India-based Neutrino Observatory (INO)

Status Report

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For the INO Collaboration

(http://www.imsc.res.in/∼ino)

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  - The ICAL Detector: RPC’s and magnet design
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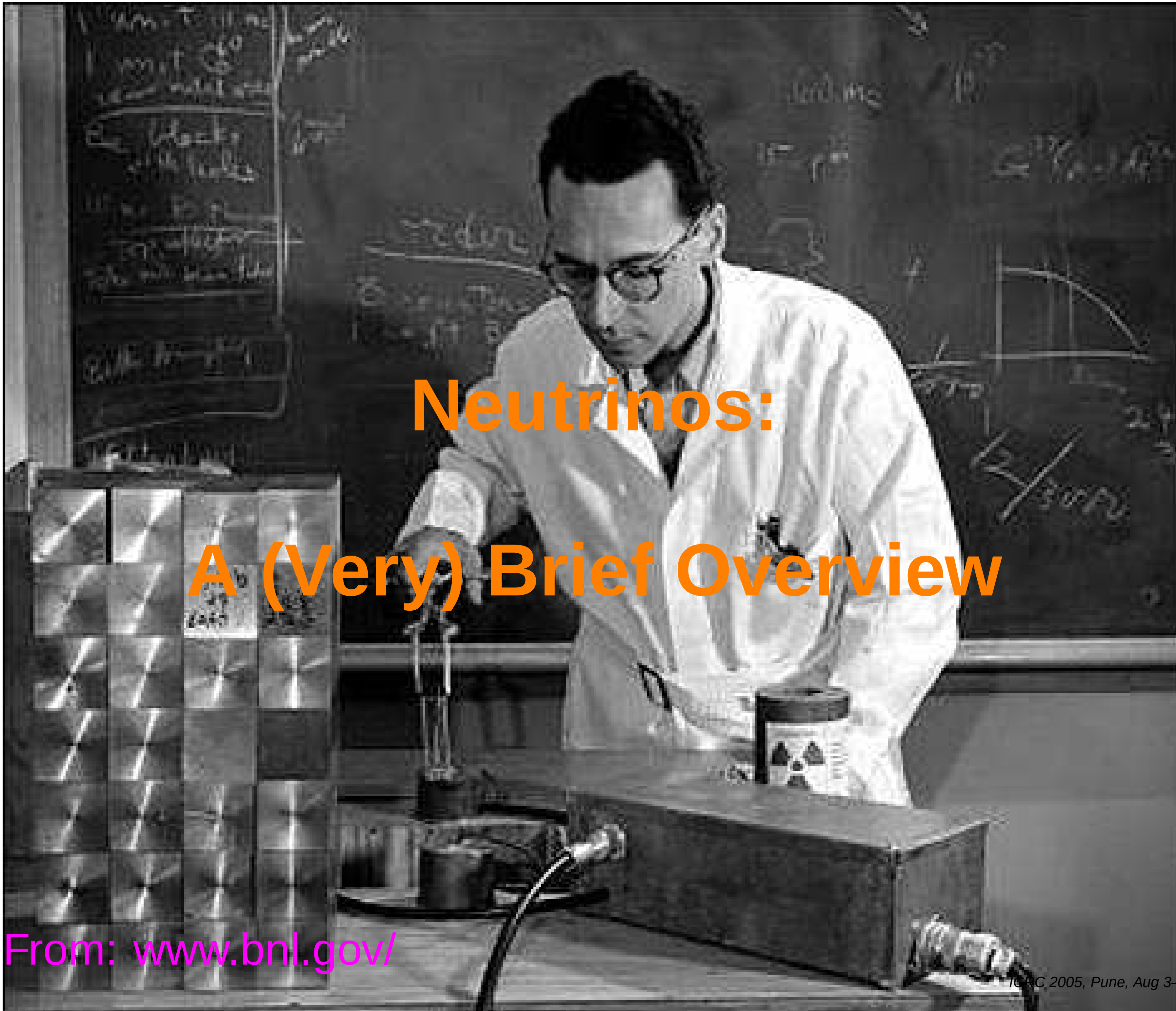
  - Physics possibilities at ICAL: atmospheric and long-baseline physics
- Other physics studies possible at INO

Neutrinos:

A (Very) Brief Overview



From: www.bnl.gov/

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- It is now conclusively established that neutrinos are not massless.
- Furthermore, neutrino flavours mix quantum-mechanically, so that, as they propagate, they exhibit the phenomenon of oscillation.
- This means that at least two of the masses should be distinct.

How do we know this?

- The Homestake Chlorine experiment by Davis and collaborators first observed a deficit in the observed solar neutrino flux.
- The Super-Kamiokande real-time water Cerenkov experiment proved that the observed neutrinos indeed originated in the Sun.
- The SNO heavy water experiment provided the very important corroboration that the electron neutrino flux is depleted while the total solar neutrino flux is consistent with theory.
- The Super-Kamiokande experiment also showed that atmospheric muon neutrinos (and anti-neutrinos) were depleted; atmospheric electron neutrinos (and anti-neutrinos) did not seem significantly different from expectations.
- More precisely, the ratio of observed to expected muon neutrinos was depleted, especially for neutrinos that had travelled a large path-length through the Earth before they were observed in the detector.

A Schematic of Neutrino Properties

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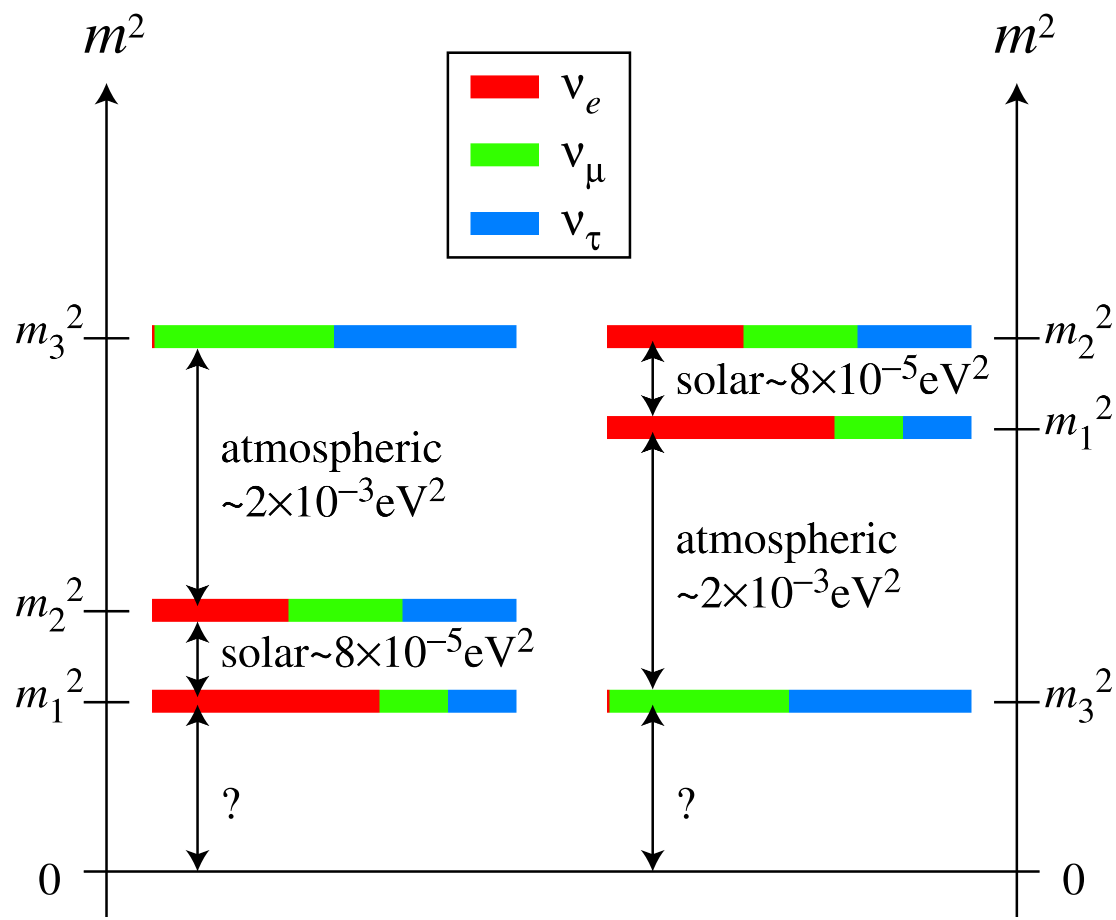

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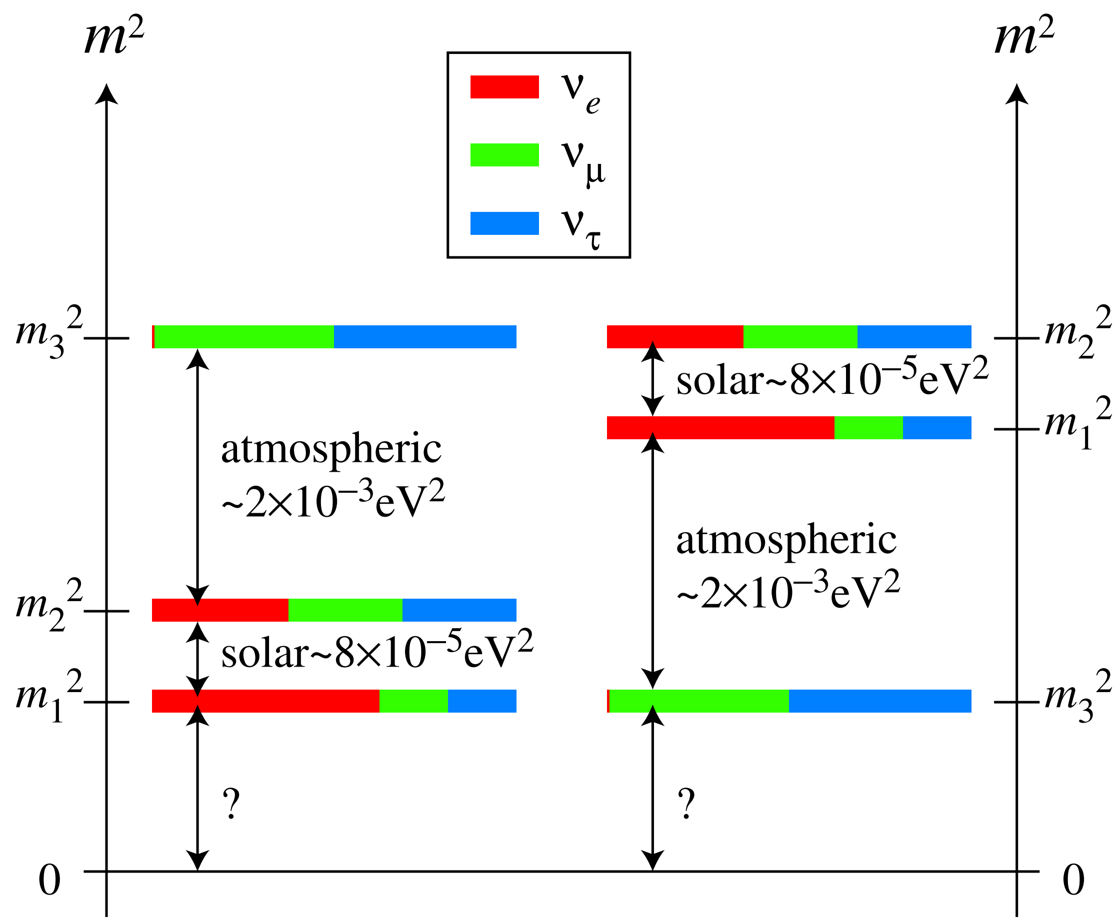
$\Delta m^2_{21} \sim 0.8 \times 10^{-4}$ eV^2 ;
$|\Delta m^2_{32}| \sim 2.0 \times 10^{-3}$ eV^2 ;
$\sum_i m_i < 0.7$–2 eV.



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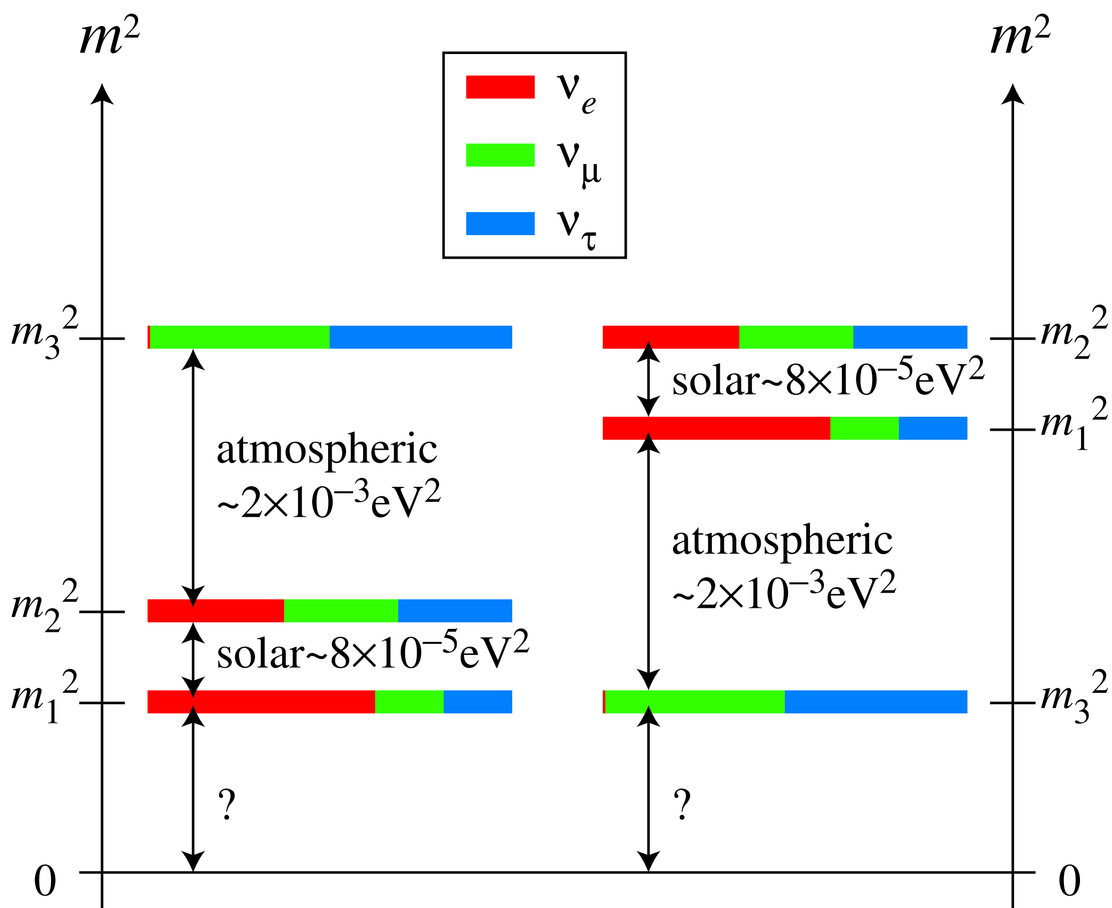
- $m_1 \sim m_2 \sim m_3 \sim 0.2$ eV (Degenerate hierarchy)
- $m_1 < m_2 \ll m_3$ (Normal hierarchy)
- $m_3 \ll m_1 < m_2$ Inverted hierarchy)

