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The Reliability on the Direction of the Incident Neutrino for Fully Contained Events and Partially Contained Events due to QEL in the Super-Kamiokande

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Abstract: Quasi Elastic Scattering is the dominant mechanism for producing both Fully Contained Events and Partially Contained Events for the examination of the neutrino oscillation in the Super-Kasmiokande(SK) detector for the atmospheric neutrinos in the range several hundreds MeV to several GeV. In the analysis of these neutrino events, SK collaboration assume that the direction of the incident neutrino is as same as that of the emitted lepton. We examine the validity of the SK assumption in detail.

Introduction

The neutrino event detected in the Super-Kamiokande collaboration – hereafter simply SK –is classified into two categories. One is the neutrino event which occurs inside the detector and the other is the neutrino event which occurs outside the detector. The former is further classified into *the Fully Contained Event(FC event)* and *the Partially Contained Events*. Similarly, the latter is classified into *the Stopping Muon Events* and *the Upward Through Going Muon Events*. As far as the qualities as the experimental data are concerned, the former event is of higher qualities than that in the latter. Also, as far as the determination for the direction of the incident neutrino is concerned, the qualities on this problem are lower in the former than that in the latter.

As for the accuracy on the information obtained from the experimental data concerned, *Fully Contained Event* is excellent among the four types of the events mentioned above. From the view point of the SK to *the Fully Contained Events*, they claim they could determine the type of the incident neutrino (electron neutrino and the muon neutrino), the direction of the incident neutrino and the energy of the event concerned.

However, there are two ”cornerstones” in the interpretation toward the neutrino events detected inside the SK detector, without which the interpretation itself might lose its based point. The one is the excellent discrimination between electron neutrino and muon neutrino. The other is the reliable determination for the direction of the incident neutrino. As for one ”cornerstone” among two ”cornerstones” in the SK, we have skeptical opinion on the excellent discrimination between muon neutrino and electron neutrino by SK[1].

In the present paper, we examine the second ”cornerstone”, i.e. the reliability on the direction of the incident neutrino for *the Fully Contained Events*.

The assumption on the direction of the neutrino events occurring inside the detector

SK assume the direction of the incident neutrino is as same as that of emitted lepton(s).

In order to avoid any misunderstanding toward *the SK assumption on the direction* we reproduce this assumption from the original SK paper in italic:
"*However, the direction of the neutrino must be estimated from the reconstructed direction of the products of the neutrino interaction. In water Cherenkov detectors, the direction of an observed lepton is assumed to be the direction of the neutrino. Fig.11 and Fig.12 show the estimated correlation angle between neutrinos and leptons as a function of lepton momentum. At energies below 400 MeV/c, the lepton direction has little correlation with the neutrino direction. The correlation angle becomes smaller with increasing lepton momentum. Therefore, the zenith angle dependence of the flux as a consequence of neutrino oscillation is largely washed out below 400 MeV/c lepton momentum. With increasing momentum, the effect can be seen more clearly.* " [2]

Also, Ishitsuka states in his Ph.D thesis which is exclusively devoted into the L/E analysis of the atmospheric neutrino from Super Kamiokande as follows:

" *8.4 Reconstruction of L_ν*

Flight length of neutrino is determined from the neutrino incident zenith angle, although the energy and the flavor are also involved. First, the direction of neutrino is estimated for each sample by a different way. Then, the neutrino flight lenght is calclulated from the zenith angle of the reconstructed direction.

8.4.1 Reconstruction of Neutrino Direction

FC Single-ring Sample

The direction of neutrino for FC single-ring sample is simply assumed to be the same as the reconstructed direction of muon. Zenith angle of neutrino is reconstructed as follows:

$$\cos\Theta_\nu^{rec} = \cos\Theta_\mu, \qquad (8.17)$$

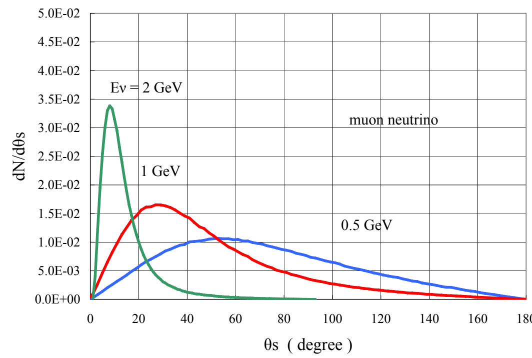

Figure 1: Distribution functions for the scattering angle of the muon for muon-neutrino with incident energies, 0.5 GeV, 1.0 GeV and 2 GeV. Each curve is obtained by the Monte Carlo method (one million sampling per each curve).

