

Can One Extract the Neutrino Oscillation Signature from the SuperKamiokande Experiment ?

An Analysis of Neutrino Events Occurring outside the Detector

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The SuperKamiokande group assert that they have found an oscillatory signature in atmospheric neutrinos through the analysis of *Fully Contained Events* and *Partially Contained Events*. We have performed an L/E (length/energy) analysis of *Upward Through-Going Muon Events* and *Stopping Muon Events* in a numerical computer simulations both with and without neutrino oscillations but were unable to find an oscillatory signature. We give likely explanations for the absence of the oscillatory signature in our simulations and its apparent presence in the SuperKamiokande data.

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The SuperKamiokande group (hereafter SK) have reported the presence of an oscillatory signature in atmospheric neutrino data through an L/E_ν analysis of neutrino events occurring inside the detector, using *Fully Contained Events* and *Partially Contained Events* with energies ranging from several hundred MeV to several GeV [1]. Recently, it has become recognized that the scattering angle of the emitted lepton greatly influences the estimation of the direction of the incident neutrino, which is directly connected with the determination of L in the energy region of several hundred MeV to several GeV [2]. In the SK analysis, it is necessary for L to be decided more accurately, because the oscillatory signature is strongly sensitive to L/E_ν .

For the L/E_ν analysis in the SK experiment, it is more appropriate to analyze neutrino events occurring outside the detector, such as *Upward Through-Going Muon Events* and *Stopping Muon Events* whose energies range from several GeV to several hundreds of GeV, because the scattering angle of the emitted lepton in the neutrino reactions can be neglected at such higher energies and consequently the direction of the emitted muon can be approximated as that of the neutrino events, which results in higher accuracy in the determination of L . In this paper, we report the result of an analysis for an oscillatory signature in *Upward Through-Going Muon Events* and *Upward Stopping Muon Events* in a virtual SuperKamiokande experiment by numerical computer simulations. The particles which produce such events are regarded exclusively as muons (or muon neutrinos) due to their long flight length compared to the cascade shower initiated by electrons (or electron neutrinos).

In both the present analysis of the neutrino events and

that of SK, a careful examination on the validity of the technique for the Monte Carlo Method utilized is vital, and we therefore start by explaining the procedures of the Monte Carlo Method we utilize in the present report. Our simulation can be regarded as a *Time Sequential Simulation*, while the SK groups is a *Detector Simulation*.

We start our simulation, which is schematically shown in Figure 1, with the atmospheric neutrino energy spectrum at the opposite side of the Earth to the detector. We utilize Honda's spectrum [3] as the incident atmospheric neutrino energy spectrum. We adopt a maximum energy of 1000 GeV, and therefore the maximum energy of the muon emitted from the neutrino interaction, here, is 1000 GeV. We calculate the range fluctuation of 1000 GeV muons by the exact Monte Carlo method, taking into the physical processes concerned — bremsstrahlung, direct pair production, nuclear interaction and ionization loss — and show the result in Figure 2.

We conclude from Figure 2 that it is sufficient to consider the neutrino events for *Upward Through-Going Muon Events* and *Stopping Muon Events*, which are generated in the region within 400000 g/cm² of the SK detector (less than 2000 meters), because neutrino interactions further than 2000 m from the detector could not contribute physical events into the detector.

Then, we define $N_{int}(E_\nu, t, \cos\theta_\nu)dt$, the interaction neutrino energy spectrum at depth t from the detector underground for the incident neutrino with energy E_ν from the zenith angle θ_ν , in the following.

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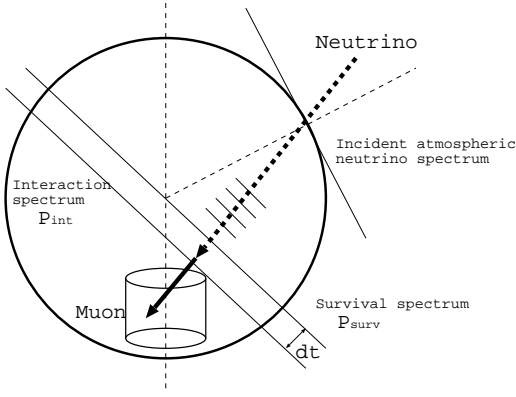


FIG. 1: Schematic illustration of the experiment.