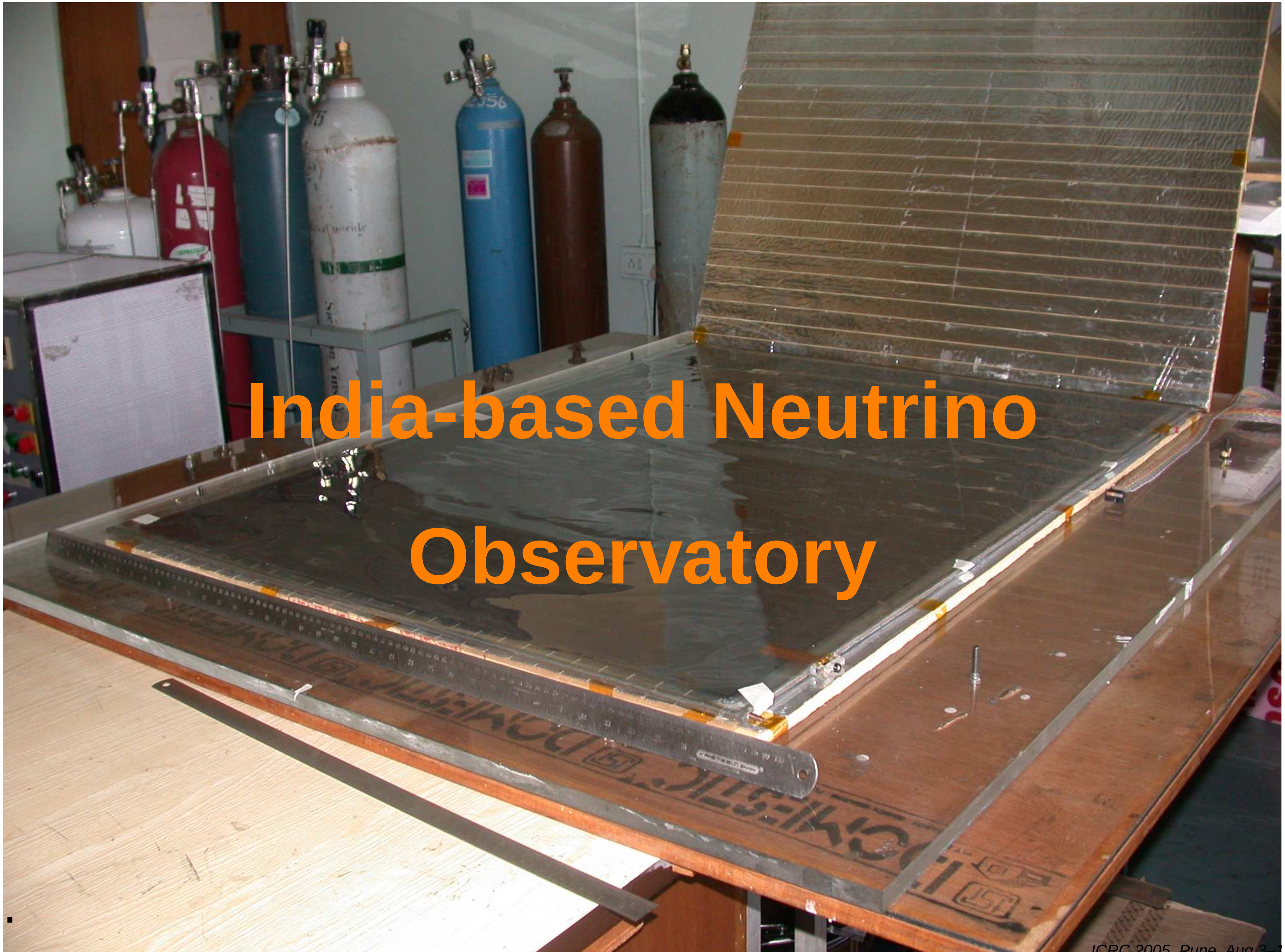


(APS multi-divisional neutrino study, physics/0411216)

In Summary

- Neutrinos are the least understood particles in nature.
- They have exotic properties: non-zero, distinct masses, and non-trivial mixing among the different flavours: this is because of compelling evidence for neutrino oscillation.
- While the depletion effects of oscillation are well-studied, a complete oscillation (with one minimum and one maximum) has not yet been directly studied in any single experiment and has only been inferred.
- The mass-squared differences as well as the masses are very small; the origin of small masses is a puzzle.

India-based Neutrino Observatory



The INO Collaboration

- Stage I : Study of atmospheric neutrinos

  The feasibility study of about 2 years duration for both the laboratory and detector is under-way. Issues under study are

  - Site Survey
  - Detector R & D, including construction of a prototype
  - Physics Studies
  - Human resources development

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- Other detectors/physics like neutrinoless double beta decay?

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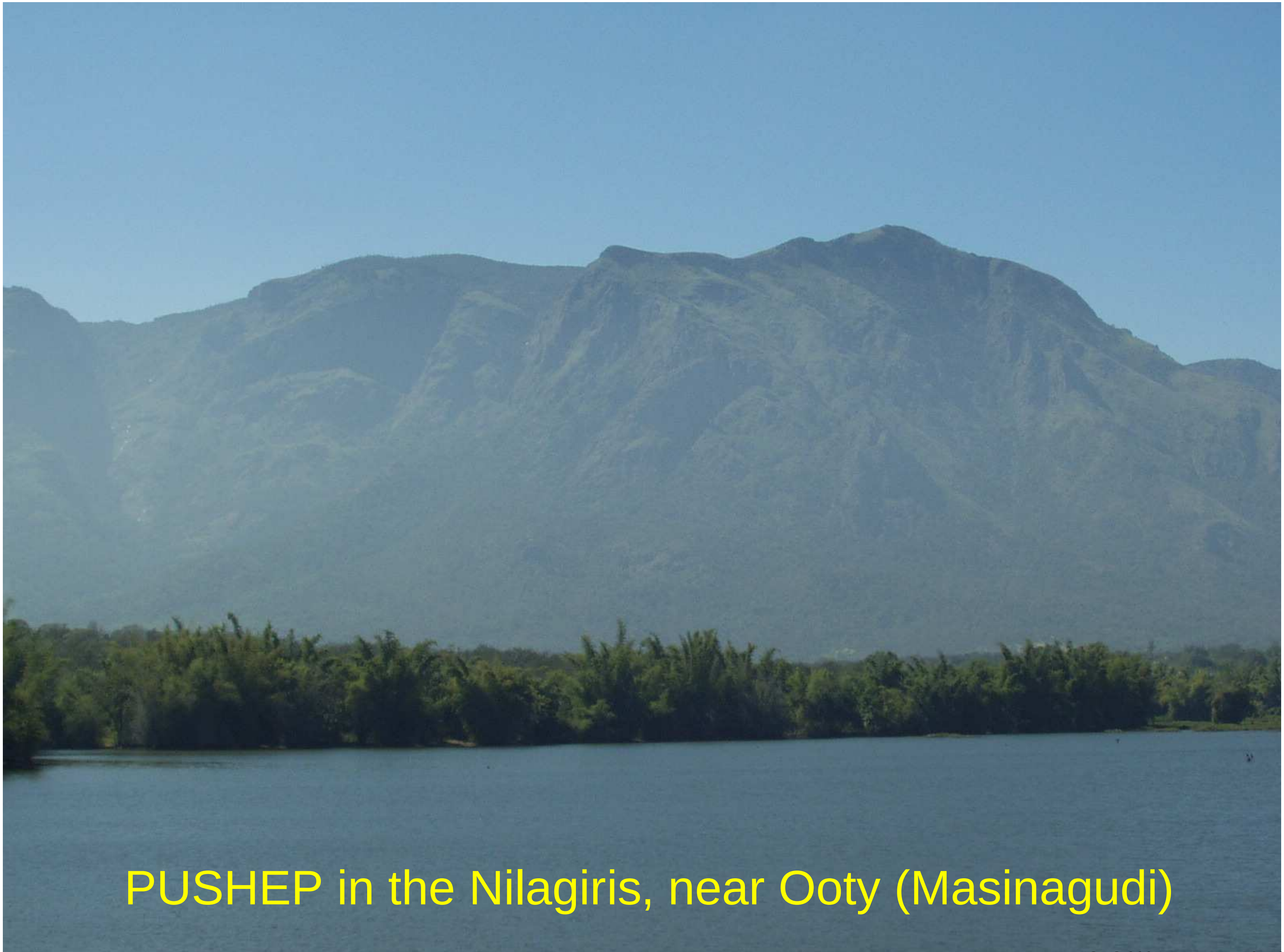
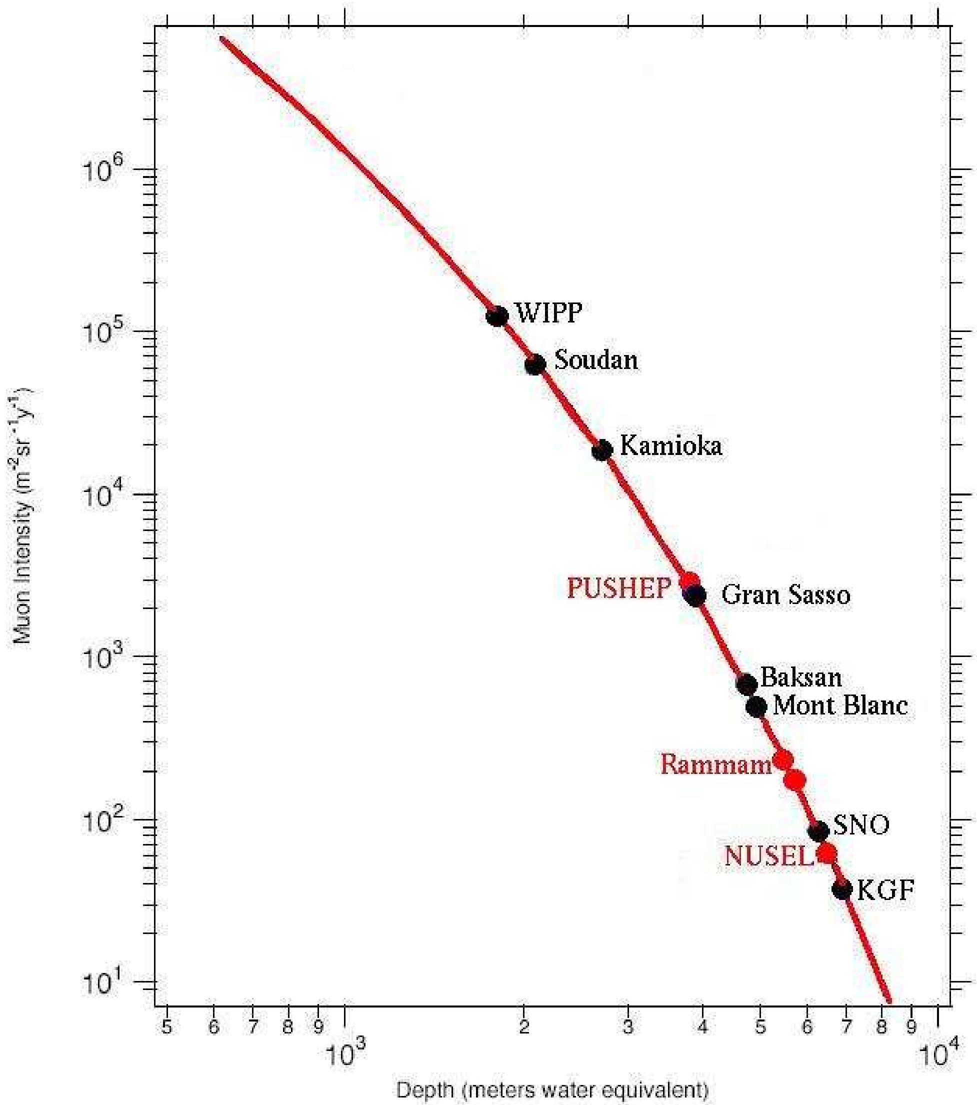
- Stage II : Study of long-baseline neutrinos, from a neutrino factory?
- Other detectors/physics like neutrinoless double beta decay?
- Should be an international facility

