A Study of Up-going Muons in ICAL at India-based Neutrino Observatory (INO)

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Outline of the Talk

- Introduction
- Motivation of the Study
- Data generation
- Results
- Summary

ICAL@INO

INO: Proposed underground facility at Bodi West hills of Theni District of Tamil Nadu, with rock cover of approx 1200 m, which is desirable to look for atmospheric muon neutrinos

Iron CALorimeter (ICAL):

- Good charge resolution
- Good tracking and energy resolution

Overview of detector:

- Dimension: 48 m × 16m × 14.4m

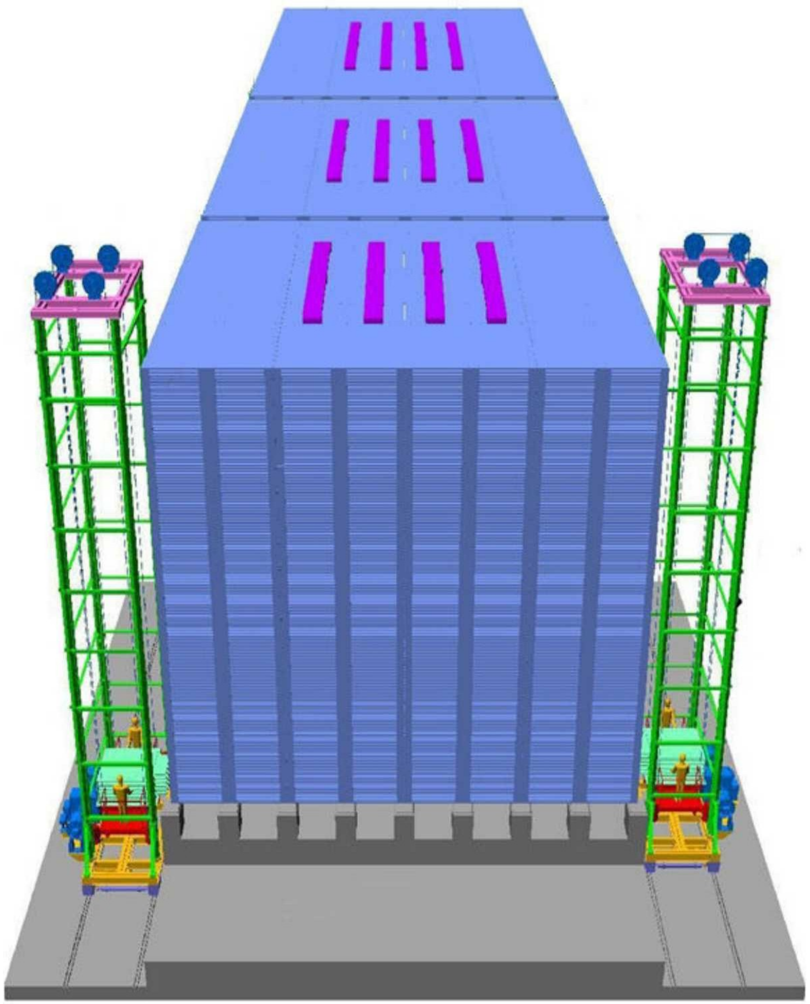
(3 modules of dimensions 16 m × 16m × 14.4m each)

- Mass: 50 kTon (approx)

- Absorber: Iron plates of thickness 5.6 cm

- Active detector volume: Resistive Plate Chamber (RPC) (2m × 2m × 8mm). The readout of the RPC is carried out by external orthogonal pick up strips (X & Y strips)

- Inhomogenous Magnetic Field: ~ 1.3 Tesla



A sketch of proposed INO-ICAL detector

INO-ICAL GOALS

Main INO-ICAL goals are listed as:

- To re-confirm the occurrence of oscillation in atmospheric muon neutrinos
- To search for matter effects in neutrino oscillations
- To determine the sign of Δm^2_{32} using the matter effect
- To distinguish between $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_s$ (sterile ν) oscillation
- Probing CPT violation in the neutrino sector

