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Reducing uncertainty in atmospheric neutrino flux prediction

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Abstract: The atmospheric neutrino is still an important tool in the study of neutrino physics. The uncertainty of the predicted atmospheric neutrino flux is caused by the uncertainties in the physical assumptions and in the calculation scheme. We discuss them quantitatively, and present the works to reduce them. The uncertainty related to the hadronic interaction model was discussed before, therefore, we mainly study other uncertainty sources than the hadronic interaction model here.

Introduction

The atmospheric neutrino is still an important source for the study of neutrino oscillations. As the atmospheric neutrino experiments cover a wide $L/E (= [flight\ length]/[energy])$ range, the atmospheric neutrino experiment are complementary to the accelerator neutrino experiment. It is important to reduce the uncertainty in the prediction of atmospheric neutrino flux for the forthcoming atmospheric neutrino experiments with larger detectors.

In the preceding publications [1, 2], we presented the study of the uncertainty resulting from the hadronic interaction model using atmospheric muon fluxes. Then estimated the systematic uncertainty in the prediction of atmospheric neutrino flux as in figure 1.

In this paper, we discuss the uncertainties other than the hadronic interaction model. We mainly study the solar modulation of cosmic rays, and the effect of the mountain over a neutrino detector, as such "uncertainties" in this paper. The effect might be smaller than that of the hadronic interaction uncertainty, but an improper treatment of them may cause a sizable error ($\sim$ 10%) in the prediction of atmospheric neutrino flux. Note, the recent BESS observations [3] improved the the knowledge of solar modulation of cosmic rays largely.

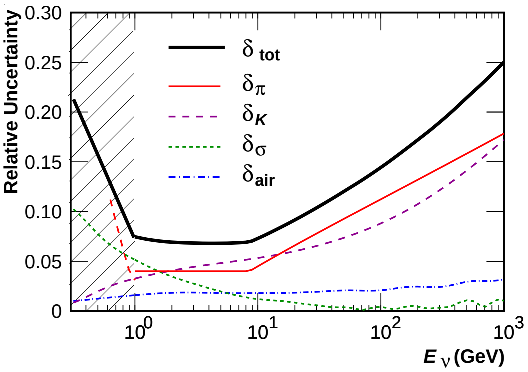

Figure 1: The systematic uncertainty of each error source for atmospheric neutrino flux.

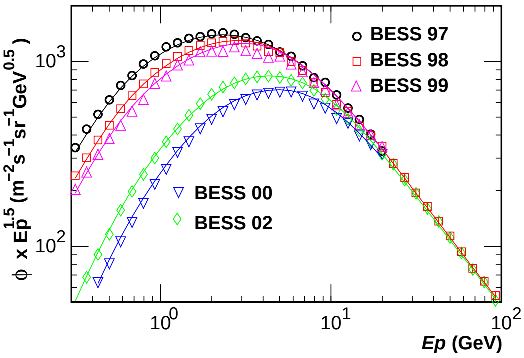

Figure 2: Cosmic ray proton spectra observed by BESS from 1997 to 2002.

Solar modulation

The solar modulations of cosmic rays are known for many years. However, the modulated spectra of the cosmic rays above a few GeV were not well known until the series observation by BESS group [3] in the 6 years from 1997 to 2002, including the minimum and maximum phases of the solar activities.

In figure 2, we depicted the cosmic ray proton spectra observed by BESS group. The lines in the figure show a parameterization of them based on the neutron monitor count at Climax.

The fitting formula consists of the spectra for solar minimum and a modulation function. For the cosmic ray protons, it is written as

$$\phi_p(N, E_k) = \phi_p^{min}(E_k) \cdot M(N, r) \ , \qquad (1)$$

where N is the count of the neutron monitor at Climax, E_k the kinetic energy of cosmic ray protons, and r the rigidity of them.

The proton spectrum for solar minimum is modified from Ref. [4], so that it has the asymptotic power index of -2.71, and reproduce the BESS97 observation at lower energies as,

$$\phi_p^{min}(E_k) = P_1(e + P_2 \exp(-P_3 e^{P_4}))^{-2.71} \cdot \eta(e) \qquad (2)$$

where $e = E_k/1$(GeV), $P_1 = 12663$, $P_2 = 1.51$, $P_3 = 0.0637$, and $P_4 = 1.3$.

$$\eta(e) = \exp(P_5(\ln(e/P_6) - \sqrt{\ln(e/P_6)^2 + P_7})), \qquad (3)$$

is introduced to fit the data below 1 GeV with $P_5 = 0.229$, $P_6 = 0.575$, and $P_7 = 0.179$.

