Status of Simulations at INO

D. Indumathi,
The Institute of Mathematical Sciences
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STATUS ON WORK DONE (MAINLY) AT

- Harish-Chandra Research Institute, Allahabad,
- Saha Institute of Nuclear Physics, Kolkata,
- Tata Institute of Fundamental Research, Mumbai,
- → The Institute of Mathematical Sciences, Chennai,
- University of Calcutta, Kolkata

Status Overview :

- Neutrino Generator
  - Nuance: ICAL configuration with 3-flavour oscillation code (D. Casper)
  - Local: (HRI)
  - (Neugen : H. Gallagher) ✘ Not been used so far
- Detector Simulation
  - Geant (3.2.1 Fortran) program in place; now with magnetic field map as well.
- Track Reconstruction
  - ROOT (3.03 C++) program fits muons to helical trajectory, with energy loss; still to be refined.
  - Hadron hit reconstruction: still some problems.

$\ast$ One-line status summary: programs tested and more or less ok; “data” being analysed.

1 The Nuance generator

➢ Atmospheric neutrinos alone analysed so far.

➢ Simplified ICAL detector geometry encoded, in which events are generated.

➢ Typically interesting events have $E > 1$–2 GeV.

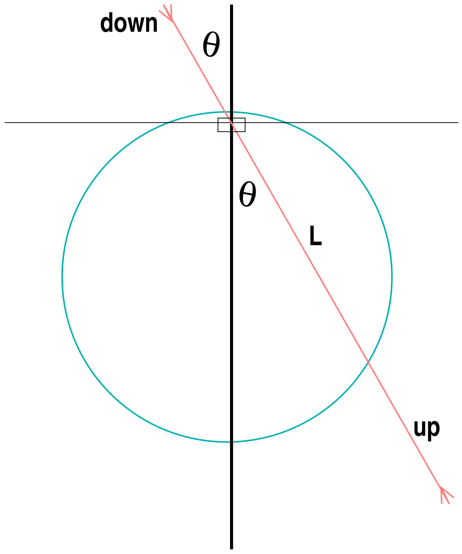
➠ Quasielastic, resonant, DIS, coherent, electron scattering events, roughly in $1/3 \sim 1/3 \sim 1/3 \sim 0 \sim 0$ ratio

➢ Analysis ONLY of CC events with μ in the final state (electron CC events mostly lost)

➢ MAJOR ISSUE YET TO BE STUDIED: Mis-identification of pions as muons coming from NC as well as a subset of CC events.

1.1 Physics goals of analysis

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



(Pietropicchi)

$$\frac{\text{up events}}{\text{down events}} = \text{‘}P'_{\mu\mu} = 1 - \frac{\sin^2\theta_{23}}{2}\left(1 - R\cos 2.54\delta_{23}\frac{L}{E}\right) \; ,$$

where the resolution function is given by the Lorentzian

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

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

We therefore perform

➢ A detailed study of the resolutions in E, θ and therefore L and L/E.

➢ ICAL geometry is similar to that of the MONOLITH collab.

➢ Our aim: to re-invent this wheel

2 Results

• The generator understands the ICAL detector configuration in a simplified fashion (includes iron and glass, mainly).
• Here we present some results with atmospheric neutrinos, using the Honda flux for ICAL detector with 140 layers of 6 cm thick iron plates. (Some detector optimisation at the end of the first complete round of simulation is envisaged).

2.1 Energy distribution

Event distribution in energy for 25 years' data at ICAL.

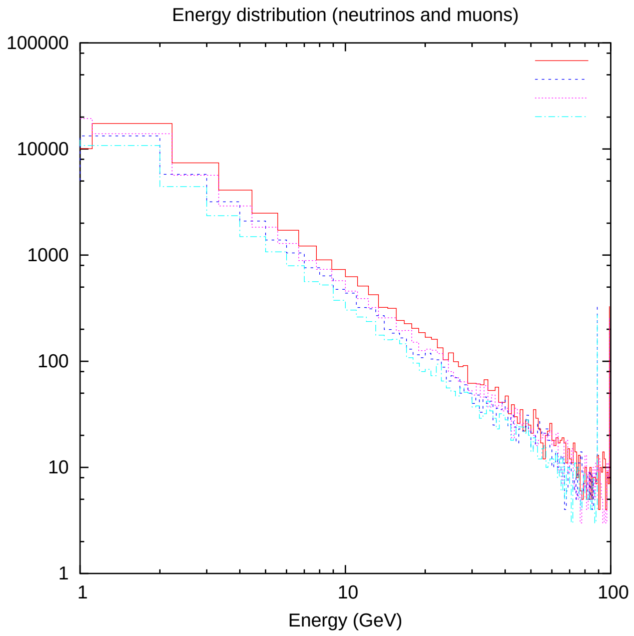
Figure on left :