Motivation of the Study

- Rock muons analysis provides an independent measurement of the oscillation parameters
- The sensitivity of rock muons to the oscillation parameters is lower than contained vertex events
- The independent measurement will provide a consistency check with the contained vertex analysis and would result in slight improvement of the overall measurement. Hence, the analysis is helpful in any neutrino experiment
- Up-muons: Usual interactions of atmospheric neutrinos with the rock material surrounding the detector, but carries signature of oscillation. As muon energy increases Probability ($P_{\mu\mu}$) goes to one
- Where, survival probability as calculated using 2-flavour oscillation code:

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

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

- Muon loses energy in rock before it reaches detector so oscillation signature becomes more complicated
- But neutrino experiments have low count rate and so every possible data must be used

Contd...

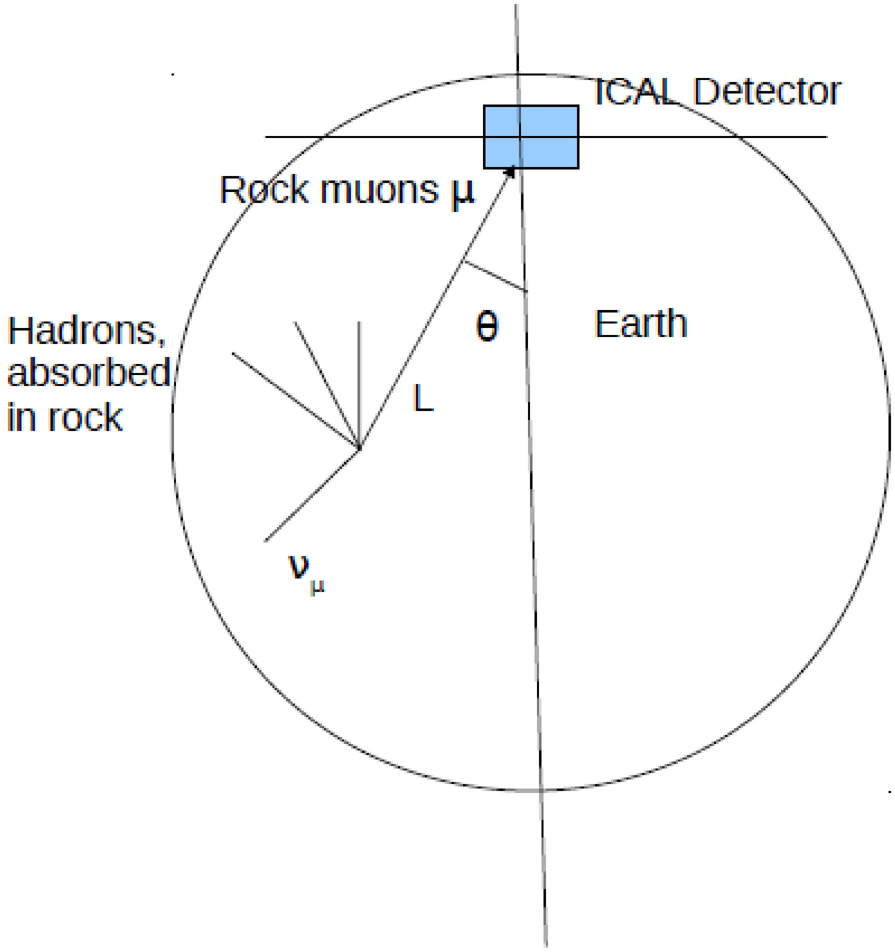
So, up muons discriminated from:

- Neutrino events producing muons through interactions inside ICAL detector, which comes under the main studies of ICAL.

