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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- Brief overview of the current status of neutrino physics

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  - The ICAL Detector: RPC’s and magnet design
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- 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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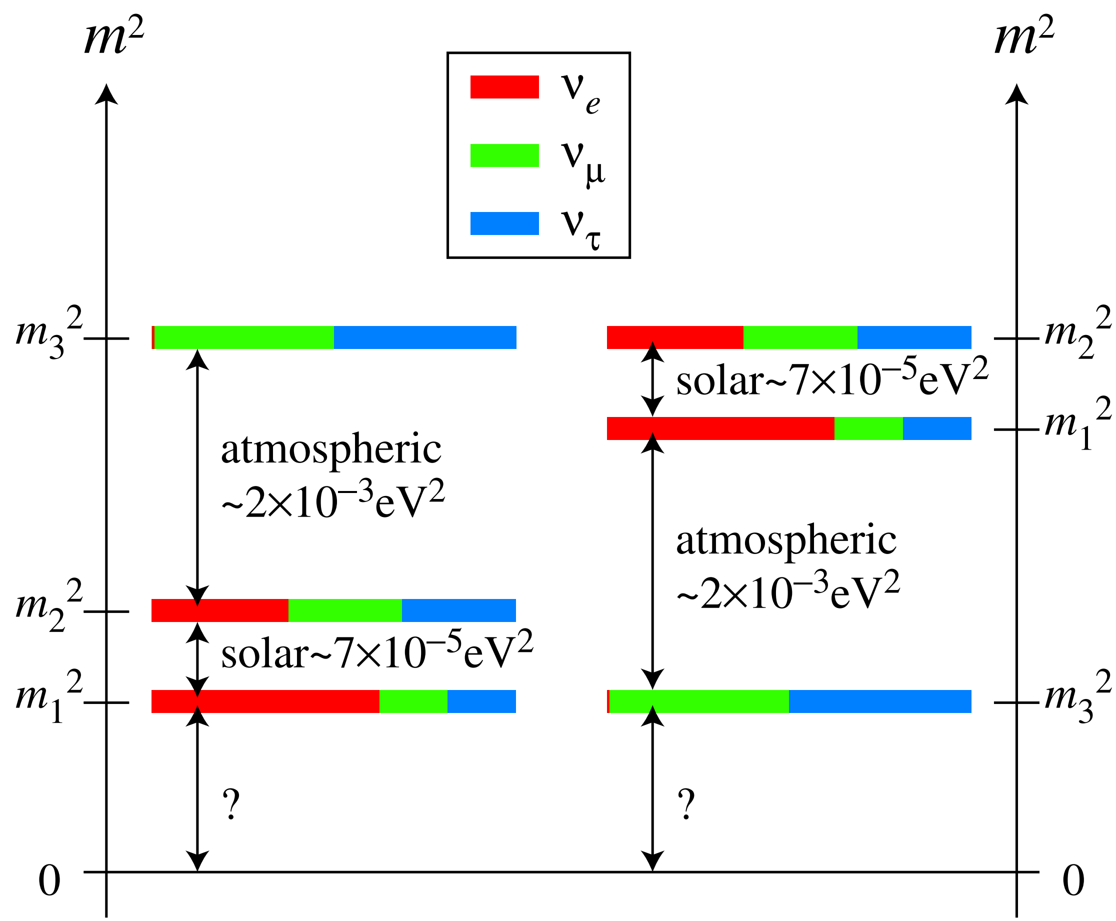

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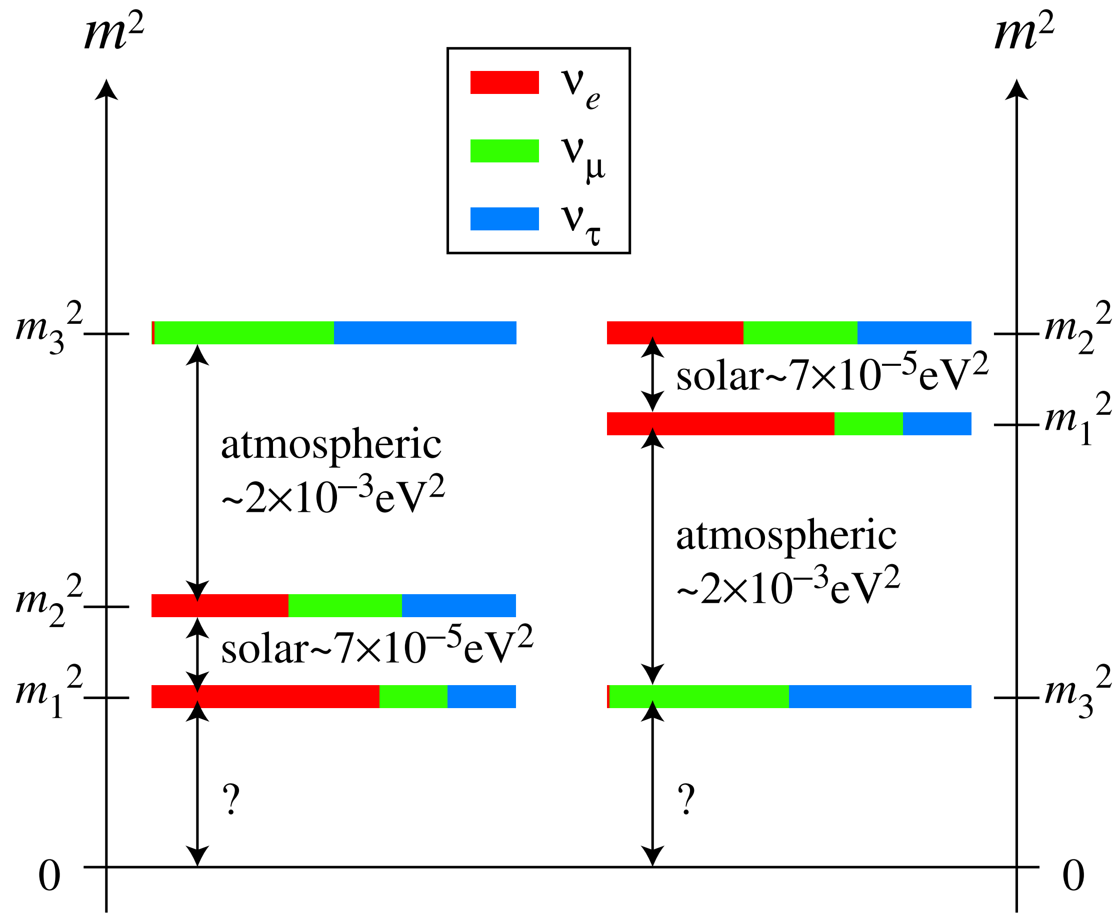
$\Delta m^2_{21} \sim 0.8 \times 10^{-4}$ eV^2 ;
$|\Delta m^2_{32}| \sim 2.0 \times 10^{-3}$ eV^2 ;
$\sum_i m_i < 0.7$–2 eV.



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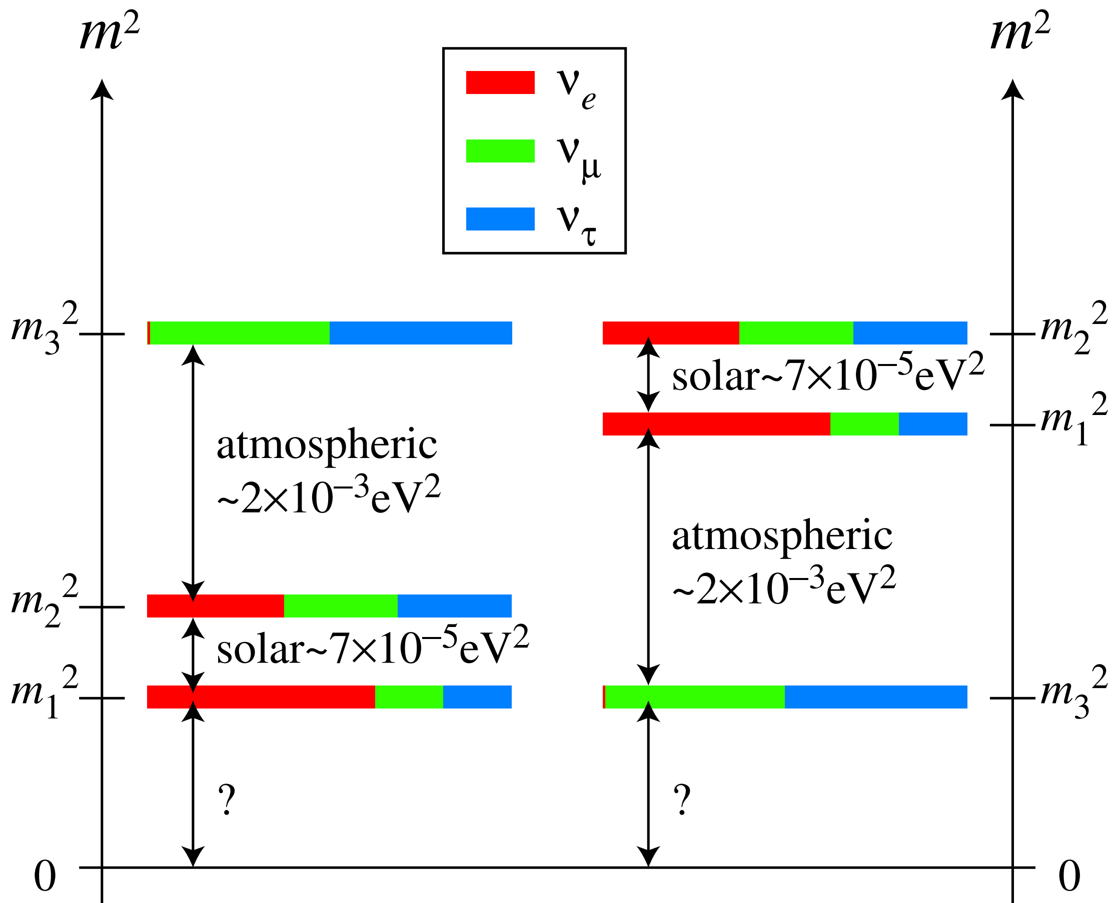
- $m_1 \sim m_2 \sim m_3 \sim 0.2$ eV (Degenerate hierarchy)
- $m_1 < m_2 \ll m_3$ (Normal hierarchy)
- $m_3 \ll m_1 < m_2$ Inverted hierarchy)

