

# LIMIT ON UHE NEUTRINO FLUXES FROM THE PIERRE AUGER OBSERVATORY

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**ABSTRACT.** The surface detector of the Pierre Auger Observatory is sensitive to Ultra High Energy (UHE) neutrinos. Neutrinos of all flavors can interact in the atmosphere producing inclined showers near the ground. Moreover, ultra high energy Earth-skimming tau neutrinos can be observed through the detection of showers induced by the decay of tau leptons created by interactions in the Earth's crust. In both cases, neutrino showers can be identified through the time structure of the signals in the surface detector stations. Two sets of identification criteria have been designed to search for down-going and up-going neutrinos in the recorded data, with no candidates found. We will discuss the identification criteria used, and we will present the corresponding limits on the diffuse and point source neutrino fluxes.

**KEYWORDS:** UHE neutrinos, Pierre Auger Observatory.

## 1. INTRODUCTION

All the proposed models for the origin of Ultra High Energy Cosmic Rays (UHECR, as are usually named cosmic rays with  $E > 10^{18}$  eV) predict a flux of high energy neutrinos, mainly via charged pion decay following interactions on matter and radiation. Such interactions can occur at the acceleration site itself (“astrophysical neutrinos”) or during the propagation in the background radiation field (“cosmogenic neutrinos”) [1, 2]. The detection of UHE neutrinos would open a new observation window to the universe.

The Pierre Auger Observatory, is located in the province of Mendoza, Argentina at a mean altitude of 1400 m a.s.l. It uses two different techniques to detect the air showers: an array of about 1660 water Cherenkov detectors, placed at a distance of 1.5 km from each other, samples the particles at ground level over an area of about 3000 km<sup>2</sup> (surface detector, SD [3]), while a fluorescence detector (FD [4]) observes the ultra-violet light emitted by atmospheric nitrogen excited by the particles of the shower. The FD consists of 27 telescopes located at four sites at the edges of the ground array. As it operates only during moon-less nights it has a duty cycle of  $\sim 15\%$ , while the SD has a duty cycle of almost 100%.

Although the main goal of the Auger Observatory is the detection of extensive air showers produced by UHECRs, it has a good detection and identification capability for neutrinos with energies above  $10^{17}$  eV. At such energy, neutrinos of all flavors can interact in the atmosphere inducing a “down-going” (DG) shower that can be detected at ground. In addition, Earth-skimming (ES) tau neutrinos can undergo charge current interaction inside the Earth, generat-

ing a tau lepton that can emerge and decay in the atmosphere, giving an upward-going air shower. Even if tau neutrinos are not predicted to be produced at astrophysical sources, the flux at Earth will be equally distributed between all neutrino flavors due to neutrino oscillations. The neutrino search is based on the data from the surface detector. Each SD station consists of a cylindrical polyethylene tank, 3.6 m in diameter and 1.2 m tall, containing 12 tons of purified water. Three large photocatode photomultipliers detect the Cherenkov light emitted by relativistic particles crossing the water volume and their signals are digitalized with sampling rate of 40 MHz. Two different trigger modes are implemented in the stations, a simple threshold trigger and a time over threshold trigger (ToT) requiring that at least 13 samples are over a lower threshold within a sliding window of 3  $\mu$ s (120 samples).

## 2. IDENTIFICATION OF $\nu$ CANDIDATES

Neutrino induced showers have to be extracted from a large background of cosmic ray showers (protons or heavier nuclei). At large zenith angles ( $\theta > 75^\circ$ ), nucleonic showers will be dominated at the ground by the muonic component, as the electromagnetic ones are almost completely absorbed in the atmosphere (old showers). On the other hand neutrino induced showers (DG or ES) initiated near the detector will be electromagnetic rich (young showers). The key point for the neutrino discrimination is therefore the selection of deeply interacting (young) inclined showers. At very large zenith angles (above  $90^\circ$  in the ES case) the standard event reconstruction algorithms are not reliable and, therefore, in order to select very

inclined events, some more general shower characteristics are exploited: the shape of the shower footprint at ground and the apparent ground speed. The pattern of the triggered SD stations for an inclined shower is an elongated ellipse, with the major axis ( $L$ ) along the shower arrival direction and the minor axis ( $W$ ) perpendicular to that direction (see [5] for the details of the definitions of  $L$  and  $W$ ). A very inclined event has a large  $L/W$  ratio. The ground speed is defined as  $V_{ij} = d_{ij}/\Delta t_{ij}$ , where  $d_{ij}$  is the distance between two stations participating in the event, and  $\Delta t_{ij}$  is the difference between the start time of the signal in the two stations. The average ground speed (obtained by averaging over all the pairs of stations in the event) is close to the speed of light for a horizontal shower, while it is much larger in the case of a vertical event. A set of cuts (listed in Tab. 1) on the  $L/W$ , the average signal speed ( $V$ ) and its dispersion ( $\sigma_V$ ) have been implemented for the DG and ES channels to select showers in the zenith angle ranges between  $75^\circ < \theta < 90^\circ$  and  $90^\circ < \theta < 96^\circ$  respectively. In addition we require at least 3 and 4 triggered stations for the ES and DG channels and in the case of the DG analysis a further cut on the reconstructed zenith angle is used.

The selection of events with a large electromagnetic component is based on the time structure of the signals recorded by the ground detectors. In fact, a shower with a significant electromagnetic component at the ground produces a signal in the triggered SD stations which is broader in time (hundreds of nanoseconds) with respect to the one given by “old”, muon-dominated showers (tens of nanoseconds). The main observable is the ratio of the integrated signal charge collected by the photomultipliers over its peak height (Area over Peak, AoP) normalized to that of isolated muons (periodically collected for calibration and monitoring purposes), which is sensitive to the time spread of the signal. In addition, stations with a broad signal usually satisfy the time over threshold (ToT) local trigger condition.

The selection criteria have been optimized using Monte-Carlo simulations to estimate the expectations from neutrino induced showers while the background is estimated using a subsample of the SD data (training data), to take into account the actual primary cosmic rays composition and all possible detector effects that may not be reproduced by simulations. In the Earth-skimming analysis the selection of young showers is done applying a cut on the fraction of stations satisfying the ToT trigger condition and with  $\text{AoP} > 1.4$ . In the down-going case, the discrimination is performed using the Fisher discriminant method [6] to improve the separation of neutrinos and background. The variables used are the AoP of the first (time ordered) 4 triggered stations and some combinations of them (their squares and their product), and the difference in AoP between “early” and “late” stations. The cut on the Fisher discriminant is fixed requiring 1 background event in 20 years.

Down-going (DG)	Earth skimming (ES)
n. stations $\geq 4$	n. stations $\geq 3$
$\theta_{\text{rec}} > 75^\circ$	
$L/W > 3$	$L/W > 5$
$V < 0.313 \text{ m ns}^{-1}$	$0.29 \text{ m ns}^{-1} < V < 0.31 \text{ m ns}^{-1}$
$\sigma_V/V < 0.08$	$\sigma_V < 0.08 \text{ m ns}^{-1}$
Fisher discriminant based on AoP	fraction of stations with ToT trigger AND AoP $> 1.4$ greater than 60%

TABLE 1. Criteria used for the selection of inclined events (upper part) and for the neutrino discrimination (lower part).

In the Earth-skimming case the training data subsample goes from 1 Nov 2004 to 31 Dec 2004, while it is from 1 Jan 2004 to 31 Oct 2007 for DG events<sup>1</sup>. The remaining events (search sample) were not used until all the selection algorithms were defined, and only at that point they were “unblinded”.

### 3. EXPOSURE AND LIMITS TO DIFFUSE FLUX

The neutrino selection criteria are applied to the search samples (from 1 Jan 2004 to 31 May 2010 for ES and from 1 Nov 2007 to 31 May 2010 for DG) for both the down-going and Earth-skimming searches, resulting in zero candidates being found. To be able to give an upper limit to the neutrino flux, we need to compute the neutrino exposure of the surface detector. This is obtained by folding the array aperture, the efficiency of the neutrino identification (given by the combination of the trigger probability of the array and the selection cuts) and the  $\nu$  interaction probability, and integrating over time. For down-going neutrinos the identification efficiency depends on the neutrino flavor and interaction channel, its energy, incident zenith angle  $\theta$ , and depth of the interaction. In the case of Earth-skimming  $\nu_\tau$  it depends mainly on the neutrino energy and on the height above ground of the shower induced by tau decay.

The exposure is computed by means of Monte-Carlo simulations, taking into account the time evolution of the SD array. The first interaction between a neutrino and nucleon is simulated with the HERWIG package [7], the development of the shower in the atmosphere with AIRES [8], and the response of the SD detectors using the Auger simulation framework. In the case of  $\nu_\tau$  CC interactions, the decay of the  $\tau$  lepton is simulated with TAUOLA [9]. For the DG  $\nu_\tau$  channel a detailed description of the topography around the detector was used to estimate the contribution from  $\nu_\tau$  interacting in the Andes. The accumulated exposure corresponding to the search periods for the

<sup>1</sup>As DG  $\nu$ -induced showers are more similar to cosmic ray showers, more statistics is required for the evaluation of the background.

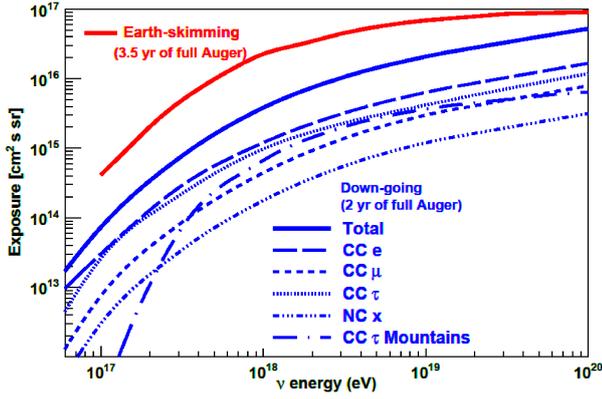


FIGURE 1. Exposure of the surface detector for ES and DG neutrino induced showers, corresponding respectively to 3.5 and 2 years of the complete and fully efficient surface detector (the deployment of the SD was concluded by the end of 2008).

Earth-skimming	down-going
$k < 3.2 \times 10^{-8} \frac{\text{GeV}}{\text{cm}^2 \text{s sr}}$	$k < 1.7 \times 10^{-7} \frac{\text{GeV}}{\text{cm}^2 \text{s sr}}$
$\sim 0.16 < E_\nu [\text{EeV}] < 20.0$	$\sim 0.1 < E_\nu [\text{EeV}] < 100.0$

TABLE 2. 90 % C.L. upper limits to the single flavor neutrino flux and corresponding energy range, for Earth-skimming and down-going searches.

Earth-skimming and down-going analysis are shown in Fig. 1. The main sources of uncertainties for DG neutrinos came from the  $\nu$  induced shower simulation and the hadronic models used (+9%, -33%), and from neutrino cross-sections ( $\pm 7\%$ ). For ES neutrinos the dominant uncertainties comes from the tau energy losses (+25%, -10%), shower simulation (+20%, -5%), and topography (+18%, 0%). Assuming a neutrino flux  $f(E_\nu) = k E^{-2}$ , and a complete neutrino mixing (flavor ratio 1:1:1), the upper limits to the single flavor neutrino flux are derived using a semi-Bayesian extension [10] of the Feldman–Cousins approach [11], that allows one to include in the limits the systematic uncertainties on the exposure cited above. The 90 % C.L. limits are shown in Tab. 2, together with the energy range in which they are derived.

The resulting flux upper limits are also shown in Fig. 2, together with the results from IceCube Neutrino Observatory [12] and the ANITA experiment [13], and flux predictions for cosmogenic neutrinos under different assumptions [14, 15]. The limits on the differential flux are also shown, assuming a spectrum of the form  $E^{-2}$  in each energy bin.

#### 4. LIMITS TO POINT-LIKE SOURCES

As the neutrino search is limited to large zenith angles (75° to 96°), a point-like source can be seen only for a fraction of the sidereal day, depending on its declination. In fact, a point in the sky with declination

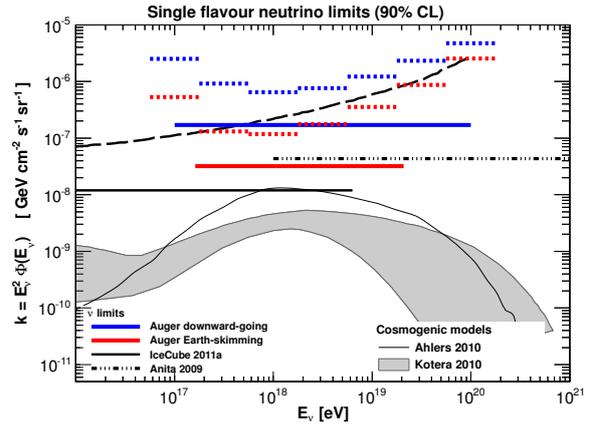


FIGURE 2. Integrated (solid lines) and differential (dashed lines) 90 % C.L. upper limits to the single flavor diffuse flux of down-going  $\nu$  and Earth-skimming  $\nu_\tau$ , as a function of neutrino energy. Limits from the IceCube [12] and ANITA [13] experiments and predictions for cosmogenic neutrinos under different assumptions [14, 15] are also shown.