where $\cos\Theta_\nu^{rec}$ *and* $\cos\Theta_\mu$ *are cosine of the reconstructed zenith angle of muon and neutrino, respectively.* " [3]

The Fully Contained single ring events in SK are obtained from the following elementary processes in quasi-elastic scattering(QEL) process :

$$\nu_e + n \longrightarrow p + e^-$$
$$\nu_\mu + n \longrightarrow p + \mu^-$$
$$\bar{\nu}_e + p \longrightarrow n + e^+$$
$$\bar{\nu}_\mu + p \longrightarrow n + \mu^+$$

The corresponding differential cross sections for QEL are given in [4]. By the differential cross sections, we obtain the distribution functions for scattering angle of muon from muon-neutrino in Figure 1.

From Figure 1, it seems to be clear that *the SK assumption on the direction* does not hold, taking into account the situation that energies contributed to the neutrino events concerned cover from several hundred MeV to about 10 GeV. Now, we examine this assumption in detail.

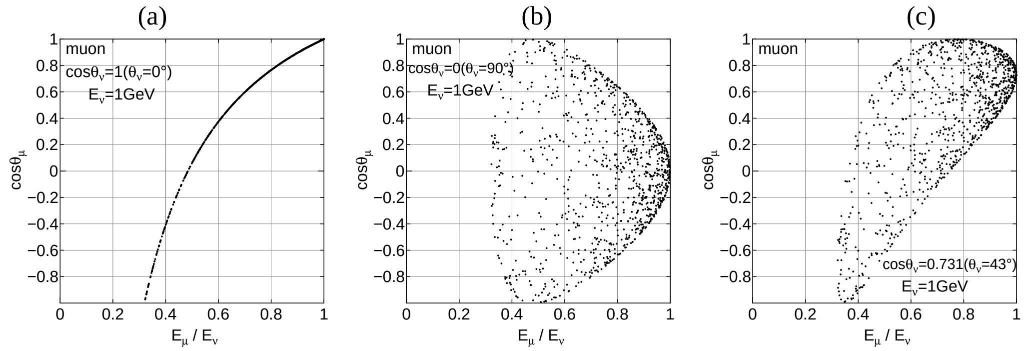

Figure 2: The scatter plots between the fractional energies of the produced muons and their zenith angles for vertically, horizontally and diagonally incident muon neutrinos with 1 GeV, respectively. The sampling number is 1000 for each case.

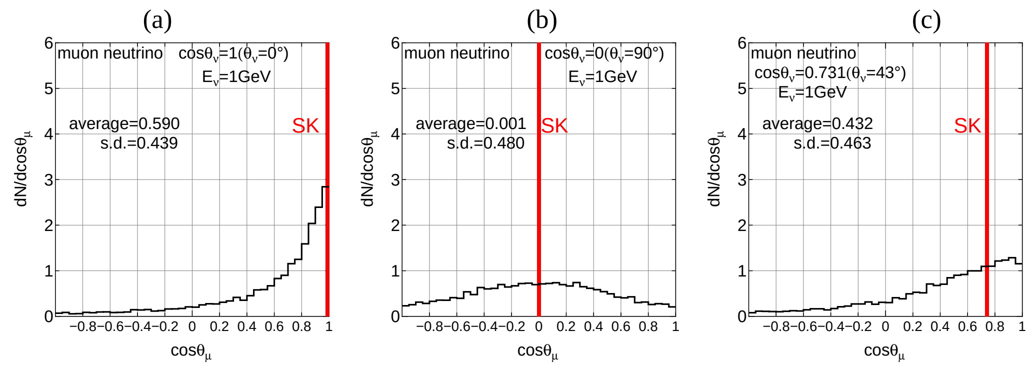

Figure 3: Zenith angle distribution of the muon for the vertically, horizontally and diagonally incident muon neutrino with 1 GeV respectively. The sampling number is 10000 for each case. SK stand for the corresponding ones under the SK assumption.

