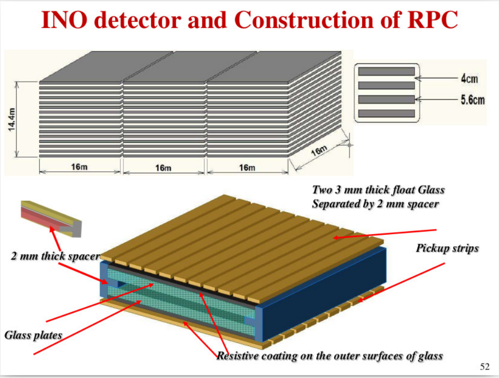
- INO/ICAL proposed to determine 2–3 parameters and mass ordering, *independent* of the CP phase.

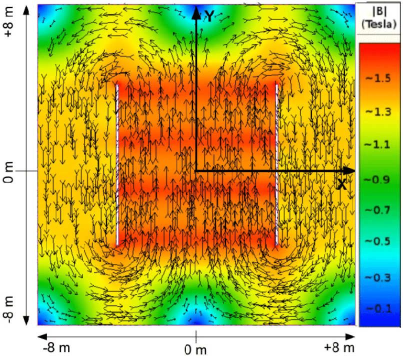
ICAL and Atmospheric Neutrinos



- Study of atmospheric neutrinos with magnetised iron calorimeter detector, ICAL
- Hence cosmic rays produce ν_μ ($\overline{\nu}_\mu$) and ν_e ($\overline{\nu}_e$) in about 2:1 ratio. Any deviation from this raio, especially as a function of direction (path length travelled in the Earth) is a signature of oscillations.
- The CC interactions of interest are:
  $\nu_\mu + N \to \mu^- + X$,
  $\overline{\nu}_\mu + N \to \mu^+ + X$, where X is any hadronic debris.
- Crucially, the magnetic field differentiates between ν_μ-induced and $\overline{\nu}_\mu$-induced events.
- So we can use the data to precisely determine the oscillation parameters, including mass hierarchy.

The ICAL detector





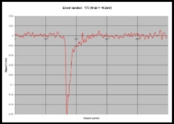
Specifications of the ICAL detector

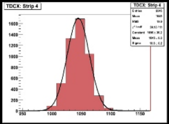
ICAL	
No. of modules	3
Module dimension	16 m $\times$ 16 m $\times$ 14.4 m
Detector dimension	48 m $\times$ 16 m $\times$ 14.4 m
No. of layers	150
Iron plate thickness	5.6 cm
Gap for RPC trays	4.0 cm
Magnetic field	1.5 Tesla
RPC	
RPC unit dimension	2 m $\times$ 2 m
Readout strip width	3 cm
No. of RPC units/Road/Layer	8
No. of Roads/Layer/Module	8
No. of RPC units/Layer	192
Total no. of RPC units	$\sim$ 30,000
No. of electronic readout channels	3.9×10^6

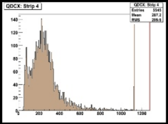
Completely indigenous. Needs large industry interface.

Building ICAL, step by step

Prototype RPC Stack at TIFR tracking Muons







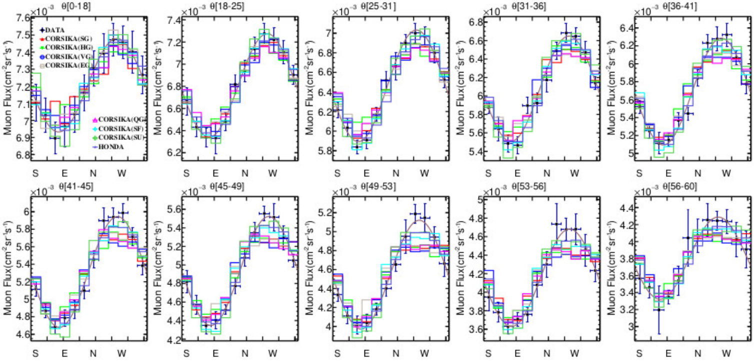
35

2m x 2m glass RPC test stand

36

RPC Stack, Madurai: Cosmic Ray Flux

- Knowledge of cosmic ray fluxes crucial to determine atmospheric neutrino fluxes.
- *Location* (lat/long) dependent lat/long.
- At low energies, well-known east-west asymmetry due to earth's magnetic field and proton excess.
- Recently measured: S. Pethuraj et al. INO Collab.

