Limits on the diffuse flux of ultra high energy neutrinos set using the Pierre Auger Observatory

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***Abstract*. The array of water-Cherenkov detectors of the Pierre Auger Observatory is sensitive to neutrinos of $>$ 1 EeV of all flavours. These interact through charged and neutral currents in the atmosphere (down-going) and, for tau neutrinos, through the "Earth skimming" mechanism (up-going). Both types of neutrinos can be identified by the presence of a broad time structure of signals in the water-Cherenkov detectors in the inclined showers that they induce when interacting close to ground. Using data collected from 1 January 2004 to 28 February 2009, we present for the first time an analysis based on down-going neutrinos and place a competitive limit on the all-flavour diffuse neutrino flux. We also update the previous limit for up-going tau neutrinos. Sources of possible backgrounds and systematic uncertainties are discussed.**

***Keywords*: UHE neutrinos, cosmic rays, Pierre Auger Observatory**

I. 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 CRs 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 (UHEνs) in the EeV range and above.

Earth-skimming tau neutrinos [4], [5] are expected to be observed through the detection of showers induced by the decay products of an emerging τ lepton, after the propagation and interaction of a flux of ν_τ inside the Earth. A limit on the diffuse flux of UHE ν_τ was already placed using this technique with data collected from 1 Jan 04 to 31 Aug 07 [5].

The SD of the Pierre Auger Observatory has also been shown to be sensitive to "down-going" neutrinos of all flavours interacting in the atmosphere, and inducing a shower close to the ground [6]. In this contribution we present for the first time an analysis based on down-going neutrinos and place a competitive limit on the all-flavour diffuse neutrino flux using data from 1 Jan 04 up to 28 Feb 09. We also update the limit on the up-going tau neutrinos.

II. 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 (Fig. 1 right). In contrast, UHE particles such as protons or heavier nuclei interact within a few tens of $\mathrm{g\ cm^{-2}}$ after entering the atmosphere, producing "old" showers with shower fronts narrower in time (Fig. 1 left).

Although the SD is not directly sensitive to the nature of the arriving particles, the 25 ns time resolution of the FADC traces in 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 [8] where their discrimination power is also studied.

Down-going neutrinos of any flavour interacting through charged (CC) or neutral (NC) current, may induce showers in the atmosphere that can be detected using the SD of the Pierre Auger Observatory (Fig. 2). Detailed simulations of UHE neutrinos forced to interact deep in the atmosphere were produced. Both CC and NC neutrino interactions were simulated using HERWIG [9] for the first interaction and AIRES [10] for the shower development. "Double bang" showers produced by tau neutrinos (CC interaction followed by the decay in flight of the tau lepton) are also generated using Tauola [8] to simulate the tau decay products.

The simulations indicate that only the signals in the first few triggered tanks are expected to be broader in time than those induced by a shower initiated high in the atmosphere [8]. This asymmetry is due to the larger grammage of atmosphere that the later portion of the shower front crosses before reaching ground [12], (Fig. 1 right).

A set of conditions has been designed to select inclined showers initiated by down-going neutrinos. As they are expected to be identified over a wide range of zenith angles, an identification criterion different from the one applied to search for up-going neutrinos [5], [8] has been developed. For this purpose data collected with the SD between 1 Jan 04 and 31 Oct 07 - cor-

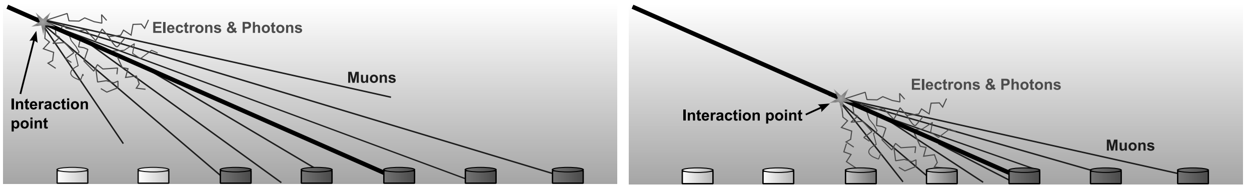

Fig. 1. Left panel: sketch of an inclined shower induced by a hadron interacting high in the atmosphere. The EM component is absorbed and only the muons reach the detector. Right panel: deep inclined shower. Its early region has a significant EM component at the detector level.

