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The Energy Determination for the High Energy Muon in the Large Volume Detector for High Energy Astrophysics

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Abstract: This paper is a preliminary study for seeking the reliable method in future by which we could determine the direction of the high energy muon accurately. As the high energy muons are inevitably accompanied by the aggregation of electron showers, we need detailed knowledge on the three-dimensional cascade showers for the reliable determination for the direction of the high energy muon neutrino events.

Introduction

There are two fundamental parameters which play essential roles in the analysis of high energy neutrino astrophysics experiment, such as, NT200+, AMANDA, ANTARES,NESTOR and ICE CUBE and others, the scale of which may exceed over 1kilometer in future. One is the energy of the neutrino event concerned and the other is its direction. For the moment, electron neutrino events and muon neutrino events are the usual candidates to be carefully examined. Both electron neutrino events and muon neutrino events have advantages and disadvantages in their analysis. Electron neutrino events are regarded as *Fully Contained Events* up to 10^{20} eV even in the presence of the LPM effect [1] but it is rather difficult to determine their direction without detailed understanding the three-dimensional structure of the electron showers. On the other hand, the muon neutrino events are regarded as the *Partially Contained Events* exclusively at 5×10^9 eV even in 1 cubic kilometer detectors due to their longer paths of high energy muons, but one claims to determine their direction reliably, utilizing their long path. However, it is not so easy task to determine the directions of muon neutrino events reliably in higer energies, even if one could utilize their longer paths, because of their complicated stochastic structure due to accompanied electron showers. In the present paper, we examine the uncertainty in the behaviors of higher energy muons which are produced by the muon neutrino events

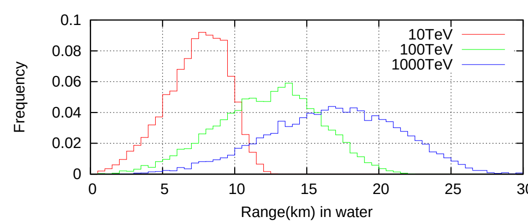

Figure 1: Range fluctuation of muon with 1TeV to 1000TeV

Range Straggling of High Energy Muons and the Cherenkov light from the original plus the accompanied electron showers

The behaviors of high energy muons are influenced by the fluctuation effects in their energy losses which come from bremsstrahlung, direct electron

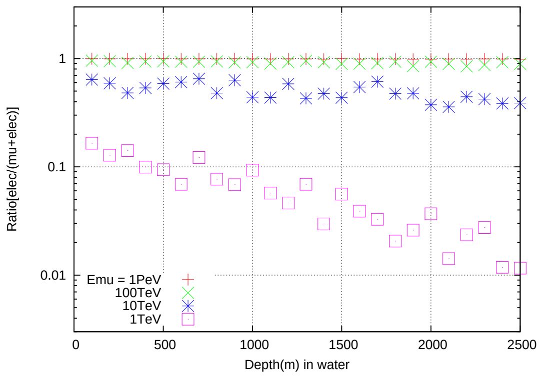

Figure 2: The transition curves for the integral of the track lengths from muon. Sampling number is 100.

pair production and nuclear interaction due to the muon.

In Figures 1, we give the range fluctuation of muons with different primary energies. As seen in the figure, we find stronger fluctuation in the track lengths of muons as increase of their primary energy. It should be noticed that the muons which have shorter range smaller than their average ranges may be influenced by catastrophic energy loss due to either bremsstrahlung or nuclear interaction.

As track lengths of the muons are proportional to total Cherenkov light due to muons themselves. However, total energies of the original muons are determined from the measurement of the summation of the Cherenkov light due to muons themselves and total Cherenkov light from accompanied electron showers which muons concerned produce. It is,however, impossible to separate the Cherenkov light due to muons themselves from the corresponding ones due to all electron showers produced by muons concerned. Therefore, it seems rather difficult to determine the direction of the high energy muon reliably, if we have not enough information for the three-dimensional structure on the electron shower.

