Investigation of Matter Effects in Neutrino Oscillations with IceCube Sensitivity

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IceCube

DESY

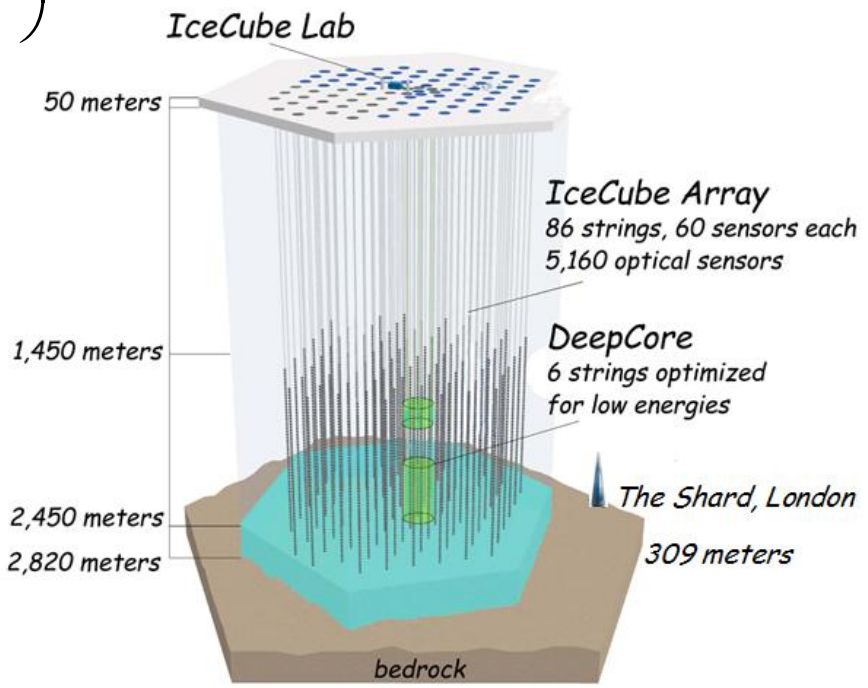
Neutrino Oscillations

- All neutrinos undergo oscillations as they propagate
- Simplest case probability formula:

$$\left|\nu_l\right\rangle = \sum_{i=1}^{3} U_{li}^{*} \left|\nu_i\right\rangle$$

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- Effect is enhanced for larger $\frac{L}{E}$
- DeepCore:
  - ~10-100GeV
  - 0-12,720km

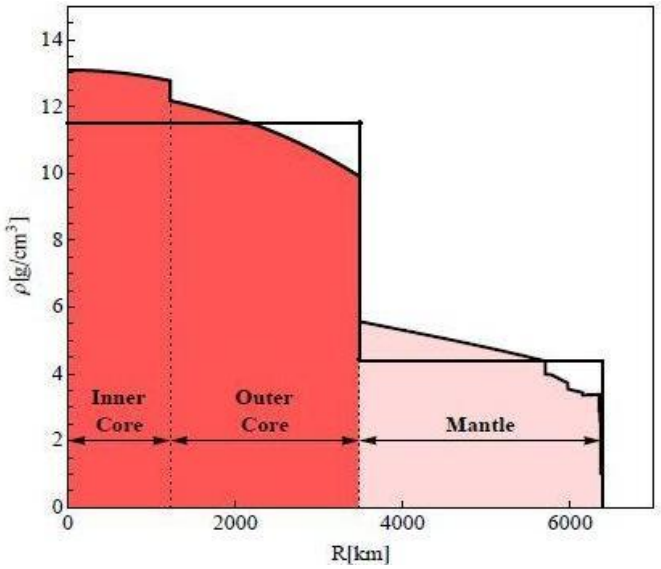


Earth's Density and State Amplitude

- In matter, a potential term is added:

$$V(x) = \sqrt{2} G_F N_e(x) = \frac{A_{CC}(x)}{2E}$$

- Density profile for the Earth:



A. M. Dziewonski, D. L. Anderson, Phys. Earth Planet. Interiors, 25, 297 (1981)

- In every layer, state amplitude changes:

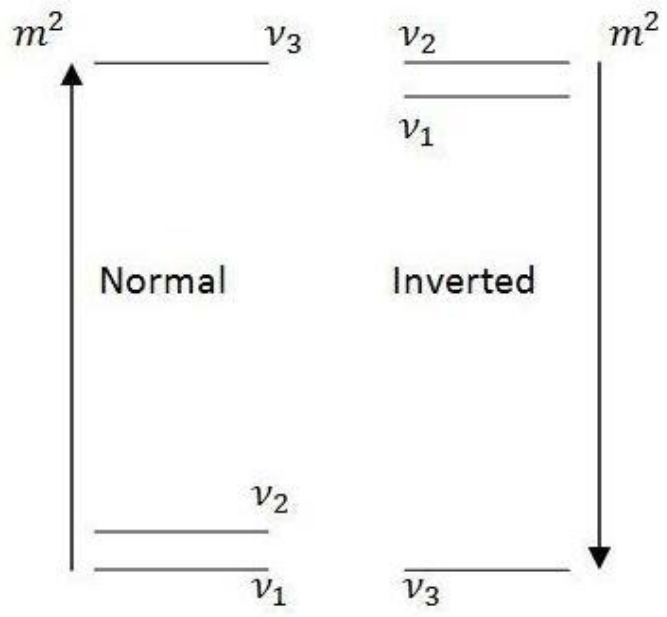
$$\left|\Psi_\alpha\right\rangle = U_M M U_M^* \left|\Psi_\alpha\right\rangle$$

