The Pierre Auger Observatory and ultra-high energy neutrinos: upper limits to the diffuse and point source fluxes

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Abstract: With the Surface Detector of the Pierre Auger Observatory, we can detect ultra-high energy neutrinos in the sub-EeV energy range and above. Neutrinos of all flavours can interact in the atmosphere and induce inclined showers close to the ground (down-going). The sensitivity of the Surface Detector to tau neutrinos is further enhanced through the “Earth-skimming” mechanism (up-going). Both types of neutrino interactions can be identified through the broad time structure of the signals induced in the Surface Detector stations. Two independent sets of identification criteria were designed to search for down and up-going neutrinos in the data collected from 1 January 2004 to 31 May 2010, with no candidates found. Assuming a differential flux \( f(E_{\nu}) = kE_{\nu}^{-2} \), we place a 90% CL upper limit on the single flavour neutrino flux of \( k < 2.8 \times 10^{-9} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \) in the energy interval \( 1.0 \times 10^{17} \text{ eV} - 2.0 \times 10^{19} \text{ eV} \) based on Earth-skimming neutrinos and \( k < 1.7 \times 10^{-7} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \) in the energy interval \( 1 \times 10^{17} \text{ eV} - 1 \times 10^{20} \text{ eV} \) based on down-going neutrinos. We also show that the Auger Observatory is sensitive to ultra-high energy neutrinos from a large fraction of the sky, and we place limits on the neutrino flux from point-like sources as a function of declination, and in particular from the active galaxy Centaurus A.

Keywords: UHE neutrinos, cosmic rays, Pierre Auger Observatory

1 Introduction

Essentially all models of Ultra High Energy Cosmic Ray (UHECR) production predict neutrinos as the result of the decay of charged pions, produced in interactions of the cosmic rays within the sources themselves or in their propagation through background radiation fields [1, 2]. Neutrinos are also copiously produced in top-down models proposed as alternatives to explain the production of UHECRs [1]. With the surface detector (SD) of the Pierre Auger Observatory [3] we can detect and identify UHE neutrinos (UHE\(\nu\)s) in the 0.1 EeV range and above. “Earth-skimming” tau neutrinos [4] are expected to be observed through the detection of showers induced by the decay products of an emerging \( \tau \) lepton, after the propagation and interaction of a \( \nu_\tau \) inside the Earth. “Down-going” neutrinos of all flavours can interact in the atmosphere and induce a shower close to the ground [5].

This contribution updates both, Earth-skimming [6, 7, 8] and down-going [8] analyses with data until the 31 May 2010 and shows, for the first time, the sensitivity of the Pierre Auger surface detector to neutrinos from point-like sources.

2 Identifying neutrinos in data

Identifying neutrino-induced showers in the much larger background of the ones initiated by nucleonic cosmic rays is based on a simple idea: neutrinos can penetrate large amounts of matter and generate “young” inclined showers developing close to the SD, exhibiting shower fronts extended in time. In contrast, UHE particles such as protons or heavier nuclei interact within a few tens of g cm\(^{-2}\) after entering the atmosphere, producing “old” showers with shower fronts narrower in time. In Fig. 1 we show a sketch of these two kinds of showers together with an Earth-skimming shower and a \( \nu_\tau \) interacting in the Andes, which can also be identified.

Although the SD is not directly sensitive to the nature of the arriving particles, the 25 ns time resolution of the FADC traces, with which the signal is digitised in the SD stations, allows us to distinguish the narrow signals in time expected from a shower initiated high in the atmosphere from the broad signals expected from a young shower. Several observables can be used to characterise the time structure and shape of the FADC traces. They are described in [9] where their discrimination power is also studied.

In this work we use two different sets of identification criteria to select neutrinos. One is used to define Earth
skimming tau neutrinos and the other for down-going neutrinos. They are given in Table 1 and described in the following.

Table 1: Criteria to select Earth-skimming $\nu_\tau$ and down-going $\nu$. See text for details.

<table>
<thead>
<tr>
<th></th>
<th>Earth-skimming</th>
<th>Down-going</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclined</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Showers</td>
<td>$N^o$ of Stations $\geq 3$</td>
<td>$N^o$ of Stations $\geq 4$</td>
</tr>
<tr>
<td></td>
<td>$L/W &gt; 5$</td>
<td>$L/W &gt; 3$</td>
</tr>
<tr>
<td></td>
<td>$0.29 &lt; V &lt; 0.31$</td>
<td>$V &lt; 0.313$</td>
</tr>
<tr>
<td></td>
<td>RMS($V$) $&lt; 0.08$</td>
<td>RMS($V$) $&lt; 0.08$</td>
</tr>
<tr>
<td></td>
<td>$\theta_\text{rec} &gt; 75^\circ$</td>
<td>$\theta_\text{rec} &gt; 75^\circ$</td>
</tr>
<tr>
<td>Young</td>
<td>ToT fraction $&gt; 0.6$</td>
<td>Fisher discriminator based on AoP</td>
</tr>
</tbody>
</table>