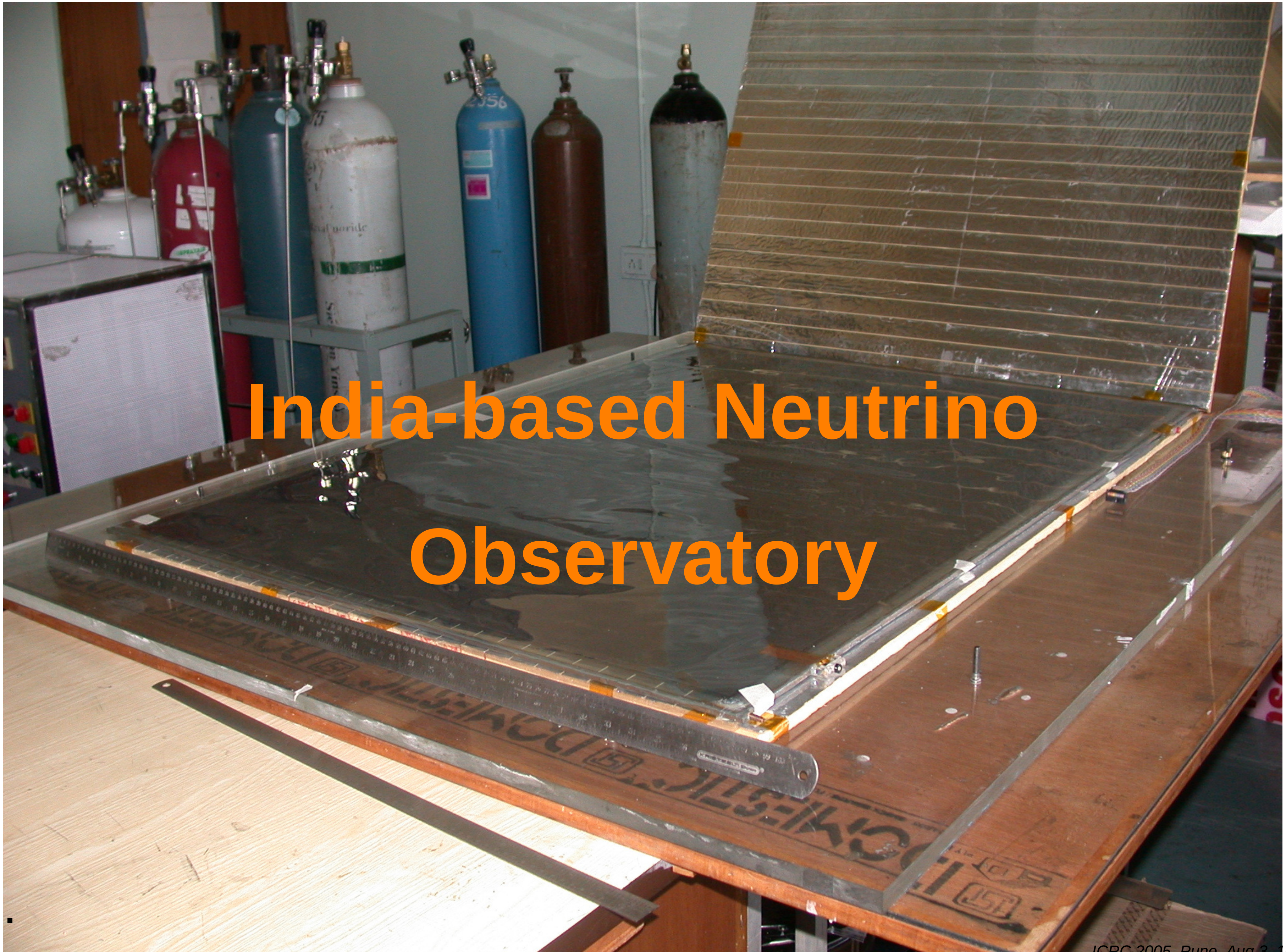


(APS multi-divisional neutrino study, physics/0411216)

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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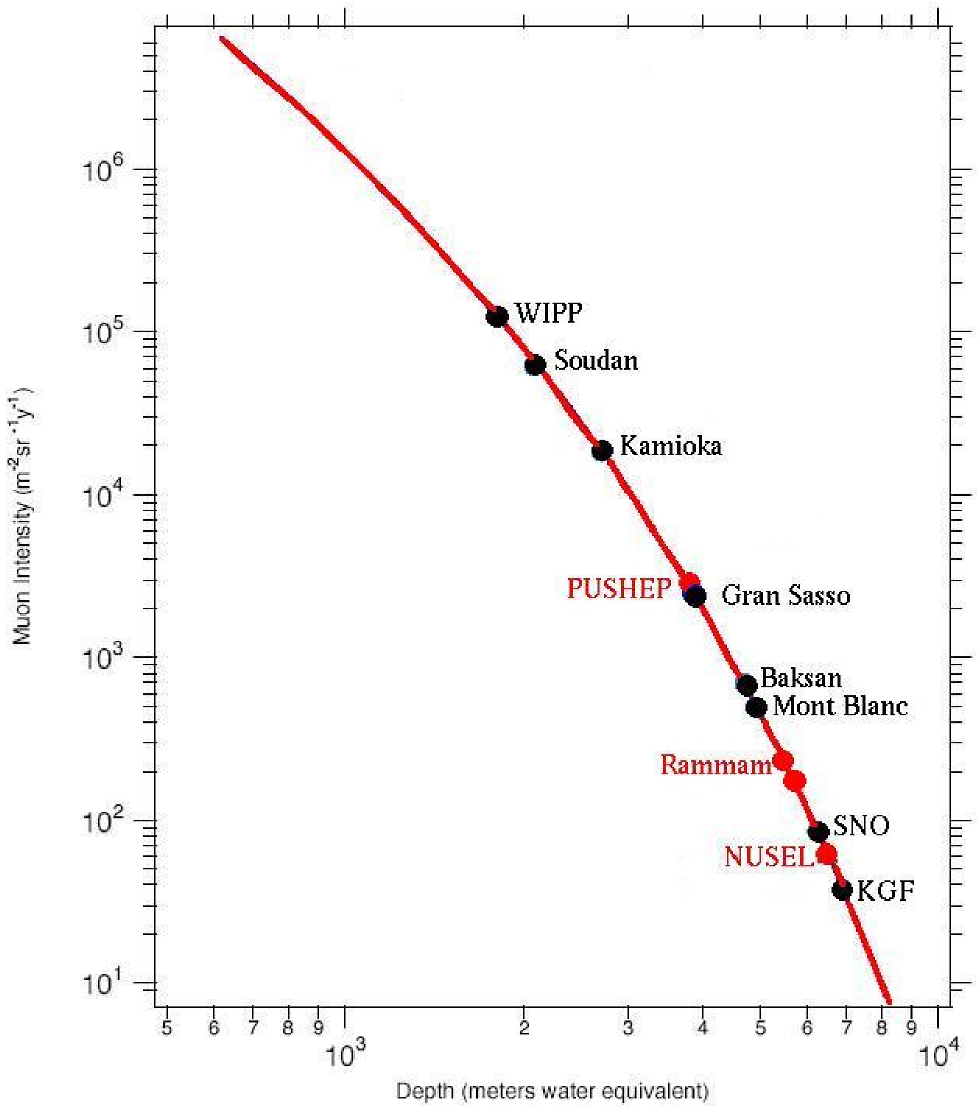
- Should be an international facility

Site survey: PUSHEP

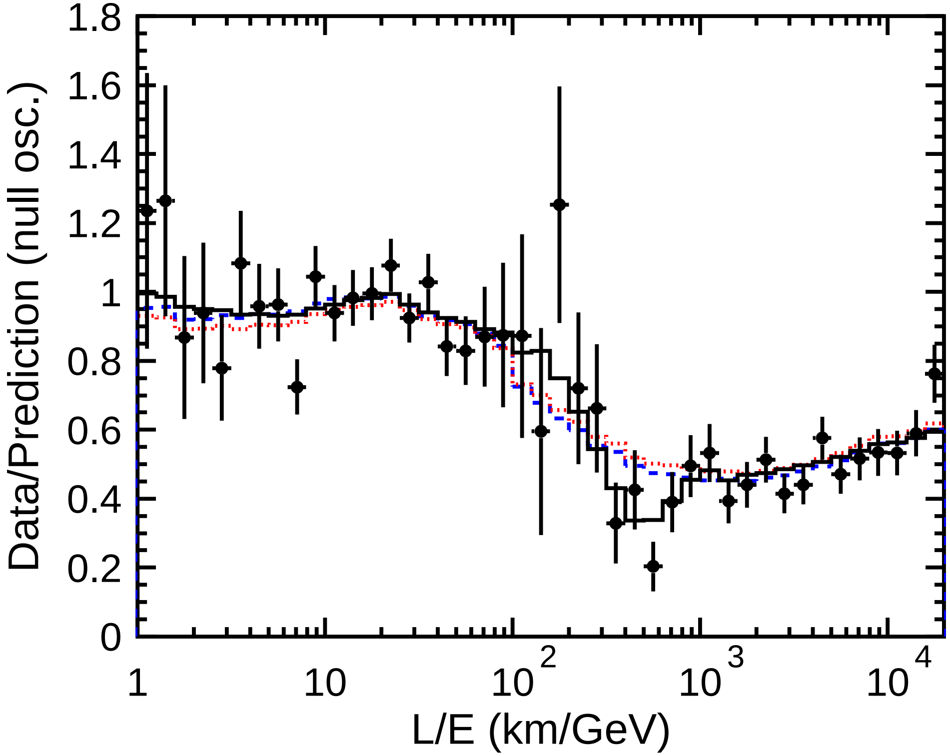
Site Survey: Rammam

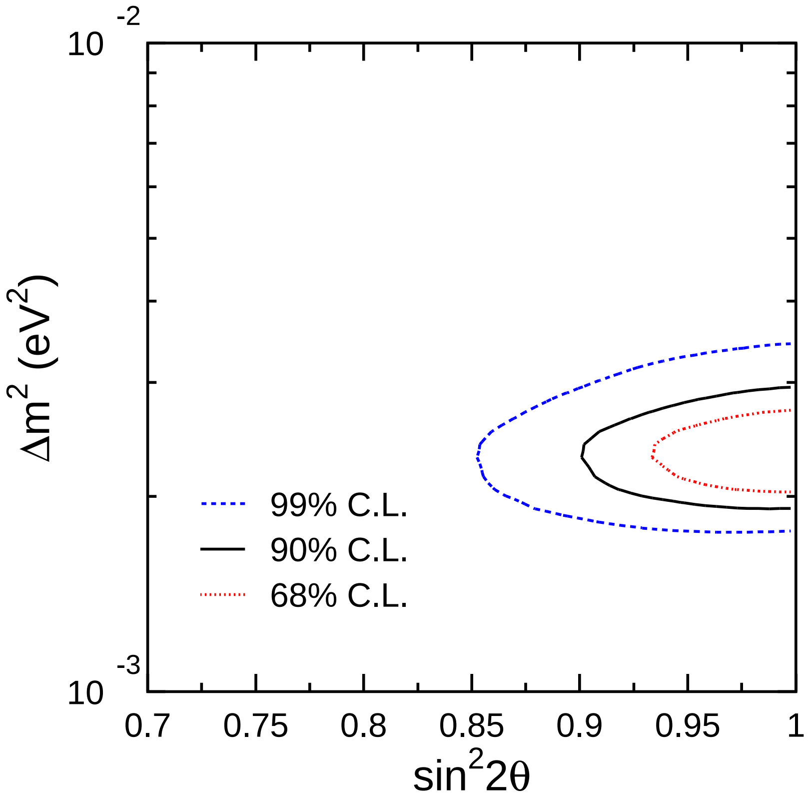
The depth at the sites



- 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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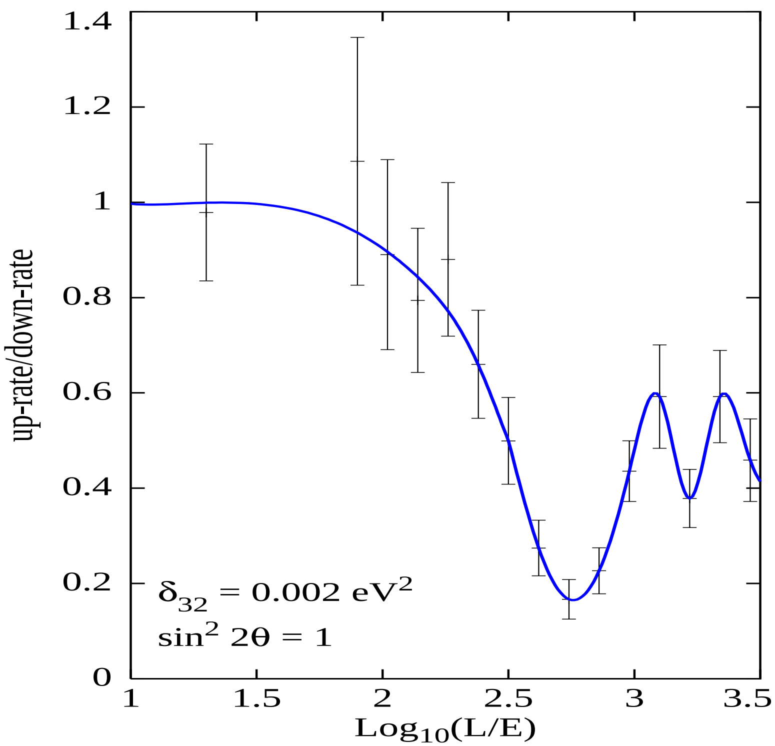
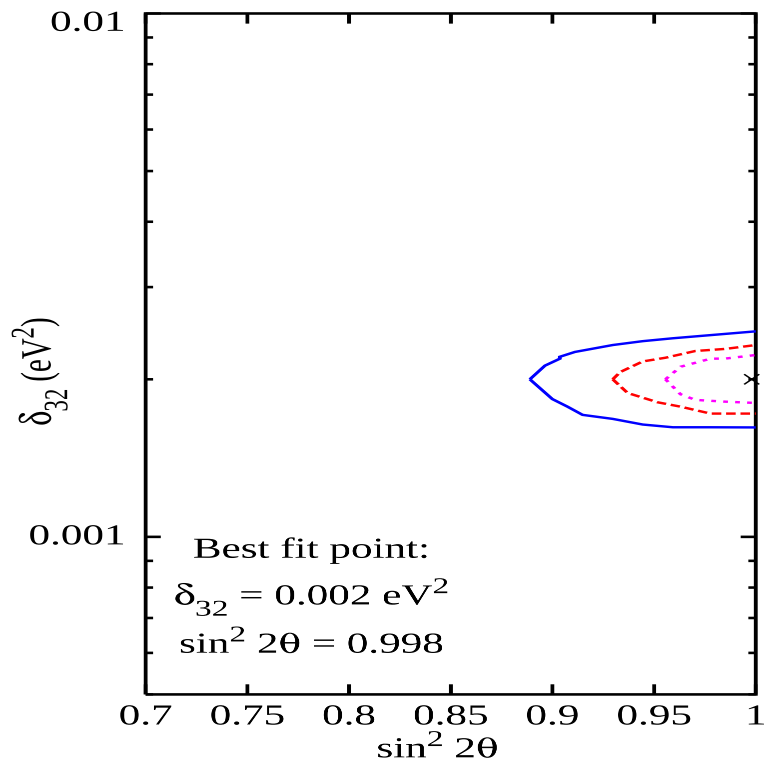




