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UPPER LIMIT ON THE DIFFUSE FLUX OF UHE TAU NEUTRINOS FROM THE PIERRE AUGER OBSERVATORY

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Abstract. The Pierre Auger Observatory is able to discriminate showers induced by Ultra High Energy neutrinos from every other primaries. More particularly, it is sensitive to Earth-skimming ν_τ that interact in the Earth's crust to produce a τ lepton that may emerge and trigger an extensive air shower used to sign the presence of the initial neutrino. The data from 1 January 2004 to 31 August 2007 contains no such neutrino candidate, but is used to place a limit on the flux of ν_τ at EeV energies. The result from the Pierre Auger Observatory gives a limit in the energy range $2 \times 10^{17} eV < E_\nu < 2 \times 10^{19}$eV for an E_ν^{-2} differential energy spectrum. The limit set at 90% C.L. is $E_\nu^{-2} dN_{\nu_\tau}/dE_\nu < 1.3 \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}.

1 Introduction

Through the last years, the observation of ultra-high energy (UHE) neutrinos has become one of the challenges of astroparticle physics. Many models, either astrophysical or exotic models, predict a substantial flux of neutrinos. One of the most certain contribution to this neutrino flux are the so-called GZK-neutrinos (Engel et al. 2001) produced in the decay of pions and kaons, from the interaction of ultra-high energy protons with the CMB. Such a mechanism provides a substantial flux of muon and electron neutrinos at the point of interaction. But given the large distances traveled by the particles, an observer can expect equal fluxes of electron, muon and ν_τ at the observation point, due to flavour mixing and neutrino oscillations. During the last years, an increasing effort has been put forward to develop a new generation of dedicated neutrino telescopes, that are relevant for an energy range of 10^{-6} to 10^{-1} EeV. An Ultra-high energy cosmic-ray detector such as the Pierre Auger Observatory (Abraham et al. 2004), although it was not developed for the detection of neutrinos, may have equal or even better potential in the UHE range of 10^{-1} to 10^{2} EeV, where the GZK-neutrinos are expected. In fact, it has been pointed out recently that the detection potential could be enhanced by the presence of τ neutrinos, due to oscillations, in the cosmic neutrinos flux. Upward-going UHE ν_τ that graze the Earth just below the horizon (also called "Earth-skimming neutrinos") have a quite high probability to interact in the crust and produce a τ lepton which, if produced close enough from the surface, may emerge and trigger an extensive air shower which may be detected by the surface detector (SD) array of the Pierre Auger Observatory, provided it does not decay too far from the ground. After giving a brief description of the Pierre Auger observatory in section 2, and discussing the issues of the detection and identification of UHE neutrinos in section 3, we will present the result of the search for UHE ν_τ with the SD in section 4.

2 The Pierre Auger Observatory

The Pierre Auger Observatory is located near the town of Malargüe, in the province of Mendoza, Argentina and has just reached completion. The originality of the Pierre Auger Observatory is that it combines two different techniques for the detection of Extensive Air Showers (EAS), that were originally used separately in previous experiments.

The Fluorescence Detector (FD) is composed of 4 buildings, each one housing 6 fluorescence telescopes designed to cover the entire SD. These instruments detect the ultraviolet light emitted by the nitrogen molecules of the air that are excited by the secondary charged particles of the EAS. The amount of light detected by the

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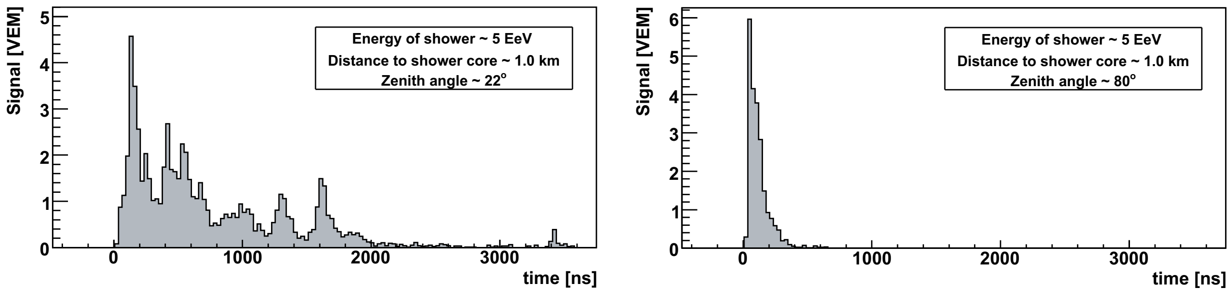

