India-Based Neutrino Observatory
Physics Potential and Status Report
of the proposed magnetised ICAL detector

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Horizons ··· ICTS, Nov 17, 2022

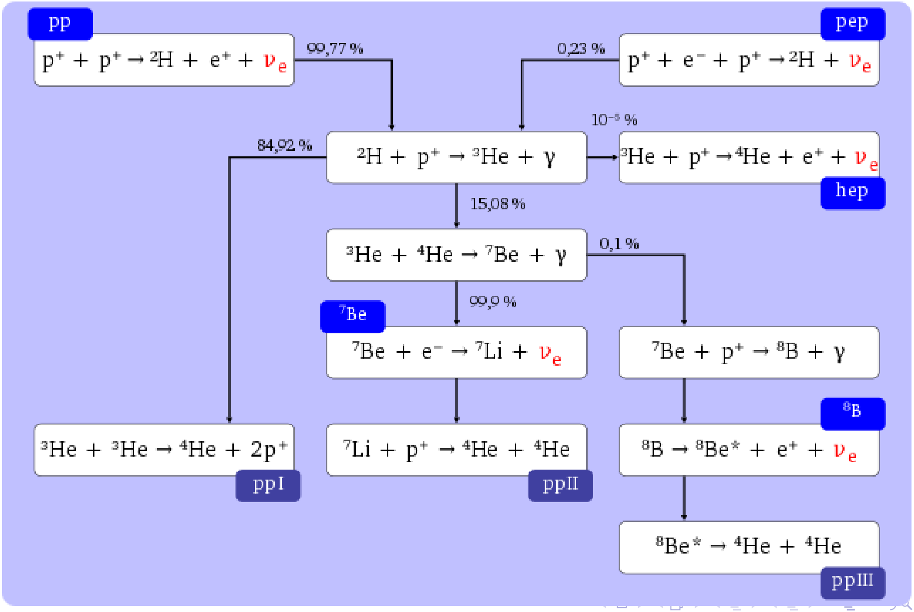
Overview

1. Solar Neutrino Physics
   - India-based Neutrino Observatory (INO)
2. Physics reach of ICAL/INO
   - Additional Slides: More details on INO
3. INO Current Status
4. Outlook, and Outreach, or what is $T = 0$?

Towards Neutrino Physics

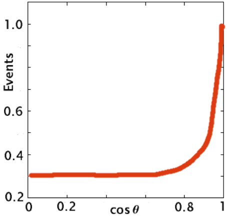
Pic: Wikipedia

Solar fusion and the pp chain



Early solar neutrino experiments

- Davis and collaborators, first results in 1968. About 600 tons of perchloroethylene (drycleaning fluid!) :
  $\nu_e + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^-$.
  Event rate about 1 in 3 days.
  $$R^{CC} = \frac{\text{Number of events observed}}{\text{Number of events expected}} \simeq \frac{1}{3}$$

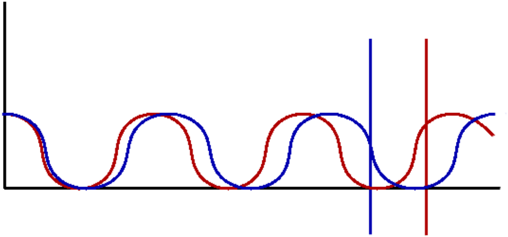


- Totsuka, Kamioka, 1989: Pure water.
  $\nu_X + e \to \nu_X + e$, $X = \nu_e : \nu_\mu :: 6 : 1$.
  – These are from the instantaneous direction of the Sun.
  $$R^{EL} = \frac{\text{Number of events observed}}{\text{Number of events expected}} \simeq \frac{1}{2} .$$
- SNO, Sudbury, Canada, 1000 tons heavy water D_2O, 2002.
  $$R^{CC} = \frac{\text{Number of events observed}}{\text{Number of events expected}} \simeq \frac{1}{3} \text{ as from Cl.}$$
  $$R^{EL} = \frac{\text{Number of events observed}}{\text{Number of events expected}} \simeq \frac{1}{2} \text{ as from Kamioka.}$$
  $$R^{NC} = \frac{\text{Number of events observed}}{\text{Number of events expected}} \simeq 1 \text{ as expected!}$$
  $\nu_X + d \to \nu_X + p + n$: all flavours NC.

Solution to the puzzle: Neutrino oscillations

- Neutrinos come in more than one *flavour* or *type*. Consider, for simplicity, two-flavours, ν_e and ν_μ.

- If neutrinos are massive (different masses), and, further, show the quantum mechanical phenomenom called *flavour mixing*, then neutrinos can *oscillate* between flavours.



ν_1

ν_2

$$\begin{aligned} \nu_e(t) &= \cos\theta \circlearrowright + \sin\theta \circlearrowright , \\ \nu_\mu(t) &= -\sin\theta \circlearrowright + \cos\theta \circlearrowright , \end{aligned} \tag{1}$$

and can extend this to mixing between the three flavours ν_e, ν_μ, ν_τ.

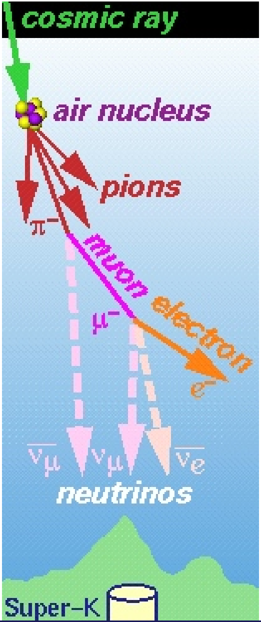
Other observations of neutrinos

- So far, discussed Solar neutrinos : US, Russia/USSR, Japan, Canada
- Atmospheric neutrinos : US, Japan, Mediterranean Sea, South Pole
- Reactor neutrinos : France, Korea, China
- Beam neutrinos : US, Japan, Switzerland, Italy
- Geo neutrinos : US, Japan
- There are also neutrinos which are a part of the cosmic background. Relics of the Big Bang, estimated about 300 neutrinos per cc in the Universe! Very difficult to detect, but indirect detection.
- Tremendous interest in neutrino physics due to its implications in particle physics, astrophysics, cosmology, including the origin and evolution of the Universe.
- A proposal, the India-based Neutrino Observatory (INO) is exploring the possibility to build an underground neutrino detector in India.