Simulation with ICAL detector, assuming 50% efficiency in L/E reconstruction

The choice of detector

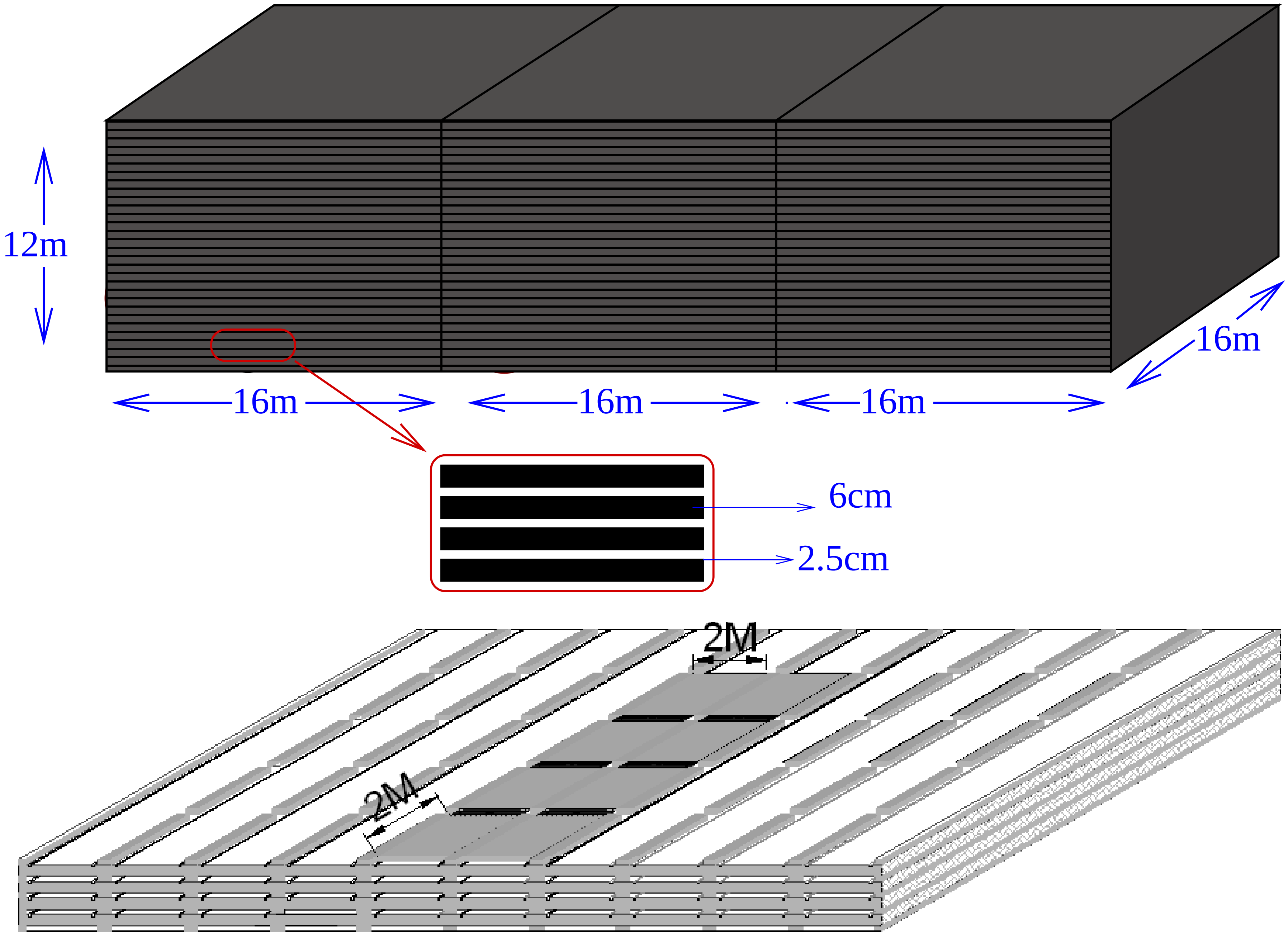
The detector should have the following features:

- 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

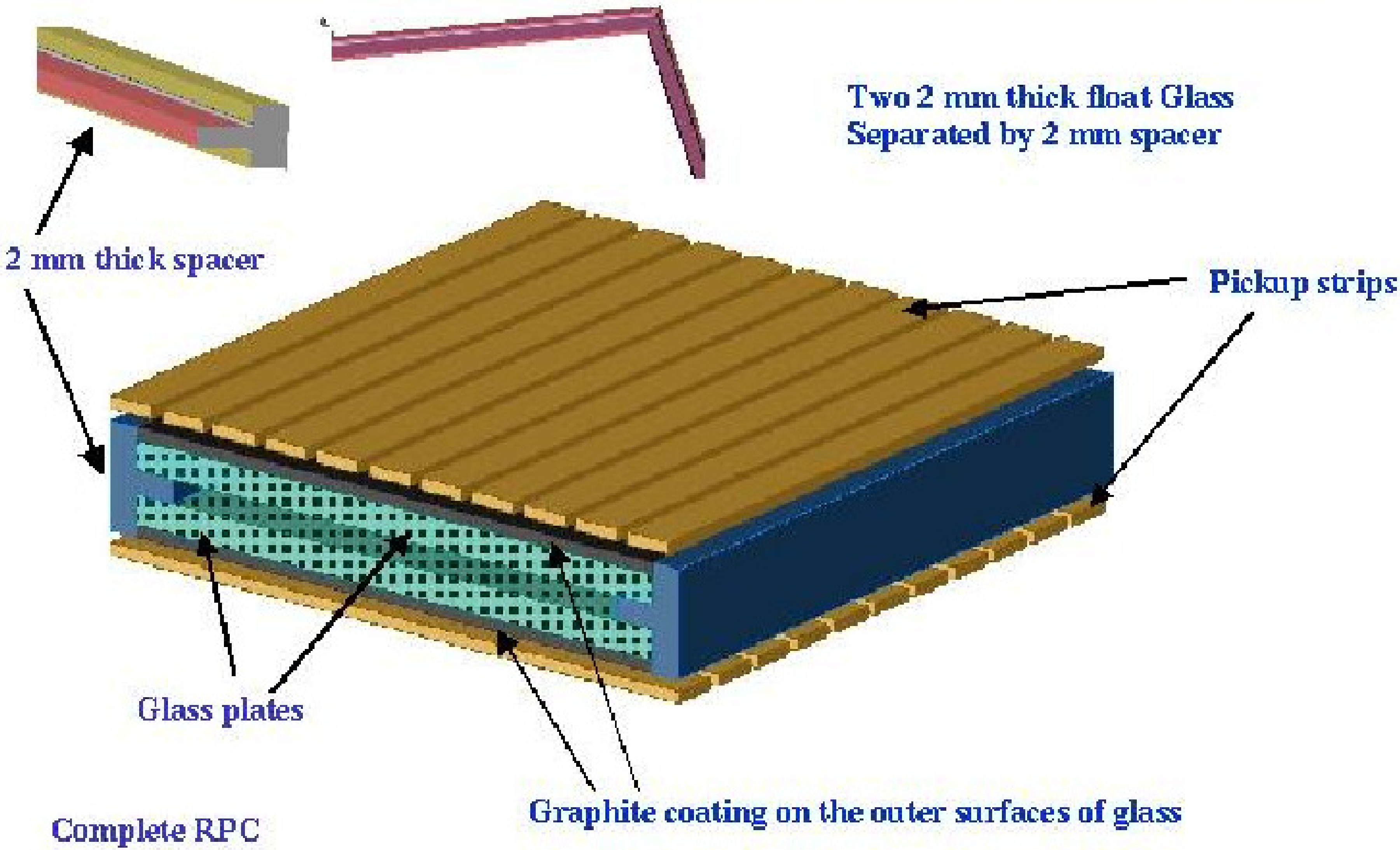
Note: Is sensitive to muons only

The ICAL detector



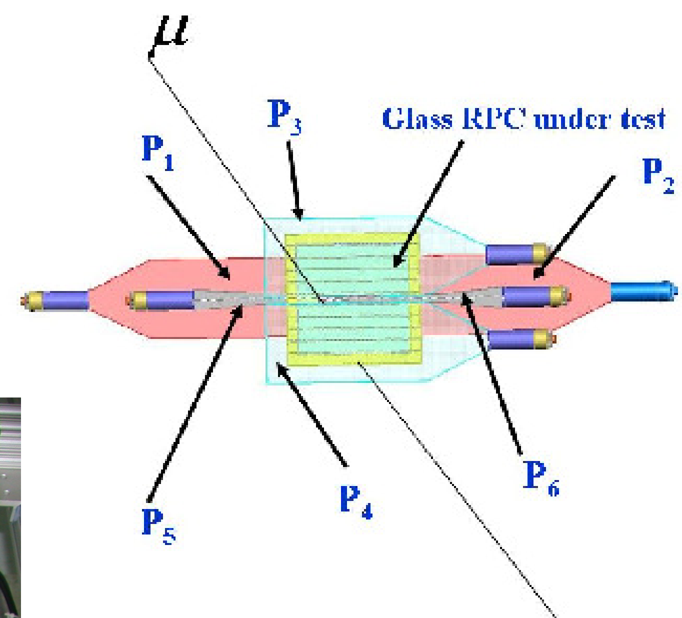
The active detector elements: RPC

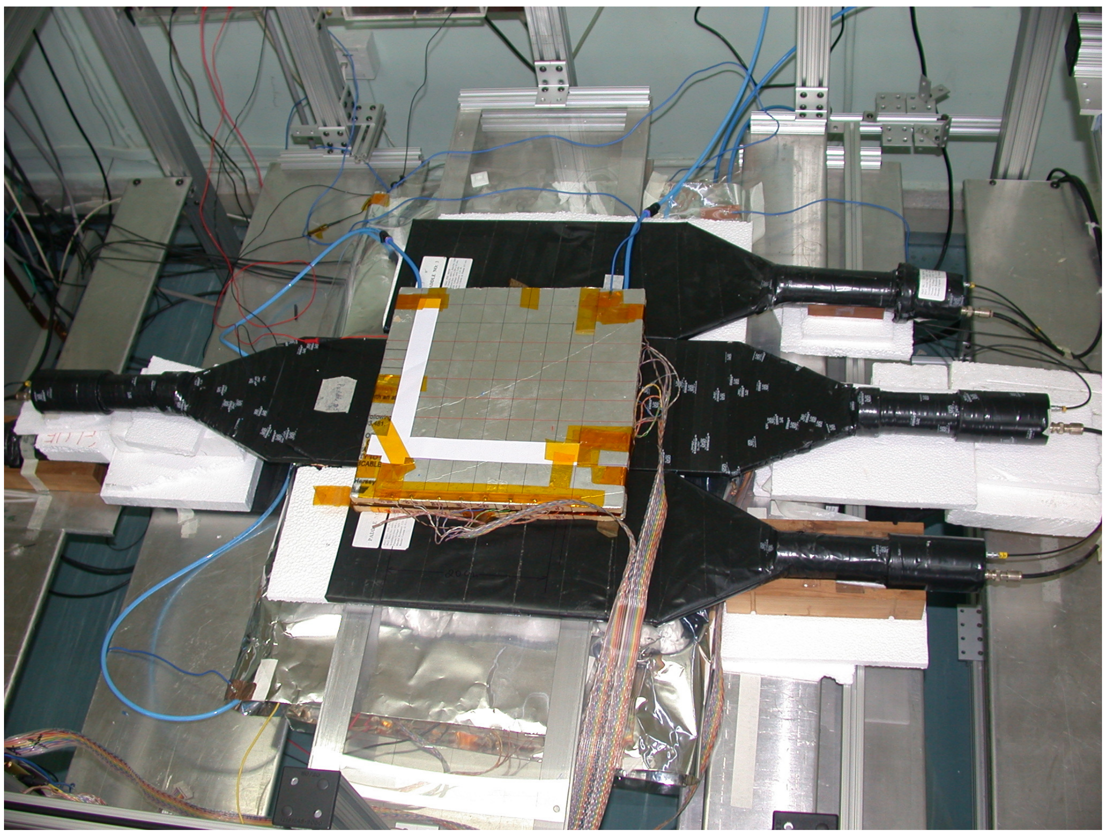
RPC Construction: Float glass, graphite, and spacers



Fabricating RPC's

at TIFR . . .





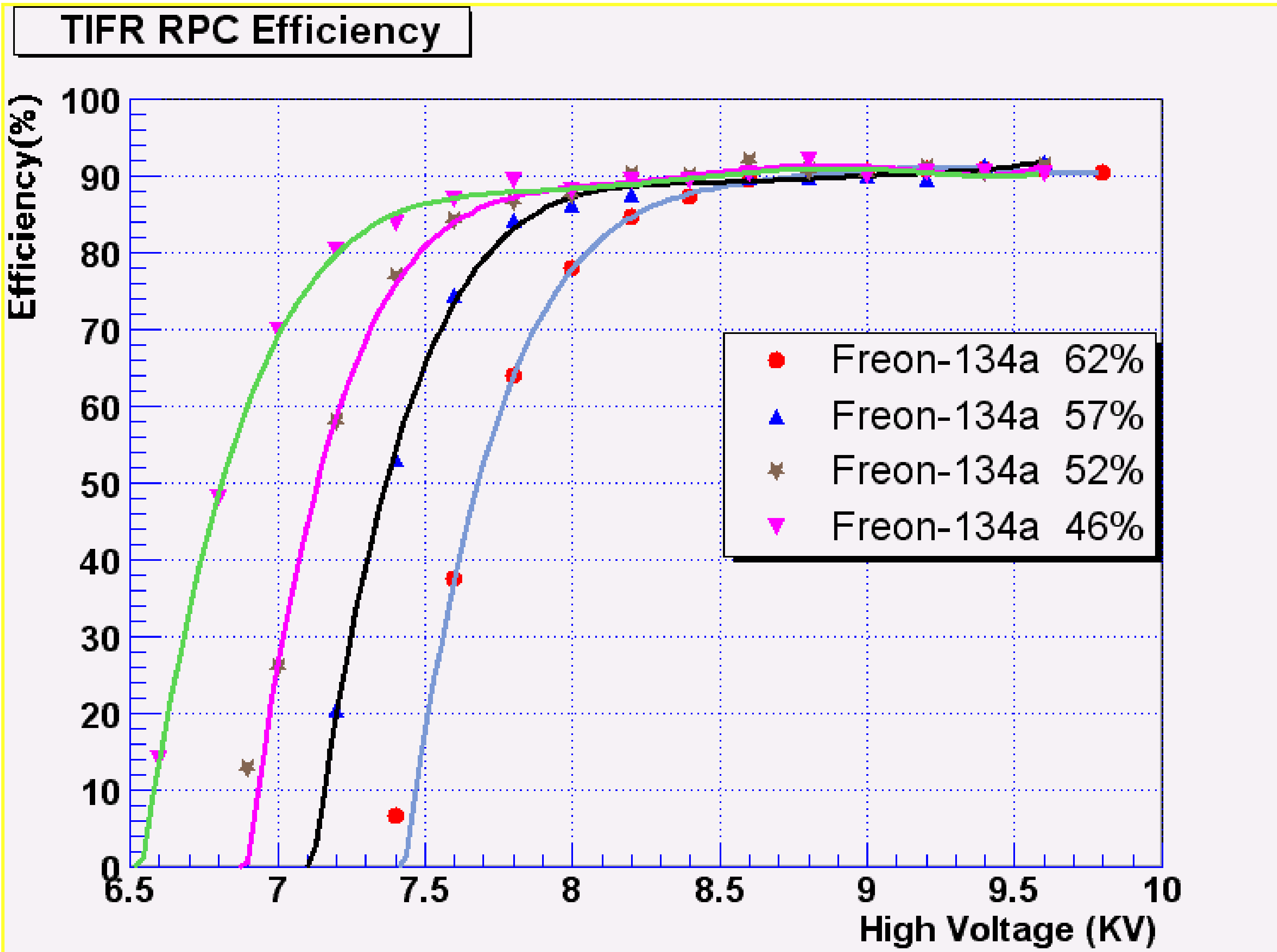
And of course . . .

Specifications of the ICAL detector

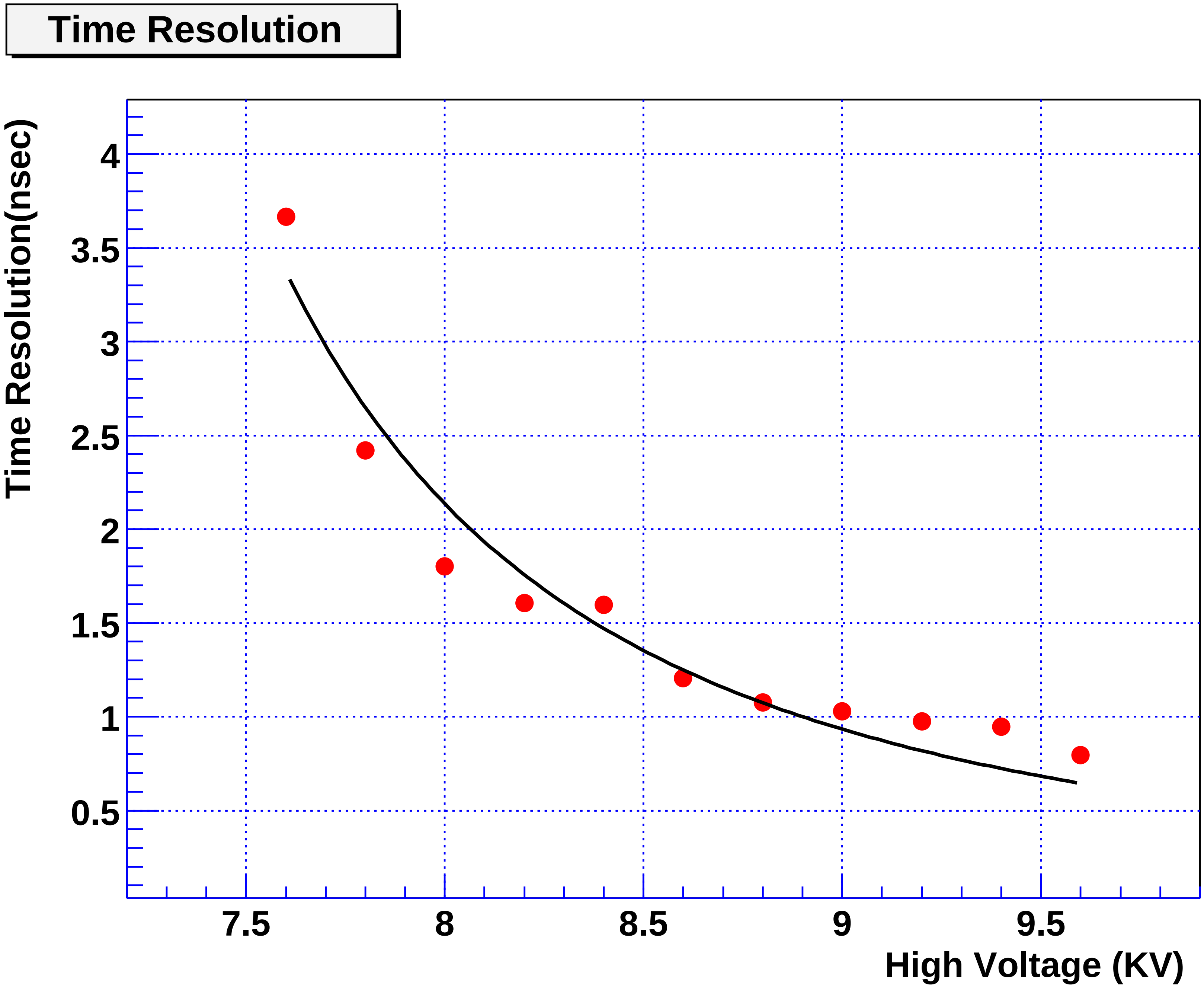
ICAL	
No. of modules	3
Module dimension	16 m $\times$ 16 m $\times$ 12 m
Detector dimension	48 m $\times$ 16 m $\times$ 12 m
No. of layers	140
Iron plate thickness	$\sim$ 6 cm
Gap for RPC trays	2.5 cm
Magnetic field	1.3 Tesla
RPC	
RPC unit dimension	2 m $\times$ 2 m
Readout strip width	3 cm
No. of RPC 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