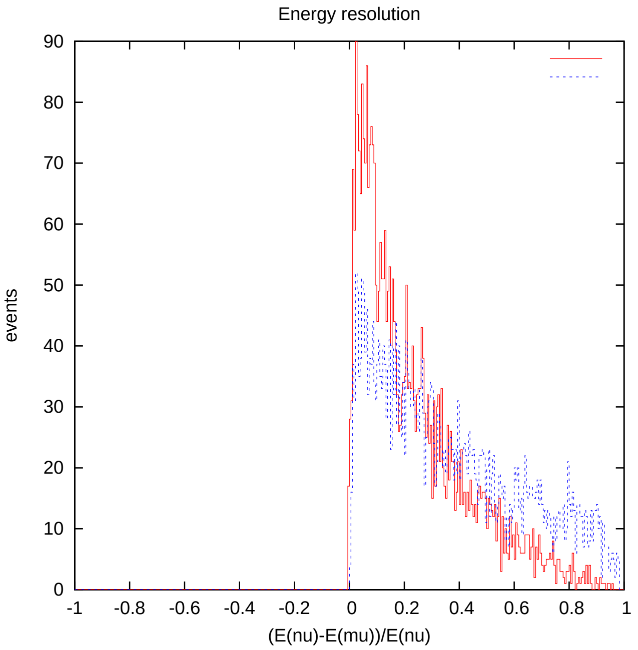
• Muons (red) and neutrinos (pink) lines (with oscillations) and as blue and green lines (without oscillations).

• Ratio of number of muons to neutrinos at a given energy (in bins of 1 GeV) ~ 0.7–0.8, especially for energies less than 10 GeV.

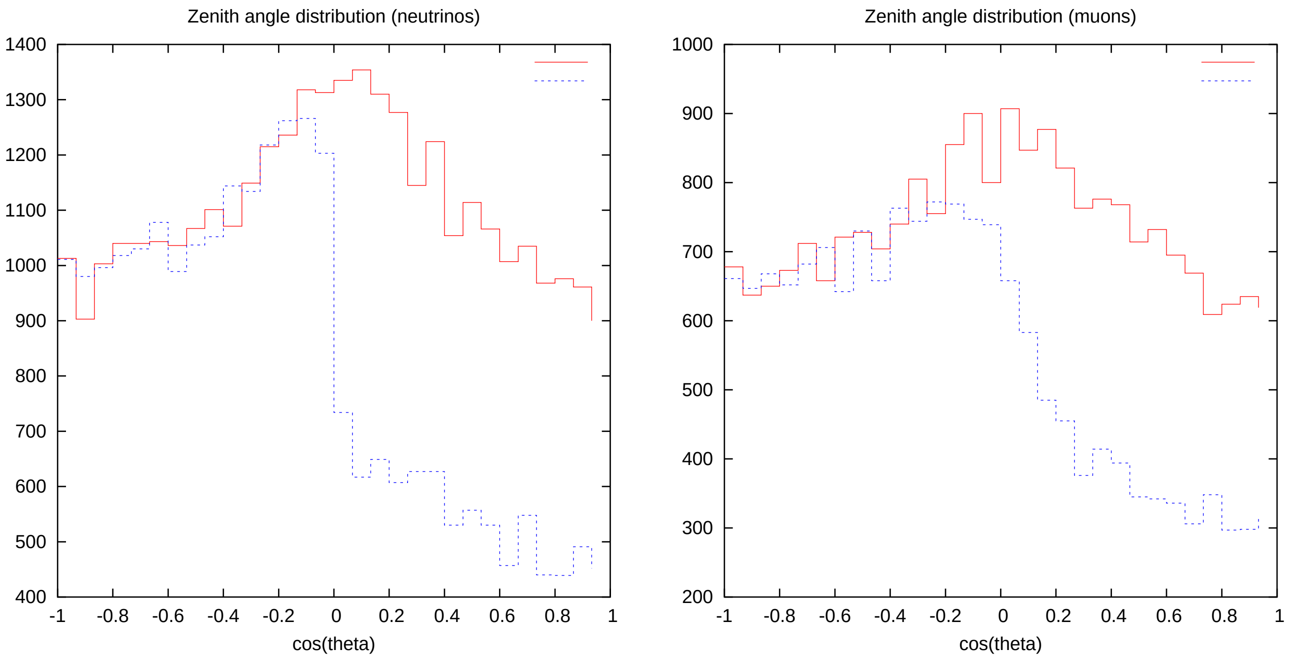
Figure on right :

• Energy resolution with muons alone and including hadrons as well.