The INO Project

- A mega Science Project funded by the Dept. of Science and Technology and Dept. of Atomic Energy, Govt. of India
- Immediate goal: Creation of an underground laboratory for research in neutrino physics
- Will develop into a full fledged underground laboratory over the years for other studies in physics, biology and geology
- Main detector proposed is magnetised Iron CALorimeter (ICAL) to study primarily atmospheric neutrinos
- Will incorporate a centre for particle physics and detector technology and its varied applications: functioning at Madurai
- The INO graduate training program to train students on both the theoretical and experimental aspects.
- Completely indigenous.

ICAL and Atmospheric Neutrinos

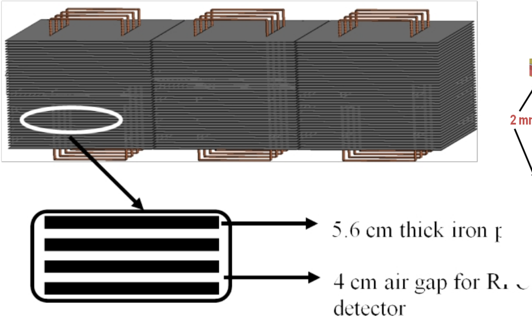


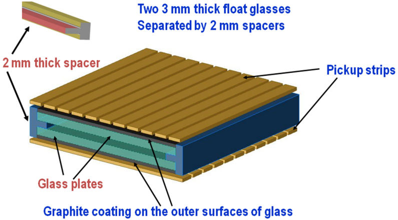
- Study of atmospheric neutrinos with magnetised iron calorimeter detector, ICAL:

$$\pi \to \mu + \nu_\mu \ ,$$
$$\mu \to \nu_\mu + e + \nu_e \ .$$

- Hence cosmic rays produce ν_μ ($\overline{\nu}_\mu$) and ν_e ($\overline{\nu}_e$) in about 2:1 ratio. Any deviation from this ratio, 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.
- Hence we can use the data to precisely determine the oscillation parameters, including the mass hierarchy. *Pic: Courtesy Super-Kamiokande*

- 50 kton iron, magnetised to ~ 1.5 T with 150 layers of 5.6 cm plates in three modules
- Each module $= 16 \times 16 \times 14.4$ m^3
- Will be world's most massive magnet, when built





Active detector elements: RPCs

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/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.

Physics reach of ICAL/INO

What can we learn from ICAL?

A Schematic of Neutrino Properties

Neutrino masses are not well-known. Oscillation studies only determine mass-squared differences: $\Delta m_{ij}^2 = m_i^2 - m_j^2$ and mixing angles θ_{ij}.

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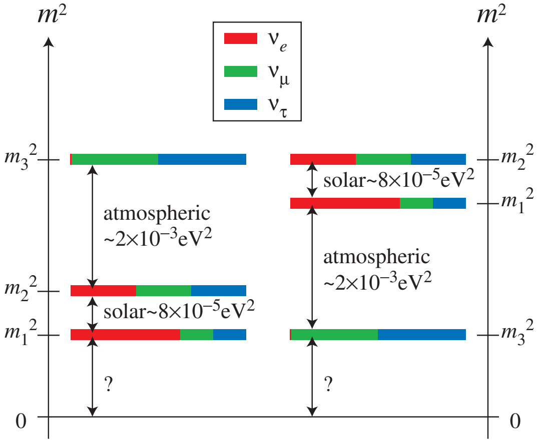

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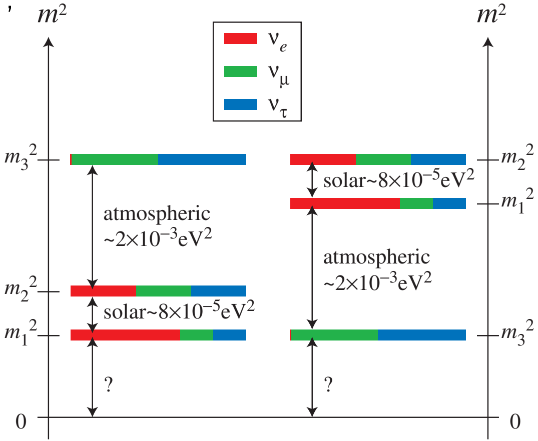

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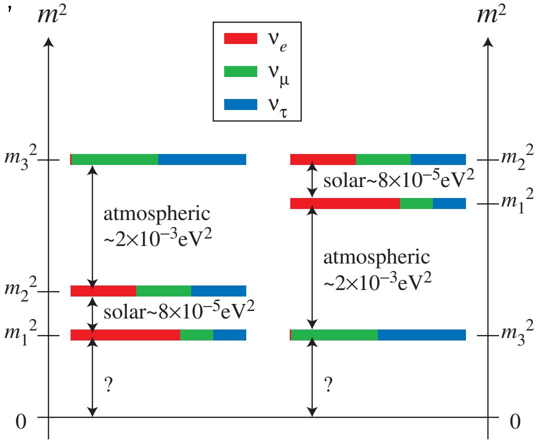