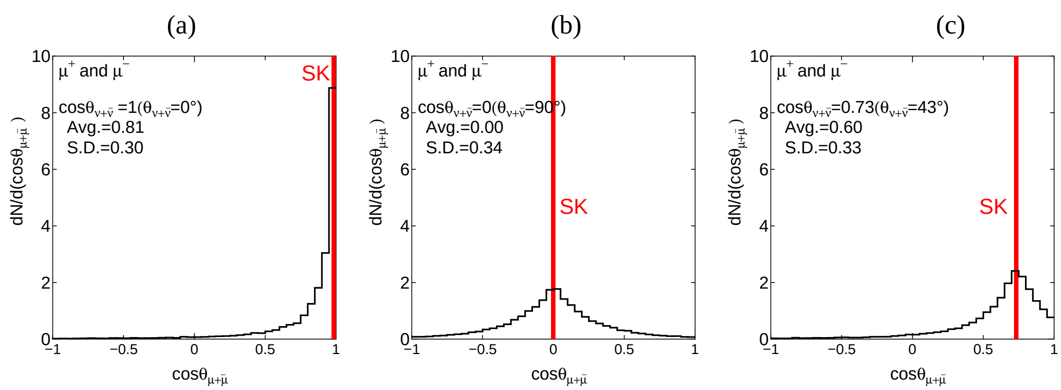

Figure 4: Zenith angle distribution of μ^- and μ^+ for ν and $\bar{\nu}$ for the incident neutrinos with the vertical, horizontal and diagonal directions, respectively. The overall neutrino spectrum at Kamioka site is taken into account. The sampling number is 10000 for each case. SK stand for the corresponding ones under the SK assumption.

Simulation procedures for the examination on the *SK assumption on the direction*

The effect of the azimuthal angle over the zenith angle

When we could not neglect the scattering angle of the emitted lepton, we must consider the effect of the azimuthal angle over the zenith angle of emitted muons for definite zenith angles of the incident neutrinos. Then we obtain the scatter plots between the fractional energies of the produced muons and their zenith angles with 1 GeV for the different zenith angles of the incident neutrino by the exact Monte Carlo method. In Figures 2(a), (b) and (c) , we give the scatter plots for the incident neutrinos with $\cos\theta_\nu$=1.0, 0 and 0.731. It is clear from these figures that we could not neglect the effect of the azimuthal angles of the emitted muons over their zenith angles, paticularly for smaller zenith angles of the incident neutrinos. If we sum up muon's energies for definite $\cos\theta_\nu$, then we obtain Figures 3(a), (b) and (c). These figures denote zenith angle distributions for the emitted muons for definite $\cos\theta_\nu$ and definite incident neutrino energy. In the figures, [SK] lines denote *SK assumption on the direction*. It is clear from the figures that *SK assumption on the direction* does not hold. In Figures 4(a), (b) and (c), we give the zenith angle distributions of the emitted muons (μ^- and μ^+) after sampling of the incident neutrinos which obey incident neutrino energy spectrum (ν and $\bar{\nu}$) for different $\cos\theta_{\nu(\bar{\nu})}$. Also [SK] lines in the figures denote *SK assumption on the direction* and it does not hold again.

The correlation between $\cos\theta_\nu$ and $\cos\theta_\mu$

Now, we sample $\cos\theta_\nu$ from our Computer Numerical Experiment. For such sampled $\cos\theta_{\nu(\bar{\nu})}$, we obtain the similar zenith angle distribution as in Figures 4(a), (b) and (c). Finally, we obtain the correlation between $\cos\theta_\nu$ and $\cos\theta_\mu$, which is shown in Figure 5. It is clear from the figure that *SK assumption on the direction* hold at $\mathrm{E}_\nu > 5\mathrm{GeV}$, but it does not hold at all at $\mathrm{E}_\nu < 5\mathrm{GeV}$ where almost SK experimental data are concentrated.

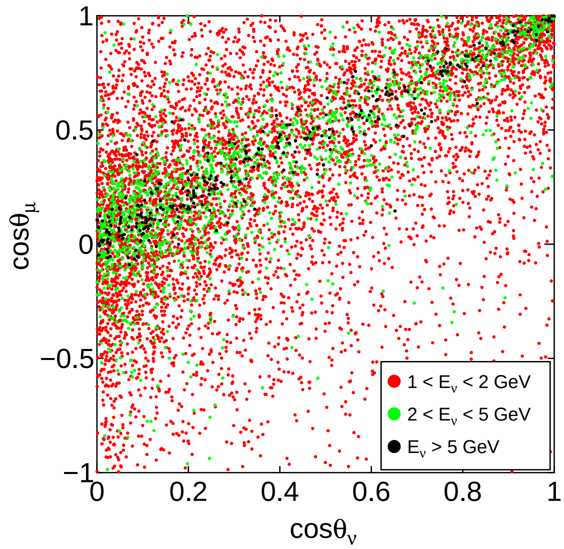

Figure 5: Correlation diagram between $\cos\theta_\nu$ and $\cos\theta_\mu$ for different neutrino energy regions.

Conclusion

The *SK assumption on the direction* of $\cos\theta_\nu$= $\cos\theta_\mu$ is just the cornerstone without which SK could not build up. It should be emphasized that *SK assumption on the direction* does not hold, even if statistically.

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