- U is a mixing matrix
- From the Schrödinger equation, M consists of terms of the form:

$$\exp\left(\frac{-i\Delta m^2 L}{2E}\right)$$

- First approximation: a series of constant density layers

Matter Modification Matters



- Neutrino mass hierarchy is unknown – changing hierarchy changes the sign of Δm^2_{31}
- Modified mixing angle:

$$\tan 2\theta_{13}^{M} = \frac{\tan 2\theta_{13}}{1 - \dfrac{A_{CC}}{\Delta m^2_{31} \cos 2\theta_{13}}}$$

- The mass difference is modified in matter:

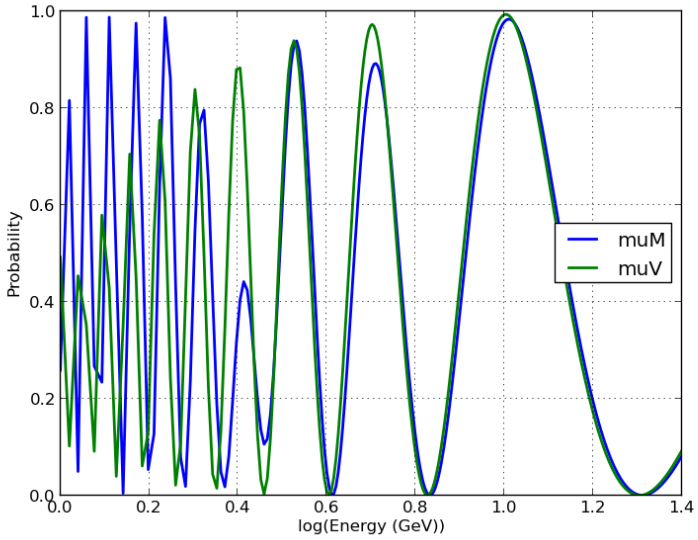
$$\Delta m^2_{M31} = \sqrt{(\Delta m^2_{31} \cos 2\theta_{13} - A_{CC})^2 + (\Delta m^2_{31} \sin 2\theta_{13})^2}$$

- Different values of Δm^2_{M31} depend on the mass hierarchy
- This leads to different values of the probability
- Is it detectable?

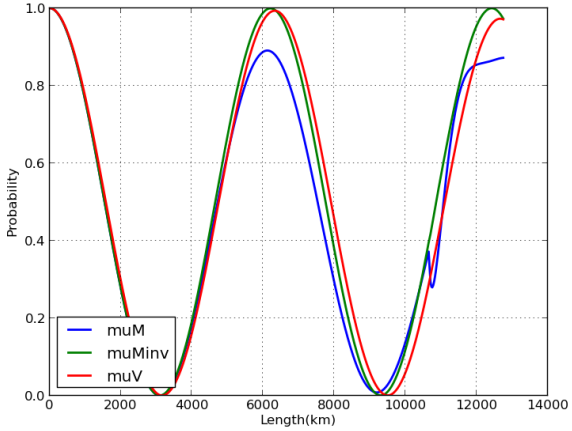
Probability Variation

- Using a mantle-core-mantle step function density profile
- Using an initial muon neutrino

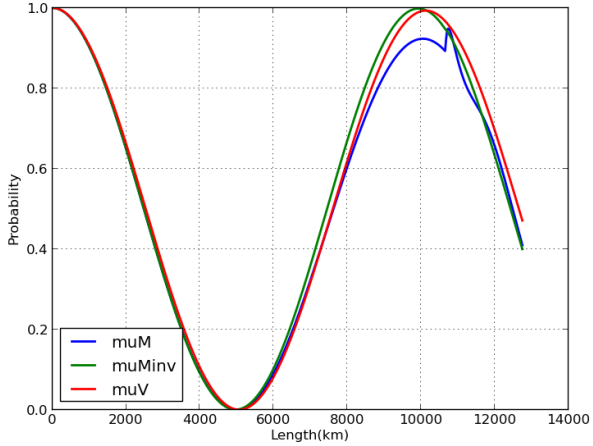
- As a function of energy
- 12,720km



- As a function of length
- 5GeV:

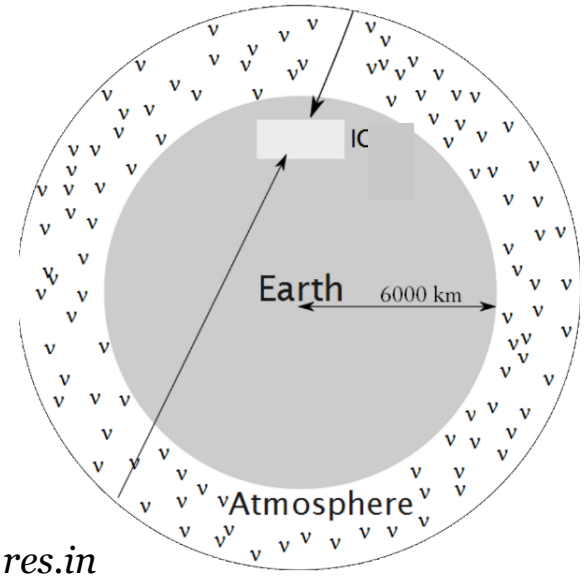


- 8GeV:



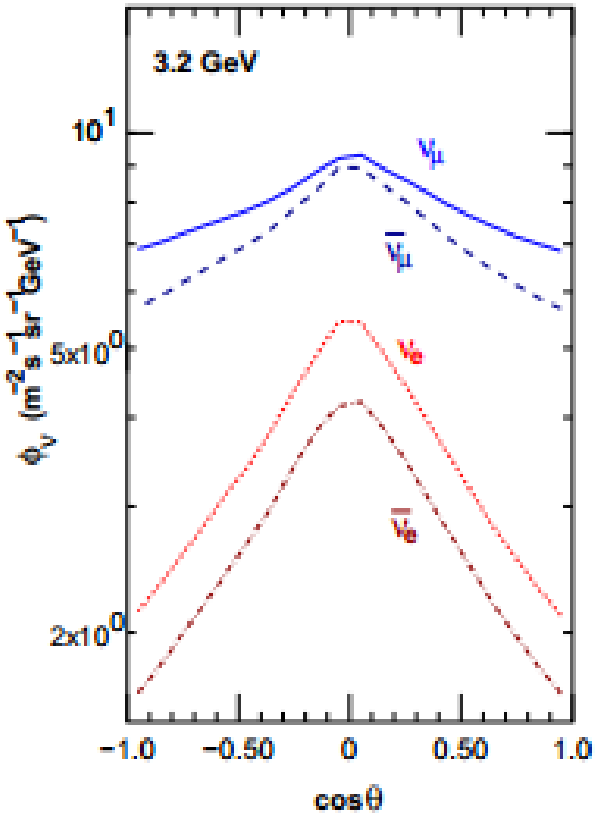
Atmospheric Flux Spectrum

- Used the Honda atmospheric neutrino flux spectrum
  - This means the initial state is mixed



