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

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Abstract. The surface array of water-Cherenkov detectors of the Pierre Auger Observatory is sensitive to neutrinos of energies around or above 1 EeV. All flavours interact through charged and neutral current interactions in the atmosphere (down-going), and tau neutrinos may also induce the “earth skimming” mechanism (up-going or crossing mountains). Both types of interaction may produce nearly horizontal atmospheric showers close to the ground, triggering the surface array; they may be distinguished from normal showers thanks to the broad time structure of the signals in the water tanks. Using data collected from January 2004 to February 2009, we use an analysis based on down-going neutrinos to obtain a 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.

1. Introduction

Neutrinos of energy in the EeV range are predicted by essentially all models of Ultra High Energy Cosmic Rays (UHECR), as the result of meson decays. In the standard scenario of acceleration mechanism, the mesons are produced in the interaction of the CRs, either in the medium surrounding their source, or along their propagation through the background radiation fields (GZK mechanism) [1, 2]. In the so-called “top-down” mechanisms, they are copiously produced by the decay of very massive exotic objects, with a hard spectrum [1].

The surface detector (SD) of the Pierre Auger Observatory (PAO) [3] is able to detect UHE neutrinos in the EeV range and above. In particular, nearly horizontal tau neutrinos interacting within the Earth produce a τ lepton which can emerge and decay in the lower atmosphere (“earth-skimming” mechanism [4]), producing a shower with a lateral expansion down to the ground. A limit on the diffuse flux of UHE \( \nu_\tau \) was already obtained through this technique using data collected from Jan 04 to Aug 07 [5]. This limit is updated including the new data (up to Feb 09) with the same analysis.

With similar criteria the SD of the PAO may detect nearly horizontal “down-going” neutrinos interacting deeply in the atmosphere [6]. Using the first part of the data (Jan 04 to Oct 07) as a training sample, discriminating variables have been tuned for zenith angles above 75 degrees, and then applied to the rest of the data (Nov 07 to Feb 09) to obtain a limit on the diffuse flux of all flavours.
2. Discriminating neutrinos in data

The background of nucleonic showers is much larger than the expected rate of neutrino events (typically one event per year or less). However, UHE protons or nuclei interact in the upper atmosphere, and at zenith angles larger than 75 degrees the shower crosses more than 2000 g/cm$^2$ before reaching the ground. At this stage the electromagnetic cascade is fully extinguished, and only high energy muons can hit the ground: in this “old” stage, all particles (including the products of the decay and the radiative interactions of the muons) are concentrated into a thin and flat shower front moving practically at the speed of light. On the contrary, neutrinos interact proportionally to the density, and a shower induced in the lower atmosphere can reach the ground in a “young” stage: the arrivals of the particles into the SD detector, especially the low energy photons and electrons, are spread over a time which is much larger than the sampling time of the FADC traces (25 ns) and the decay time of the Cherenkov light in a tank (70 ns). The first triggered tanks have broader signals, because they see an earlier stage of the electromagnetic cascade, and because the divergence of the photons and electrons favours late arrivals in the tanks under the shower core. Requesting several detectors to have signals significantly broader than the one of a single particle provides a powerful discrimination against the background of nucleonic showers. In [7] several variables describing the time structure of the signals are defined and their discriminating power is discussed.

Figure 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.

Detailed simulations of UHE neutrinos of all flavours interacting in the lower atmosphere were produced, in both charged current (CC) and neutral current (NC) modes, using Herwig [8] for the first interaction and AIRES [9] for the shower development. “Double bang” (showers produced by a CC interaction of $\nu_e$ followed by the decay in flight of the $\tau$ lepton) were generated using TAUOLA [10] to compute the decay products, to be reinjected in AIRES as additional primary particles. In all modes, a hadronic jet is produced, with, in average, a small fraction of the initial neutrino energy, which induces a mixed shower (hadronic+electromagnetic components). In the CC $\nu_e$ mode, the energy of the electron is fully transmitted to the electromagnetic shower. In the CC $\nu_\tau$ mode, a part of the $\tau$ energy is given to a secondary shower if it decays. In NC or CC $\nu_\mu$ modes, only the energy of the hadronic jet shower is visible.