Site survey: PUSHEP



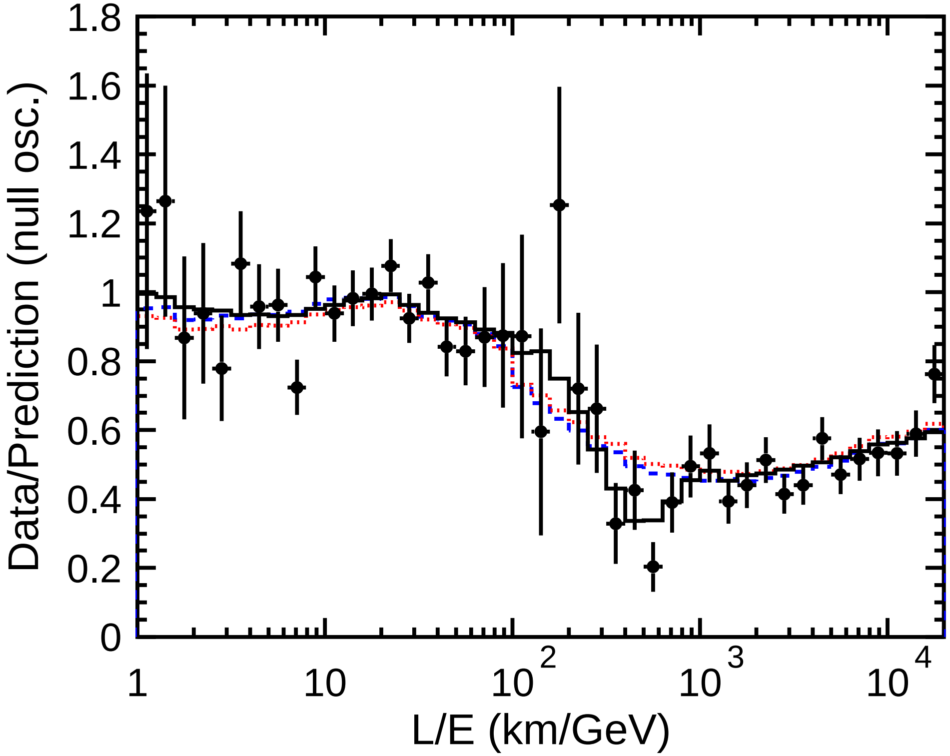
Site Survey: Rammam

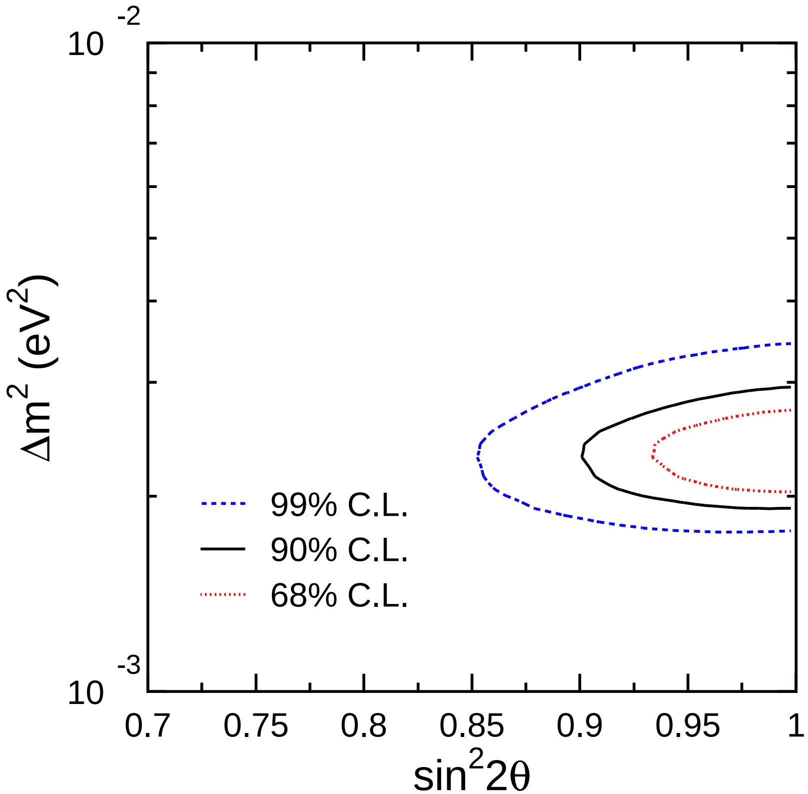
The depth at the sites



- Vertical energy-integrated flux is 2.5×10^3 /m^2/sr/yr at PUSHEP and 1.9×10^2 /m^2/sr/yr at Rammam.
- Cosmic ray background about 3000 events/hour for ICAL at PUSHEP.
- Cosmic ray background roughly ten times smaller at Rammam.

The difficulty . . . and the hope





- $\Delta m^2 = 2.4 \times 10^{-3}$ eV^2 ; $\sin^2 2\theta = 1.0$.
- Decay, decoherence, disfavoured at more than 3σ

Y. Ashie et al., Super-K Collab., Phys.Rev.Lett. 93 (2004) 101801 [hep-ex/0404034]

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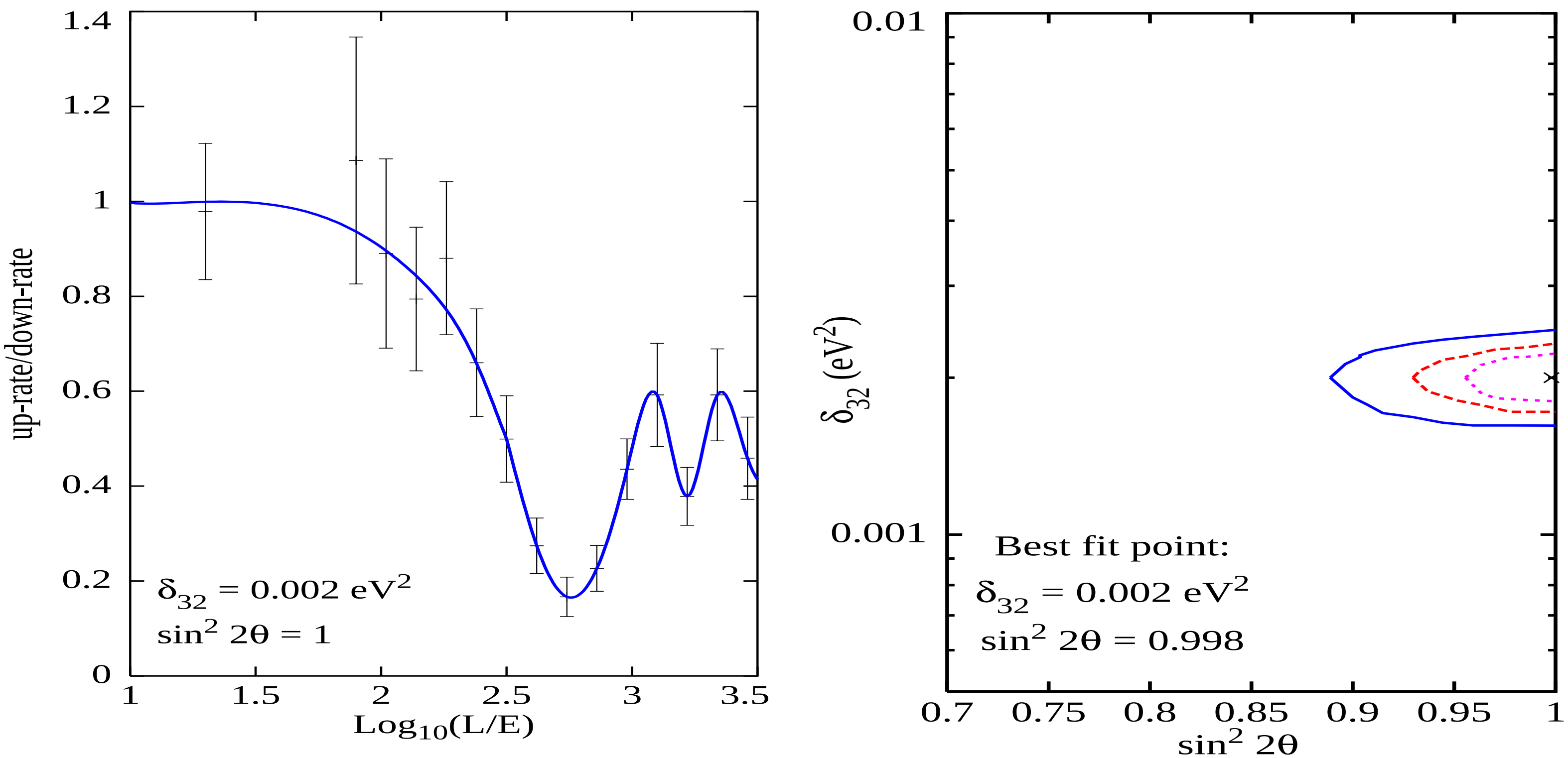


Simulation with ICAL detector, assuming 50% efficiency in L/E reconstruction

The choice of detector

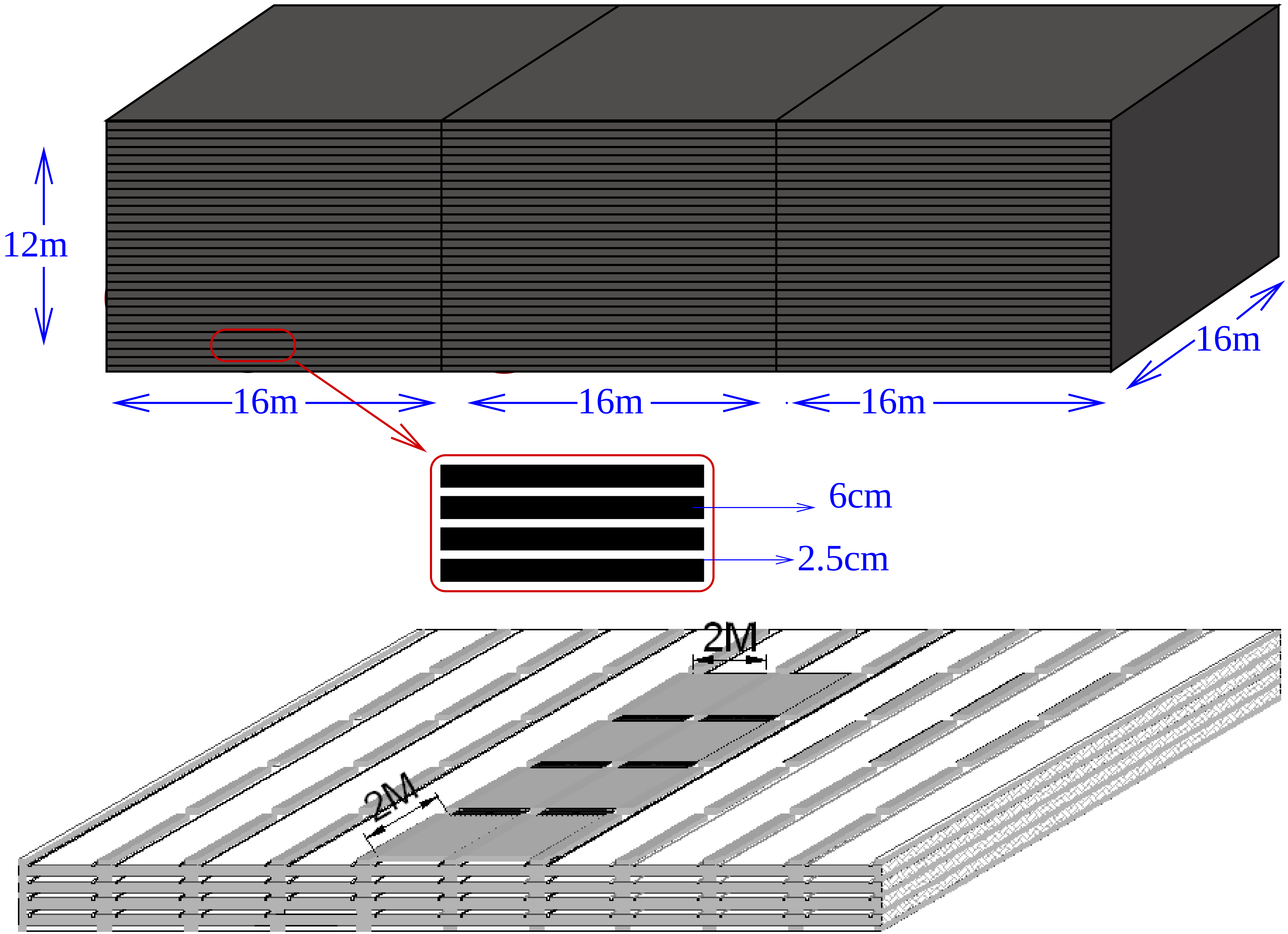
The detector should have the following features:

- Large target mass: 30 kton, 50 kton, 100 kton . . .
- Good tracking and energy resolution
- Good directionality; hence nano-second time resolution for up/down discrimination
- Good charge resolution
- Ease of construction (modular)