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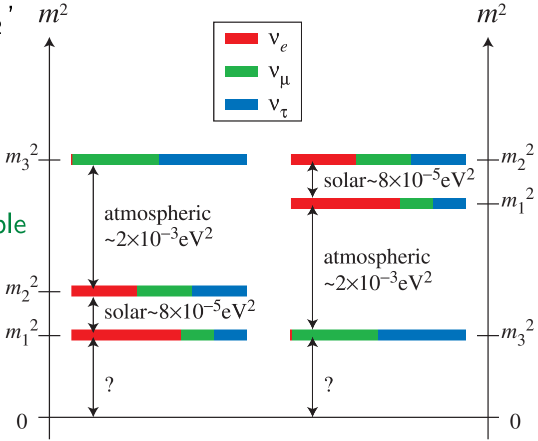

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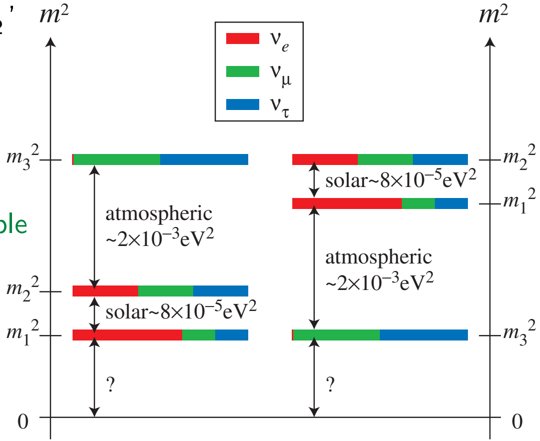
- $\delta_{CP} =$?:
  diff. between interaction of ν, $\overline{\nu}$ with matter



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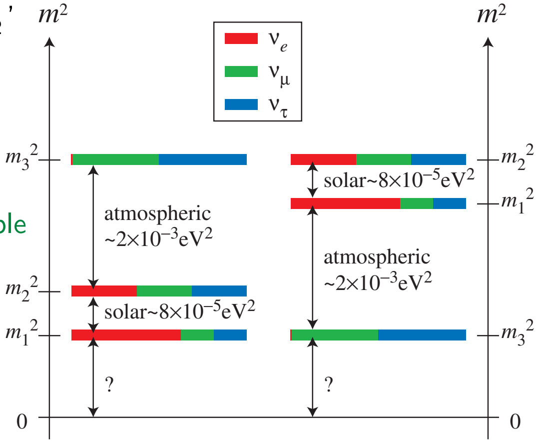
- INO being built in this context



Mixing angles in matter

Simplification because $\Delta m^2_{21} \ll \Delta m^2_{31}$, so effectively a one mass-scale problem with $\Delta m^2_{32} \approx \Delta m^2_{31}$. Then

$$
\begin{aligned}
\sin 2\theta_{12,m} &\approx \frac{\sin 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} - (A/\Delta m^2_{21})\cos^2\theta_{13})^2 + \sin^2 2\theta_{12}}} ; \\
\sin 2\theta_{13,m} &= \frac{\sin 2\theta_{13}}{\sqrt{(\cos 2\theta_{13} - A/\Delta m^2_{31})^2 + (\sin 2\theta_{13})^2}} ; \\
\sin 2\theta_{23,m} &\approx \sin 2\theta_{23} ,
\end{aligned}
\tag{2}
$$

where $A = 7.6 \times 10^{-5}\ \rho E\ \mathrm{eV}^2$; $\quad \Delta m^2_{32} = m^2_3 - m^2_2$, etc.
$\rho =$ earth density (gms/cc)
$E =$ neutrino energy in GeV.

- Neutrinos $(A) \Leftrightarrow$ antineutrinos $(-A)$.
- The matter effect depends only on ratio $A/\Delta m^2_{31} \equiv A/\Delta$ (to a very good approximation).

Probabilities in matter

Hierarchy discriminator: Earth matter, difference in interactions between ν and $\overline{\nu}$.

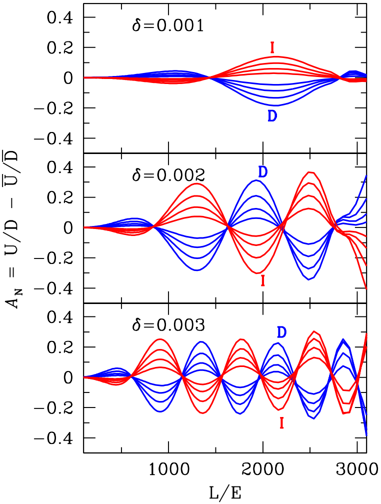
$$
\begin{aligned}
P^m_{\mu\mu}(A,\Delta) &\approx P^{(2)}_{\mu\mu} - \sin^2\theta_{13} \times \\
&\left[\frac{A}{\Delta - A} T_1 + \left(\frac{\Delta}{\Delta - A}\right)^2 \left(T_2 \sin^2[(\Delta - A)x] + T_3\right)\right] , \\
\overline{P}^m_{\mu\mu}(A,\Delta) &\approx P^{(2)}_{\mu\mu} - \sin^2\theta_{13} \times \\
&\left[\frac{-A}{\Delta + A} T_1 + \left(\frac{\Delta}{\Delta + A}\right)^2 \left(T_2 \sin^2[(\Delta + A)x] + T_3\right)\right] ,
\end{aligned}
$$

$A \propto \rho E$. **Changes sign between neutrinos and anti-neutrinos.**

Hence the sign of $\Delta \equiv \Delta m^2_{31}$ will determine whether the MSW resonance occurs in the neutrino or anti-neutrino sector.

The matter dependent oscillations

Asymmetry $A = U/D - \overline{U}/\overline{D}$ as a function of θ_{13} and $L(\text{km})/E(\text{GeV})$.



• Sensitivity to sign of $\delta \equiv \Delta m^2_{31}$ for $\theta_{13} = 5, 7, 9, 11^\circ$ and Normal (D) and Inverted (I) mass orderings.

