Search for Ultra-High Energy Neutrinos with the Pierre Auger Observatory

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Abstract

The Pierre Auger Observatory is sensitive to extensive air showers induced by ultra-high energy neutrinos of all flavours as they interact with the atmosphere and inside the Earth's crust. These air showers display characteristic features that allow their identification. We report on recent searches for ultra-high-energy neutrinos at the Pierre Auger Observatory. We present the different identification criteria used, discuss the sources of background and systematic uncertainties, and place the corresponding limits on the neutrino fluxes.

1. Introduction

It has long been recognized that neutrinos should be produced while cosmic rays are being accelerated to ultra-high energies, thereby creating sources of *astrophysical neutrinos*. In addition to that, ultra-high energy cosmic rays (UHECRs) could produce neutrinos as they interact with the cosmic background radiation fields, producing a diffuse flux of *cosmogenic neutrinos* [1, 2]. The observation of these neutrinos would open new possibilities to study the universe.

Although the primary goal of the Pierre Auger Observatory is to detect UHECRs, UHE Earth-skimming τ neutrinos can be observed through the detection of showers induced by the decay of emerging τ leptons which are created by ν_τ interactions in the Earth's crust [3] and neutrinos of all flavours can be detected when they interact deep in the atmosphere [4]. Limits on the diffuse flux of τ neutrinos in the EeV range and above have been set recently [5] and using earlier Auger data [6, 7].

The main challenge in detecting UHE neutrinos with the Pierre Auger Observatory is the identification of a neutrino-induced shower in the background of showers initiated by UHECRs, most probably protons or heavy nuclei [8] and perhaps photons, although in a much smaller proportion [9–11].

In this contribution we will discuss the different modes of neutrino detection and discrimination with the Pierre Auger Observatory. We will update the limits on the diffuse flux of τ neutrinos presented in [7] and present limits on the diffuse and point source fluxes of neutrinos of all flavours.

2. Detector Description

The surface detector (SD) of the Pierre Auger Observatory consists of 1660 water Cherenkov detectors over an area of $3000\,\mathrm{km}^2$, arranged on a triangular grid of 1.5 km spacing. Each detector station consists of a cylindrical polyethylene tank, 3.6 m in diameter and 1.2 m tall, lined with highly reflective diffusive Tyvek®, and containing 12 tons of purified water. A detailed description can be found in [12].

Two different trigger modes are implemented in the stations, a simple threshold peak trigger requiring that the signal on some photomultipliers exceeds certain value and a *time over threshold* trigger (TOT) requiring that, within a specified time window, a minimum number of time bins is over a given value.

3. Event Selection and Neutrino Discrimination

Neutrino-induced showers can be detected in two different modes: an *Earth-skimming* mode in which a tau neutrino interacts inside the Earth at a point in the vicinity of the detector, producing an air shower that emerges from the ground and passes through the detector; and a *down-going* mode in which a neutrino of any flavour interacts deeply in the atmosphere (at depths of several $100\,\mathrm{g\,cm}^{-2}$ or more) and the resulting air shower falls on the detector.

Table 1: Criteria for selecting inclined events (middle rows) and neutrino discrimination (bottom row).

Down-going	Earth-skimming
4 stations	3 stations
$\theta > 75°$	
L/W > 3	L/W > 5
$V < 0.313\ \frac{m}{ns}$	$0.29\ \frac{m}{ns} < V < 0.31\ \frac{m}{ns}$
$\delta V/V < 8\%$	$\delta V < 0.08\ \frac{m}{ns}$
Fisher discriminant	ToT fraction >6

The background in the search for air showers induced by neutrinos consists of showers induced by hadronic primaries and photons. These showers are initiated within the first several 100 g cm^{-2} of traversed atmosphere and their electromagnetic component is absorbed after traversing about twice the vertical depth of the Auger Observatory (880 g cm^{-2}). On the other hand, neutrinos can interact deep in the atmosphere. We therefore look for *young* showers that have traversed a significant depth in the atmosphere. That is: highly inclined showers that still have a measurable electromagnetic component.

The observables used to select highly inclined showers are associated with the *footprint* of the shower: the geometric pattern formed by the stations with signals. This pattern has a roughly ellipsoidal shape, with a major (L) and a minor axis (W) given by the square roots of the eigenvalues of a symmetric matrix with each term given by:

$$A_{ab} = \frac{\sum_i s_i (x_i^a - \langle x^a \rangle)(x_i^b - \langle x^b \rangle)}{\langle s \rangle} \tag{1}$$

where $\langle s \rangle$ is the average station signal, i is an index over the stations in the event, s_i is the signal of the i-th station, a and b are indices over the two plane coordinates (x and y), and $\langle x^a \rangle$ is given by

$$\langle x^a \rangle = \frac{\sum_i s_i x_i^a}{\langle s \rangle} \tag{2}$$

One can also define a *ground speed* of the signal between two stations (i,j) as $V_{ij} = d_{ij}/\Delta t_{ij}$, where d_{ij} is the distance between the stations, projected on the major axis of the footprint, and Δt_{ij} is the difference in the start times of the signals. It is then possible to select highly inclined events by imposing a cut on the values of L/W, the average ground speed $\langle V \rangle$, and the standard deviation of the ground speed distribution (δV). The values of the cuts are shown in table 1.