www.ino.tifr.res.in

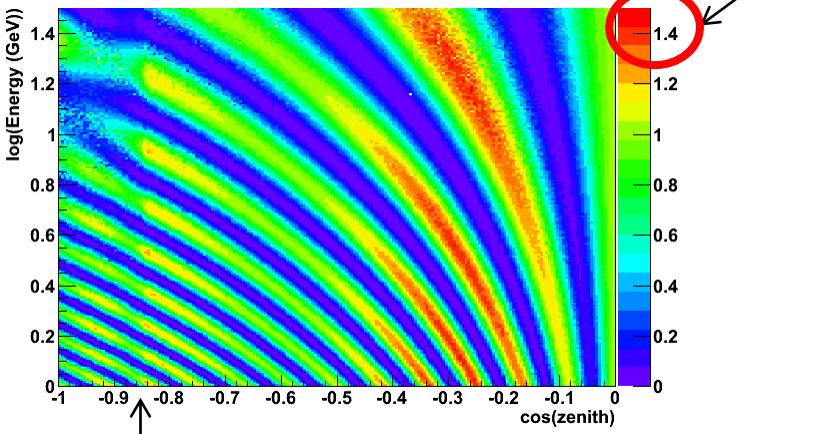
- Used the GENIE neutrino Simulator



M. Honda, T. Kajita, K. Kasahara, S. Midorikawa, Phys. Rev. D, 83 123001 (2011)

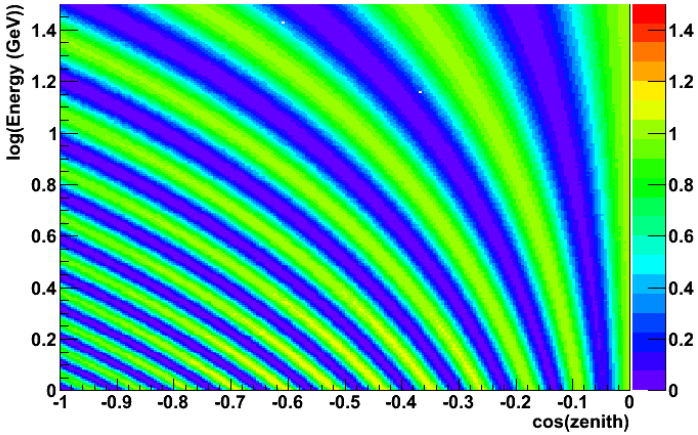
Neutrino Oscillograms

- 2: Matter; normal hierarchy



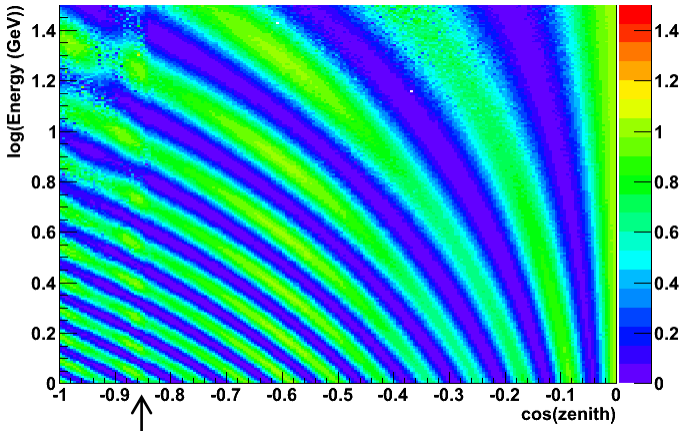
Core-Mantle boundary

- 1: Vacuum case



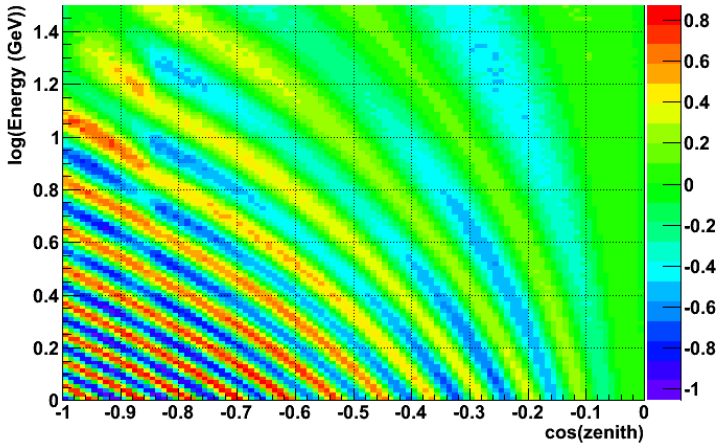
Colour = Likelihood of numu detection

- 3: Matter; inverse hierarchy



Core-Mantle boundary

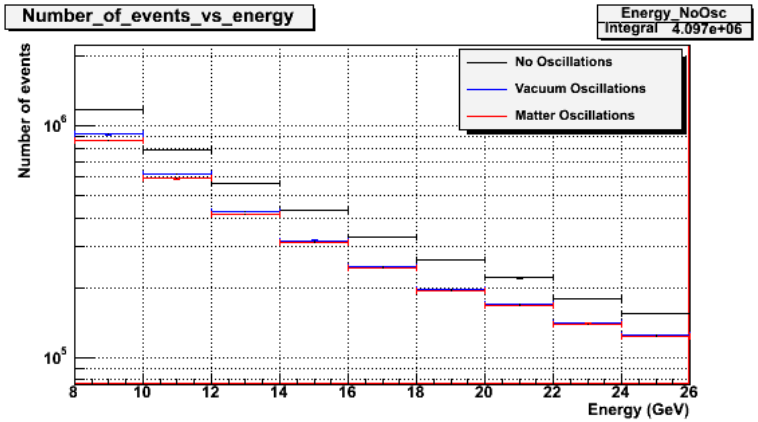
- 4: Vacuum - Matter difference

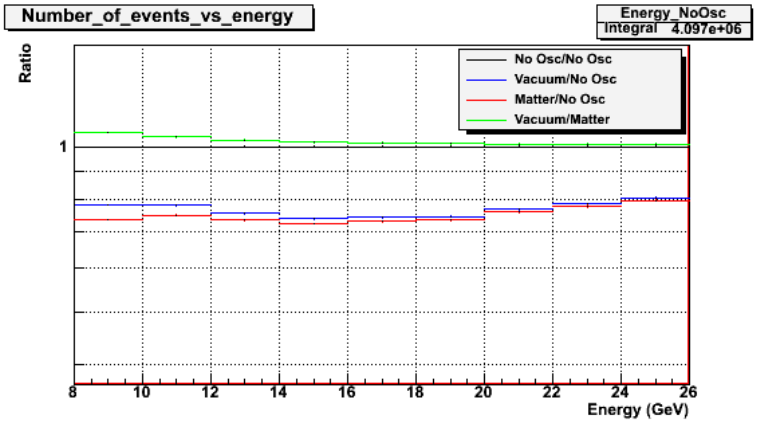


- (normal hierarchy)