Fig. 1. FADC traces of stations at 1 km from the shower core for two real showers of 5 EeV. Left panel: Shower with electromagnetic component ($\theta \simeq 22°$); Right: muonic signal ($\theta \simeq 80°$)

telescopes is directly related to the energy of the EAS and thus offers a relatively precise measurement of the energy of the primary particle, allowing to limit the systematic uncertainties due to Monte Carlo (MC) simulations. The FD however suffers from its 10% duty cycle, especially when searching for rare events such as neutrinos.

The SD consists in an array of 1600 water Cherenkov tanks arranged in a hexagonal grid of 1.5 km covering a total area of 3000 km^2 and is used to sample the secondary particles of the EAS at the ground level. Each of these tanks contains 12 tons of purified water instrumented with $3 \times 9''$ photomultiplier tubes sampled by 40 MHz Flash Analog Digital Converters (FADCs). The signal in each tank is calibrated in units of Vertical Equivalent Muon (VEM) that is defined as the signal produced by a vertical muon crossing the tank. Contrarily to the FD, the SD has a 100 % duty cycle that provides a non negligible sensitivity to UHE neutrinos events.

3 Detection of UHE neutrinos

UHE particles that interact in the atmosphere produce EAS that contain muons and an electromagnetic (EM) component of electrons, positrons and photons. The muonic component can penetrate deeply in the atmosphere due to the long decay time of the muons. The EM component however is attenuated much faster and becomes negligible for showers traveling more than 2000 g cm^{-2} through the atmosphere. Protons and iron nuclei interact quickly in the upper layers of the atmosphere which means that at large zenith angles ($> 75°$), where the atmosphere gets thicker, showers produced by such primaries have to travel through an important quantity of matter (typically more than 3800 g cm^{-2}) before reaching the ground. Such showers are thus dominated by muons arriving at the detector in a thin and flat shower front. This is not necessarily the case for Earth-skimming ν_τ as they produce a τ lepton that is likely to emerge and decay close to the detector, triggering a shower that can reach the detector with a still important EM component. Looking for such "young" showers at large zenith angles is the best way to discriminate between UHE neutrinos and other primaries.

For this purpose we can use two important informations from the SD: the arrival times of the shower front in the different tanks give an estimate of the zenith angle of the shower, while the time duration of the signal in the tanks signs the presence of EM component. A shower front composed only of high energy muons produces a narrow FADC trace whereas EM component induces broad signals (see Figure 1).

Devising a selection criterion for UHE ν_τ implies the use of different simulations. First the τ decay is simulated using the TAUOLA package (Jadach et al 1993) and the secondary particles created are then injected in the AIRES code (Sciutto 2002) to simulate the developement of the shower in the atmosphere. Such EAS generated by the product of the decaying τ lepton were simulated with energies between 10^{17} and 3×10^{20} eV, zenith angles from 90.1° to 95.9° and for different altitudes of the decay point above the Pierre Auger Observatory in the range $0 - 2500$ m. Then, the shower secondary particles at the ground level are injected in a detailed simulation of the SD (Ghia 2007). Based on these simulations, a set of conditions has been designed to select showers induced by Earth-skimming ν_τ and reject those induced by other primaries. As stated above, this criterion can be separated into two parts. First, the FADC traces of the different tanks present in the event are examined to find broad signals as shown in the figure 1. For this purpose each tank for which the main segment of the FADC trace has 13 or more neighbouring bins over a threshold of 0.2 VEM and for which the ratio of the integrated signal over the peak height exceeds 1.4 is tagged as an "EM tank". And the "young shower" condition is fulfilled if at least 60% of the tanks in the event are successfully tagged.