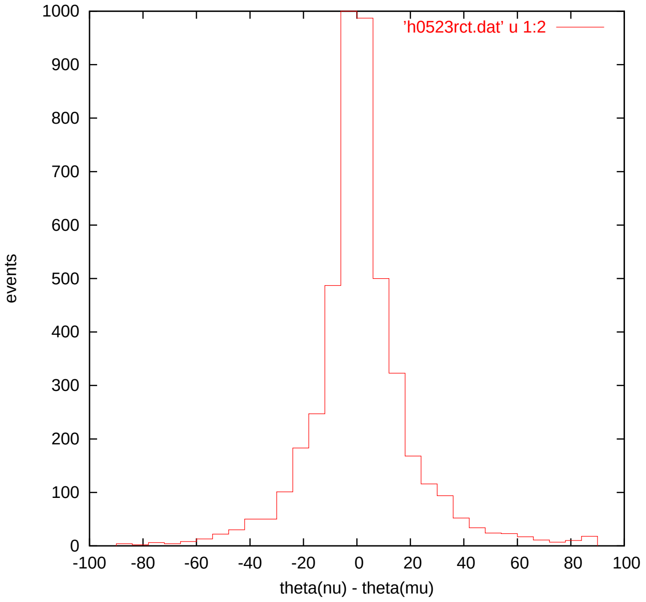




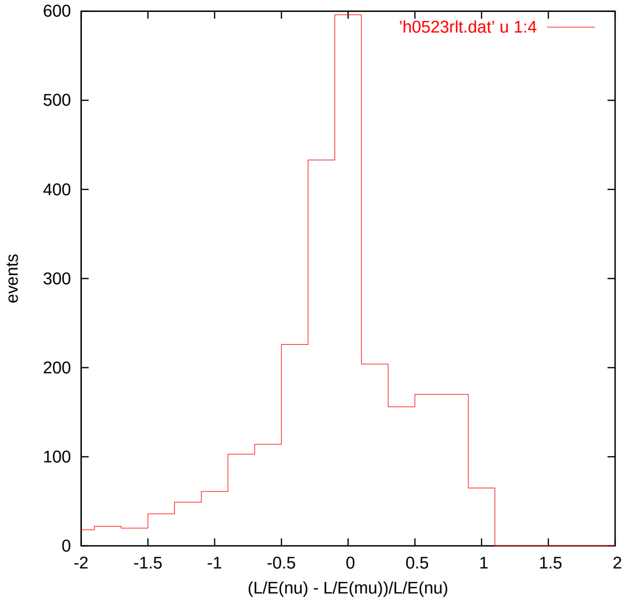
- $\cos\theta_z$ distribution; left: for neutrinos, right: for muons, with and without oscillations.



Left: Angle resolution



Right: L/E resolution



- ➢ Nuance events are passed through the GEANT program to get a pattern of hits in ICAL.
- ➢ The hits are recontructed to get E_μ, θ_μ, E_{had}, in a ROOT program.
- ➢ The relevant resolutions are studied.

E resolution

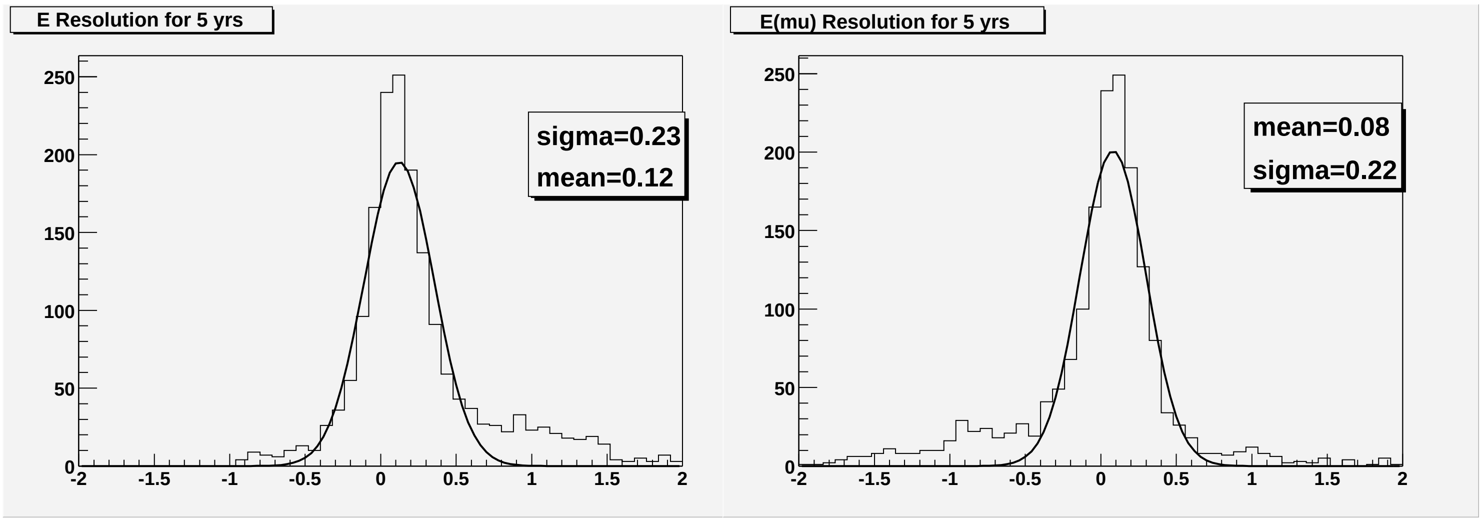


Figure 1: E resolution from reconstruction (left); muon only (right).