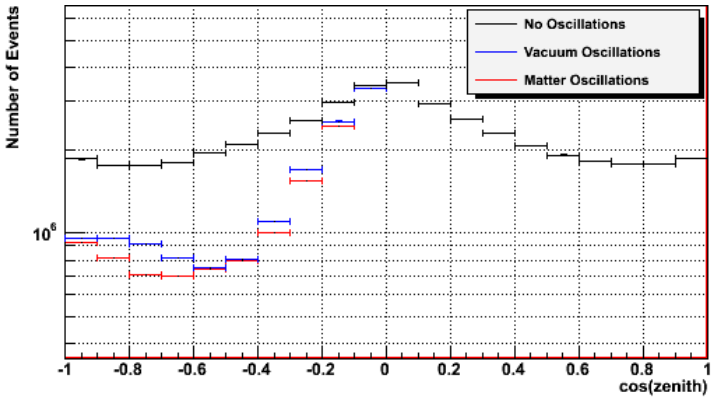
Flux of NuMu events

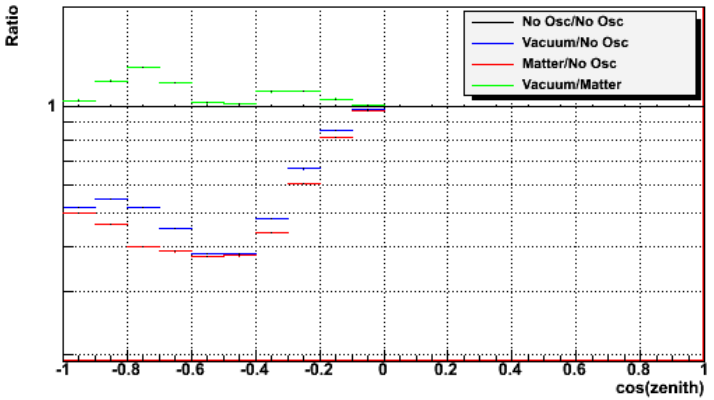
- Variation with energy





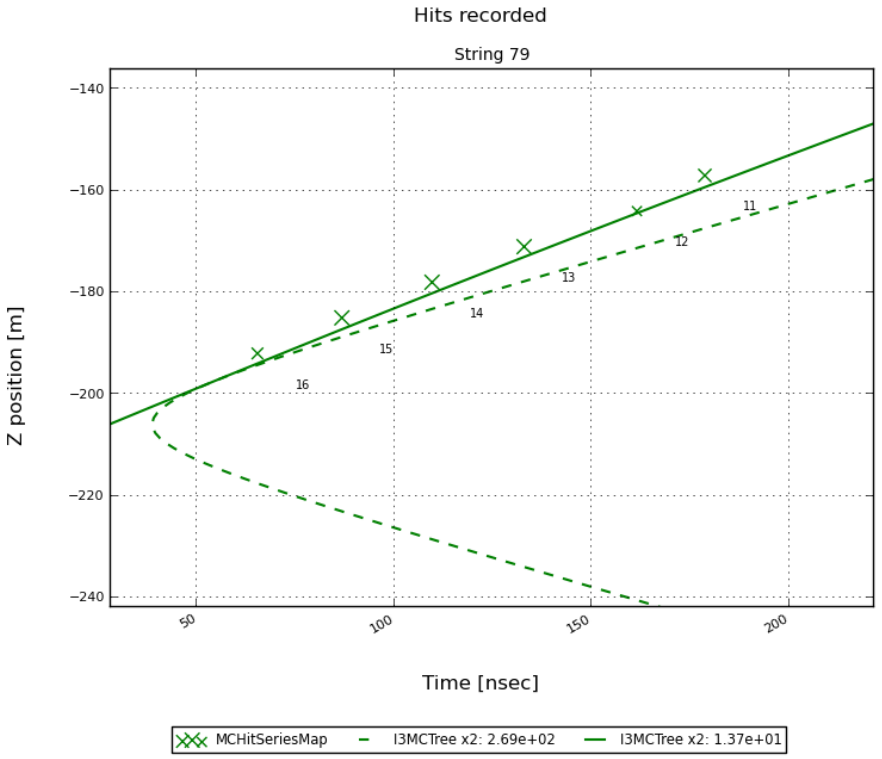
- Variation with zenith angle





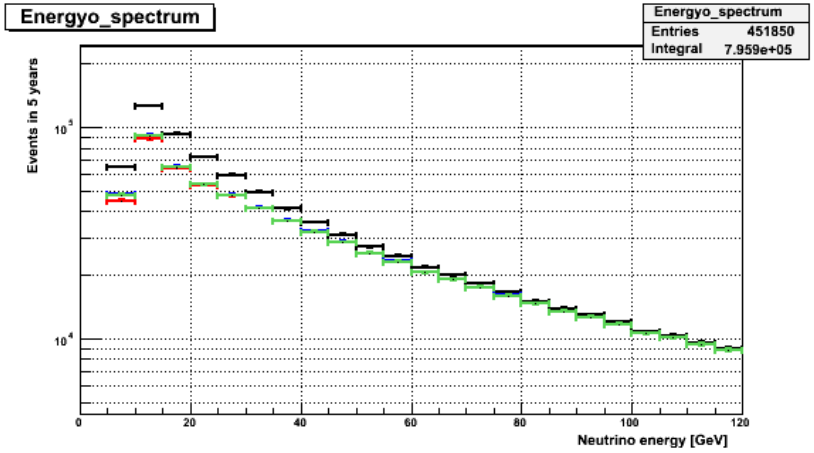
Triggering and filtering of detector

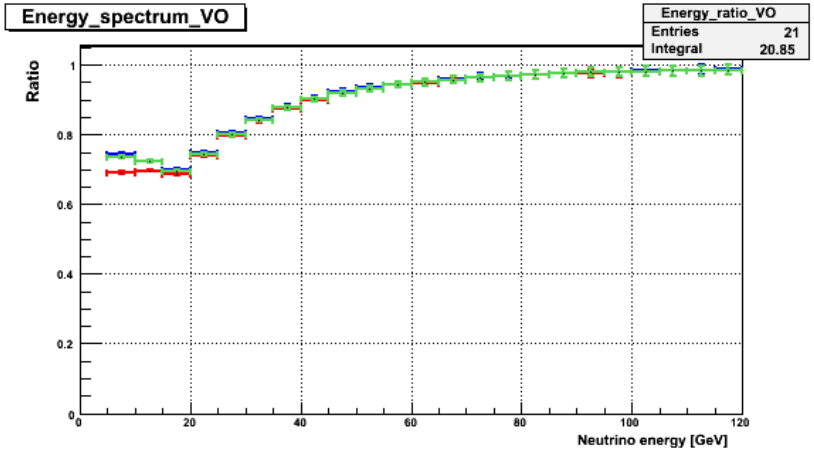
- Reconstruct to find the direction: x, y, z, zenith and azimuth
- Can fit to 5/6 DOM hits
- Can fit to a single string:
  - Only 5 hits now required