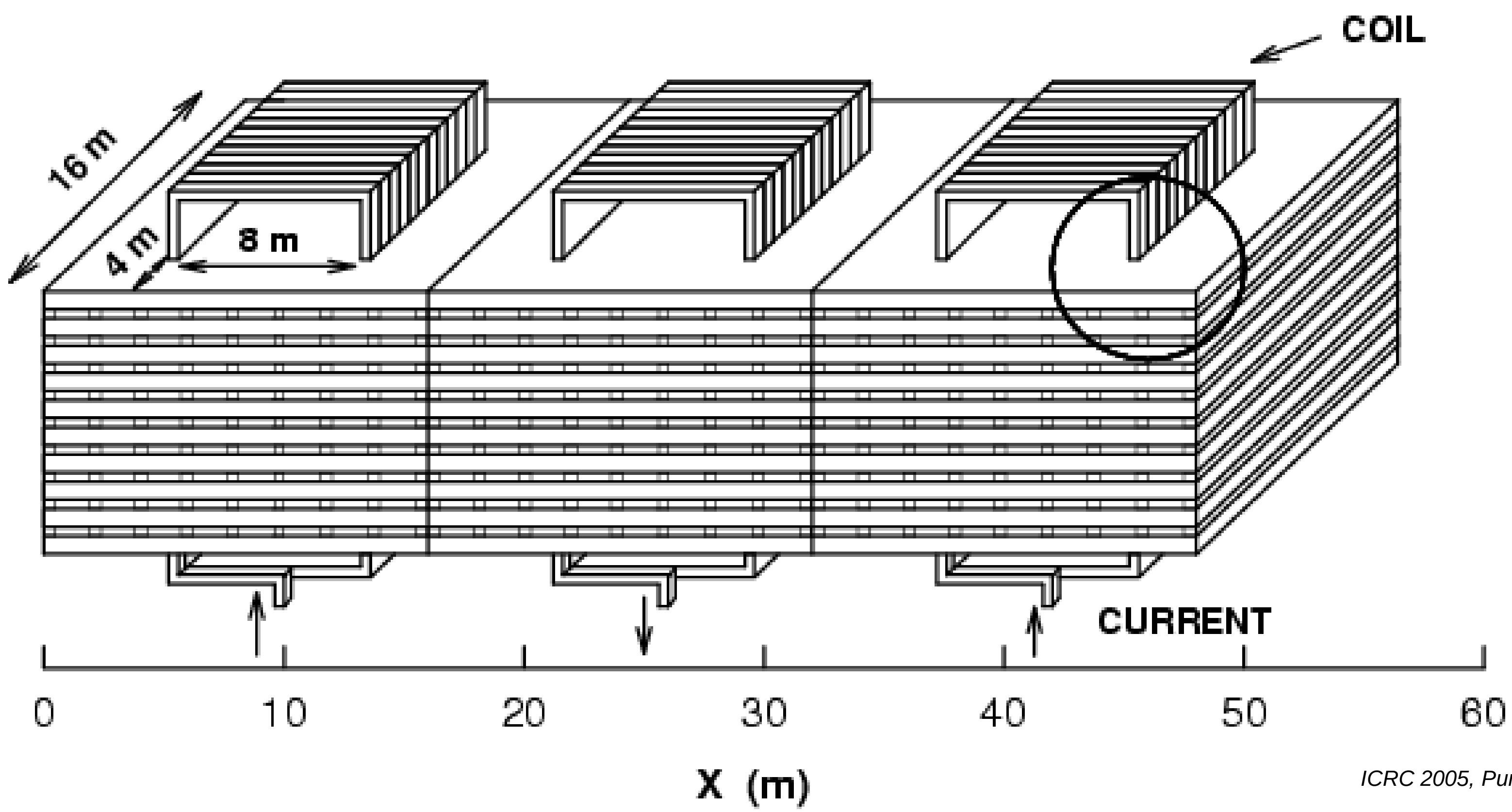
- RPC timing
- RPC charge distribution
- Mean charge vs voltage (seen to be linear)
- RPC noise
- Gas composition ($C_2H_2F_4$ (R-134a), Argon, Isobutane ($\leq$ 8%))
- RPC Cross talk (as a function of gas mixture)
- Gas mixing

Magnet studies

Design criteria:

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

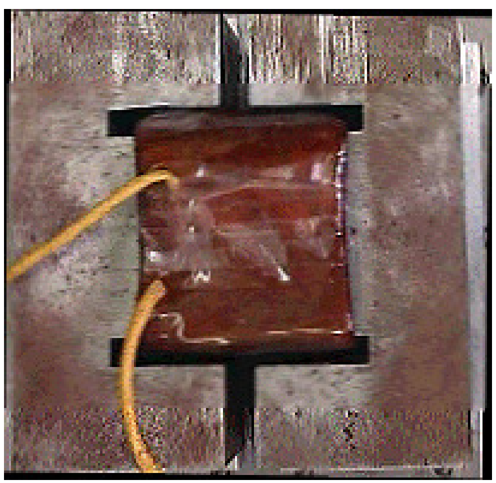
Toroidal Magnet design

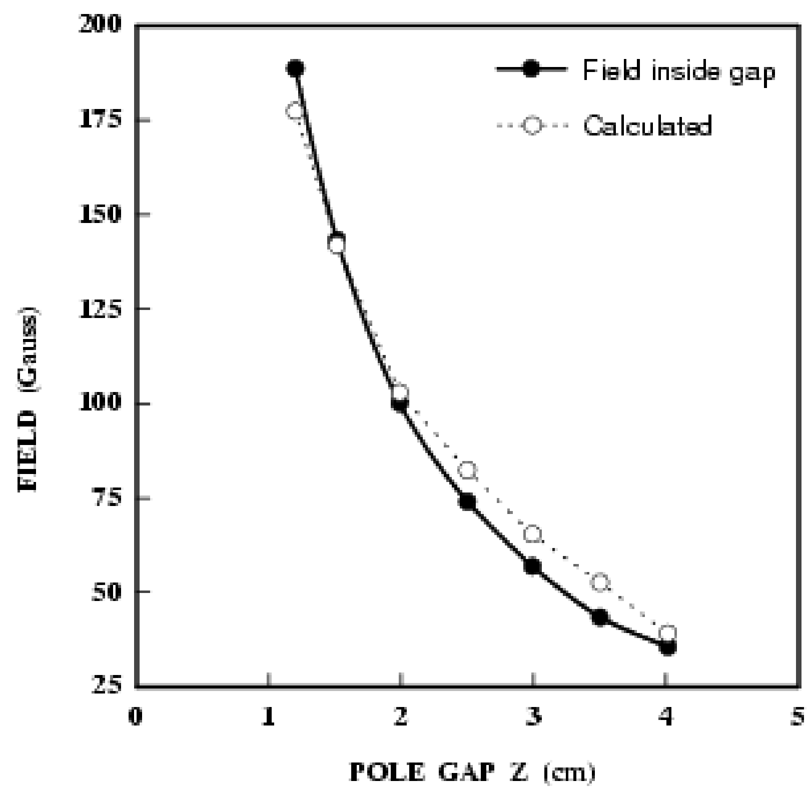


The prototype magnet

- 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.

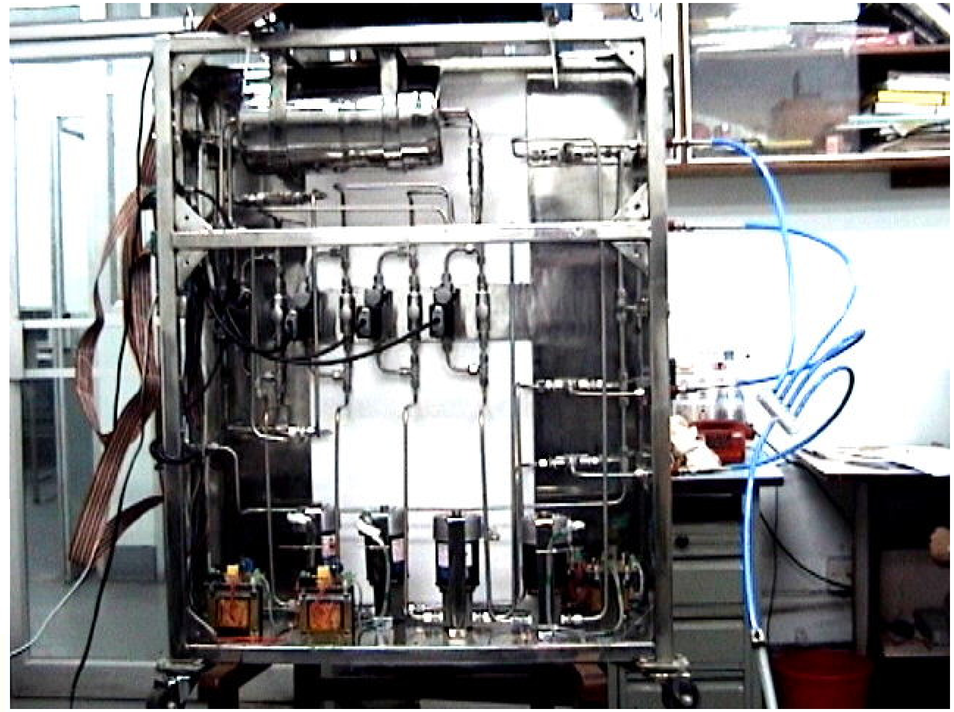


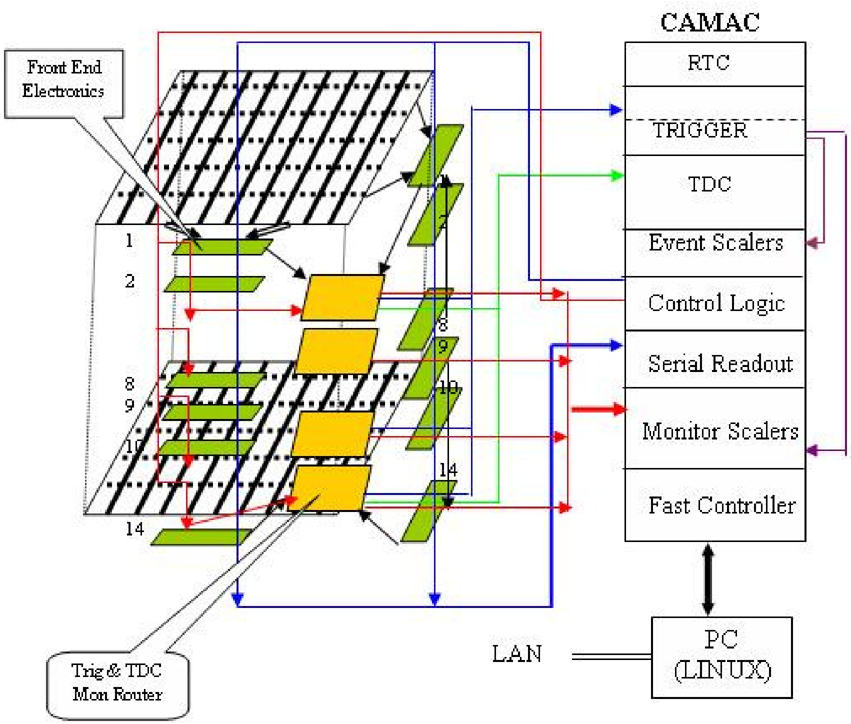


All new studies with MagNet6.0 3D software

For the prototype . . .

