Neutrino flavor discrimination at the highest energies

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Abstract: High energy neutrinos of astrophysical origin are carriers of very important astrophysical information. In particular, they can be produced during the cosmic ray propagation in the intergalactic medium or by their interactions on the acceleration sites. The determination of the flavor composition at the highest energies presents a unique chance to prove our understanding of neutrino flavor oscillations and to search for new fundamental physics in this unexplored energy range. In this work we present a new statistical method specially developed for neutrino flavor identification at the highest energies. It is based on the different multiplet structure present in the longitudinal profiles of very deep electron and tau neutrino horizontal air showers. This technique is more suitable for the observation of the neutrino showers from the space because of the much larger aperture of the orbital fluorescence telescopes compared with ground based ones.

Keywords: Neutrinos, Flavor Discrimination, Space Observations

1 Introduction

The existence of neutrinos of $E_\nu \gtrsim 10^{12}$ eV is strongly motivated by the observation of cosmic rays up to energies of order of $10^{20}$ eV. These cosmic ray particles, mainly composed by protons and heavier nuclei, interact in the sources (see, for instance, Ref. [1]) or during their propagation through the intergalactic medium [2], producing weakly decaying particles such as pions and kaons that decay into neutrinos. High energy neutrinos can also be generated as the main product of the decay of superheavy relic particles [3, 4].

Cosmic ray observatories are sensitive to high energy neutrinos. Horizontal and quasihorizontal neutrino showers as well as Earth skimming tau neutrino showers can be observed by using surface detectors or fluorescence telescopes placed over the Earth’s surface or in space. At present no astrophysical neutrino has been observed in cosmic ray observatories and then, upper limits on its flux have been obtained [5].

In this work we present a new technique to discriminate between scenarios with different compositions of electron and tau neutrinos, by using very deep tau and electron neutrino horizontal showers [6]. This new technique is based on the morphology of the longitudinal profiles of the horizontal neutrino showers that can be observed by means of fluorescence telescopes. In particular, we study in detail the highest energy region of the neutrino flux that is relevant for space observations with the upcoming orbital fluorescence telescopes like JEM-EUSO [7].

2 Electron and tau neutrino showers

Neutrinos can initiate atmospheric air showers when they interact with the nucleons in the air molecules. The probability that a neutrino interacts in the atmosphere increases with the zenith angle because of the increase of the number of target nucleons. High energy neutrinos, propagating through the atmosphere, can suffer charge (CC) and neutral (NC) current interactions. The CC interactions are the most important for space observations.

As a result of a CC interaction, a very high energy lepton, which takes most of the energy of the incident neutrino, is generated, $\nu_l + N \rightarrow \ell + X$, where $N$ is a nucleon, $\ell = \{e^-, \mu^-, \tau^-\}$, and $X$ is the hadronic component. Typically, the produced lepton $\ell$ takes $\sim 80\%$ of the neutrino energy at $E_\nu \approx 10^{20}$ eV, and the rest of the energy goes into the hadronic component $X$. In the case of electron neutrino showers, the produced electron together with the hadronic component initiate an air shower right after the neutrino interaction. Because most of the times the electron takes most of the neutrino energy, the electron neutrino showers have characteristics more similar to the electromagnetic showers than to the hadronic showers; however, the effects of the hadronic component are not negligible specially for showers developing in dense regions of the atmosphere (see Ref. [8] for details).

In the case of tau neutrinos, while the hadronic component $X$ initiates a low energy shower immediately after the CC interaction (first bang), the tau lepton produced propagates through the atmosphere almost without interacting and then, after a given distance, decays. The particles produced in the decay initiate a more energetic shower than the first one, producing a second bang. There are several channels for tau decay which can be classified in three groups [9].

- Electromagnetic channel: $\tau \rightarrow \nu_\tau + e^- + \nu_e$.
- Hadronic channel: $\tau \rightarrow \nu_\tau + X$, where $X$ can be pions, kaons, etc.
- Muonic channels: $\tau \rightarrow \nu_\tau + \mu^- + \nu_\mu$.

