Neutrino Physics: Lecture 3

Atmospheric neutrinos, Vacuum oscillations

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Outline

1. Atmospheric neutrinos and the puzzle

2. Neutrino masses and vacuum oscillations

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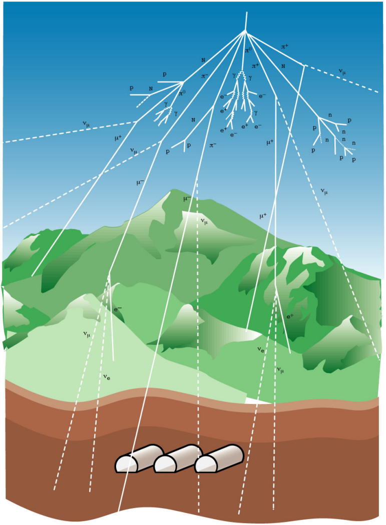
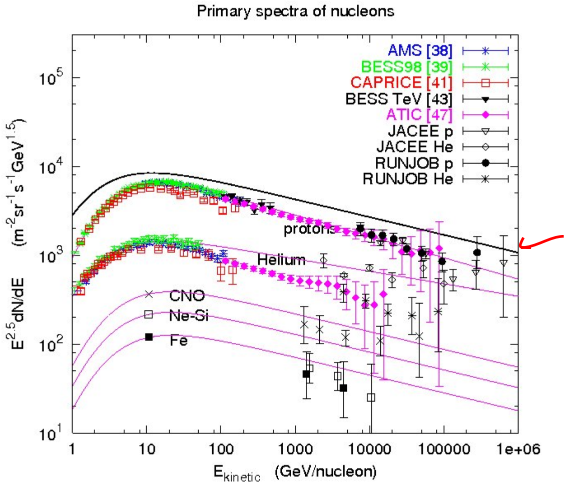
Neutrino production from cosmic rays

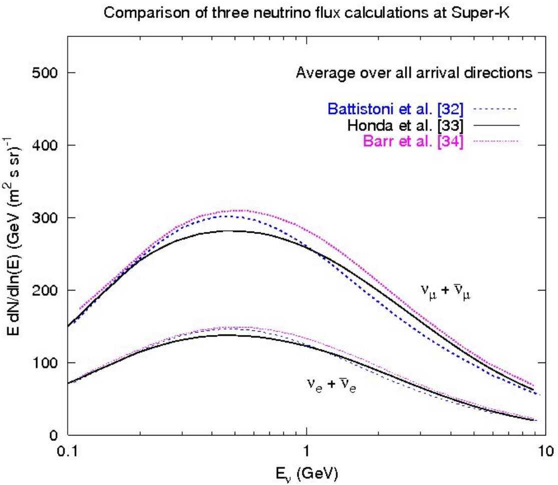


- $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- "ν_μ" flux $= 2\times$ "ν_e" flux
- "Down" flux = "Up" flux

Incoming nucleon fluxes

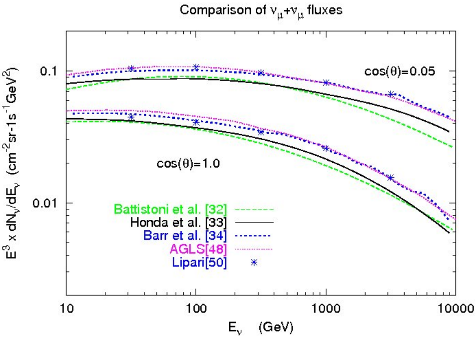


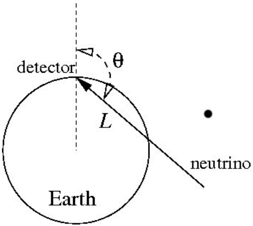
Expected neutrino fluxes at the Earth surface



