UHE neutrino signatures in the surface detector of the Pierre Auger Observatory

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***Abstract*. The Pierre Auger Observatory has the capability of detecting ultra-high energy neutrinos. The method adopted is to search for very inclined young showers. The properties of such showers that start deep in the atmosphere are very different at ground level from those of showers initiated in the upper atmosphere by protons or nuclei. The neutrino events would have a significant electromagnetic component leading to a broad time structure of detected signals in contrast to nucleonic-induced showers. In this paper we present several observables that are being used to identify neutrino candidates and show that the configuration of the surface detectors of the Auger Observatory has a satisfactory discrimination power against the larger background of nucleonic showers over a broad angular range.**

***Keywords*: UHE neutrino signatures, the Pierre Auger Observatory**

I. Introduction

The detection of ultra high energy (UHE) cosmic neutrinos, above 10^{18} eV, is important as it may allow us to identify the most powerful sources of cosmic rays (CR) in the Universe. Essentially all models of UHECRs production predict neutrinos as a result of the decay of charged pions produced in interactions of cosmic rays within the sources themselves or while propagating through background radiation fields [1]. For example, UHECR protons interacting with the cosmic microwave background (CMB) give rise to the so called "cosmogenic" or GZK neutrinos [2]. The cosmogenic neutrino flux is somewhat uncertain since it depends on the primary UHECR composition and on the nature and cosmological evolution of the sources as well as on their spatial distribution [3]. In general, about 1% of cosmogenic neutrinos from the ultra-high energy cosmic ray flux is expected.

Due to their low interaction probability, neutrinos need to interact with a large amount of matter to be detected. One of the detection techniques is based on the observation of extensive air showers (EAS) in the atmosphere. In the atmosphere so-called down-going neutrinos of all flavours interacting through charge or neutral currents can produce EAS potentially detectable by a large ground detector such as the Pierre Auger Observatory [4]. When propagating through the Earth only tau neutrinos skimming the Earth and producing an emerging tau lepton which decays in flight may initiate detectable air showers above the ground [5], [6].

One of the experimental challenges is to discriminate neutrino-induced showers from the background of showers initiated by UHECRs. The underlying concept of neutrino identification is rather straightforward. Whereas proton or nuclei and photons interact shortly after having entered the atmosphere, neutrinos may penetrate a large amount of matter undisturbed and generate showers close to the surface array. The differences between showers developing close to the detector – so-called young showers – and showers interacting early in the atmosphere – old showers – becomes more and more pronounced as we consider larger angles of incidence. In case of showers initiated by protons and nuclei, which interact soon after entering the atmosphere, only high-energy muons can survive at high zenith angles. As a result, the detected showers show a thin and flat front which leads to short detected signals (~ 100 ns). In case of young neutrino-induced showers a significant electromagnetic component (EM) is present at the ground as well. The shower front is curved and thick and leads to broad signals, lasting up to a few microseconds.

With the surface detector array (SD) of the Auger Observatory, which consists of 1600 water Cherenkov detectors with 1.5 km spacing, we can identify young showers because the signal in each tank is digitized with 25 ns time resolution, allowing us to distinguish the narrow signals in time expected from old showers, from the broad signals expected from a young shower.

In this contribution, we present the criteria used to identify neutrino-induced showers, the important observables, the neutrino identification efficiencies, and the procedure to simulate neutrino induced showers.

II. "Earth-skimming" tau neutrinos

The SD detector of the Auger Observatory is sensitive to Earth-skimming tau neutrinos [7], [8], [9]. These are expected to be observed by detecting showers induced by the decay of emerging τ leptons, after the propagation of of ν_τs through the Earth, see Fig. 1 (upper panel). The first step towards identification of ν_τ induced showers consists of selecting very inclined showers that have most of the stations with signals sufficiently spread in time. Young showers are expected to trigger detector stations with broad signals releasing a so-called 'Time Over Threshold' (ToT) trigger [7]. Counting ToTs stations can help identifying young showers. At this stage