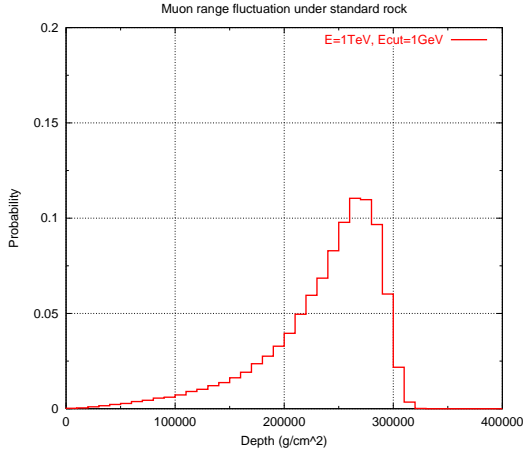


FIG. 2: Range Energy Fluctuation of 1000 GeV muons.

$$\begin{aligned}
 N_{int}(E_\nu, t, \cos\theta_\nu)dt &= N_{sp}(E_\nu, \cos\theta_\nu) \times \\
 &\left(1 - \frac{dt}{\Lambda_1(E_\nu, t_1, \rho_1)}\right) \times \left(1 - \frac{dt}{\Lambda_2(E_\nu, t_2, \rho_2)}\right) \times \dots \\
 &\dots \times \left(1 - \frac{dt}{\Lambda_{n-1}(E_\nu, t_{n-1}, \rho_{n-1})}\right) \times \left(\frac{dt}{\Lambda_n(E_\nu, t_n, \rho_n)}\right)
 \end{aligned} \quad (1)$$

Here, $\Lambda_i(E_\nu, t_i, \rho_i)$ is given by

$$\frac{1}{\Lambda_i(E_\nu, t_i, \rho_i)} = \frac{1}{\lambda_i(E_\nu, t_i, \rho_i)} + \frac{1}{\lambda_i(E_{\bar{\nu}}, t_i, \rho_i)}$$

where $\lambda_i(E_\nu, t_i, \rho_i)$ denotes the mean free path of the neutrino with energy E_ν at the distance t_i from the opposite surface of the Earth whose density is ρ_i and $\lambda_i(E_{\bar{\nu}}, t_i, \rho_i)$ denotes the corresponding mean free path of the anti-neutrino whose energy is given by $E_{\bar{\nu}}$. These mean free paths are calculated from the deep inelastic scattering cross sections [4]. The density of the Earth is adopted from the Preliminary Earth Model for the density profile [5].

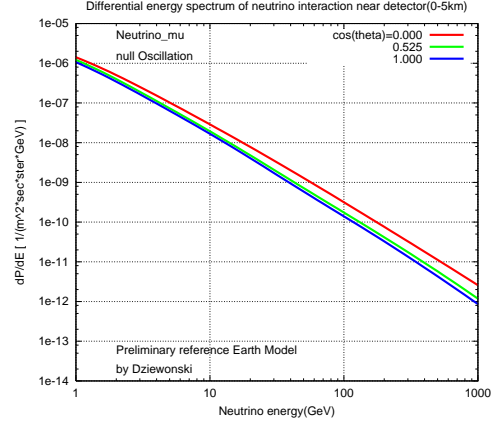


FIG. 3: Interaction energy spectrum without neutrino oscillation.

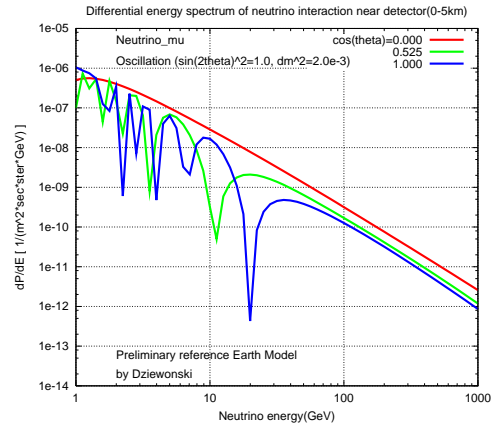


FIG. 4: Interaction energy spectrum with neutrino oscillation.