The analyses start with the inclined shower selection (down-going $\theta > 75^\circ$ and Earth-skimming $\theta < 96^\circ$). These showers usually have elongated patterns on the ground along the azimuthal arrival direction. A length $L$ and a width $W$ are assigned to the pattern and a cut on their ratio $L/W$ is applied. We also calculate the apparent speed $V$ of an event using the times of signals at ground and the distances between stations projected onto $L$. Finally, for down-going events, we reconstruct the zenith angle $\theta_\text{rec}$. Once we have selected inclined showers we look for young showers. A station having signals extended in time usually has a Time over Threshold (ToT) local trigger while narrow signals have other local triggers [3, 10]. The Earth-skimming analysis identifies young showers placing a cut on the fraction of ToT stations (ToT fraction). For down-going events, to optimize the discrimination power, we use the Fisher discriminant method using AoP (area of the FADC trace over its peak value, which gives an estimate of the spread in time of the signal) as input variables. The advantage of the Fisher discriminant is that it allows us to place an optimized cut to reject backgrounds from regular hadronic showers, and that it provides an a priori measure of how neutrino-like a possible candidate is.

3 Exposure and limit on the diffuse flux

The Earth skimming and down-going criteria are applied to data collected from 1 Jan 04 to 31 May 10, and from 1 Nov 07 to 31 May 10, respectively. The down-going sample is smaller than the Earth-skimming one because data from 1 Jan 04 to 31 Oct 07 was used as a training sample for the Fisher discriminator $^1$. Due to the fact that the Observatory was continuously growing during the construction phase (2004 - 2008) and that the SD is a dynamic array (some stations can occasionally be not operative), the previous periods correspond to 3.5 yr (Earth-skimming) and 2 yr (down-going) of data of a full SD array. No neutrino candidates were found and an upper limit on the diffuse flux of ultra-high energy neutrinos can be placed.

For this purpose the exposure of the SD array to UHE neutrinos is calculated. For down-going neutrinos, this involves folding the SD array aperture with the interaction probability and the identification efficiency, and integrating in time, taking into account changes in the array configuration due to the installation of new stations and other changes. The identification efficiency $\varepsilon$ for the set of cuts defined above depends on the neutrino energy $E_{\nu}$, the slant depth $D$ from ground to the neutrino interaction point, the zenith angle $\theta$, the core position $\vec{r} = (x, y)$ of the shower in the surface $S$ covered by the array, and the time $t$ through the instantaneous configuration of the array. Moreover it depends on the neutrino flavour ($\nu_e$, $\nu_\mu$, or $\nu_\tau$), and the type of interaction – charged (CC) or neutral current (NC) – since the different combinations of flavour and interaction induce different types of showers. The efficiencies $\varepsilon$ were obtained through MC simulations of the first interaction between the $\nu$ and a nucleon with HERWIG [11], of the development of the shower in the atmosphere with AIRES [12], and of the response of the surface detector array, see [9] for more details. Assuming a 1:1:1 flavour

$^1$ In the case of Earth-skimming analysis, data from 1 Nov to 31 Dec 04 was used as a test sample and excluded from the search sample.
ratio, the total exposure can be written as:

$$E_{DG}^{k}(E_{\nu}) = \frac{2\pi}{m} \sum \sigma^{i}(E_{\nu}) \int dt \, d\theta \, dD \, dS \sin \theta \cos \theta \, e^{i(\bar{r}, \theta, D, E_{\nu}, t)}$$  \hspace{1cm} (1)$$

where the sum runs over the 3 neutrino flavours and the CC and NC interactions, $m$ is the mass of a nucleon, and $\sigma^{i}$ is the $\nu$ cross section with a nucleon. For $\nu_{\tau}$ we have taken into account the possibility that it produces a double shower in the atmosphere triggering the array – one in the $\nu_{\tau}$ CC interaction itself and another in the decay of the $\tau$ lepton. Furthermore, we consider the possibility of a $\nu_{\tau}$ interacting in the Andes inducing a shower through the decay products of the $\tau$ lepton.

For the Earth-skimming neutrinos the procedure is described in Ref [7].

In Fig. 2 we show both the Earth-skimming and down-going exposures for the respective search periods. Several sources of systematic uncertainties have been taken into account and their effect on the exposure evaluated. For down-going neutrinos there is $\sim 30\%, 10\%$] systematic uncertainty in the exposure due to the neutrino-induced shower simulations and the hadronic models. Another source of uncertainty comes from the neutrino cross section which is $\sim 10\%$ [13]. For the Earth-skimming showers the systematic uncertainties are dominated by the tau energy losses, the topography and the shower simulations [7].

