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# Upper limit on the diffuse flux of UHE tau neutrinos from the Pierre Auger Observatory

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## Abstract

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. Tau leptons from $\nu_\tau$ charged-current interactions can emerge and decay in the atmosphere to produce a nearly horizontal shower with a significant electromagnetic component. The data collected between 1 January 2004 and 31 August 2007 is used to place an upper limit on the diffuse flux of $\nu_\tau$ at EeV energies. Assuming an $E_\nu^{-2}$ differential energy spectrum the limit set at 90 % C.L. is $E_\nu^2\ \mathrm{d}N_{\nu_\tau}/\mathrm{d}E_\nu < 1.3 \times 10^{-7}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ in the energy range $2 \times 10^{17}\mathrm{eV} < E_\nu < 2 \times 10^{19}$ eV.

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The detection of Ultra High Energy (UHE) cosmic neutrinos at EeV (1 EeV $\equiv 10^{18}$ eV) energies and above is a long standing experimental challenge. Many experiments are searching for such neutrinos, and there are several ongoing efforts to construct dedicated experiments to detect them [1, 2, 3]. Their discovery would open a new window to the universe [4], and provide an unique opportunity to test fundamental particle physics at energies well beyond current or planned accelerators. The observation of UHE Cosmic Rays (UHECRs) requires that there exist UHE cosmic neutrinos, even though the nature of the UHECR particles and their production mechanisms are still uncertain. All models of UHECR origin predict neutrino fluxes from the decay of charged pions which are produced either in interactions of the cosmic rays in their sources, or in their subsequent interactions with background radiation fields. For example, UHECR protons interacting with the Cosmic Microwave Background (CMB) give rise to the so-called 'cosmogenic' or GZK neutrinos [5]. The recently reported suppression of the cosmic ray flux above $\sim 4 \times 10^{19}$ eV [6, 7, 8] as well as the observed correlation of the highest energy cosmic rays with relatively nearby extragalactic objects [9] both point to UHECR interactions on the infrared or microwave backgrounds during extragalactic propagation. These interactions must result in UHE neutrinos although their flux is somewhat uncertain since this depends on the primary UHECR composition and on the nature and cosmological evolution of the sources as well as on their spatial distribution [10, 11].

Tau neutrinos are suppressed in such production processes relative to $\nu_e$ or $\nu_\mu$, because they are not an end product of the charged pion decay chain and far fewer are made through the production and decay of heavy flavours such as charm. Nevertheless, because of neutrino flavour mixing, the usual 1:2 ratio of $\nu_e$ to $\nu_\mu$ at production is altered to approximately equal fluxes for all flavours after travelling cosmological distances [12]. Soon after the discovery of neutrino oscillations [13] it was shown that tau neutrinos entering the Earth just below the horizon (Earth-skimming) [14, 15, 16] can undergo charged-current interactions and produce $\tau$ leptons. Since a tau lepton can travel tens of kilometers in the Earth at EeV energies, it can emerge into the atmosphere and decay in flight producing an nearly horizontal extensive air shower (EAS) above the detector. In this way the effective target volume for neutrinos can be rather large.

The Pierre Auger Observatory [17] has been designed to measure UHECRs with unprecedented precision. Detection of UHECRs is being achieved exploiting the two available techniques to detect EAS, namely, arrays of surface particle detectors and telescopes that detect fluorescence radiation. UHE particles such as protons or heavier nuclei interact high in the atmosphere, producing showers that contain muons and an electromagnetic component of electrons, positrons and photons. This latter component reaches a maximum at an atmospheric depth of order 800 g cm$^{-2}$, after which it is gradually attenuated. Inclined showers that reach the ground after travelling through 2000 g cm$^{-2}$ or more of the atmosphere are dominated by muons arriving at the detector in a thin and flat shower front.

The surface detector (SD) array of the Pierre Auger Observatory can be used to identify neutrino-induced showers [18, 19, 20]. The fluorescence detectors can also be used for neutrino searches [21, 22] but the nominal 10% duty cycle of the fluorescence technique reduces the sensitivity. The electromagnetic component of neutrino-induced showers might reach the ground if the shower develops close enough to the detector, producing a signal which has a longer time duration than for an inclined shower initiated by a nucleonic primary. Thus close examination of inclined showers enables showers developing near to the ground and those produced early in the atmosphere to be distinguished. This allows the clean identification of showers induced by neutrinos, and in particular those induced by tau-neutrinos, with the SD [23, 24, 25].

Here we present the result of a search for deep, inclined, showers in the data collected with the SD of the Pierre Auger Observatory. Identification criteria have been developed to find EAS that are generated by $\tau$ leptons emerging from the Earth. 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 planned full array.