The distribution functions for L/E_ν , obtained using Eq.(1), are given in Eq.(2) and Eq.(3) in the cases without neutrino oscillation and with neutrino oscillation, respectively.

$$\begin{aligned}
 N_\nu^{null-osc} \left(\frac{L}{E_\nu}, \cos\theta_\nu \right) d \left(\frac{L}{E_\nu} \right) \\
 = N_\nu(E_\nu, L, \cos\theta_\nu) d \left(\frac{L}{E_\nu} \right)
 \end{aligned} \quad (2)$$

$$\begin{aligned}
 N_\nu^{osc} \left(\frac{L}{E_\nu}, \cos\theta_\nu \right) d \left(\frac{L}{E_\nu} \right) \\
 = N_\nu(E_\nu, L, \cos\theta_\nu) P(\nu_\mu \rightarrow \nu_\mu) d \left(\frac{L}{E_\nu} \right)
 \end{aligned} \quad (3)$$

where $P(\nu_\mu \rightarrow \nu_\mu)$ denotes the survival probability for a neutrino in the presence of neutrino oscillations, which is given as

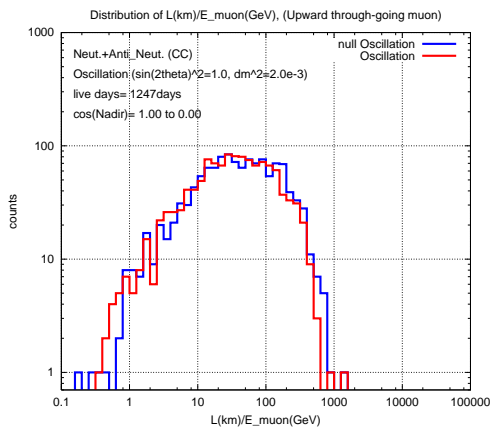


FIG. 5: Distribution of L/E_μ for *Upward Through-Going Muon Events*.

$$P(\nu_\mu \longrightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 (eV^2) L (km)}{E_\nu (GeV)} \right) \quad (4)$$

Here, we adopt $\sin^2 2\theta = 1.00$ and $\Delta m^2 = 2 \times 10^{-3} eV^2$, as obtained from the SK experiment.

In Figures 3 and 4, we give the interaction neutrino energy spectrum without, and with, neutrino oscillations as defined by Eq.(2) and Eq.(3), respectively. It is clear from Figure 4 that the effect of the neutrino oscillation for the SK parameters does not appear in the horizontal direction, $\cos\theta_\nu = 0.0$, due to short path length for the traversed neutrino while the effect clearly appears the vertical case, $\cos\theta_\nu = 1.0$

For *Upward Through-Going Muon Events* and *Stopping Muon Events*, we can assume that the direction of the incident neutrino is the same as that of the emitted muon, because the scattering angle of the emitted muon can be neglected due to its high energy. The simulation procedures for the events concerned for a given zenith angle of the incident neutrinos are as follows.

Procedure A: Using ξ , a uniform random number between 0 and 1, we sample $E_{\nu(\bar{\nu})}$, the energy of the incident (anti-)neutrino, which is obtained from the following equation:

$$\xi = \frac{\int_{E_{\nu, min}}^{E_\nu} N_{int}(E_\nu, t, \cos\theta_\nu) dt}{\int_{E_{\nu, min}}^{E_{\nu, max}} N_{int}(E_\nu, t, \cos\theta_\nu) dt} \quad (5)$$

Procedure B: For $E_{\nu(\bar{\nu})}$, the energy of the (anti-)neutrino obtained by Procedure A, we define

$$\xi_1 = \frac{\sigma(E_\nu)}{\sigma(E_\nu) + \sigma(E_{\bar{\nu}})}$$

where $\sigma(E_\nu)$ and $\sigma(E_{\bar{\nu}})$ denote the total cross-section of the neutrino and the anti-neutrino, respectively. Then

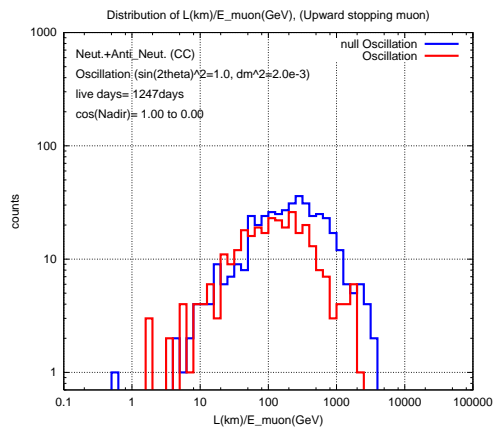


FIG. 6: Distribution of L/E_μ for *Upward Stopping Muon Events*.

we sample the random number ξ again and if $\xi \leq \xi_1$ we take the incident lepton to be a neutrino, otherwise we take it to be an anti-neutrino.

