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

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Outline of the Talk

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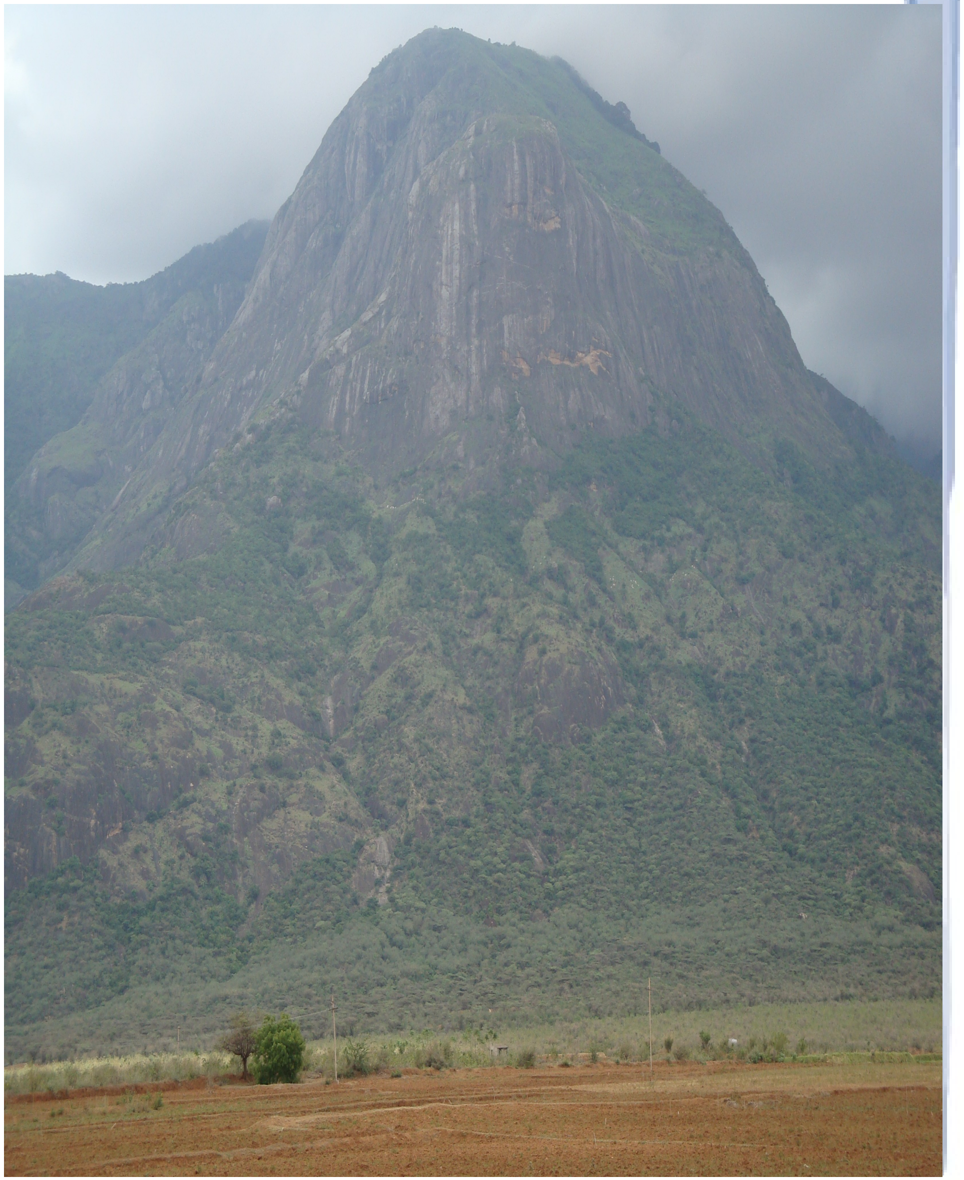
- Motivation of the Study
- Data generation
- Results
- Summary



