Detection of Tau Neutrinos in Underwater Neutrino Telescopes

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Abstract

If neutrinos produced in cosmological sources oscillate, neutrino telescopes can have a chance to detect signals from τ-neutrinos. We present an estimate of the 'double bang' event rate produced by ν_τ's in km^3 scale detectors.

1. Introduction

$\nu_\mu \leftrightarrow \nu_\tau$ oscillations should lead to the proportion $\nu_e{:}\nu_\mu{:}\nu_\tau = 1{:}1{:}1$ for neutrinos produced in cosmological sources that reach the Earth, though the flavor ratio at production is expected to be 1:2:0 (if all muons decay). Passing through the Earth, ν_τ's generate τ-leptons via charged current (CC) interactions. Being short-lived particles, τ's decay in flight producing ν_τ's and (in ~35% cases) also ν_μ's or ν_e's. Hence, neutrinos of all flavors undergo a regeneration process. The Earth is transparent for VHE ν_τ's and, moreover, ν_τ's are able to recover partially also $\nu_{\mu,e}$ fluxes for which the Earth is opaque at VHE. ν_τ's can be detected via τ's produced in CC interactions. At energies $E_\nu < 10^6$ GeV τ range is short ($R_\tau < 30$ m) and showers at CC interaction and τ decay vertices cannot be reconstructed separately in underwater/ice neutrino telescopes (UNT). Hence the 2 hadronic or hadronic+electromagnetic showers cannot be distinguished by a point-like hadronic+electromagnetic shower, produced by a ν_e. For $E_\nu \approx 10^{6\div7}$ GeV the 'double bang' (DB) signature (τ track between 2 showers at ν_τ interaction point and τ decay vertex [7]) can be a clear and background-free evidence of ν_τ detection. At $E_\nu > 3\cdot10^7$ GeV τ-lepton range becomes larger than 1 km and τ's cannot be distinguished from muons in km^3 scale UNT. Using the muon and τ propagation code MUM [13], we estimate that even though τ's and muons have different energy loss properties, a lower energy muon can produce through stochastic processes showers with similar features than a τ-lepton.

Estimates of DB rates in km^3 UNT were done in [1] for down-going ν_τ's, while events from the lower hemisphere were not considered. Calculations of up-going ν_τ propagation were done in [3]. It was concluded that, though VHE ν_τ's are not absorbed by the Earth, their energies decrease; hence the amount of τ

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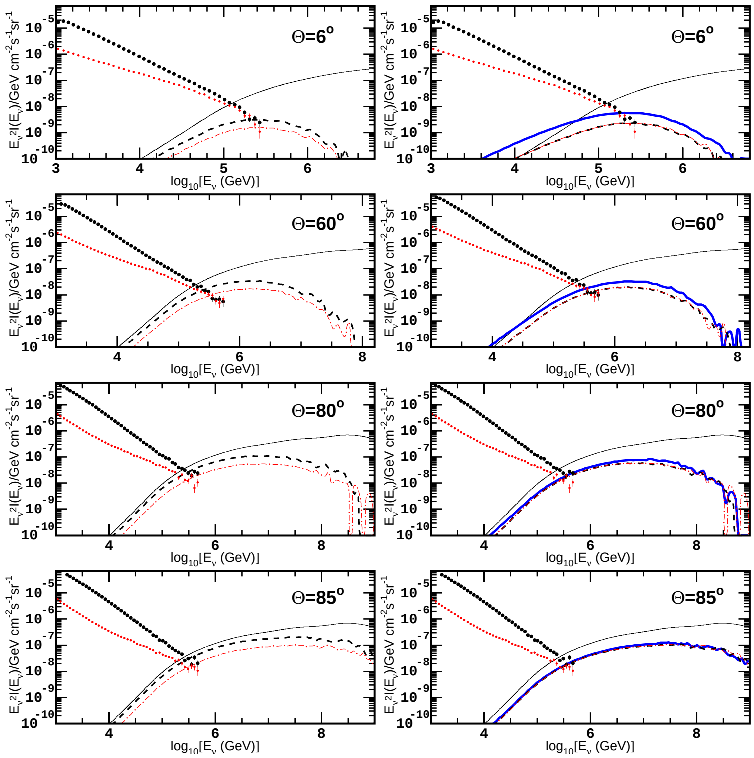