Procedure C: We decide the interaction point of the (anti-)neutrino event determined by Procedure B in the range (0, 2000) meters. This is the distance from the detector to the interaction point and is obtained simply by sampling a uniform random number between (0,1) as this range is many orders of magnitude smaller than the mean free path of the neutrino concerned.

Procedure D: We sample E_μ , the energy of the (anti-)muon emitted for the deep inelastic scattering by using the uniform random number between (0,1), which is logically same as in Eq.(5).

Procedure E: For the (anti-)muon whose energy and production point is determined from Procedures C and D, we examine the behavior of the trajectory of the (anti-)muon toward the SK detector in a stochastic manner. Namely, each individual muon is pursued by taking into consideration bremsstrahlung, direct pair production, nuclear interaction, and ionization loss without utilizing the average behavior of the muon concerned. As the result, we determine which category each individual muons falls into: [a] stopping before it reaches the detector, [b] stopping inside detector, or [c] passing through the detector.

We repeat Procedures A to E and obtain the neutrino events concerned for a given live time for the real experiment. In our computer numerical simulation, we have accumulated the events concerned which correspond to the real live time for SK. For each neutrino event, we know E_ν , the energy of the parent neutrino, E_μ , the energy of the daughter (anti-)muon, $\cos\theta_\nu$ ($\cos\theta_\mu$), the direction of both the incident (anti-)neutrino and the emitted (anti-)muon, and L , the distance between the interaction point of the neutrino events and the opposite side of the Earth.

As only E_μ can be measured in the actual SK experiment, and not E_ν , we give the frequency of the number of the events as a function of L/E_μ for *Upward Through-*

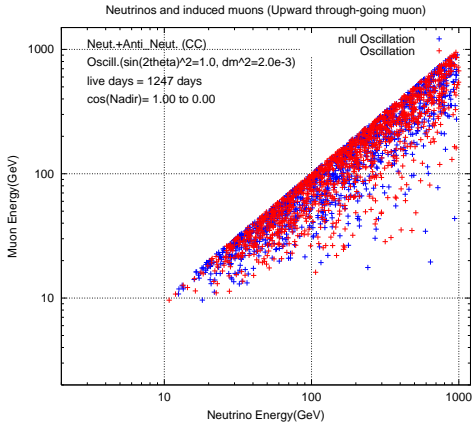


FIG. 7: E_ν vs E_μ scatter plot for *Upward Through-Going Muon Events*.

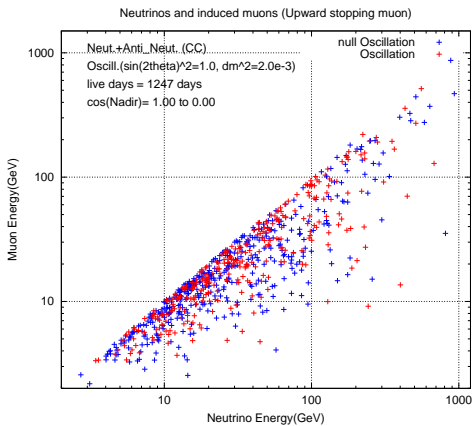


FIG. 8: E_ν vs E_μ scatter plot for *Upward Stopping Muon Events*.

Going Muon in Figure 5 and the corresponding quantity for *Stopping Muon Events* in Figure 6 in both the cases without and with neutrino oscillations. It is clear from those figures that no oscillatory signature is apparent, with almost no difference between the cases with and without oscillation when plotted against the measured SK parameter. Of course, according to the logic adopted by SK, the oscillatory signature should appear in the function of L/E_ν , not L/E_μ .

The energy of the emitted lepton for a given energy of the neutrino is generated in the deep elastic scattering, producing a wider energy distribution. In Figures 7 and 8, we give the scatter plots between E_ν and E_μ for *Upward Through-Going Muon Events* and *Stopping Muon Events*, respectively. It is clear from the figures that the fluctuations in the energy distributions are not small. The density of points in the figures is proportional to the numbers of events.