- which can be removed by taking muon track which comes from outside of ICAL detector

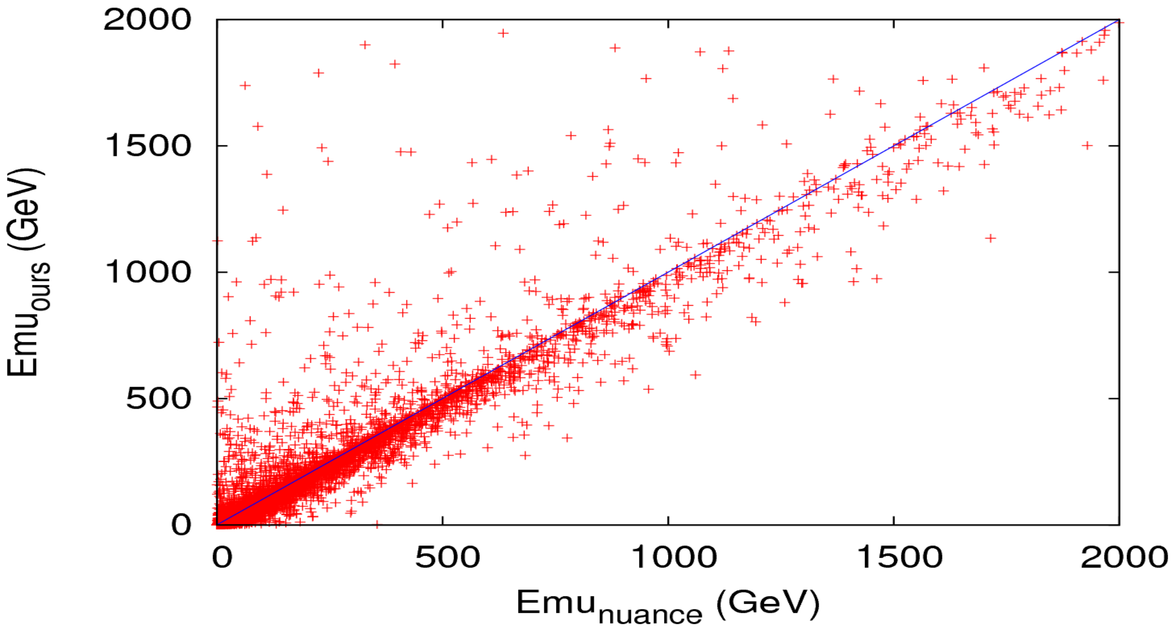
- Cosmic ray muon events produced in the earth's atmosphere directly interacting with ICAL, which are the main background of the ICAL detector

- which can be removed by putting angle cut which allows only up-muons for the analysis



Data Generation and Analysis

- Generated 200 year data with Nuance version 3.504, which propagates muons through rock
- Input parameters taken for data generation θ_{23} = 45° ($\sin\theta_{23}$ = 0.707), Δm^2 = 2.4 e-3 eV^2, θ_{12} = 34°, θ_{13} =0°, δ_{cp}=0
- Angle cut taken to cut off cosmic ray backgrounds: 0°<θ<70°
- No events are generated inside the detector; only its external geometry is required
- The actual material in which interactions happen is rock, whose density is taken to be 2.65 gm/cc
- Only cc ν_μ events are taken for analysis and not passed through ICAL detector through INO-ICAL code



E_μ calculated from formula (expected) vs. E_μ from nuance at the detector (Observed)

Contd...