Use (magnetised) iron as target mass and RPC as active detector element

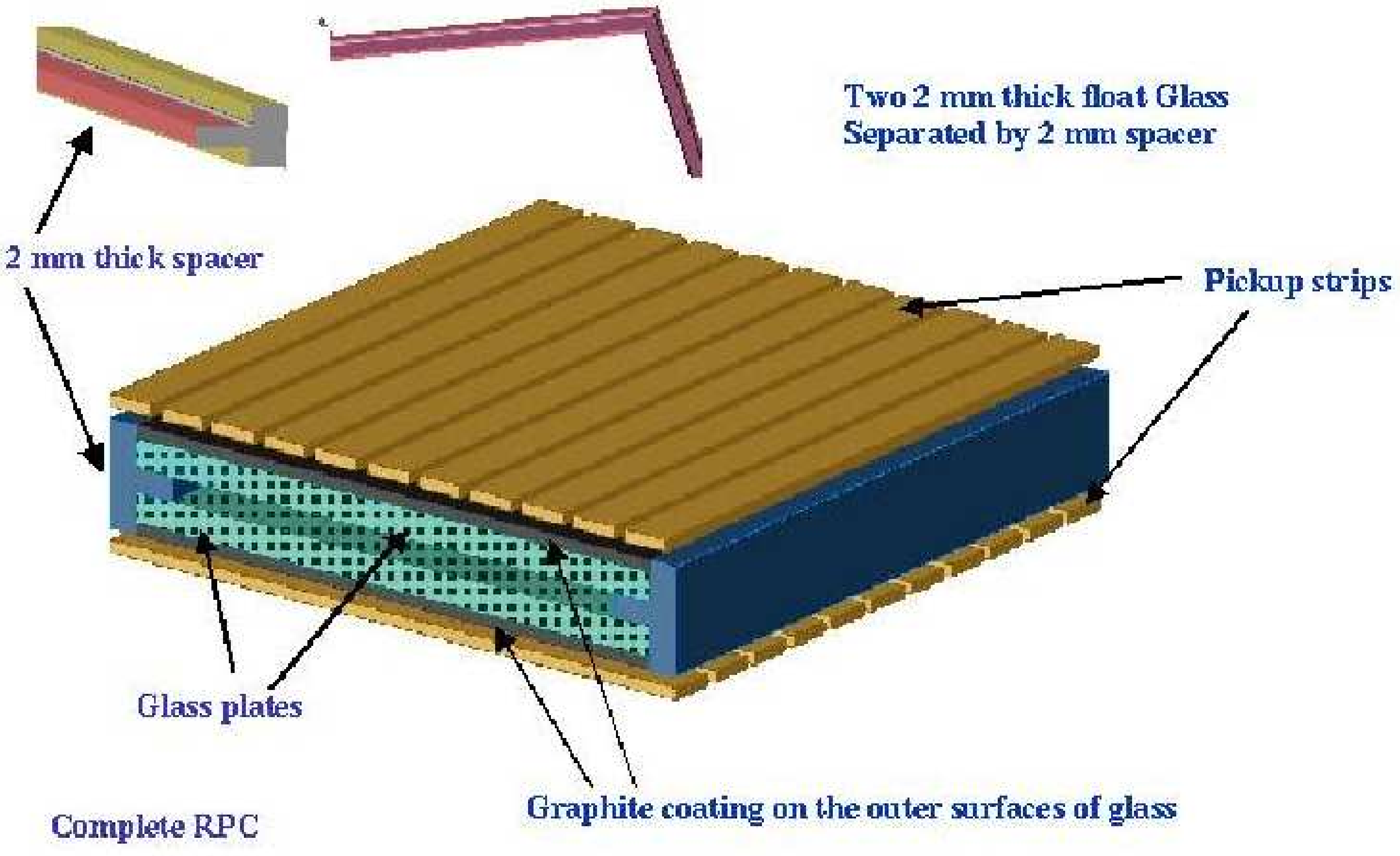
Note: Is sensitive to muons only

The ICAL detector



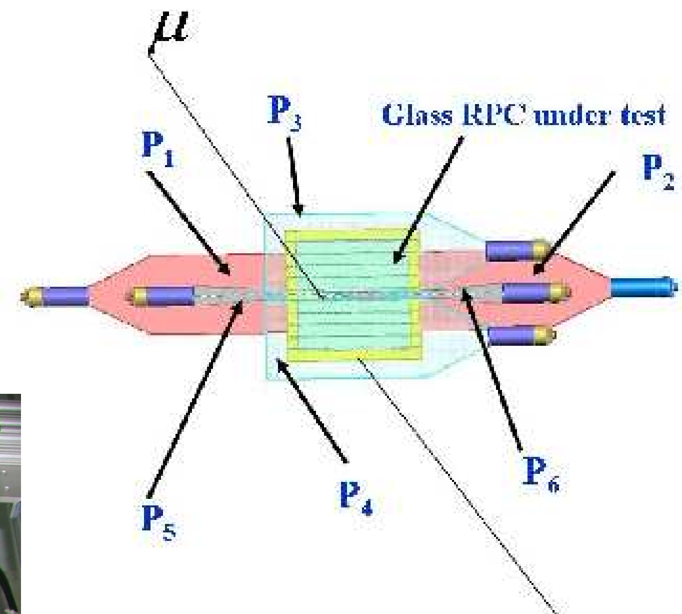
The active detector elements: RPC

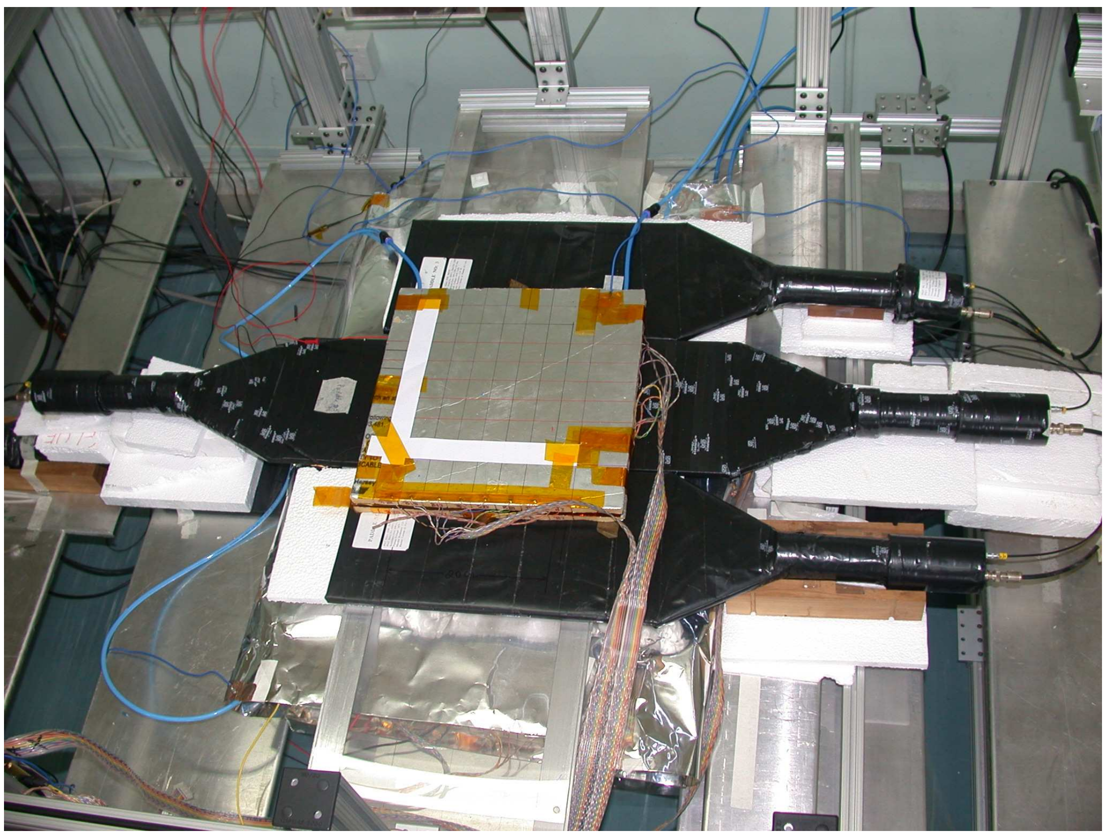
RPC Construction: Float glass, graphite, and spacers



Fabricating RPC's

at TIFR . . .





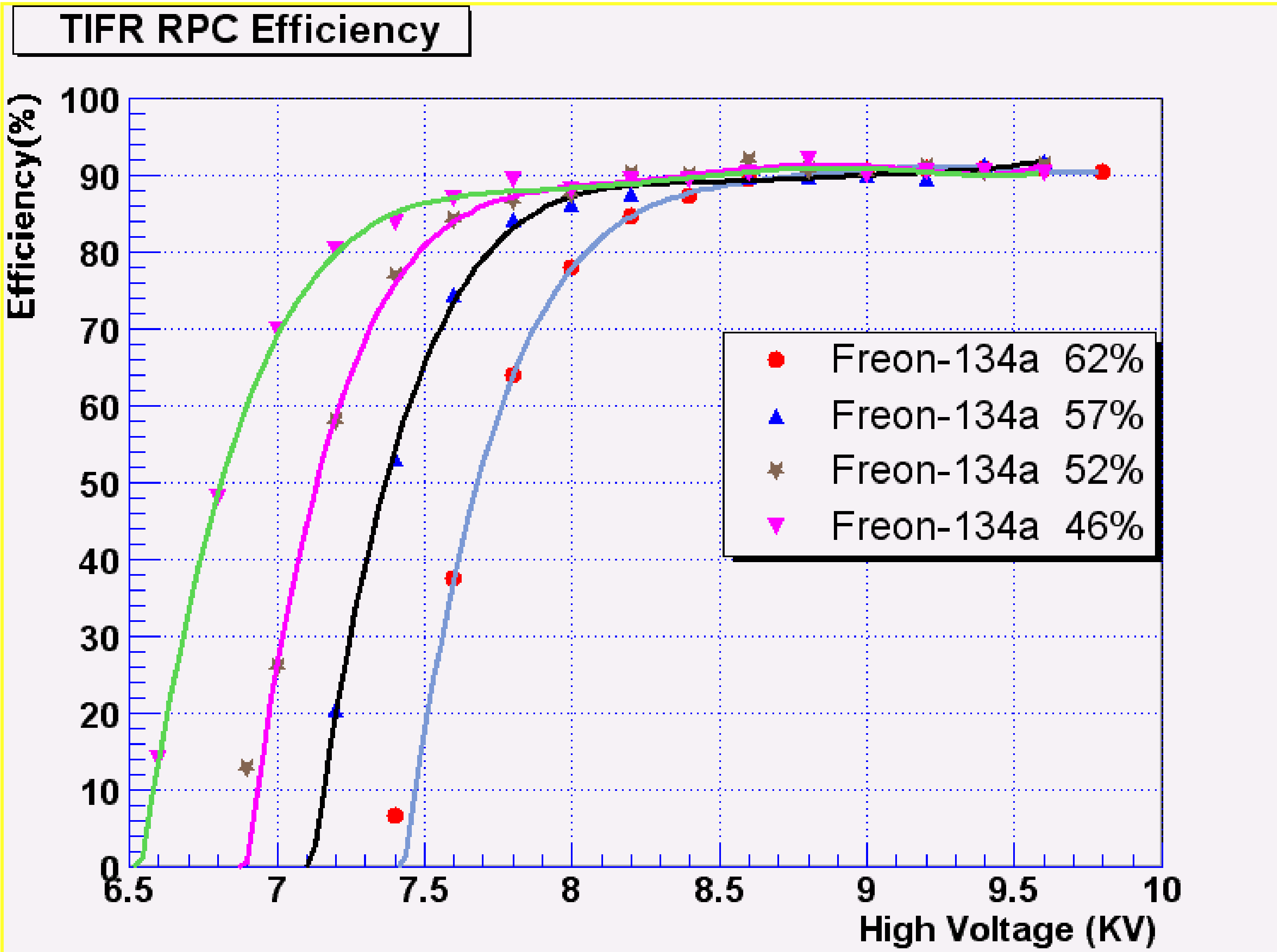
And of course . . .

Specifications of the ICAL detector

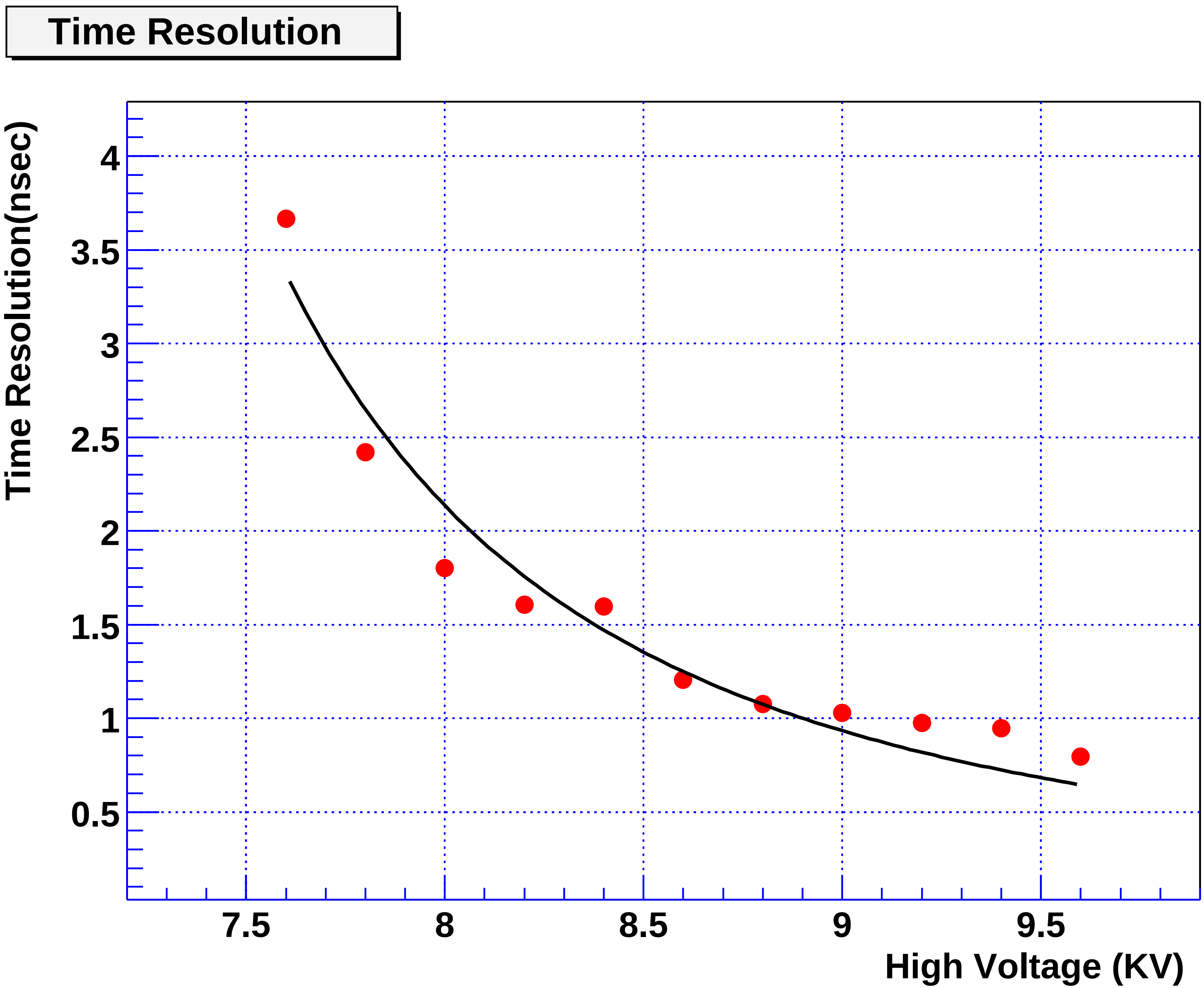
ICAL	
No. of modules	3
Module dimension	16 m $\times$ 16 m $\times$ 12 m
Detector dimension	48 m $\times$ 16 m $\times$ 12 m
No. of layers	140
Iron plate thickness	$\sim$ 6 cm
Gap for RPC trays	2.5 cm
Magnetic field	1.3 Tesla
RPC	
RPC unit dimension	2 m $\times$ 2 m
Readout strip width	3 cm
No. of RPC units/Road/Layer	8
No. of Roads/Layer/Module	8
No. of RPC units/Layer	192
Total no. of RPC units	$\sim$ 27000
No. of electronic readout channels	3.6 $\times$ 10^6

