Neutrino Physics: Lecture 4

Atmospheric neutrinos: quantitative details confirming oscillations, ruling out alternatives

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Outline

1. Atmospheric neutrinos: quantitative treatment
2. Confirming vacuum oscillations: short baseline experiments
3. Alternative solutions: Decoherence, decay, ...

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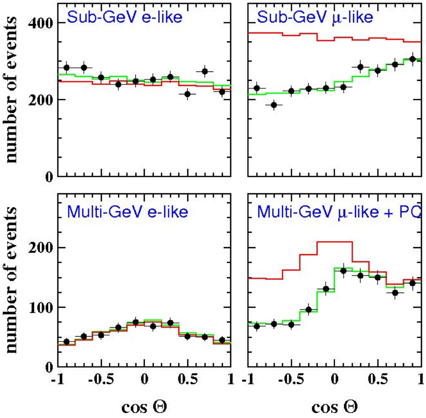
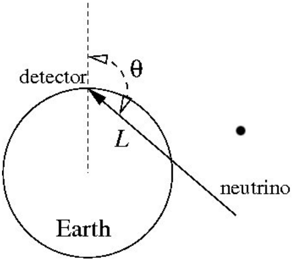
Atmospheric neutrino puzzle

Zenith angle dependence:





Super-Kamiokande

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

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

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

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

Quantifying the good-ness of a guess: χ^2

$$\chi^2 = \sum_{bins} \frac{(N_i^{\mathrm{exp}} - N_i^{\mathrm{th}})^2}{\sigma_i^2}$$

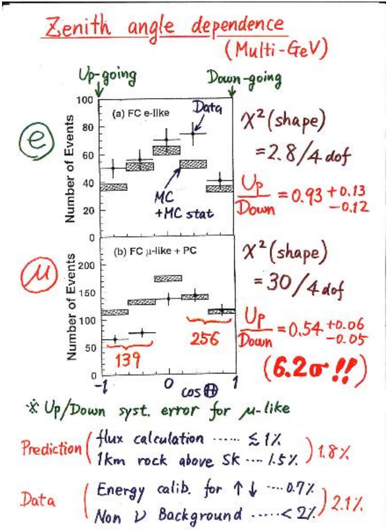
Calculation of N_i^{th}:

$$N(\tilde{E}_\mu, \tilde{\theta}_\mu) = R(E_\mu, \tilde{E}_\mu)\, R(\theta_\mu, \tilde{\theta}_\mu)$$

$$\times \frac{d^2\sigma(\nu_\mu N \to \mu^- N')}{dE_\mu\, d\cos\theta_\mu}$$

$$\times P_{\mu\mu}(E_{\nu_\mu}, \theta_{\nu_\mu})\; \Phi^0_{\nu_\mu}(E_{\nu_\mu}, \theta_{\nu_\mu})$$

Quantifying the “bad-ness” of no-oscillation solution



Zenith angle dependence

(Multi-GeV)

χ^2(shape) $= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape) $= 30/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

(6.2σ !!)

※ Up/Down syst. error for μ-like

Prediction (flux calculation ······ ≲ 1%
1km rock above SK ···· 1.5%) 1.8%

Data (Energy calib. for ↑↓ ···· 0.7%
Non ν Background ····· < 2%) 2.1%

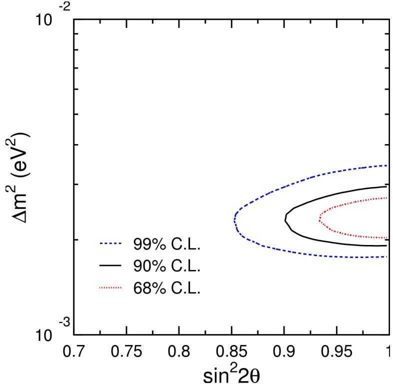
dof = degrees of freedom

= # data points

− # parameters

Best fit values for oscillation solution

Contours in the Δm^2-$\sin^2\theta$ plane: $\chi^2(\Delta m^2, \sin^2\theta)$



Mixing parameters

$$\Delta m^2_{\rm atm} \approx (1.3\text{–}3.4) \times 10^{-3}\ \mathrm{eV}^2$$

Mixing angle $\theta_{\rm atm} \approx 36^\circ$–$54^\circ$

Further details of atmospheric neutrino problem

- *"Evidence for oscillation of atmospheric neutrinos"*, Super-Kamiokande Collaboration, hep-ex/9807033v2, PRL81, 1562 (1998)
- *"Measurement of neutrino oscillation parameters by Super-kamiokande I"*, Super-Kamiokande Collaboration, PRD71, 112005 (2005)
- *"Super-Kamiokande atmospheric neutrino results"*, K. Okamura, Czech. J. Phys. 56, A271 (2006)
- *"Three flavor neutrino oscillation analysis of atmospheric neutrinos in Super-Kamiokande"*, hep-ex/0604011v2, PRD74, 032002 (2006)

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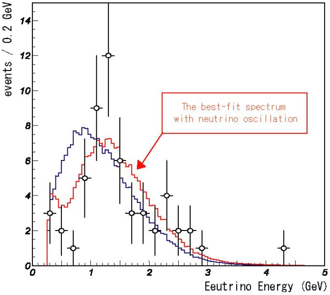
A "practical" oscillation formula