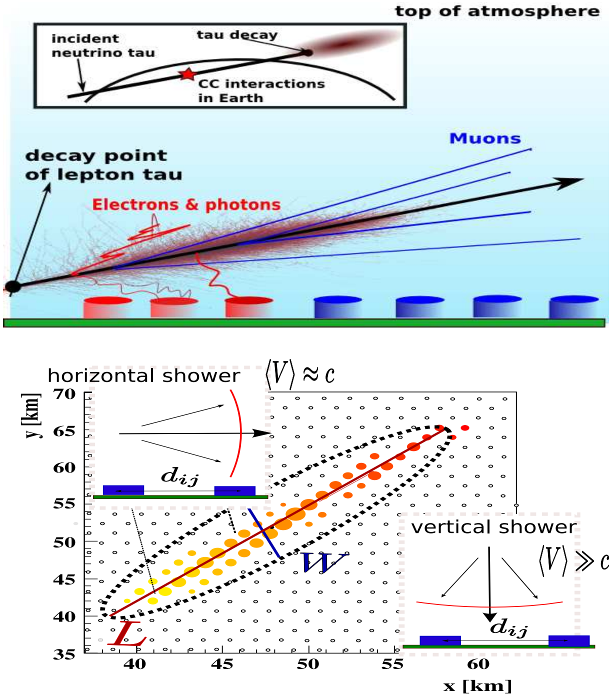

Fig. 1. (Upper panel) The sketch of a shower induced by the decay of a τ lepton emerging from the Earth after originating from an Earth-skimming ν_τ. The earliest stations are mostly triggered by electrons and γs; (bottom panel) sketch of length (L) over width (W) of a footprint and determination of the apparent velocity ($\langle V\rangle$). The $\langle V\rangle$ is given by averaging the apparent velocity, $v_{ij} = d_{ij}/\Delta t_{ij}$ where d_{ij} is the distance between couples of stations, projected onto the direction defined by the length of the footprint, L, and Δt_{ij} the difference in their signal start times.

also a cut of the area of the signal over its peak (AoP)[1] value is applied to reject ToT local triggers produced by consecutive muons hitting a station. Then the elongation of footprint, defined by the ratio of length (L) over width (W) of the shower pattern on ground, and the mean apparent velocity, are basic ingredients to identify very inclined showers [7], see Fig. 1 (bottom panel) for the explanation of these observables.

The mean apparent velocity, $\langle V\rangle$ is expected to be compatible with the speed of light for quasi-horizontal showers within its statistical uncertainty $\sigma_{\langle V\rangle}$ [8]. Finally compact configurations of selected ToTs complete the expected picture of young ν_τ-induced shower footprints. These criteria were used to calculate an upper limit on the diffuse flux UHE ν_τ [8] with the Auger Observatory and an update of this limit [9], [10].

III. "DOWN-GOING" NEUTRINOS

The SD array is also sensitive to neutrinos interacting in the atmosphere and inducing showers close to the ground [11], [12]. Down-going neutrinos of any flavours may interact through both charged (CC) and neutral current (NC) interactions producing hadronic and/or electromagnetic showers. In case of ν_e CC interactions,

[1]The peak corresponds to the maximum measured current of recorded trace at a single water-Cherenkov detector.

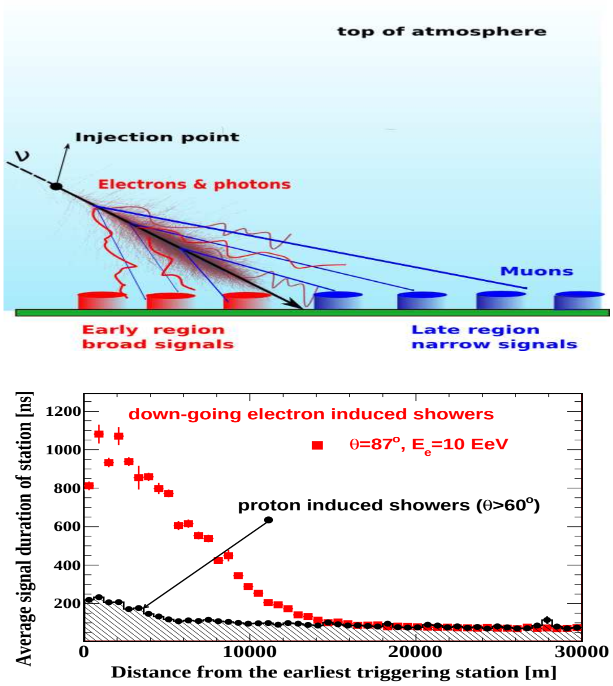

Fig. 2. (Upper panel) Sketch of a down-going shower initiated in the interaction of a ν in the atmosphere close to the ground; In the "early" ("late") region of the shower before (after) the shower axis hits the ground we expect broad (narrow) signals in time due to electromagnetic (muonic) component of the shower; (bottom panel) the average signal duration of the station as a function of the distance from the earliest triggering station.

the resulting electrons are expected to induce EM showers at the same point where hadronic products induce a hadronic shower. In this case the CC reaction are simulated in detail using HERWIG Monte Carlo event generator [13]. HERWIG is an event generator for high-energy processes, including the simulation of hadronic final states and the internal jet structure. The hadronic showers induced by outgoing hadrons are practically indistinguishable in case of ν NC interactions, so they are simulated in the same way for three neutrino flavours. In case of ν_μ CC interactions the produced muon is expected to induce shower which are generally weaker i.e. with a smaller energy transfer to the EAS, and thus with suppressed longitudinal profile and much fewer particles on ground. As a consequence, the detection probability of such shower is low and therefore the produced muon is neglected and only the hadronic component is simulated with the same procedure adopted for ν NC interactions. In case of down-going ν_τ the produced τ lepton can travel some distance in the atmosphere, and then decay into particle which can induce a detectable shower. Thus, the outcoming hadronic showers initiated by ν_τ interactions are usually separated by a certain distance from the shower initiated by the tau decay. In this particular case, τ decays were simulated using TAUOLA [16]. The secondary particles produced by HERWIG or TAUOLA are injected into the extensive air shower generator AIRES [17] to produce lateral profiles of the shower development. Shower simulations were