The gas-mixing unit at SINP



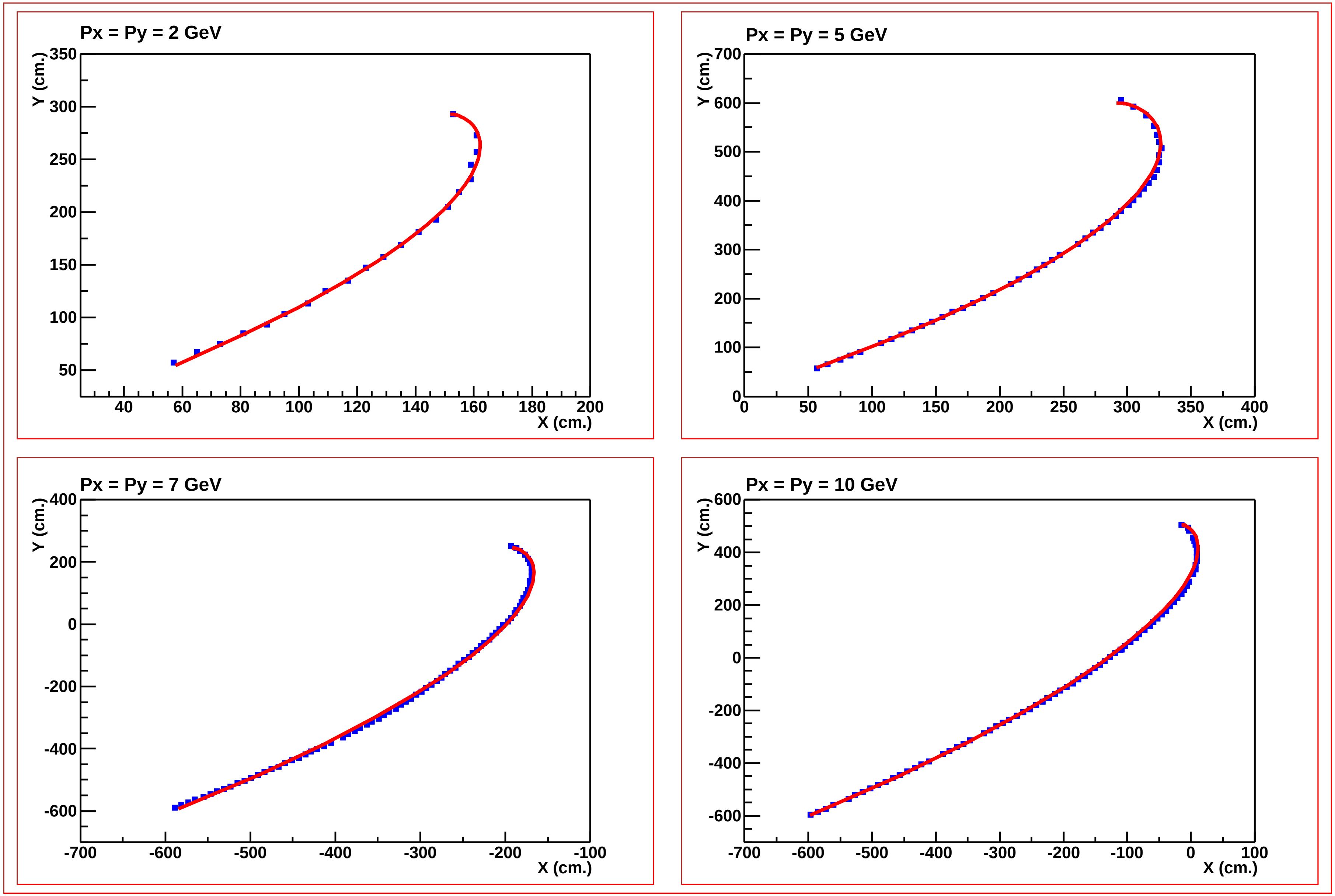


A schematic of the read-out electronics for the prototype

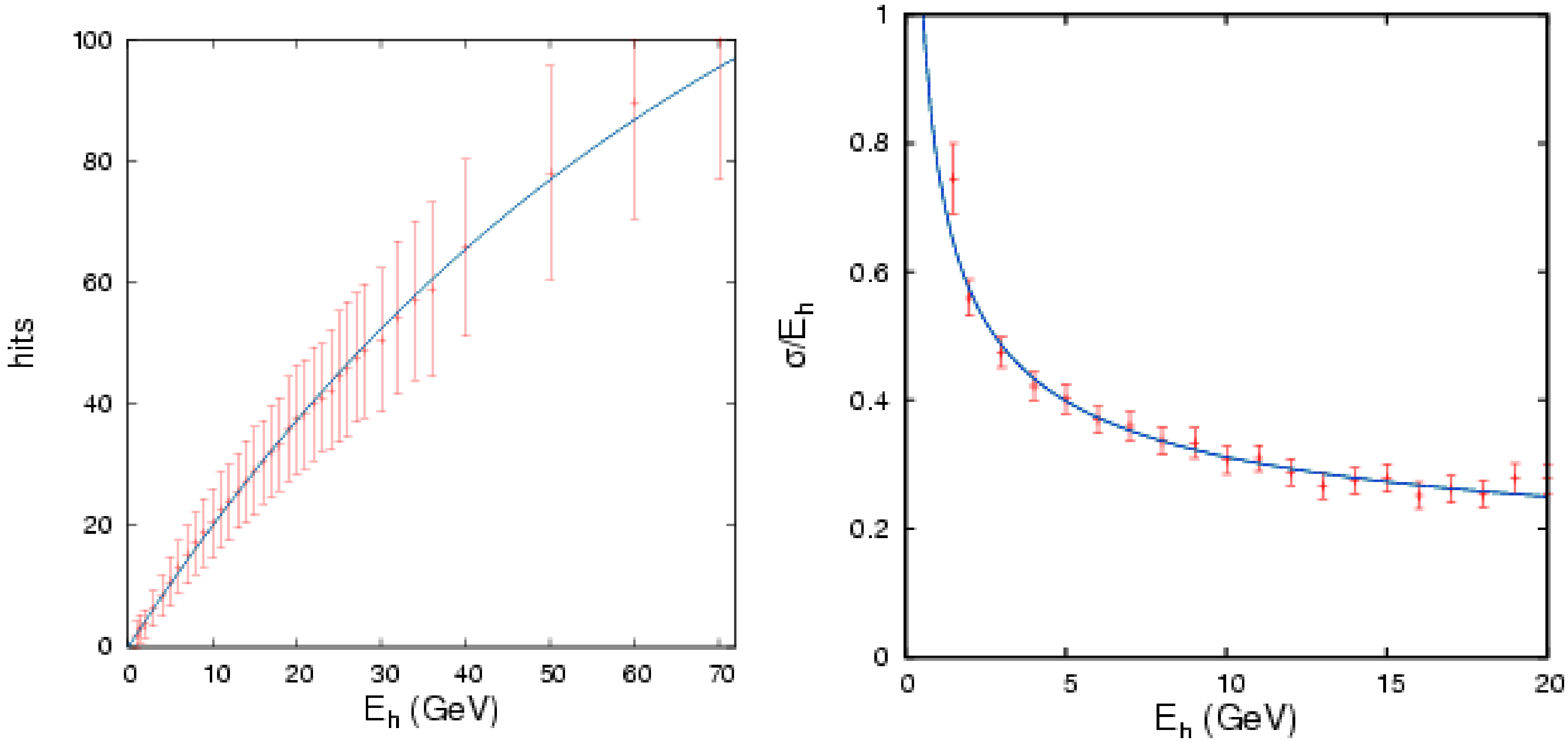
Physics with Atmospheric Neutrinos

- 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

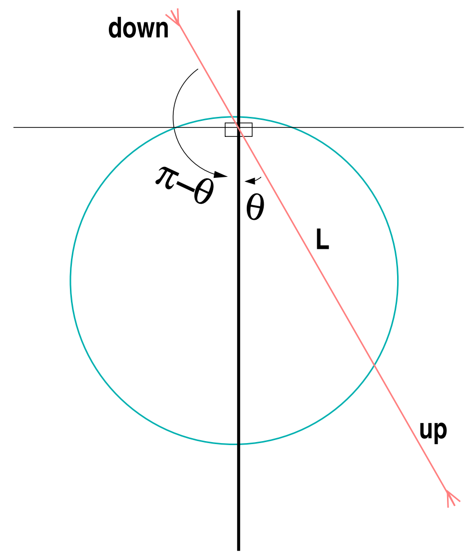


- Analysed two sets of data: with and without magnetic field.
- For the former, could analyse both the fully-contained as well as partially contained events.
- About 40–50% of the generated events survived the cuts

Physics goals

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

(Pietropaolo and Picchi)

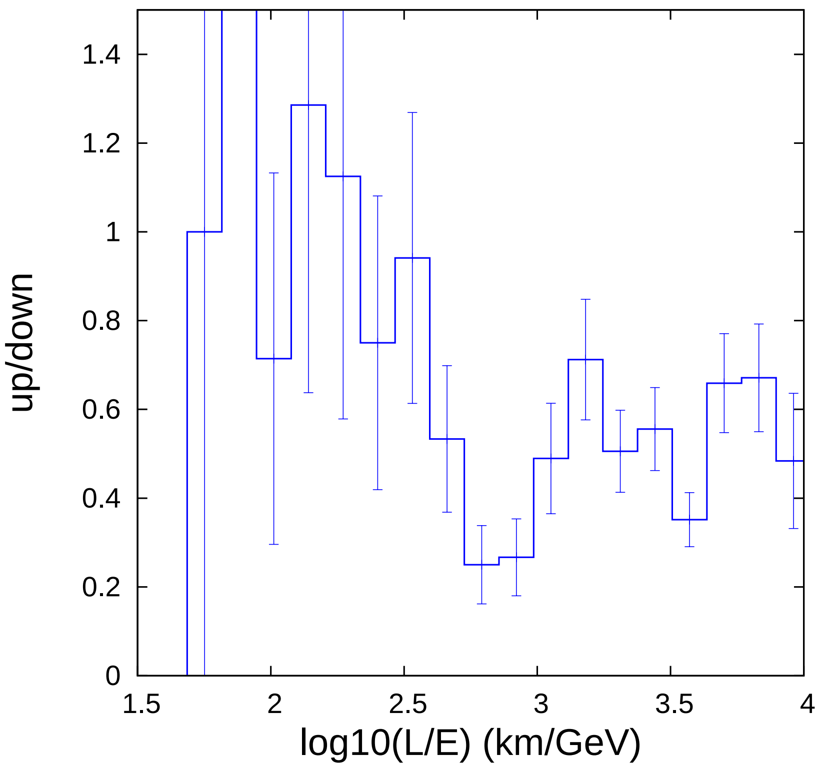


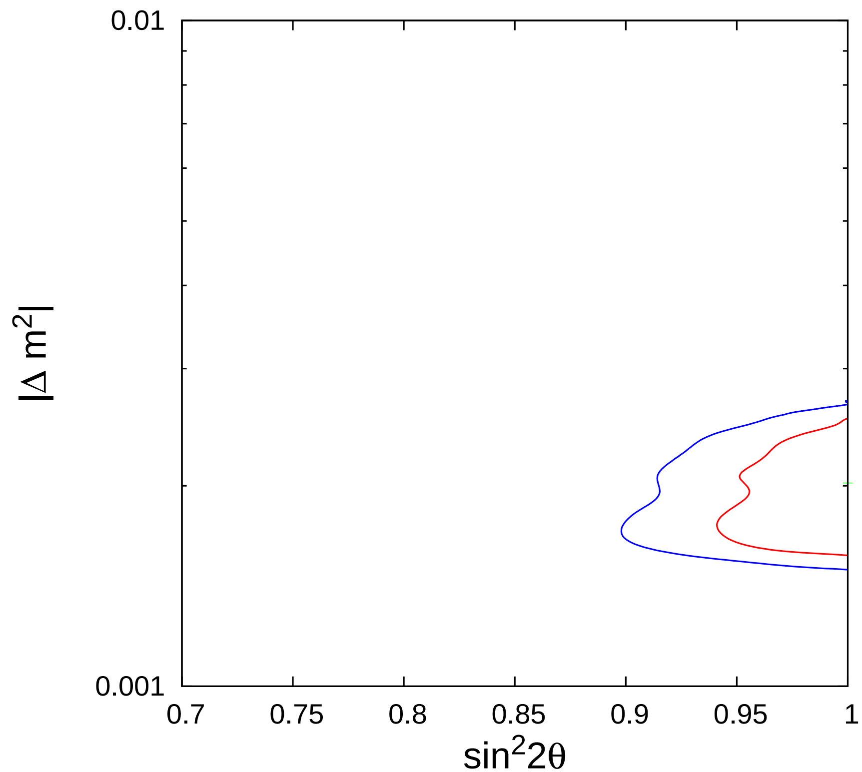
$$\frac{\text{up rate}}{\text{down rate}} = P_{\mu\mu} = R \otimes \left\{ 1 - \frac{\sin^2\theta_{23}}{2}\left(1 - \cos 2.54\,\delta_{23}\,\frac{L}{E}\right)\right\} .$$

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 $B_y = 1$T



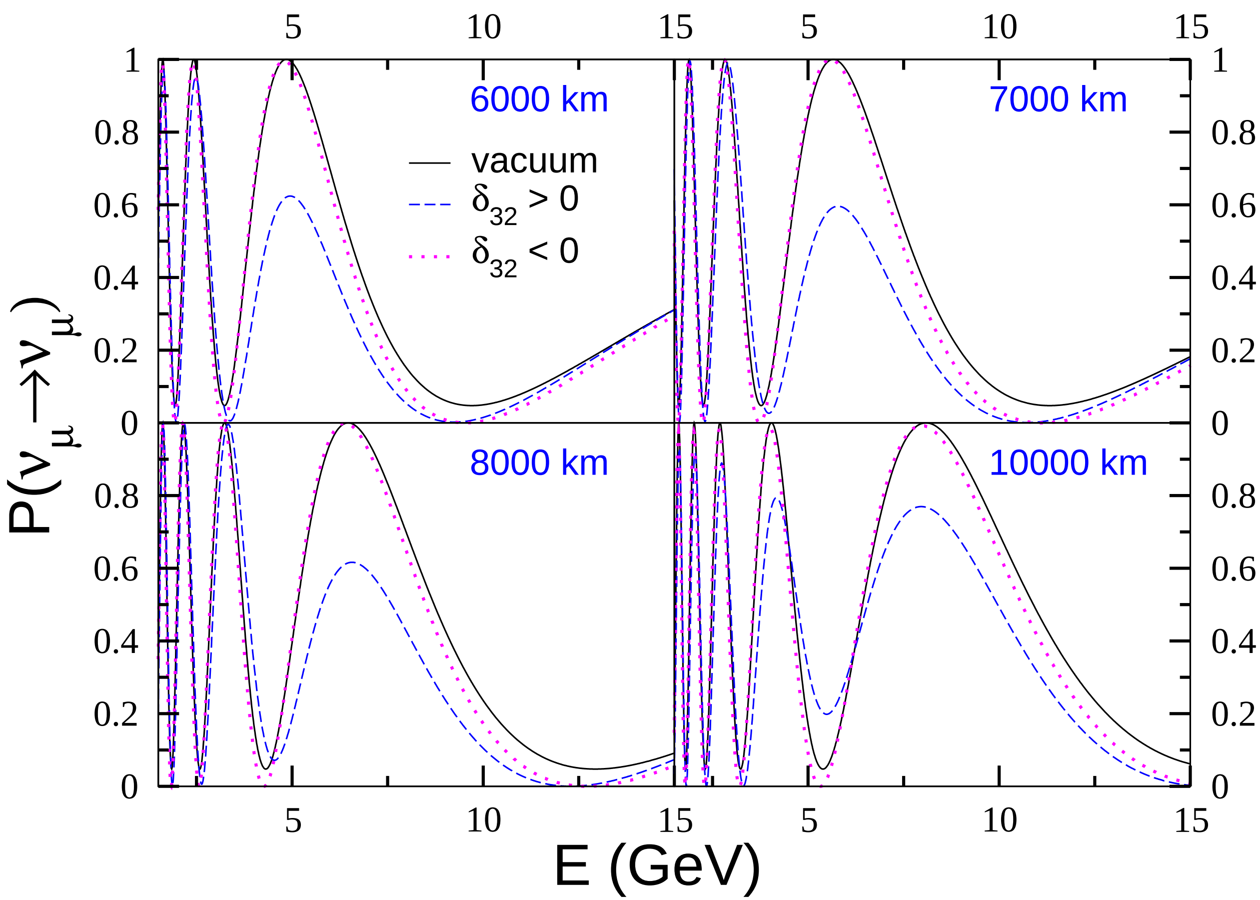


Shown are 90 and 99% CL contours, along with the best-fit value.

- 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; $\sin^2 2\theta_{23} > 0.96$

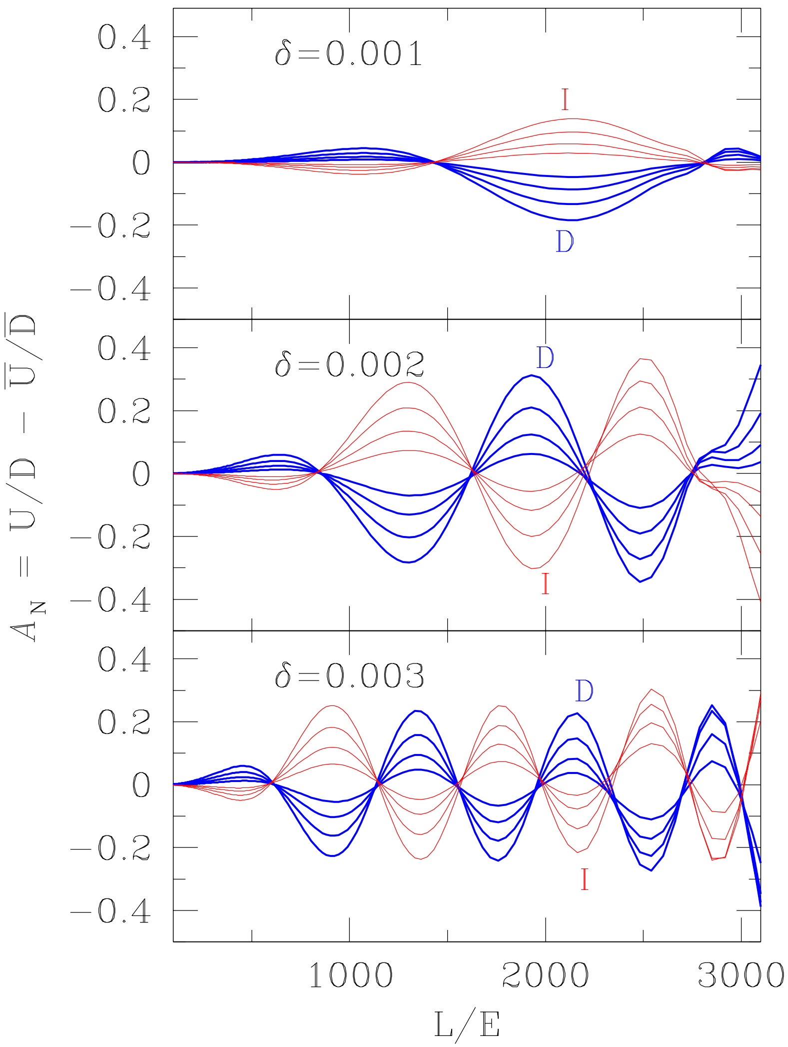
sk

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



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

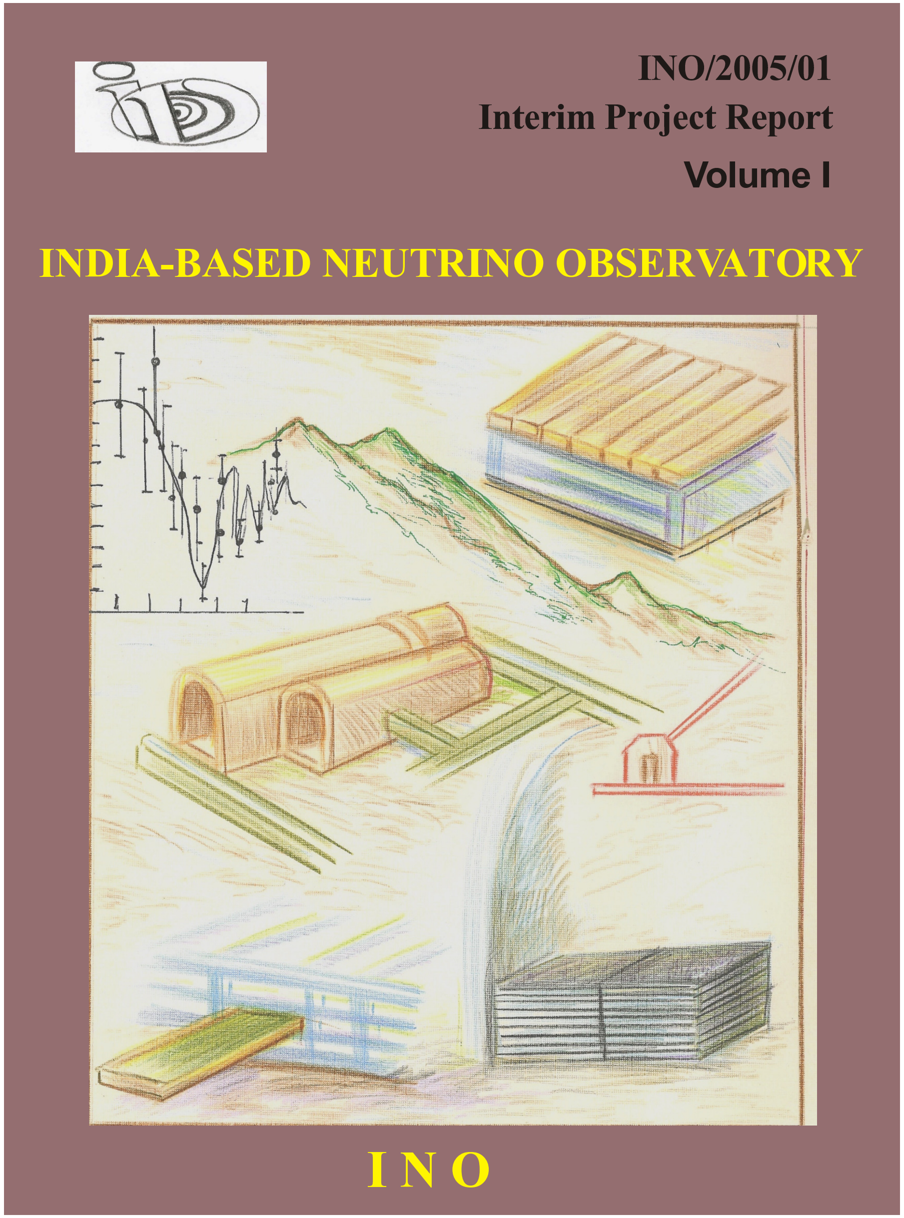
Hence sensitive to the mass ordering (red vs blue) of the 2–3 states; however, needs large exposures of about 1000 kTon-years.

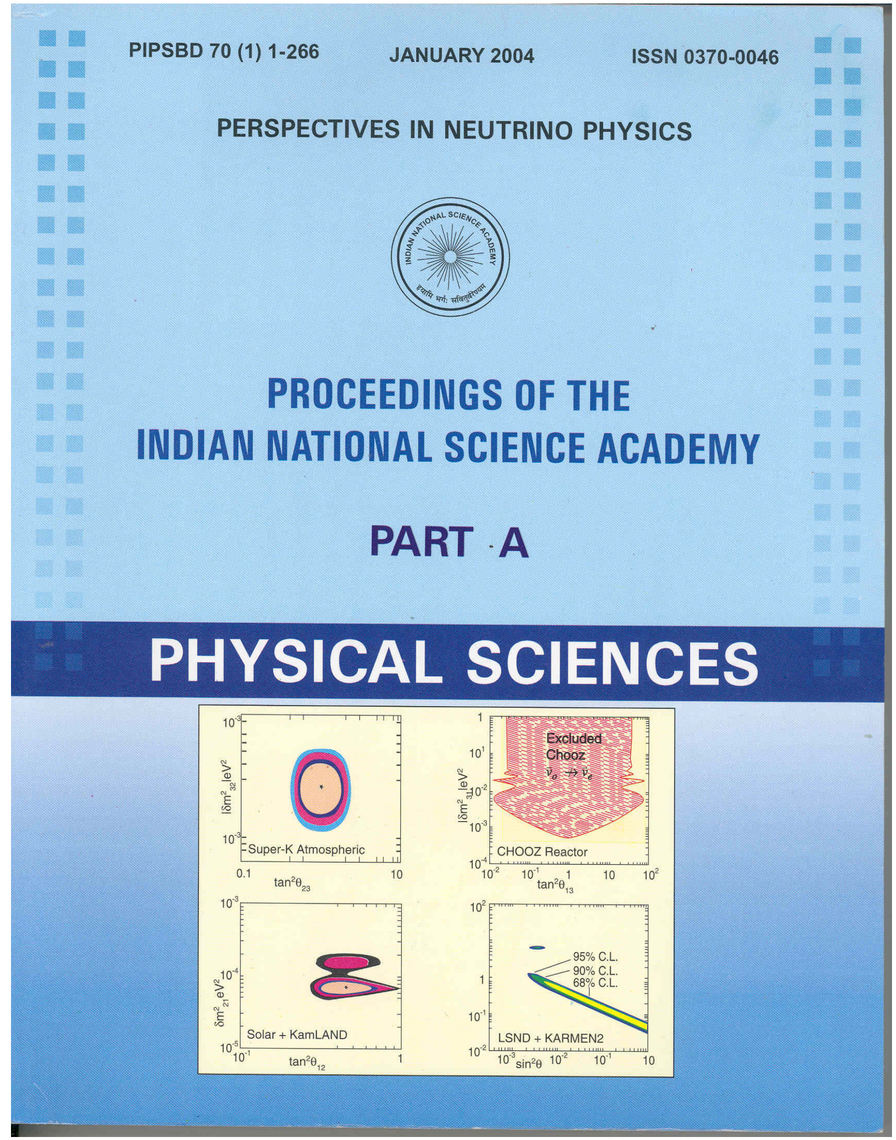
Other physics possibilities

. . . 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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- sign of the (23) mass-squared difference $\delta_{32} = m_3^2 - m_2^2$
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- INO (ICAL++) is a possible far-end detector for such long baseline experiments

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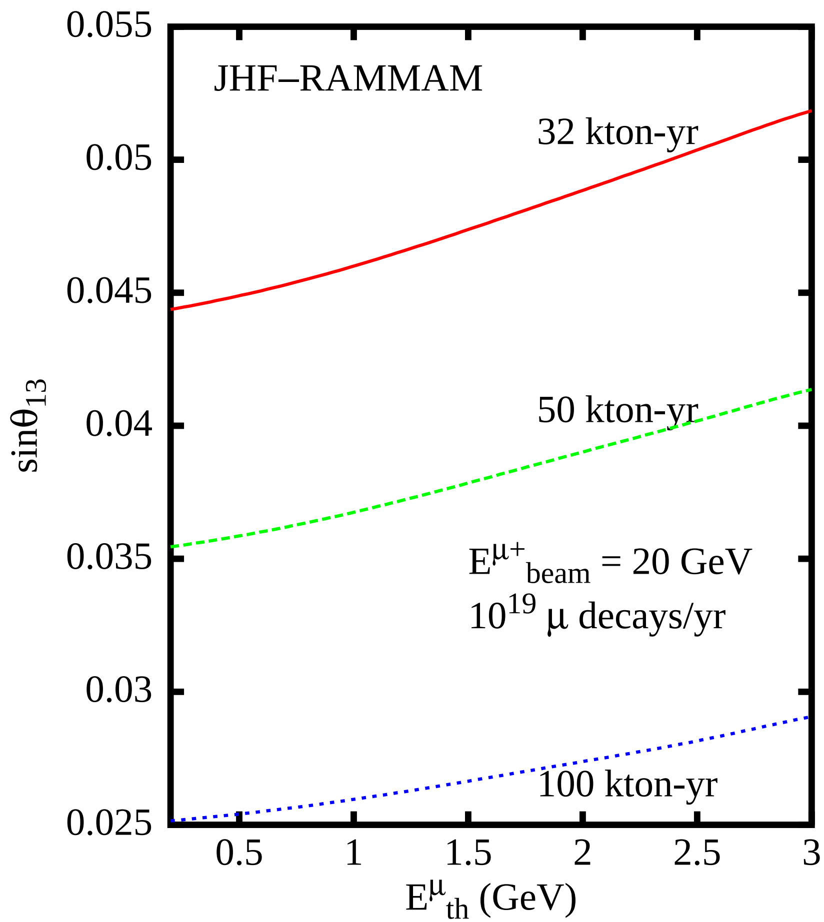
- Result: wrong sign muon (10/kton = signal)

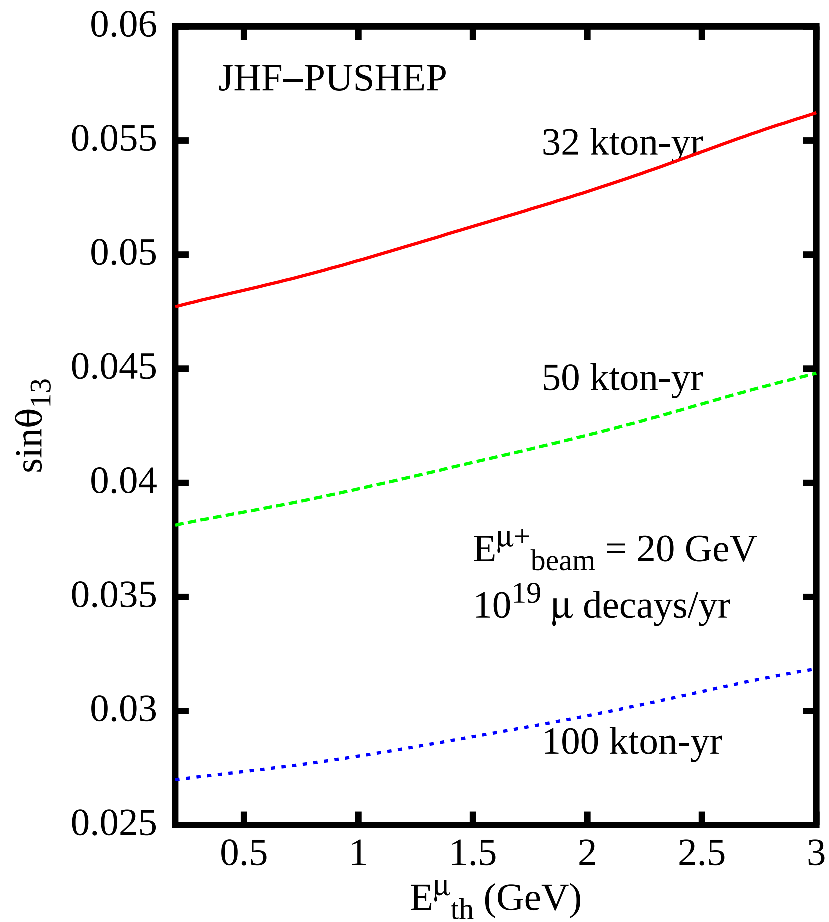
  Note: Since ICAL is not very sensitive to electrons, the mode in which the wrong-sign event is from electron detection (sensitive to $P_{\mu e}$) is not considered here.

Reach of $\sin\theta_{13}$

JHF to Rammam



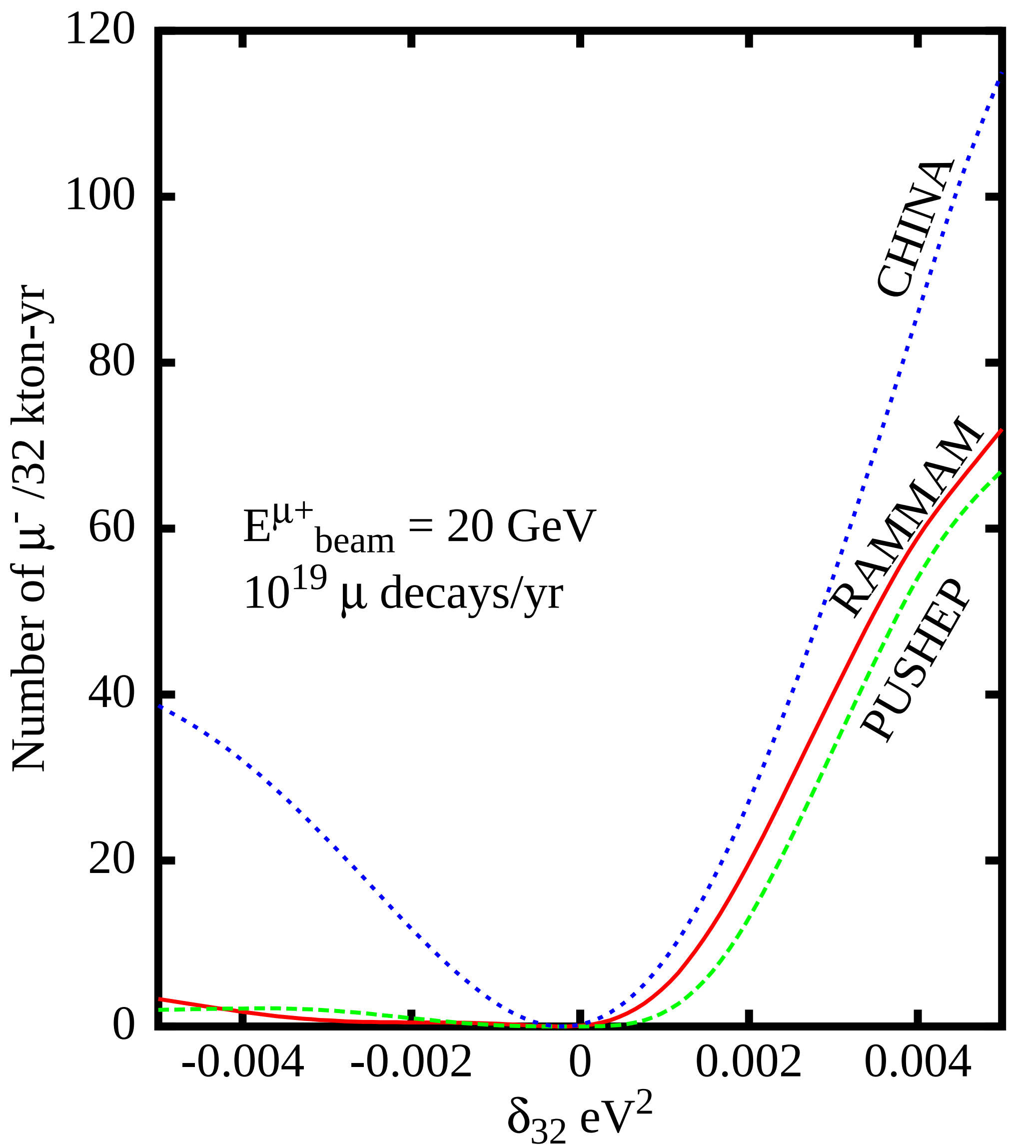
Fermilab to PUSHEP



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

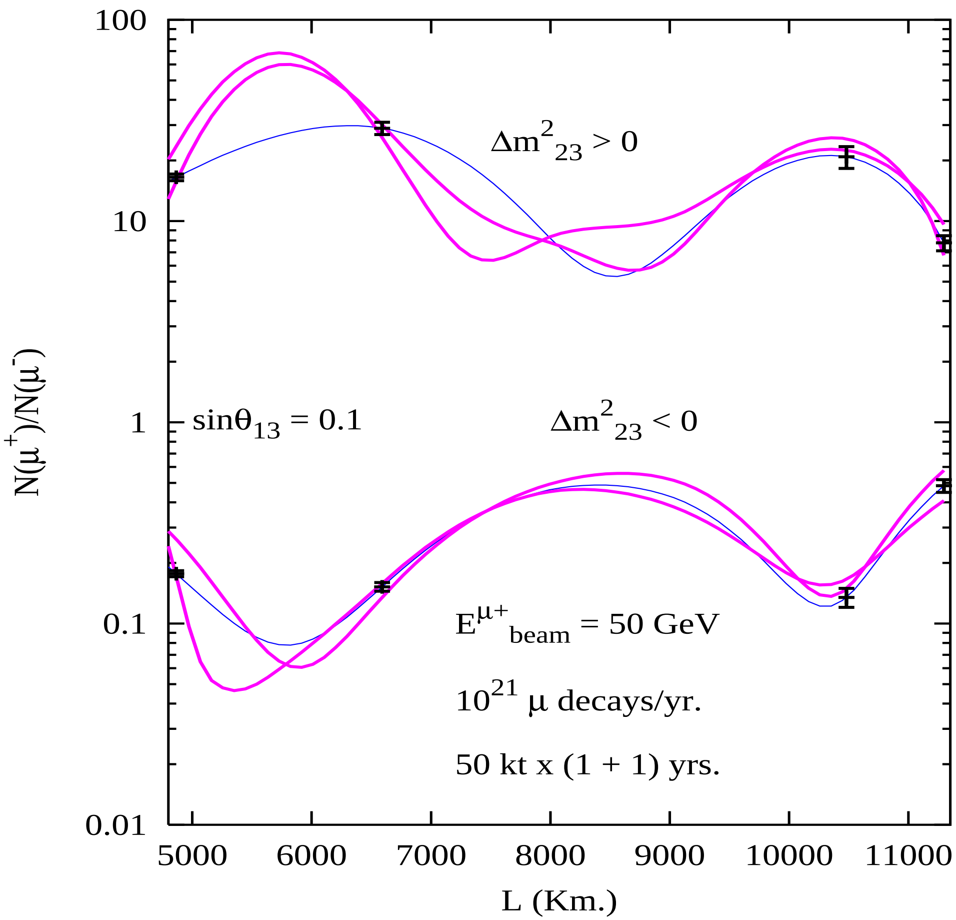
Sign of Δm^2_{32} vs wrong sign μ

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
- Detector prototype is ready for construction
- 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

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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.