

A novel tau signature in neutrino telescopes

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Abstract. Kilometer-scale neutrino telescopes will detect muon and electron neutrinos from astrophysical sources at the TeV scale and above. Tau neutrinos are also expected from these sources due to neutrino oscillations over astrophysical baselines. Identification of tau neutrinos is expected to be possible above the PeV energy range through the “double bang” and “lollipop” signatures. We discuss another signature of tau in the PeV–EeV range, arising from the decay of tau leptons inside the detector to much brighter muons.

1. Introduction

Kilometer-scale Cherenkov neutrino detectors now planned or under construction, such as IceCube [1] at the South Pole and KM3NeT [2] in the Mediterranean, are poised to detect high energy neutrinos from astrophysical sources such as gamma-ray bursts (GRBs) and active galactic nuclei (AGN). In addition to measuring the energy and direction of astrophysical neutrinos, these neutrino telescopes will be able to distinguish between the three known flavors of neutrinos (and anti-neutrinos) through the signature(s) of their interactions in the detection media.

Tau neutrinos are not produced in appreciable numbers in astrophysical sources, but will appear in numbers comparable to ν_e and ν_μ as a consequence of flavor oscillation between their sources and Earth. Tau neutrinos are particularly interesting because local backgrounds to astrophysical ν_τ signals are low. The possible backgrounds are from UHE cosmic rays interacting in Earth’s atmosphere and producing short-lived charmed mesons which decay to ν_τ , known as the “prompt” neutrino flux [3, 4], and from conventional atmospheric ν_e or ν_μ produced in these cosmic ray air showers oscillating to ν_τ as they traverse the Earth before being detected. The total rate of ν_τ events from these fluxes is expected to be much less than one event above 1 PeV per year per km³ [4, 5, 6, 7, 8].

Tau neutrinos are also interesting because of the phenomenon of ν_τ regeneration [9]. Although the Earth is opaque to ν_e and ν_μ at PeV energies and above, due to the rising neutrino interaction cross-section, the τ^\pm produced in a charged current (CC) ν_τ interaction will usually decay back to ν_τ before losing significant amounts of energy, effectively regenerating the ν_τ beam and leaving an upgoing ν_τ flux up to the PeV scale.

The best-known signature for detecting ν_τ in a water or ice Cherenkov detector is called the “double bang” [10]. In these events, a CC neutrino-nucleon interaction $\nu_\tau N \rightarrow \tau X$ produces a hadronic shower (denoted X), with the subsequent decay of the τ lepton producing a second shower, connected to the first by the τ lepton track. The second shower may also be hadronic,

or it may be electromagnetic in the case of $\tau \rightarrow e\nu_\tau\bar{\nu}_e$. The τ produced in the CC interaction has energy $\langle E_\tau \rangle \approx 0.75E_\nu$ [11], and the two showers are separated by the tau decay length $l_\tau = \gamma ct_\tau \sim 50(E_\tau/\text{PeV})\text{m}$ (neglecting energy losses along the track). Due to the short τ lifetime and wide spacing of the detection elements in kilometer-scale neutrino telescopes, this signature is only expected to be detectable for ν_τ with energy $E_\nu \gtrsim \text{PeV}$. Above $\sim 20 \text{ PeV}$, the typical decay length exceeds 1 km, so both showers usually will not be contained in a kilometer-scale detector; the resulting signature of a tau track and one shower is known as a “lollipop” [12].

In this paper, we point out another distinctive signature of extremely high energy (EHE, PeV–EeV) tau leptons, produced by the muonic decay of a τ inside the instrumented detection volume. Although the muon has lower energy than the parent tau lepton, it will emit more light than the tau. The lepton track will thus appear to suddenly increase in brightness by an amount which should be detectable in a neutrino telescope.

The energy range over which this signature is observable is constrained at the lower end by the requirement that a reasonably long tau lepton track be observed prior to the tau decay. At the higher end, the rising rate of tau photonuclear energy loss causes the brightness of the tau to approach that of the daughter muon above EeV energies. It should be noted that these limits apply to the energy of the τ lepton in the detector; events from higher energy ν_τ could be observed if the initial neutrino interaction vertex is some distance from the detector so that the τ lepton loses energy in stochastic interactions before decaying within the detector.

2. Signature of Muonic Decay

Identification of tau events through muonic decay, $\tau \rightarrow \mu\nu_\tau\nu_\mu$, requires the decay to occur within the detector so that the increase in brightness will be observed. The branching ratio for this decay channel is measured to be $\Gamma_\mu = 17.36\%$ [13], so only a fraction of tau leptons will manifest themselves via this signature. However, at energies $\gtrsim 20 \text{ PeV}$, the tau track length L_τ becomes longer than the geometric scale of the detector and double bangs are no longer visible. Only the lollipop and muonic decay signatures can be used to identify taus in this regime.

Tau leptons are produced in neutrino $V - A$ interactions, which at the energies of interest produce polarized taus. The spectrum of muon energies from the decay of polarized τ is $dn/dx = \frac{4}{3}(1 - x^3)$, where $x = E_\mu/E_\tau$ [14, 15, 6]. The expected muon energy is thus $\langle E_\mu \rangle = 0.4 E_\tau$.

Although the muon has less than half the energy of the tau, it appears brighter because the muon loses energy more rapidly than the tau. The average energy loss of heavy leptons per unit distance traveled in matter (in g/cm^2) is often approximated as $-\langle dE/dX \rangle \approx a + bE$. The constant part, due to ionization losses, is negligible in the EHE regime compared to the stochastic losses $\sim bE$ due to e^+e^- pair production, bremsstrahlung and photonuclear effects. The radiative energy loss parameter $b = b(E)$ varies slowly with energy for extremely high energy leptons, primarily due to an increase in the photonuclear energy loss rate b_{pn} at very high energies. Although the radiative energy losses are in fact due to a series of discrete stochastic events, at high energies these interactions occur frequently enough that they can be considered quasi-continuous, increasing the overall brightness of the lepton track.

While e^+e^- pair production and bremsstrahlung are the dominant energy loss channels for muons above the TeV scale, for taus bremsstrahlung is negligible and photonuclear effects dominate at EHE. Photonuclear energy losses by EHE leptons are not precisely known, and there are several models available in the literature [17, 18, 19, 20, 21, 22, 23]. Different models of the nuclear structure function are also available [22, 23, 24]. The predicted loss rates for τ leptons in ice are shown in Fig. 1. Numerical values for energy loss rates given in this paper were evaluated using the MMC software package [25], using ice as the default detection medium.

The showers produced in the Cherenkov medium by both bremsstrahlung and pair production

are purely electromagnetic, with γ 's converting to e^+e^- pairs and the e^+ and e^- in turn radiating more γ 's. Photonuclear interactions, on the other hand, disrupt the nucleon involved and produce showers of hadrons which go on to interact with other nucleons in the medium. The light produced in a shower comes from the Cherenkov radiation of the many secondary particles involved in the shower, and the total light yield is proportional to the integrated track length of the relativistic particles. The yield per unit shower energy is lower in hadronic showers because heavy particles have a higher threshold for Cherenkov radiation, energy is lost to the binding energies of the hadrons involved, and invisible slow neutrons are produced [26].

Quantitatively, the ratio of the light yield per unit energy in hadronic showers to that in electromagnetic showers depends on energy. For small (~ 10 GeV) showers the ratio of light yields is about 65%, rising to about 85% for a 10 TeV shower [27, 28] and asymptotically approaching 100%. In the calculations presented in Sect. 3 we have assumed an average value of 75% for the energy deposited in hadronic photonuclear interactions along the τ (and μ) track.

Taking into account the most probable fraction of the tau energy carried by the muon, the average energy loss rates of the two leptons, and the relative light yields of hadronic and electromagnetic showers, the factor by which a tau track will appear to increase in brightness as the τ decays to μ is shown in Fig. 2. Losses to ionization, pair production and bremsstrahlung are included in the calculation.

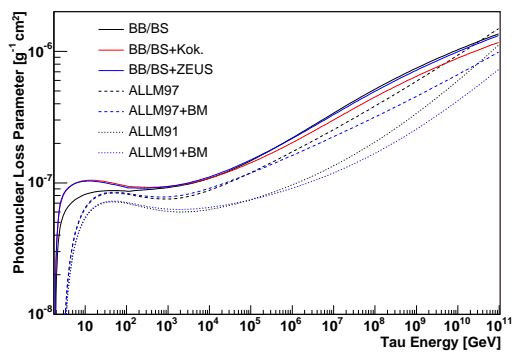


Figure 1. Photonuclear energy loss per unit energy (b_{pn}) for τ leptons in ice, according to various models. BB/BS refers to [18], plus the hard component of [19]. Kok and ZEUS include the photon-nucleon cross sections of [20] and [21], respectively, instead of that from [18]. ALLM91 and ALLM97 refer to [22] and [23], with BM following [22, 23] but using the nuclear structure function from [24].

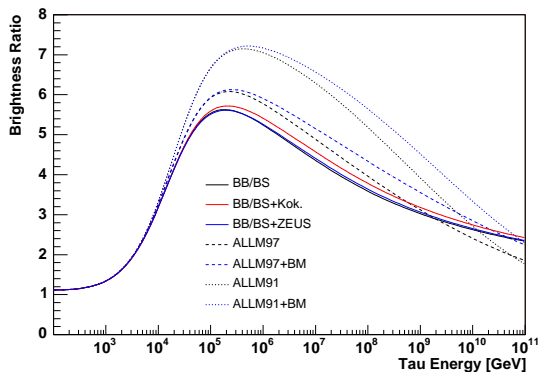


Figure 2. The magnitude of the increase in brightness as a τ decays to μ , as a function of the τ energy. The μ is assumed to take $1 - \langle y \rangle = 0.4$ of the τ energy. The various lines correspond to different models for photonuclear energy loss, as in Fig. 1. In the region of interest from 1 PeV to 1 EeV, the brightness steps up by a factor of between 3 and 7, depending on the model and on the energy of the τ .

3. Detectability

Although the IceCube collaboration has not published any estimate of track energy resolution for the IceCube detector, a resolution of $\sigma(\log_{10} E_\mu) \simeq 0.3$, corresponding to a factor of 2 in E_μ , was claimed for AMANDA-II [29]. (In the radiative-dominated regime, the brightness scales approximately linearly with muon energy, so the resolution in brightness should be the same as the energy resolution.) One would expect IceCube to do at least this well, given the larger detector volume and better optical module electronics.

The ANTARES collaboration expects a track energy resolution of $\sigma(\log_{10} E_\mu) \simeq 0.3\text{--}0.4$ for PeV muons [30] (resolution at higher energies was not given). Estimates of track energy resolution for the Baikal, NESTOR, and NEMO detectors are not available in the literature, but should be comparable to the ANTARES resolution.

It appears that, for both ice and water km³ neutrino telescopes, the expected track energy resolution should be sufficient to distinguish the brightness of the initial τ track from that of the final μ track. We note that the energy resolutions given above refer to measuring a single energy for a through-going track, rather than trying to make separate energy measurements for different segments of a track. However, in a km³ detector, the observed tracks will be several times longer than those visible in smaller instruments such as AMANDA or ANTARES, so enough information should be recorded for measurements of comparable accuracy.

We believe the signature of muonic tau decay will be useful in identifying astrophysical tau neutrino events in the coming generation of kilometer-scale Cherenkov neutrino telescopes such as IceCube. This signature may be particularly important in the energy region above a few tens of PeV, where the classic double-bang signature is no longer observable.

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