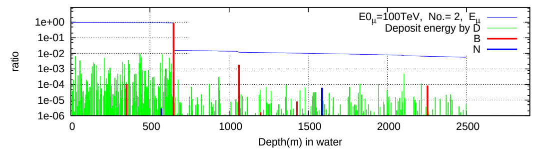

Figure 3: The exactly simulated behavior of energy losses by accompanied electron showers for 100 TeV muon. D means due to direct electron pair production, B, bremstrahlung,and N,nuclear interaction

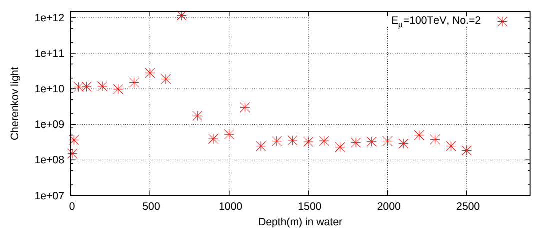

Figure 4: The exactly simulated transition curve for the Cherenkov light for a muon with 100 TeV which just correspond to Figure 3.

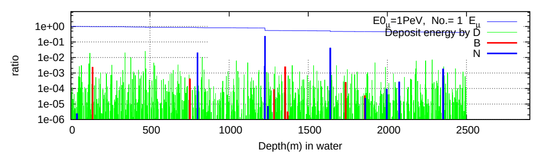

Figure 5: The exactly simulated behavior of energy losses by accompanied electron showers for 1 PeV muon. D means due to direct electron pair production, B, bremstrahlung,and N,nuclear interaction

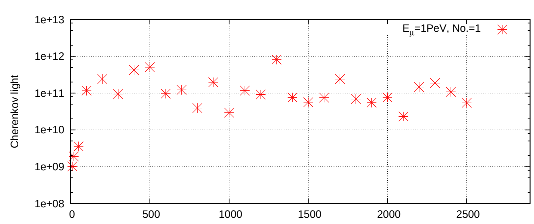

Figure 6: The exactly simulated transition curve for the Cherenkov light for a muon with 1 PeV which just correspond to Figure 5.

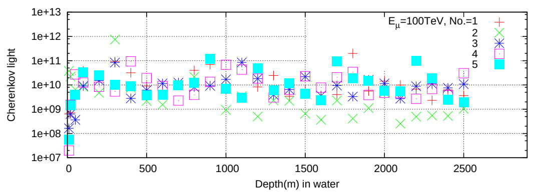

Figure 7: Five examples of transition curves for the Cherenkov light by muons with 100 TeV

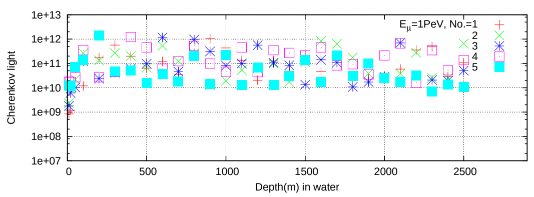

Figure 8: Five examples of transition curves for the Cherenkov light by muons with 1 PeV

Fluctuations on various quantities produced by high energy muons

As the energy of the muon due to muon neutrino event increases, a number of electron showers due to direct electron pair production, bremstrahlung and nuclear interaction are generated twining around the muon which is also the possible origin of the Cherenkov light. Thus, high energy muons travel through the detector , being surrounded with " electron cloud" (accompanied electron showers due to the muons) so that the muon with such characteristics produces the Cherenkov light totally. In Figure 2, the ratios of the track length due to accompanied electron showers to the sum of the track lengths due to both the muon and the electron showers are given as the function of the distance traversed by the muon. It is understood from the figure that the muons with 1TeV radiate Cherenkov light exclusively by themselves , the muons with 10 Tev radiate 80 % of the total Cherenkov light by their accompanied electron showers and muons with 100 TeV radiate almost the total Cherenkov light by their accompanied electron showers, not by the muons themselves.

In the traverse of the muons, we simulate where and what kinds of interaction (direct electron pair production, beremstrahlung and nuclear interaction) with certain emitted energies occur exactly. In Figure 3, we give one example of the emitted energies by a muon with 100 TeV as the function of the interaction points and kinds of the interaction. It should be noticed from the figure that the most accompanied electron showers comes from the direct electron pair production with smaller energies and the catastrophic energy losses of the muon is attributed to the bremstrahlung in this case. The electron showers thus produced radiate Cherenkov light. In Figure 4, we give the transition curve for the Cherenkov light which corresponds to Figure 3. We give an another example in Figures 5 and 6 in the case of 1 PeV muon. In this example, we could see non-negligible energy loss is caused by nuclear interaction. In Figure 7, we give the transition curves for Cherenkov light for 5 sampled muons with 100 TeV. In Figure 8, we give an another example in the case of 1 PeV muons. It should be noticed from Figure 7 and 8 that there are large varieties of the Cherenkov light production given by the muons with the same energies. Now, we assume the production spectrum of the muon for 10 TeV to 1 PeV in the following.