The selection of young showers is done by requiring a significant contribution from the electromagnetic component in some stations in the event. A station with significant electromagnetic contribution is characterized by broad signals that produce a TOT trigger or by large values of the *Area over Peak* variable (AoP), defined as the ratio of the integrated signal to its peak value normalized to 1 for signals from a single particle. In the Earth-skimming mode, the discrimination is done by requiring that a given percentage of the stations in the event produce TOT triggers (*cf.* table 1).

In the down-going mode the discrimination is done using the Fisher discriminant method using ten variables: the AoP variable of the first four (time-ordered) stations, their squares, their product and a global AoP asymmetry parameter. The cut on the Fisher discriminant is chosen so that the estimated number of background events, assuming an exponential extrapolation of the tail of the data distribution, is less than one every 20 years.

For the *down-going* mode, the discrimination method was tuned using data taken in the period from January 1st 2004 until October 31st 2007 while for the *Earth-skimming* mode it was tuned using data taken in the period from November 1st 2004 until December 31st 2004.

4. Neutrino Exposure

In order to calculate the exposure to (*down-going*) neutrinos, we first estimate the probability, ε, that a shower triggers the surface detector and is identified as a neutrino. This probability depends on the neutrino flavour and

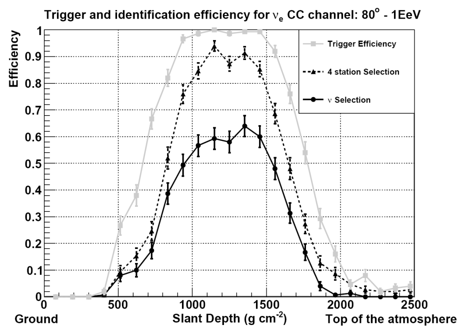

Figure 1: Example of trigger, selection and identification efficiencies for 1 EeV, 80° zenith angle neutrino showers.

interaction channel, either charged current (CC) or neutral current (NC), and is also a function of neutrino energy E_ν, incident zenith angle θ, the atmospheric depth of the interaction X, and the detector configuration at the time considered, t. This was estimated using MC simulations of the first interaction between the neutrino and a nucleon with HERWIG [13], the development of the shower in the atmosphere with AIRES [14] and the response of the SD array using the Auger $\overline{\text{Off}}\underline{\text{line}}$ simulation package [15]. The τ lepton decay is simulated with TAUOLA [16]. For these simulations, a detailed description of the topography around the detector was used to estimate the contribution from ν_τ interacting in the mountains.

The effective area of the detector at a given energy, arrival direction and depth of first interaction and time is given by:

$$A_{eff}(E_\nu, \theta, X, t) = \int \varepsilon(\vec{r}, E_\nu, \theta, X, t) dA \tag{3}$$

and this can in turn be used to calculate the exposure

$$\begin{aligned} \mathcal{E}(E_\nu) =& 2\pi \sum_i \left[\frac{\omega^i \sigma^i(E_\nu)}{m} \right. \\ & \left. \iiint \sin\theta \cos\theta A^i_{eff}(E_\nu, \theta, X, t) d\theta \, dX \, dt \right] \end{aligned} \tag{4}$$

where the sum runs over the three neutrino flavours and the CC and NC interaction channels, σ is the neutrino cross section, and m is the mass of a nucleon.

Table 2: Ratio of expected number of Earth-skimming ν_τ for either GZK-like or for E^{-2} incident spectra in the most and least favorable scenarios for each source of systematic uncertainties [7].

Source	Factor
EAS Simulations	1.30
Topography	1.18
Cross section	1.15
Energy losses	1.40

If we assume a full $\nu_\tau \leftrightarrow \nu_\mu$ mixing, $\omega^i = 1$ for the three flavours.

Different sources of systematic uncertainty have been considered. In the case of Earth-skimming neutrinos, the uncertainty is dominated by the τ energy losses, and air shower simulations, as shown in table 2 [7] while for down-going neutrinos there is a [-30%, 10%] systematic uncertainty in the exposure due to air shower simulation and uncertainties in hadronic interaction models, and 10% [17] due to the uncertainty in the neutrino cross section.

5. Diffuse Flux Limit

A blind scan over the data from November 1st 2007 until May 31st 2010 ($\sim$ 2 years of full SD data collection) in the *down-going* mode, and from January 1st 2004 until May 31st 2010 excluding the training sample ($\sim$ 3.5 years of full SD) in the *Earth-skimming* mode, reveals no candidates and we can place limits on the flux of UHE neutrinos. This corresponds to an upper bound of 2.44 events with a confidence level of 90%, assuming 0 expected background events [18]. The expected number of events, for several theoretical models of UHE neutrino production, are displayed in the upper part of table 3. The systematic uncertainties in the exposure can be included in the determination of the limit. This is done using a semi-bayesian extension of the Feldman-Cousins method proposed by Conrad et al. [19].