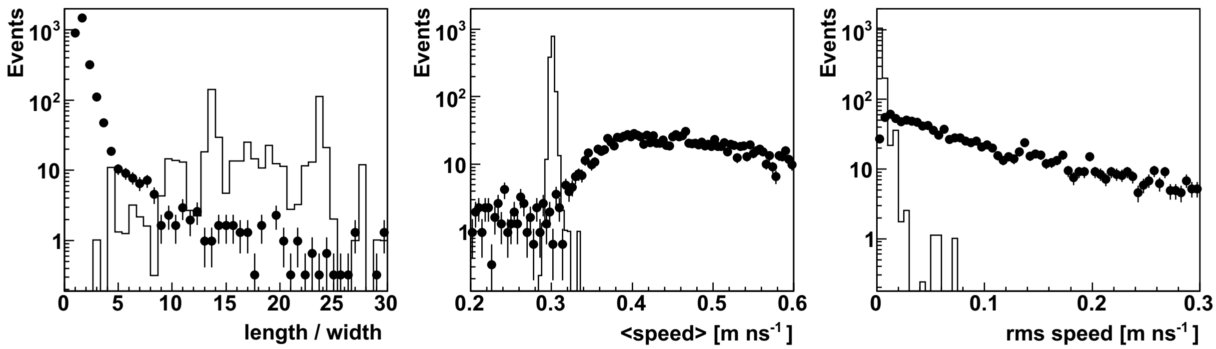

Fig. 2. Distributions of discriminating variables for showers initiated by τs decaying in the atmosphere, generated by ν_τs with energies sampled from an E_ν^{-2} flux (histogram), and for real events passing the "young shower" selection (points). Left: length/width ratio of the footprint of the shower on the ground; middle: average speed between pairs of stations; right: r.m.s scatter of the speeds.

Along with this EM condition, the event must also be compatible with a very inclined shower. The triggered tanks are thus required to have an elongated pattern on the ground by assigning a length and a width to the pattern and restricting its ratio (length/width > 5) and the apparent speed of the signal moving across the ground along the azimuthal direction is required to be very close to the speed of light (as expected for very inclined showers), in the range $(0.29, 0.31)$ m ns^{-1} with an r.m.s scatter below 0.08 m ns^{-1}. In figure 2, we show the distributions of the different discriminating variables for real events and simulated τ showers.

These conditions allow to reject the background from UHECR-induced showers and retain more than 80% of the simulated ν_τ showers.

4 Results

The conditions defined above were applied to the data set and over the whole period no neutrino candidate was found. The data of the Pierre Auger Observatory can thus be used to place a limit on the diffuse flux of UHE ν_τ. For this purpose we must calculte the exposure of the observatory. The total exposure must take into account the fact that the detector has grown while it was being constructed and is thus the time integral of the aperture for a given configuration. This aperture is then folded with the $\nu_\tau \to \tau$ conversion probability and the identification efficiency $\epsilon_{\rm ff}$. The latter is evaluated thanks to the selection criteria presented above and to the knowledge of the instantaneous configuration of the detector at a given time. It is a function of the τ energy E_τ, the altitude above ground of the central part of the shower h_c, the position (x, y) of the shower in the surface S covered by the array, and the time t.

The conversion probability is obtained using a MC simulation of the propagation of ν_τ and τ leptons inside the Earth. Such a simulation takes into account the different relevant processes: charged current and neutral current weak interactions for both particles; decay and electromagnetic energy losses through bremsstrahlung, pair production and photonuclear interaction for the τ lepton. Folding the conversion probability with the τ decay probability as a function of the flight distance gives the differential probability $d^2P_\tau/(dE_\tau dh_c)$ of obtaining an emerging τ lepton of energy E_τ that will produce a shower with central part at an altitude hc.