- Resolutions used:

  - We have NOT used the correct resolutions, only used central region resolution

  - We have also not used the correct ones at high energies but simply used the same as in the last bin for which we have information

- Analysis:

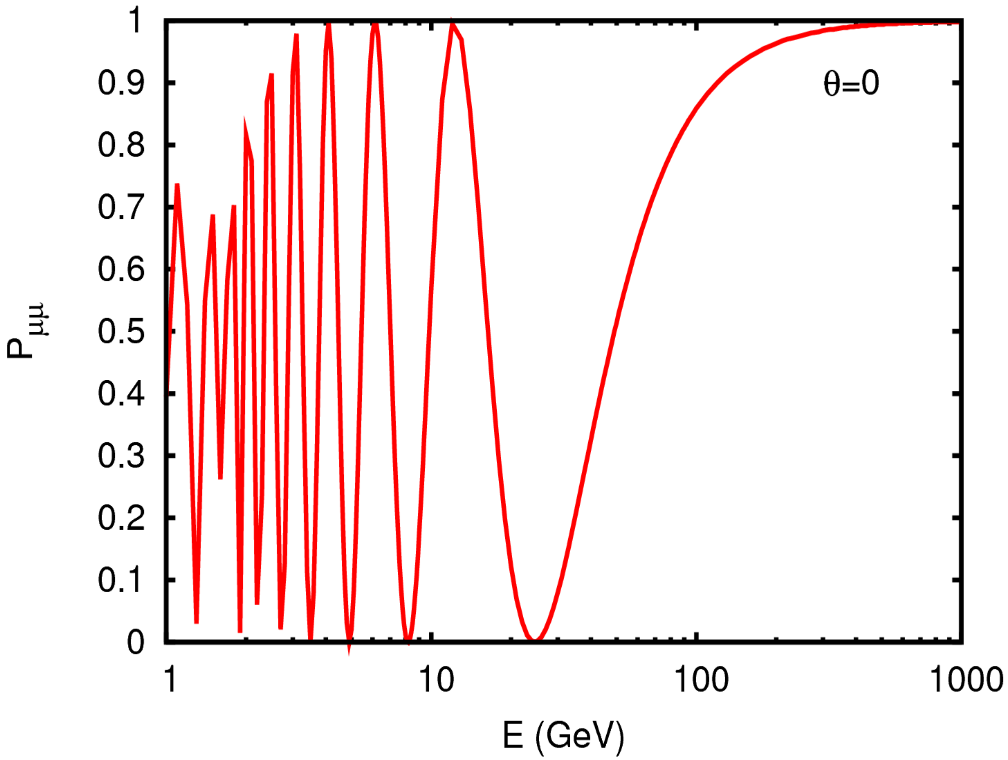
- Smeared muon energy and angle according to lookup tables of central region of detector. Later we will use the tables for the peripheral region since these are up muons which are just avialable

- Data is oscillated using 2-flavor formula given by equation (i) on slide 4 and binned it into energy and cosθ bins, then scaled down to 4.5 years

Contd...

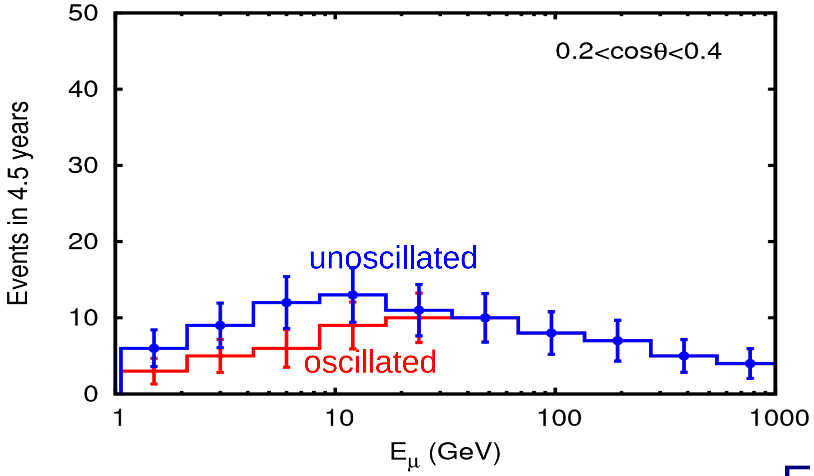
- The generated data sample has proportionately larger component of higher energy events which are not sensitive to oscillations, so we have taken finer bins at lower energy, for cosθ > 0.342 data taken
- Bins: E= 1-2, 2-4, 4-8, 8-16, 16-32, 32-64, 64-128, 128-256, 256-512, 512-1024 (GeV)