The construction of the Southern Pierre Auger Observatory in Mendoza, Argentina, is currently close to being completed. It consists of an array of water Cherenkov tanks arranged in a hexagonal grid of 1.5 km covering an area of 3000 km$^2$ that is overlooked by 24 fluorescence telescopes located at four sites around the perimeter. The array comprises 1600 cylindrical tanks of 10 m$^2$ surface area containing purified water, 1.2 m deep, each instrumented with $3 \times 9''$ photomultiplier tubes sampled by 40 MHz Flash Analog Digital Converters (FADCs)[17]. Each tank is regularly monitored and calibrated in units of Vertical Equivalent Muon (VEM) corresponding to the signal produced by a muon traversing the tank vertically [26].

The procedure devised to identify neutrino candidate events within the data set is based on an end-to-end simulation of the whole process, from the interaction of the tau-neutrinos

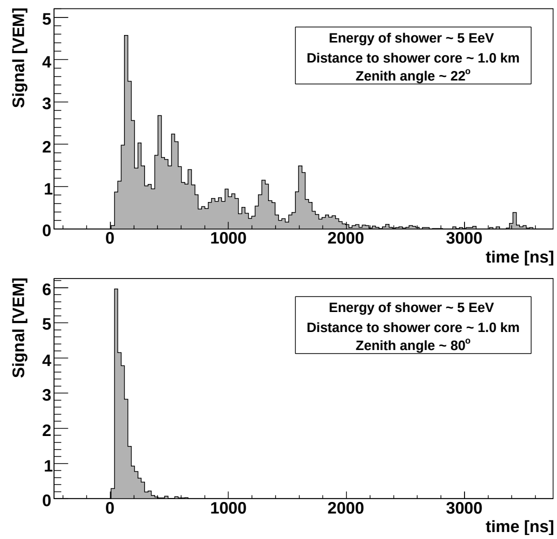


FIG. 1: FADC traces of stations at 1 km from the shower core for two real showers of 5 EeV. Top panel: electromagnetic component ($\theta \sim 22$ °); bottom: muonic signal ($\theta \sim 80$ °).

inside the Earth to the detection of the signals in the tanks. The first step is the calculation of the tau flux emerging from the Earth. This is done using a simulation of the coupled interplay between the $\tau$ and the $\nu_\tau$ fluxes through charged-current weak-interactions and $\tau$ decay, taking into account also the energy losses due to neutral current interactions for both particles, and bremsstrahlung, pair production and nuclear interactions for the $\tau$ lepton. The emerging tau flux can be folded with the tau decay probability to give the differential probability of tau decaying in the atmosphere as a function of its energy and decay altitude, $\mathrm{d}^2 p_\tau / \mathrm{d}E_\tau \mathrm{d}h_c$.

Modelling of the showers from $\tau$ decays in the atmosphere is performed using the AIRES code [27]. The TAUOLA package [28] is used to simulate $\tau$ decay and obtain the secondary particles and their energies. Showers induced by the products of decaying $\tau$s with energies between $10^{17}$ to $3 \times 10^{20}$ eV are simulated 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. 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 [29].

A set of conditions has been designed and optimized to select showers induced by Earth-skimming tau-neutrinos, rejecting those induced by UHECR. The 25 ns time resolution of the FADC traces allows unambiguous distinction between the narrow signals induced by muons and the broad signals induced by the electromagnetic component (Figure 1). For

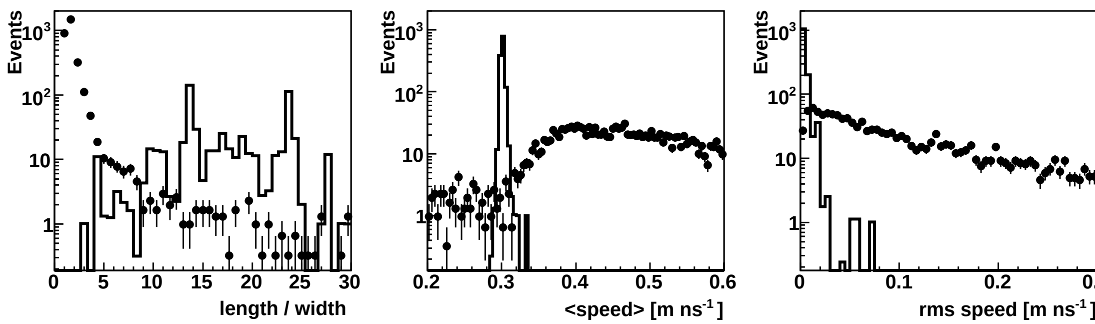


FIG. 2: Distribution of discriminating variables for showers initiated by $\tau$s decaying in the atmosphere, generated by $\nu_\tau$s with energies sampled from an $E_\nu^{-2}$ flux (histogram), and for real events passing the "young shower" selection (points). Left: length/width ratio of the footprint 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.

