High Energy Tau Neutrinos

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The intrinsic tau neutrino flux from cosmological and astrophysical sources has usually been considered negligible in comparison to the electron and muon neutrino fluxes. However, the inclusion of the tau neutrino component coming from hadronic decay at the source can significantly modify the tau neutrino spectrum expected at Earth. We report our results on the high energy tau neutrino production and its implications for the observation of high energy neutrino events.

1. INTRODUCTION

Presently much effort is being expended to resolve the flavor of the incoming neutrino flux (for a review see [1]). One motivation for doing this is that the absolute sensitivity, or relative sensitivity compared with background, may be significantly greater for one neutrino species than for other species [2]. Another primary motivation for identifying the neutrino flavor is to test the hypothesis that neutrinos undergo flavor oscillation as they propagate from source to Earth. Because the non-oscillation production of $\nu_\tau$ is assumed to be negligible relative to $\nu_e$ and $\nu_\mu$ production, and the cascade $\nu_e$ and $\nu_\mu$ flux with the relic cosmic neutrino background is orders of magnitude less than the primary $\nu_e$ and $\nu_\mu$ flux, any detected $\nu_\tau$ component from a source outside the Solar System is currently expected to be indicative of oscillation. In this paper, we briefly report some results of our investigation into high energy $\nu_\tau$ production, presented elsewhere [3]. We illustrate that the $\nu_\tau$ component at the high energy end in the hadronic decays is significantly higher than previously assumed and that this can have observational consequences.

2. NEUTRINO PRODUCTION

High energy neutrinos are expected to be produced by several cosmological and astrophysical sources, among others: active galactic nuclei (AGN) [4]; topological defects (TD) such as superconducting, ordinary or VHS cosmic strings [5–7]; supermassive and scalar particle (X-particle) decay or annihilation [8]; and Hawking evaporation of primordial black holes (PBH) [9–11]. Also, neutrinos can originate from the decay of photoproduced hadrons on the cosmic background radiation (CMB). In all these scenarios the production of tau neutrinos has been assumed to be negligible compared to the production of electron and muon neutrinos.

We focus our attention on those cases where, irrespective of the scenario, there are sufficiently energetic interactions that quarks and gluons which fragment into jets of hadrons are expected to be produced. The spectra of these hadrons should be very similar to those measured in $e^+e^- \rightarrow q\bar{q} \rightarrow \text{hadrons}$ events in colliders. As a consequence, the final state particle distributions in these scenarios are expected to be dominated by hadronic decays at the source. In these decays over 90% of the final state products will be $\pi^0$, $\pi^+$, and $\pi^-$, with the remainder mainly nucleons which decay into protons and antiprotons. On astrophysical timescales, the $\pi^\pm$ decay into $\nu_e$ and $\nu_\mu$ and $e^\pm$. The final cluster states (pions and nucleons) in QCD jets at accelerator energies can be loosely approximated by the Hill, Schramm, and Walker (HSW) fragmentation function

$$\frac{dN}{dx} = \frac{15}{16} x^{-3/2} (1 - x)^2,$$

where $x = E/m_J$ and $m_J$ is the total energy of the
decaying jet \([\bar{q}q]\). This distribution continues down to \(E \sim 1\) GeV. When convolved with the \(\pi^\pm\) decay, Eq. (1) leads to a similarly dominant \(E^{-3/2}\) term in the \(\nu_e\) and \(\nu_\mu\) spectra at \(x \lesssim 0.1\) and \(dN_{\nu_e,\nu_\mu}/dE \rightarrow 0\) as \(x \rightarrow 1\). (For a full derivation of the \(\nu_e\) and \(\nu_\mu\) spectra using fragmentation function (1) see \([7]\).)

Because \(\nu_\tau\) production is suppressed compared with other species, it has been assumed in previous astrophysical and cosmological flux calculations that the \(\nu_\tau\) spectrum from hadronic jets is orders of magnitude less than the \(\nu_e\) and \(\nu_\mu\) spectra at all \(x\). This is not so, once the energy of the jets surpasses the tau lepton and heavy quark masses. While indeed the total number of \(\nu_\tau\) produced per jet is less than \(10^{-3}\) of the total number of \(\nu_e\) and \(\nu_\mu\), the high \(x\) tau neutrinos are predominantly produced by the initial decays of the heavier quarks with shorter lifetimes (the greatest contribution comes from the \(t\) quark decay) and the \(\nu_e\) and \(\nu_\mu\) are produced by the final state cluster decays of the much lighter pions. This leads to significantly greater relative contribution from \(\nu_\tau\) at high \(x\) than previously assumed. The fragmentation distribution (1) is no longer relevant for the tau neutrino.