Cosθ = 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8-1

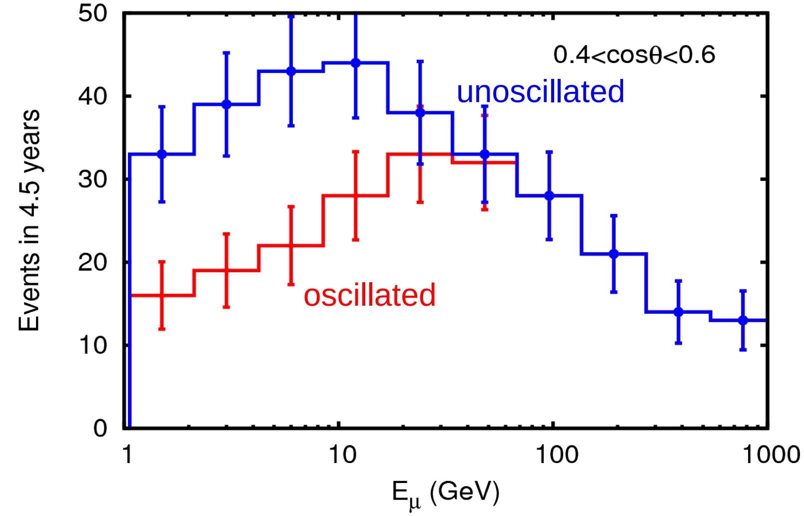


Survival probability for $\theta_{13} = 0$

Energy of Muon

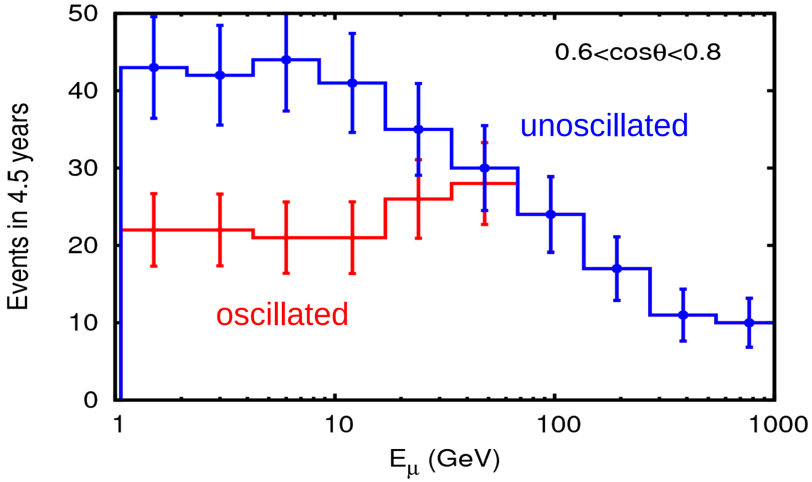


Cosθ range: 0.2-0.4

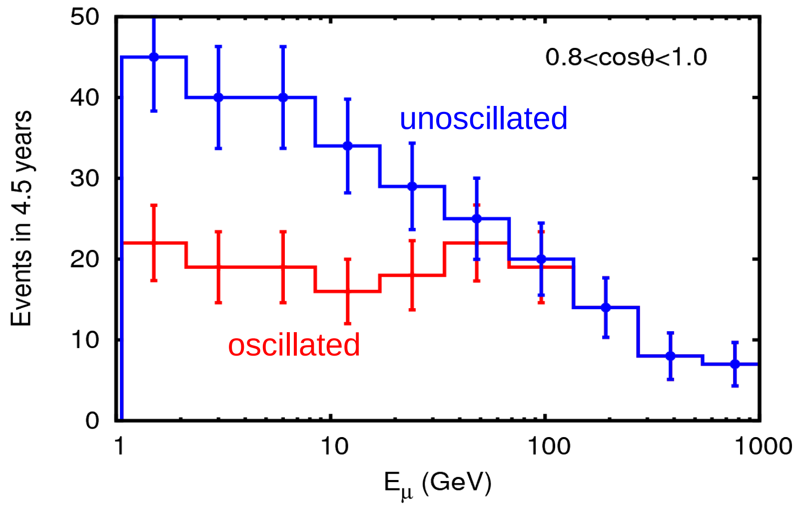


Cosθ range: 0.4-0.6

