Ultra-high energy neutrinos at the Pierre Auger Observatory

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Abstract: Neutrinos in the sub-EeV energy range and above can be detected with the Surface Detector array (SD) of the Pierre Auger Observatory. They can be identified through the broad time-structure of the signals expected to be induced in the SD stations. The identification can be efficiently done for neutrinos of all flavours interacting in the atmosphere at large zenith angles, typically above $60°$ (downward-going), as well as for Earth-skimming neutrino interactions in the case of tau neutrinos (upward-going). The wide angular range calls naturally for three sets of identification criteria designed to search for downward-going neutrinos in the zenith angle bins $60° - 75°$ and $75° - 90°$ as well as for upward-going neutrinos. In this contribution the three searches are combined to give a single limit, providing, in the absence of candidates in data from 1 January 04 until 31 December 12, an updated and stringent limit to the diffuse flux of ultra-high energy neutrinos.

Keywords: Pierre Auger Observatory, ultra-high energy neutrinos, inclined showers

1 Introduction

Ultra-high energy (UHE) neutrinos in the EeV range have so far escaped the scrutiny of existing experiments. At these energies, neutrinos may be the only probe of the still-enigmatic sources of UHE cosmic rays at distances further than ~ 100 Mpc. UHE neutrinos are produced in the decay of pions created in the interactions of cosmic rays with matter and/or radiation at their potential sources, such as gamma-ray bursts or Active Galactic Nuclei among others [1]. In addition, above $\sim 4\ 10^{19}$ eV cosmic-ray protons interact with cosmic microwave background photons and produce *cosmogenic* neutrinos of energies typically 1/20 of the proton energy. However, their fluxes are uncertain, and if the primary cosmic-ray flux is dominated by heavy nuclei the UHE neutrino yield would be strongly suppressed [2].

Neutrinos in the sub-EeV energy range and above can be detected with the Surface Detector array (SD) of the Pierre Auger Observatory [3]. A search in Auger data from 1 January 04 up to 31 December 12 has yielded no candidates and updated limits to the UHE neutrino flux are presented.

2 Searching for UHE neutrinos in Auger

Although the SD array of the Pierre Auger Observatory is primarily used for the collection of UHE cosmic rays, UHE neutrinos can also be observed. Unlike cosmic-rays, UHE neutrinos can initiate downward-going showers starting at very large depths in the atmosphere as well as upward-going showers close to the ground in interactions in the Earth's crust (see Fig. 1). Due to this, a strong background reduction is possible so that the search for neutrinos with Auger is currently limited not by background but by exposure.

Since the depth at which the shower is initiated cannot be measured directly, surrogate observables are used. In the stations of the SD of the Auger Observatory, the signals produced by the passage of shower particles are digitised with 25 ns resolution. This allows us to distinguish narrow signals in time induced by inclined showers initiated high
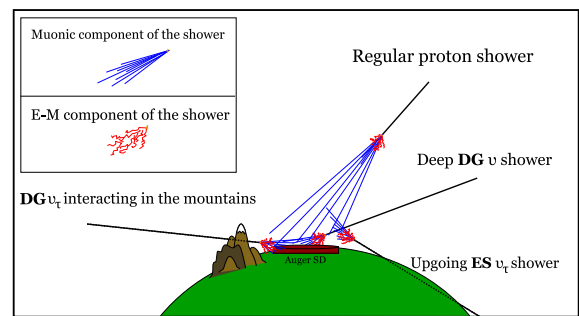

Figure 1: Pictorial representation of the different types of inclined showers that can be detected at the SD of the Pierre Auger Observatory. A regular inclined shower induced by a proton interacting high in the atmosphere; a deep downward-going (DG) ν-induced shower (downward-going high angle - DGH, and downward-going low angle - DGL channels, see Table 1); an Earth-skimming (ES) ν_τ interacting in the Earth's crust and producing an upward-going τ lepton decaying in flight and inducing a shower in the atmosphere; and a ν_τ interacting in the mountains, producing a downward-going τ lepton decaying and initiating a shower close to the SD (contributing to the DGH channel).

in the atmosphere, from the broad signals expected in inclined showers initiated close to the ground [4]. From the observational point of view, a Time-over-Threshold (ToT) trigger is usually present in SD stations with signals extended in time, while narrow signals induce other local triggers. Also the Area-over-Peak (AoP) of the signals, defined as the signal divided by its peak value, provides an estimate of the spread-in-time of the traces, and serves as an observable to discriminate broad from narrow shower fronts.

