India-based Neutrino Observatory (INO)

Physics Prospects and Status Report

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For the INO Collaboration

(http://www.imsc.res.in/∼ino)

Outline of talk

Status report

- The INO Collaboration

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- Motivation: Atmospheric neutrinos and oscillation physics

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  - RPCs, the active detector elements
  - The magnet design
  - Physics Simulation of ICAL

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  - Oscillation physics with atmospheric neutrinos
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    - ICAL or upgraded-ICAL as far-end detector for nu-factory

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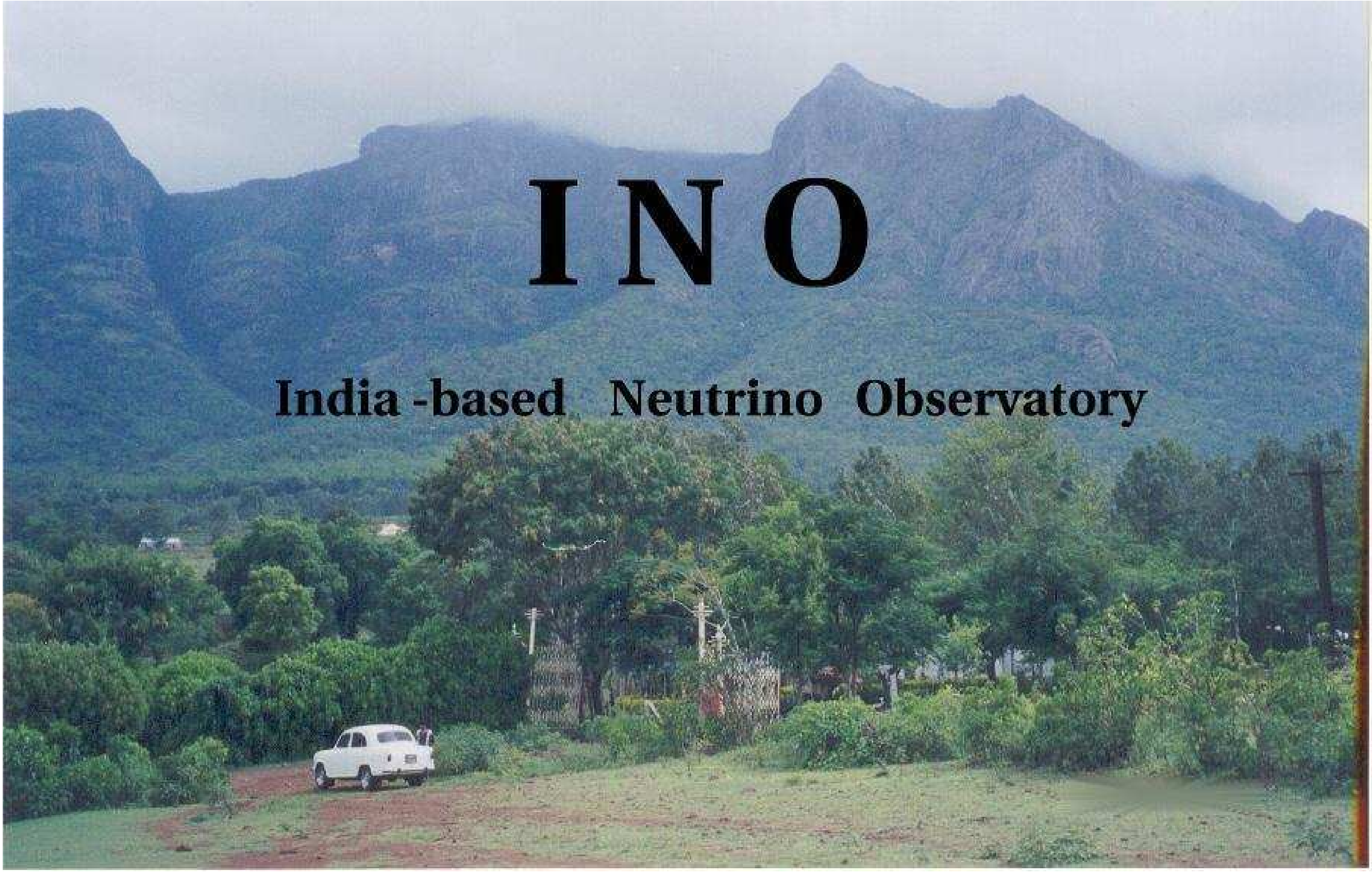
- Non-oscillation physics
  - Ultra high energy cosmic rays, “Kolar events”, . . . ✘

Status Report



The INO Collaboration

- Phase I : Around 2 years (On-going)
  - Detector R & D
  - Physics Studies
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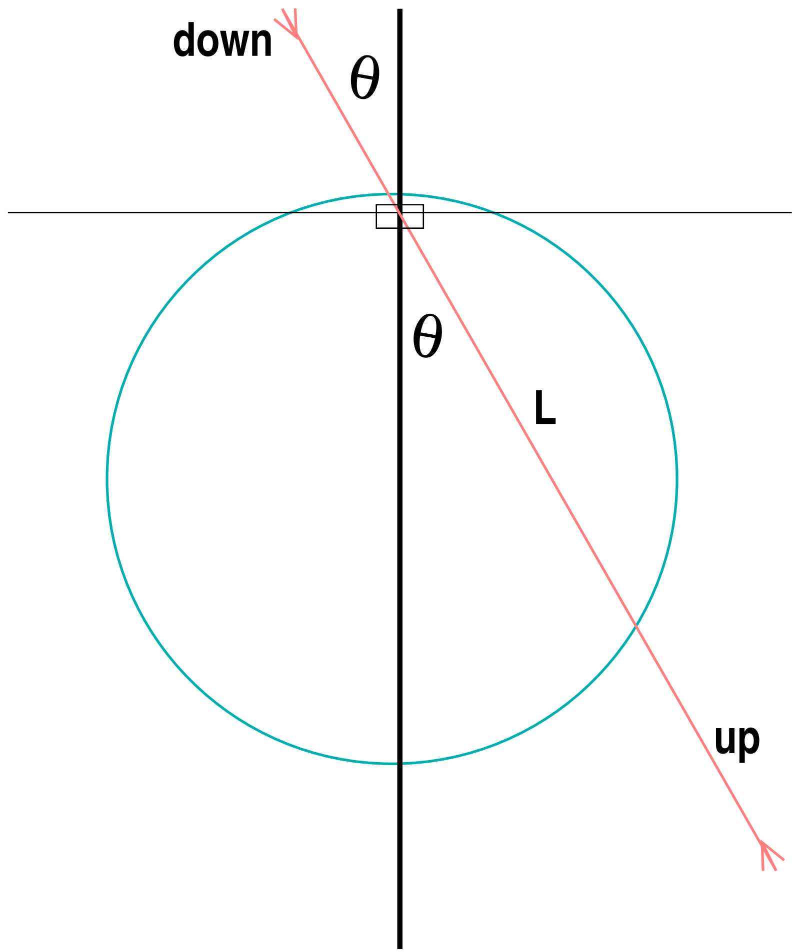
Detector Possibilities

- Magnetised iron with RPCs or glass spark chambers
- Alternate design ✘

Should be an international facility

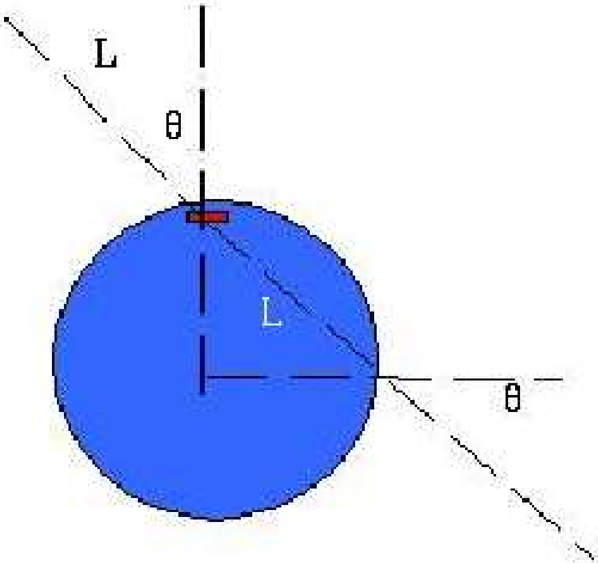
Physics goals of analysis

Stage I:
Study
oscillation pattern
in atmospheric
neutrino events.



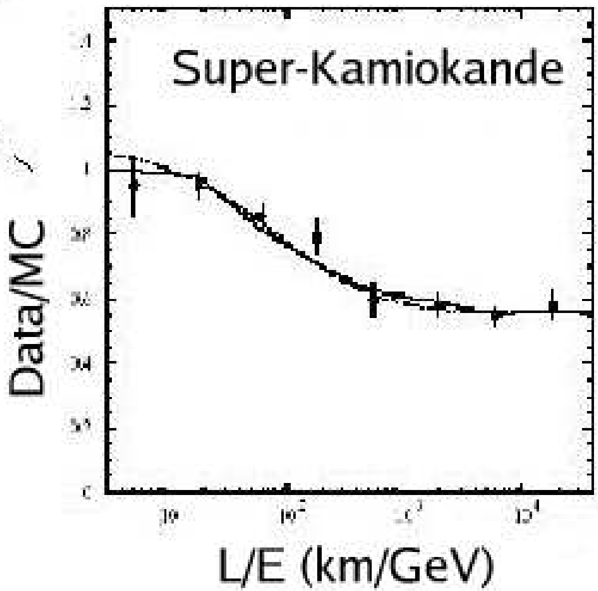
(Pietropicchi)

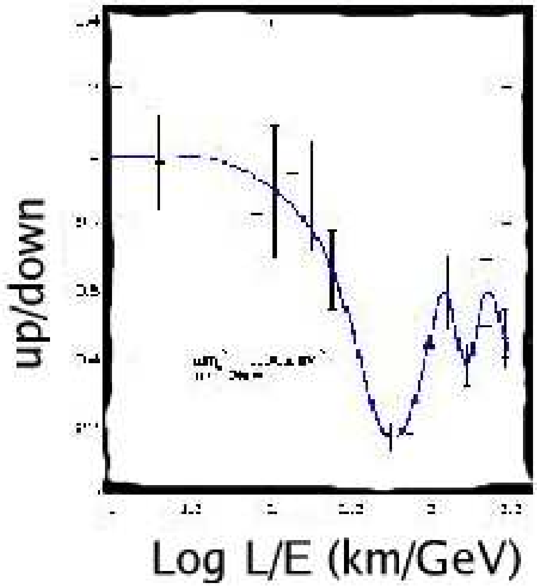
The difficulty and the hope



The disappearance probability can be measured with a single detector and two equal sources:

$$\frac{N_{up}(L/E)}{N_{down}(L/E)} = P(\nu_\mu \to \nu_\mu; L/E)$$
$$= 1 - \sin^2(2\Theta)\sin^2(1.27\,\Delta m^2\, L/E)$$





Choice of Neutrino Source and detector

Neutrino Source

- Need to cover a large L/E range
- Use atmospheric neutrinos as source
- Large L range; also large E range
- Need good resolution in both E and L (that is, in zenith angle θ_z)