In Figures 9 and 10, we give the corresponding distributions for L/E_ν to Figures 5 and 6 for L/E_μ . From the comparison of Figures 5 and 6 with Figures 9 and 10,

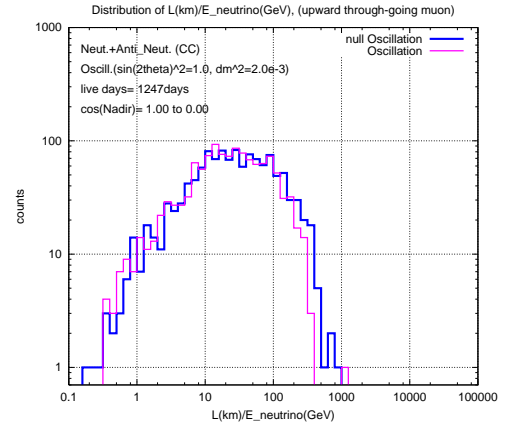


FIG. 9: Distribution of L/E_ν for *Upward Through-Going Muon Events*.

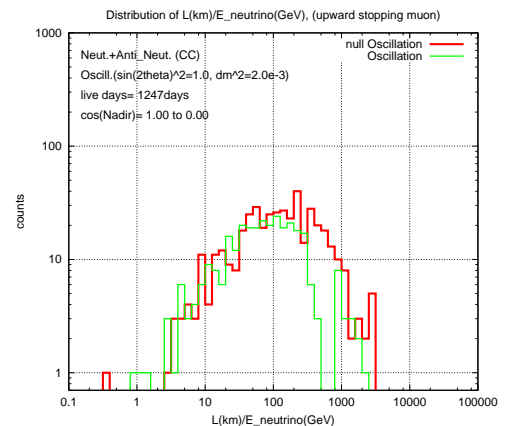


FIG. 10: Distribution of L/E_ν for *Upward Stopping Muon Events*.

it can be concluded that oscillatory signatures are not observed in both L/E_ν and L/E_μ distributions. Also, there are only small differences between the L/E distributions with and without neutrino distribution, as seen in Figures 5 and 6 and in Figures 9 and 10, which is consistent with our previous conclusion that there is no evidence for neutrino oscillation through the analysis of the zenith angle distribution for *Upward Through-Going Muon Events* and *Stopping Muon Events* [6].

In Figures 11 and 12, we give the ratios of “with oscillation” to “without oscillation” as the function of L/E_ν for *Upward Through-Going Muon Events* and *Stopping Muon Events*, respectively. Generally, the fact that fluctuations are rather larger comes from relatively small number of events, and further, the fluctuations are larger in *Upward Stopping Muon Events* than in *Upward Through-Going Muon Events*, as they must be. In Figures 13 and 14, we give the corresponding quantities for L/E_μ . Comparing Figures 11 and 12 with Figures 13 and 14, the fluctuations are larger in the latter than in the former, which is easily understandable when consid-

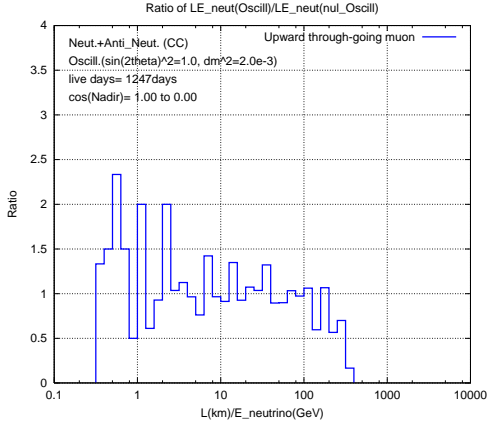


FIG. 11: The ratio of “oscillation” to “null oscillation” of L/E_ν distribution for *Upward Through-Going Muon Events*.

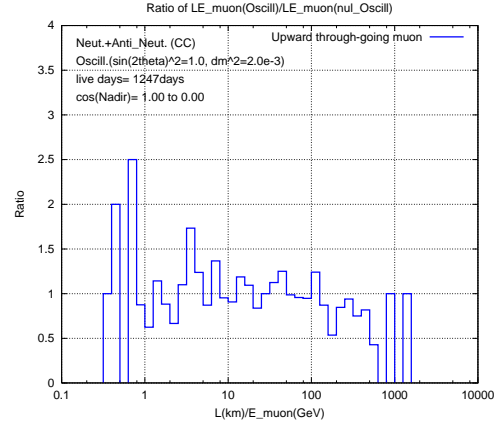


FIG. 13: The ratio of “oscillation” to “null oscillation” of L/E_μ distribution for *Upward Through-Going Muon Events*.