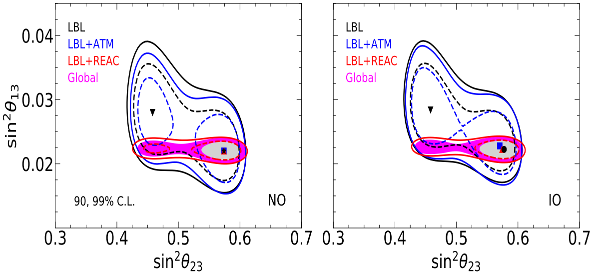
• *Current values close to middle panel and second curve from the outermost envelope.*

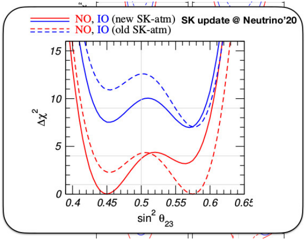
• Hence sensitive to the mass ordering (red vs blue); however, needs large exposures of about 500–1000 kton-years (determines the error bars!)

• How to realise this experimentally? Will come to this in a moment.

The octant of θ_{23}

$$
\begin{aligned}
P^m_{\mu\mu} &\approx 1 - \sin^2 2\theta_{23}\left[\sin^2\theta^m_{13}\sin^2\Delta^m_{21} + \cos^2\theta^m_{13}\sin^2\Delta^m_{32}\right] \\
&\qquad -\sin^4\theta_{23}\sin^2 2\theta^m_{13}\sin^2\Delta^m_{31}\,, \\
P_{e\mu} &\approx \sin^2\theta_{23}\sin^2 2\theta^m_{13}\sin^2\Delta^m_{31}\,,
\end{aligned}
$$

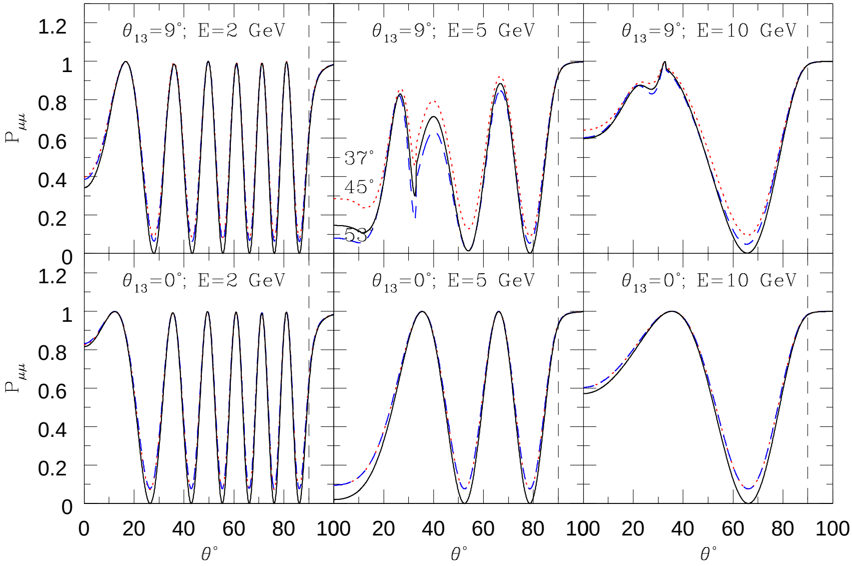




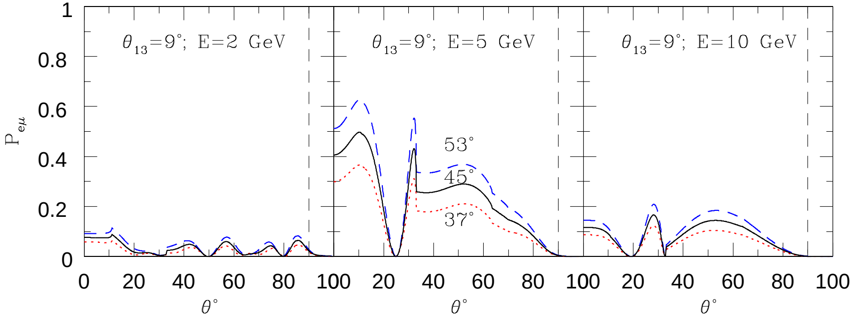
arXiv:2007.14792v1; arXiv: 2006.11237 [hep-ph]

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

Sensitivity of $P_{\mu\mu}$ to the octant

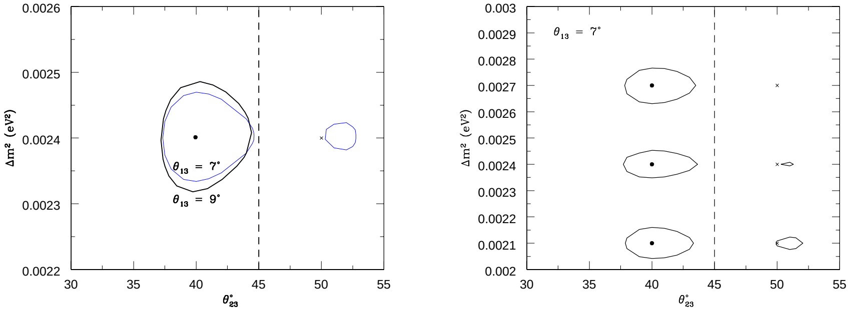


Sensitivity of $P_{e\mu}$ to the octant



- Both $P_{\mu\mu}$ and $P_{e\mu}$ contribute to the observed muon rates at a detector; latter contribution is small.
- Effect different from that of θ_{13}: larger θ_{13} will decrease the height of the maxima and increase the height of the minima.
- Lower sensitivity if true octant is the second one.