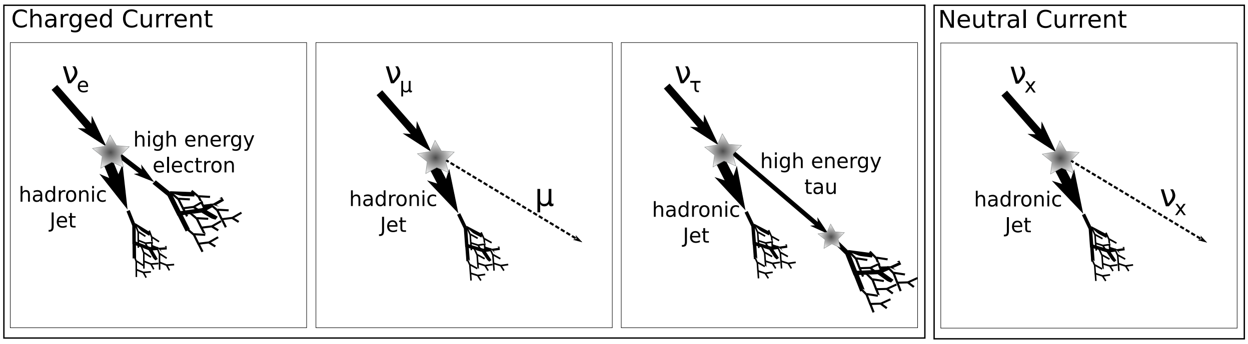

Fig. 2. Neutrinos can initiate atmospheric showers through charged (CC) or neutral (NC) current interactions. In ν_e CC interactions all the energy of the primary neutrino is transferred to the shower. This is not the case of the NC channel where the primary neutrino energy is only partially transferred to the shower while a significant fraction is carried away by the scattered neutrino. Similar behaviour is seen in the ν_μ CC induced showers where the emerging high energy muon usually decays under the ground and doesn't produce a shower. Note that ν_τ CC initiated showers may have a "double bang" structure due to the fact that the out-coming high energy τ may travel a long distance before decay producing a second displaced shower vertex.

responding to ~ 1.2 years of the full SD array - was used as "training" data. From the showers that trigger the SD array [3], those arriving during periods in which instabilities in data acquisition occur are excluded. After that the FADC traces are cleaned to remove segments that are due to accidental muons not belonging to the shower but arriving close in time with the shower front. Moreover, if 2 or more segments of comparable area appear in a trace the station is classified as ambiguous and it is not used. Then a selection of the stations actually belonging to the event is done based on space-time compatibility among them. Events with less than 4 tanks passing the level 2 trigger algorithm [3] are rejected. This sample is then searched for inclined events requiring that the triggered tanks have elongated patterns on the ground along the azimuthal arrival direction. A length L and a width W are assigned to the pattern [5], [8], and a cut on their ratio is applied ($L/W >$3). Then we calculate the apparent speed of the signal in the event moving across the ground along L, using the arrival times of the signals at ground and the distances between tanks projected onto L [13]. The average speed $\langle V \rangle$ is measured between pairs of triggered stations, and is required to be compatible with that expected in a simple planar model of the shower front in an inclined event with $\theta \geq 75°$, allowing for some spread due to fluctuations ($\langle V \rangle \leq 0.313$ m ns^{-1}). Furthermore, since in inclined events the speed measured between pairs of tanks is concentrated around $\langle V \rangle$ [5] we require that the r.m.s. scatter of V in an event to be smaller than $0.08 \cdot \langle V \rangle$. The zenith angle θ of the shower is also reconstructed, and those events with $\theta \geq 75°$ are selected. Exactly the same set of conditions is applied to the simulated neutrinos.

The sample of inclined events is searched for "young" showers using observables characterising the time duration of the FADC traces in the early region of the event. To optimize their discrimination power we applied the Fisher discriminant method [7] to the training data – overwhelmingly, if not totally constituted of nucleonic showers – and to the Monte Carlo (MC) simulations – exclusively composed of neutrino-induced showers. Given two populations of events – nucleonic inclined showers and ν-induced showers in our case – characterised by a set of observables, the Fisher method produces a linear combination of the various observables – f the Fisher discriminant – so that the separation between the means of f in the two samples is maximised, while the quadratic sum of the r.m.s. of f in each of them is minimised. Since events with a large number of tanks N (large multiplicity) are different from events with small multiplicity the sample of training data is divided into 3 sub-samples corresponding to events with number of tanks $4 \leq N \leq 6$, $7 \leq N \leq 11$ and $N \geq 12$, and a Fisher discriminant is obtained using each of the sub-samples as training data. We use the Area-over-Peak (AoP) [8] and its square of the first 4 tanks in each event, their product, and a global early-late asymmetry parameter of the event as the discriminant variables of the Fisher estimator. Distributions of these observables

