Neutrino identification with Auger and $\nu_\tau$ flux limit

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The surface detector array of the Pierre Auger Observatory is sensitive to Earth-skimming $\nu_\tau$. The topological properties of such showers are quite different from hadronic events. Neutrino-induced showers are characterized by very elongated and asymmetric footprints and a significant electromagnetic component. Electrons and gammas produce broad timing signals, whereas hadronic showers give rise to signals mostly due to the surviving secondary muons with a shorter signal in time with respect to an electromagnetic signal. The data collected between 1st January 2004 and 31st August 2007 is used to place an upper limit on the diffuse flux of $\nu_\tau$. Over this period there is not a single event that fulfills the selection criteria. The limit for an $E^{-2}$ differential energy spectrum at 90% C.L. is:

$$E^2 dN_{\nu_\tau}/dE < 1.3 \times 10^{-7} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}.$$ 

1. Introduction

The detection of ultra-high energy (UHE) cosmic neutrinos, above 1 EeV ($10^{18}$ eV), is important as it may allow to identify the most powerful sources in the Universe. In general, a low incoming flux of neutrinos is expected. Due to their low interaction probability, neutrinos need to interact with a large amount of matter in order to be detected. The atmosphere and the Earth offer such a target. Since the Earth is not transparent for neutrinos at the highest energies, one of the detection techniques is based on the detection of extensive air showers (EAS) in the atmosphere. In air, very inclined EAS can be detected only by detectors observing a large volume. Propagating through the Earth, only the so-called Earth skimming tau neutrinos may initiate detectable air showers above the ground [1]. In this case $\nu_\tau$ may interact within the Earth and produce charged leptons which in turn decay into neutrinos with lower energies. This regeneration process repeats until neutrinos reach the detector. Since the interaction length for the produced $\tau$ leptons is a few kilometers at an energy of about 1 EeV, the leptons produced close to the Earth’s surface may emerge from the Earth, decay above the ground and produce EAS potentially detectable by large ground detectors such as the Pierre Auger Observatory [2,3].

The surface detector (SD) of the Pierre Auger Observatory [4] is also sensitive to down-going neutrinos in the EeV range and above. Down-going neutrinos of any flavour may interact through both charged and neutral current interactions producing hadronic and/or electromagnetic showers. Simulations suggest that a good identification criterium is required that there are broad signals in the first two triggered tanks of the event [5].

In this paper we study the signature of up-going $\nu_\tau$-induced showers in the case of the SD of the Pierre Auger Observatory and we report one of the most recent results of the Observatory: an upper limit on the diffuse flux of $\nu_\tau$ [6].

2. Method

Simulation of neutrino signatures, using the surface array of the Observatory, consists of three phases: propagation and interaction inside the Earth and in the atmosphere to produce primaries able to initiate potentially detectable showers in the atmosphere; simulation of lateral
profiles of shower development in the atmosphere and, finally, simulation of the detector response [2]. In particular, the propagation of $\tau$ leptons through the Earth was simulated with different energy loss models. The flux of outgoing leptons as well as their energy and decay vertex position were calculated. Lateral profiles (particle density distributions of secondaries) of shower developments were generated using TAUOLA [7] output as input for the EAS MC generator AIRES [8]. A special mode was used to simultaneously inject several particles or primaries at a given interaction point. A typical footprint from an up-going $\tau$ decay, simulated with AIRES, is shown in Fig. 1. The very elongated structure of the footprint, about 100 km in the x-direction and 8 km in the y-direction, is displayed. Finally a simulation response of the tank to the passage of particles at ground level, obtained in the shower simulation, to an actual detector signal. The central trigger algorithms are applied and the event is stored in the same format as actual data.

3. Results: Identifying and discriminating $\nu$-induced showers

One of the the main experimental challenges for the Pierre Auger Observatory is to discriminate neutrino-induced showers from the background of showers initiated by cosmic rays. The underlying concept of neutrino identification is rather straightforward. Whereas hadrons and photons interact shortly after having entered the atmosphere, neutrinos may penetrate large amounts of matter undisturbed and generate showers close to the surface array. The differences between showers developing close to the detector – so-called young showers – and showers interacting early in the atmosphere – old showers – becomes more and more pronounced as we consider larger zenith angles. For showers initiated by hadronic primaries, which interact within a few $100$ g/cm$^2$, only high-energy muons can survive. As a result, the detected showers show a thin and flat front which leads to short detected signals, lasting only a few hundred nanoseconds. For the case of young neutrino-induced showers a significant electromagnetic component is also present at ground level. The shower front is curved and thick and leads to broad signals, lasting up to a few microseconds. The first step towards the identification of $\nu$-events is the discrimination of inclined young from old showers. The topology of the footprints and the asymmetry in the station signals are the basic ingredients [3,5]. Elongated footprints identify inclined showers (Fig. 2). A tensor of inertia was calculated to evaluate the length ($L$) over the width ($W$) of the patterns on ground. The positions of the stations were weighted by their signals. The elongation of a footprint is defined as $L/W$. An additional parameter which was taken into account is the
so-called mean apparent velocity of a shower on the ground, \(\langle V \rangle\). The mean apparent velocity is defined by averaging the apparent velocity between pairs of stations, defined as \(v_{ij} = \frac{d_{ij}}{\Delta t_{ij}}\) where \(d_{ij}\) is the distance between the pairs, projected onto the direction defined by the length of the footprint, and \(\Delta t_{ij}\) the difference in their signal start times. The mean apparent velocity is expected to be compatible with the speed of light for quasi-horizontal showers, within its statistical error \(\sigma_{\langle V \rangle}\). Young showers are expected to trigger detector stations with broad signals, so called ToT triggers. Such signals are clearly broad signals and counting them can help in identifying young showers. Compact configurations of selected ToTs complete the expected picture of young \(\nu\) shower footprints [3]. The distributions of these discriminating variables for real events and simulated \(\tau\) induced showers are shown in Fig. 3. We see that neutrino candidates are required to have elongated patterns on the ground with ratio \(L/W > 5\) and the average speed is expected to be very close to the speed of light, in the range \((0.29, 0.31)\) m ns\(^{-1}\) with r.m.s. scatter below 0.08 m ns\(^{-1}\).