Sensitivity to the octant

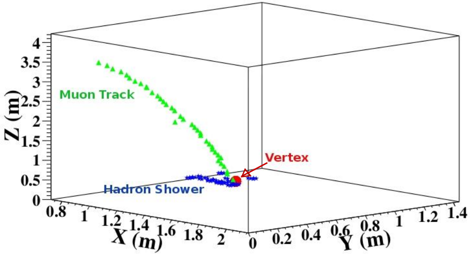


hep-ph/0603264

- Sensitivity for 1000 kton-yr exposure.
- Sensitivity to $\sin^2\theta_{13}$, Δm^2_{31}.
  Note the current value of $\theta_{13} \sim 8.5^\circ$ and
  $\theta_{23} = 40^\circ \implies \sin^2\theta_{23} = 0.41$ close to present 99CL limit:
  $(|\Delta m^2_{31}| \sim 2.5 \times 10^{-3}$ eV^2; $\sin^2\theta_{23} \sim 0.41$–$0.62)$.
- Results much poorer for inverted hierarchy and solution in second octant.

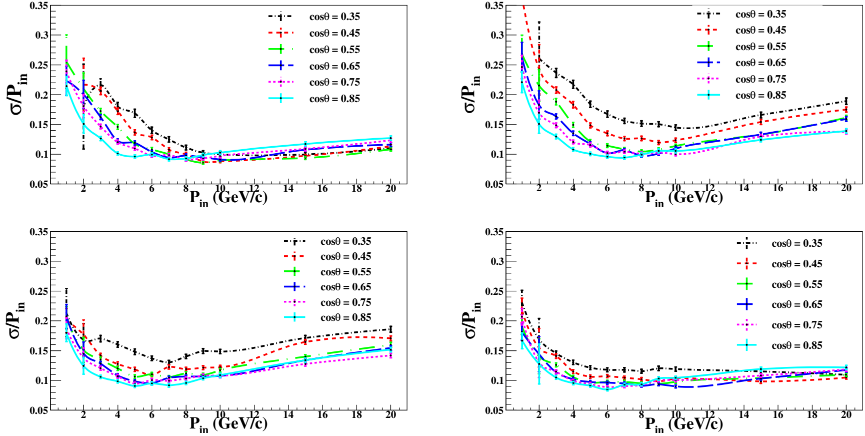
Physics with ICAL: Simulations studies

- Detailed GEANT4-based simulations studies.
- Most results obtained using Honda-3d fluxes and NUANCE (v3.5) neutrino generator
- Magnetic field map generated using MAGNET6.0 software

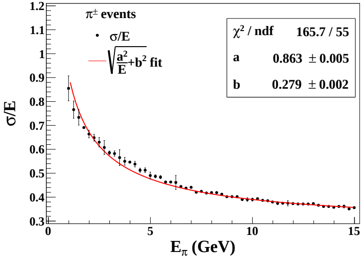


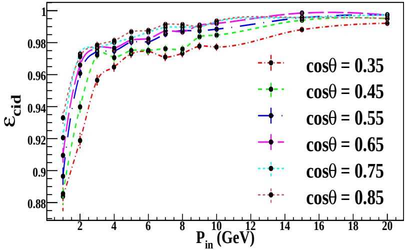
- Kalman filter algorithm used to reconstruct sign of charge and momentum of muons from the track
- Hadron energy reconstructed by calibrating to total hits in event.
- Most results from INO White Paper 1505.07380.

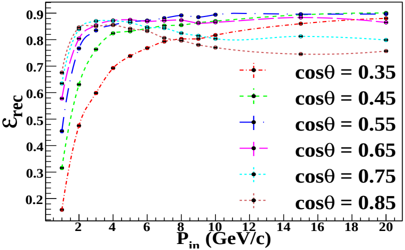
Muon momentum reconstruction (θ, ϕ)



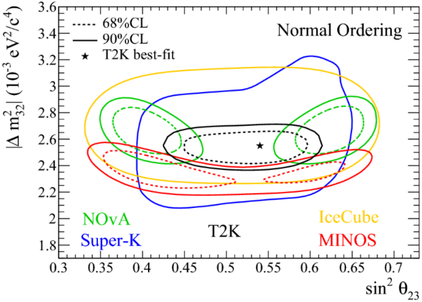
Hadron energy, Reconstruction and Charge-id efficiency

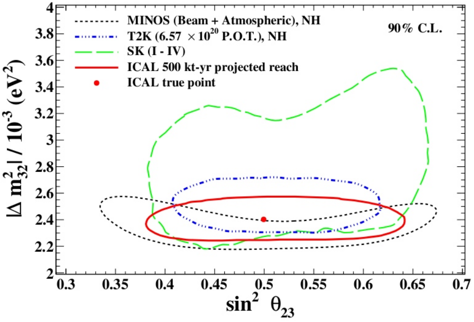






Physics reach of ICAL/INO: Precision Measurements



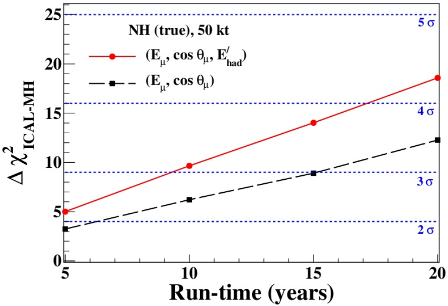


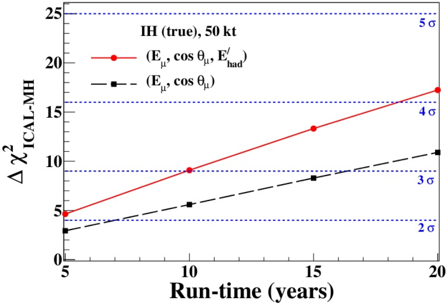
Eur.Phys.J.C 80 (2020) 4, 344

1505.07380 [physics.ins-det]

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

Physics reach of INO: Mass Ordering



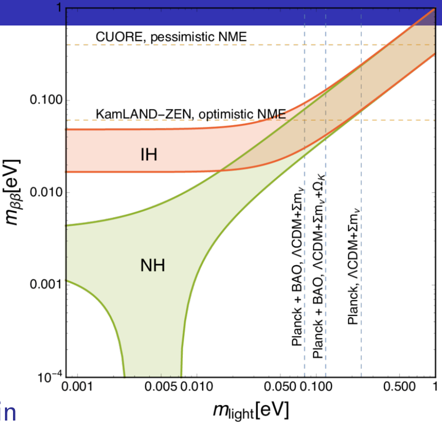


- Note improvement with addition of hadrons
- Result marginalised over magnitude of Δm^2_{31}, as well as θ_{23} and θ_{13}.
- This result is completely independent of the unknown CP phase.