RPC Efficiency studies

Using different combinations of gas



RPC Time resolution



Other issues w.r.t RPC R & D

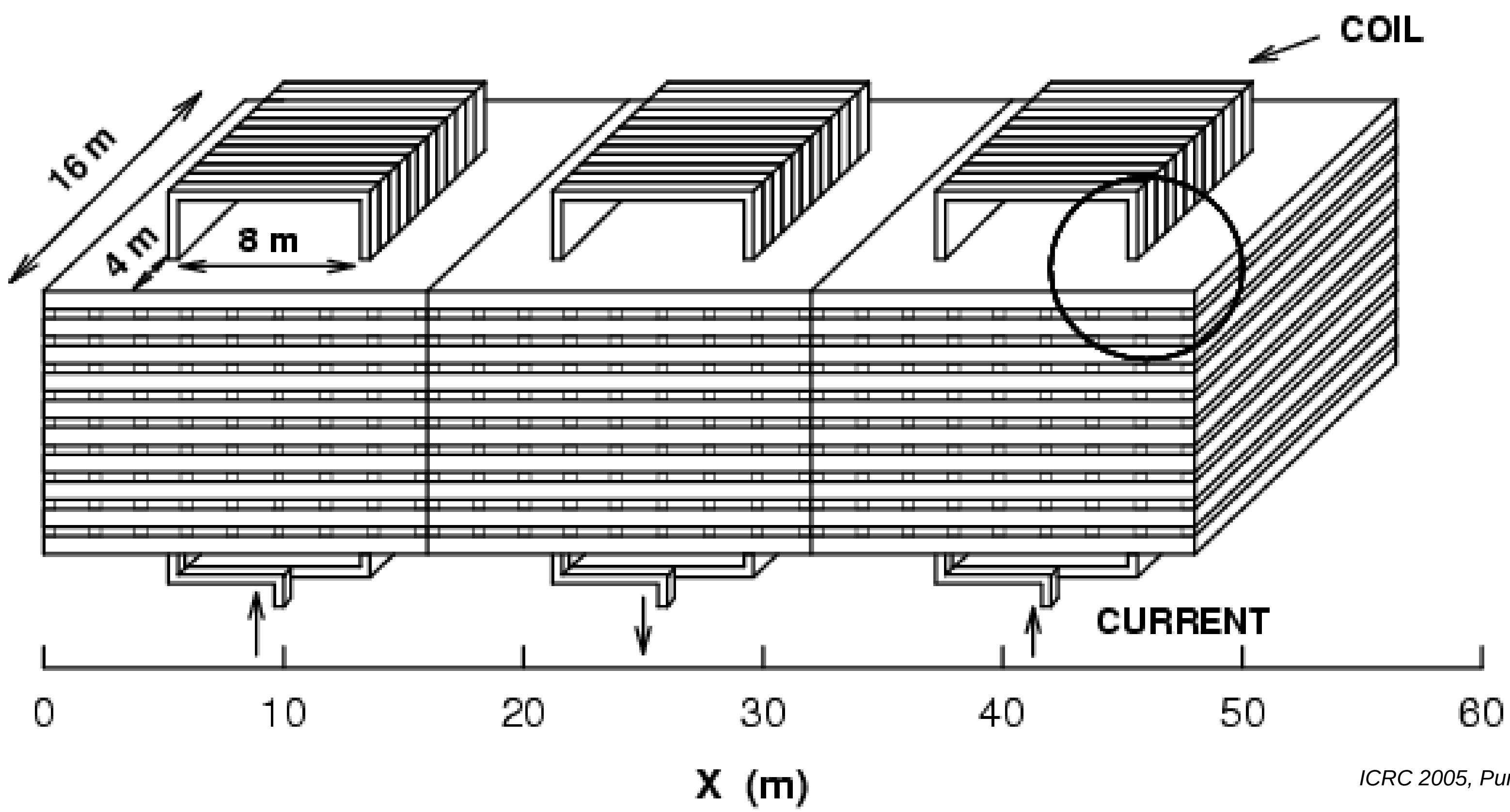
- RPC timing
- RPC charge distribution
- Mean charge vs voltage (seen to be linear)
- RPC noise
- Gas composition ($C_2H_2F_4$ (R-134a), Argon, Isobutane ($\leq$ 8%))
- RPC Cross talk (as a function of gas mixture)
- Gas mixing

Magnet studies

Design criteria:

- Field uniformity
- Modularity
- Optimum copper-to-steel ratio
- Access for maintenance

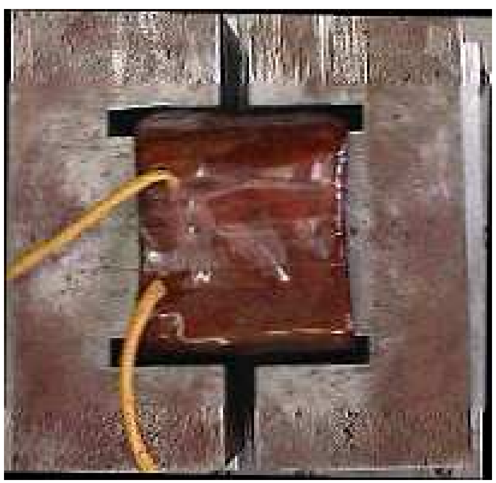
Toroidal Magnet design

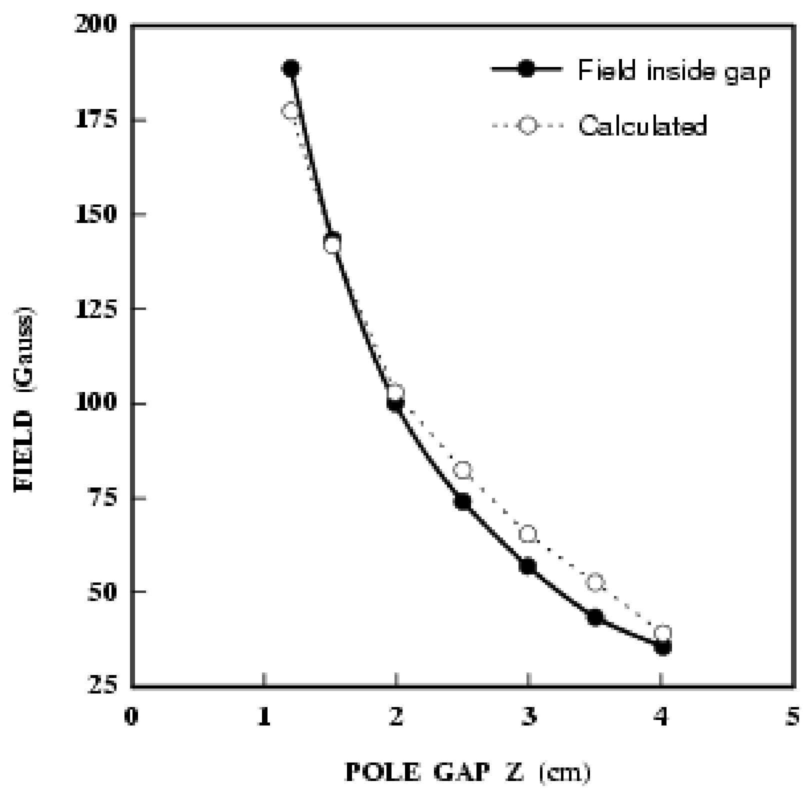


The prototype magnet

- 13 layers of 1 m $\times$ 1 m 6 cm thick iron
- It may be easier to use a Helmholtz-coil pair magnet with yoke

The VECC scaled-down 1:100 model agrees quite well with a 2D magnet code.

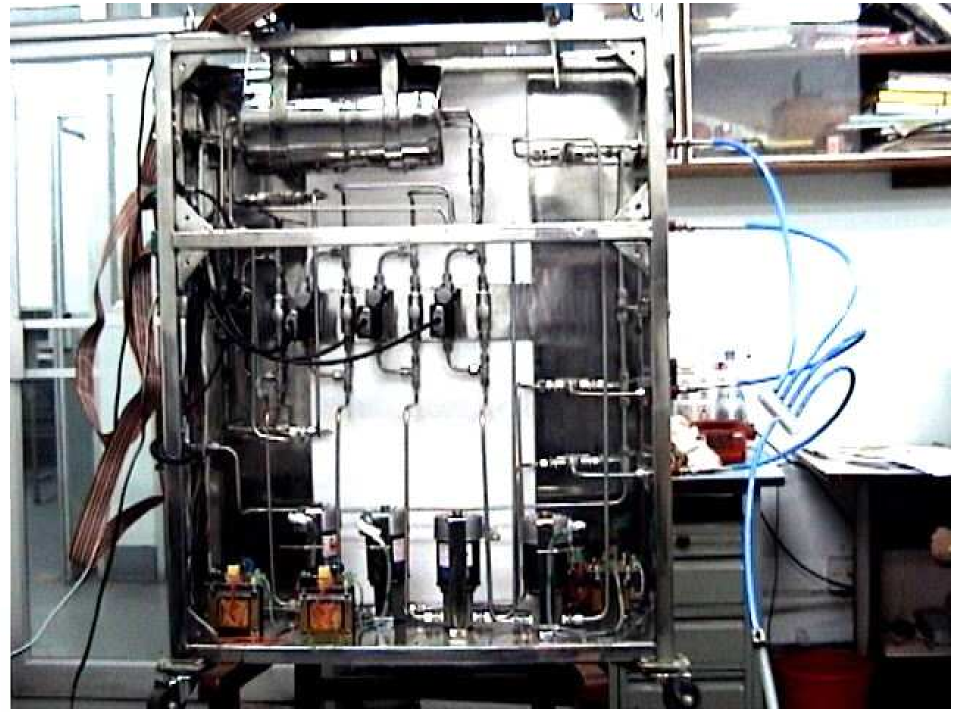


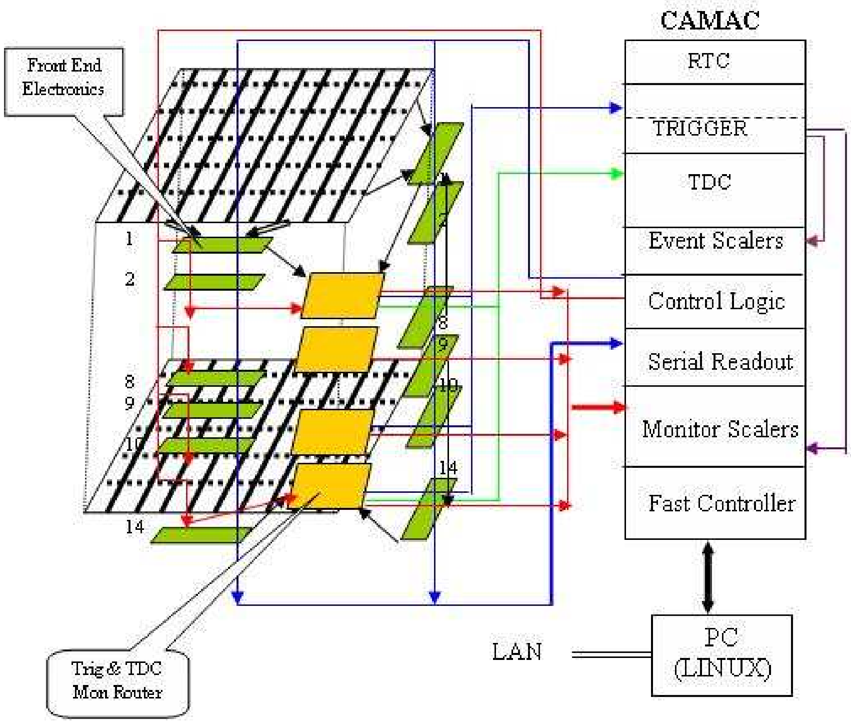


All new studies with MagNet6.0 3D software

For the prototype . . .

