Oscillation Sensitivity with Upward-going Muons in ICAL at India-based Neutrino Observatory (INO)

*Kanishka Rawat, Vipin Bhatnagar, D. Indumathi
Physics Department, Panjab University, Chandigarh-160014, India
The Institute of Mathematical Sciences, Chennai-600113, India
*kanishka@puhep.res.in

1. Introduction

The India-based Neutrino Observatory (INO) [1] is a proposed underground facility to look for atmospheric neutrinos.
The magnetized Iron CALorimeter (ICAL) detector at INO with its charge identification capability will study the oscillation pattern of atmospheric neutrinos. It aims at precise measurement of oscillation parameters, probing neutrino mass hierarchy as well as new physics.

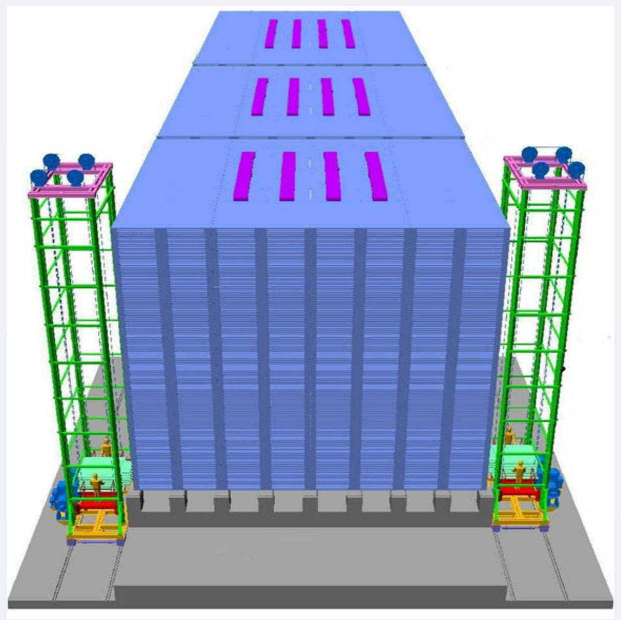

Fig 1: INO-ICAL Detector

ICAL (Passive component)	
- No. Of modules	3
- Module dimension	16 m X 16 m X 14.4 m
- Detector dimension	48 m X 16 m X 14.4 m
- No. Of layers	150
- Iron plate thickness	~ 5.6 cm
- Gap for RPC trays	4.0 cm
- Magnetic field	1.4 T
RPC (active component)	
- RPC unit dimension	1.84 m X 1.84 m X 24 mm
- Read out strip width	3 cm
- No. of RPC units/Road/Layer	8
- No. of RPC Roads/Layer/Module	8
- No. of RPC units/Layer	192
- Total no. of RPC units	~ 28800
- No. of electronic readout channels	3.6864×10^6

ICAL detector specifications

2. Motivation

- Upward-going/rock muons [2] [3] provide an independent measurement of the oscillation parameters and a consistency check with the contained vertex analysis.
- Upward-going muons analysis would result in slight improvement of the overall measurement, though the sensitivity of upward-going muons to the oscillation parameters is lower than contained vertex events.
- Upward-going muons are produced by the interactions of atmospheric neutrinos with the rock material surrounding the detector, but carries signature of oscillation. As muon energy increases survival Probability ($P_{\mu\mu}$) goes to one.
- We use, survival probability ($P_{\mu\mu}$) as calculated using 2-flavour oscillation code is:

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 (1.27 \times \Delta m^2_{32} \times L/E) \quad \text{(i)}$$

where $\theta_{23} = 45°$, $\Delta m^2_{32} = 2.4 \times 10^{-3}\ \text{eV}^2$

- Since muon lose energy in rock before reaching the detector, oscillation signature becomes more complicated.
- But neutrino experiments have low count rate and so every possible data must be used.
- Upward-going muons are discriminated from:
  - Neutrino events producing muons through interactions inside ICAL detector, which come under the main studies of ICAL.
  -- These can be removed by taking muon track which comes from outside of ICAL detector.
  - Cosmic ray muon events produced in the earth's atmosphere directly interacting with ICAL, which are the main background of the ICAL detector.
  -- These can be removed by putting angle cut which allows only upward-going muons for the analysis.