Using Monte Carlo simulations, it has been established that neutrino identification with the SD of the Auger Observatory can be performed efficiently as long as the search
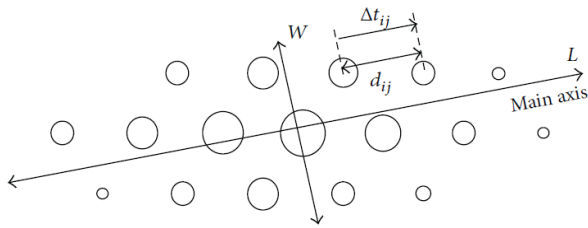
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Figure 2: Schematic representation of the footprint of a shower triggering the SD array from the left to the right of the figure, along the "main axis". The circles represent the position of the stations, with their sizes being proportional to the signals collected in the PMTs. The length and width of the footprint (see text for details) are also indicated.

Figure 3: Distributions of $\langle AoP \rangle$ (the variable used to identifiy neutrinos in the ES selection for data after 1 June 2010 - see Table 1). Gray-filled histogram: distribution of $\langle AoP \rangle$ for the data in the training period. Black thin line: distribution of $\langle AoP \rangle$ for the data in the search period. The distributions are normalised to the same amount of events for comparison purposes. Red thick line: distribution of $\langle AoP \rangle$ for the simulated ES ν_τ events. The dashed vertical line represents the cut on $\langle AoP \rangle > 1.83$ above which a data event is regarded as a neutrino candidate.

is restricted to showers with zenith angles $\theta > 60°$. The search was performed in three angular ranges. For this purpose three different sets of identification criteria were established to maximise the discrimination power. The selections exploit the different characteristics of the showers in each angular bin as determined from Monte Carlo simulations (see Table 1). For instance, at high zenith angles, above $\theta \sim 75°$, Monte Carlo simulations of showers initiated close to ground indicate that their fronts are broader in time than those of conventional cosmic-ray showers, but only in the stations that are triggered first (*early* stations) [6]. This is to be expected as the electromagnetic component is attenuated by the additional air that is traversed by the shower to reach the later water-Cherenkov detectors. The same study performed with simulations of deep, inclined, showers with $\theta \in (60°, 75°)$ indicate that this happens in the early stations closer to the shower core [8].

The three selections (denoted as ES, DGH, DGL - see Table 1 and Fig. 1) start with a "trace cleaning" procedure that removes most of the accidental signals (mainly due to atmospheric muons). Also PMTs not passing quality cuts are removed. After that, inclined showers are identified. In these events the triggered stations typically form elongated patterns on the ground along the azimuthal direction of arrival of the event. A length L and a width W can be assigned to the pattern [5], as shown in Fig. 2, and a cut on their ratio L/W is applied in the ES and DGH selections. Also, the apparent speed V of propagation of the signal on ground as the shower front arrives contains information on the inclination of the event [5]. V is used in the ES and DGH selections, and can be calculated from the difference in trigger times of the signals Δt_{ij} and the distances d_{ij} between stations projected onto L (Fig. 2). Finally, in the DGH and DGL selections, we reconstruct the event zenith angle θ_{rec} and place a cut on it as given in Table 1.

The next step is to identify in the data sample containing inclined showers, those with a broad time structure (*young* showers). The strategy to do this is the same for the three selections. First, different fractions of data are used to *train* each selection, assuming the *training data samples* are overwhelmingly, if not totally, made up by background showers. In these samples, the distributions of the observables applied to discriminate young showers, are used to obtain the values of the cuts as explained below. In the ES selections the discriminating variables include the fraction of stations with ToT for data prior to 31 May 10 [5], and the average value of AoP ($\langle AoP \rangle$) for data beyond 1 June 10. In the DGH [6] and DGL [8] selections, the AoP of various