INO (India-based Neutrino Observatory)

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

ICAL:

- Good charge resolution
- Good tracking and energy resolution

Overview of detector:

- Dimension: 48 m × 16m × 14.4m

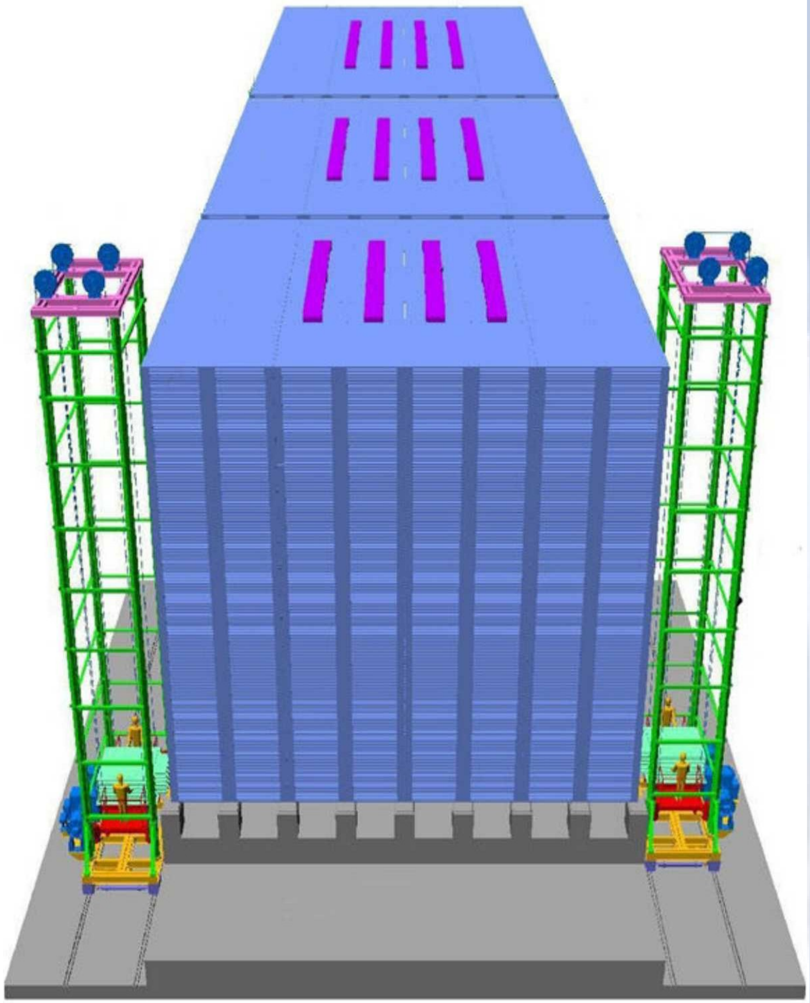
(3 modules of dimensions 16 m × 16m × 14.4m each)

- 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: ~ 1.4 Tesla



A sketch of proposed INO-ICAL detector

Motivation of the Study

- Proposed magnetised Iron Calorimeter (ICAL) detector at India-based Neutrino Observatory (INO) aims to determine neutrino oscillation parameters precisely with atmospheric muon neutrinos, matter effect in neutrino oscillations and the sign of Δm^2_{32} using matter effect
- 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:

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

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...