Using the computed exposures and assuming a typical $f(E_{\nu}) = k \cdot E_{\nu}^{-2}$ differential neutrino flux and a 1:1:1 flavour ratio, an upper limit on the value of $k$ can be obtained. We use a semi-Bayesian extension [14] of the Feldman-Cousins approach [15] to include the uncertainties in the exposure. The updated single-flavour 90\% C.L. limit based on Earth-skimming neutrinos is: $k < 2.8 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ in the energy interval $1.6 \times 10^{17}$ eV $- 2.0 \times 10^{19}$ eV and the updated single-flavour 90\% C.L. limit based on down-going neutrinos is: $k < 1.7 \times 10^{-7}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ in the energy interval $1.0 \times 10^{17}$ eV $- 1.0 \times 10^{20}$ eV. These results are shown in Fig. 3 incorporating the limit in different bins of width 0.5 in log$_{10} E_{\nu}$ (differential limit) to show at which energies the sensitivity of the Pierre Auger Observoty peaks. The expected number of events from a cosmogenic [17] (neutrinos produced by the interaction of cosmic rays with background radiation fields) and an exotic model [18] (neutrinos produced due to the decay of heavy particles) are given in Table 2.

4 Limits to point-like sources

As we found no candidate events in the search period, we can place a limit on the UHE neutrino flux from a source at declination $\delta$.

A point source moves through the sky so that it is visible from the SD of the Pierre Auger Observatory with zenith angle $\theta(t)$ which depends on the sidereal time $t$. For an observatory located at a latitude $\lambda$ the relation between the zenith angle and the declination of the source $\delta$ is given by:

$$\cos \theta(t) = \sin \lambda \sin \delta + \cos \lambda \cos \delta \sin(\omega t - \alpha_0)$$  \hspace{1cm} (2)$$

with $\omega = 2\pi/T$, where $T$ is the duration of one sidereal day and $\alpha_0$ depends on the right ascension.

The sensitivity to UHE$\nu$s is limited to large zenith angles so the rate of events from a point source in the sky depends strongly on its declination. The point-source exposure $E_{PS}^{k}(E_{\nu}, \delta)$ can be obtained in a similar way as the diffuse exposure but avoiding the integration in solid angle and taking into account that the probability of neutrino
Identification $\varepsilon$ depends on $\theta$, while the $\theta$ of the source depends on sidereal time through Eq. (2). Also $\varepsilon$ itself depends explicitly on time because the configuration of the SD array changes with time.

We perform the integration over time and we obtain the point source exposure which depends not only on $E_\nu$, but also on $\delta$. Assuming now a point source flux which decreases in energy as $g(E_\nu) = k^{PS} E_\nu^{-2}$ and a 1:1:1 flavour ratio, we can obtain a point source upper limit $k^{PS}(\delta)$.

In Fig. 4 we show the value of $k^{PS}$ as a function of the declination of the source. In both Earth-skimming and down-going analyses the sensitivity has a broad "plateau" spanning $\Delta \delta \sim 100^\circ$ in declination. We also show the sensitivity of IceCube which is at a lower neutrino energy.

In Fig. 5 we show the constraints on $k$ for the case of the active galaxy Centaurus A (CenA) at a declination $\delta \sim -43^\circ$. We also show three models of UHE$\nu$ production in the jets and the core of CenA [21]. The expected number of events from each of these models with the current exposure is given in Table 2.

<table>
<thead>
<tr>
<th>Diffuse flux model</th>
<th>Earth-skimming</th>
<th>Down-going</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmogenic</td>
<td>0.71</td>
<td>0.14</td>
</tr>
<tr>
<td>Exotic</td>
<td>3.5</td>
<td>0.97</td>
</tr>
<tr>
<td>CenA flux model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cuoco et al.</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>Kachelriess et al.</td>
<td>0.006</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Table 2: Expected number of events for two diffuse neutrino flux models and two CenA neutrino flux models.

Figure 4: Neutrino flux limits to a $E^{-2}$ differential neutrino flux from a point source as a function of the declination of the source, as obtained with the SD of the Pierre Auger Observatory for $1.6 \times 10^{17}$ eV $- 2.0 \times 10^{19}$ eV (Earth-skimming) and $1 \times 10^{17}$ eV $- 1 \times 10^{20}$ eV (down-going). Also shown is the limit obtained by IceCube [19] that applies below $10^{17}$ eV (or lower depending on declination).

Figure 5: Limits on Cen A coming from the Earth-skimming and down-going analyses. Also shown are limits from IceCube [19] and LUNASKA [20] in different energy ranges and three theoretical predictions [21].

References