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?

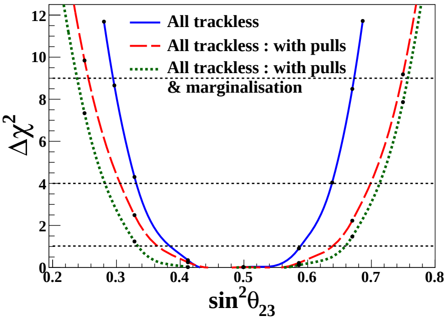
1712.07109 [astro-ph.CO]

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; can accomplish this only for a fraction of possible δ_{CP} from $-\pi$ to π.

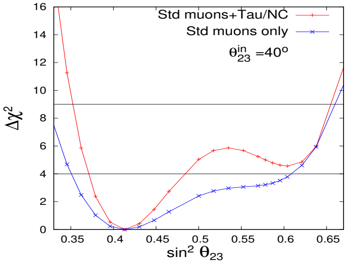
Inclusion of electron neutrinos. Hard to do since need to separate electron shower from hadron shower.

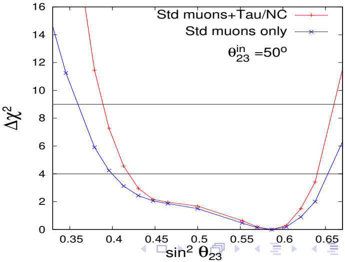
1912.07898 [physics.ins-det]



Inclusion of tau neutrinos: combined analysis

2203.09863 [hep-ph]

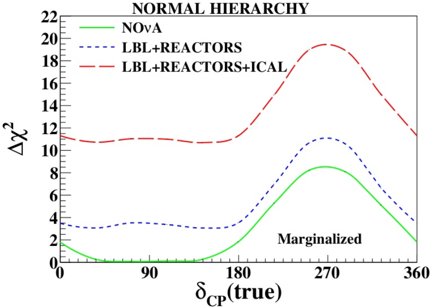


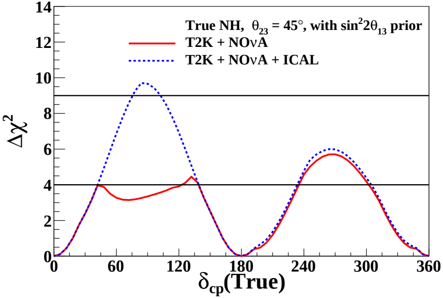


Other Physics, continued

- Inclusion of sterile neutrinos. Hard to do since need to measure all neutrino flavours.
- Can have non-standard neutrino interactions; neutrino decay. Probe by looking for deviations from usual oscillations.
- Look for signatures of CP violation, Lorentz invariance violation, etc.
- Can use the detectors to probe non-oscillation, non-neutrino physics: cosmic muons, dark matter, etc.
- Bottom line: lots of exciting possibilities!

Additional Synergies

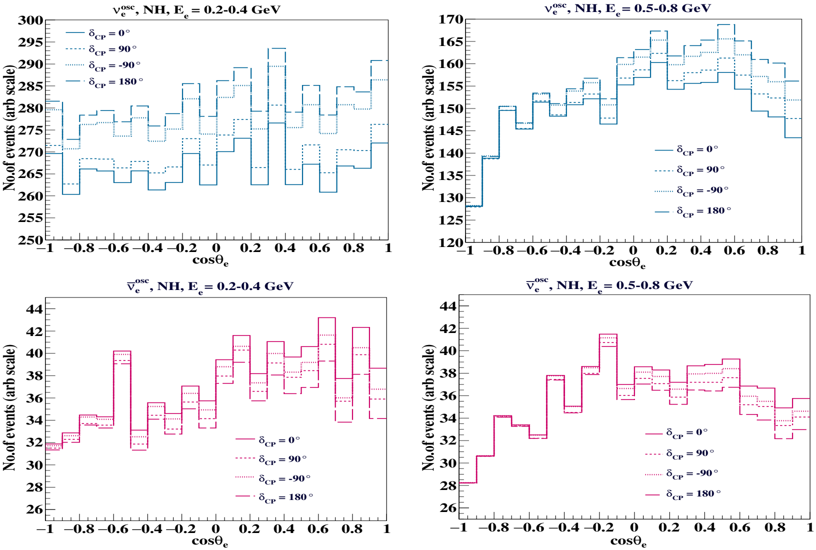




- Left: Synergies with other experiments that improve the determination of the mass ordering over the entire δ_{CP} range. Here the full proposed runs of the long baseline and reactor experiments are taken, with 10 years' running of ICAL.
- Right: Synergies that improve the determination of δ_{CP}.