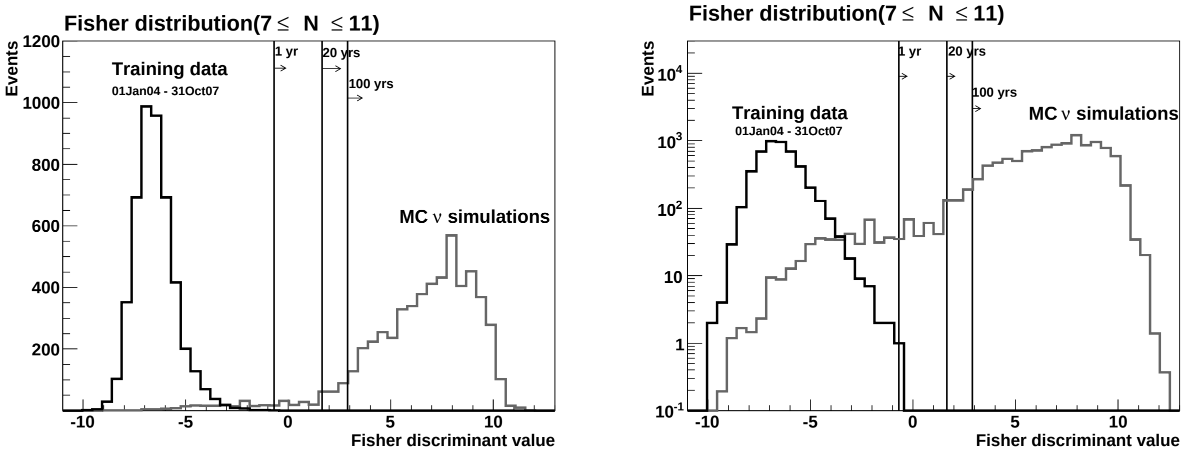

Fig. 3. Distribution of the Fisher discriminant (see text for details) in linear (left) and logaritmic (right) scale for real data in the training period (1 Jan 04 - 31 Oct 07) and Monte Carlo simulated down-going neutrinos for events with multiplicity $7 \leq N \leq 11$.

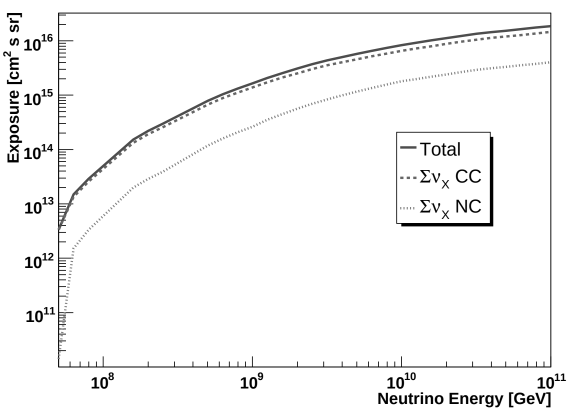

Fig. 4. Exposure of the SD array to down-going neutrinos in the search period (1 Nov 07 - 28 Feb 09).

for real data and MC simulated neutrinos are shown in [8]. In Fig. 3 we show the distribution of the Fisher discriminant for data collected between 1 Jan 04 and 31 Oct 07 and for the neutrino simulations. A clear separation between the two samples is achieved. The expected number of background events can be computed by extrapolating the exponential tail of the distribution of the data. By this means three cut values $f_{\rm cut}$ – corresponding to each of the sub-samples– are chosen, so that we expect less than one background event every 20 years above its value. Events with $f > f_{\rm cut}$ are considered to be neutrino candidates. These cuts reject all real events in the training data samples while keeping a significant fraction of the neutrino simulations.

III. Exposure and limit on UHE neutrinos

Exactly the same selection procedure and cuts in f are applied "blindly" to data collected between 1 Nov 07 and 28 Feb 09 – corresponding to ~ 0.8 yr of the full SD array[1]. These data were not used for training of the Fisher method. No neutrino candidates were found and an upper limit on the UHE 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 instabilities in data taking. The identification efficiency ϵ, for the set of cuts defined above, depends on the neutrino energy E_ν, the depth along the atmosphere at which the neutrino interacts D, the zenith angle θ, the 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 ν_τ), and the type of interaction – charged (CC) or neutral current (NC) – since the different combinations of flavour and interaction induce different type of showers. The efficiencies ϵ were obtained through MC simulations of the development of the shower in the atmosphere and the simulation of the surface detector array, see [8] for more details. The exposure can be written as:

$$\mathcal{E}(E_\nu) = \frac{1}{m} \sum_i \left[\sigma^i(E_\nu) \int M^i_{\rm ap}(E_\nu, t)\, dt \right] \qquad (1)$$

where the sum runs over the 3 neutrino flavours and the CC and NC interactions, and m is the mass of a nucleon. In this equation $M^i_{\rm ap}$ is the mass aperture given by:

$$M^i_{\rm ap}(E_\nu) = 2\pi \iiiint \sin\theta \cos\theta \; \epsilon^i(\vec{r}, \theta, D, E_\nu, t)\, d\theta\, dD\, dx\, dy \qquad (2)$$

[1]Although our current test sample is slightly smaller than the training one, with the SD fully commissioned, test data will grow fast and will rapidly surpass that acquired during the training period.

