Upper limit on the diffuse flux of UHE tau neutrinos

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The Pierre Auger Observatory has been designed to study the cosmic rays of ultra-high energy by observing extensive atmospheric showers. It also has the capability of detecting ultra-high energy neutrinos by searching for very inclined showers with a significant electromagnetic component. The surface detector array of the Pierre Auger Observatory is sensitive to Earth-skimming tau-neutrinos $\nu_\tau$ that interact in the Earth’s crust. For neutrinos in the energy range $2 \times 10^{17}$ eV $< E_\nu < 2 \times 10^{19}$ eV, assuming a diffuse spectrum of the form $E_\nu^{-2}$, data collected between 1 January 2004 and 31 August 2007 yield a 90% confidence-level upper limit on the diffuse $\nu_\tau$ flux of $E_\nu^2 dN_{\nu_\tau}/dE_\nu < 1.3 \times 10^{-7}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$.

1. INTRODUCTION

The detection of Ultra High Energy (UHE) cosmic neutrinos is a long standing experimental challenge. Many experiments are already searching for such neutrinos, and efforts to build other dedicated experiments are going on [1–3]. The nature and the production mechanism of the cosmic rays of UHE (UHECRs) is still unknown but their observation requires that there exists UHE cosmic neutrinos. All proposed mechanisms that lead to UHECRs are expected to produce neutrinos. Classical acceleration processes of charged particles in astrophysical objects create neutrinos through interactions with the radiation within the source region or with the Cosmic Microwave Background. In other type scenarios they arise as direct or indirect products of supermassive particles. The recently reported suppression of the cosmic ray flux above $4 \times 10^{19}$ eV [4,5] as well as the observed anisotropy of the highest energy cosmic rays [6,7] both point to UHECR interactions with the infrared or microwave backgrounds during extragalactic propagation. These interactions must result in the so-called ‘cosmogenic’ or GZK neutrinos [8] although their flux is somewhat uncertain. It depends on the primary UHECR composition and on the nature and cosmological evolution of the sources as well as on their spatial distribution [9,10].

Although the Pierre Auger Observatory has been designed to measure UHECR with unprecedented precision, the surface detector (SD) array can also be used to identify neutrino-induced showers [11–13]. Their detection is not easy, because the cross sections remain well below the hadronic ones. Then the possible neutrino interactions have to be carefully isolated from a huge background of hadronic showers. When selecting an almost horizontal incidence, the hadronic shower is extinguished at ground and they are reduced to a muonic tail. On the contrary, neutrino showers may be induced deeply in the atmosphere and reach the ground in their electromagnetic stage.

The $\tau$ neutrinos are heavily suppressed at production relative to $\nu_e$ or $\nu_\mu$. In the scenario of neutrino flavor oscillation and a maximal $\Theta_{23}$ mixing, the flavor balance changes when neutrinos reach the Earth. After travelling cosmological distances, approximately equal fluxes for each flavor are obtained [14]. Tau neutrinos that enter the Earth just below the horizon, the so-called skimming neutrinos, may undergo a charged-current interaction to produce a $\tau$ [15–17]. When the interaction happens close to the

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surface a $\tau$ can exit the Earth and its decay in the atmosphere can produce an Extensive Air Shower (EAS) detectable with the Pierre Auger Observatory. In the EeV range, this channel has been shown to increase the prospect of detecting UHE neutrinos [12].

Here we report the result published in [18] of a search for deep, inclined, showers in the data collected with the SD of the Pierre Auger Observatory. In Sec.2 the Pierre Auger Observatory is described. The Monte Carlo simulations used are detailed in Sec.3. In Sec.4 the principle of the discrimination of neutrino-induced showers is explained and the selection procedure is defined. In Sec.5 the exposure to skimming neutrinos and its uncertainties are presented. It yields to the upper limit on the diffuse $\nu_\tau$ flux shown in Sec.6. Finally in Sec.7 the work is summarized. No candidates have been found in the data collected between 1 January 2004 and 31 August 2007 — equivalent to roughly one year of operation of the full planned array.

2. THE PIERRE AUGER OBSERVATORY

The Observatory is designed as an hybrid detector of atmospheric showers: a Surface Detector covering a huge area associated to a set of Fluorescence Telescopes looking over this area. The southern site covers 3000 km$^2$ and has been recently completed in Malargüe, province of Mendoza, Argentina. The northern site is planned in Colorado, USA [19], on the same basic principle.

The SD consists in a regular triangular array of 1600 Cherenkov water tanks (diameter 3.6 m, water height 1.2 m) separated by 1.5 km, covering an almost flat surface, at an altitude around 1400 m a.s.l. Each tank is internally coated with a diffusive bag (Tyvek®) filled with de-ionized water, with three PMTs on the top, sampled by 40 MHz FADCs [20]. The tanks are regularly monitored and individually calibrated in units of Vertical Equivalent Muon (VEM) corresponding to the signal produced by a $\mu$ traversing the tank vertically [21]. The PMTs, a local processor, a GPS receiver and a communication antenna are powered by a battery with solar panels. Once installed, the local stations work continuously without external intervention. A central acquisition system receives the local triggers and builds a global trigger based on a time coincidence between neighbor stations.