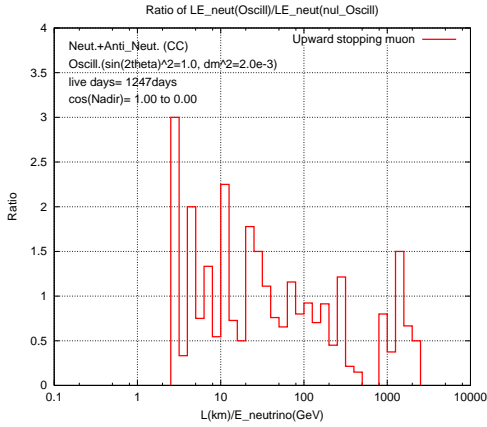


FIG. 12: The ratio of “oscillation” to “null oscillation” of L/E_ν distribution for *Upward Stopping Muon Events*.

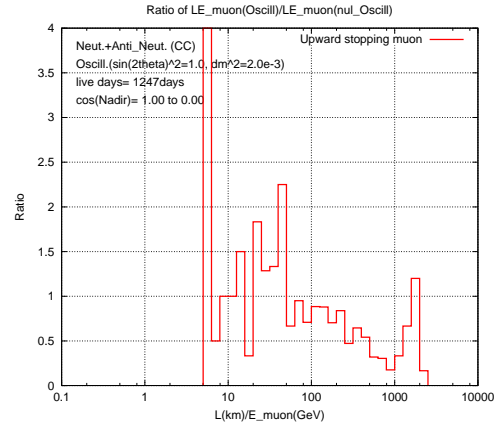


FIG. 14: The ratio of “oscillation” to “null oscillation” of L/E_μ distribution for *Upward Stopping Muon Events*.

ering the energy distribution of E_μ for a definite E_ν . It is clear from these figures that it is exceedingly difficult to extract some positive evidence for neutrino oscillations. In Figures 15 and 16, we give scatter plots between L and E_ν with and without neutrino oscillation for *Upward Through-Going Muon Events* and *Stopping Muon Events*, respectively. Also, we give the corresponding plots between L and E_μ in Figures 17 and 18.

Here, we comment on the evidence for an oscillatory signature claimed by SK. In our opinion, it is practically impossible to observe such an oscillatory signature in atmospheric neutrino oscillation for the following reasons:

(i) The L/E distribution for the muon events occurring inside the detector in the SK experiment, $N(L/E_\nu)d(L/E_\nu)$ is given as,

$$N\left(\frac{L}{E_\nu}\right)d\left(\frac{L}{E_\nu}\right) = d\left(\frac{L}{E_\nu}\right) \int d\cos\theta_\nu D_{nsp}(E_\nu, \cos\theta_\nu, L(\cos\theta_\nu)) \times P(\nu_\mu \rightarrow \nu_\mu) \int_{E_{\mu,min}}^{E_{\mu,max}} \sigma_{\nu \rightarrow \mu}(E_\nu, E_\mu) dE_\mu \quad (6)$$

where $D_{nsp}(E_\nu, \cos\theta_\nu, L(\cos\theta_\nu))$ is the differential neutrino incident energy spectrum at the given zenith angle, θ_ν , and L , which is also the function of $\cos\theta_\nu$. $P(\nu_\mu \rightarrow \nu_\mu)$ denotes the probability function for the neutrino oscillation and $\sigma_{\nu \rightarrow \mu}(E_\nu, E_\mu)dE_\mu$ denotes the differential cross-section for the incident neutrino to produce the emitted muon inside the detector. The character of an oscillatory signature obtained by SK comes exclusively from the part of $P(\nu_\mu \rightarrow \nu_\mu)$ in Eq.(6). However, $P(\nu_\mu \rightarrow \nu_\mu)$ in Eq.(6) is imbedded into the steep neutrino energy spectra like that shown in Figure 4 and is itself a continuously and strongly varying function with

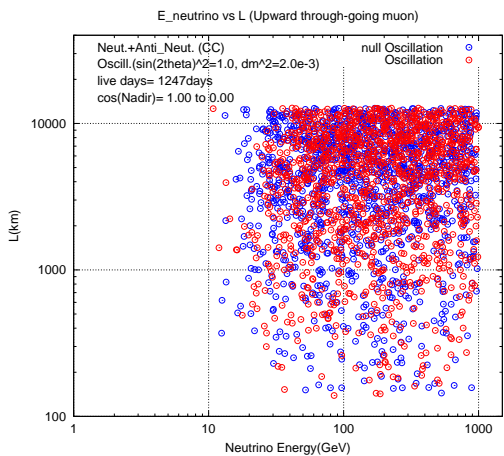


FIG. 15: L vs E_ν scatter plot for *Upward Through-Going Muon Events*.