this purpose we tag the tanks for which the main segment of the FADC trace has 13 or more neighbouring bins over a threshold of 0.2 VEM, and for which the ratio of the integrated signal over the peak height exceeds 1.4. A neutrino candidate is required to have over 60% of the triggered tanks satisfying these "young shower" conditions as well as fulfilling the central trigger condition [17] with these tanks. In addition the triggered tanks are required to have elongated patterns on the ground defining the azimuthal arrival direction (as expected for inclined events) by assigning a length and a width to the pattern and restricting its ratio. Finally, we calculate the apparent speed of the signal moving across the ground along the azimuthal direction, using the arrival times of the signals at ground and the projected distances between tanks. The average speed, as measured between pairs of triggered stations, is required to be compatible with that expected for an event traveling close to the horizontal direction by requiring it to be very close to the speed of light, in the range (0.29, 0.31) m ns$^{-1}$ with an r.m.s. scatter below 0.08 m ns$^{-1}$. These conditions are found to retain about 80 % of the simulated $\tau$ showers triggering the SD. The final sample is expected to be free of background from UHECR-induced showers. In Figure 2, we show the distributions of these discriminating variables for real events and simulated tau showers.

Over the period analyzed, no candidate events were found that fulfilled the selection criteria. Based on this, the Pierre Auger Observatory data can be used to place a limit on the diffuse flux of UHE tau-neutrinos. For this purpose the exposure of the detector must be evaluated. The total exposure is the time integral of the instantaneous aperture which has changed as the detector has grown while it was being constructed and set into operation.

Calculation of the effective aperture for a fixed neutrino energy $E_\nu$ involves folding the aperture with the conversion probability and the identification efficiency. The identification efficiency $\epsilon_{\rm ff}$ depends on the tau energy $E_\tau$, the altitude above ground of the central part of the shower $h_c$ (defined at 10 km after the decay point [19]), the position $(x, y)$ of the shower in the surface $S$ covered by the array, and the time $t$ through the instantaneous configuration of the array. The expression for the exposure can be written as:

$$\mathrm{Exp} = \int_\Omega \mathrm{d}\Omega \int_0^{E_\nu} \mathrm{d}E_\tau \int_0^\infty \mathrm{d}h_c \frac{\mathrm{d}^2 p_\tau}{\mathrm{d}E_\tau \mathrm{d}h_c} B_\tau, \tag{1}$$

where

$$B_\tau(E_\tau, h_c) = \int_T \mathrm{d}t \int_S \mathrm{d}x\mathrm{d}y \, \cos\theta \, \epsilon_{\rm ff}[E_\tau, h_c, x, y, t] \tag{2}$$

where $\theta$ and $\Omega$ are the zenith and solid angles.

The exposure is calculated using standard Monte Carlo techniques (MC) in two steps. The first integral deals with the detector-dependent part, including the time evolution of the array over the period $T$ considered (eq.2). The integral in $E_\tau$ and $h_c$ involves only the differential conversion probability and $B_\tau$ (eq.1). The estimated statistical uncertainty for the exposure is below 3%.

The MC simulations require some physical quantities that have not been experimentally measured in the relevant energy range, namely the $\nu$ interaction cross-section, the $\tau$ energy loss, and the $\tau$ polarisation. The main uncertainty in these comes from the QCD structure functions in the relevant kinematic range. We estimate the uncertainty in the exposure due to the $\nu$ cross-section to be 15% based on the allowed range explored in [30]. The uncertainties in the tau energy losses are dominated by the tau photonuclear cross section. Different calculations of $\tau$ energy losses through hadronic interactions using different structure functions [21, 31, 32] lead to a 40% systematic uncertainty. The two extreme cases of polarization give 30% difference in exposure and we take this as the corresponding uncertainty. The relevant range of the structure functions includes regions of Bjorken-$x$ and squared 4-momentum transfer, $Q^2$, where no experimental data exist. Calculations with alternative extrapolations to low $x$ and high $Q^2$ lead to quite different values of the $\nu$ cross-section as well as the $\tau$ energy loss. Such possibilities have not been considered when estimating the systematics.

We also take into account uncertainties coming from neglecting the topography around the site of the Pierre Auger Observatory [33] (18%). We adopt a 25% systematic uncertainty due to MC simulations of the EAS and the detector, dominated by differences between hadronic models (QGSJET [34] and SIBYLL [35]).