- ν_μ / ν_e ratio: increases with energy

Expected neutrino fluxes at Earth surface

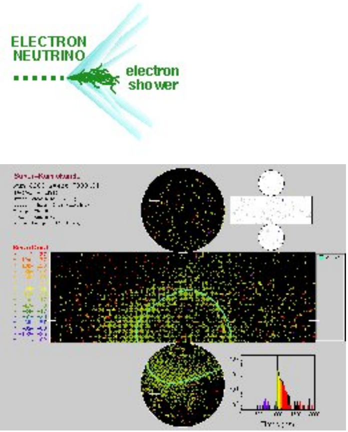




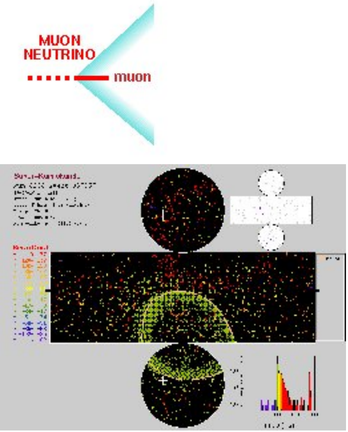
- ν_μ flux: smaller at larger $|\cos\theta|$
- However:

$$\boxed{\text{Flux}_{\cos\theta=a} = \text{Flux}_{\cos\theta=-a}}$$

How to detect ν_e and ν_μ through Cherenkov cones



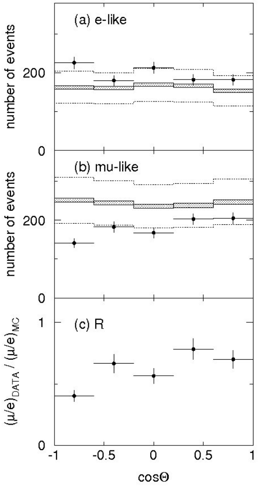
Diffused ring



Sharp ring

Atmospheric neutrino puzzle

Double ratio:



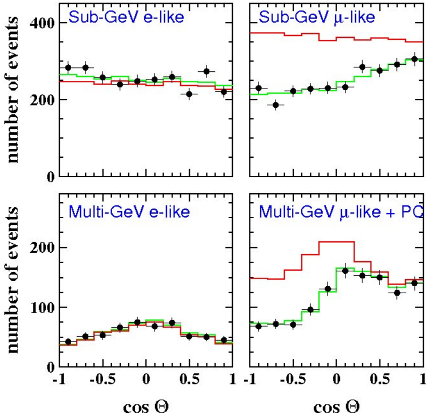
Observed $R < 1$

Expected $R \gtrsim 2$

Super-Kamiokande

Atmospheric neutrino puzzle

Zenith angle dependence:

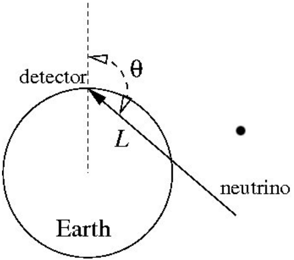


↑

ν_e OK

↑

ν_μ lost



Super-Kamiokande

Preliminary observations from zenith angle data

- Electron neutrinos match predictions
- High energy ν_μ from above: match predictions
- High energy ν_μ through the earth: partially lost
- Low energy ν_μ: lost even when coming from above, loss while passing through the Earth even greater

Outline

1. Atmospheric neutrinos and the puzzle

2. Neutrino masses and vacuum oscillations

Effective Hamiltonian for a single neutrino

$$H = \sqrt{p^2 + m^2} \approx p + \frac{m^2}{2p} \approx p + \frac{m^2}{2E}$$

Schrödinger's equation:

$$i\frac{d}{dt}|\nu(t)\rangle = H|\nu(t)\rangle$$

Time evolution:

$$\begin{aligned} |\nu(t)\rangle &= |\nu(0)\rangle e^{-iHt} \\ &= |\nu(0)\rangle e^{-ipt} e^{-\frac{m^2}{2E}t} \end{aligned}$$

- Simple for a mass eigenstate with fixed momentum !

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Time evolution for a flavour eigenstate

$$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

$$|\nu_\alpha(t)\rangle = \cos\theta\;|\nu_1(0)\rangle\, e^{-im_1^2 t/(2E)}\, e^{-ipt}$$
$$+ \sin\theta\;|\nu_2(0)\rangle\, e^{-im_2^2 t/(2E)}\, e^{-ipt}$$

$$P_{\nu_\alpha\to\nu_\alpha} = |\langle\nu_\alpha|\nu_\alpha(t)\rangle|^2$$

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Time evolution for a flavour eigenstate