$\delta$  and right ascension  $\alpha$  at a given sidereal time  $t$  is seen at the observatory latitude ( $\lambda = -35.2^\circ$ ) with a zenith angle  $\theta$  given by

$$\cos(\theta) = \sin \lambda \sin \delta + \cos \lambda \cos \delta \sin(2\pi t/T - \alpha) \quad (1)$$

being  $T$  the duration of sidereal day. The declination range accessible with this analysis is between  $-65^\circ$  and  $55^\circ$ , while the regions near the terrestrial poles are not observable.

The point source exposure is evaluated in a similar way as the diffuse exposure but avoiding to integrate over the solid angle [16]. Assuming a differential flux  $f(E_\nu) = k_{\text{PS}} E^{-2}$ , 1:1:1 neutrino flavor ratio, the upper limits to  $k_{\text{PS}}$  are derived as function of source declination, in the same way as in the diffuse case. The 90 % C.L. upper limits for the DG and ES analyses are shown in Fig. 3 as a function of declination. In both analyses we have a region of about  $100^\circ$  in declination where the sensitivity is almost constant, and the limits on  $k_{\text{PS}}$  are at the levels of  $\approx 5 \times 10^{-7}$  for the ES analysis and  $\approx 2.5 \times 10^{-6} \text{ GeV cm}^{-2} \text{ s}^{-1}$  for the DG analysis. The shapes of the declination dependent limits are determined mainly by the fraction of time in which a source is within the zenith angle range of DG and ES searches. The upper limits are derived for neutrino energies from  $1.6 \times 10^{17}$  to  $2.0 \times 10^{19}$  eV and from  $1 \times 10^{17}$  to  $1 \times 10^{20}$  eV for the Earth-skimming and the down-going analysis respectively.

In Fig. 4 we show the limits on  $k_{\text{PS}}$  for the particular case of the active galaxy Centaurus A ( $\delta = -43^\circ$ ), a potential acceleration site for UHECR. Neutrino flux predictions for three different models of UHE  $\nu$  production in the jets and in the core of CenA are also shown [17–19]. The expected number of events for a flux like in [17] is about 0.1 for the ES and 0.02 for the DG searches respectively. They are about one order of magnitude smaller for the flux predicted in [18].

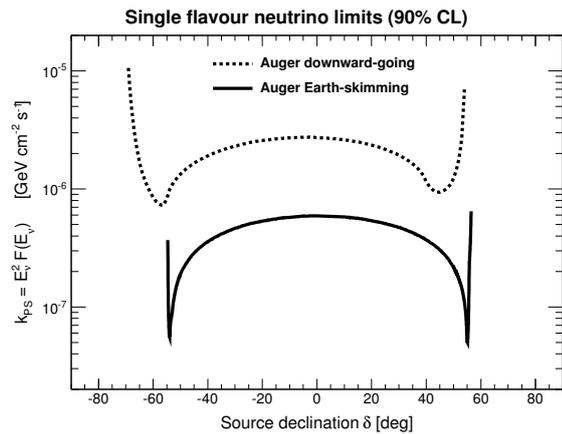


FIGURE 3. Upper limits (90 % C.L.) for the integral flux of single flavour neutrinos from a point-like source as a function of source declination.

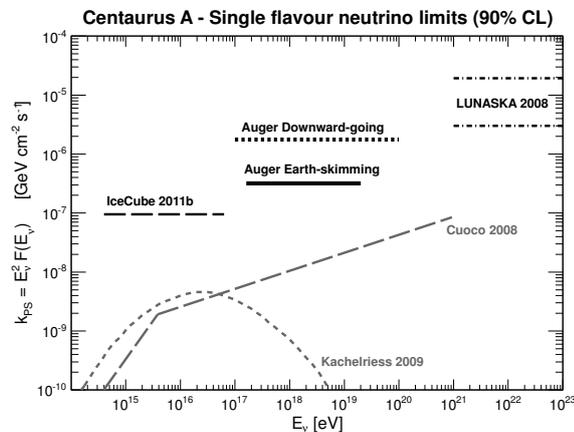


FIGURE 4. Upper limits (90 % C.L.) on the integral flux of neutrinos from Centaurus A, together with the limits from other experiments (IceCube [20], LUNASKA [21]) in different energy ranges and theoretical predictions.

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