1505.07380 [physics.ins-det]

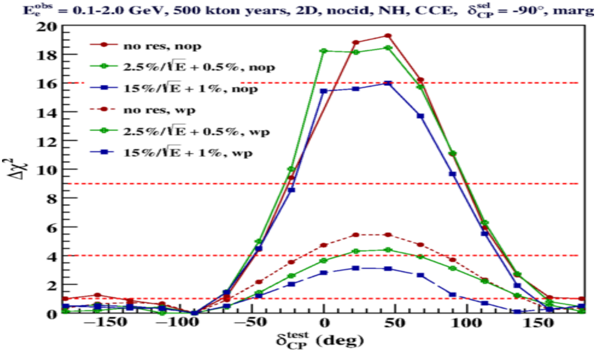
Beyond ICAL: The CP phase at low energies



1701.08997 [hep-ph]

Sensitivity to δ_{CP}

- Consider a hypothetical detector looking at atmospheric neutrinos but with sensitivity to low energy events.
- Huge fluxes since the atmospheric neutrino spectrum peaks at $E_\nu \sim 0.2$ GeV.

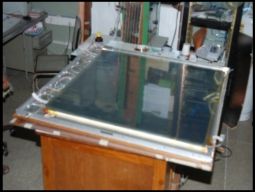


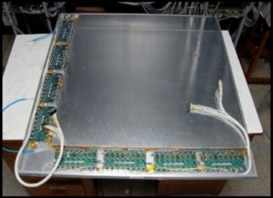
INO R& D and Current Status

- What is the current status of ICAL/INO?
- Mini-ICAL and engineering module
- Cosmic veto set-up

Fabrication of 1m x 1m RPCs





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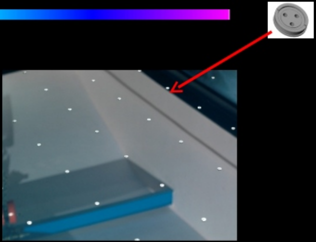
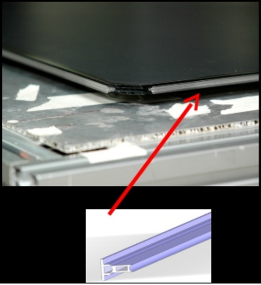
Final RPC Frontier - Making of 2m x 2m RPCs





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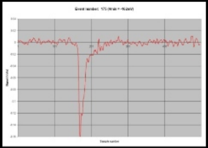
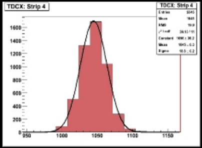
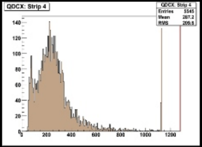
Prototype RPC Stack at TIFR tracking Muons







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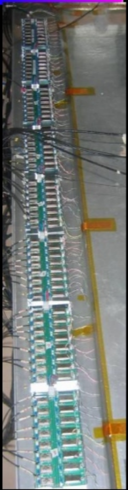
2m x 2m glass RPC test stand



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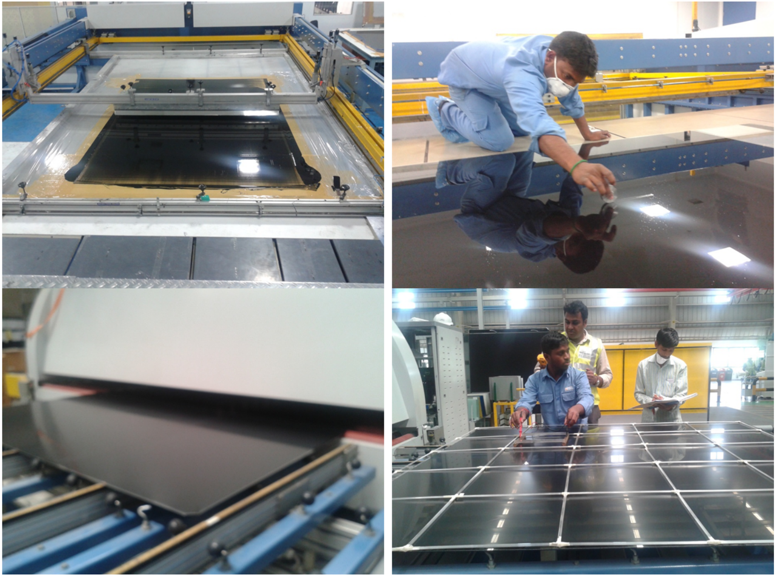
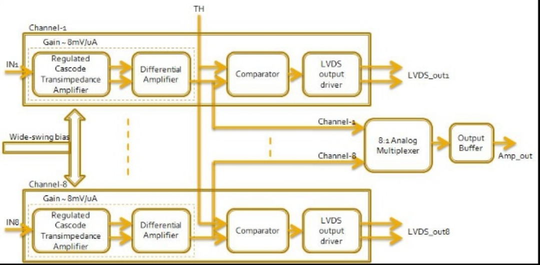
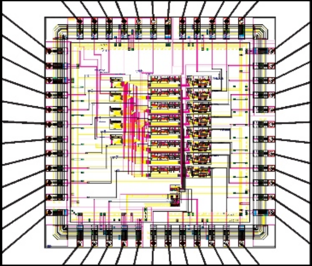
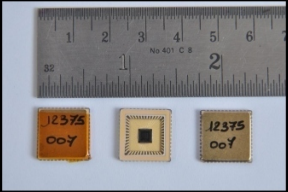
Automation of RPC manufacture by industry