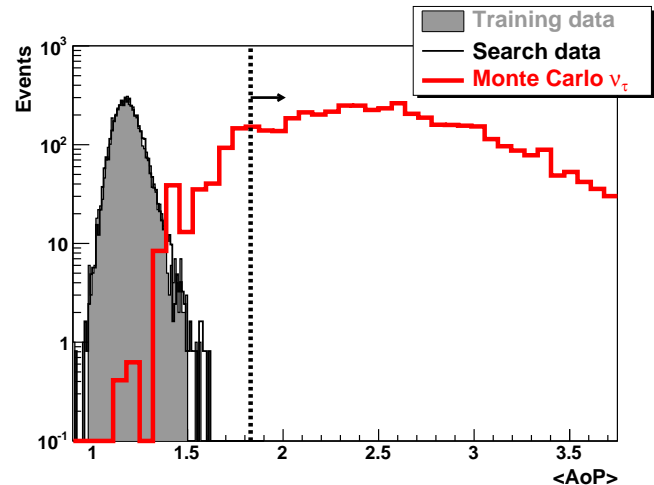stations along with other observables constructed from AoP, are combined in a linear Fisher-discriminant polynomial (see Table 1). As an example of the power of the discriminators used, we show in Fig. 3 the distribution of $\langle AoP \rangle$ in data after the inclined ES selection is applied, as well as the corresponding distribution in Monte Carlo simulations of Earth-Skimming ν_τ interacting in the Earth's crust and producing a τ that flys through the Earth and decays close to the SD.

We have observed that the tails of the Fisher and $\langle AoP \rangle$ distributions are consistent with an exponential shape in all cases, and we fitted and extrapolated them to find the value of the cuts corresponding to less than 1 expected event per 50 yr on the full SD array for each selection [6, 8]. Roughly $\sim 95\%$, $\sim 85\%$, and $\sim 60\%$ of the inclined neutrino events interacting through the charged-current channel, are kept after the ES, DGH and DGL selection of young showers respectively. The smaller efficiencies for the identification of neutrinos in the DGL selection are due to the more stringent criteria in the angular bin $\theta \in (60°, 75°)$ needed to reject the larger contamination from cosmic-ray induced showers.

The three selection criteria are applied to data between 1 January 04 up to 31 December 12 in a search for neutrino candidates. This period includes a new *search sample* corresponding to data from 1 June 10 until 31 December 12 not previously *unblinded* under any of the three selections. For each selection the corresponding training periods, which are different for each channel, as well as periods with problems in the data acquisition [5], are excluded from the search. No neutrino candidates were found with any of the selections in any of the blind search periods and three distinct upper limits on the diffuse flux of UHE neutrinos can be placed.

After the unblinding, we tested the compatibility of the

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Selection	Earth-skimming (ES)	Downward-going *high* angle (DGH)	Downward-going *low* angle (DGL)
Flavours & Interactions	ν_τ CC	ν_e, ν_μ , ν_τ CC & NC	ν_e, ν_μ , ν_τ CC & NC
Angular range	$\theta > 90°$	$\theta \in (75°, 90°)$	$\theta \in (60°, 75°)$
N° of Stations (Nst)	Nst ≥ 3	Nst ≥ 4	Nst ≥ 4
Inclined Showers	$-$ $L/W > 5$ $\langle V \rangle \in (0.29, 0.31)$ m ns^{-1} RMS$(V) < 0.08$ m ns^{-1}	$\theta_{\rm rec} > 75°$ $L/W > 3$ $\langle V \rangle < 0.313$ m ns^{-1} RMS$(V)/\langle V \rangle < 0.08$	$\theta_{\rm rec} \in (58.5°, 76.5°)$ $-$ $-$ $-$
Young Showers	Data: 1 January 04 - 31 May 10 $\geq 60\%$ of stations with ToT trigger & AoP > 1.4 Data: 1 June 10 - 31 December 12 $\langle AoP \rangle > 1.83$ AoP$_{\rm min} > 1.4$ if Nst=3	Fisher discriminant based on AoP of *early* stations	$\geq 75\%$ of stations close to shower core with ToT trigger & Fisher discriminant based on AoP of *early* stations close to shower core

Table 1: Observables and numerical values of cuts applied to select *inclined* and *young* showers for Earth-skimming and downward-going neutrinos. See text for explanation.

distributions of the young shower discriminating observables in the *search* and *training* samples. These two distributions are shown for the example of the $\langle AoP \rangle$ variable in Fig. 3. No statistically significant differences of the shapes are observed. In particular the parameters of exponential fits to the tails of the distributions are compatible within statistical uncertainties ($\sim 1\,\sigma$). All the events in the search sample are still rather far from the cut value $\langle AoP \rangle = 1.83$. The same is true for the Fisher-discriminant distributions of the training and search samples used in the downward-going selections [6, 8].

3 Combined exposure

To make the best use of the Auger data and put the most stringent limits to the diffuse flux of UHE neutrinos, the three individual exposures are combined into a single total exposure by means of a simple procedure. The three sets of selection criteria are applied to each simulated neutrino event regardless of the angular bin in which it was simulated. If the event passes any of the three selections it is identified as a neutrino and contributes to the exposure at the point in the parameter space, where it was simulated (for instance neutrino energy E_ν, zenith angle θ, and interaction depth in the case of the downward-going channels). An integration over the whole parameter space except for energy, yields the exposure $\mathcal{E}_i(E_\nu)$ for each of the selections (i can be ES, DGH or DGL). Then, the total combined exposure $\mathcal{E}_{\rm tot}(E_\nu)$ is obtained by adding the three individual exposures obtained in this way, $\mathcal{E}_{\rm tot} = \mathcal{E}_{\rm ES} + \mathcal{E}_{\rm DGH} + \mathcal{E}_{\rm DGL}$, as shown in Fig. 4. With this procedure the exposure is enhanced as, for instance, an atmospheric shower induced by a tau neutrino interacting in the Earth's crust, might not fulfill the requirements of the ES selection, but might pass the cuts of the DGH and contribute to $\mathcal{E}_{\rm ES}(E_\nu)$. Moreover, with this procedure we avoid double-counting of events: once a simulated neutrino fulfills the criteria of at least one of the selections it contributes only once to the total exposure. Finally, it is worth mentioning that in the calculation of $\mathcal{E}_i(E_\nu)$ we take into account changes in the array config-
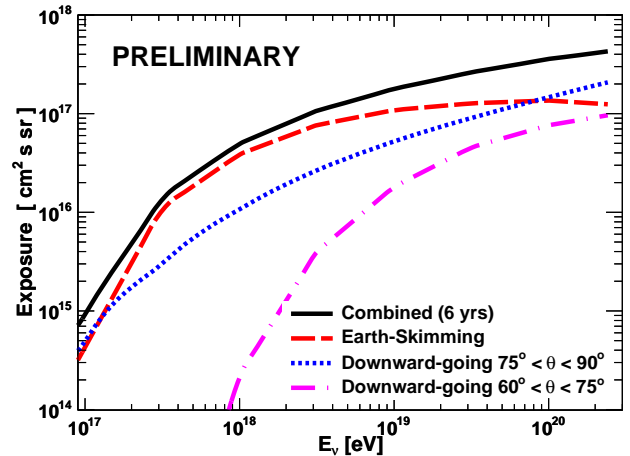

Figure 4: Combined exposure of the SD of the Pierre Auger Observatory as a function of neutrino energy after applying the three sets of selection criteria in Table 1 to Monte Carlo simulations of UHE neutrinos. Also shown are the individual exposures corresponding to each of the three selections. For the downward-going channels the exposure represents the sum over the three neutrino flavours as well as CC and NC interactions. For the Earth-Skimming channel, only ν_τ CC interactions are relevant. For this channel the exposure falls at the highest energies as there is an increasing probability that the τ decays high in the atmosphere producing a no triggering shower, or even that the τ escapes the atmosphere before decaying.

uration due to installation of new stations (up to 2008) and array instabilities (see [5, 6, 8] for details).

Several sources of systematic uncertainties in the exposure have been investigated [5, 6]. For the downward-going analysis, the major contributions in terms of deviation from a reference exposure come from the knowledge of neutrino-

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induced shower simulations (+9%, -33%) and of the neutrino cross-section (± 7%) [11]. For the ES analysis, the systematic uncertainties are dominated by the energy losses of the tau (+25%, -10%), the shower simulations (+20%, -5%), and the topography (+18%, 0%).