L resolution

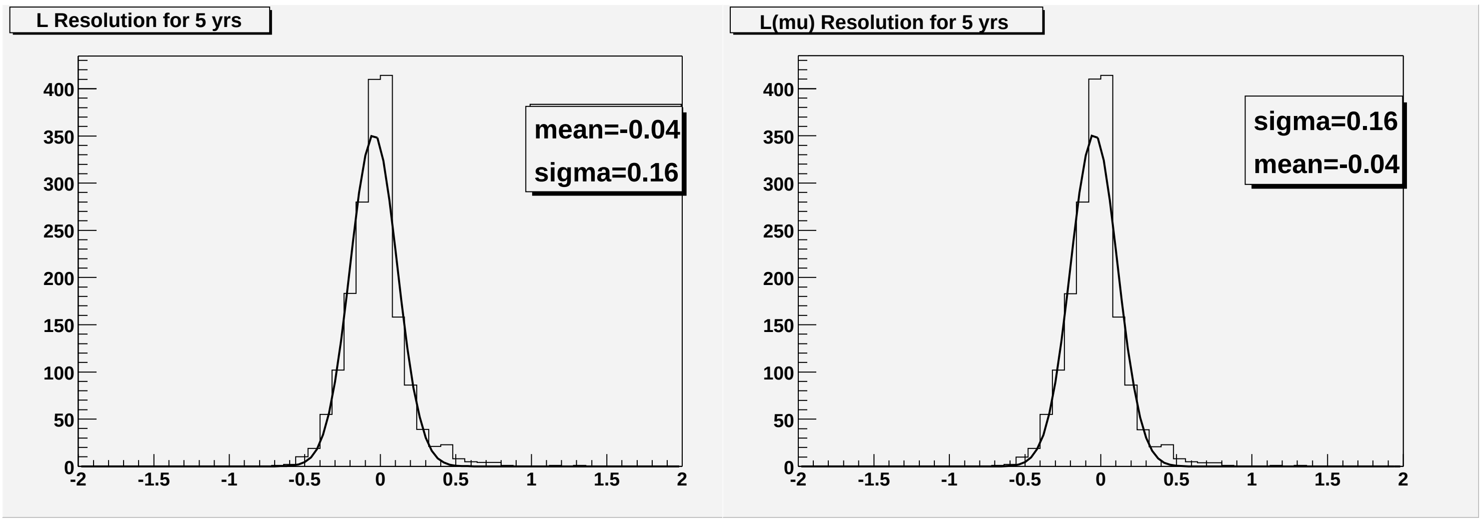


Figure 2: L resolution from reconstruction (left); muon only (right).

L/E resolution

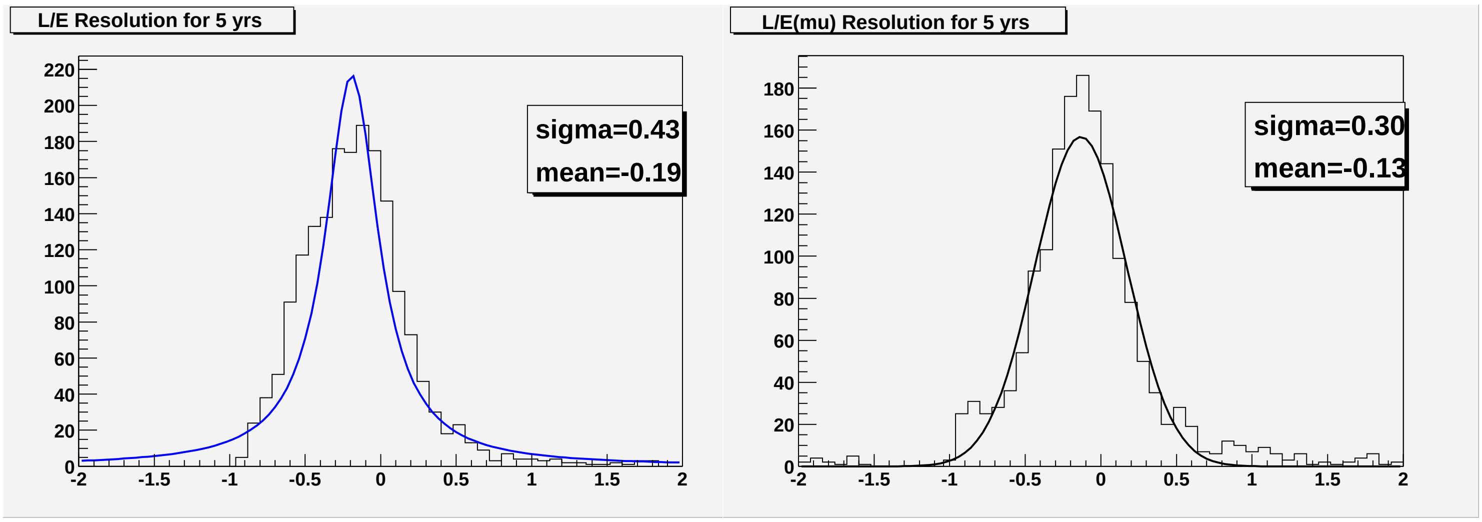


Figure 3: L resolution from reconstruction (left); muon only (right).

➢ The worst data is at small L/E where there are small number of events. May be interesting to bin the actual data in many different bin sets to see the sensitivity to this small L/E region. One possibility is to look at *vertical* planes of iron.

➢ We therefore get a resolution of $\Delta L/E = (0.43/2)L/E$. We will use this to do a Physics analysis (reconstruction of oscillation parameters) of the Nuance events.

➢ We use different input values of δ_{23} and θ_{23} to generate different sets of Nuance data.

➢ We collect them according to the 'up' and 'down' criteria, to generate the standard L/E plot. We then fit this using the formula for $P_{\mu\mu}$ shown earlier, to recover these parameters.

➢ Following are a set of plots for events and the reconstructed values of the parameters for $\delta_{23} = 2, 3, 5, 8 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1$.

Parameter	Original Value	Fitted Value	χ^2 14 d.o.f.
5 years data			
δ_{23} $\sin\psi$	2×10^{-3} 0.707	1.76×10^{-3} 0.707	17.86
δ_{23} $\sin\psi$	3×10^{-3} 0.707	2.62×10^{-3} 0.707	25.44
δ_{23} $\sin\psi$	5×10^{-3} 0.707	4.41×10^{-3} 0.656	12.80
δ_{23} $\sin\psi$	8×10^{-3} 0.707	8.85×10^{-3} 0.650	8.03

Table 1: Fits to parameters δ_{23} and $\sin\psi$ for 5 years data set. There are 16 L/E bins with the resolution parameter kept fixed to the value of 0.22.

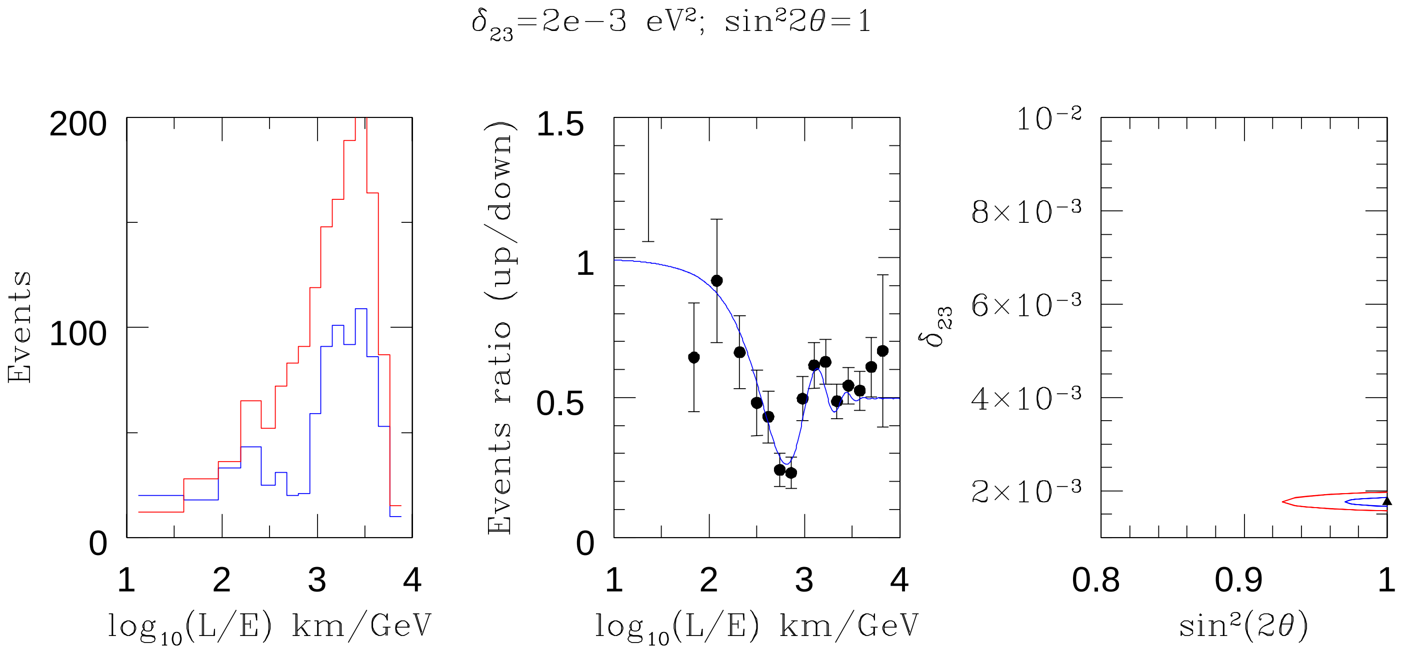


Figure 4: Analysis of 5 years up/down events with two-flavour oscillations $\delta_{23} = 2 \times 10^{-3}$ eV^2 and $\tan\psi = 1$.

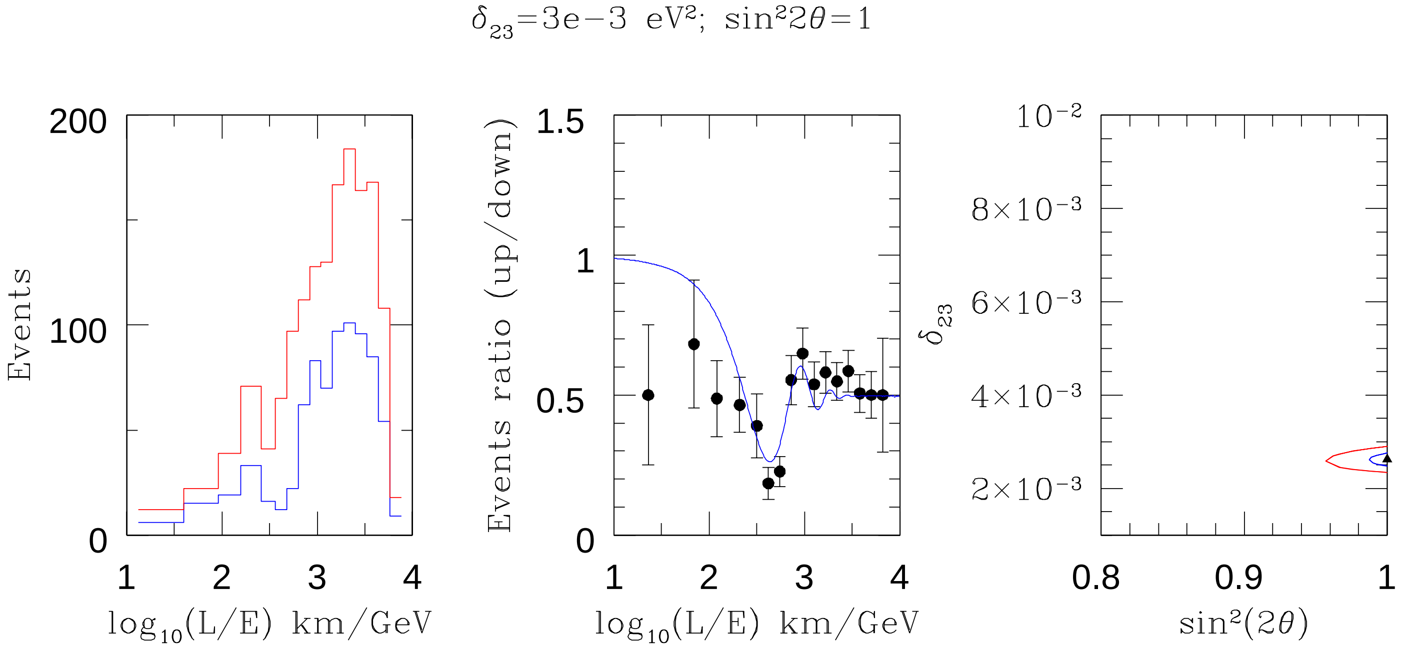


Figure 5: Analysis of 5 years up/down events with two-flavour oscillations $\delta_{23} = 3 \times 10^{-3}$ eV^2 and $\tan\psi = 1$.

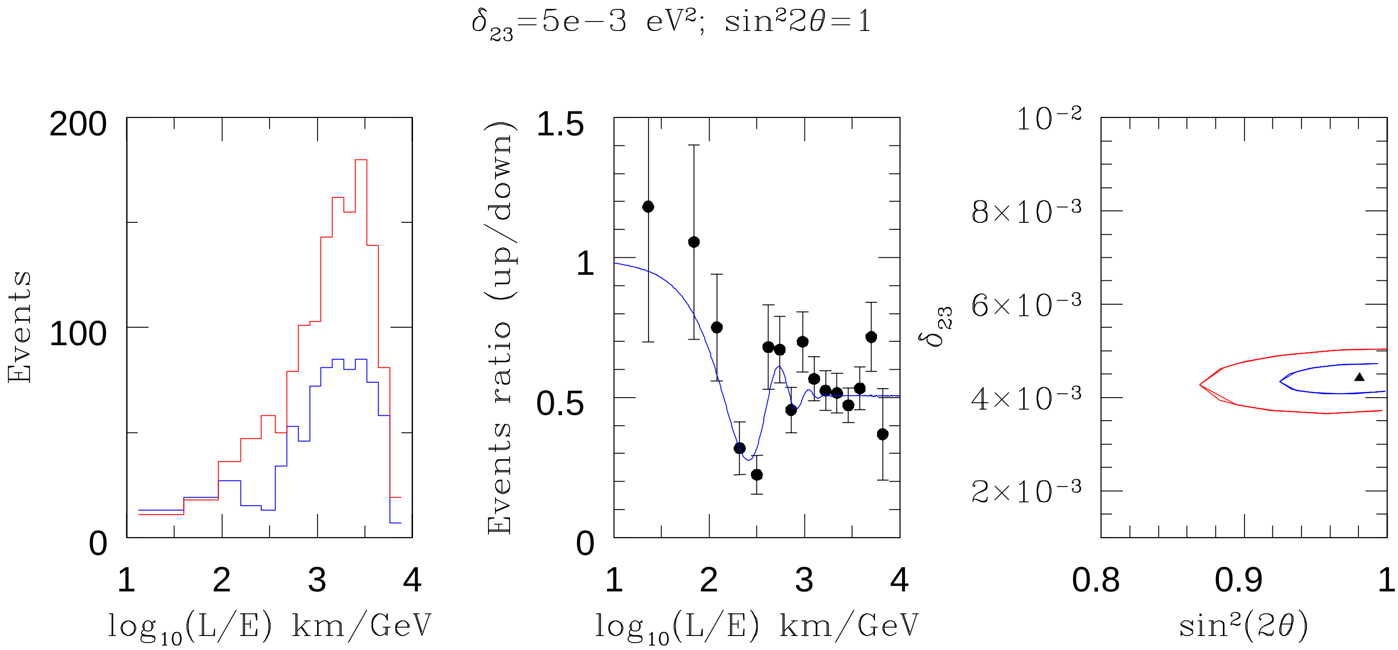


Figure 6: Analysis of 5 years up/down events with two-flavour oscillations $\delta_{23} = 5 \times 10^{-3}$ eV^2 and $\tan\psi = 1$.

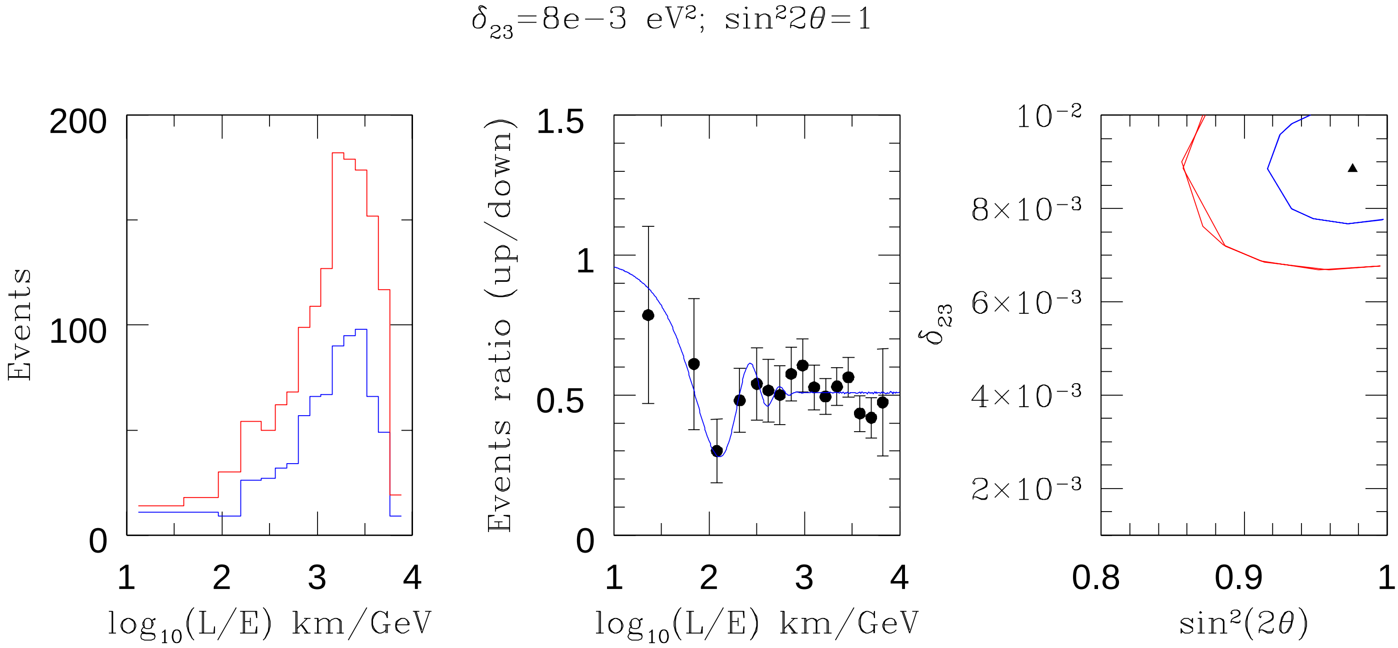


Figure 7: Analysis of 5 years up/down events with two-flavour oscillations $\delta_{23} = 8 \times 10^{-3}$ eV^2 and $\tan\psi = 1$.

- Other physics at INO: Phase II

➢ This is interesting if and only if (1) $\sin\theta_{13} \neq 0$ (and not too small) and (2) if we get a beam from a neutrino-factory in the future.

➢ The inputs used are muon detection threshold of 2 GeV and muon energy resolution of 5 percent. All measurements in phase II involve wrong sign muon detection and so backgrounds are low.

➢ Reach of $\sin\theta_{13}$:

For a nu factory as a function of the muon detection threshold energy. The reach is defined as the value that will yield 10 signal events (wrong sign muons) for a given kT-yr exposure.

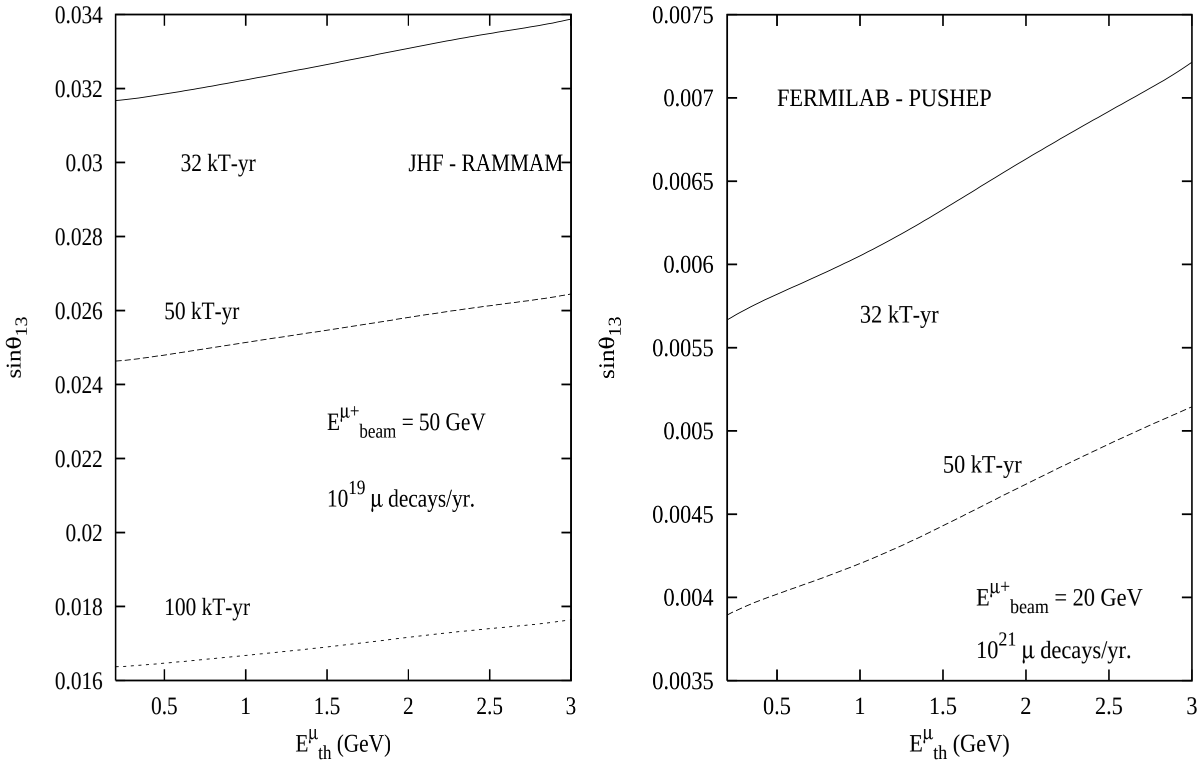


Figure 8: $\sin\theta_{13}$ reach as a function of the muon threshold energy. Left panel is for JHF to Rammam baseline. Right panel is for Fermilab to PUSHEP baseline.

➢ Sign of δ_{23}: The number of wrong-sign muon events as a function of δ_{23} for three base lines from a neutrino factory in Japan, the detector being at Beijing,Rammam or PUSHEP.The sign discriminating capability for either of the two sites Rammam or PUSHEP is clearly demonstrated.

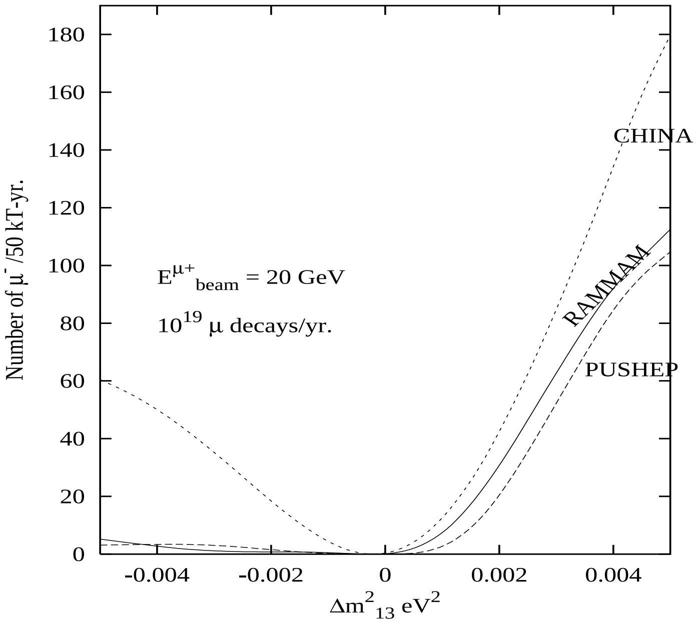


Figure 9: The number of wrong-sign muon events vs Δm^2_{23} corresponding to baselines from JHF to Beijing, Rammam and PUSHEP.

➢ CP violation is weak for the Japan-PUSHEP baseline, it is clearly present for the Japan-Rammam baseline.

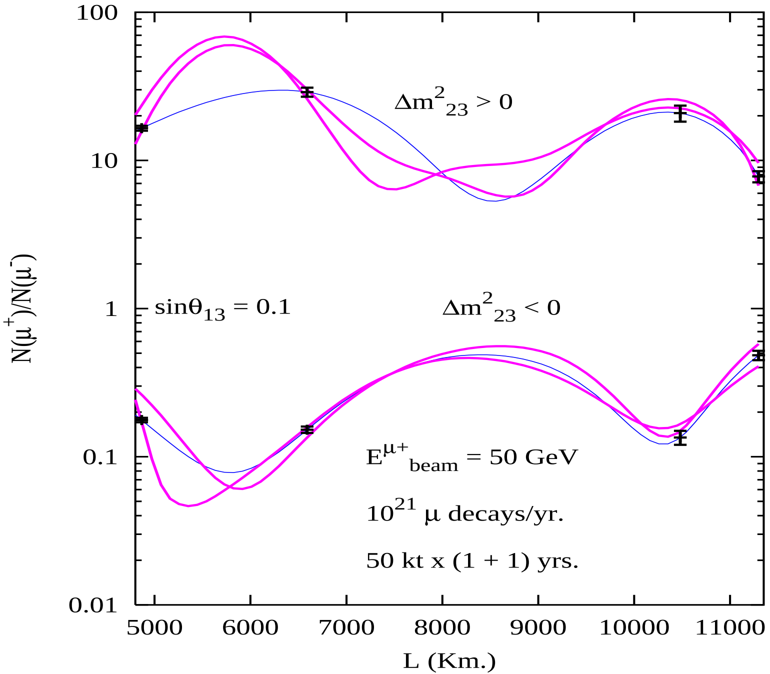


Figure 10: CP phase as a function of L.