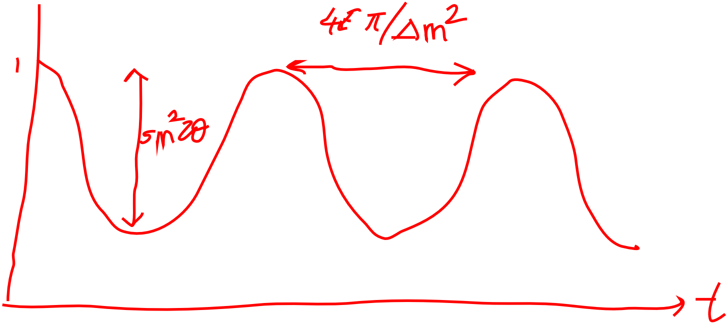
$$P_{\nu_\alpha \to \nu_\alpha} = \cos^4\theta + \sin^4\theta + 2\sin^2\theta\cos^2\theta\cos\left(\frac{m_2^2 - m_1^2}{2E}t\right)$$

$$= 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Vacuum oscillations

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

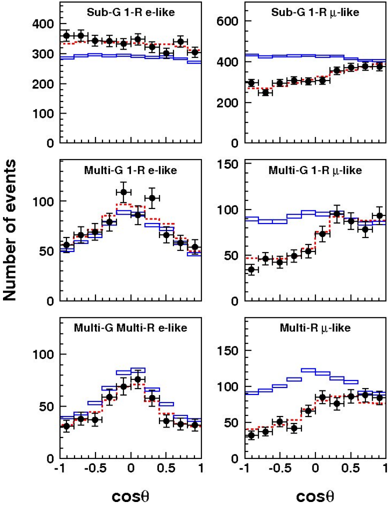
Amplitude, wavelength:



Explaining broad features of atmospheric ν data

- Electron neutrinos match predictions ✓
- High energy ν_μ from above: match predictions ✓
- High energy ν_μ through the earth: partially lost ✓
- Low energy ν_μ: lost even when coming from above, loss while passing through the Earth even greater ✓

Detailed features of atmospheric ν data

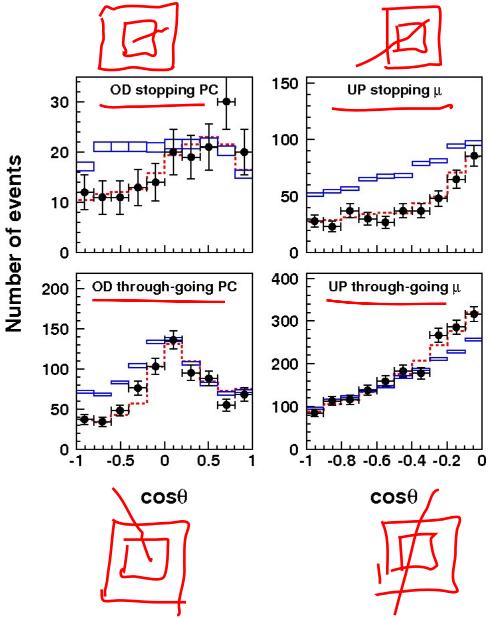


Sub-GeV 1-ring

multi-GeV 1 ring

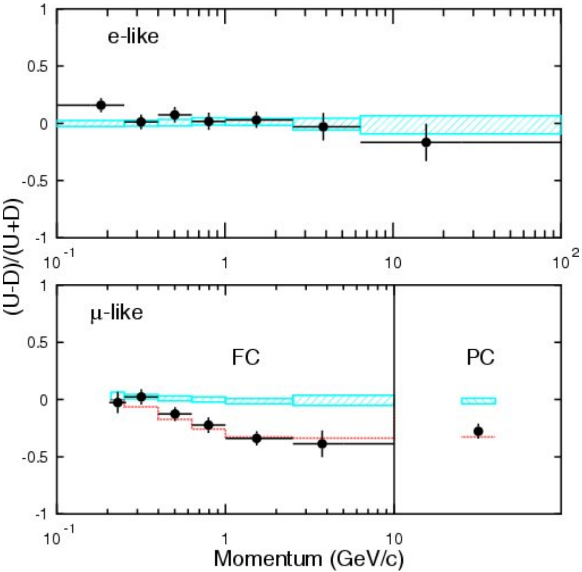
multi GeV multi ring

Detailed features of atmospheric ν data



Different energy regimes

Detailed features of atmospheric ν data



To be checked in Assignment

Atmospheric ν solution through “vacuum oscillations”

Prerequisites

- Neutrino flavours mix with each other
- Neutrinos have different masses
- ν_e do not participate in the oscillations

Neutrino oscillations: ν_μ oscillate into ν_τ

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

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