The expression for the exposure as a function of neutrino energy $\mathrm{Exp}(E_\nu)$, with θ and Ω the zenith and solid angles, is then:

$$\mathrm{Exp}(E_\nu) = \int_\Omega d\Omega \int_0^{E_\nu} dE_\tau \int_0^\infty dh_c \left[\frac{d^2p_\tau}{dE_\tau dh_c} \times \int_T dt \int_S dxdy \cos\theta \epsilon_{\rm ff}\left[E_\tau, h_c, x, y, t\right]\right] \quad (4.1)$$

This exposure is calculated using MC techniques and the estimated statistical uncertainty is below 3%. Simulating interactions in the relevant energy range requires the use of parton distribution and structure functions that have to be extrapolated to energies where no data is available. This is the main source of systematic uncertainties of this work. The uncertainty in the exposure due to the ν cross-section is estimated to be 15%. The 40% difference among existing calculations for the τ energy losses is used as the systematic uncertainty. Also, we consider a 30% uncertainty due to the polarization of the decaying τ lepton. We considered only

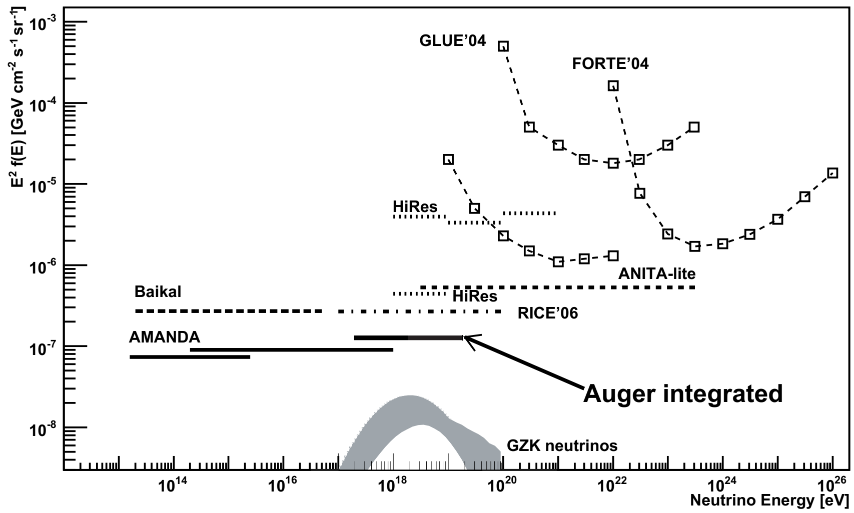

Fig. 3. Limits at 90% C.L. for a diffuse flux of ν_τ from the Pierre Auger Observatory. Limits from other experiments are converted to a single flavour assuming a 1:1:1 ratio of the 3 neutrino flavours and scaled to 90% C.L. where needed. The shaded curve shows the range of expected fluxes of GZK neutrinos from (Engel et al. 2001; Allard et al 2006).

extrapolations that follow the behaviour observed in the regions with experimental data. We also consider a 18% uncertainty from neglecting the contribution of the mountains around the Pierre Auger Observatory to the emerging τ flux and adopt a 25 % systematic uncertainty for the simulations of the EAS and the detector.

The limit set at 90% C.L. is then calculated using the following formula (integrated format):

$$K_{90} = \frac{2.44}{\int \Phi(E_\nu).Exp(E_\nu)dE_\nu} \tag{4.2}$$

This value defines a limit flux K_{90}/E_ν^2 that would lead to 2.44 detected neutrinos for the considered exposure. Assuming a $\Phi(E_\nu) = E_\nu^{-2}$ differential flux of ν_τ, and adopting the most pessimistic scenario for the systematic uncertainties, we obtain:

$$K_{90} = 1.3 \times 10^{-7}\text{GeV cm}^{-2}\text{ s}^{-1}\text{ sr}^{-1} \tag{4.3}$$

The limit is shown in figure 3. In the most optimistic scenario for the systematics, the K_{90} value is divided by a factor ~ 3.

The data collected with the SD of the Pierre Auger Observatory provides at present the most sensitive bound on neutrinos at EeV energies, the most relevant energies to explore the GZK neutrinos. The Pierre Auger Observatory will continue to take data for about 20 years over which time the limit should improve by over an order of magnitude if no neutrino candidate is found.

The full list of references may be found in the original paper (Abraham et al. 2008).

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