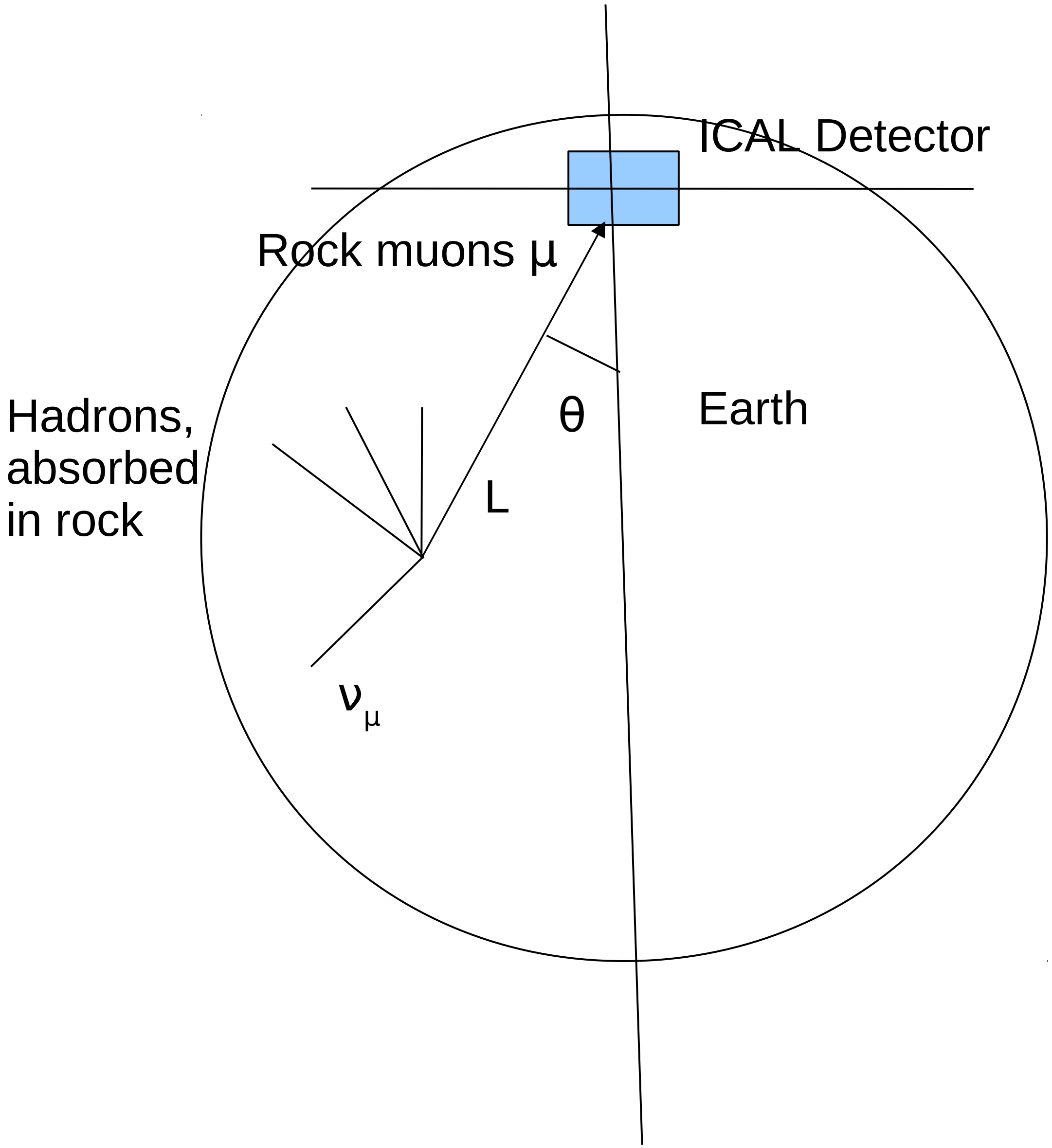
So, up muons discriminated from:

- 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



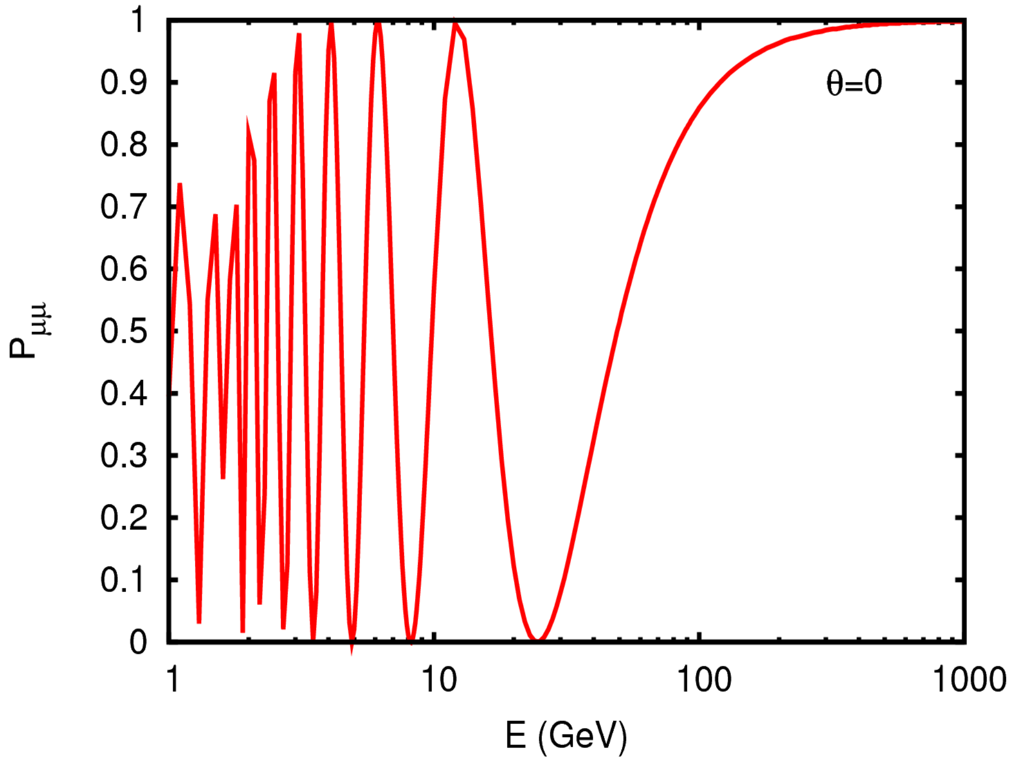
Data Generation

- Generated 200 year data with Nuance version 3.504, which propagates muons through rock
- Input parameters taken for data generation $\theta_{23} = 45°$ ($\sin\theta_{23} = 0.707$), $\Delta m^2 = 2.4$ e-3 eV^2, $\theta_{12} = 34°$, $\theta_{13} = 0°$, $\delta_{cp} = 0$
- Angle cut taken to cut off cosmic ray backgrounds: $0° < \theta < 70°$
- Dimension of detector = 'CUBE' 2420. 800. 722.8 (these are 1/2 x,y,z). 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
- 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 $\cos\theta$ bins, then scaled down to 4.5 years

Contd...

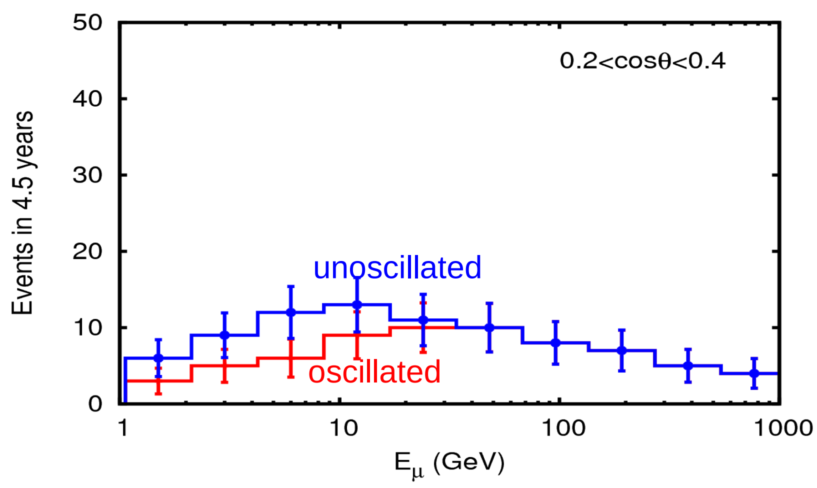
- The generated data sample has proportionately larger component of higher energy events which are not sensitive to oscillations, so we have taken finer bins at lower energy, for cosθ > 0.342 data taken
- Bins: E= 1-2, 2-4, 4-8, 8-16, 16-32, 32-64, 64-128, 128-256, 256-512, 512-1024 (GeV)

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



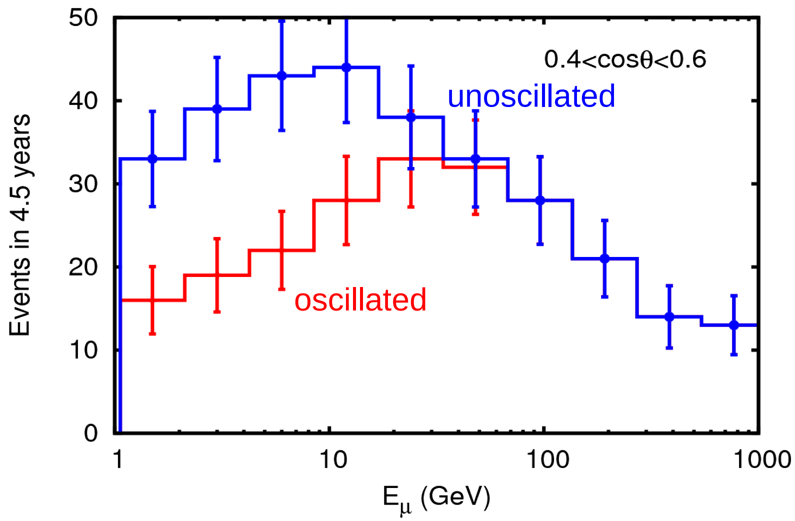
Survival probability for θ_{13} = 0

Energy of Muon

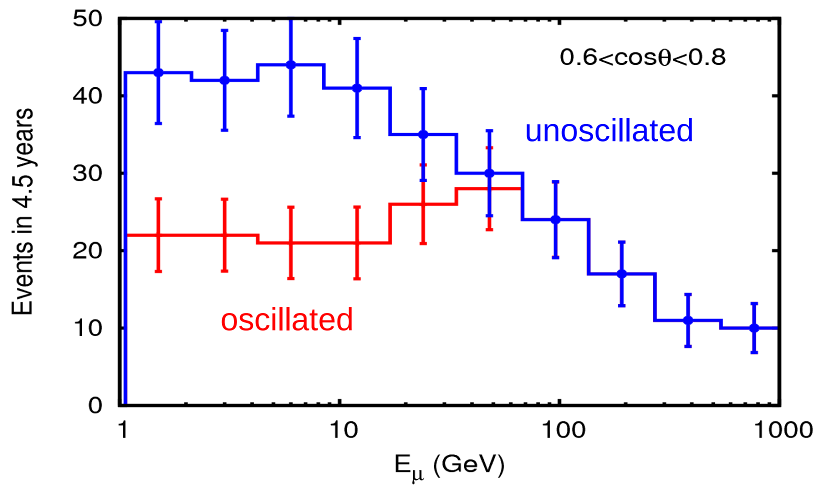


Cosθ range: 0.2-0.4

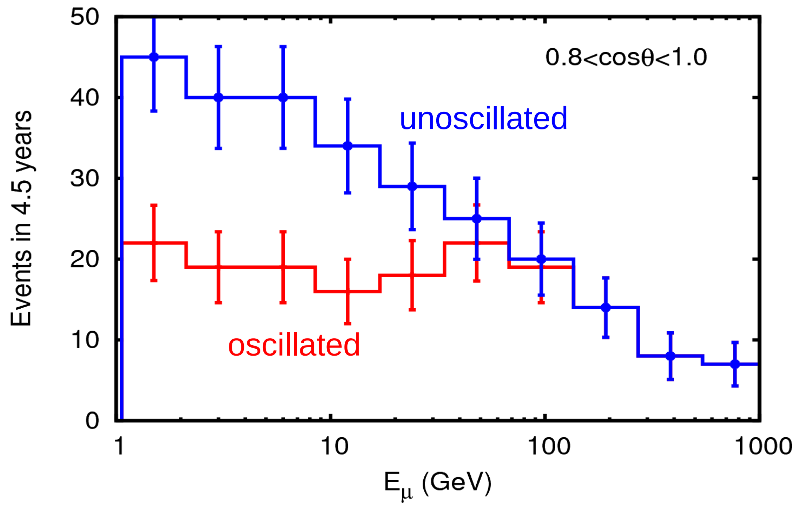
Energy distribution of muon E_μ for different cosθ bins



Cosθ range: 0.4-0.6



Cosθ range: 0.6-0.8



Cosθ range: 0.8-1

Summary

- Up-going muon studies is important and indeed it gives oscillation senstivity
- Combining the up-muon studies with the main studies of ICAL detector will help in improving the senstivity, which is in progress
- Both studies involves same atmospheric υ flux, many systematic errors will be same for both and will be usefull.

Thank you for your kind attention ! 

Back up Slides

Back-up 1

- 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

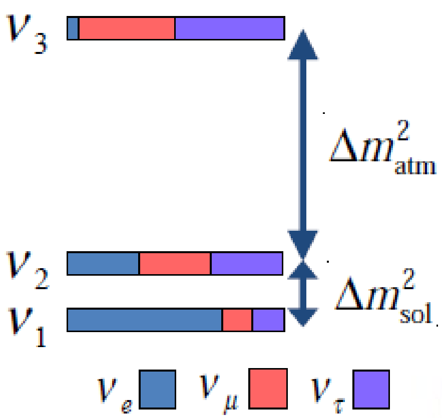
Back-up 2

Mass eigenstates ≠ Flavour eigenstates

Unitary Matrix -> Flavour Eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass Eigenstates



- Flavour composition of neutrino can change as it propagates. For 2-neutrino case, muon survival probability:

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

- Three possible arrangements of the neutrino masses are allowed which are:

  - Normal hierarchy: In this case, m1 < m2 << m3 hence, $\Delta m^2_{23} \equiv m^2_3 - m^2_2 > 0$ (lighter levels)
  - Inverted hirearchy: In this case, m1 $\simeq$ m2 >> m3 hence, $\Delta m^2_{23} \equiv m^2_3 - m^2_2 < 0$ (higher levels)
  - Degenerate Neutrinos: m1 $\simeq$ m2 $\simeq$ m3

Back up slide 3

ICAL being sensitive to the atmospheric neutrinos, which interact inside the detector through the different processes giving muons and hadrons. Neutrino energy is given by:

$$E_\nu = E_{muons} + E_{hadrons} \quad (1)$$

Where muon* gives distinct track, and hadron produces shower

Different processes in energy range 1 GeV-100 GeV:

- Below 1GeV, Quasi-Elastic Charge Current (QECC) interactions dominate and produce associated leptons

  $\nu_\mu n \rightarrow \mu^- p$, $\bar{\nu}_\mu p \rightarrow \mu^+ n$

- At a few GeV, resonance production becomes important and produce single pion events

  $\nu_\mu N \rightarrow \mu^- N^*$, $N^* \rightarrow \pi N'$

- Above a few GeV, the dominant process is Deep Inelastic Scattering (DIS) and produce associated leptons and hadrons

  $N_\mu n \rightarrow \mu X$ (scattering off quarks in the nucleus)

Back up slide 4

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.