The gas-mixing unit at SINP



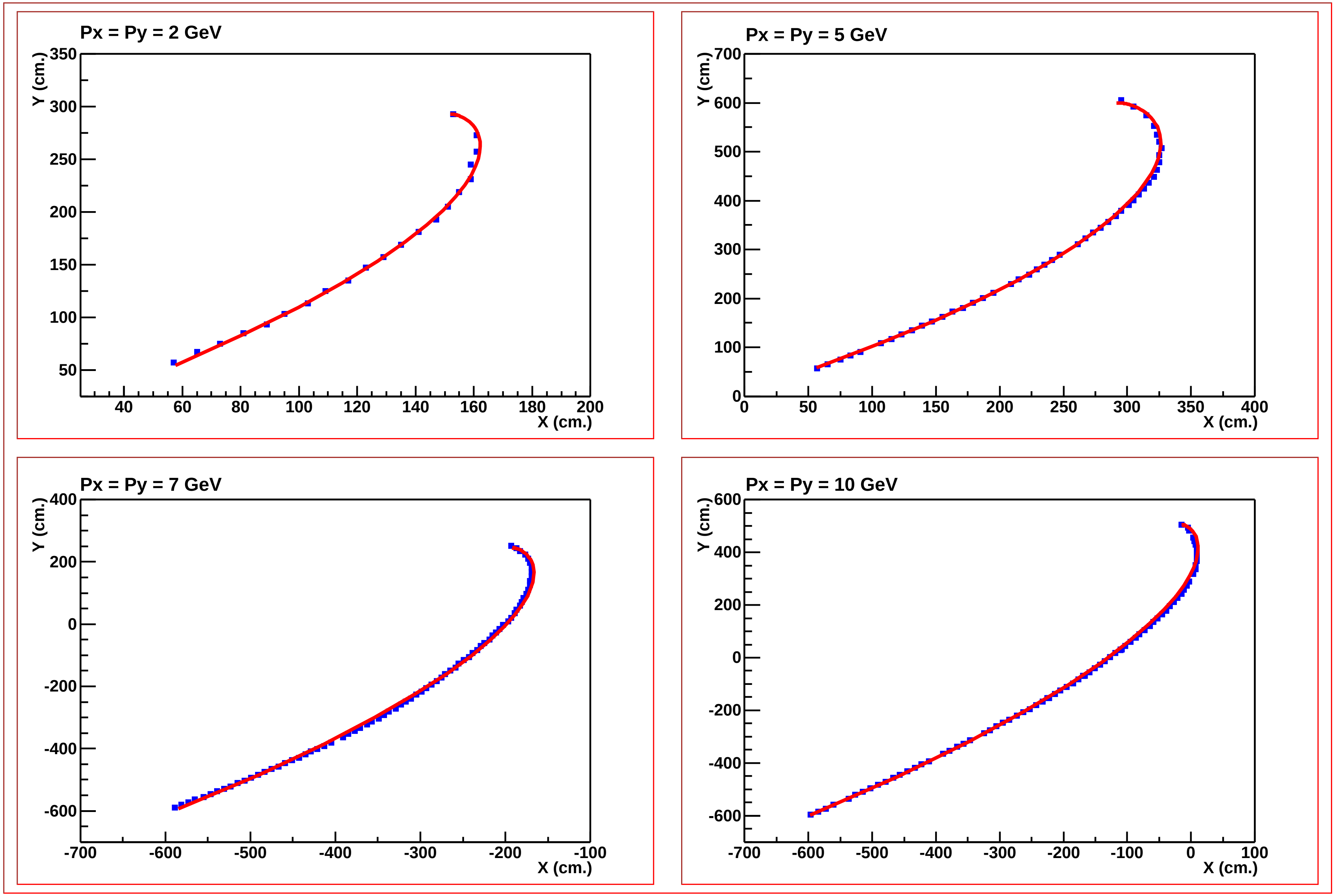


A schematic of the read-out electronics for the prototype

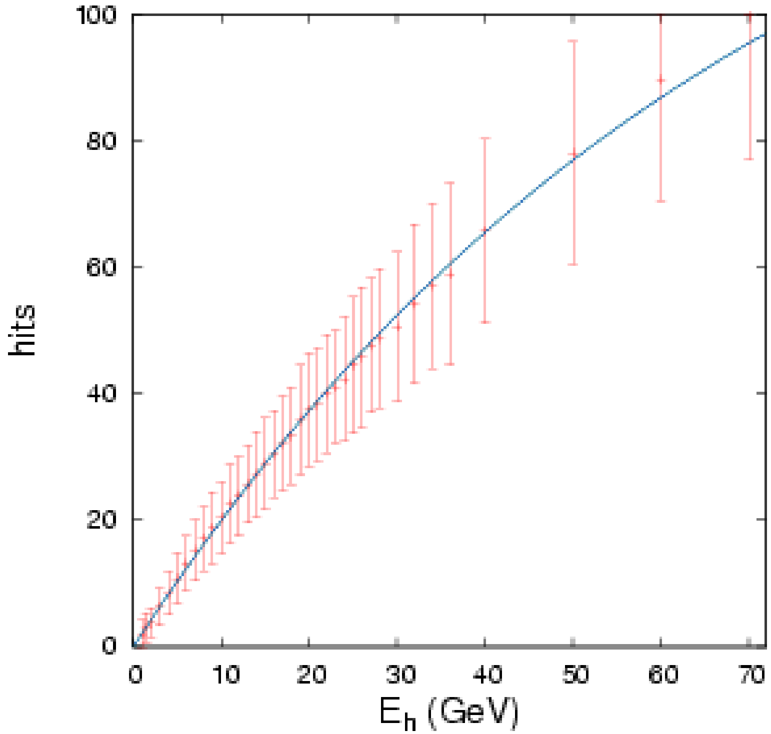
Physics with Atmospheric Neutrinos

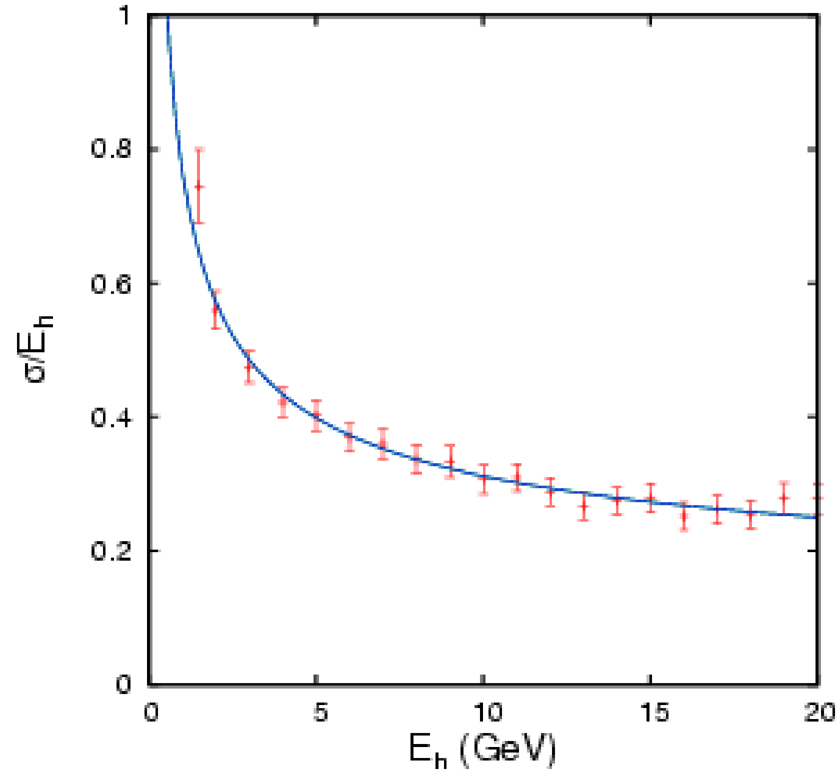
- Simplified ICAL detector geometry encoded in Nuance neutrino generator.
- Events are generated using HONDA flux with some input oscillation parameters δ_{23}, θ_{23}, and θ_{13}.
- Analysis ONLY of CC events with μ in the final state (electron CC events mostly lost); typically interesting events have $E > 1$–2 GeV.
- These events are passed through a simulated ICAL detector using the GEANT detector simulation tool.
- Uniform magnetic fields (in the z- and y-directions only have been studied.
- The tracks are reconstructed for muons and the energy/momentum/charge determined.
- Recall: ICAL geometry is similar to that of MONOLITH.

Event Reconstruction



Hadron Energy Reconstruction



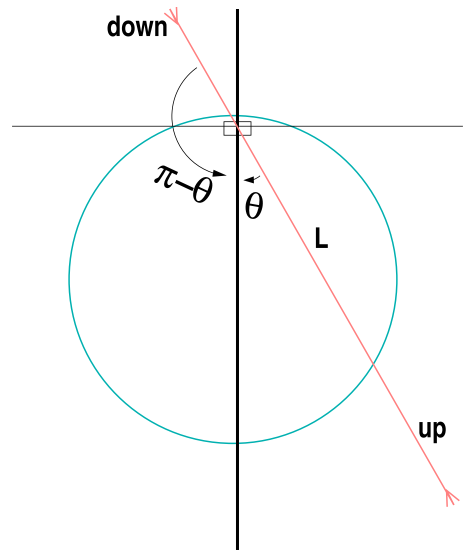


- Analysed two sets of data: with and without magnetic field.
- For the former, could analyse both the fully-contained as well as partially contained events.
- About 40–50% of the generated events survived the cuts

Physics goals

➢ Main goal: Study oscillation pattern in atmospheric neutrino events. The up/down events ratio is sensitive to oscillation parameters.

(Pietropaolo and Picchi)

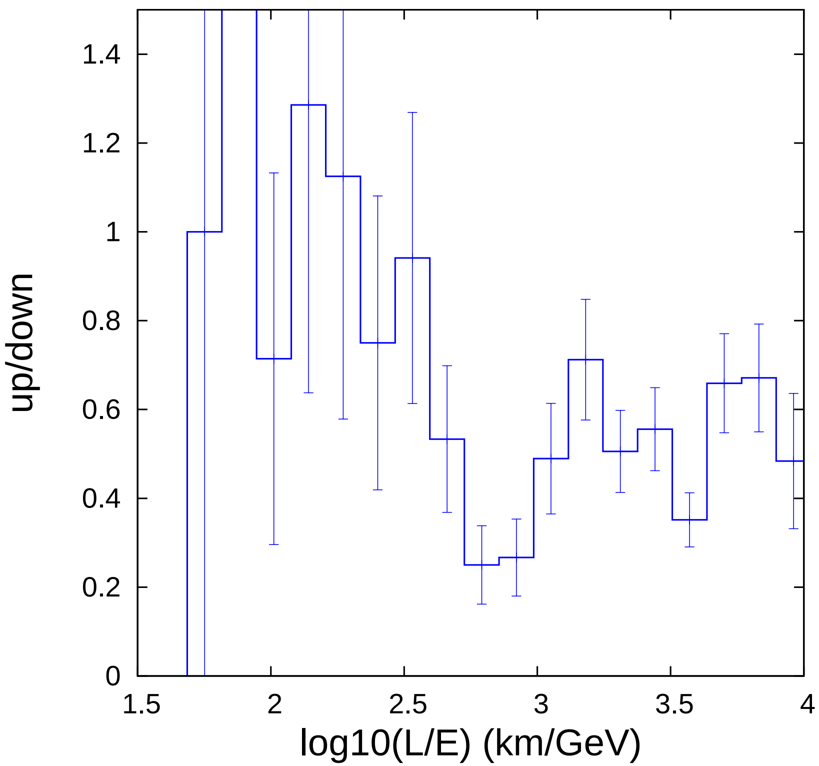


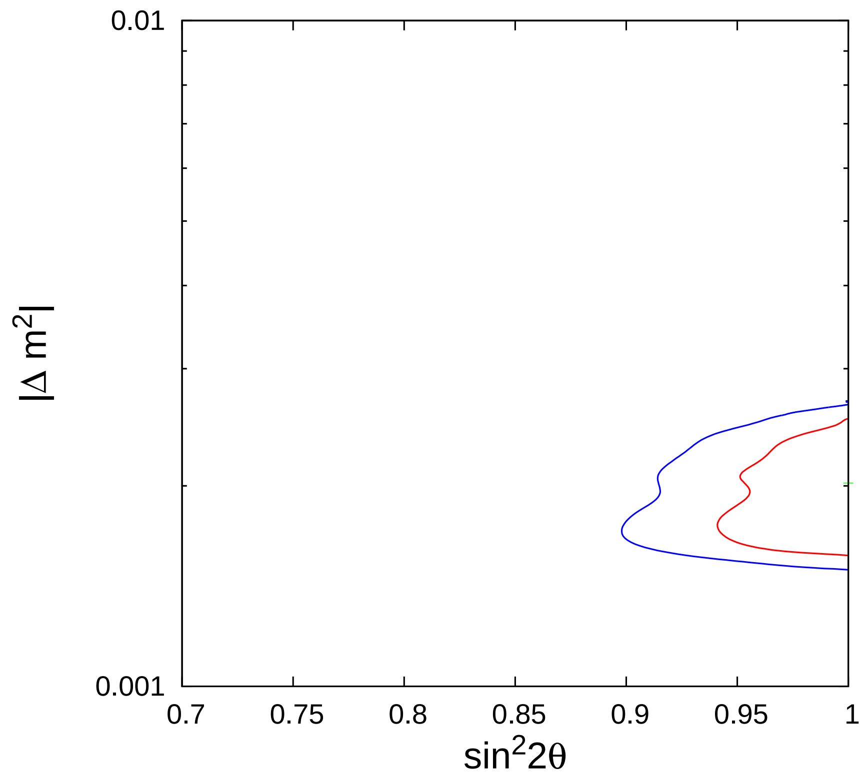
$$\frac{\text{up rate}}{\text{down rate}} = P_{\mu\mu} = R \otimes \left\{ 1 - \frac{\sin^2 2\theta_{23}}{2} \left(1 - \cos 2.54\, \Delta m^2_{32} \frac{L}{E} \right) \right\} .$$

R is determined by the L/E resolution of the ICAL detector

So, analysis *needs* a knowledge of this resolution function, which depends on the quality of reconstruction of tracks in the detector.

Results for the FC case with $B_y = 1\mathrm{T}$





Shown are 90 and 99% CL contours, along with the best-fit value.