Energy distribution of muon E_μ for different cosθ bins



Cosθ range: 0.6-0.8



Cosθ range: 0.8-1

Contd...

- 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

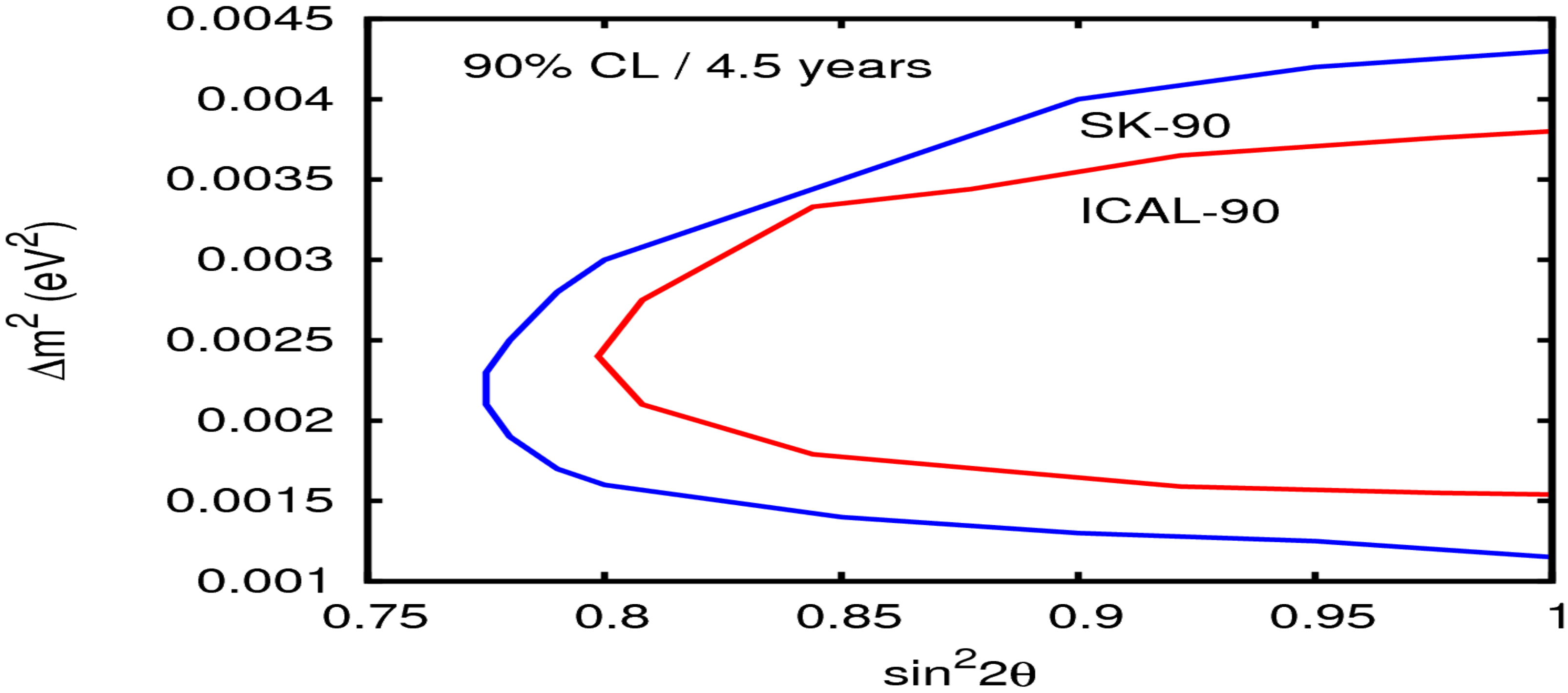
- π_i = systematic errors taken; normalisation error of 30%, no tilt factor included