In Fig. 1 we show the \(\nu_\tau\) spectrum, together with the \(\nu_e\) and \(\nu_\mu\) spectra, generated by the decay of 10 TeV \(q\bar{q}\) jets. To simulate these spectra we used the QCD event generator HERWIG \([2]\) and the process \(e^+e^- \rightarrow q\bar{q} (g), i = \text{all } q\) flavors. Consistent spectra are obtained with PYTHIA/JETSET (see \([3]\)). Note that in the region \(0.1 \lesssim x \lesssim 1\), the tau neutrinos make up more than one tenth of the total neutrino contribution. Note also that below \(x \lesssim 0.1\), \(dN_{\nu_\tau}/dE\) falls off with roughly an \(E^{-1/2}\) slope, and not the \(E^{-3/2}\) slope of the \(\nu_e\) and \(\nu_\mu\) spectra. From our 300 GeV – 75 TeV simulations, we find that the \(\nu_\tau\) spectrum generated by \(q\bar{q}\) jet decay can be parametrized as

\[
\frac{dN_{\nu_\tau}}{dE_{\nu_\tau}} \approx \left(\frac{1}{2m_J}\right) \left[0.15 \frac{E_{\nu_\tau}}{m_J} \right]^{-1/2} - 0.36 + 0.27 \left(\frac{E_{\nu_\tau}}{m_J}\right)^{1/2} - 0.06 \left(\frac{E_{\nu_\tau}}{m_J}\right)^{3/2}
\]

(2)

per jet.

Here we apply our results to two scenarios (for an expanded treatment see \([3]\)). The first one is the VHS cosmic string scenario. In the VHS scenario, 1 GeV – UHE particle fluxes are generated by the decay of supermassive scalar and gauge particles emitted by the long strings over the age of the Universe. In Fig. 2 we show the neutrino spectra expected at Earth from VHS strings with a mass per unit length of \(G\mu = 10^{-8}\) \([4]\). The partial \(\nu_e\) component which is solely produced in the collisions of the primary \(\nu_e\) and \(\nu_\mu\) with the relic cosmic 1.9\(^o\)K neutrino background \([3]\) is also shown in Fig. 2. This collision-produced \(\nu_\tau\) component is the only one presented in previous cosmic string papers. As can be seen, our results give a significant increase in the expected \(\nu_\tau\) signal at the highest energies. In the second scenario, the evaporation of PBHs, we calculate the neutrino flux from the Hawking evaporation of a \(T_{BH} \sim 100\) GeV PBH using HERWIG and following the method of Ref. \([10]\). The instantaneous emission per degree of freedom prior to decay is given by

\[
\frac{d^2N_\nu}{dQdt} = \frac{\Gamma_e(T_{BH}, Q)}{2\pi\hbar} \left[\frac{\phi}{e^{\frac{\phi}{kT_{BH}}} - (1)^s}\right]^{-1},
\]

(3)

where \(\Gamma_e\) is the absorption probability for species, \(s\) is the spin, and \(T_{BH}\) is the black hole temperature. The neutrino flux from the evaporating PBH including hadronic decays is shown in Fig. 3.

3. CONCLUSIONS

Previous work has assumed the \(\nu_\tau\) component in TeV – UHE hadronic decays to be negligible com-
Figure 2. The neutrino spectra from VHS cosmic strings with a mass per unit length of $G\mu = 10^{-8}$. The dash-dotted curve is the $\nu_\tau$ component produced by cascades off the relic neutrino background [13] and the thick solid line is the $\nu_\tau$ component produced by hadronic decays.

pared with the $\nu_e$ and $\nu_\mu$ components, at all neutrino energies. We find that this is not so once the decays are sufficiently energetic to include the heavier quarks. In particular, for neutrino energies in the decade below the energy of the initial decaying particle, the tau neutrino component is of similar magnitude to the $\nu_e$ and $\nu_\mu$ components. Below these energies the $\nu_e$ spectrum exhibits a slope of slightly less than $E^{-1/2}$ compared with the $E^{-3/2}$ slope of the $\nu_e$ and $\nu_\mu$ spectra. This analysis modifies the expected spectra in many astrophysical and cosmological high energy neutrino production scenarios. As a consequence, the observation of a significant $\nu_\tau$ to $\nu_\mu$ ratio at a given energy in high energy neutrino telescopes and detectors may be due to hadronic decay at the source and not $\nu_\mu \rightarrow \nu_\tau$ oscillation in transit.

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