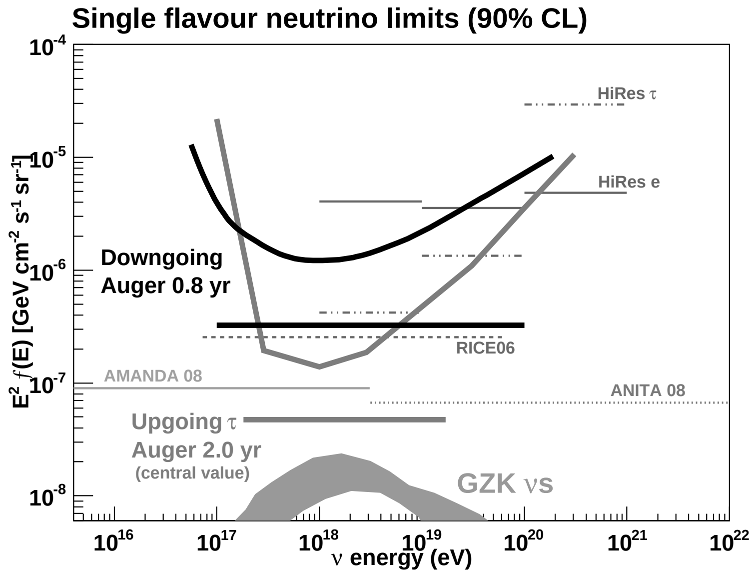

Fig. 5. Differential and integrated upper limits (90% C.L.) from the Pierre Auger Observatory for a diffuse flux of down-going ν in the period 1 Nov 07 - 28 Feb 09 and up-going ν_τ (1 Jan 04 - 28 Feb 09). Limits from other experiments [14] are also plotted. A theoretical flux for GZK neutrinos Ref. [2] is shown.

The exposure was calculated using purely MC techniques and also integrating the neutrino identification efficiencies ε over the whole parameter space [8]. All the neutrino flavours and interactions are accounted for in the simulations. In particular for ν_τ we have taken into account the possibility that it produces a double shower in the atmosphere triggering the array – one in the ν_τ CC interaction itself and another in the decay of the τ lepton. The exposure for the period 1 Nov 07 up to 28 Feb 09 is shown in Fig. 4 for CC and NC channels.

Several sources of systematic uncertainties have been taken into account and their effect on the exposure evaluated. We tentatively assign a $\sim 20\%$ systematic uncertainty due to the neutrino-induced shower simulations and the hadronic model (SIBYLL 2.1 vs QGSJETII.03). Another source of uncertainty comes from the neutrino cross section. Using [15] we estimate a systematic uncertainty of $\sim 10\%$. The topography around the Southern Site of the Pierre Auger Observatory enhances the flux of secondary tau leptons. In this work we neglected this effect. Our current simulations indicate that including it will improve the limit by roughly $\sim 15-20\%$.

Finally assuming a $f(E_\nu) = k \cdot E_\nu^{-2}$ differential neutrino flux we have obtained a 90% C.L. limit on the all-flavour neutrino flux using down-going showers:

$$k < 3.2 \times 10^{-7}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}} \quad (3)$$

shown in Fig. 5. We also present the updated limit based on Earth-skimming up-going neutrinos:

$$k < 4.7^{-2.5}_{+2.2} \times 10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}} \quad (4)$$

where the upper/lower values correspond to best/worse scenario of systematics [13]. We have also included the limit in differential format to show the range in energies at which the sensitivity of the Pierre Auger Observatory to down-going and Earth-skimming ν peaks.

A preliminary limit on the flux of UHE neutrinos from the position of Centaurus A (equatorial coords. $\delta \sim -43.0°$, $l \sim -35.2°$) – assuming a point source at that position – was also obtained. For that purpose we have integrated the identification efficiency ε over the fraction of the time ($\sim 15.6\%$) the source is seen in the SD array with θ between $75°$ and $90°$. The preliminary limit is $\sim 3 \times 10^{-6}$ neutrinos per $\mathrm{GeV\ cm^{-2}\ s^{-1}}$.

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