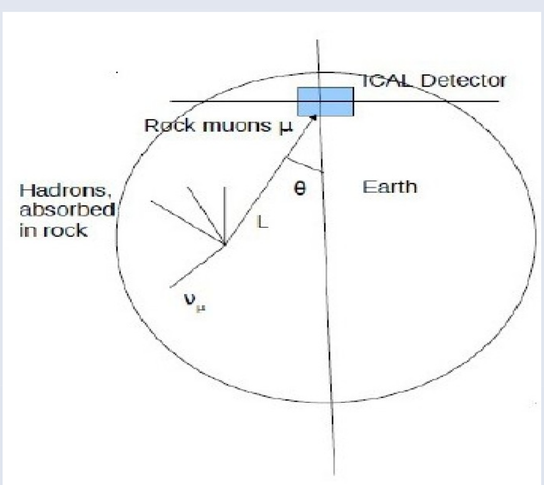

Fig2: Production of Upward-going muons

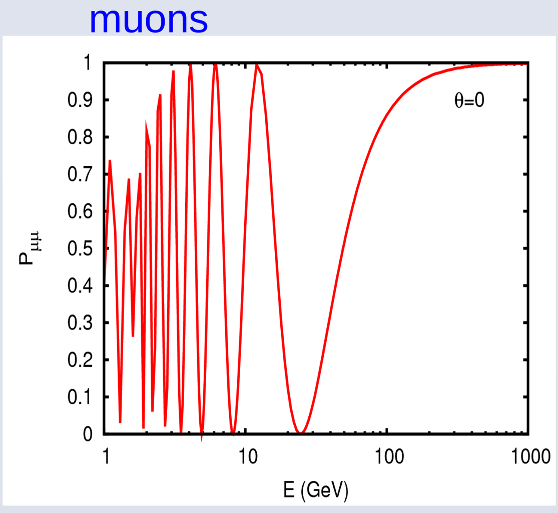

Fig3: Survival Probability for $\theta_{13} = 0$

3. Methodology

- Input parameters taken for data generation $\theta_{23} = 45°$ ($\sin\theta_{23} = 0.707$), $\Delta m^2_{32} = 2.4 \times 10^{-3}\ \text{eV}^2$, $\theta_{12} = 34°$, $\theta_{13} = 0°$, $\delta_{cp} = 0$
- Angle cut taken to cut off cosmic ray backgrounds: $0° < \theta < 70°$
- No events are generated inside the detector; only its external geometry is required.
- The actual material in which interactions happen is rock , density of rock = 2.65 gm/cc.
- Only CC ν_μ events are taken for analysis and not passed through ICAL detector through INO-ICAL code [4]
- Smeared muon energy and angle according to lookup tables generated from the resolutions taken from bottom part (peripheral region [5]) of the detector.
- Generated data sample has proportionately larger component of higher energy events which are not sensitive to oscillations. So we have taken finer bins at lower energy, data taken for $\cos\theta > 0.342$.
- Data is oscillated using 2-flavor formula and binned it into energy and $\cos\theta$ bins and then scaled down to 4.5 years.
- Bins: E= 1-2, 2-4, 4-8, 8-16, 16-32, 32-64, 64-128, 128-256 (GeV)
- $\cos\theta$ = 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8-1
- Chisq with pulls method is used:

$$\chi^2 = \sum_i ((N_i^{th}(1 + \pi_i \times \xi) - N_i^{ex})/\sigma_i^{stat})^2 + \xi^2$$

  - N_i^{th} , N_i^{ex} = theoretically predicted data, observed data
  - π_i = systematic errors taken; normalisation error of 20%, no tilt factor included
  - ξ = Pull variable with respect to which χ^2 is minimized
  - σ_i^{stat} = Statistical errors, defined as sqrt (N_i^{ex})
- Plotted 90 % CL contours for $\sin^2 2\theta_{23}$ and Δm^2_{32} ($\Delta\chi^2 = 4.61$)
- Analysis does not include backgrounds
- No cid efficiency needed, since combined μ- with μ+ events