Choice of Neutrino Source and detector

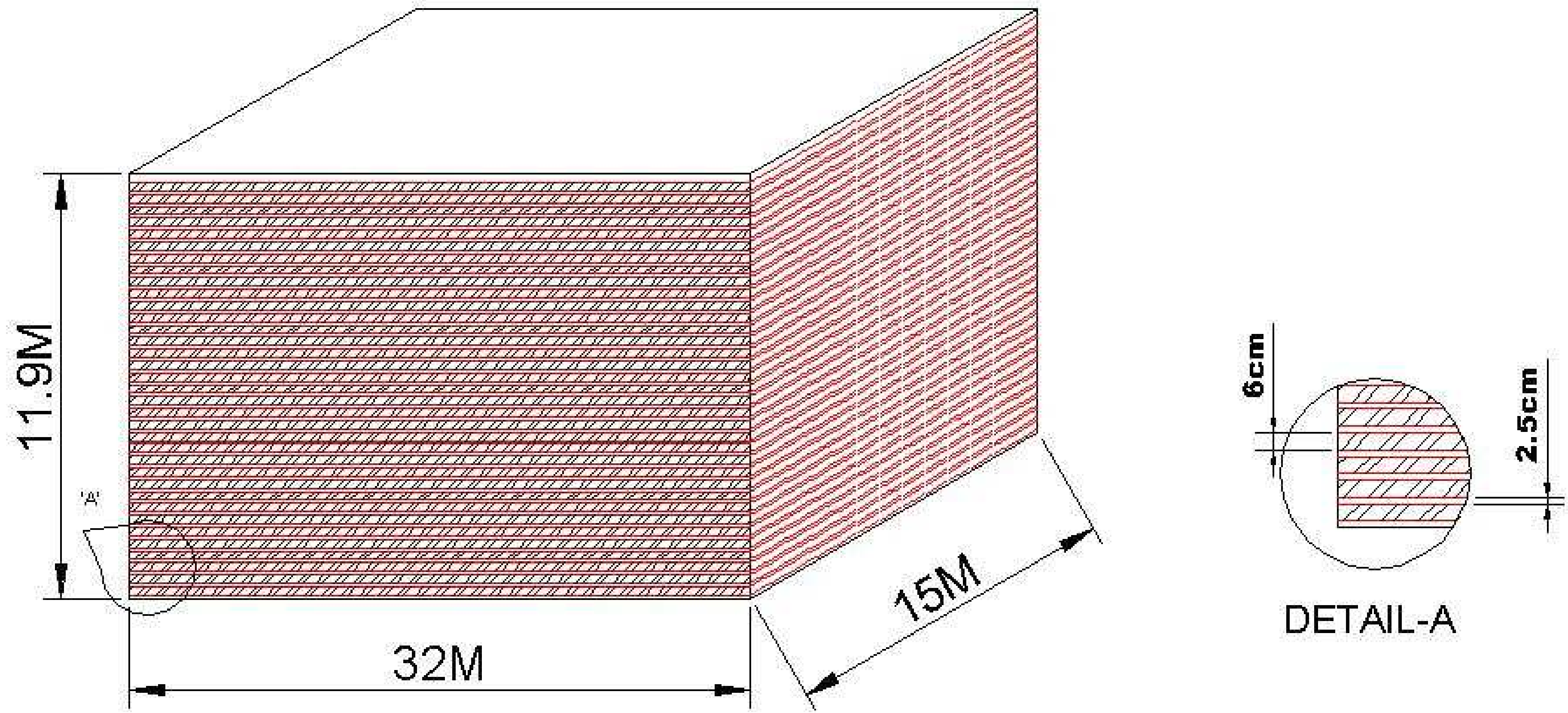
Detector choice

- Should have large target mass: 30 kton, 50 kton, 100 kton . . .
- Good tracking and energy resolution
- Good directionality (≤ 1 ns time resolution)
- Good charge resolution (for Stage II)
- Ease of construction

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

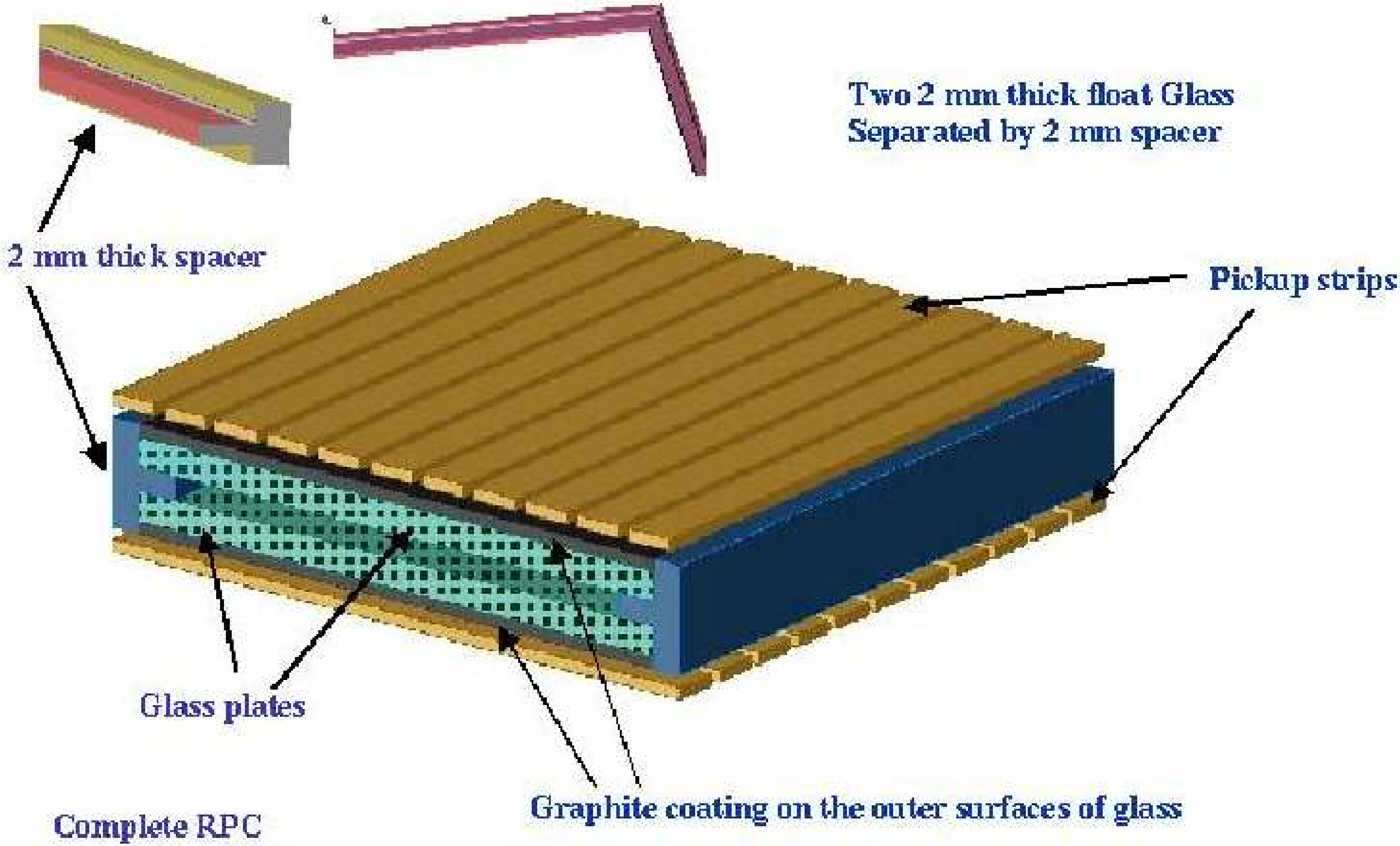
Note: Is sensitive to muons only

The ICAL detector



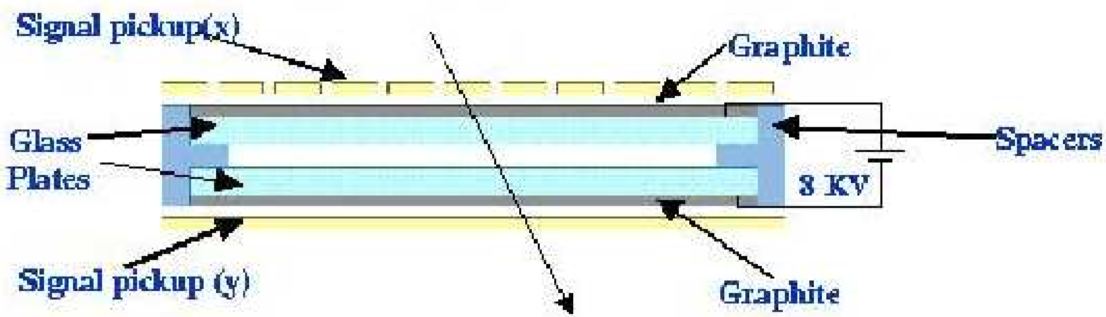
The active detector elements: RPC

RPC Construction: Float glass, graphite, and spacers



The active detector elements: RPC

RPC Principles of operation: Streamer vs Spark mode



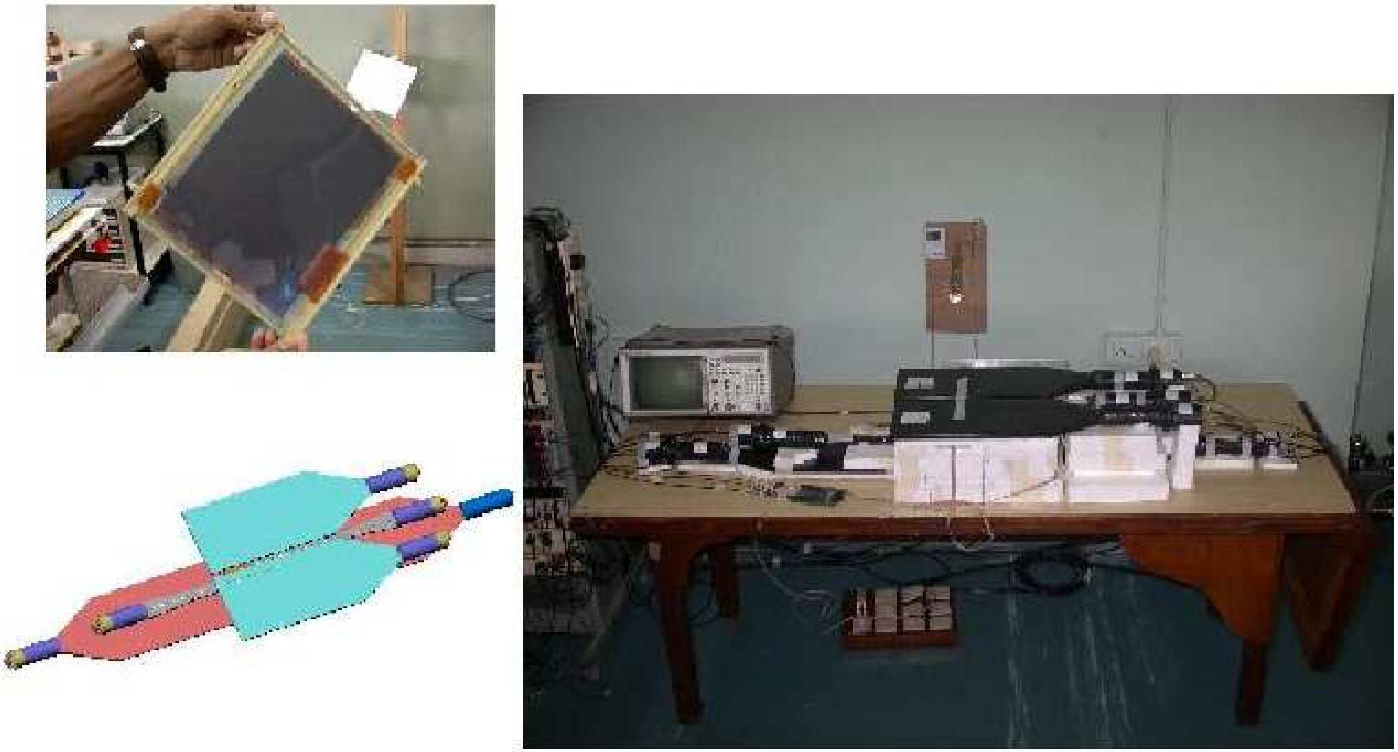
A passing charged particle induces an avalanche, which develops into a spark. The discharge is quenched when all of the locally available charge is consumed.

The discharged area recharges slowly through the high-resistivity glass plates.