- 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 these two parameters (Delta chisq = 4.61)
- Analysis does not include backgrounds
- No cid efficiency needed, since combined μ^- with μ^+ events

Results



***SK: 90 % CL for $\theta_{13} = 0$ for 4.5 years up-muon, $\sin^2 2\theta_{23} = 0.765$, $\Delta m^2_{32} = 1.2$ to 4.3 X e-3**

ICAL: 90 % CL for $\theta_{13} = 0$ for 4.5 years up-muon, $\sin^2 2\theta_{23} = 0.8$, $\Delta m^2_{32} = 1.55$ to 3.7 X e-3

From main studies of ICAL: $\sin^2 2\theta_{23} = 0.979$, $\Delta m^2_{32} = 2.1$ to 2.9 X e-3

*SK, Nitta Thesis 2003

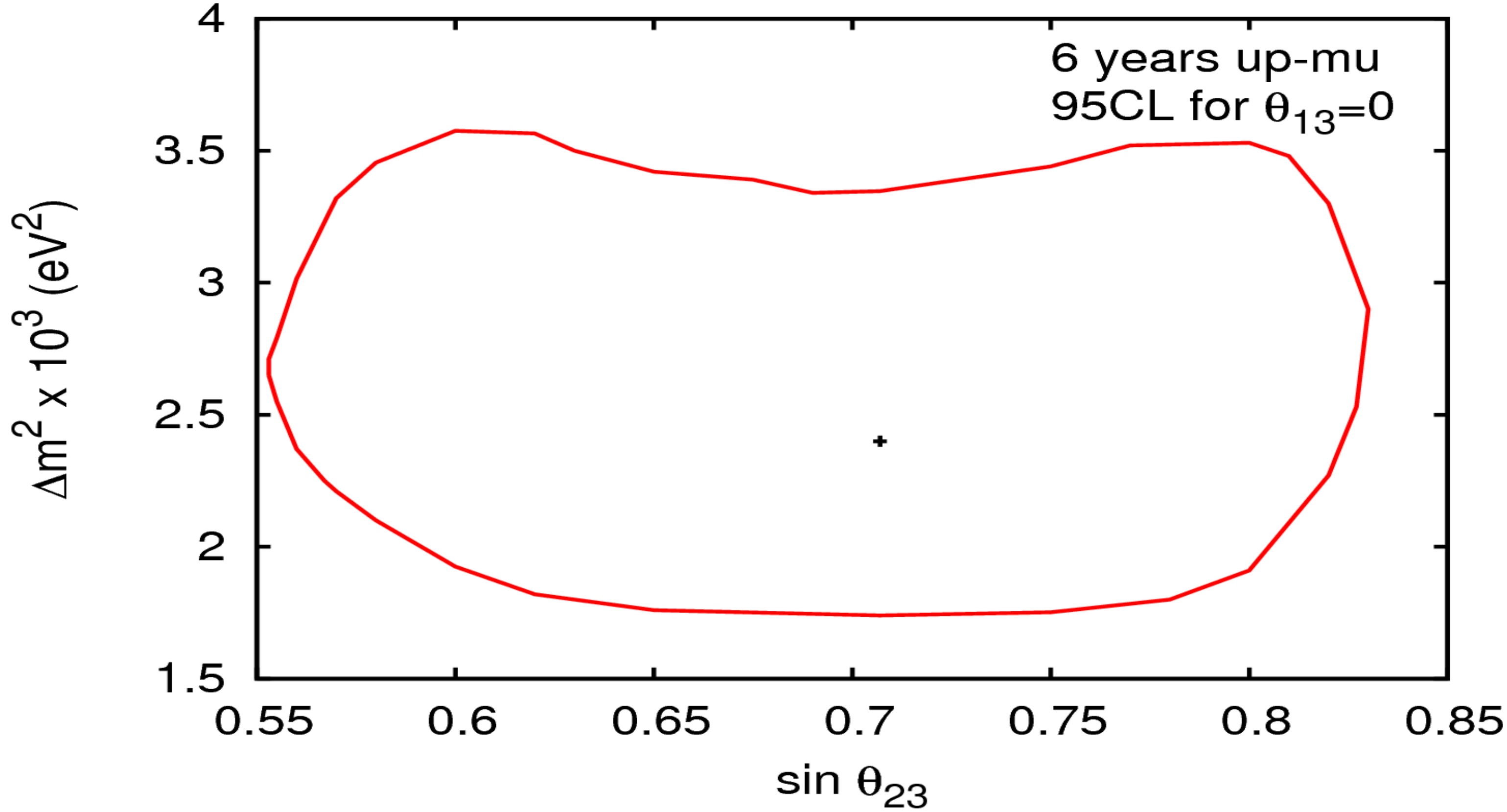
Summary

- Up-going muon studies is important and indeed it gives oscillation senstivity
- Peripheral resolutions to be used for contour plots
- Combining the up-muon studies with the main studies of ICAL detector will help in improving the senstivity, which needs to be done
- Both studies involves same atmospheric υ flux, many systematic errors will be same for both and will be useful.

Thank you for your kind attention !

Back up Slides

Back-up 1



95 CL for θ_{13} = 0 for 6 years up-mu

From main studies of ICAL: sin 2θ_{23} = 0.979, Δm^2_{32} = 2.1 to 2.9 X e-3

Back-up 2

- Roughly nu : antinu is 3:1 ratio
- ICAL: About 1500 events in 6 years as contrasted with 8000 in usual atmospheric case.
- SK: ~2000 events for 5 year
- Pulls that includes unoscillated data constraints overall shape & normalisation of data and improved fits