The Fluorescence Detector (FD) is made of 4 buildings on the edge of the array housing 6 telescopes covering each a field of 30 × 30 deg$^2$. Through a Schmidt optics, a spherical mirror produces an image on a camera made of 1.5 deg hexagonal cells, each one with a PMT sampled at 10 MHz. At short distances (a few km), the FD can detect showers from $10^{17}$ eV. Above $10^{19}$ eV, a large fraction of the showers falling on the array are seen from at least two buildings. The FD takes data during about 10 to 15% of the time (clear and moonless nights).

3. END TO END SIMULATION CHAIN

The procedure devised to identify neutrino candidate events within the data set is based on an end-to-end simulation of the whole process. A specific chain of simulations was implemented in three different steps:

- First, an incident flux of $\nu_\tau$ is injected in the Earth at energies ranging from $10^{17}$ to $3 \times 10^{20}$ eV. Neutral current and charged current interactions are simulated with cross sections according to [22], allowing for multiple steps, and accounting for the energy loss of the $\tau$.

- Then, showers induced by the products of decaying $\tau$s with energies between $10^{17}$ to $3 \times 10^{20}$ eV at zenith angles ranging between 90.1° and 95.9° and at an altitude of the decay point above the Pierre Auger Observatory in the range 0 – 2500 m are simulated. The $\tau$ decay is simulated with the TAUOLA package [23] and the products of the decay are injected into the AIRES code [24].

- Finally, to evaluate the response of the SD to such events, the particles reaching the ground in the simulation are stored and injected into a detailed simulation of the SD [25].
4. SEARCH FOR NEUTRINOS

UHE particles interacting in the atmosphere give rise to EAS with the electromagnetic component reaching its maximal development after a depth of the order of 1000 g cm$^{-2}$ and extinguishing gradually within the next 800 g cm$^{-2}$. After a couple of vertical atmospheric depths only the muons survive. As a consequence very inclined showers induced by nuclei (or possibly photons) in the upper atmosphere reach the ground as a thin and flat front of hard muons. On the contrary, if a shower begins development deep in the atmosphere (a tau decay) its electromagnetic component can reach the ground and give a distinct broad signal. Therefore, the detection of very inclined showers with a significant electromagnetic component is a clear indication for UHE neutrinos.

The digitization of the signal in each station using FADCs allows us to unambiguously distinguish the broad signals from the narrow ones and thus to discriminate stations with and without electromagnetic component (figure 1). We tag the stations for which the main segment of its FADC trace has 13 or more neighbor bins over the threshold of 0.2 VEM and for which the ratio of the integrated signal over the peak height exceeds 1.4. The event is selected if the tagged stations are more than 60% of the triggered ones and they fulfill the central trigger condition [20]. After this selection, an almost pure sample of young showers is isolated.

The next step uses the footprint of local stations included in the global trigger to select very inclined showers. First a tensor is built using the station signals and the ground positions (in analogy to the inertia tensor) and the corresponding major and minor axes are used to define a “length” and a “width”. Then, for each pair $(i,j)$ of tanks, a “ground speed” is defined as $d_{i,j}/|\Delta t_{i,j}|$, where $d_{i,j}$ is the distance between them (projected onto the major axis) and $|\Delta t_{i,j}|$ is the difference between the start times of their signals. Horizontal showers have an elongated shaped (large value of length/width) and they have ground speeds tightly concentrated around the speed of light. In figure 2, we show the distributions of these discriminating variables for real events passing the young shower cut and simulated tau showers. The following cuts are applied: length/width $> 5$, average speed $\in (0.29,0.31)$ m ns$^{-1}$ and r.m.s.(speed) $< 0.08$ m ns$^{-1}$. We keep about 80% of the $\tau$ showers that trigger the SD. The final sample is expected to be free of background.

5. EXPOSURE AND SYSTEMATIC UNCERTAINTIES

The total exposure collected from January 2004 until August 2007 with the Pierre Auger Observatory is the time integration of the instantaneous aperture. The expression for the exposure can be written as:

$$
Acc(E_\nu) = \int_0^{E_\nu} dE_\tau \int_0^\infty dh_c \left( \frac{d^2N_\tau}{dE_\tau dh_c} Acc_\tau \right)
$$

$$
Acc_\tau(E_\tau, h_c) = \int_T^T dt \int_A dx dy I_{eff}(E_\tau, h_c, x, y, AConf(t))
$$
Figure 2. Distribution of discriminating variables for showers initiated by $\tau$s decaying in the atmosphere, generated by $\nu_\tau$s with energies sampled from an $E_\nu^{-2}$ flux (histogram), and for real events passing the "young shower" selection (points). Left: length/width ratio of the footprint of the shower on the ground; middle: average speed between pairs of stations; right: r.m.s. scatter of the speeds. See text for details.

where $dN_{\tau}/dE_\tau dh_c$ is the flux of emerging $\tau$s and $I_{eff}$ the probability to identify a $\tau$. The latter depends on the energy of the $\tau$ ($E_\tau$), the altitude of the shower center defined 10 km after the decay point ($h_c$) [12], the instantaneous configuration of the detector ($A_{Conf}(t)$), and the relative position of the shower in the array ($x, y$).

