229C HW # 3 (due Oct 15)

Read the article "Atmospheric neutrino results from Super-Kamiokande and Kamiokande — Evidence for ν_μ oscillations —" by Takaaki Kajita, hep-ex/9810001, presented at Neutrino 98 conference.

1. From the numbers given in Table 1, calculate R-values yourself and discuss possible interpretations.

2. Figure 1 shows the zenith angle distribution of the e-like and μ-like data both for sub-GeV and multi-GeV. The dashed histogram shows the Monte Carlo prediction with $\nu_\mu \to \nu_\tau$ oscillation with $\Delta m^2 = 2.2 \times 10^{-3}$ eV^2 and $\sin^2 2\theta = 1$, which gives a good fit to the data. Answer the following questions on μ-like data based on the interpretation that there is neutrino oscillation with the above parameters. (a) Explain why there is about a factor-of-two depletion for $\cos\Theta < 0$ both for sub-GeV and multi-GeV data. (b) Explain why there is basically no depletion for $\cos\Theta > 0.2$ in multi-GeV data, but there is some depletion in sub-GeV data. (c) Figure 6 gives the Δm^2, $\sin^2 2\theta$ region preferred by their data. Discuss why the data prefers $\Delta m^2 \simeq 10^{-3}$–$10^{-2}$ eV^2 and a large $\sin^2 2\theta$ using an order-of-magnitude argument.

3. One of the pressing questions is if the ν_μ oscillates into ν_τ or ν_s (an exotic particle which does not interact at all in the detector). They can address this question by studying neutral-current induced π^0 in the data. Make a rough estimate on how much depeletion in π^0 events you would expect if the oscillation is ν_μ to ν_s, and discuss how it compares to the data discussed in Section 3. Assume that neutrinos responsible for producting π^0 are mostly multi-GeV neutrinos.

4. MINOS experiment attempts to study the neutrino oscillation $\nu_\mu \to \nu_\tau$ by looking for the appearance of τ from ν_μ beam motivated by this atmospheric neutrino anomaly. Using a neutrino beam of $E_\nu \sim 30$ GeV, how long baseline do they need to study the relevant Δm^2 range? Given their baseline of about 700 km (Illinois to Minnesota), what energy would be optimal for the purpose?

5. Despite the anomaly, the Super-Kamiokande data confirms that the cosmic ray particles produce neutrinos in the atmosphere which penetrate all the way through the Earth. Using the number of sub-GeV e-like events they have seen, estimate the neutrino flux (# particles per unit time per unit area). The CC cross section of neutrino at this energy range is roughly 5 fb.

6. Point out systematic issues in Super-Kamiokande data you can think of. (Then I can write a paper with you! `:-)`)