- Dimension of detector = 'CUBE' 2420. 800. 722.8 (these are 1/2 x,y,z).
- $\sin^2 2\theta_{13}$ from Reno and Daya bay experiments as 0.103 ± 0.013 And 0.092 ± 0.017 respectively

Back-up 3

Muon propagation in rock, water, ice:

The classical way to describe the average muon energy loss is

$dE_\mu/dx = -a - bE_\mu$, b = b_brm + b_prod + b_ph

accounts for the three radiation processes:

- bremsstrahlung
- production of electron positron pairs
- photoproduction

and a accounts for ionization losses. Very roughly a is 2 MeV/(g/sq.cm) and b is 4x10-6 (g/sq.cm)

Using this definition one can estimate how much energy muons lose in propagation.

Using this definition of the energy loss the muon energy after propagation on X g/sq.cm will be:

$E_\mu = (E_\mu^0 + e)\exp(-bX) - e$, $e = a/b = 500$ GeV

The inverse relation is: $E_\mu^0 = (E_\mu + e)\exp(-bX) - e$, $e = a/b = 500$ GeV

and the minimum muon energy to propagate to a depth X is: $E_\mu^{min} = e(\exp(bX) - 1)$

These expressions are important when a muon of certain energy is detected underground (or underice) and we are interested in its energy on the surface.

Back-up 4

- Central Region – Uniform magnetic field
- Side Region – Uniform magnetic field but smaller (15% less) and opposite than central region. Acceptance effects
- Peripheral Region – Changing magnetic field, smaller in magnitude. Acceptance effects