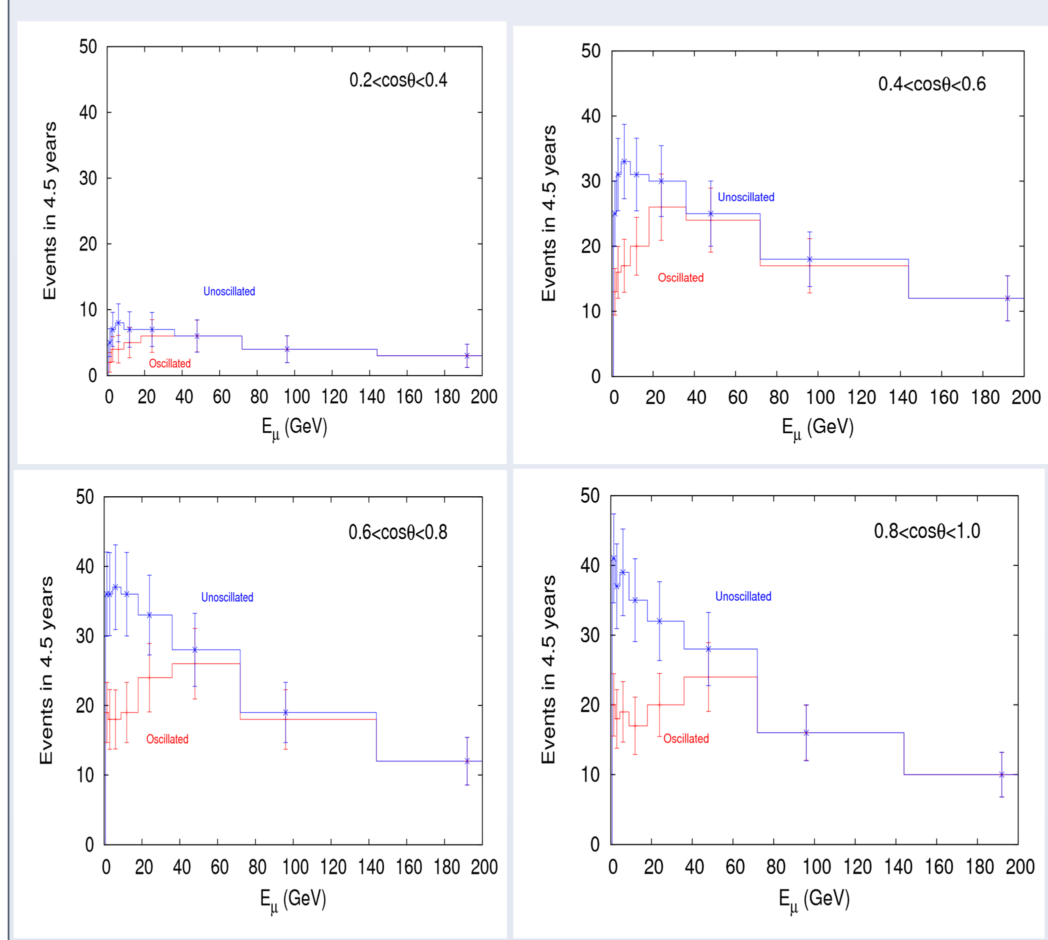

Fig 4. Energy distribution of muon (E_μ) for different $\cos\theta$ bins

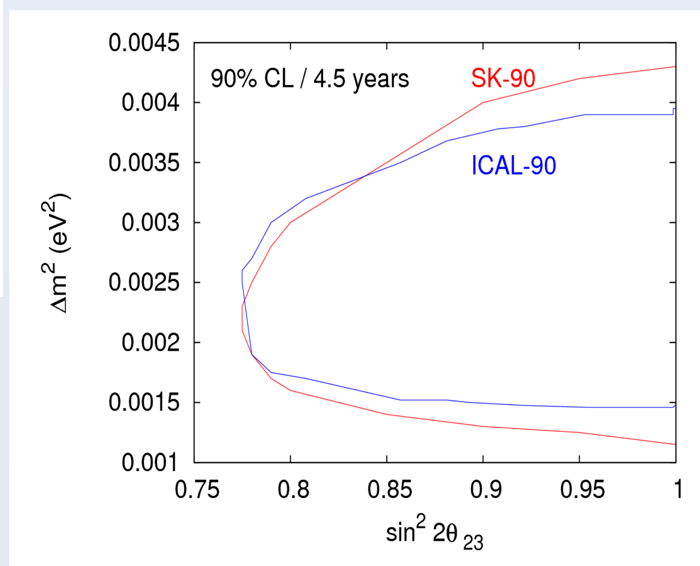

Fig 5. 90 % CL contour of ICAL and Super-K in 4.5 years of data

- SK [6] : 90% CL for 4.5 years upward-going muon, $\sin^2 2\theta_{23} = 0.765$, Δm^2_{32} = 1.2 to $4.3 \times 10^{-3}\ \text{eV}^2$
- ICAL: 90% CL for 4.5 years upward-going muon, $\sin^2 2\theta_{23} = 0.77$, Δm^2_{32} = 1.48 to $3.7 \times 10^{-3}\ \text{eV}^2$

4. Conclusions

- An independent measurement of the oscillation parameters is provided by upward-going muons which would improve the overall measurement, though the sensitivity of rock muons to the oscillation parameters is lower than contained vertex events.
- Sensitivity for upward-going muons of ICAL and SK are comparable.

5. References

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[2] A. Habig et al., “Measurement of the flux and zenith-angle distribution of upward through-going muons by Super-Kamiokande”, arXiv:hep-ex/9812014v2, 18 March 1999
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[4] INO Collaboration, ICAL simulation using GEANT tool-kit, in preparation, 2014
[5] INO Collaboration “Simulations Study of Muon Response in the Peripheral Regions of the Iron Calorimeter Detector at the India-based Neutrin Observatory”, in preparation, 2014
[6] Kazunori Nitta, Neutrino Oscillation Analysis of Upward Through-going and StoppingMuons in Super-Kamiokande, PhD thesis, (Department of Physics, Osaka University, 2003) http://www-sk.icrr.u-tokyo.ac.jp/sk/pub/nitta.pdf

Thank You !

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