- Inputs: $\Delta m^2_{32} = 2 \times 10^{-3}$ eV^2; $\sin^2 2\theta_{23} = 1.0$
- Best-fit: $2.02^{+0.27}_{-0.24} \times 10^{-3}$ eV^2; $\sin^2 2\theta_{23} > 0.96$

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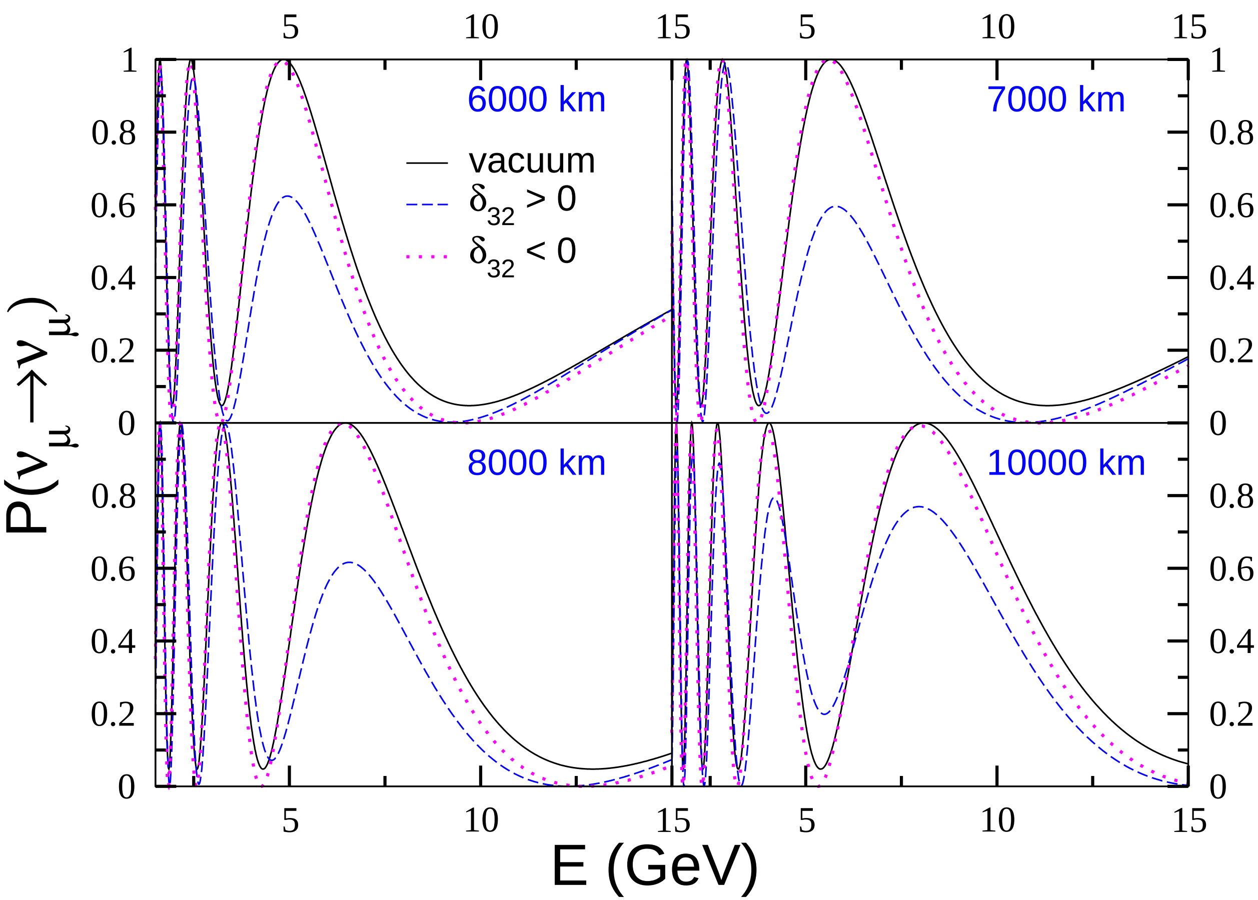
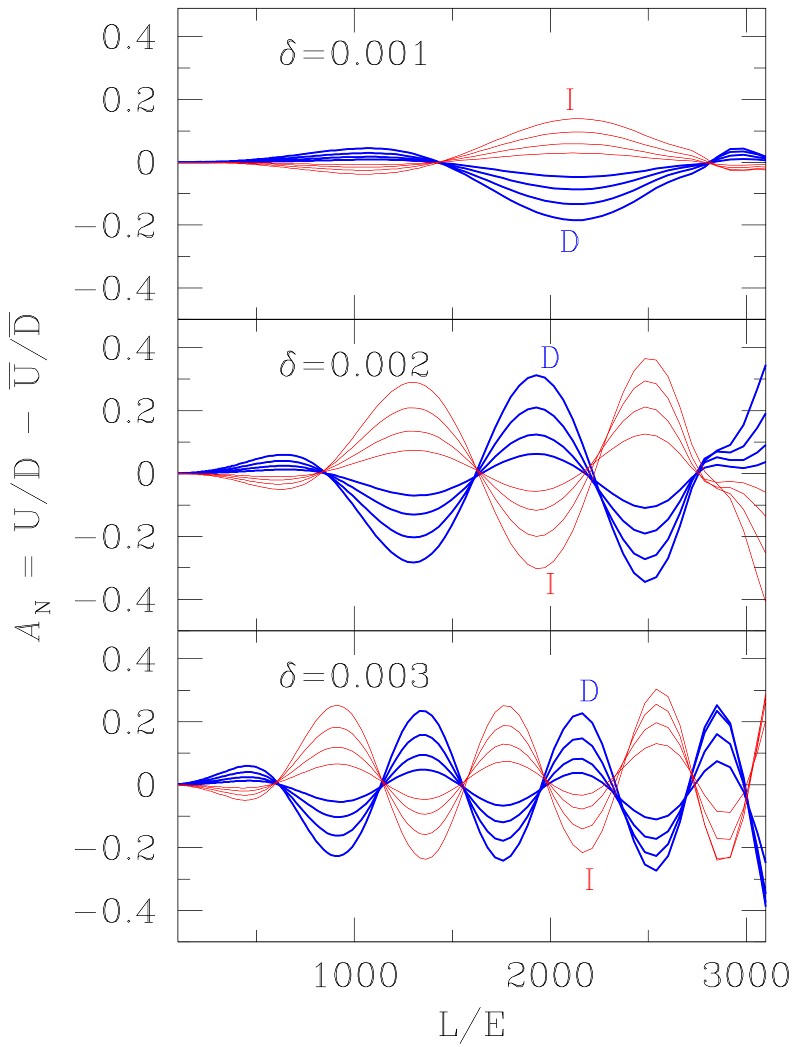
Matter effects with atmospheric neutrinos



- Matter effects involve the participation of all three (active) flavours; hence involves both $\sin\theta_{13}$ and the CP phase δ.

The difference asymmetry



$\delta \equiv \Delta m^2_{32}$

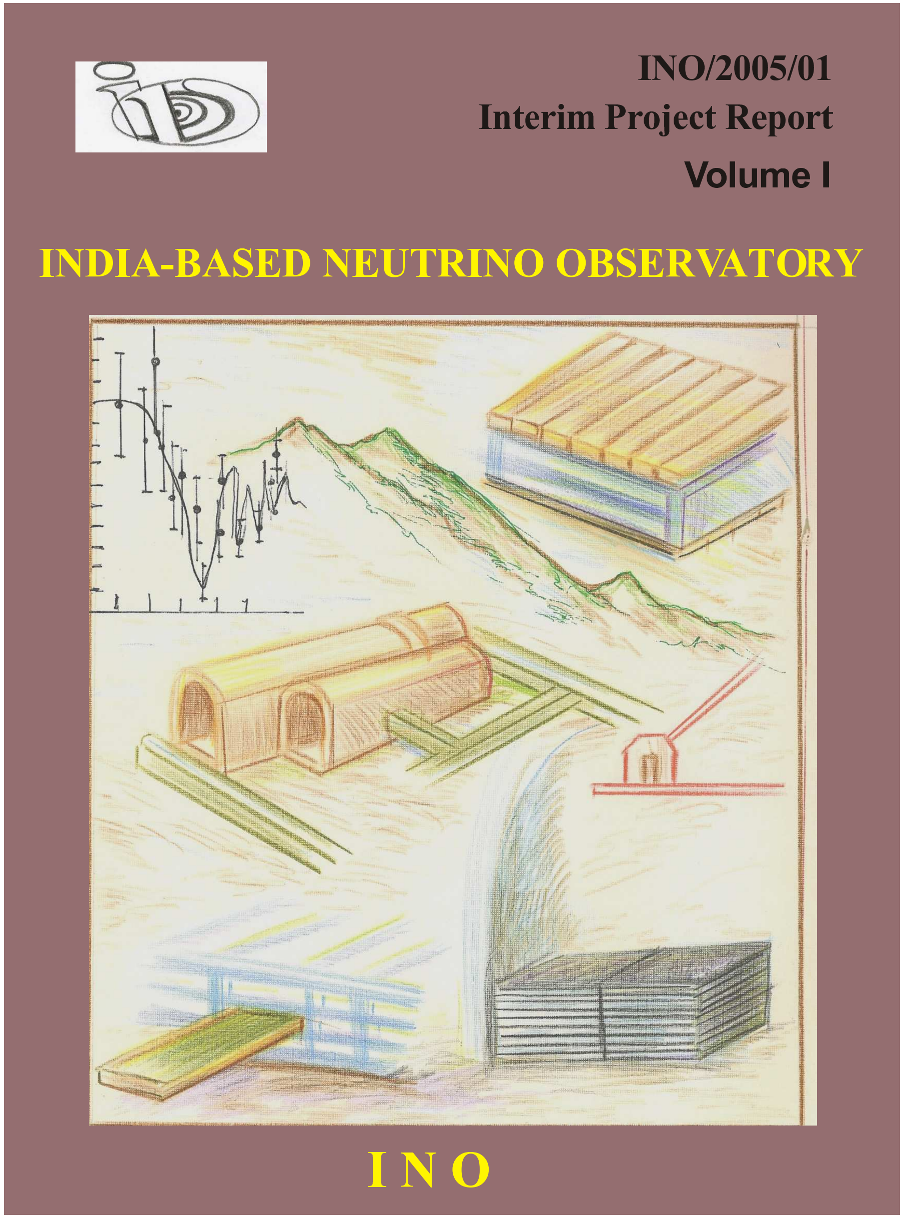
Hence sensitive to the mass ordering (red vs blue) of the 2–3 states; however, needs large exposures of about 1000 kTon-years.

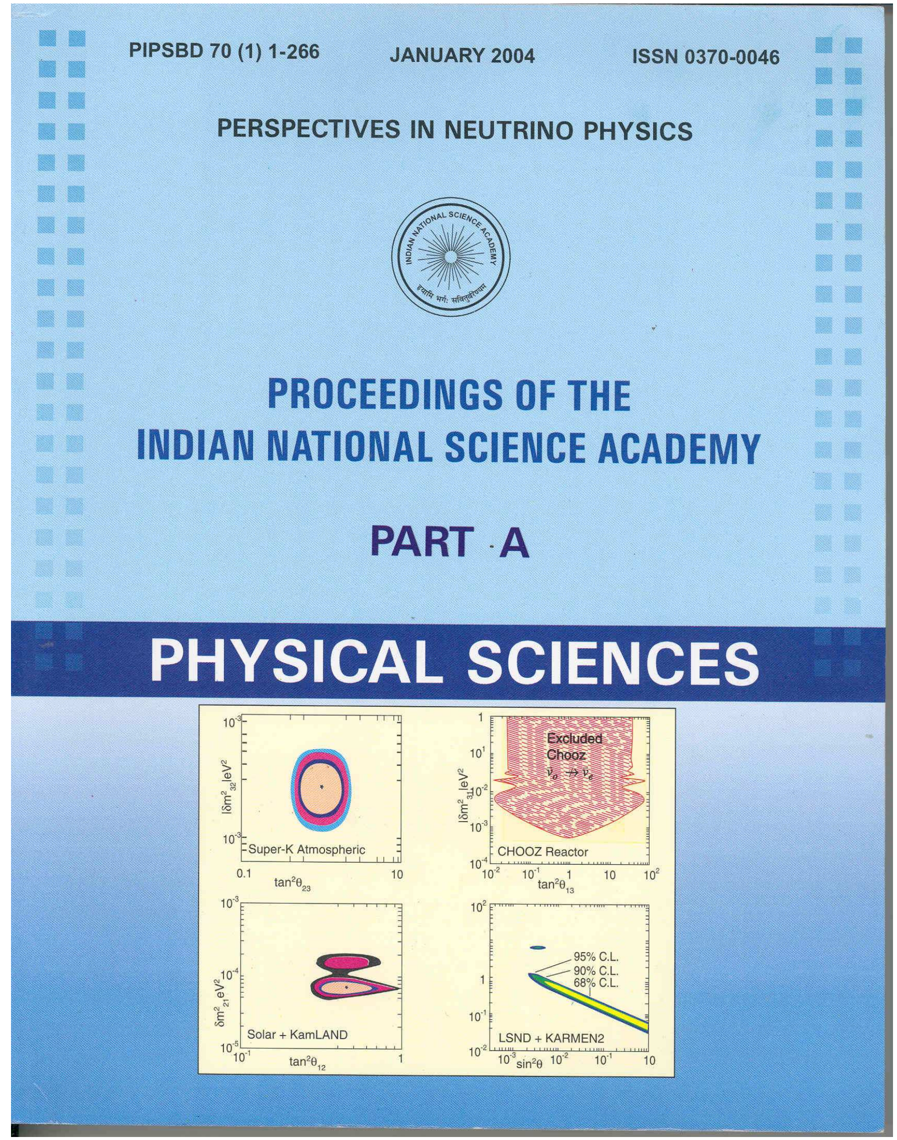
Other physics possibilities

. . . with atmospheric neutrinos

- Discrimination between oscillation of ν_μ to active ν_τ and sterile ν_s from up/down ratio in “muon-less” events.
- Probing CPT violation from rates of neutrino- to rates of anti-neutrino events in the detector: sensitive to δb, which adds to $\Delta m^2_{32}/(2E)$ in oscillation probability expression.
- Constraining long-range leptonic forces by introducing a matter-dependent term in the oscillation probability even in the absence of U_{e3}, so that neutrinos and anti-neutrinos oscillate differently.