$$N(E_\mu)dE_\mu \propto E_\mu^{(r+1)}dE_\mu \quad (1)$$

, where we examine the cases with $\gamma = 1, 2, 3$. We sampled the muon energy from the Eq.(1) and the sampled results is given in Figure 9 which shows the validity of the sampling. In high energy neutrino astrophysics experiments in water, we esti-

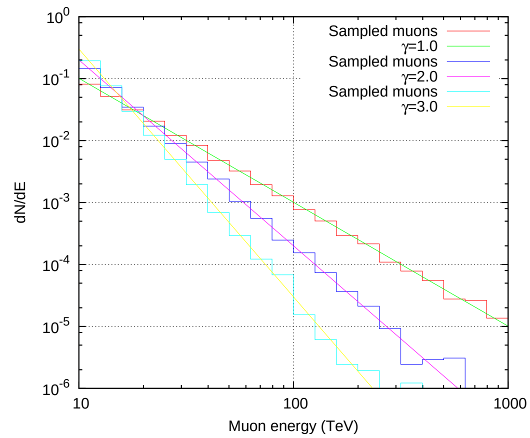

Figure 9: The reproduction of the incident muon spectrum by our random sampling

mate the muon energy from the measurement of the Cherenkov light. In Figure 10, we obtain the dependence of the energy distributions of the muon which generate the same amount of the Cherenkov light on the shapes of the incident muon spectrum. In Figure 11, we give the different case for different Cherenkov light. It is easily understand from the figures that the energy estimation of the muon neutrino events from the measurement of the Cherenkov light is strongly influenced by the energy spectrum of the muon neutrino events and, therefore, we could not decide the energy of the muon uniquely.

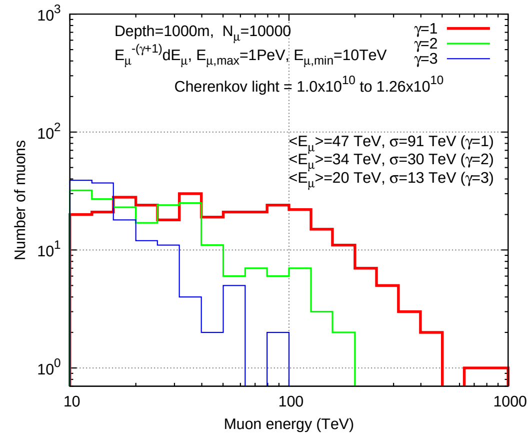

Figure 10: The dependence of the energy distribution of muon neutrino events for producing Cherenkov light (1.00×10^{10} to 1.26×10^{10}) on the incident neutrino spectrum

Conclusion

There is essential difference between muon neutrino events and electron neutrino events as for their energy estimation. In the cubic scale experiments, electron neutrino events are the Fully Contained Events. Therefore, we could determine essentially their energy, apart from the degree of error, and we construct the energy spectrum of electron neutrino events, while muon neutrino events are exclusively the Partially Contained Events ($\sim$ 500 GeV) and in principle, we could not even estimate their energies as we mention (see Figure 10 and 11) if we assume the energy spectrum of the muon events.

Therefore, if we want to obtain the reliable experimental data in high energy neutrino astrophysics in water, we would like to suggest to detect electron neutrino events, not muon neutrino events as the first step of such experiments. However, in ultra-high energies, even electron neutrino events may be classified as the Partially Contained events ($\sim 10^{21}$ eV).

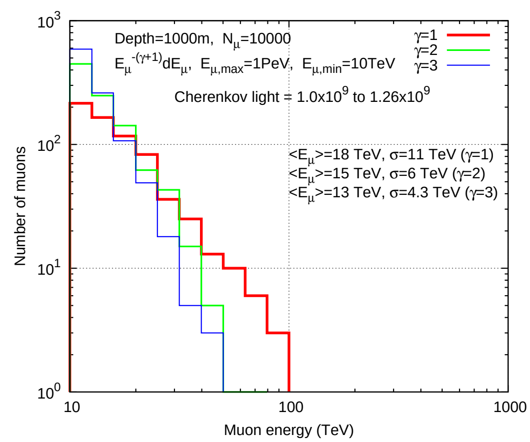

Figure 11: The dependence of the energy distribution of muon neutrino events for producing Cherenkov light (1.00×10^{9} to 1.26×10^{9}) on the incident neutrino spectrum

References

[1] A. Misaki, Fortschr. Phys 38 (1990) 413.