The active detector elements: RPC

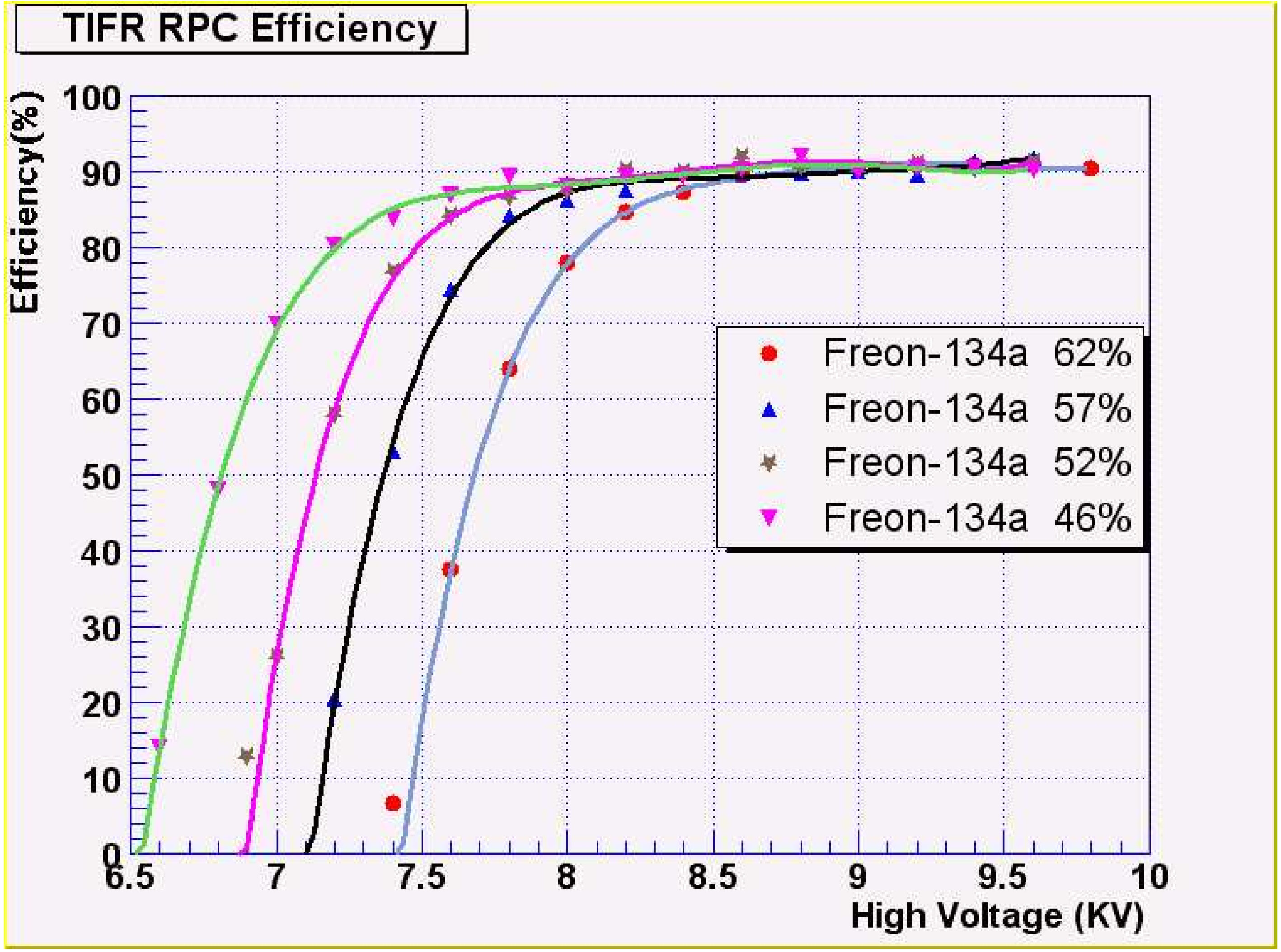
at TIFR . . .

Test of RPC

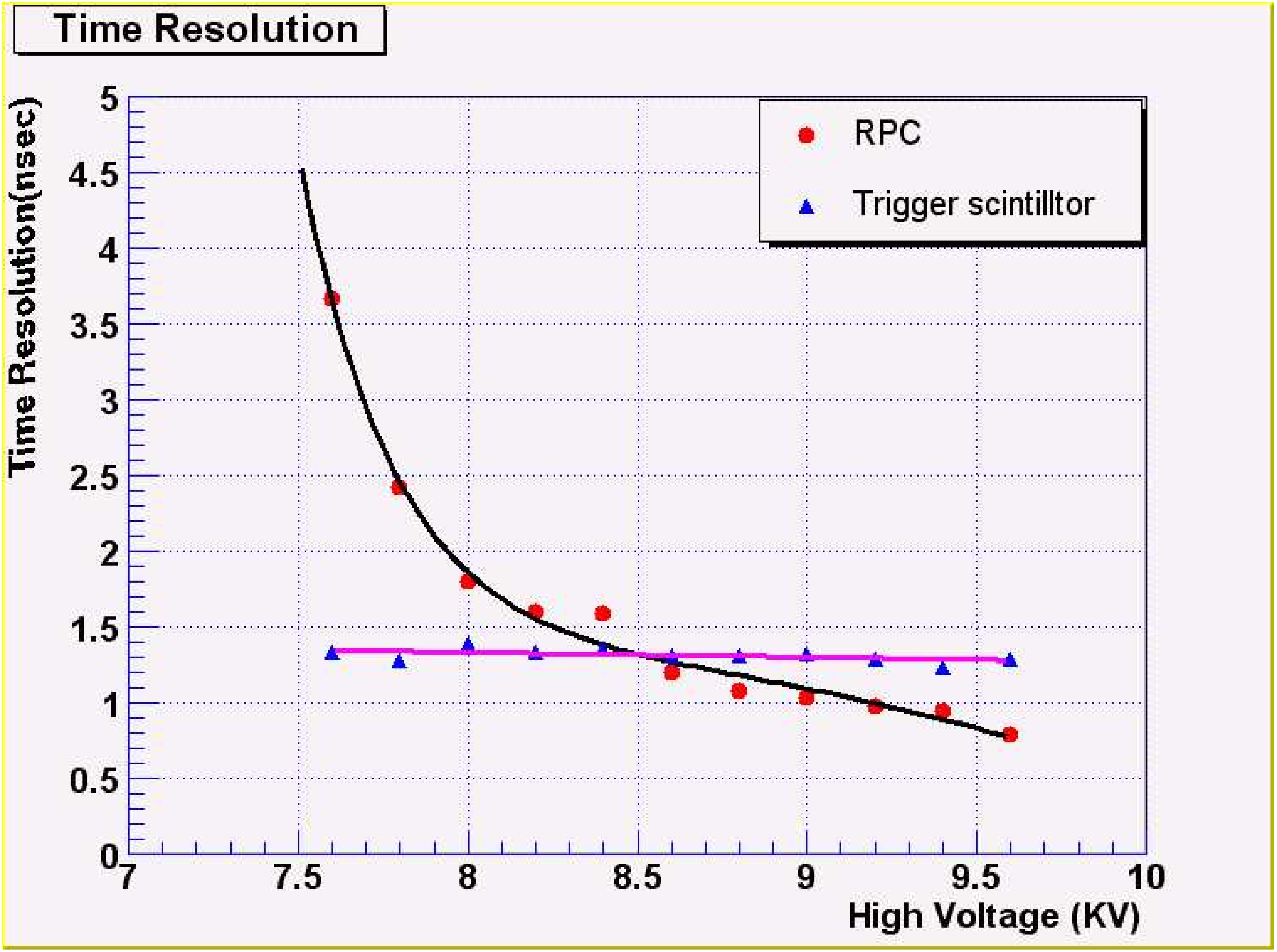


RPC Efficiency studies

Using different combinations of gas



RPC Time resolution



at TIFR

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 ($C_2H_2F_4$, C_4H_{10}, Ar, Isobutane (8%))
- RPC Cross talk (as a function of gas mixture)
- Gas mixing

Magnet studies

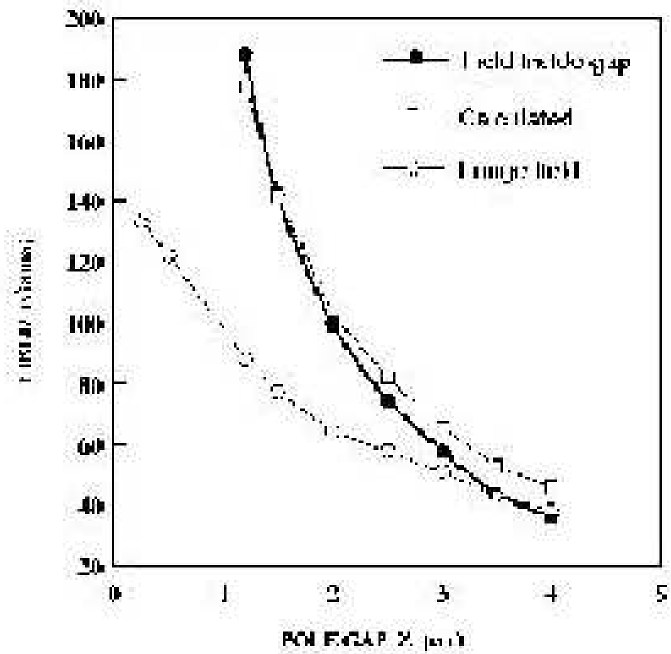
A model of the INO magnet has been fabricated at VECC to understand

If the measured field agrees with calculation.

Whether 2D calculation is OK

To understand magnet energizing time

Field measurement in the INO model (1/100 scale)



Expected field inside iron 14 KG

Detector and Physics Simulation

- NUANCE Event generator: Generates atmospheric neutrino events inside ICAL
- GEANT Monte Carlo package: Simulates the detector response for the neutrino event
- Event Reconstruction: Fits the “raw data” to extract neutrino energy and direction
- Physics Performance: Analysis of reconstructed events to extract physics

Simulations: Status report

- Neutrino Generator

  – Nuance: ICAL configuration with 3-flavour oscillation code (D. Casper)

  – Local: (HRI)

  – (Neugen : H. Gallagher) ✘ Not used so far

Simulations: Status report

- Detector Simulation

  – Geant (3.2.1 Fortran) program in place; now with magnetic field map as well.

Simulations: Status report

- Track Reconstruction using Fortran/ROOT in C++

  – Without magnetic field: program fits muons to straight lines, with energy loss; still to be refined.

  – With magnetic field: program fits muons to helical trajectory, with energy loss; still to be refined.

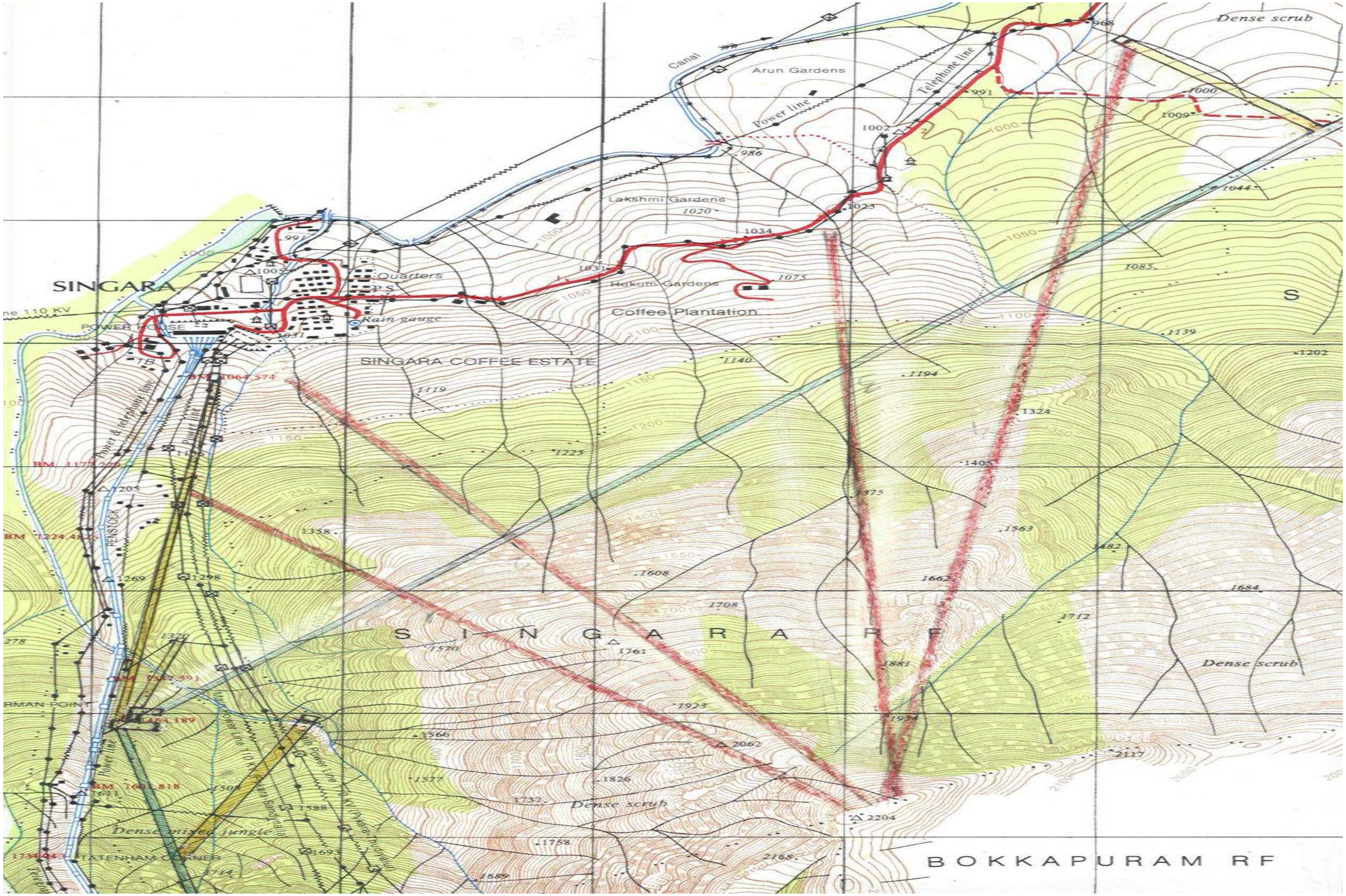
  – Hadron hit reconstruction: to be refined.

Simulations: Status report

- One-line status summary:

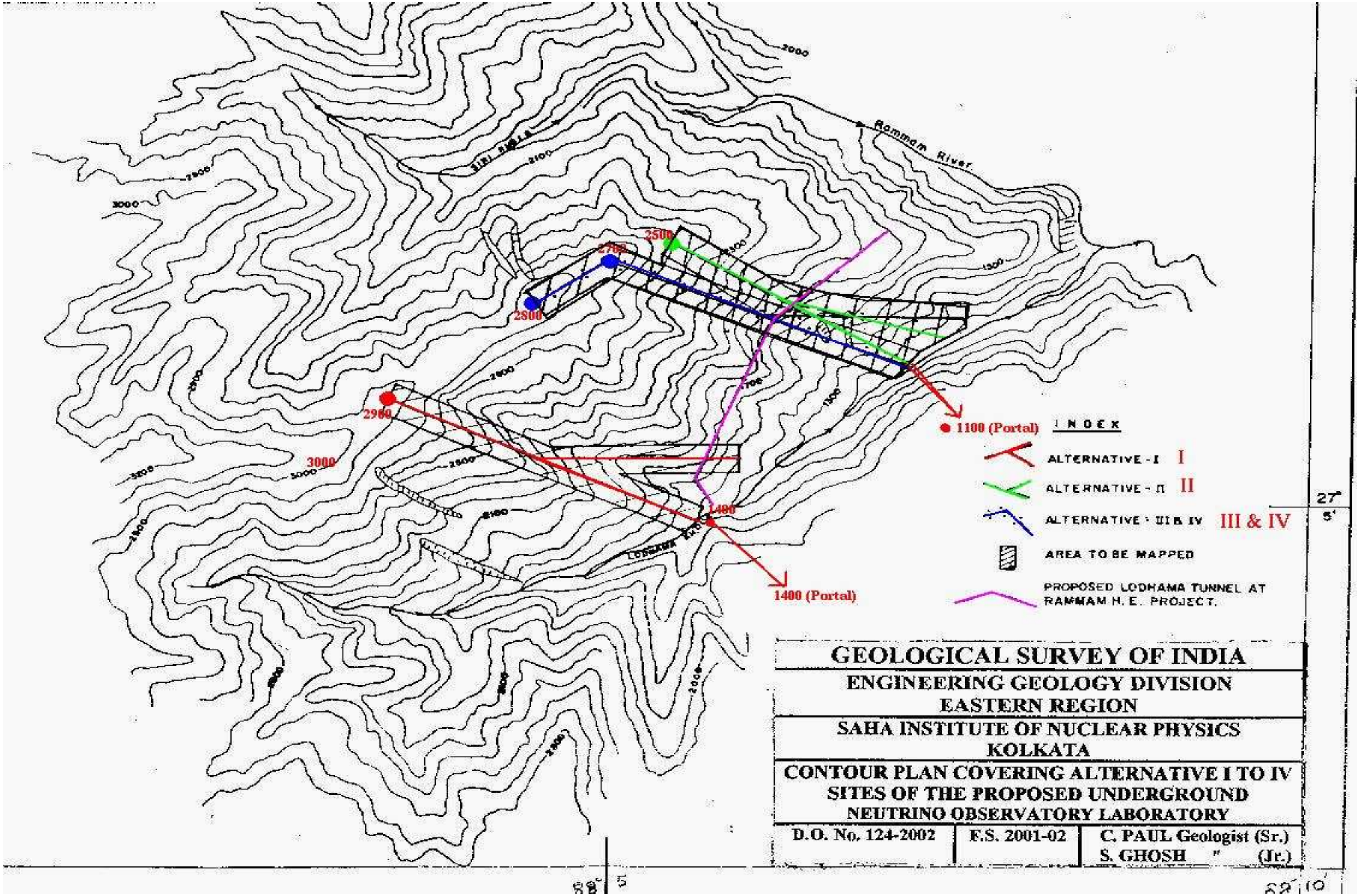
  programs in place and being tested; “data” being analysed.

Site survey: PUSHEP



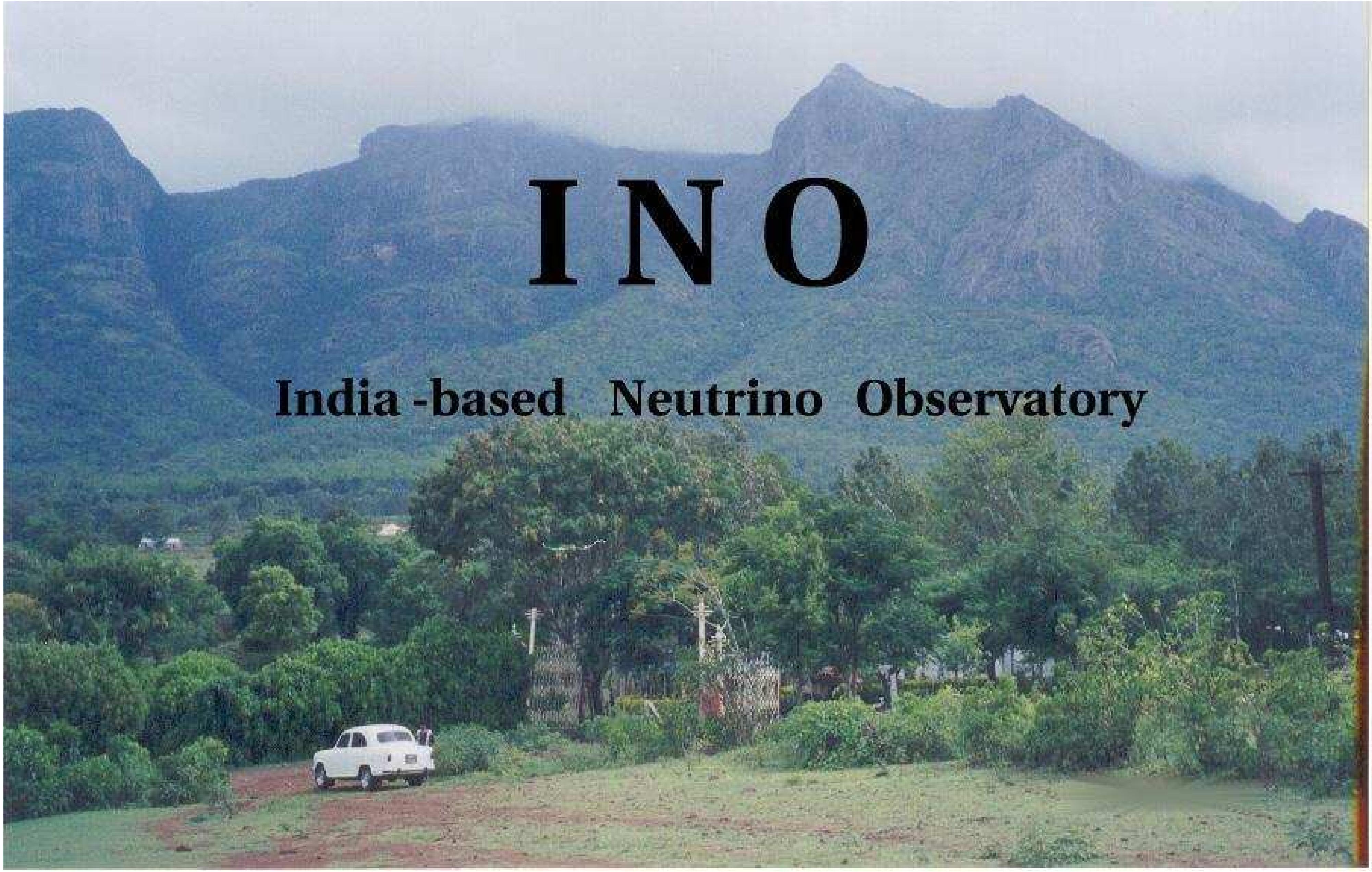
PUSHEP in Nilagiris, near Ooty (Masinagudi)

Site Survey: Rammam



Rammam in Darjeeling District

Physics Prospects

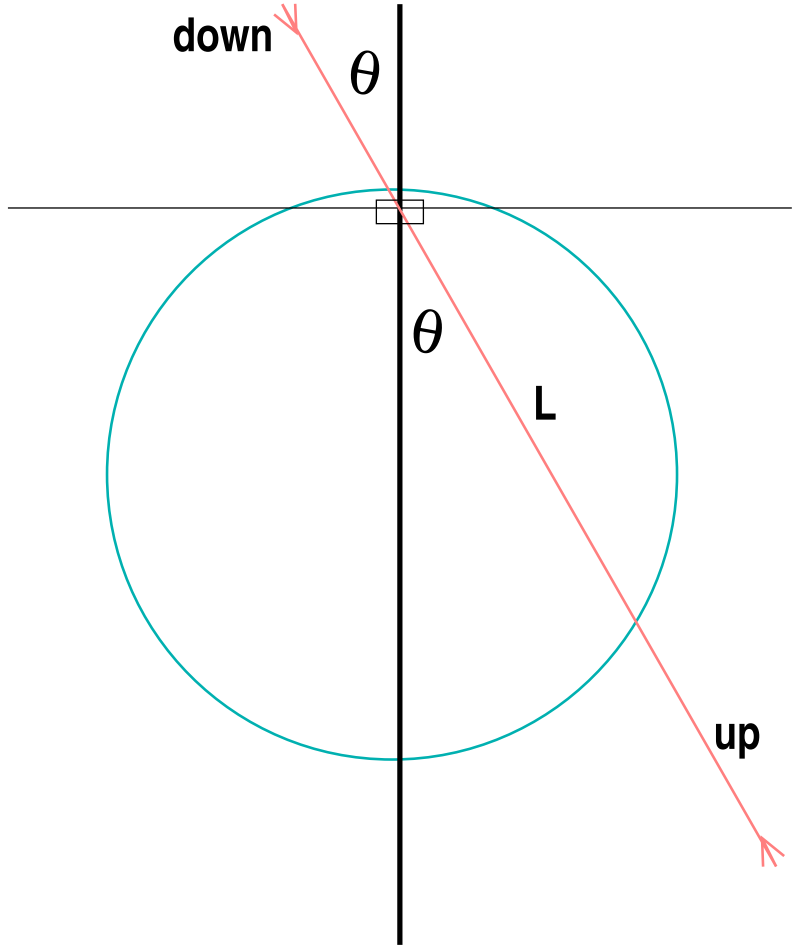


Physics with Atmospheric Neutrinos

- Simplified ICAL detector geometry encoded in Nuance generator.
- Events are generated using HONDA flux with some input oscillation parameters δ_{23}, θ_{23}, and $\theta_{13} = 0$ (ICAL may not be sensitive to 1-3 mixing).
- Quasielastic, resonant, DIS events, roughly in $1/3$: $1/3$: $1/3$ ratio
- Analysis ONLY of 5 year CC events with μ in the final state (electron CC events mostly lost); typically interesting events have $E > 1$–2 GeV.
- MAJOR ISSUE, YET TO BE STUDIED: Mis-identification of pions as muons from NC as well as a subset of CC events.
- Recall: ICAL geometry is similar to that of MONOLITH.