The branching ratios of the electromagnetic, hadronic, and muonic channels are $b_{em} = 0.18$, $b_h = 0.645$, and $b_\mu = 0.175$, respectively. The tau neutrino showers corresponding to the muonic channel are difficult to observe because of the large decay length of the muons at the
energies considered, and then, only the electromagnetic and hadronic channels are relevant for the detection of tau showers. Therefore, considering just the electromagnetic and hadronic channels, \(\sim 78\%\) of the tau neutrino showers are of hadronic origin whereas \(\sim 22\%\) are of electromagnetic origin.

Electron neutrino showers are simulated following the procedure introduced in Ref. [8]. The charge current neutrino-nucleon interaction is simulated by using PYTHIA [10], linked with the LHAPDF library [11], which allows the use of different sets of parton distribution functions (PDFs). The CTEQ66 [12] set of PDFs, the most commonly used at the highest energies, is used in this work. The secondary particles, produced in the interaction, are used as input in the program CONEX [13] (v2r2.3), in order to simulate the shower development. The high energy hadronic interaction model used for the shower simulations is QGSJET-II [14].

The CC tau neutrino-nucleon interaction and the production of the corresponding tau lepton, are simulated using PYTHIA with the CETQ66 set of PDFs. The decay of the tau is simulated with the program TAUOLA [9]. Then, the particles produced in the decays are used as input in CONEX (with QGSJET-II) in order to simulate the shower development.

A library of horizontal neutrino showers is generated by using the simulation chain described above. The primary energy of the neutrinos ranges from \(10^{18}\) eV to \(10^{20.5}\) eV in steps of \(\Delta \log(E_{\nu})/\text{eV} = 0.25\). The interaction point of the electron neutrinos and the decay of the taus are just above the Earth’s surface, the densest region of the atmosphere. Note that the interaction point is such that the trajectory of the showers starts at the vertical axis of a nadir-pointing orbital telescope at sea level. Therefore, hereafter we denote very deep horizontal (VDH) showers to the showers initiated by the interaction of horizontal electron neutrinos or the decay of tau leptons (generated by the interaction of horizontal tau neutrinos), such that the interaction point of the electron neutrinos, or the decay of the tau leptons, is placed at the vertical axis of a nadir-pointing telescope at sea level.

Figure 1 shows the longitudinal profiles (deposited energy per unit of atmospheric depth) for VDH electron and tau neutrino showers of \(E_{\nu} = 10^{20}\) eV. The upper panel of figure 2 shows the distribution of the position of the first peak, \(X_{\text{max}}^{\nu} \), found from the beginning of the shower, \(X_0\), for electron and tau neutrino showers of \(E_{\nu} = 10^{20}\) eV. Note that the distribution function of \(\Delta X_{\text{max}}^{\nu} = X_{\text{max}}^{\nu} - X_0\) for VDH electron neutrino showers is bivalued and its first peak is located at \(\Delta X_{\text{max}}^{\nu} \sim 800\) g cm\(^{-2}\), while the second one is centered at \(\Delta X_{\text{max}}^{\nu} \sim 1500\) g cm\(^{-2}\). The first peak is related to the development of the hadronic component of the cascade, whereas the second one mainly reflects the electromagnetic components of the shower (see Ref. [8] for a detailed discussion). As expected, the distribution function of \(\Delta X_{\text{max}}^{\tau} \) for VDH tau neutrino showers is also bivalued but the hadronic peak is much more important. The profiles corresponding to electron neutrino showers have a larger probability to have more than one peak. In particular, the probability to have just one peak for VDH tau neutrino showers of \(E_{\nu} = 10^{20}\) eV is \(\sim 0.67\), whereas for VDH tau neutrino showers it is \(\sim 0.98\).

Figure 3 shows the probability to find just one peak, \(P_{X_{\text{max}}^{\nu}}\), in a profile corresponding to VDH electron and tau neutrino showers as a function of the primary energy. The solid lines in the figure are fits to the data points with the function

\[
P_{X_{\text{max}}^{\nu}}(E_{\nu}) = \frac{p_0}{1 + \left(\frac{E_{\nu}}{E_0}\right)^\gamma},
\]

where \(p_0\), \(E_0\), and \(\gamma\) are free fit parameters. The probability to find a profile with just one peak decreases with primary energy, owing to the fact that the LPM effect becomes

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**3 Flavor discrimination**

As mentioned before, VDH neutrino showers present a multipeak structure caused by the fluctuations introduced by the LPM effect. In particular, electron neutrino showers are more affected by this effect because they are dominated by the electromagnetic component. In contrast, tau showers are less affected by this effect, because \(\sim 78\%\) of the times the tau decays are of the hadronic type. Therefore, the number of peaks present in a given longitudinal profile should be a good parameter to discriminate between VDH electron and tau neutrino showers.

Given a simulated longitudinal profile, the number of peaks and their positions are determined following the procedure described in Ref. [8]. The probability to have just one peak, \(X_{\text{max}}^{\nu}\), found from the beginning of the shower, \(X_0\), for electron and tau neutrino showers of \(E_{\nu} = 10^{20}\) eV. Note that the distribution function of \(\Delta X_{\text{max}}^{\nu} = X_{\text{max}}^{\nu} - X_0\) for VDH electron neutrino showers is bivalued and its first peak is located at \(\Delta X_{\text{max}}^{\nu} \sim 800\) g cm\(^{-2}\), while the second one is centered at \(\Delta X_{\text{max}}^{\nu} \sim 1500\) g cm\(^{-2}\). The first peak is related to the development of the hadronic component of the cascade, whereas the second one mainly reflects the electromagnetic components of the shower (see Ref. [8] for a detailed discussion). As expected, the distribution function of \(\Delta X_{\text{max}}^{\tau} \) for VDH tau neutrino showers is also bivalued but the hadronic peak is much more important. The profiles corresponding to electron neutrino showers have a larger probability to have more than one peak. In particular, the probability to have just one peak for VDH tau neutrino showers of \(E_{\nu} = 10^{20}\) eV is \(\sim 0.67\), whereas for VDH tau neutrino showers it is \(\sim 0.98\).

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where \(p_0\), \(E_0\), and \(\gamma\) are free fit parameters. The probability to find a profile with just one peak decreases with primary energy, owing to the fact that the LPM effect becomes
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33rd International Cosmic Ray Conference, Rio de Janeiro 2013

more important at higher energies. As expected, $P_{X_{\text{max}}}(E_\nu)$ for tau neutrinos is larger than the corresponding one for electron neutrinos.

The decay length of a tau lepton of energy $E_\tau$ is given by $L_\tau(E_\tau) \equiv 4900 \, (E_\tau/10^{20}\text{eV}) \, \text{km}$. Therefore, the probability that a high energy tau, generated in a CC interaction of a horizontal tau neutrino with an atmospheric nucleon, decays just above the Earth’s surface is smaller than the probability that an horizontal electron neutrino suffers a CC interaction with an atmospheric nucleon at the same point. Because of this, the number of VDH tau neutrino showers are suppressed compared with the electron neutrino ones at higher energies [6].

Figure 4 shows the ratio, $R_\nu$, between the number of VDH tau neutrino showers and VDH electron neutrino showers for an incident flux with the same number of electron and tau neutrinos as a function of the neutrino energy. $R_\nu$ decreases with the neutrino energy in such a way that between $E_\nu = 10^{18}$ eV and $E_\nu = 10^{19.75}$ eV it falls from $\sim 1$ to $\sim 0.13$. Note that when the tau neutrino energy decreases, the energy of the tau lepton produced in the interaction also decreases; as a consequence the lifetime of the tau lepton, in the laboratory frame, also decreases. Therefore, when the tau neutrino energy is small enough, the tau lepton decays almost immediately after being produced, and then the shower starts very close to the point corresponding to the case of electron neutrinos, producing values of $R_\nu$ close to one.

Although the number of VDH tau neutrino showers is smaller compared with the VDH electron neutrino ones, few events can give relevant information about the different flavors present in a sample. Figure 5 shows the regions of 95% probability to find a fraction of neutrino showers with one peak, $f_1 = n_1/N$, as a function of the sample size $N$ for VDH electron and tau neutrino showers of $E_\nu = 10^{19.75}$ eV. For the case of VDH electron neutrino showers this region is enclosed by $f_1 = 0$ and $f_1 = f_{\text{max}}(N)$ and for tau neutrino showers by $f_1 = f_{\text{min}}(N)$ and $f_1 = 1$ where $f_{\text{max}}(N)$, and $f_{\text{min}}(N)$ are calculated by using $n_1$ as a binomial random variable. The probability to find just one peak in a longitudinal profile is obtained from the fits of $P_{X_{\text{max}}}$ (see Eq. (1)). It can be seen that with a sample of a small number of events, it is possible to say something about the neutrino flavors present in the sample, depending on the observed number of profiles with just one peak, $n_1$. If $f_1$, obtained from the observations, falls in the non-shadowed region, the hypothesis of having a pure sample of electron or tau neutrinos is rejected with at least 95% probability. Also for $N \gtrsim 10$, if $f_1$ falls in some of the two shadowed regions, it indicates that it is possible to reject the hypothesis of having a pure sample of neutrinos of the opposite flavor, with at least 95% probability.

The distribution function of $f_1$ for a given energy, sample size, and the electron neutrino abundance of the incident flux for a binary mixture of electron and tau neutrinos, $c_{\nu_e} = N(\nu_e)/(N(\nu_e) + N(\nu_\tau))$, is obtained from Monte Carlo simulations. Figure 6 shows the intervals of 68% probability of $f_1$, as a function of the sample size, for three different values of electron neutrino abundances, $c_{\nu_e} = \{0.25, 0.5, 0.75\}$, and for $E_\nu = 10^{19.75}$ eV. It can be seen that scenarios in which the incident flux is dominated by tau neutrinos are easier to discriminate, i.e. samples of a smaller size are required.

Given the flavor content of the incident flux, it is possible to use the parameter $f_1$ to calculate the minimum number of events, $N_{\text{min}}$, required to reject a false hypothesis [6]. Scenarios in which the incident flux is dominated by
tau neutrinos are easy to identify, and samples with several events, depending on the primary energy, are required in order to reject the hypothesis of having electron neutrinos alone. However, because of the suppression of very deep horizontal tau neutrino showers with respect to electron neutrino ones, a large number of events is required to discriminate between scenarios with electron neutrinos alone and a mix of an equal number of tau and electron neutrinos.

Note that the energy deposition of electron and tau neutrino showers is very different because the tau leptons, generated in the CC interactions of tau neutrinos with the nucleons of the atmosphere, decay to tau neutrinos and other particles; thus the energy taken by this secondary tau neutrino do not go to the shower. Therefore, if the deposited energy is used to reconstruct the primary energy without any correction, the standard procedure when fluorescence telescopes are used to observe the showers, then tau showers are reconstructed with smaller energies than that corresponding to electron neutrinos. The impact of the energy determination on the method developed above is studied in detail in Ref. [6].

4 Conclusions

In this work we have presented a new statistical technique intended to study the flavor content of the incident flux of high energy astrophysical neutrinos. This new method is based on the morphological differences between the longitudinal profiles corresponding to very deep horizontal electron and tau neutrino showers that can be observed by means of fluorescence telescopes. In particular, the multi-peak structure of the profiles strongly depends on the flavor of the incident neutrino. Very deep horizontal showers initiated by electron neutrinos present more fluctuations, owing to the LPM effect, than the corresponding one to tau neutrinos. Therefore, the number of showers with just one peak can be used to discriminate between different scenarios for the flavor content of the incident neutrino flux.

The difference between the probability to find just one peak, in a given profile, for very deep horizontal electron and tau neutrino showers starts to be important for energies $\gtrsim 10^{19.5}$ eV. Then this technique is more relevant for fluorescence telescopes in orbit around the Earth, like the upcoming JEM-EUSO mission and Super-EUSO, owing to their huge exposure.

Acknowledgment: A.D.S. is a member of the Carrera del Investigador Científico of CONICET, Argentina. The work of ADS is supported by CONICET PIP 114-201101-00360 and ANPCyT PICT-2011-2223, Argentina.

References