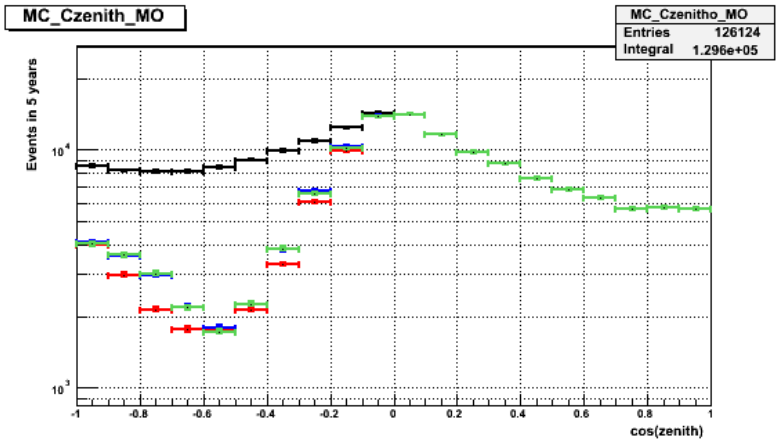
Energy Spectrum and Detector Response

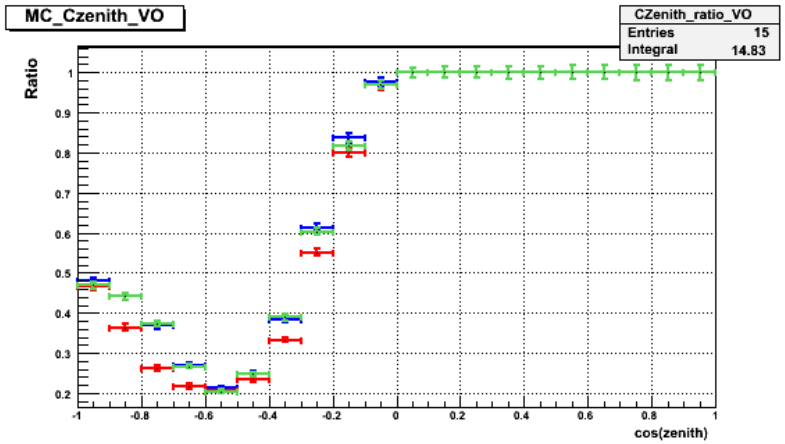
- Energy Spectrum





- Results including triggering and filtering



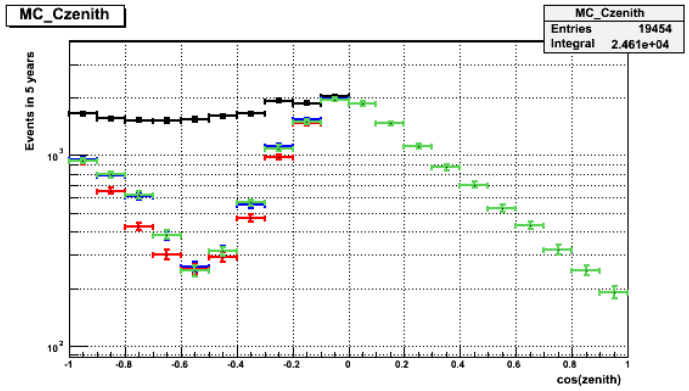


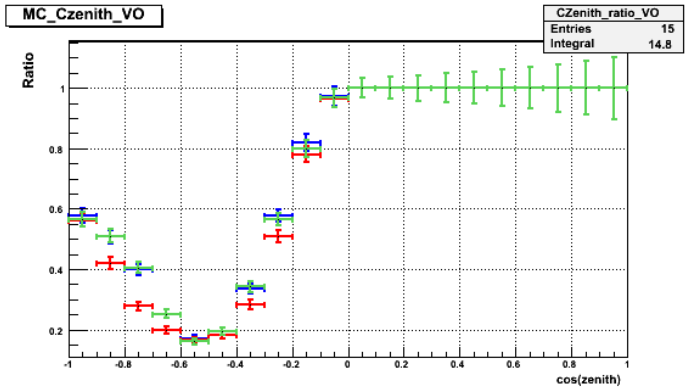
Cuts to the simulation

- Energies above 25GeV
- Angles above the horizon
- Track lengths shorter than 20m
- Fewer than 5/6 DOMs hit
- Non- Charged Current Muon interactions (track-like events only)

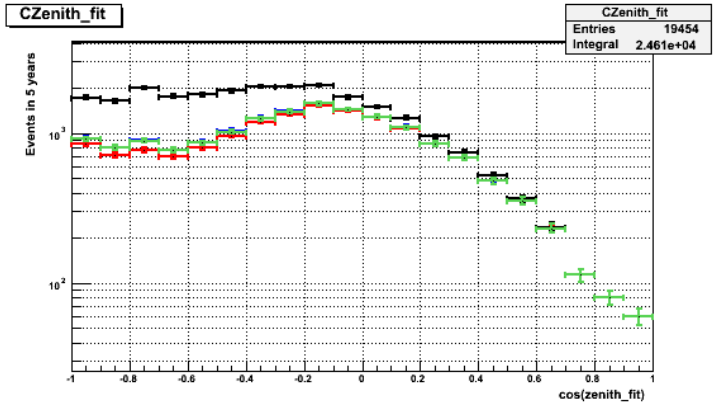
Results after cuts

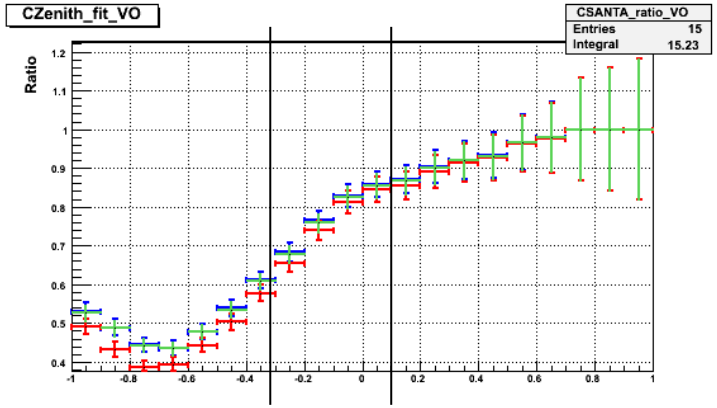
- Results including cuts to Monte Carlo:





- Results after reconstruction to Monte Carlo:





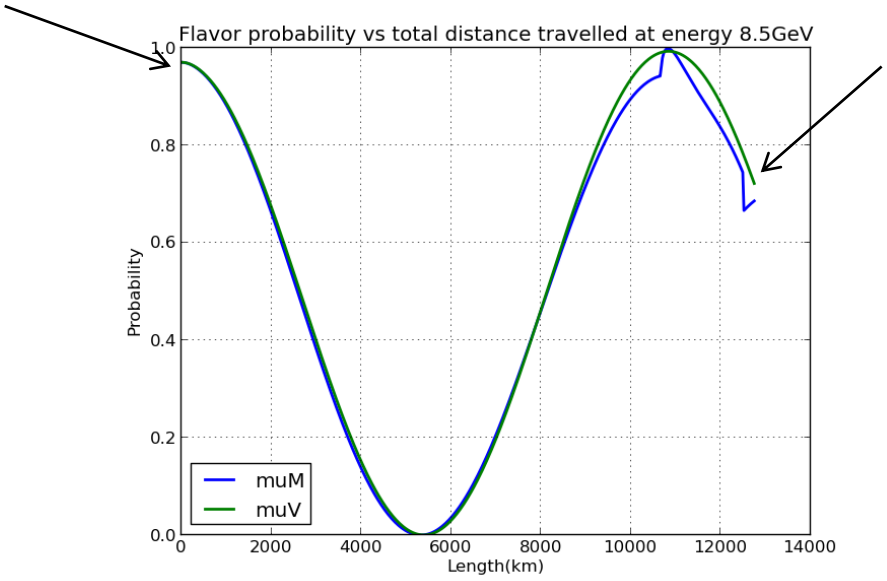
- Significance of results: 4.95σ 1.54σ 0.3σ