Physics Analysis (2-flavour)

➢ Main goal: Study oscillation pattern in atmospheric neutrino events.



(Pietropicchi)

Physics Analysis (2-flavour)

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

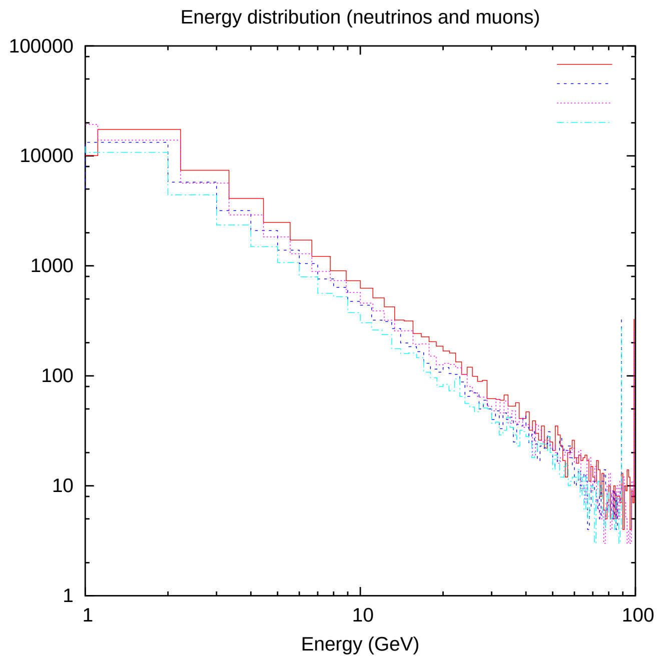
Resolution function is given by the Lorentzian:

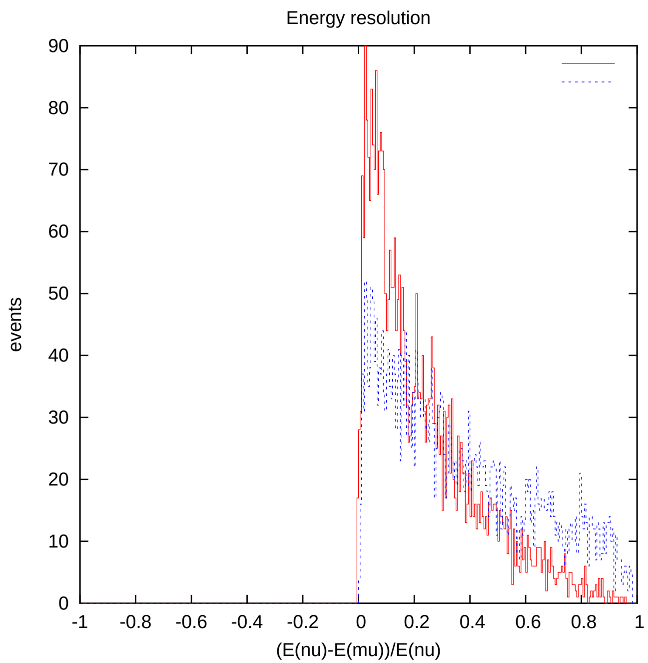
$$R(x = L/E) = \frac{1}{\pi}\left(\frac{\sigma}{\sigma^2 + (x - x_0)^2}\right) \ ;$$

σ is the resolution in L/E of the ICAL detector.

So, analysis *needs* a knowledge of this resolution function.

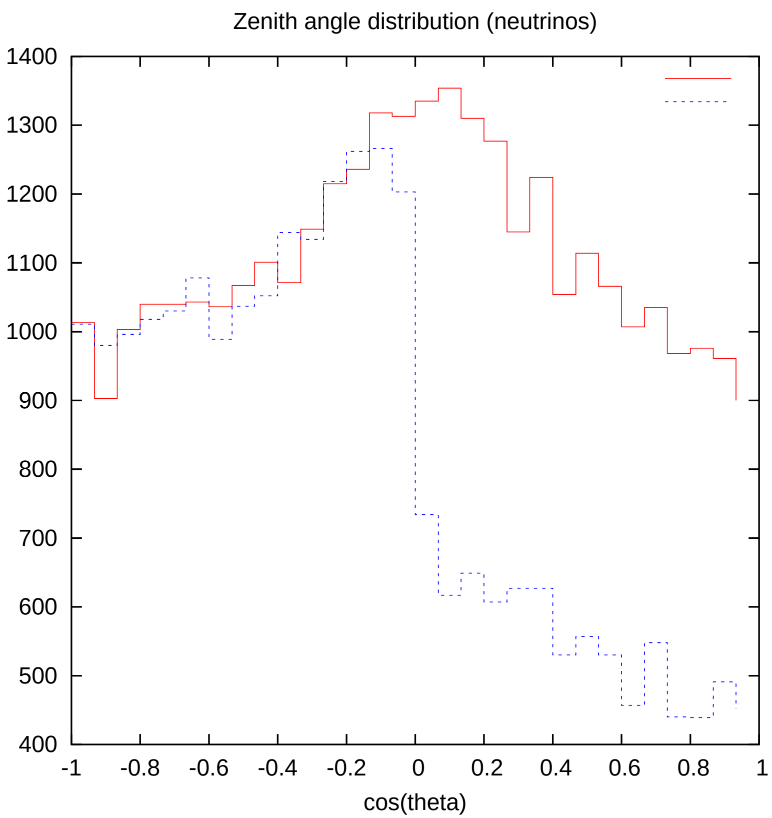
Energy Resolution

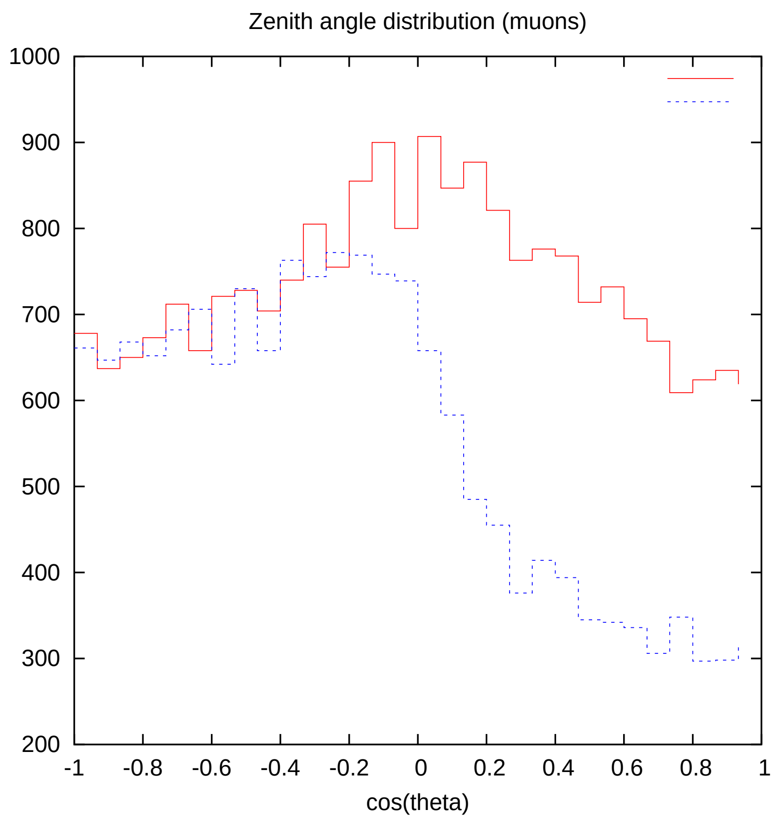




- Energy resolution with muons alone and including hadrons as well.
- $E_\mu \sim 0.7 E_\nu$

Nuance output





Neutrinos (left) Muons (right)

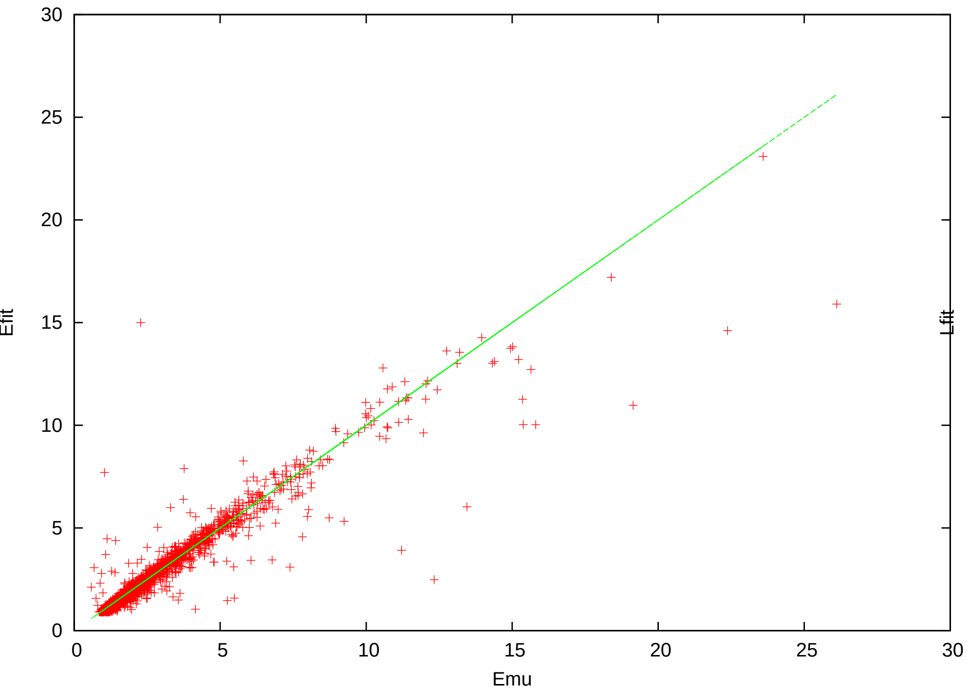
with oscillations . . . . without oscillations

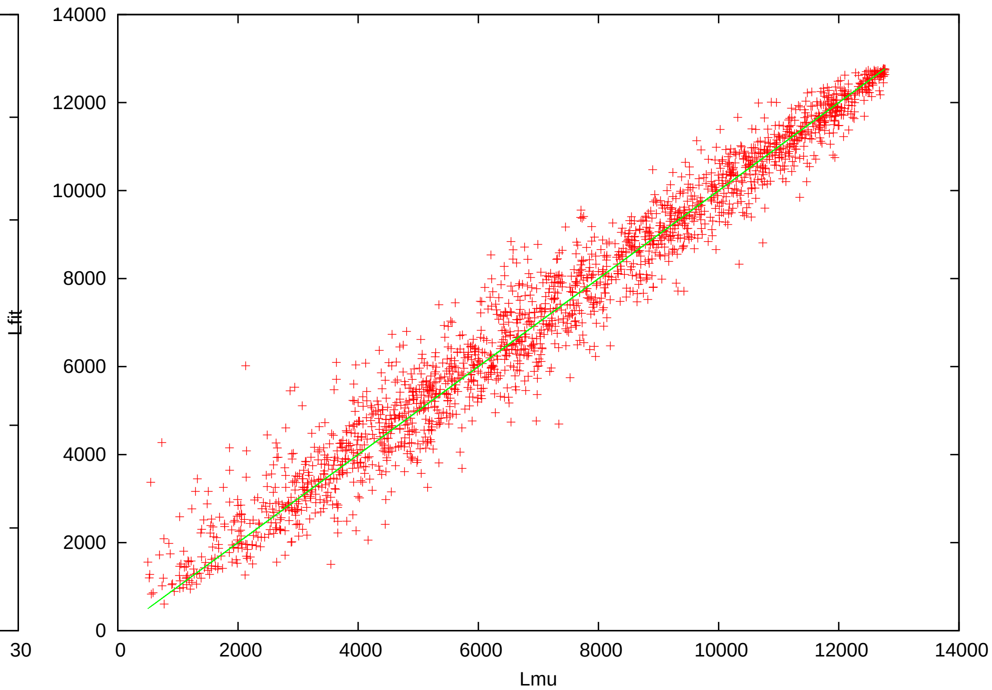
Analysis of GEANT-processed events

- The Nuance events were generated with some starting oscillation parameters (δ_{23} and θ) for the neutrino fluxes.
- The CC events containing muons are passed through the GEANT program to get a pattern of hits in the simulated ICAL detector.
- The hits are recontructed to get E_μ, θ_μ, E_{had}.
- The relevant resolutions including R are studied.
- R is used to fit the oscillation pattern in the reconstructed ratio of up/down events.
- The fit results in estimates of the oscillation parameters.
- This determines the sensitivity of the detector configuration to the oscillation parameters.

WITHOUT Magnetic Field

E & L distributions from reconstructing muon tracks in ICAL detector (hadron contribution not included here).

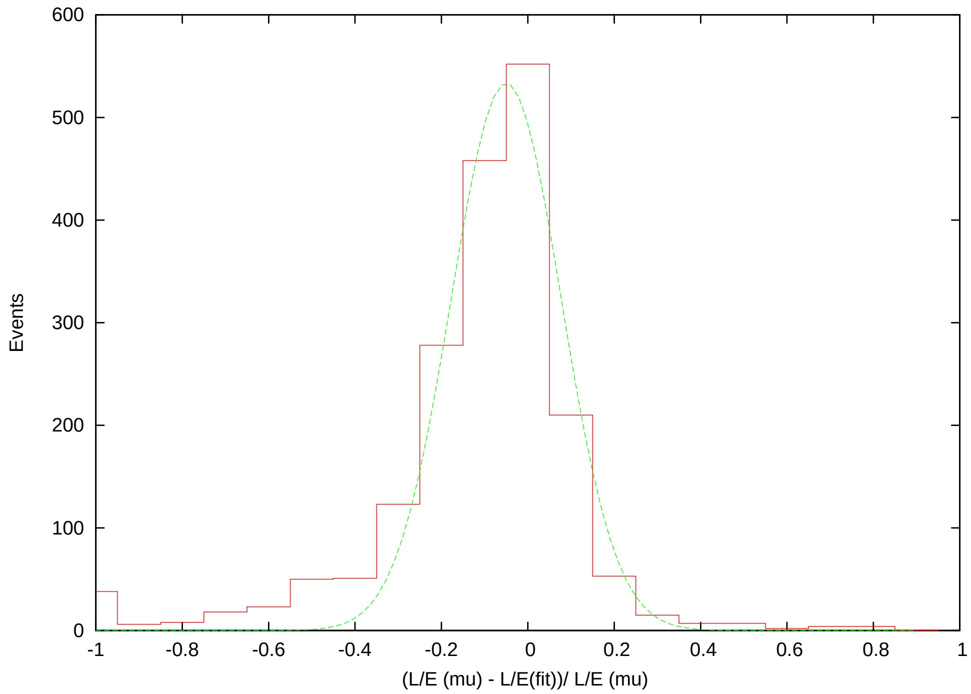




Left: $E_{\rm fit}$ from hit reconstruction vs. E_μ from Nuance

Right: $L_{\rm fit}$ from hit reconstruction vs. L_μ from Nuance

L/E Resolution

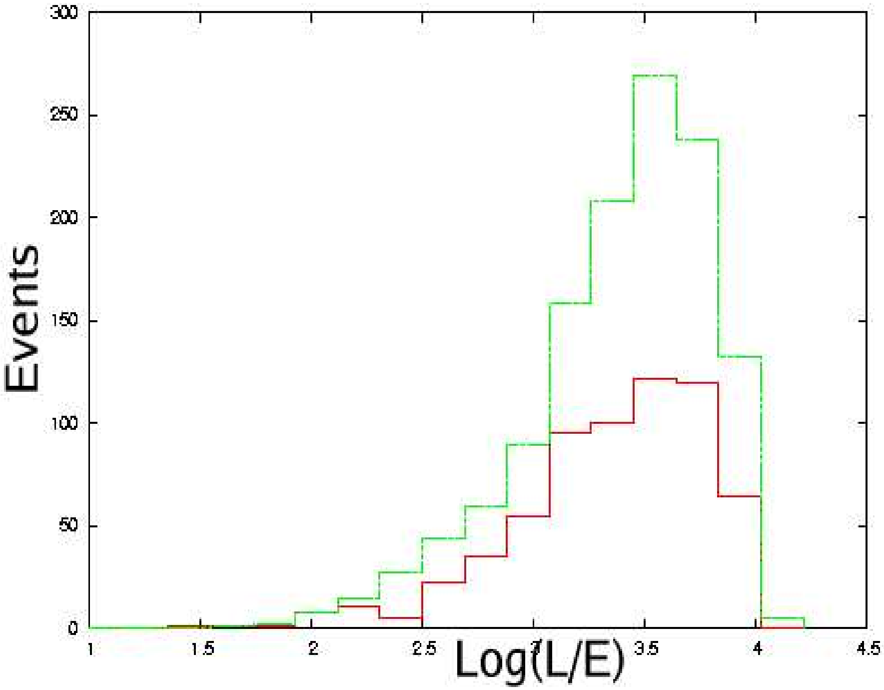


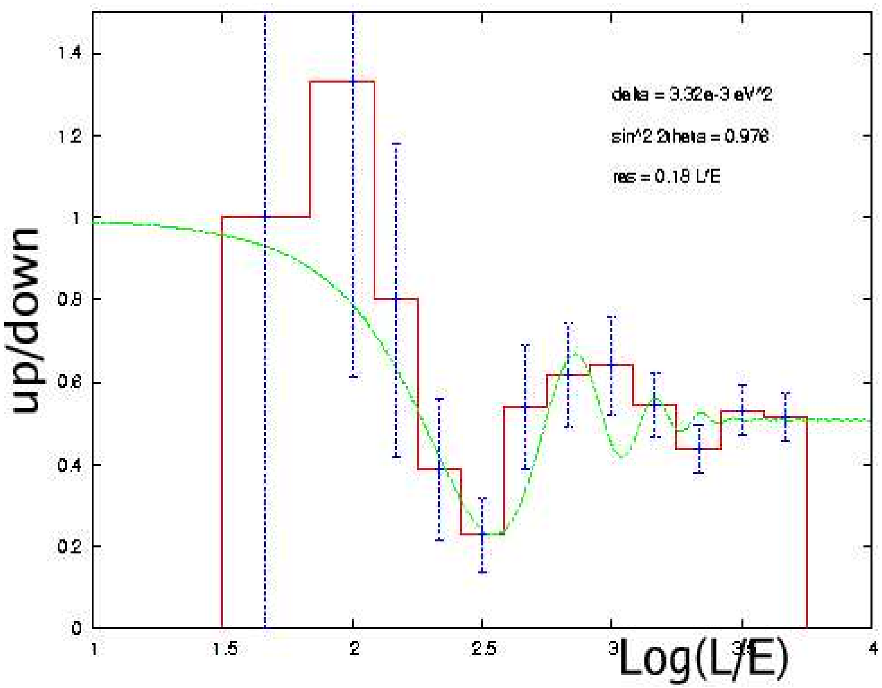
Resolution obtained, in the absence of magnetic field:

$$\Delta \frac{L}{E} = 0.18 \, \frac{L}{E}$$

Physics analysis with Geant events

- Oscillation Parameters: $\delta_{23} = 3 \times 10^{-3}$ eV^2; $\sin^2 2\theta_{23} = 1.0$
- Resolution function: $\sigma = 0.18\, L/E$

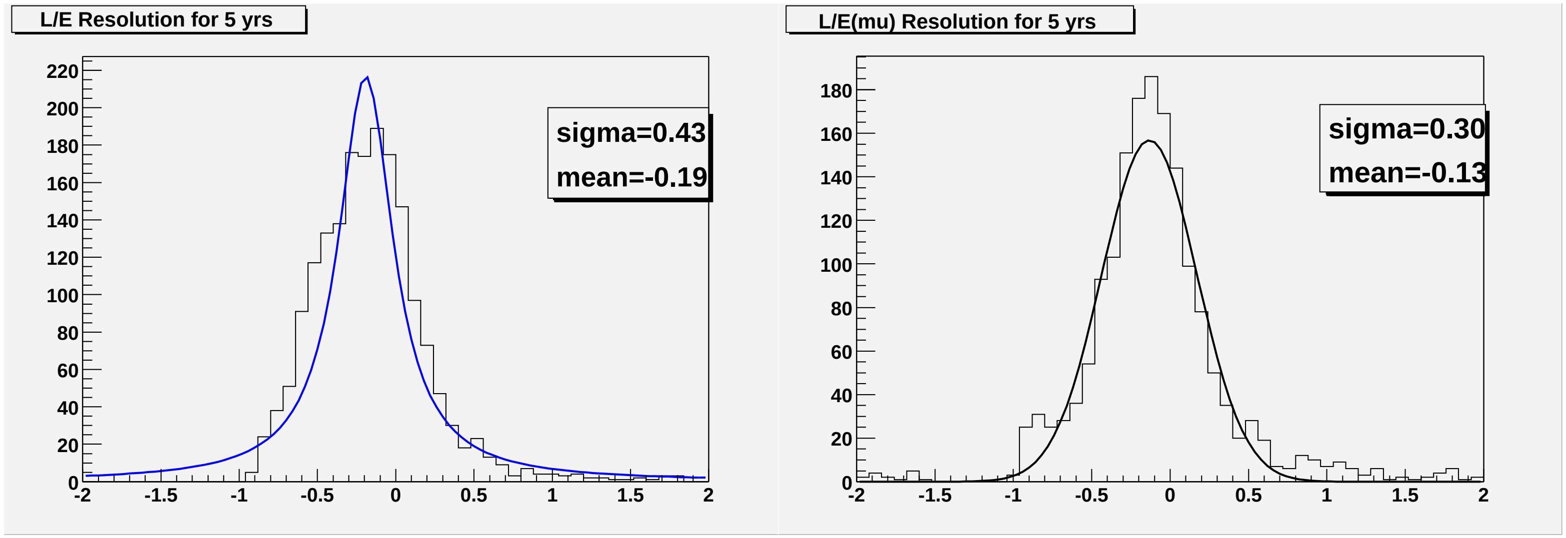




$\delta_{23} = (3.3^{+0.3}_{-0.6}) \times 10^{-3}$ eV^2 (3.0)
$\sin^2 2\theta_{23} = 0.98^{+0.02}_{-0.07}$ (1.0)

NEW! since INSA meeting, New Delhi, Nov 03

L/E Resolution with magnetic field



L/E resolution from reconstruction (left); muon only (right).
Resolution obtained, with magnetic field:

$$\Delta \frac{L}{E} = 0.215 \, \frac{L}{E} \; .$$

Program has since been improved

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- Various refinements in progress.