4 Results and conclusions

Using the combined exposure and assuming a $\Phi(E_\nu) = k \cdot E_\nu^{-2}$ differential neutrino flux and a 1:1:1 flavour ratio, an upper limit on the value of k can be obtained as:

$$k = \frac{N_{up}}{\int_{E_{min}}^{E_{max}} E_\nu^{-2} \, \mathscr{E}_{tot}(E_\nu) \, dE_\nu} \quad (1)$$

The actual value of the upper limit on the signal events (N_{up}) depends on the number of observed and expected background events as well as on the confidence level required. Using a semi-Bayesian extension [9] of the Feldman-Cousins approach [10] to include the uncertainties in the exposure, N_{up} is different from the nominal value for zero candidates and no expected background ($N_{up} = 2.44$ at 90% C.L.), and is different for each channel depending on the type of systematic uncertainties, and the reference exposure chosen [6, 7].

The updated single-flavour 90% C.L. limit is:

$$k_{90} \; < \; 1.3 \times 10^{-8} \; \text{GeV cm}^{-2} \; \text{s}^{-1} \; \text{sr}^{-1} \quad (2)$$

and applies in the energy interval $\sim 1.0 \times 10^{17}$ eV $- 1.0 \times 10^{20}$ eV where $\sim 90\%$ of the event rate is expected. The result is shown in Fig. 5 along with 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 SD of the Pierre Auger Observatory peaks. The search period corresponds to an equivalent of almost 6 years of a complete Auger SD array working continuously. The inclusion of the latest data from 1 June 10 until 31 December 12 in the search represents an increase of a factor ~ 1.7 in event number with respect to previous searches [6, 7]. The relative contributions of the ES:DGH:DGL channels to the total expected event rate assuming a flux behaving with neutrino energy as E_ν^{-2}, are 0.73:0.23:0.04 respectively.

The current Auger limit is below the Waxman-Bahcall bound on neutrino production in optically thin sources [14]. With data unblinded up to 31 December 12, we are starting to constrain models of cosmogenic ν fluxes that assume a pure primary proton composition injected at the sources. As an example we expect ~ 1.4 cosmogenic neutrino events from a model normalised to Fermi-LAT observations (solid line, bottom right panel in Fig. 4 of [15], also shown in Fig. 5 in this work). The gray shaded area in Fig. 5 brackets the cosmogenic neutrinos fluxes predicted under a wide range of assumptions for the cosmological evolution of the sources, for the transition between the galactic and extragalactic component of cosmic rays, and for the UHECR composition [17]. The corresponding expected number of cosmogenic neutrino events ranges between ~ 0.2 and ~ 0.6.

The two events in the PeV energy range recently reported by the IceCube collaboration are compatible with a power-law flux which follows E_ν^{-2} with normalisation $E_\nu^2 F_\nu = 1.2 \; 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} for each flavour (see Fig. 5 in [18]). Extending this upper limit to the flux with the same power-law up to 10^{20} eV we would expect ~ 2.2 events
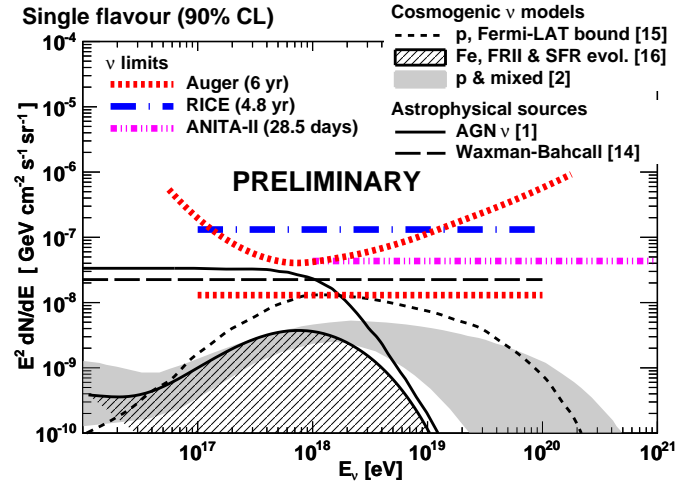

Figure 5: Differential and integrated upper limits (at 90% C.L.) from the Pierre Auger Observatory for a diffuse flux of UHE neutrinos. The search period corresponds to ~ 6 yr of a complete SD. We also show the integrated limits from ANITAII [12] and RICE [13] experiments, along with expected fluxes for several cosmogenic neutrino models [15, 16, 17] as well as for astrophysical sources [1, 14].

in Auger while none is observed. The possibility that such a neutrino flux also represents the flux at UHE energies is excluded at close to 90% C.L.

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