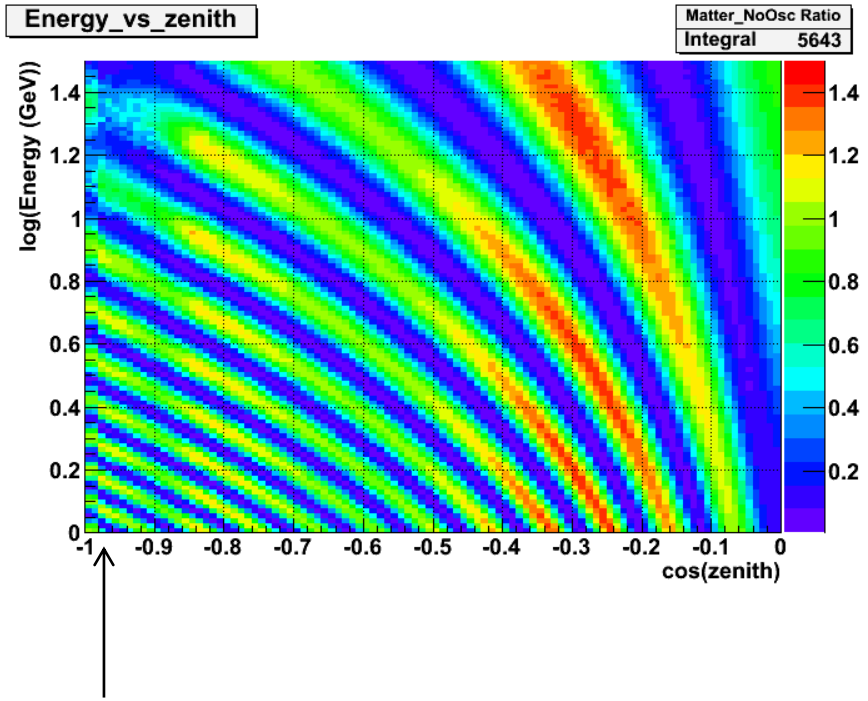
What Next?

- Study of Systematic Errors:
  - IceCube flux reconstruction
  - DOM acceptance
  - Properties of the ice
  - Improvement of low energy reconstruction
- Extension to the model:
  - Inclusion of further layers
  - Different density profile