The Modulation function is expressed as,

$$M(N, r) = \exp(A(x - (|x|^\alpha + \varepsilon^\alpha)^{1/\alpha})) \ , \qquad (4)$$

where $\alpha = 2.52$, $x = r/4.97$(GV), $A = -7.3 \times 10^{-4} \cdot (N - 4311)$, and $\varepsilon = 1.1 \times 10^{-3} \cdot (N - 4311)$. Note, the neutron monitor count (N) was 4295 for BESS97, 4170 for BESS98, 4100 for BESS99, 3454 for BESS00, and 3600 for BESS02. Those formulae are not elegant at all, but more importantly they reproduce the BESS observations within the error $\lesssim$ 5% for most of data above 0.3 GeV.

For the cosmic ray Heliums, the same modulation function (4) and the spectrum for solar minimum reproduce the Helium spectra of BESS observations within the error $\lesssim$ 10%.

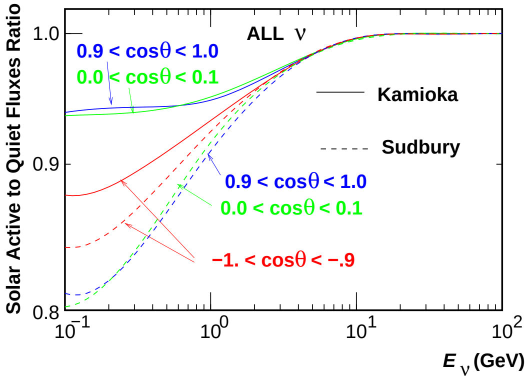

Figure 3: The ratio of neutrino flux calculated for solar active phase to that for solar quiet phase.

The atmospheric neutrino flux is calculated for the solar quiet phase (N=4170) and solar active phases (N=3650). Then the ratio are shown in figure 3 for several zenith angle bins. The modulation of the atmospheric neutrino flux by solar activity is small for downward going neutrinos at Kamioka, due to the high rigidity cutoff. On the other hand, it is a large effect at Sudbury (SNO site). Also even at Kamioka, the modulation is larger for upward going directions.

Mountain Over the Detector

Some of the neutrino detectors are constructed under mountains as SK. The mountain over a neutrino detector also affects the atmospheric neutrino flux. When a parent particle of neutrino enters the rock, it loose energy due to the energy loss, and produces very low energy neutrinos (< 0.1 GeV) only. Then, we expect a smaller neutrino flux value under a high mountain for $E_\nu > 0.1$ GeV.

To study the effect of the mountain over a neutrino detector, we first study the production height of the atmospheric neutrino, then estimated the reduction rate due to the mountains. In figures 4 and 5, we plotted the production height of neutrinos for vertical and horizontal down going directions respectively, in the accumulated production probability for the height. As the production height of $\bar{\nu}_e$ is almost identical to ν_e, we do not plot the production height of $\bar{\nu}_e$ separately from ν_e.

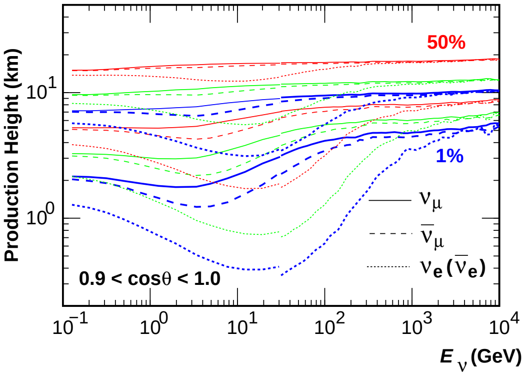

Figure 4: Accumulated production probabilities of neutrinos for the height for vertically downward going neutrinos at Kamioka. 6 lines, 50%, 20%, 10%, 5%. 2%, and 1%, are depicted for each of ν_μ, $\bar{\nu}_\mu$, and $\nu_e(\bar{\nu}_e)$. Note the 3D and 1D calculations are connected at 32 GeV.

The production heights of ν_e's or $\bar{\nu}_e$'s are lower than those of ν_μ's or $\bar{\nu}_\mu$'s. This is explained by the fact that the main source of ν_e's and $\bar{\nu}_e$'s is the μ-decay up to 100 GeV $\sim$ 1 TeV depending on the arrival direction. For ν_μ's and $\bar{\nu}_\mu$, some of them are originated from the μ-decay. However, as the proton is the main component of cosmic rays, the ratio of ν_μ produced in the μ-decay is smaller than that of $\bar{\nu}_\mu$ at fixed E_ν. Therefore, the production heights of ν_μ's are a little higher than those of $\bar{\nu}_\mu$'s.