Fig. 1. Spectra of astrophysical ν's sampled according to the spectrum in [12] transformed after propagation through the Earth at 4 different nadir angles. Left column: no oscillations, ν_e:ν_μ:$\nu_\tau = 1$:2:0, right column: oscillations with maximal mixing, ν_e:ν_μ:$\nu_\tau = 1$:1:1. Thin solid lines: total incoming flux of astrophysical ν's; thick solid (right panels), dashed and dash-dotted lines (overlapping in right panels): out-coming $\nu_\tau + \bar{\nu}_\tau$, $\nu_\mu + \bar{\nu}_\mu$, $\nu_e + \bar{\nu}_e$ after propagation through the Earth, respectively. $\nu_{\mu,e}$ spectra include secondary neutrinos produced by ν_τ's. In the right part of each panel ν_{atm} spectra (conventional+prompt [10]) after propagation through the Earth are shown, upper thick markers: $\nu_\mu + \bar{\nu}_\mu$, lower thin markers: $\nu_e + \bar{\nu}_e$.

events in the DB energy range is low. In this work we present results of a MC simulation of astrophysical ν propagation through the Earth using 2 spectra [9,12] not considered in [1,3]. The rate of DB events in km^3 scale UNT is estimated.

2. Method and Results

We simulate both DIS CC and NC interactions for all kind of neutrinos [8] in the energy range $10^3\,\mathrm{GeV} < E_\nu < 10^9\,\mathrm{GeV}$ using the CTEQ3_DIS structure functions. MUM [13] was used for τ propagation including the newest corrections for photo-nuclear interaction [2]. We used TAUOLA package [6] to generate the τ decays. Comparison of results for power-law spectra obtained by our algorithm with ones published in [4] showed a reasonable agreement. $\nu_{\mu,e}$ tracking is stopped after a CC interaction. τ's produced in ν_τ CC interactions are propagated up to their decay vertex. Incident fluxes on Earth of ν's are assumed equal to $\bar{\nu}$ fluxes

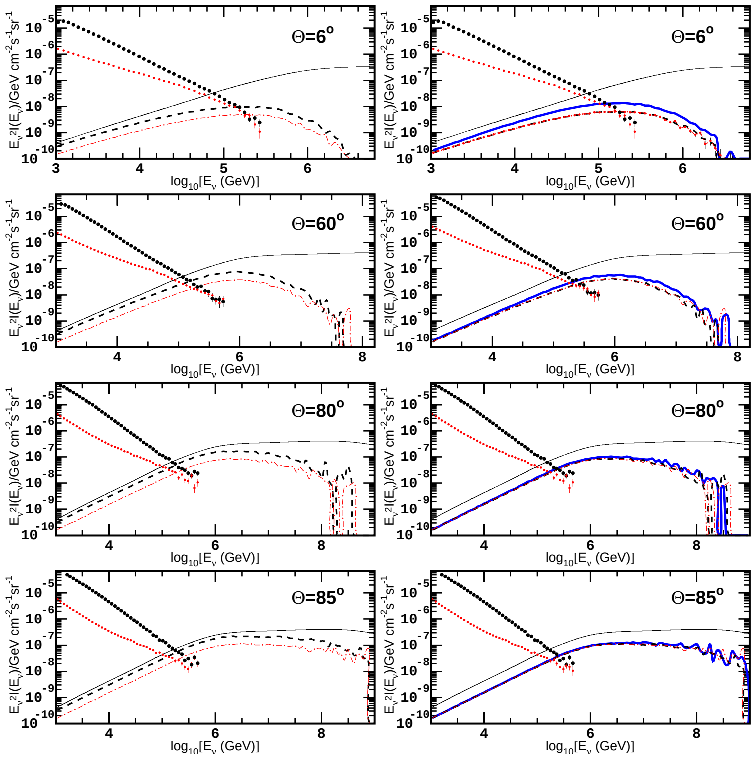

Fig. 2. The same as in Fig. 1 but astrophysical neutrinos are generated according to Mannheim, Protheroe and Rachen upper limit on diffuse neutrino flux [9].

for all flavors. The background of atmospheric (πK) and prompt (RQPM) $\nu_{\mu,e}$'s is generated using spectra in [10]. Simulation results are presented in Fig. 1. We used the ν flux predicted by Protheroe [12] for an external photon optically thick proton blazar model. In Fig. 2 results are presented or an upper bound (not a model) on diffuse ν spectrum for optically thick AGN sources (thick solid line in Fig. 5 in [9]). ν_τ fluxes exceed $\nu_{\mu,e}$ ones remarkably up to nadir angles $\theta \sim 60^o$ since ν_τ's are not absorbed by the Earth in contrast to $\nu_{\mu,e}$'s. But their spectra are shifted to lower energies due to energy degradation in regeneration process. For all θ, the outgoing flux of astrophysical neutrinos exceeds ν_{atm} flux at $E_\nu > (1 \div 3) \cdot 10^5$ GeV. Secondary $\nu_{\mu,e}$'s which are produced by τ decays contribute to total outgoing $\nu_{\mu,e}$ spectra with fractions 0.57, 0.18, 0.06, 0.02 (spectrum [12]) and 0.18, 0.06, 0.02, 0.01 (spectrum [9]) for nadir angles $\theta = 6^o$, 60^o, 80^o, and 85^o, respectively. Analysis of ratio between muon rates and shower rates that may be an indirect signature of ν_τ appearance was presented in [3]. In this work we analyze direct ν_τ detection through DB signature. The rate of totally contained DB events is given by:

$$N = 2\pi \, \rho \, N_A \int_{-1}^{0(1)} \int_{E_{min}}^{\infty} V_{eff}(E_{\nu_\tau}, \theta) \, I(E_{\nu_\tau}, \theta) \, \sigma^{CC}(E_{\nu_\tau}) \, dE_{\nu_\tau} d(\cos\theta), \qquad (1)$$

where N_A is the Avogadro number, ρ is medium density (we use $\rho = 1\,\mathrm{g\,cm^{-3}}$ which is close to sea water/ice density), $I(E_{\nu_\tau}, \theta)$ is the differential ν_τ flux. The

Earth shadowing effect is accounted for the lower hemisphere (upper limit of the integral 0, while $\cos\theta = 1$ is used to compute the number of events for the whole sphere); $V_{eff} = S_p(\theta)\,(L - R_\tau(E_{\nu_\tau}))$, with S_p projected area for tracks generated isotropically in azimuth at the fixed θ directions on a parallelepiped (IceCube-like 1×1×1 km^3 [5] and NEMO-like 1.4×1.4×0.6 km^3 [11]), L geometrical distance between entry and exit point, R_τ τ-lepton range, σ^{CC} total CC ν cross section. $E_{min} = 2 \cdot 10^6$ GeV corresponds to τ-lepton range $R_\tau^{min} = 70$ m. DB can be considered as a background-free τ signature [7] since there should be no atmospheric μ which could produce 2 showers with comparable amount of photons. Nevertheless, this reasonable assumption needs to be verified through a full simulation. Table 1 shows DB rates for lower, upper and both hemispheres. Values for upper hemisphere are 3÷6 times lower compared to [1] since more optimistic predictions for diffuse neutrino fluxes are used there.

Table 1. Number of totally contained DB events in km^3 detector per year.

Spectrum	IceCube-like ($N_{-2\pi}$ / $N_{2\pi}$ / $N_{4\pi}$)	NEMO-like ($N_{-2\pi}$ / $N_{2\pi}$ / $N_{4\pi}$)
[12]	0.7 / 1.6 / 2.3	1.0 / 2.1 / 3.1
[9]	1.0 / 2.3 / 3.3	1.4 / 3.1 / 4.5

3. Conclusions

Based on optimistic models [9,12] for AGN diffuse neutrino fluxes we found that in km^3 UNT one can expect a marginally observable rate of contained 'double bang' τ events.

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