Assuming a differential neutrino flux of the form $f(E_\nu) = k \cdot E_\nu^{-2}$, the upper

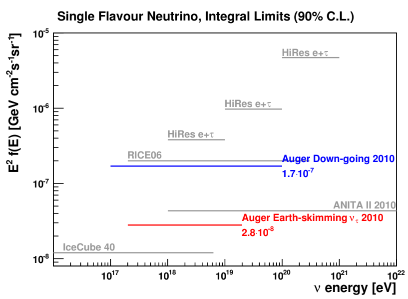

Figure 2: Integral upper limits (90% C.L.) for a diffuse flux of UHE neutrinos from the Pierre Auger Observatory [5].

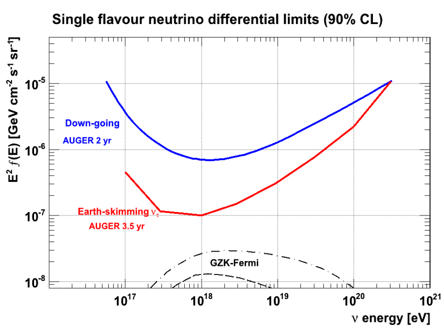

Figure 3: Differential upper limits (90% C.L.) for a diffuse flux of UHE neutrinos from the Pierre Auger Observatory [5]. Also shown is the theoretical prediction from Ahlers et al.[24].

limit for k is given by

$$k < \frac{2.44}{\int \mathcal{E}(E_\nu) E_\nu^{-2} dE_\nu} \tag{5}$$

and the resulting values can be seen in figure 2 together with the current differential flux limits from IceCube [20], ANITA II [21], RICE [22] and HiRes [23].

The limits on the differential flux are displayed in figure 3, where we assumed a spectrum of the form E_ν^{-2} within each energy bin.

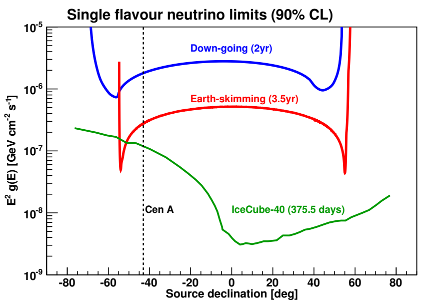

Figure 4: Upper limit (90% C.L.) for the integral flux of neutrinos from point sources at different declinations.

6. Point-like Source Flux Limit

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 δ. At a given local sidereal time t, a point source is visible from the SD of the Pierre Auger Observatory with zenith angle $\theta(t)$:

$$\cos\theta(t) = \sin\lambda\sin\delta + \cos\lambda\cos\delta\sin(\omega t - \alpha_0) \tag{6}$$

with $\omega = 2\pi/T$, where T is the duration of one sidereal day, λ is the latitude of the observatory, and α_0 is the right ascension of the point source. As a result, the sensitivity to neutrinos originating at the point source is a function of local sidereal time. We can then integrate the sensitivity over time and the resulting exposure will depend on E_ν and δ.

Assuming a point source neutrino flux of the form $f(E_\nu) = k_{PS} \cdot E_\nu^2$ and a 1:1:1 flavour ratio, we can obtain an upper limit on k_{PS}. In both the Earth-skimming and the down-going analyses the sensitivity has a broad *plateau* spanning $\Delta\delta \sim 100°$ in declination. The result is shown in figure 4 as a function of declination, together with the sensitivity of the IceCube detector, although this corresponds to energies between 2×10^6 and 6.3×10^9 GeV.

In figure 5 we show the constraints on k_{PS} for the case of the Centaurus A AGN (CenA) at a declination $\delta \sim -43°$. We also show predictions for three

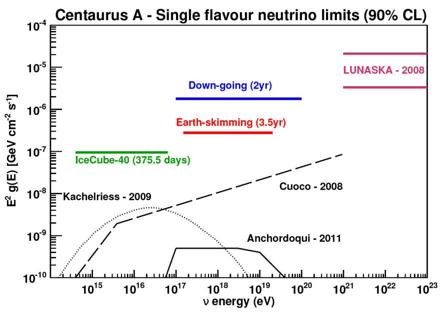

Figure 5: Upper limit (90% C.L.) for the integral flux of neutrinos from Centaurus A together with the predictions for three models [26–28].

Table 3: Expected number of events for two diffuse neutrino flux models [24, 25] and two CenA neutrino flux models [26, 27].

Diffuse flux model	Earth-skimming	Down-going
Cosmogenic	0.71	0.14
Top-down	3.5	0.97
CenA flux model	**Earth-skimming**	**Down-going**
Cuoco et al.	0.10	0.02
Kachelriess et al.	0.006	0.001

models of UHE ν production in the jets and the core of CenA. The expected number of events from each of these models with the current exposure is given in Table 3.

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