The $Acc(E_\nu)$ is computed by Monte Carlo in two independent steps. First, the integral on time and area are performed using the simulations of the EAS and the detector, allowing us to account for the time evolution of the detector. The second step computes the integral on $h_c$ and $E_\tau$ by adding $Acc_\tau(E_\tau, h_c)$ for all emerging $\tau$s, given by the simulation of the Earth interactions. The statistical precision due to the statistic of the Monte Carlo simulation is at a few percent level.

The Monte Carlo simulations use several physical magnitudes that have not been experimentally measured at the relevant energy range. They are namely: $\nu$ cross section, $\tau$ energy losses and $\tau$ polarisation. We estimate the uncertainty coming from the poor knowledge of these parameters to be about 15%, 40% and 30% respectively. It is based on physically allowed values for the latter and on Parton Distribution Function (PDF) uncertainties for the others. The relevant range of the PDFs includes regions of Bjorken-$x$ and squared 4-momentum transfer, $Q^2$, where no experimental data exist. Only extrapolations that follow the behaviour observed in the regions with experimental data have been considered. Different extrapolations on this range would lead to a wide range of values for the $\nu$ cross section as well as the $\tau$ energy losses. These alternative extrapolations as well as possible large $\nu$ cross sections have not been considered for the quoted systematics.

We also took into account uncertainties coming from neglecting the actual topography around the site of the Pierre Auger Observatory (18%). We are confident on the simulations of the interactions undergoing in the Earth at 5 % level. And we quote a 25 % systematic uncertainty due to Monte Carlo simulations of the EAS and the detector.

6. NEUTRINO LIMIT

Data from January 2004 until August 2007, which equate to about 1 year from the completed surface detector, have been analyzed. Over that period, there is not a single event that fulfills the selection criteria. Based on that, the Pierre Auger Observatory data can be used to put a limit for an injected spectrum $K \cdot \Phi(E)$ with a known shape. For an $E^{-2}$ incident spectrum of diffuse $\nu_\tau$s, the 90% CL limit is $E_\nu^2 \cdot dN_{\nu_\tau}/dE_\nu < 1.0^{+0.4}_{-0.3} \times 10^{-7}$
Figure 3. Limits at 90% C.L. for a diffuse flux of $\nu_\tau$ from the Pierre Auger Observatory. Limits from other experiments [27–34] are converted to a single flavor assuming a 1 : 1 : 1 ratio of the 3 neutrino flavors and scaled to 90% C.L. where needed. Two different formats are used: differential (squares) and integrated (constant lines). The shaded curve shows the range of expected fluxes of GZK neutrinos from Ref. [9,10], although predictions almost 1 order of magnitude lower and higher exist.

GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$, where the uncertainties come from the systematics. The central value is computed using the $\nu$ cross section from [22], the energy losses from [26] and an uniform random distribution for the tau polarisation. The bound is drawn for the energy range $2 \times 10^{17} - 2 \times 10^{19}$ eV, with a systematic uncertainty of about 15%, over which 90% of the events are expected for $\Phi(E_\nu) \propto E_\nu^{-2}$. In Figure 3, the upper limit is shown adopting the most pessimistic scenario for systematic uncertainties. Together with the integrated limit for $\Phi(E_\nu) \propto E_\nu^{-2}$, we plot a differential limit given by $2.3/(\text{Exp}(E_\nu) \times E_\nu)$ to demonstrate explicitly that the sensitivity of the Pierre Auger Observatory to Earth skimming $\nu_\tau$ peaks in a narrow energy range close to where the GZK neutrinos are expected.

7. SUMMARY AND PROSPECTS

The data set from January 2004 until August 2007, collected by the Pierre Auger Observatory, was used to set an upper limit on the diffuse incident $\nu_\tau$ flux. The skimming technique is flavor sensitive and together with the configuration of the surface detector gives the best sensitivity around few EeV, which is the most relevant energy to explore GZK neutrinos. The limit is still considerably higher than predictions for the guaranteed flux coming from the GZK. Neutrinos that interact in the atmosphere can also be distinguished from nucleon showers [35]. Hence, the Pierre Auger Observatory can explore UHE $\nu$s with two techniques that depend differently on $\nu$ properties like flavor or cross section. The Pierre Auger Observatory will keep taking data for about 20 years. That leaves time to eventually detect some neutrinos.

REFERENCES