Assuming a $f(E_\nu) \propto E_\nu^{-2}$ differential flux of $\nu_\tau$ we have obtained a 90% C.L. limit on the diffuse flux of UHE $\nu_\tau$, whose level is representative for a smooth spectral shape:

$$E_\nu^2 f(E_\nu) < 1.0^{+0.3}_{-0.5} \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (3)$$

The central value is computed using the $\nu$ cross-section from Ref. [30], the parametrisation of the energy losses from Ref. [32] and an uniform random distribution for the tau polarisation. The uncertainties correspond to the combinations of systematic uncertainties in the exposure as given above that lead to the highest/lowest neutrino event rate. The limit is applicable in the energy range $2 \times 10^{17} - 2 \times 10^{19}$ eV over which 90% of the events are expected for $f(E_\nu) \propto E_\nu^{-2}$. In Figure 3, we show our limit adopting the most pessimistic scenario for systematic uncertainties. It improves by a factor $\sim$ 3 for the most optimistic one. For energies above $10^{20}$ eV, limits are usually quoted as 2.3/Exp $\times E_\nu$ (differential format), while at lower energies they are usually given assuming an $E^{-2}$ flux (integrated format). We plot the differential format 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.

The Earth-skimming technique used with data collected at the surface detector array of the Southern Pierre Auger Observatory, provide at present the most sensitive bound on neutrinos at EeV energies. This is the most relevant energy to explore the predicted fluxes of GZK neutrinos. The Pierre Auger Observatory will continue to take data for about 20 years over which time the limit should improve by over an order of magnitude if no neutrino candidate is found.

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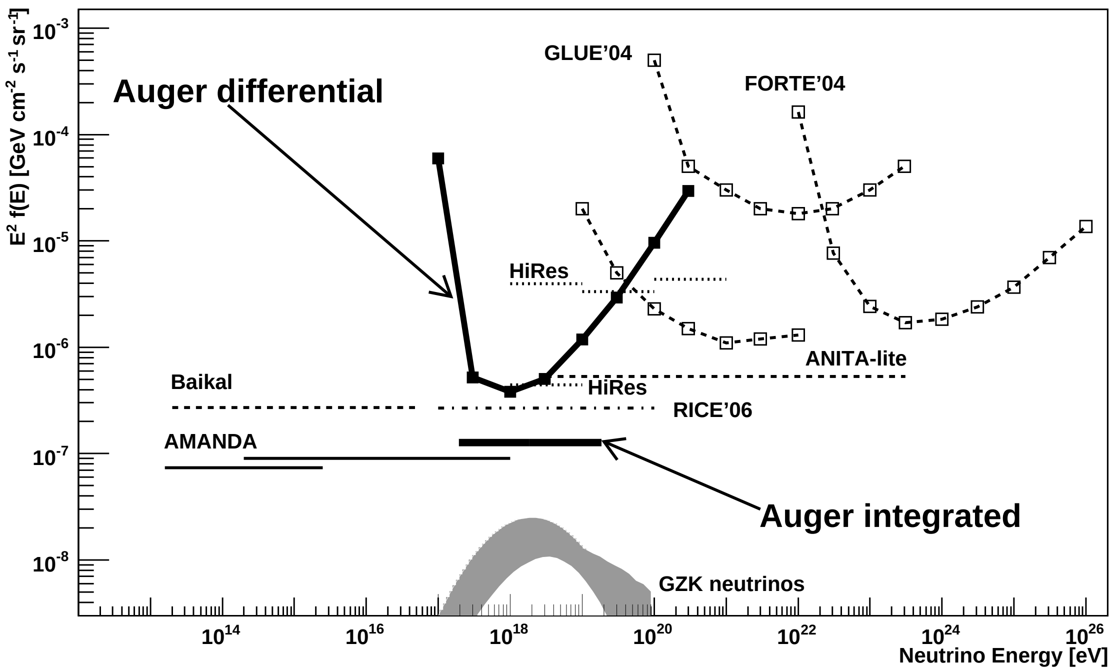


FIG. 3: Limits at 90% C.L. for a diffuse flux of $\nu_\tau$ from the Pierre Auger Observatory. Limits from other experiments [36, 37, 38, 39, 40, 41, 42, 43] are converted to a single flavour assuming a 1 : 1 : 1 ratio of the 3 neutrino flavours and scaled to 90% C.L. where needed. The shaded curve shows the range of expected fluxes of GZK neutrinos from Ref. [10, 11], although predictions almost 1 order of magnitude lower and higher exist.

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