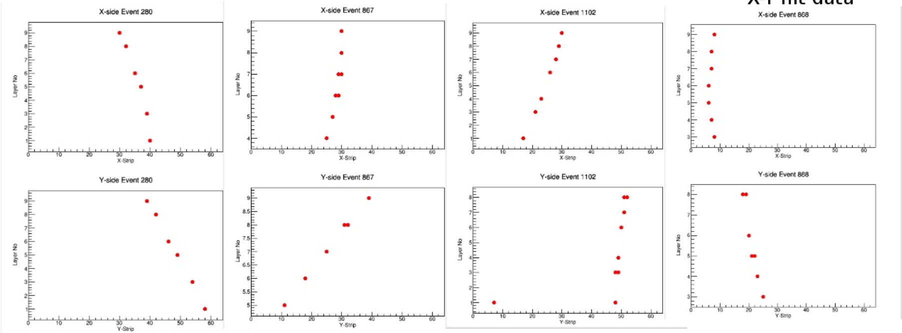


mini-ICAL Prototype at Madurai

First set of muon events

First muons seen in mini-ICAL on 8-5-2018 (6 RPCs)

Uncorrected X-Y hit data



First reconstruction of cosmic muons

- Using magnetised mini-ICAL detector with 11 layers and central magnetic field
- Also important to validate codes that have been developed:
  - Geant4 simulation (cosmic ray muon flux and atmospheric neutrino flux)
  - Kalman filter muon track identification and reconstruction
- Apoorva Bhat et al., INO Collab

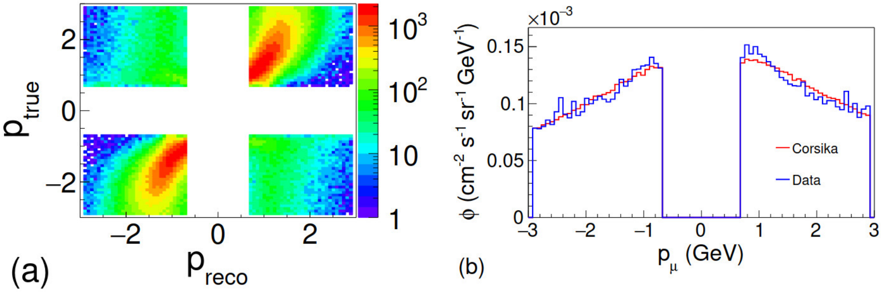
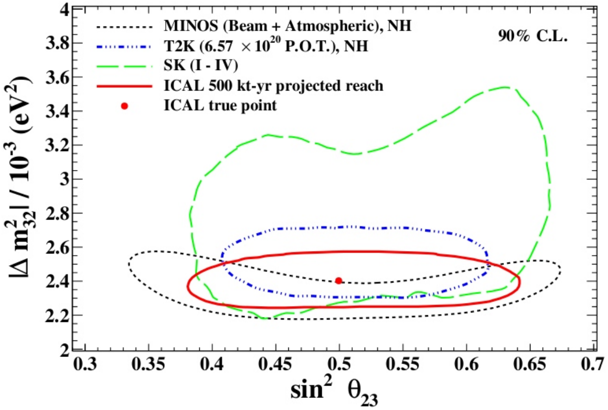


Figure 6.17: Unfolding of data with CORSIKA simulation

Physics potential of the ICAL detector

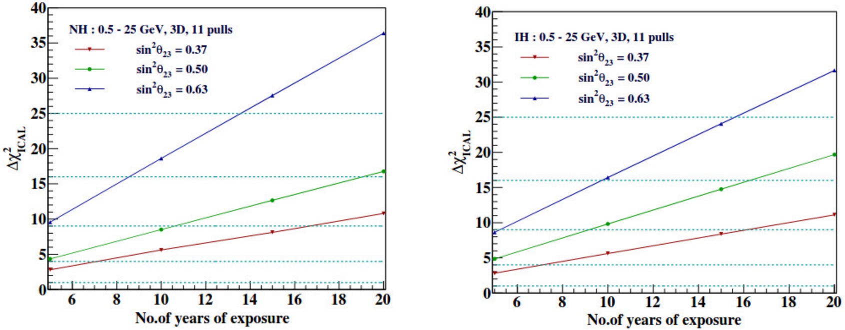
Precision Measurements



- Note ICAL yet to be built!
- Result marginalised over magnitude of Δm^2, as well as θ_{23} and θ_{13}.

Mass ordering

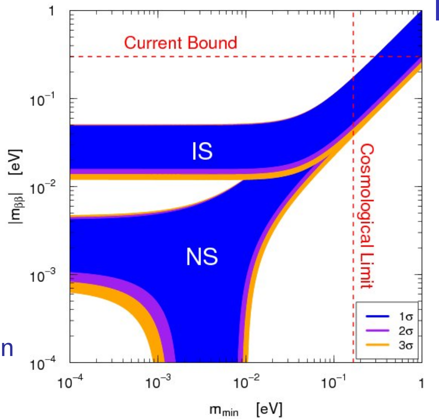
- Central goal of ICAL: independent of CP phase
- Several publications: see INO White Paper, Pramana



- Note improvement with addition of hadron information
- Result marginalised over magnitude of Δm^2, as well as θ_{23} and θ_{13}.

Global status: Mass hierarchy

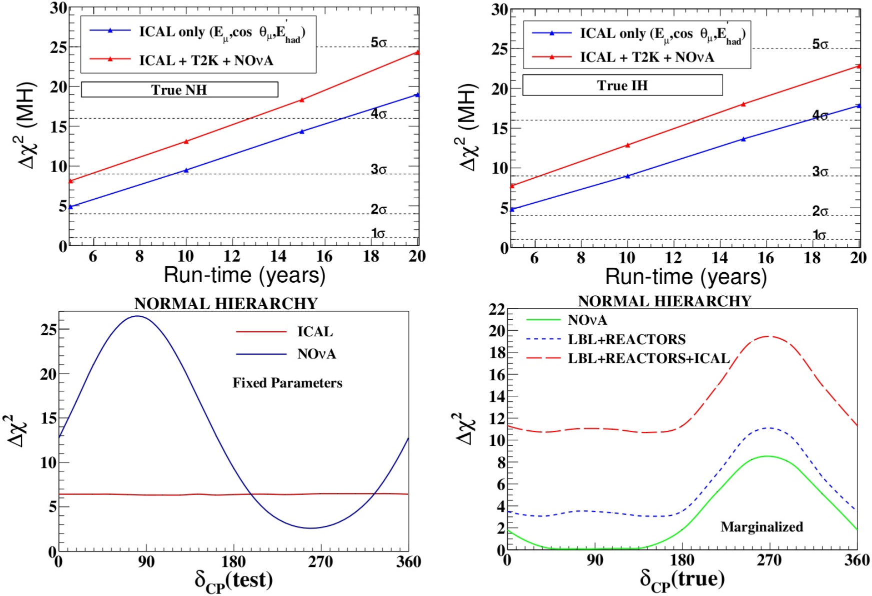
- Matter effect / mass hierarchy is the centrepiece of ICAL physics.
- It has a major role to play in understanding models of neutrino mass and mixing. It also impacts the determination of whether neutrinos are Majorana or Dirac type of fermions.



What is the role of other experiments in determining this quantity?

- Apart from INO, MINOS, T2K, NOνA, PINGU/Icecube, JUNO, DUNE, Hyper-K, LBNE all will/are probing mass hierarchy. Each is an amazing experiment.
- Most have to disentangle effects of CP phase from the hierarchy measurement; only possible for a fraction of possible $0 \leq \delta_{CP} \leq 2\pi$.
- ICAL can measure this unambiguously.

Additional Synergies



Other Physics

- Inclusion of electron neutrinos. Hard to do since cannot separate electron shower from hadron shower; also low energy muons whose tracks are not reconstructed (Aleena Chacko et al).
- Inclusion of tau neutrinos. Very interesting possibility. Work in progress (R Thirusenthil et al).
- Inclusion of sterile neutrinos. Hard to do since need to measure all neutrino flavours. (Sandhya Choubey's talk)
- Instead can think of models in which neutrinos decay (via Majorons) into steriles—indirect (L S Mohan et al).
- Can have non-standard neutrino interactions. Probe by looking for deviations from usual oscillations (Many!)
- Look for signatures of CP violation, Lorentz invariance violation, etc. (Many!)
- Can use the detectors to probe non-oscillation, non-neutrino physics: cosmic muons, dark matter, etc.
- Bottom line: lots of exciting possibilities!

Outlook

- Neutrinos probe some of the most important frontiers of physics, astrophysics and cosmology.
- Neutrinos are the cleanest probes of weak interactions, which are least studied and understood today.
- Neutrinos are the key to understanding many features about the origin and evolution of our Universe (though this was not really discussed in this talk).
- Neutrinos are therefore a new window into our Universe. About 50 experiments world-wide are devoted to study neutrinos from different sources.
- ICAL/INO is one of them. Unfortunately, while the R&D is moving well, there is no progress on the clearances front.
- With thanks, and apologies for the lack of any experimental details.

Backup Slides

Neutrino Oscillations

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle \ . \qquad (1)$$

Here U is the 3×3 unitary matrix which may be parametrised as (ignoring Majorana phases):

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta_{CP}} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta_{CP}} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix} . \quad (2)$$

δ_{CP} is the CP violating (Dirac) phase and M_ν is diagonalised in the charged-lepton mass basis by U:

$$U^\dagger M_\nu U = \mathrm{diag}(m_1, m_2, m_3). \qquad (3)$$

Matter Effects

First consider matter of constant density ρ (in gms/cc). Then we can replace the vacuum values by the corresponding matter-modified effective ones obtained by diagonalising the matter dependent matrix (Hamiltonian):

$$U \left(\begin{array}{ccc} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{array} \right) U^\dagger + \left(\begin{array}{ccc} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{array} \right), \quad (4)$$

where

$$A = 2\sqrt{2} G_F n_e E = 7.63 \times 10^{-5}\ \mathrm{eV}^2\ \rho(\mathrm{gm/cc})\ E(\mathrm{GeV})\ \mathrm{eV}^2. \quad (5)$$

Mixing angles in matter

Further simplification arises because $\Delta m^2_{21} \ll \Delta m^2_{31}$ and we can treat the propagation in matter as a one mass-scale problem involving only $\Delta m^2_{32} \approx \Delta m^2_{31}$. The matter dependent mixing angle $\theta_{12,m}$ may be approximately written as

$$\sin 2\theta_{12,m} \approx \frac{\sin 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} - (A/\Delta m^2_{21}) \cos^2 \theta_{13})^2 + \sin^2 2\theta_{12}}} . \qquad (6)$$

The effect of matter on the angle θ_{13} is non-trivial and is given by

$$\sin 2\theta_{13,m} = \frac{\sin 2\theta_{13}}{\sqrt{(\cos 2\theta_{13} - (A/\Delta m^2_{31}))^2 + (\sin 2\theta_{13})^2}} . \qquad (7)$$

$$\sin 2\theta_{23,m} \approx \sin 2\theta_{23} . \qquad (8)$$