4. Results: Neutrino exposure and flux limit

Data from January 2004 to August 2007, which equate to about 1 year from the completed surface array, have been analyzed. Over the period analyzed, no candidate events were found that fulfilled the selection criteria. Based on this, the Pierre Auger Observatory data can be used to place a limit on the diffuse flux of UHE \(\nu_{\tau}\). For this purpose the exposure of the detector must be evaluated. The total exposure is the time integral of the instantaneous aperture which has changed as the detector has grown while it was being constructed and set into operation. The expression for the exposure can be written as:

\[
\text{Exp} = \int d\Omega \int_{E_{\nu}}^{E_{\tau}} dE_{\tau} \int_{h_{c}}^{\infty} dh_{c} \frac{d^{2}N_{\tau}}{dE_{\tau} dh_{c}} P_{\tau},
\]

where \(d^{2}N_{\tau}/dE_{\tau} dh_{c}\) is the flux of emerging \(\tau\)s and

\[
P_{\tau}(E_{\tau}, h_{c}) = \int dt \int_{S} dx dy \cos \theta \epsilon(E_{\tau}, h_{c}, x, y, t),
\]

where \(\epsilon(E_{\tau}, h_{c}, x, y, t)\) is the probability to identify a \(\tau\) lepton (identification efficiency) which depends on the energy \(E_{\tau}\), the altitude above ground of the central part of the shower, \(h_{c}\), defined at 10 km after the decay point, the position, \((x, y)\), of the shower in the surface, \(S\), covered by the array, and the time, \(t\), through the instantaneous configuration of the array. Zenith and solid angle are indicated with \(\theta\) and \(\Omega\), respectively.

The calculated identification efficiency for up-going \(\tau\)-induced showers in the range between 90\(^{\circ}\) – 97\(^{\circ}\) is shown in Fig. 4. The efficiency increases with energy and reaches its maximum\(^2\) of about 0.82 for an initial \(\tau\) lepton energy larger than 3 EeV and \(h_{c}\) larger than 200 m above the ground level. However, at higher altitudes, the
detectable shower.

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\(^2\)The efficiency can reach a maximum value of 82.6% due to \(\tau\) decaying into muons which mostly do not produce a detectable shower.
identification efficiency drops again. Moreover, only \( \tau \)-induced showers at the highest energies (above 10 EeV) can trigger the surface detector with \( h_c \) being up to 2500 m above ground.

The MC simulations require some physical quantities that have not been experimentally measured in the relevant energy range, namely, the interaction cross-section, the energy loss, and the polarization. The influence of different cross sections on the calculated exposure is about 15%. The differences in existing calculations for the energy losses [9] leads to 40% uncertainty on the calculated exposure and a conservative estimate of the systematic for a \( \tau \) polarization gives 30% difference in exposure. Other uncertainties come from studying the topography around the site of the Pierre Auger Observatory (18%) and from simulations (25%) [6].

Finally on the basis of the exposure calculations, the limit for an injected spectrum \( K \times \Phi(E_{\nu}) \) with a known shape \( \Phi(E_{\nu}) \) was calculated. The 90% C.L. on the value of \( K \), according to Ref. [10] is \( K_{90\%} = 2.3/NWB \), for negligible background and zero neutrino events observed by the Auger Observatory in the case of the Waxman-Bahcall flux [11]. In such a case the upper limit for \( \nu_\tau \) is

\[
E_{\nu}^2 \Phi(E_{\nu}) < 1.0 \times 10^{-7} \text{ GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}
\]

The result is computed in the energy range from 0.1 EeV to about 10 EeV, where 90% of the expected events are found. The integrated limit is shown in Fig. 5 along with the typical spectra of astrophysical neutrinos [12,13]. Alternatively, a differential sensitivity (being proportional to the inverse of the acceptance, i.e. \( 2.3/(E_{\nu} \Delta \ln(E_{\nu})) \)) is plotted. The best sensitivity is reached at about 1 EeV.

To conclude, the dataset from January 2004 to August 2007, collected by the Pierre Auger Observatory, is used to present upper limits on the diffuse incident \( \nu_\tau \) flux. The skimming technique is flavor-sensitive and together with the configuration of the surface detector gives the best sensitivity around a few EeV, which is the most relevant energy to explore GZK neutrinos. The Pierre Auger Observatory will keep taking data for about 20 years over which the bound will im-

![Figure 5. Limits at 90% C.L. for a diffuse flux of \( \nu_\tau \) from the Pierre Auger Observatory along with limits from other experiments. The shaded curve shows the range of expected fluxes of GZK neutrinos from Ref. [12,13].](image)

prove by over an order of magnitude if no neutrino candidate is found.

REFERENCES