Status Report





Interim Report, submitted to funding authorities, May 1, 2005

Stage II: Physics goals

Stage II: Neutrino factories and INO (ICAL++)

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- A determination of $\sin\theta_{13}$ itself
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- INO (ICAL++) is a possible far-end detector for such long baseline experiments

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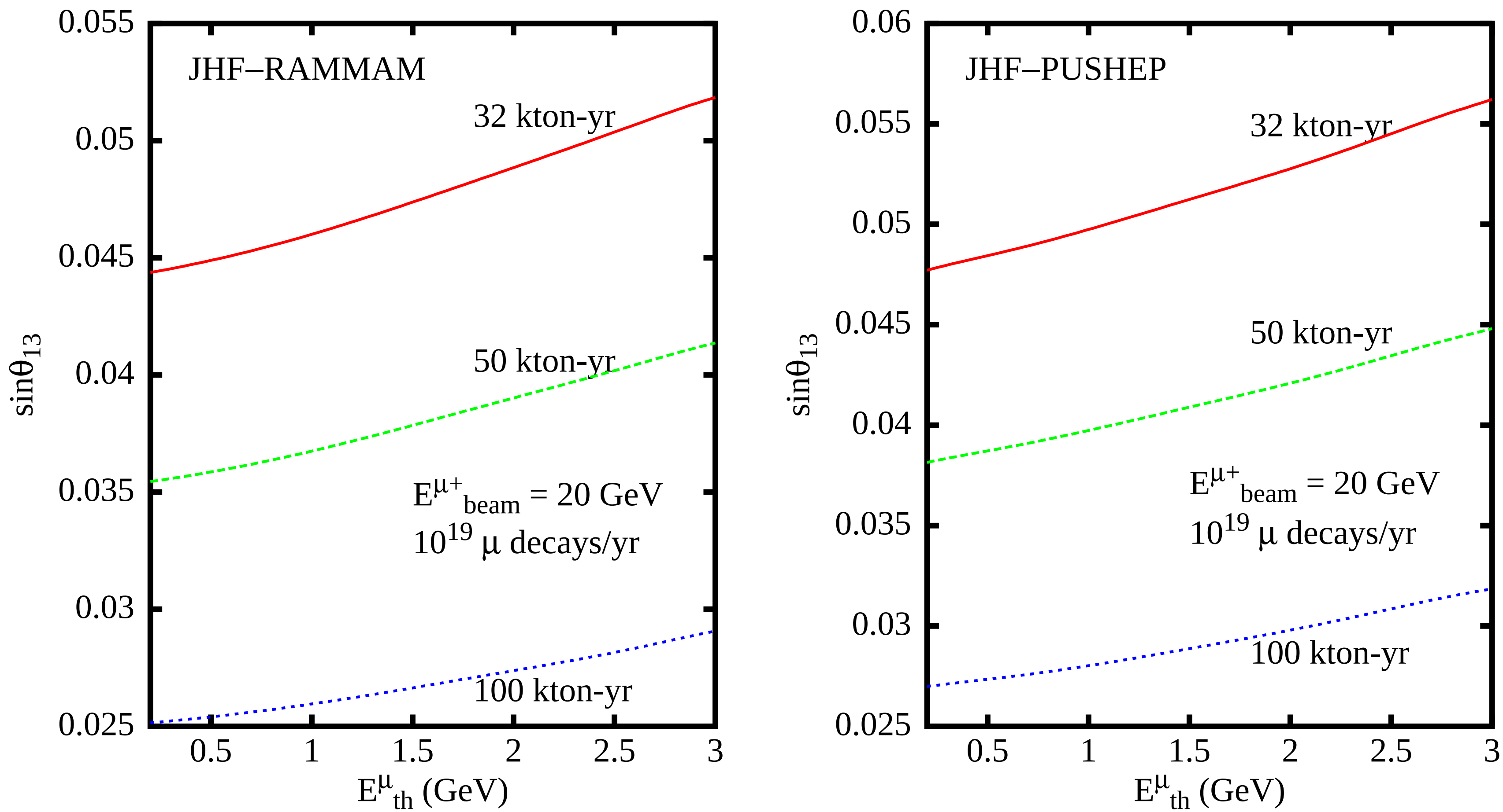
- Result: wrong sign muon (10/kton = signal)

  Note: Since ICAL is not very sensitive to electrons, the mode in which the wrong-sign event is from electron detection (sensitive to $P_{\mu e}$) is not considered here.

Reach of $\sin\theta_{13}$

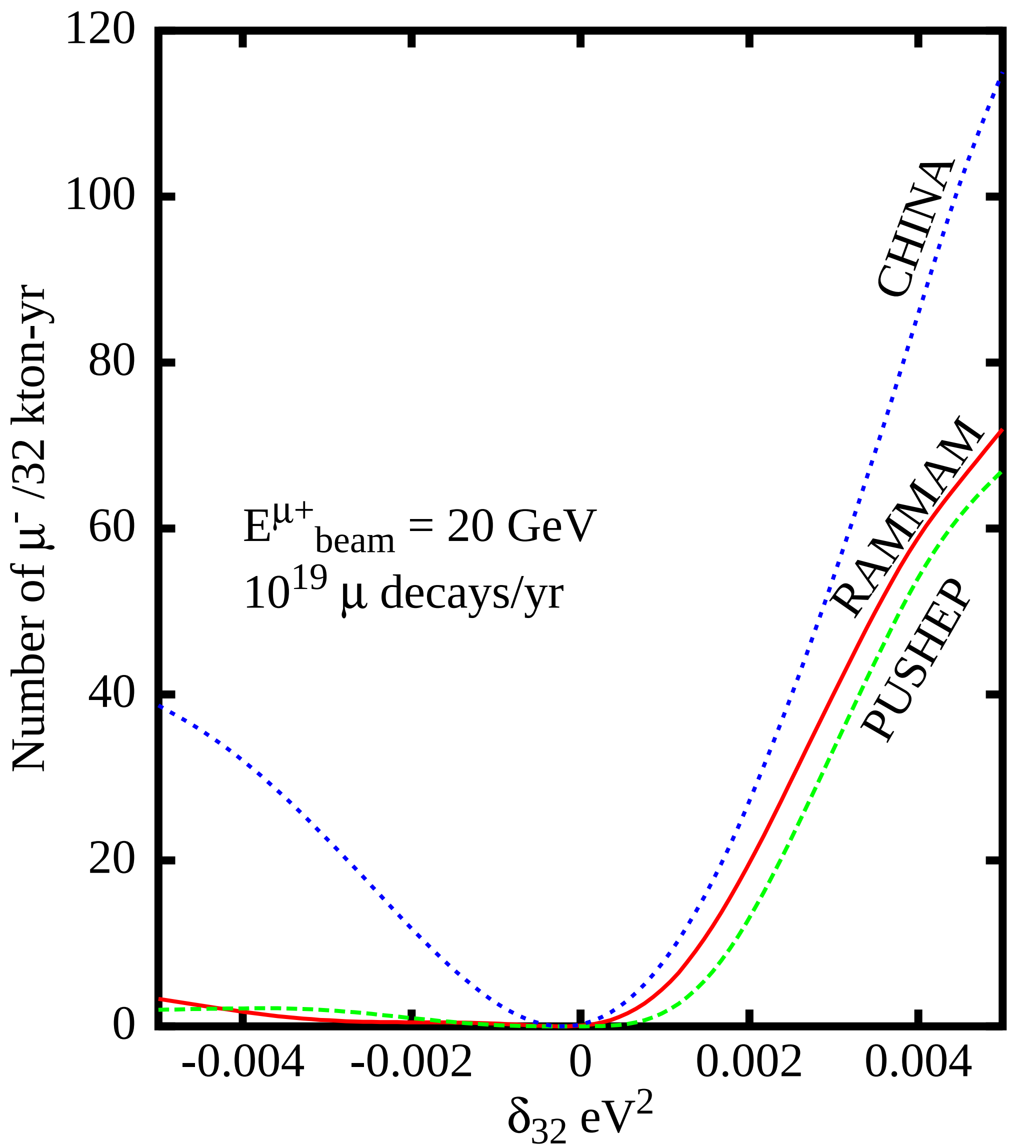
JHF to Rammam — Fermilab to PUSHEP



$\sin\theta_{13}$ reach for different muon threshold energies.

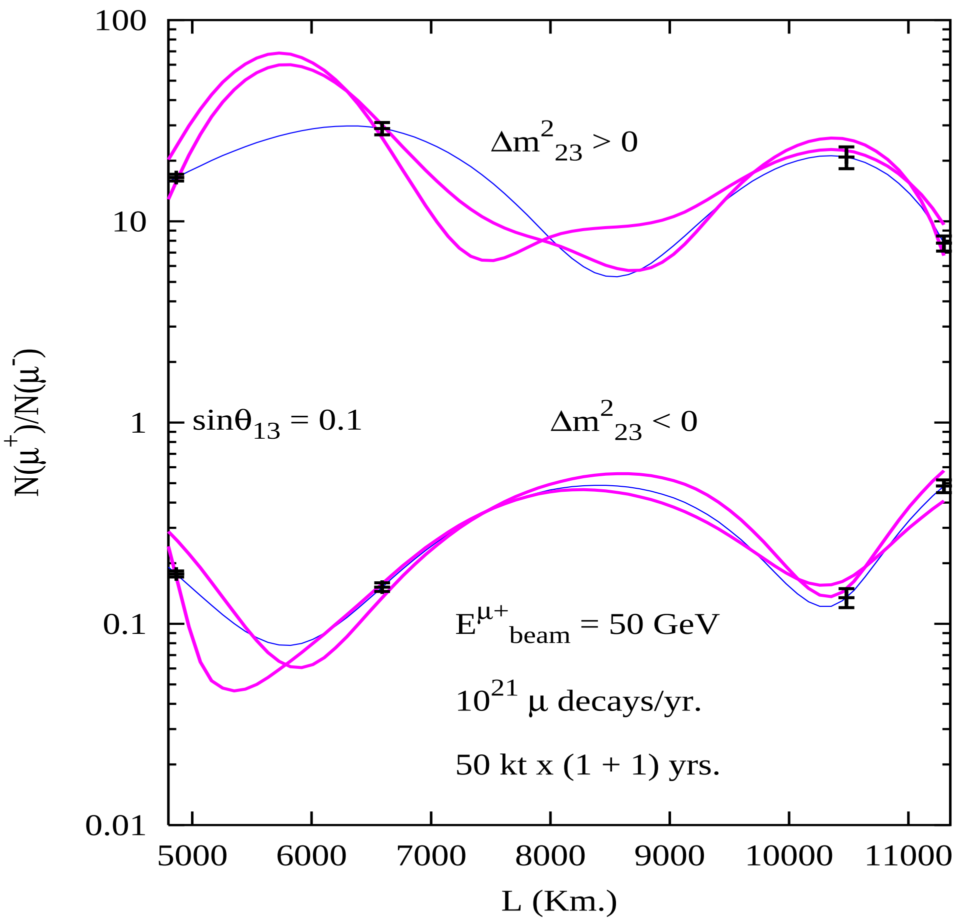
Sign of Δm^2_{32} vs wrong sign μ

JHF to Beijing, Rammam and PUSHEP



CP violation: δ vs L

JHF to Rammam and PUSHEP



FermiLab to Rammam and PUSHEP

Other studies at INO

- Neutrino-less double beta decay. A working group is looking at the possibility of cryogenic detection to measure DBD in ^{124}Sn and ^{150}Nd.

- A low energy accelerator for nuclear astrophysics. A proposal to study some thermonuclear reactions using a 3 MV tandem accelerator has been proposed.

Outlook

- Proof-of-principle working of RPC shown
- Magnet studies under-way
- Construction of prototype is immediate goal
- Site survey: two possible sites, both seem good options
- Simulations: programs in place, need refining and testing.

Outlook

- Atmospheric neutrino programme:

  ICAL sensitive to oscillation parameters to better accuracy than current Super-K.

  Also, may have the edge on MINOS iff Δm^2_{32} is smaller than expected.

  May be sensitive to matter effects and the 2–3 mass ordering if $\sin^2 2\theta_{13} > 0.05$.

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- Neutrino Factory Programme:

  ICAL++, with suitable beam from future nu-factory, is sensitive to $\sin^2 2\theta_{13}$, sign of δ_{23}, and CP phase (?) due to the very large baselines involved.

  JHF-PUSHEP baseline is near magic: may provide clean separation of matter and CP violation effects.

In short . . .

The outlook looks good! This is a massive project:

Looking for active collaboration both within India and abroad

- **Bhabha Atomic Research Centre (BARC), Mumbai:**
  V. Arumugam, Anita Behere, M. S. Bhatia, V. B. Chandratre, V. M. Datar, M. P. Diwakar, M. G. Ghodgaonkar, A. K. Mohanty, P. K. Mukhopadhyay, S. C. Ojha, L. M. Pant, K. Srinivas
- **Calcutta University (CU), Kolkata:**
  Amitava Raychaudhuri
- **Delhi University (DU), Delhi:**
  Brajesh Choudhary, Debajyoti Choudhury, Sukanta Dutta, Ashok Goyal, Kirti Ranjan
- **Harish Chandra Research Institute (HRI), Allahabad:**
  Anindya Datta, Raj Gandhi, Pomita Ghoshal, Srubabati Goswami, Poonam Mehta, S. Rakshit
- **University of Hawaii (UHW), Hawaii:**
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- **Himachal Pradesh University (HPU), Shimla:**
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- **Tata Institute of Fundamental Research (TIFR), Mumbai:**
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- **Variable Energy Cyclotron Centre (VECC), Kolkata:**
  R. K. Bhandari, Subhasish Chattopadhyay, Premomay Ghosh, B. Mohanty, G. S. N. Murthy, Tapan Nayak, S. K. Pal, P. R. Sarma, R. N. Singaraju, Y. P. Viyogi

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2σ Precision of parameters

Experiment	P($\lvert\Delta m^2_{32}$)	P($\sin^2 2\theta_{23}$)	hierarchy
MINOS	17%	65%	–
CNGS	37%	–	–
NoVa	14%	70%	–
T2K	6%	28%	–
ICAL32	$\sim$ 50%	$\sim$ 50%	$\sin^2 2\theta_{13} > 0.06$

Sensitivity to parameters will increase with addition of PC events.