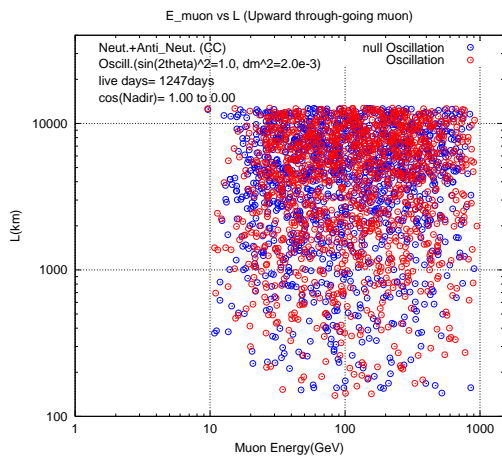


FIG. 17: L vs E_μ scatter plot for *Upward Through-Going Muon Events*.

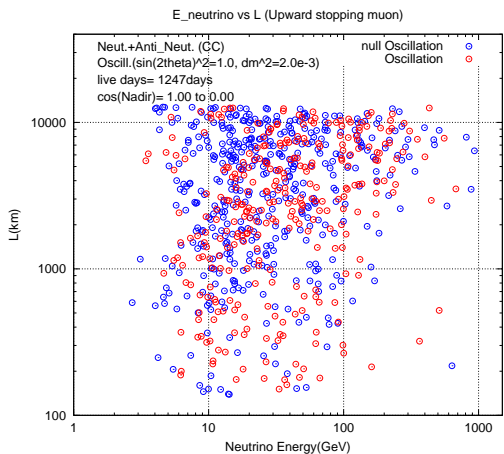


FIG. 16: L vs E_ν scatter plot for *Upward Stopping Muon Events*.

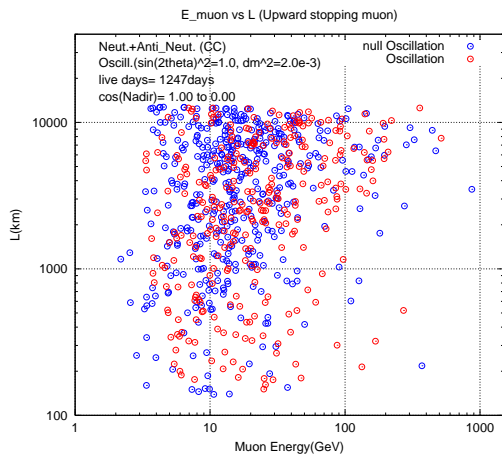


FIG. 18: L vs E_μ scatter plot for *Upward Stopping Muon Events*.

L . As a result, it can not be separated from the neutrino energy spectrum.

(ii) The SK Detector Simulation assumes that the direction of the incident neutrino is the same as that of the emitted lepton [7,8]. Thus, SK could treat neither the effect of the azimuthal angle of the emitted lepton nor the effect of the backscattering over the zenith angle of the emitted lepton and consequently could not determine L reliably, which is directly connected with $N(L/E_\nu)d(L/E_\nu)$. More concretely, under the combination of the two fundamental parameters in the neutrino oscillation derived by SK, about 40% of the upward going muons originate from downward going neutrinos, while about 10% of the downward going muons originate from upward going neutrinos [9]. Such mutual mixing in the direction of the incident neutrinos may be maximized near $L/E_\nu = 150 \sim 500$ (km/GeV), where one find the dip-like phenomena of the $N(L/E_\nu)d(L/E_\nu)$ in Figure 3 in the SK paper [1]. If we determine the direction of the incident neutrino correctly, then the dip will disap-

pear and $N(L/E_\nu)d(L/E_\nu)$ will show the something like behavior given in Figures 9 and 10. Our subsequent paper on the L/E analysis for *Fully Contained Events* and *Partially Contained Events* will be published elsewhere.

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