Extending the Model

- Inclusion of: - 15km average production height
  - the inner core

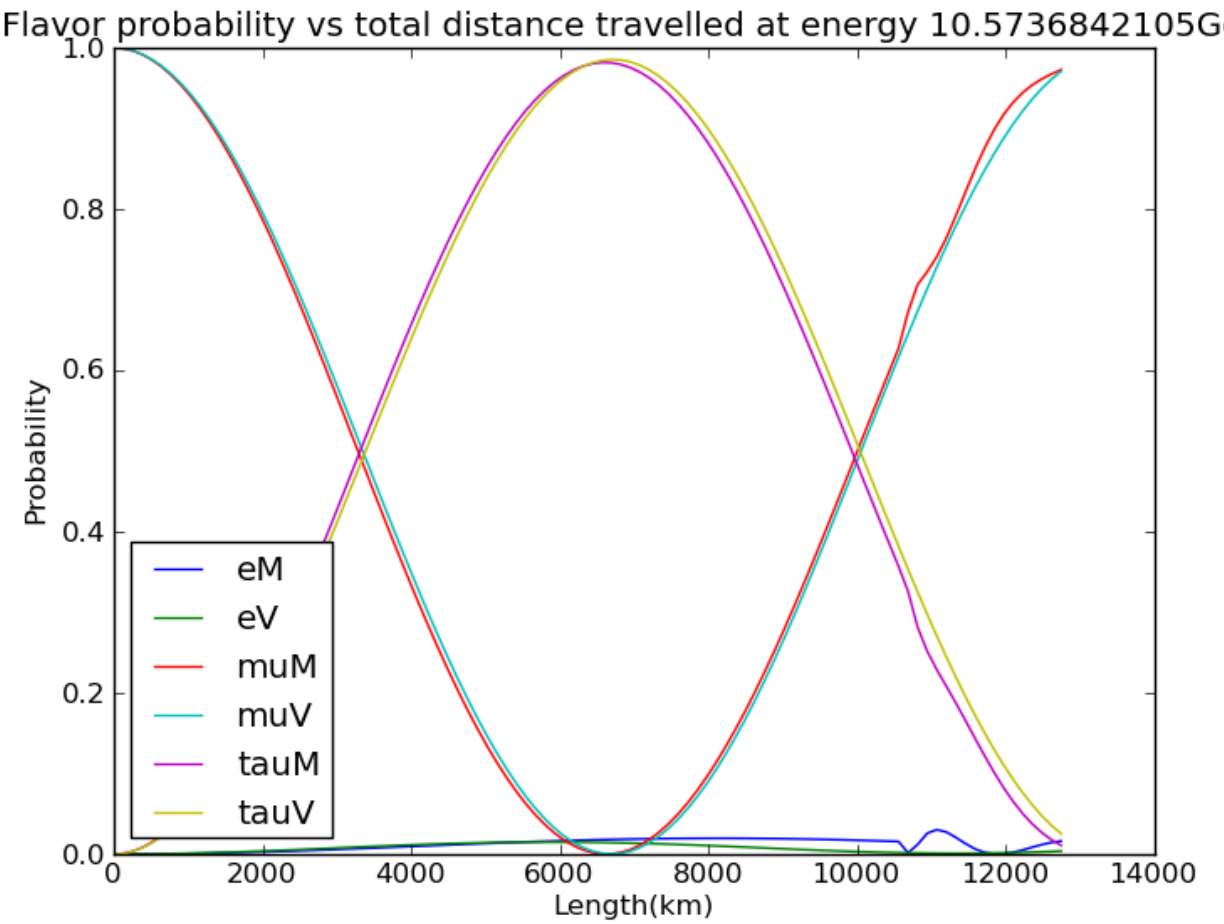




Thanks for Listening!

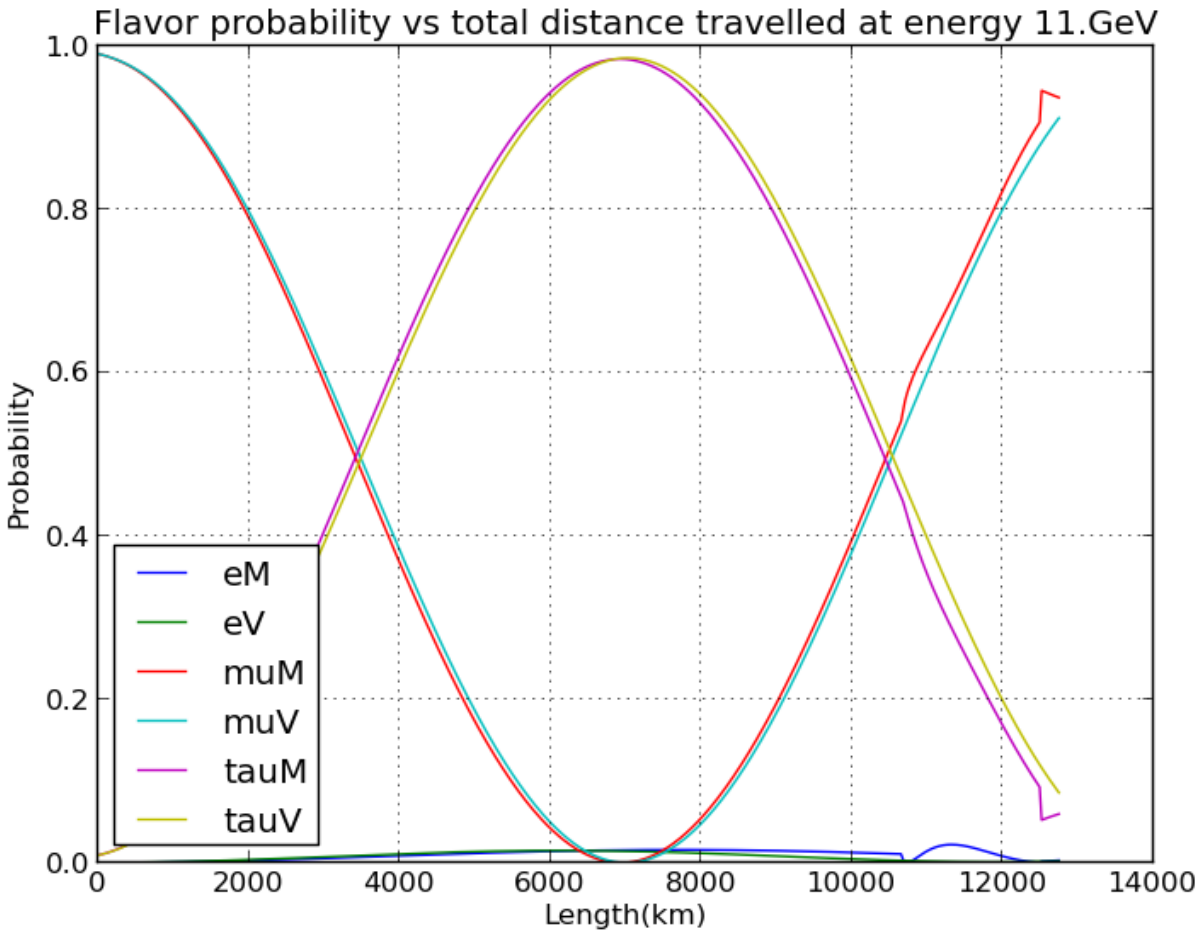
Back-Up Slides

Probability Variation



Probability Variation

Including 15km average production height and the inner core:



Matter Modified Mixing Matrix

$$U_M = \begin{pmatrix} \cos\theta_{13}^M & 0 & \sin\theta_{13}^M e^{-i\delta_{CP}} \\ -\sin\theta_{23}\sin\theta_{13}^M e^{i\delta_{CP}} & \cos\theta_{23} & \sin\theta_{23}\cos\theta_{13}^M \\ -\cos\theta_{23}\sin\theta_{13}^M e^{i\delta_{CP}} & -\sin\theta_{23} & \cos\theta_{23}\cos\theta_{13}^M \end{pmatrix}$$

Inclusion of a Layer of Atmosphere

- Neutrinos are produced at an average height of 15km
- At 5GeV: At 8GeV: