ID 754

30TH INTERNATIONAL COSMIC RAY CONFERENCE

Simulation of Double-Bang Event Induced by Neutrino in the Atmosphere

CELIO A. MOURA[1,2], MARCELO M. GUZZO[2]
[1]*Departamento de Física, Centro de Investigación y de Estudios Avanzados del IPN, Apdo. Postal 14-740, 07000 México, DF, Mexico.*
[2]*Instituto de Física "Gleb Wataghin" Universidade Estadual de Campinas, Unicamp 13083-970, Campinas, São Paulo, Brazil*
moura@ifi.unicamp.br

Abstract: We use CORSIKA+Herwig simulation code to produce ultra-high energy neutrino interactions in the atmosphere. Our aim is to reproduce extensive air showers originated by extragalactic tau-neutrinos. For charged current tau-neutrino interactions in the atmosphere, beside the air shower originated from the neutrino interaction it is expected that a tau is created and may decay before reaching the ground. That phenomenon makes possible the generation of two extensive air showers, the so called Double-Bang event. We make a quantitative analysis of the main characteristics of Double-Bang events in the atmosphere and conclude that it may be possible to observe this kind of event in ultra-high energy cosmic ray observatories such as Pierre Auger.

Introduction

It is believed that neutrinos with energies of the order of 10^{18} eV (1 EeV) arrive at the Earth from extragalactic sources and interact with nuclei in the atmosphere generating cascades of particles called Extensive Air Showers (EAS's) [1, 2]. There are basically two methods to detect those EAS's: one is to detect the particles when they reach the ground through Cherenkov tanks [3, 4, 5]. The other method is to observe the scintillation light of the atoms which are excited during the developing process of the EAS [4, 5, 6]. The detectors used for this method are called Fluorescence Detectors (FD's) because of the similarity of the scintillation with the fluorescence light. This technic of detection can be used to measure the profile of the EAS when it develops through the atmosphere.

To distinguish which particle have generated an EAS one can take advantage of the different depth of the atmosphere depending on the zenith angle. While for vertical angles the atmospheric depth is approximately 1000 g/cm^2, for horizontal angles it is approximately 36000 g/cm^2. Neutrinos, because of their very low cross section and mass, are the only particles beside the muons that can go

deep in the atmosphere before interacting or decaying. In these way it is possible that neutrinos come from very near horizontal angles and interact close to the detector. Ordinary particles when come from almost horizontal angles interact in the top of the atmosphere and when the EAS generated arrives at the detector, it has basically the muonic component because the hadronic and electromagnetic ones were absorbed by the atmosphere [7]. From the other side, neutrinos may generate EAS's near the detector and therefore they still contain the electromagnetic and hadronic components. Furthermore an EAS generated close to the detector has a curved and thick front of propagating particles, while an EAS generated far from the detector, when arrives at the detector has a thin and almost plane front of particles [8].

The case of tau-neutrinos is even more special. First of all, because it is not expected that tau-neutrinos are created in extragalactic sources. Tau-neutrinos are due to neutrino oscillation during the propagation from the source to the detector [9, 10]. Then, when the tau-neutrino interacts via charged current (CC) in the atmosphere it creates an EAS which contains a tau. For energies of the order of 1 EeV, the tau decays in a distance compara-

ble to the size of the EAS and almost all of the times it generates another EAS that may also be detectable. This kind of unique signature is named Double-Bang signature and our aim in this paper is to investigate through simulations the main characteristics of tau-neutrino induced events in the atmosphere.

Ultra-High Energy Neutrino Induced Events

Consider a neutrino arriving at the Earth and interacting via CC with a nucleon in the atmosphere generating a charged lepton and other fragments: $\nu_l + N \rightarrow l + X$, where l is the lepton flavor (e, μ, τ). For a neutral current (NC) interaction another neutrino is created rather then a charged lepton.

After the CC interaction, the neutrino energy is divided between the charged lepton and the other fragments that generate the EAS in the following way:

$$E_\nu = E_1 + E_l \,, \tag{1}$$

where E_ν is the incident neutrino energy, E_1 is the energy deposited in the fragments that generate the EAS and E_l is the charged lepton energy.

The energy distribution for each interaction is expressed by the inelasticity, that is the fraction of the neutrino energy that goes to the EAS and not to the charged lepton. The inelasticity is:

$$y = (E_\nu - E_l)/E_\nu \,. \tag{2}$$

Combining Eqs. (1) and (2) we have:

$$E_1 = yE_\nu \,, \tag{3}$$

and finally from Eqs. (1) and (3) we find the neutrino energy fraction transfered to the charged lepton:

$$E_l = (1 - y)E_\nu \,. \tag{4}$$

When a muon-neutrino interacts via CC, it creates an EAS with the same characteristics of the ones produced via NC interactions for any neutrino flavor. It is because similarly to the neutrinos created after the NC interactions, the muon created after a

CC muon-neutrino interaction almost does not interact with the atmosphere [11] and for the energies considered, the muon decay length is much longer than its interaction length.

Electron and tau-neutrino CC interactions are completely different. The electron, created after the electron-neutrino interaction, interacts immediately generating a cascade of electromagnetic particles beside the hadronic component generated by the other fragments created in the first interaction. The tau created after the tau-neutrino interaction propagates in a very similar way to the muon, but its mean lifetime is much shorter. For the energies considered the decay length of the tau is of the order of few tens of km in the laboratory frame, comparable to the length of the hadronic EAS created. When the tau decays, it may generate a second hadronic shower and both showers together generate a sign characteristic of tau-neutrino interactions only.

Tau Neutrinos

Based on the propose of ref. [9] to detect tau-neutrinos with energies of the order of 1 PeV in detectors under water or ice, it has been proposed to use Auger-like FD's to detect tau-neutrinos with energies of the order of 1 EeV interacting in the atmosphere [12, 13].

After it is created the tau propagates, before decaying in the laboratory frame, a distance given by: $L = \gamma c\tau$, where γ is the Lorentz factor and τ is the tau mean lifetime. In terms of the energy given in units of EeV, we have that the distance traveled by the tau in the laboratory frame is:

$$L \simeq \frac{E_\tau}{[\text{EeV}]} \times 49\,\text{km} = (1 - y)\frac{E_\nu}{[\text{EeV}]} \times 49\,\text{km} \,. \tag{5}$$

In our simulations we consider only the case of hadronic decay, despite we could have considered also the electronic decay which corresponds to almost 18% of the tau decay branching ratio [14]. Only the hadronic branching ratio is responsible for 64% of the tau decays. Based on the hadronic branching ratio of the tau decay, that is basically decay to pions, we consider that the energy of the

second EAS, originated by the tau decay, is in average:

$$E_2 \approx \frac{2}{3}E_\tau = \frac{2}{3}(1-y)E_\nu . \qquad (6)$$

Double-Bang Simulations

There are no experimental data confirmed of Ultra-High Energy (UHE) EAS generated by neutrino. A study of the characteristics of the UHE EAS's generated by electron and muon-neutrinos was made in [15] through CORSIKA [16] simulations. CORSIKA itself is not able to simulate neutrinos as primary particles, so the neutrino interaction is made by Herwig [17] and then, the results of this interaction are taken by CORSIKA as the primary particles which give rise to the EAS. Until the present moment, simulations with tau-neutrino as primary particle and the decay of taus in CORSIKA+Herwig are not available. Because of that we simulate Double-Bang events through phenomenological arguments, using muon neutrinos as primary particles and pions as the generators of the EAS which in principle may come from the tau decay.

The alternative we use to simulate events generated by tau-neutrinos in the atmosphere is to input muon-neutrino as primary particle. The main characteristics of muon and tau-neutrino induced events are the same with the exception that a muon-neutrino interacting via CC generates a muon. As we are simulating tau-neutrino interactions, we need the creation of a tau. To simulate the tau creation and subsequent decay we use pions. One can divide the tau decay in two main modes: 64% for the hadronic modes and 36% for the leptonic modes. In our simulations we consider only the hadronic modes in which the main decay products are pions. In this way we generate the second shower inputing the pion as primary particle in the same direction of the muon-neutrino, after a distance L corresponding to the tau mean lifetime and with the corresponding energy E_2 from Eqs. (6).

In Fig. 1 we show events for the tau energy of approximately 0.4 EeV. It means that the tau should have run a distance of about 20 km from the neutrino interaction point until the tau decay, and considering, from Eq. (6), that 2/3 of the tau energy
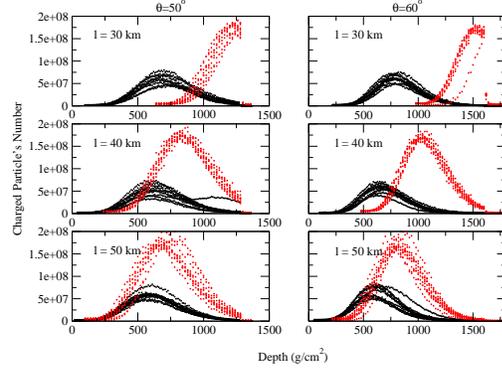

Figure 1: Double-Bangs generated by tau-neutrinos in the atmosphere. Each graphic contains ten events represented by the number of charged particles as a function of depth with primary neutrino energy of 0.5 EeV. The incident angle is of 50° in the fist column and 60° in the second one. The interaction depth is 30, 40 and 50 km respectively for each line. The first EAS's, with less than 10^8 charged particles, are represented in black and the second ones, due to the tau decay with more than the double number of particles, are represented in red.

goes to the decay products, it corresponds to a pion energy of 0.27 EeV. Each graphic of the figure contains 10 Double-Bang events, that means 10 showers initiated by muon-neutrino and 10 initiated by pion (π^-).

Discussion

UHE neutrinos probably coming from extragalactic sources may interact in the atmosphere via NC or CC. The average inelasticity for energies of the order of 1 EeV for neutrino-nucleon interaction is $y \approx 0.2$. It means that for NC interactions one hadronic EAS is produced in average with approximately 20% of the energy of the primary neutrino while for CC interactions there are three distinct cases: (*i*) when an electron-neutrino interacts an electron is created which immediately starts an electromagnetic cascade. So, after electron-

neutrino CC interactions it is created an EAS with one hadronic component bringing approximately 20% of the primary neutrino energy and one electromagnetic component with 80% of the energy of the primary neutrino. (*ii*) when a muon-neutrino interacts a muon is created which basically does not interact in the atmosphere and the EAS generated is similar to the one generated in a NC interaction. (*iii*) when a tau-neutrino interacts a tau is crated which decay in a distance comparable to the size of the hadronic EAS generated by the neutrino interaction. Nearly 64% of the times the tau decay generates a hadronic EAS and 18% of the times an electromagnetic one. Approximately 17% of the times the tau decay in muon and neutrinos that do not generate any cascade.

The profile of Double-Bang events may be observed by FD's such as those of the Pierre Auger Observatory or HiRes. The energy range must be very strict because to observe the two EAS's the energy cannot exceed about 1 EeV. But also the efficiency of the detector is an important factor and energies bellow 1 EeV are not optimal for the FD's to observe events. The ground arrays such as the Telescope Array and the Auger array may be another possibility to detect Double-Bangs. Almost horizontal Double-Bangs can develop both EAS's inside the array. And finally the other possibility is to use both technics, for example, observing the first shower with the FD and the second, due to the tau decay, with the ground array.

References

[1] P. Sokolsky, Introduction to Ultrahigh Energy Cosmic Ray Physics, Westview Press, 2004.

[2] T. K. Gaisser, Cosmic rays and particle physics, Cambridge University Press, UK, 1990.

[3] T. Yamamoto, K. Mase, M. Takeda, N. Sakaki, M. Teshima, Signatures of ultra-high energy cosmic ray composition from propagation of nuclei in intergalactic photon fields, Astropart. Phys. 20 (2004) 405–412.

[4] T. Yamamoto, The first scientific results from the pierre auger observatory, AIP Conf. Proc. 842 (2006) 1016–1018.

[5] A. Letessier-Selvon, Ultra high energy cosmic rays and the auger observatory, AIP Conf. Proc. 815 (2006) 73–84.

[6] R. Abbasi, et al., A measurement of time-averaged aerosol optical depth using airshowers observed in stereo by hires, Astropart. Phys. 25 (2006) 93–97.

[7] E. Zas, Neutrino detection with inclined air showers, New J. Phys. 7 (2005) 130.

[8] X. Bertou, P. Billoir, O. Deligny, C. Lachaud, A. Letessier-Selvon, Tau neutrinos in the auger observatory: A new window to uhecr sources, Astropart. Phys. 17 (2002) 183–193.

[9] J. G. Learned, S. Pakvasa, Detecting tau-neutrino oscillations at pev energies, Astropart. Phys. 3 (1995) 267–274.

[10] H. Athar, Mixed high energy neutrinos from cosmos, Chin. J. Phys. 42 (2004) 1–20.

[11] W. M. Yao, et al., Review of particle physics, J. Phys. G33 (2006) 267.

[12] M. M. Guzzo, C. A. Moura, Ultra high energy tau neutrinos and fluorescence detectors: A phenomenological approch, Astropart. Phys. 25 (2006) 277–283.

[13] M. M. Guzzo, C. A. Moura, Double extensive air shower induced by cosmic ultra-high energy tau-neutrino.

[14] W. M. Yao, et al., Review of particle physics, J. Phys. G33 (2006) 33.

[15] M. Ambrosio, et al., Corsika + herwig monte carlo simulation of neutrino induced atmospheric air showers.

[16] D. Heck, G. Schatz, T. Thouw, J. Knapp, J. N. Capdevielle, Corsika: A monte carlo code to simulate extensive air showersFZKA-6019.

[17] G. Corcella, et al., Herwig 6: An event generator for hadron emission reactions with interfering gluons (including supersymmetric processes), JHEP 01 (2001) 010.