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

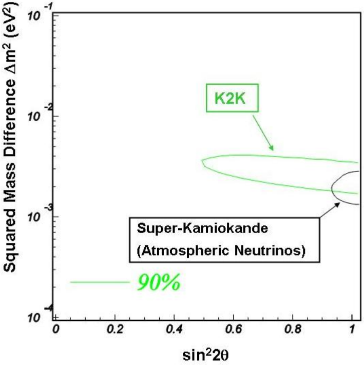
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 \ (\mathrm{eV}^2) \ L \ (\mathrm{km})}{\cancel{4} E \ (\mathrm{GeV})} \right)$$

Designing experiment for a given Δm^2:

K2K: KEK to Kamiokande: 285 km



The best-fit spectrum with neutrino oscillation

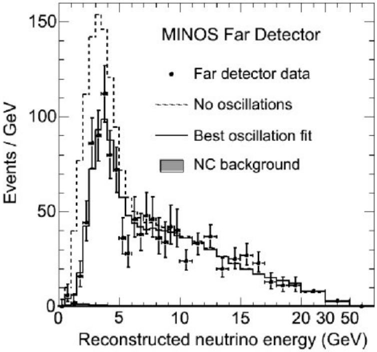


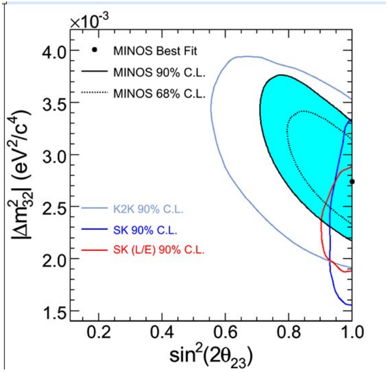
K2K

Super-Kamiokande (Atmospheric Neutrinos)

90%

MINOS: Fermilab to Soudan: 735 km





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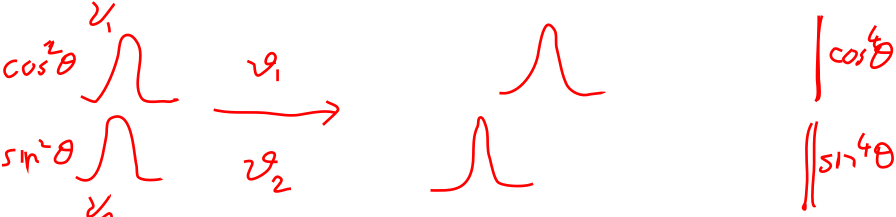
Wavepacket separation

$$v_1 - v_2 \approx \frac{\Delta m^2}{2E^2}$$



[decoherence]

$$P_{\alpha\alpha} \approx 1 - \frac{1}{2}\sin^2 2\theta = \cos^4\theta + \sin^4\theta$$

Apparent decoherence due to production/detection point uncertainty

$$\phi = |\text{phase gained by } \nu_1 - \text{phase gained by } \nu_2|$$

$$\phi = \frac{\Delta m^2 L}{2E}$$

$$\Big\downarrow$$

$$\Delta\phi = \frac{\Delta m^2}{2E}\Delta L$$

$$\Delta\phi \gtrsim 1$$

$$\Downarrow$$

No observed oscillations

$P \sim \cos^4\theta + \sin^4\theta$

[mixing effects observed]

Apparent decoherence due to finite energy resolution

$$\phi = |\text{phase gained by } \nu_1 - \text{phase gained by } \nu_2|$$

$$\phi = \frac{\Delta m^2 L}{2E}$$

$$\Big\downarrow$$

$$\Delta\phi \gtrsim 1$$

$$\Downarrow$$

decoherence
(no observed
oscillations)

$$\Delta\phi = \frac{\Delta m^2 L}{2E}\left(\frac{\Delta E}{E}\right)$$

Neutrino decay

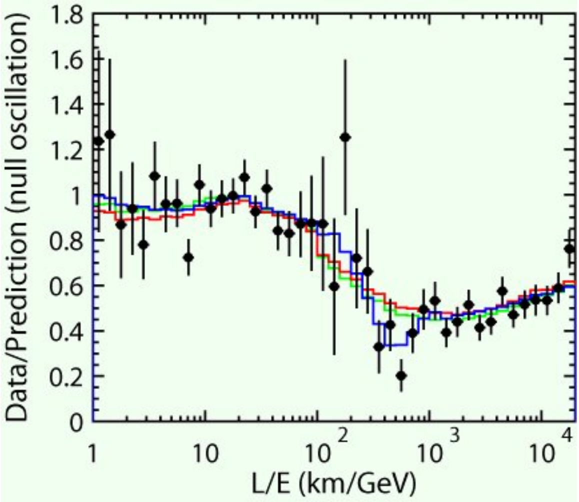
$$|\nu_2\rangle \to |\nu_1\rangle + X$$

$$|\nu_2(t)\rangle = |\nu_2(0)\rangle e^{-im_2^2 t/(2E)} e^{-t/(2\tau)}$$

To be done in HW

Distinguishing oscillations, decoherence, decay

Oscillation dip:



“Atmospheric” neutrinos: 2ν parameter space