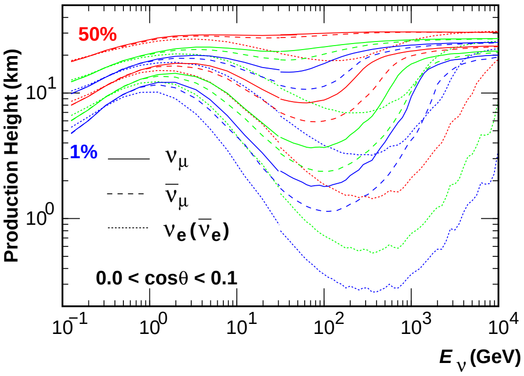

Figure 5: Accumulated production probabilities of neutrinos for the height for horizontally downward going neutrinos at Kamioka. 6 lines, 50%, 20%, 10%, 5%. 2%, and 1%, are depicted for each of ν_μ, $\bar{\nu}_\mu$, and $\nu_e(\bar{\nu}_e)$. Note the 3D and 1D calculations are connected at 32 GeV.

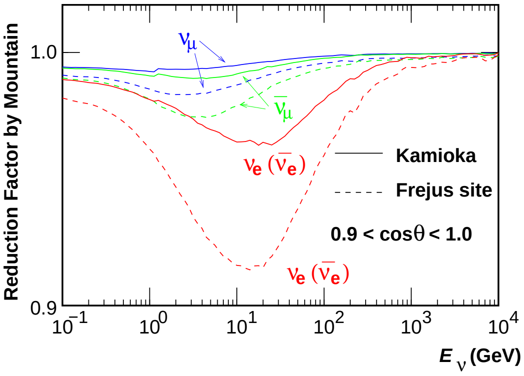

Figure 6: The deficit of atmospheric neutrino fluxes calculated for vertically downward going neutrinos at Kamioka and at Frejus site.

Next, we calculate the deficit rate of atmospheric neutrino flux at SK and Frejus sites, and show them in figures 6 and 7. The effect is smaller at SK site, since the summit of the mountain over SK is only $\sim$ 1000m a.s.l. On the other hand, the deficit of atmospheric neutrino flux is larger especially for Frejus site, especially for ν_e's and $\bar{\nu}_e$'s. The effect of the mountain over a neutrino detector may be important for the atmospheric neutrino experiments under a high mountain.

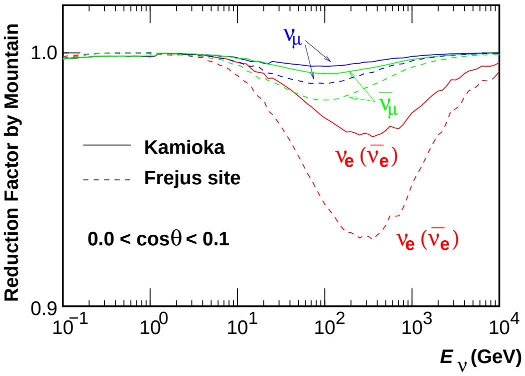

Figure 7: The deficit of atmospheric neutrino fluxes calculated for horizontally downward going neutrinos at Kamioka and at Frejus site.

In the calculation in Ref. [2], the landscape near the detector was considered for $\theta_z > -0.05$. Below that, we approximate the height of the surface as that of ocean, which covers around 70% of the total surface of the Earth. The error of this approximation is estimated $\lesssim$ 1% from the figures 4 and 5.

Note, at the discovery era of the neutrino oscillations, the depth correlation of phenomena was sometimes discussed [5]. As the deep detectors were actually sited under high mountains, the mountains might be partly responsible to the results of the deep neutrino detectors.

Statistical error

A Monte Carlo study is always accompanied with the statistical errors. After the publication of Ref. [2], we have increased the statistics and now the statistical error is smaller than 1.26% at all the energies and all the zenith directions below 1 TeV for the azimuth averaged flux. The statistical error reaches 1.26% for $\bar{\nu}_e$ at 22.4 GeV for horizontal direction, and we switch the calculation scheme from 3D to 1D at this energy.

The statistics of the Monte Carlo study in 3D scheme may be just enough for present atmospheric neutrino experiment. When we need the azimuth variation of the atmospheric neutrino flux, however, the statistical error is increased by the division of the events into many azimuth angle bins. We need more statistics in the 3D calculations to understand the azimuth angle variation of atmospheric neutrino flux.

Conclusions

In this paper, we invited attention to the variation of the atmospheric neutrino flux due to the solar activity and the landscape near the detector. The variations are smaller than the uncertainty due to the hadronic interaction model, but are not allowed to ignore in the present atmospheric neutrino experiments. We stress again that a rough treatment of these effects may result in ~10% error in the prediction of atmospheric neutrino flux.

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