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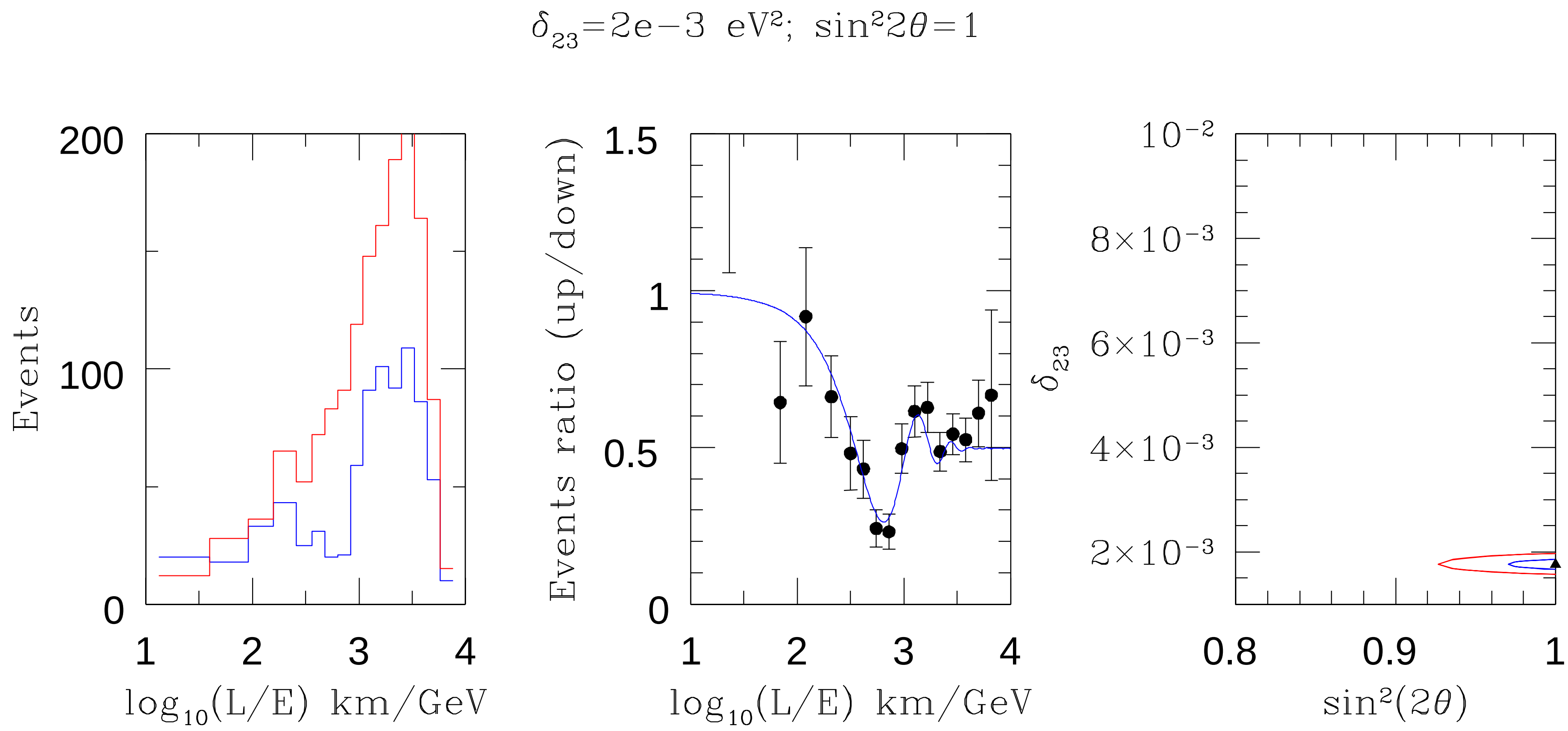
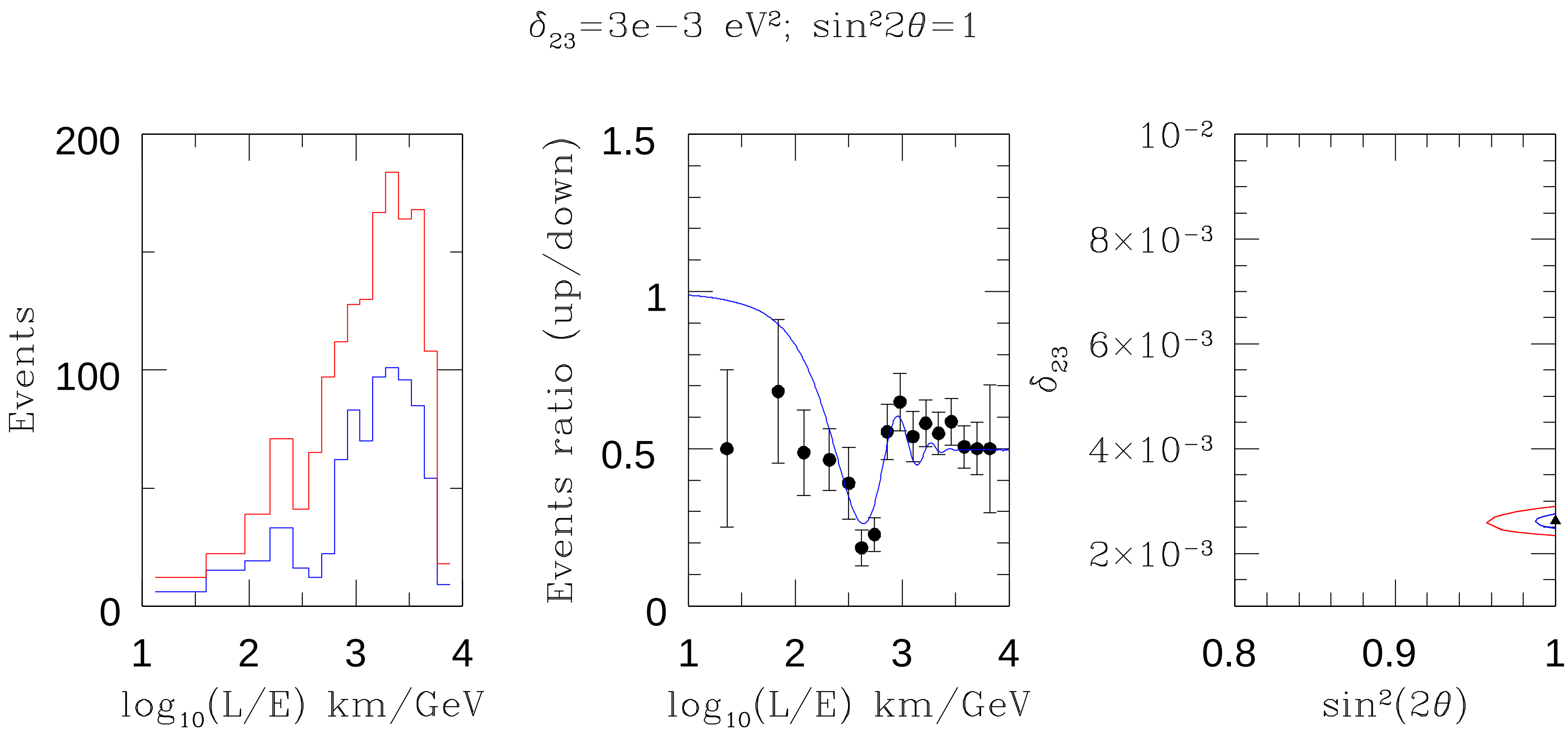
  that is, events are directly analysed without passing through detector and reconstructing hit pattern so reconstruction efficiency = 1 instead of 0.4.
- Analysis done for different input values of oscillation parameters, δ_{23} and $\sin\theta_{23}$.

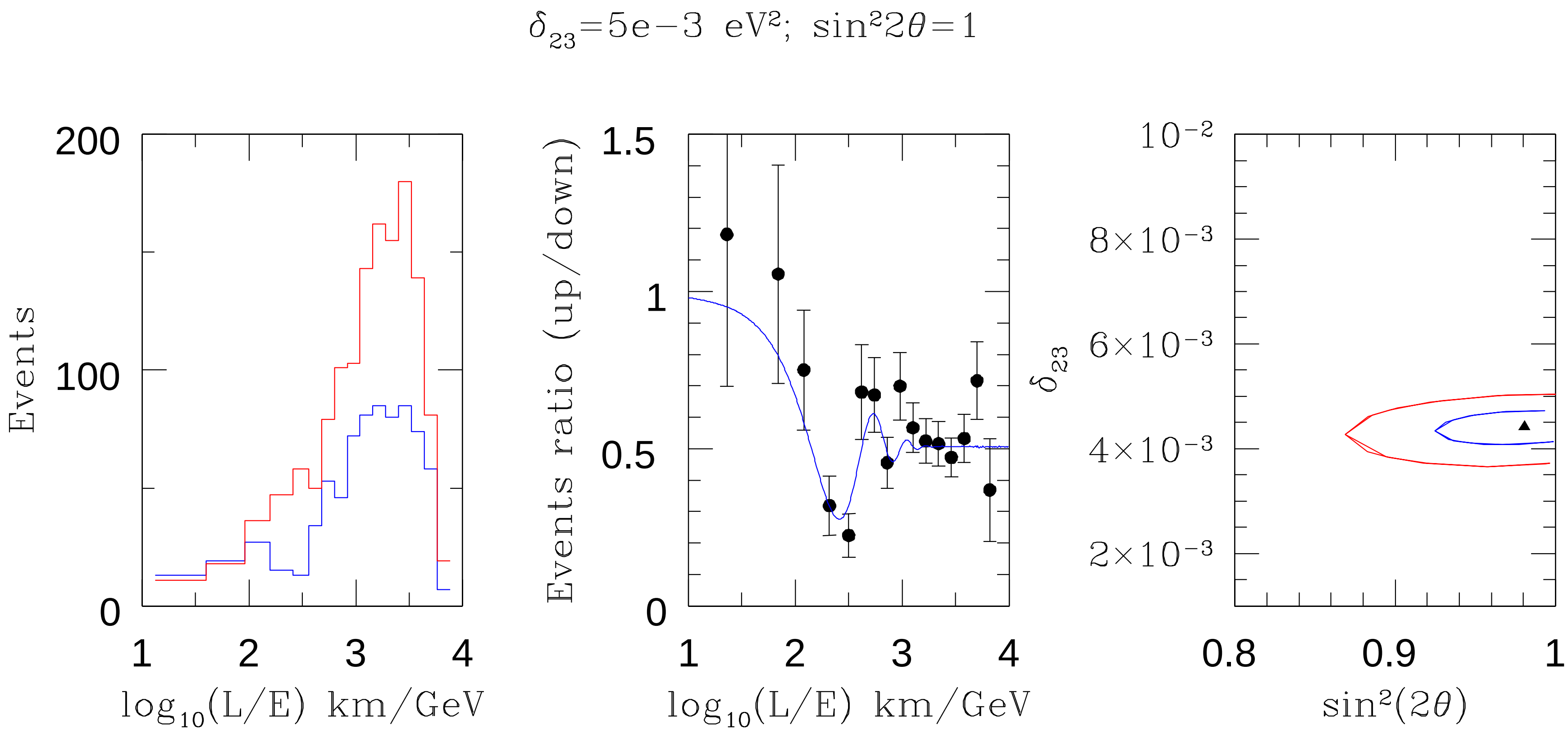
$\delta = 2 \times 10^{-3}$ eV^2



$$\delta = 3 \times 10^{-3}\ \mathbf{eV}^2$$

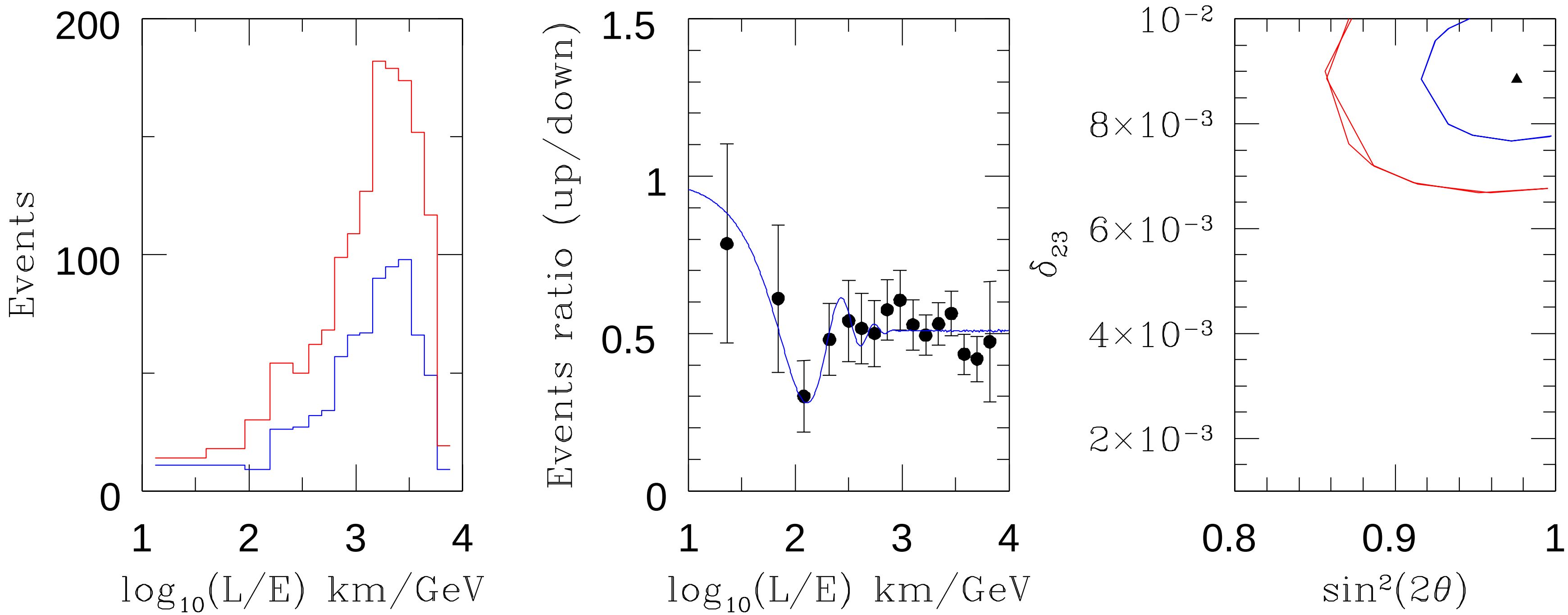


$\delta = 5 \times 10^{-3}$ eV^2



$\delta = 8 \times 10^{-3}$ eV^2

δ_{23}=8e−3 eV^2; $\sin^2 2\theta$=1



Physics goals of analysis II

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

- Burning issue in neutrino physics: is the 1-3 mixing angle zero or not? If $\sin\theta_{13} \neq 0$, can look for

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- A determination of $\sin\theta_{13}$ itself
- sign of the (23) mass-squared difference $\delta_{32} = m_3^2 - m_2^2$
- CP violation through a CP violating phase δ that occurs in the mixing matrix when there are three active coupled neutrino species.

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- Large L means large E (20 GeV or more), for seeing interesting oscillation phenomena
- Such a neutrino beam is far off into future, but lots of work going on (see neutrino oscillation industry web-page)

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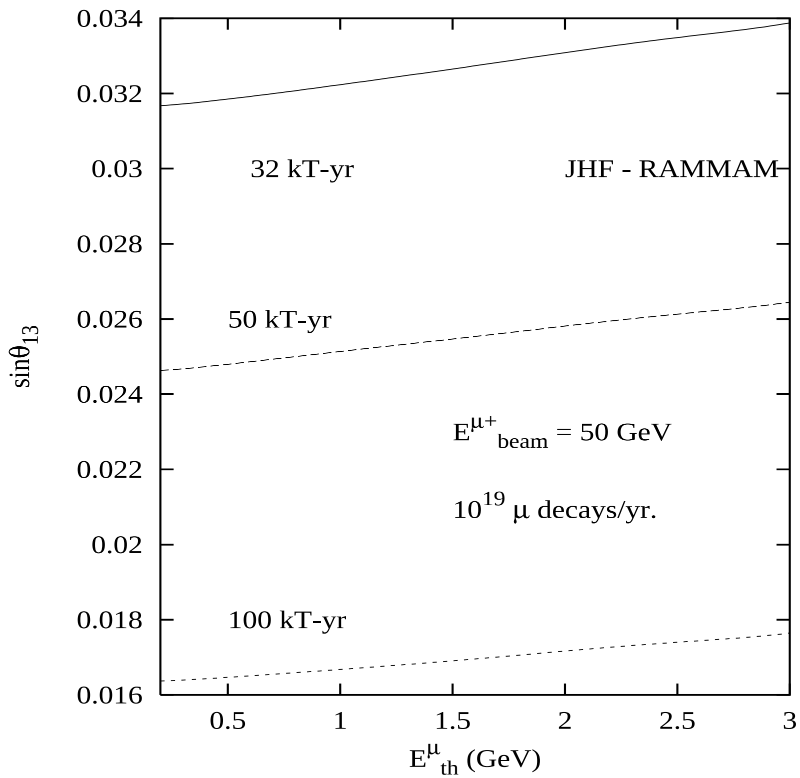
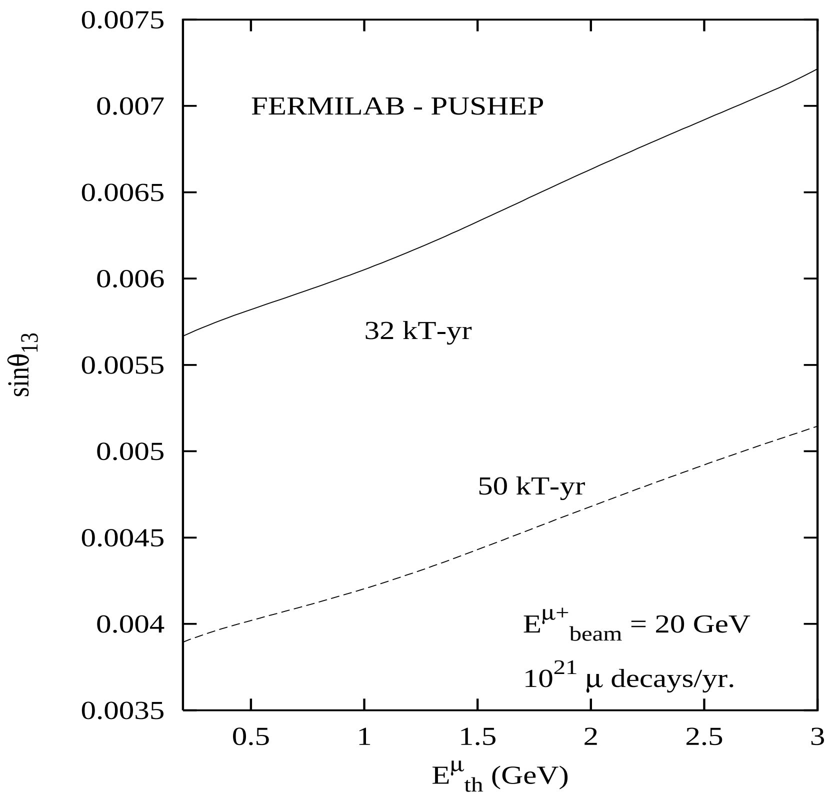
  ν_μ (osc-beam) $\longrightarrow \mu$ (detector)
- Result: wrong sign muon (10/kton = signal)

Reach of $\sin\theta_{13}$

JHF to Rammam



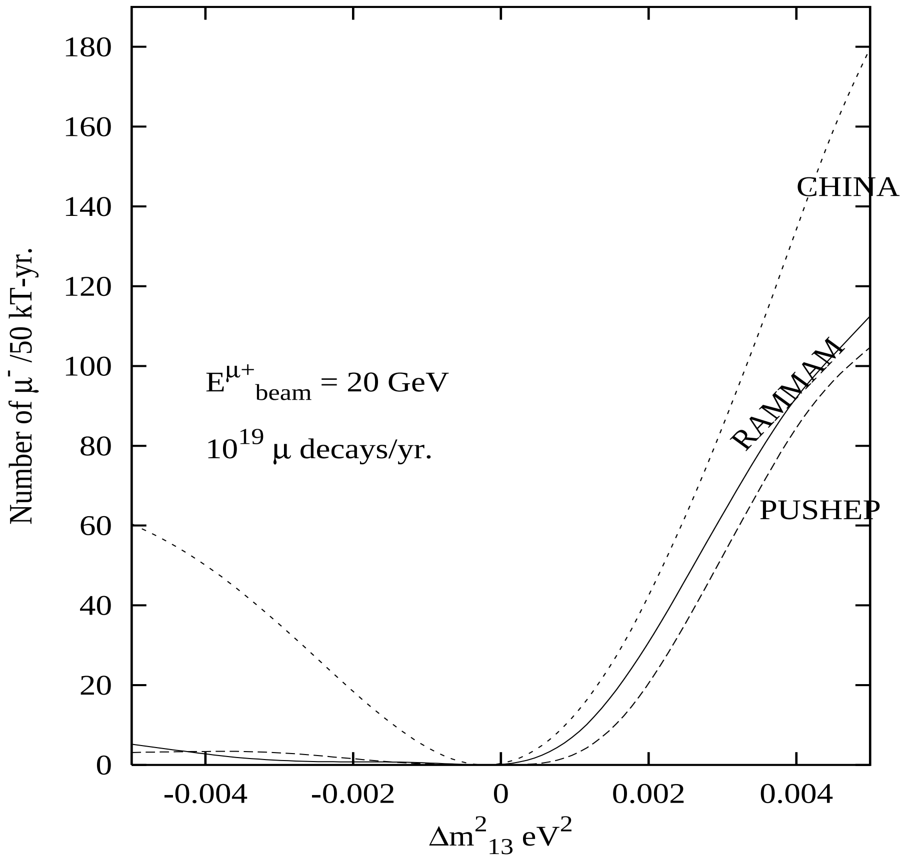
Fermilab to PUSHEP



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

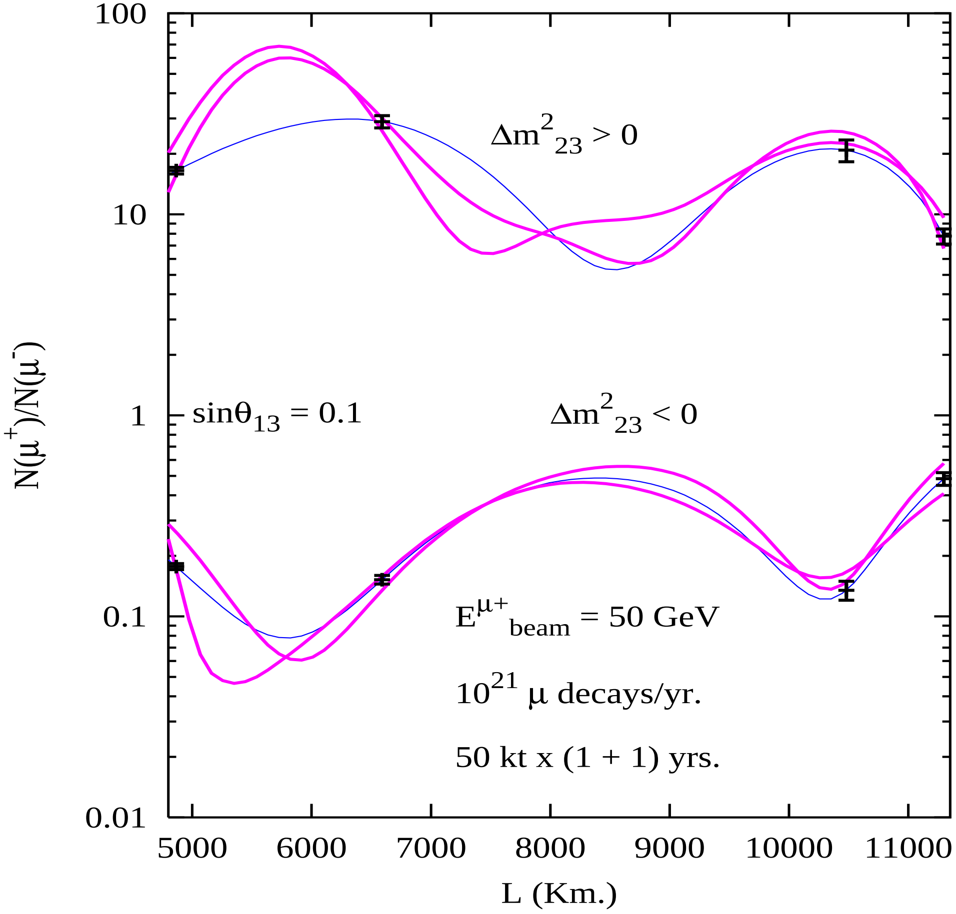
Sign of δ_{23} vs wrong sign μ

JHF to Beijing, Rammam and PUSHEP



CP violation: δ vs L

JHF to Rammam and PUSHEP



FermiLab to Rammam and PUSHEP

Outlook

The ICAL detector

- Proof-of-principle working of RPC shown

Outlook

The ICAL detector

- Magnet studies under-way

Outlook

The ICAL detector

- Hence detector prototype ready for construction

Outlook

The ICAL detector

- Site survey: two possible sites, both seem good options

Outlook

The ICAL detector

- Simulations: programs in place, need refining and testing.
- Atmospheric neutrino programme:
  ICAL sensitive to oscillation parameters to better accuracy than current Super-K.
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- Accelerator neutrino programme:
  ICAL++, with suitable beam from future nu-factory, is sensitive to $\sin^2 2\theta_{13}$, sign of δ_{23}, and CP phase.
  JHF-PUSHEP baseline is near magic: may provide clean separation of matter and CP violation effects.

Outlook . . .

The INO Collaboration

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- The outlook looks good!
- This is a massive project:
- Looking for active collaboration both within India and abroad