ICAL Front End Electronics chip developed at BARC Electronics Division







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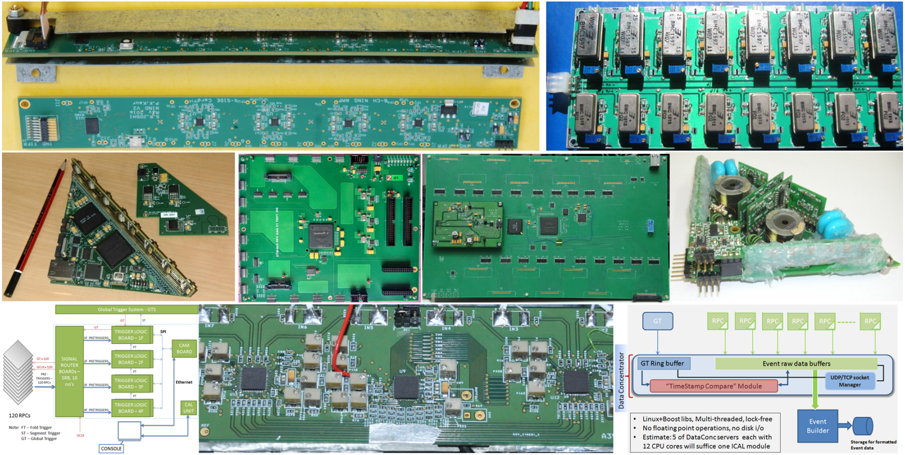
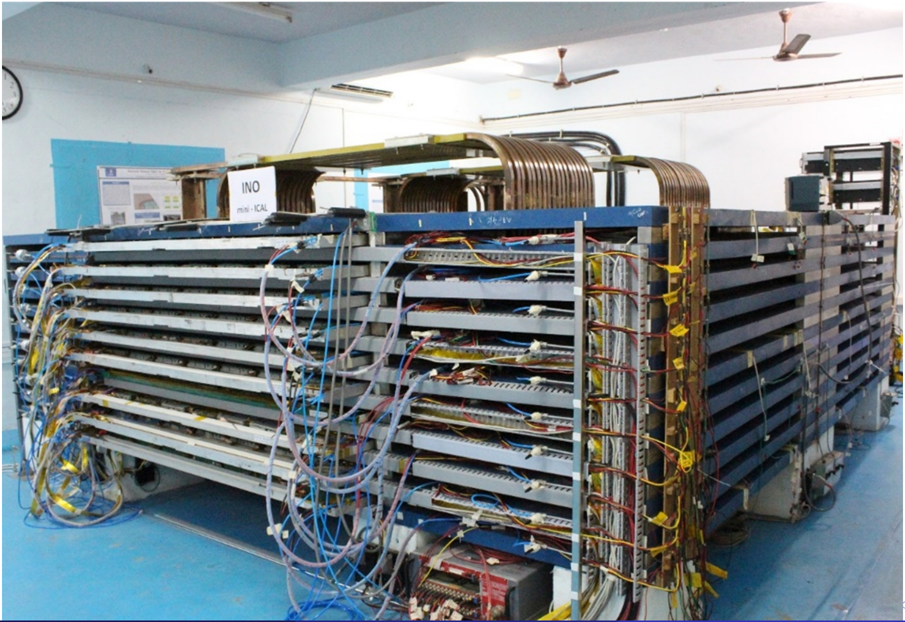
Example of RPC/Electronics



ICAL electronics, showing various parts of the front-end, back-end electronics, data acquisition systems, etc.

Prototype mini-ICAL at Madurai

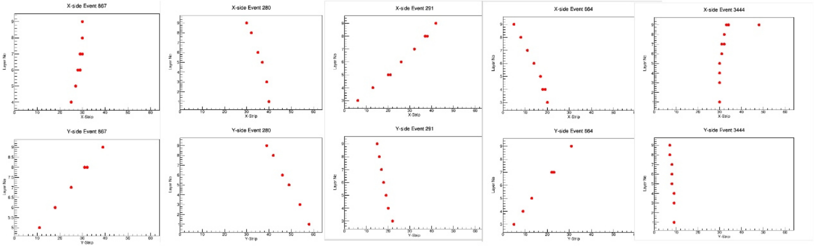


Students working on mini-ICAL

First set of muon events

8 RPCs at centre of mini-ICAL (23-5-2018)

Offset corrected X-Y hit data



I = 900 A ; B = 1.4 Tesla

- Huge and enthusiastic participation from several college students in and around Madurai and TN

Outlook and Outreach

- Many current and future proposed mega science experiments with Indian participation; some like INO are completely indigenous
- These experiments are set to probe some of the most important frontiers of physics, astrophysics and cosmology.
- Crucial to bring these innovations and ideas to the notice of the general public.

Outreach, or what is $T = 0$?

- Different kinds of audience and hence different approaches.
- Students: Basically enthused by our talks: no questions asked
- Environmental activists: detailed answers re construction and nature of neutrinos
- Bureaucracy: the importance of the project and applications to society (jobs, local industry, financial implications)
- Journalists and science journalists: media attention is short-lived
- General audience: curiosity-driven science and relation between basic science and technology.

Some examples learned from experience

- Short-term outcomes: state-of-the-art technology transfer to industry and creation of jobs
- Long-term outcomes: Applications of neutrinos themselves through their properties or applications of ex. RPCs in medical imaging, etc.
- Basic sciences research is considered exotic. Acceptance of technology (mobiles, TVs, cars) but science (and scientists) looked on with suspicion. Some possible examples to dispel doubts are:
  - Discovery of the electron 100 years ago was driven by simple curiosity. Today, we have electronics and computers
  - In 1932, the positron was discovered. Today we have PET (Positron Emission Tomography) scans. Advances in medical imaging (from X-rays to PET to MRIs ...
  - Time on a GPS satellite clock advances faster than a clock on the ground by about $(45 - 7) = 38\ \mu s$ per day (GR−SR).
  - An additional tool: computers: in fact, quantum computers are being used to study quantum physical systems!
  - Knowledge of maths can also save money: Lagrange points and the James Webb Space Telescope

In Conclusion

- Proof-of-principle of various components of ICAL available
- Mini-ICAL has preliminary results on cosmic ray muon (μ^+ and μ^-) spectrum at low energy.
- Already a great deal of interaction with local industry.
- Waiting for clearances which are proving hard to get
- In spite of these delays, believe that physics reach of ICAL will be complementary to other current and future proposed detectors.
- INO will galvanise science across the country by offering opportunities to students and industry to work in a cutting-edge research atmosphere.
- The INO community is hopeful that INO will be built.

T H A N K   Y O U