As the down-going neutrino showers are expected to be seen over a wider range of zenith angle than the up-going ones, the criteria of selection were modified and new discriminating variables were designed. Data collected between Jan 04 and Oct 07, excluding a few periods of unstable data acquisition was used as a training sample (equivalent to ~ 1.2 years of the full SD array) to optimize the discrimination of simulated neutrino showers from real data. In events triggering the SD array with at least 4 stations, the FADC traces are first cleaned to remove parasitic signals produced by accidental particles; ambiguous traces are rejected. This sample is then searched for very inclined events with an elongated pattern on the ground, in the same way as in [12]. The first condition is obtained with a cut on the average of the speeds (distance/difference of starting time) between pairs of triggered stations: $< V > \leq 0.313$ m/ns, as expected for a planar front with $\theta \geq 75^\circ$, allowing for some spread due to fluctuations; the
r.m.s. is requested to be less than 0.08 m/ns. The second condition is $L/W > 3$, where $L$ and $W$ are the length and the width of the footprint, weighted by the integrated signals in the tanks (see [12] for the precise definition). The sample of inclined events is searched for “young” showers, using the “Area-over-Peak” ratio (AoP) of the traces (integrated signal over peak value). A Fisher discriminant method is applied to the AoP’s of the earliest 4 tanks, their squares, their product, and a global early-late asymmetry parameter. To account for significant differences between small and large tank multiplicities, the method is applied separately on 3 subsamples: $4 \leq N \leq 6$, $7 \leq N \leq 11$ and $N \geq 12$. Distributions of these observables in real and simulated data are shown in [7]. In each subsample, the Fisher method provides a linear combination $f$ of the variables which maximizes the separation between the real data and the simulated $\nu$ showers. Fig. 2 shows that a clear separation is achieved. In each subsample a value $f_{\text{cut}}$ is defined such that the exponential extrapolation of the distribution of the training sample predicts less than 1 event per 20 years with $f > f_{\text{cut}}$. This cut keeps most of the neutrinos interacting in the lower atmosphere and satisfying the trigger condition.

3. Exposure and limit on the flux of UHE neutrinos
The same selection procedure and cut on $f$ was applied on the data collected from Nov 07 to Feb 09 (~0.8 year of the full SD array). No neutrino candidate was found.

The exposure of the SD array is calculated by folding the geometrical aperture, the interaction probability and the identification efficiency, and integrating over time accounting for the variable array configuration and the instabilities of the data taking. The triggering and selection efficiency is evaluated from simulated data as a function of the flavour of the neutrino, its energy, its zenith angle, the type of interaction, the depth of the interaction, the position in the instantaneous configuration of the array. The exposure is summed over all parameters and all flavours (assuming equipartition).

Several sources of systematic uncertainties have been taken into account and their effect on the exposure evaluated. We tentatively assign a ~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 ~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 ~15 – 20%.

Finally, assuming a differential neutrino flux $f(E) = k/E^2$ we obtain a 90% C.L. limit on the
single flavour flux using down-going showers: \( k < 3.2 \times 10^{-7} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \). The updated limit based on up-going tau neutrinos using the data up to Feb 09 with the same analysis as in [12] is \( k < 4.7^{+2.3}_{-2.0} \times 10^{-8} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \), where the upper/lower values correspond to best/worse scenario of systematics [12]. These limits are plotted on Fig.4, together with the limits in differential format to show how the sensitivity of the Pierre Auger Observatory depends on the initial neutrino energy.

**Figure 3.** Exposure of the SD array to down-going neutrinos in the search period (1 Nov 07 - 28 Feb 09).

**Figure 4.** Differential and integrated upper limits (90% C.L.) for a diffuse flux of down-going \( \nu \) and up-going \( \nu_\tau \). Limits from other experiments [14] are also plotted. A theoretical flux for GZK neutrinos from [2] is shown.

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