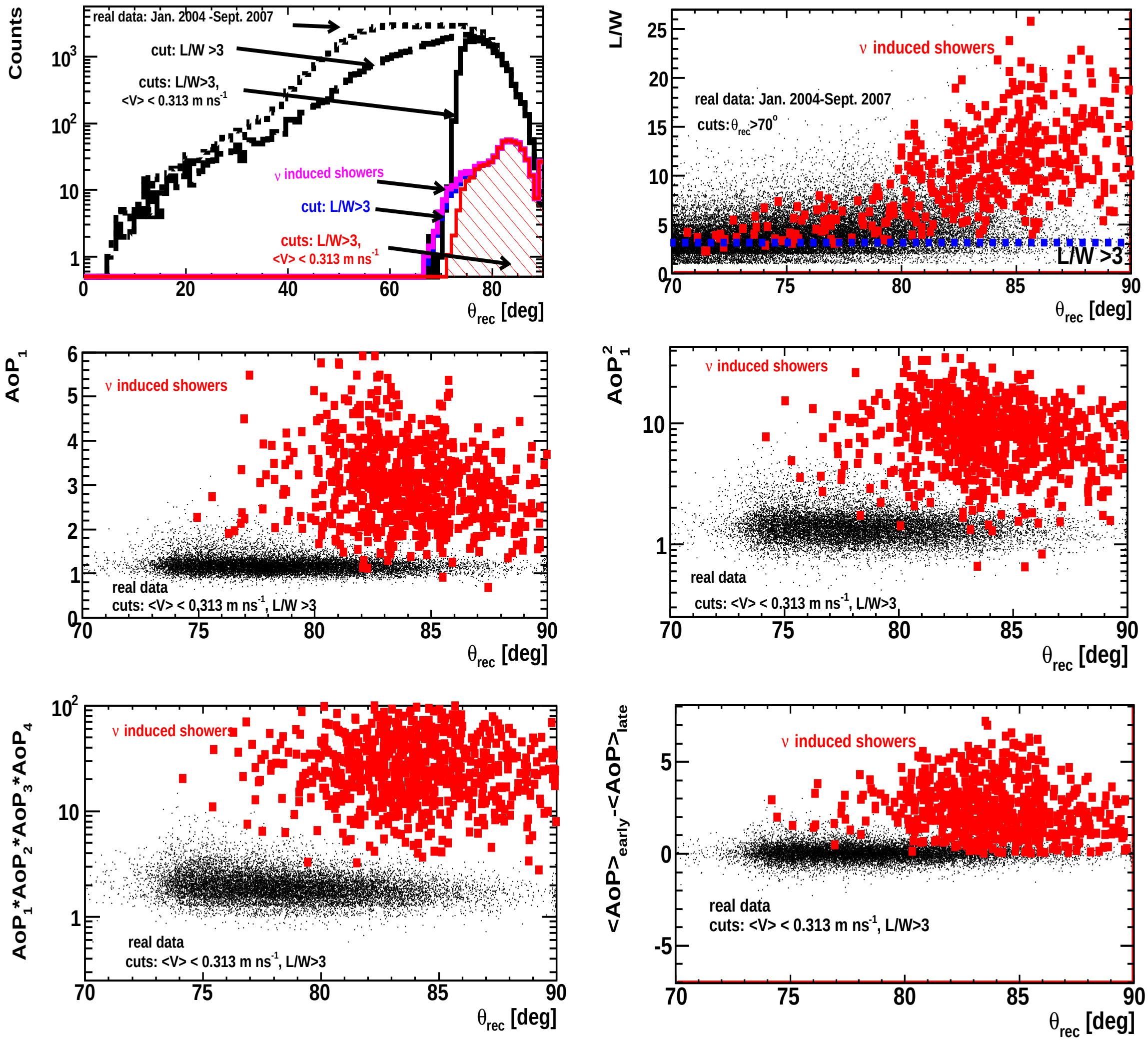

Fig. 3. (Left upper panel) The zenith angle distribution of neutrinos with E^{-2} flux and real events; (right upper panel) the ratio L/W as the function of the reconstructed zenith angle. Neutrino induced showers have larger ratio L/W than real data at high zenith angles. The area over peak for first triggering station (AoP_1) (left middle panel) the square of the area over peak for first triggering station (AoP_1^2) (right middle panel), the product of AoP of four first triggering stations (left bottom panel) and a global early-late asymmetry parameter ($\langle \mathrm{AoP} \rangle_{early} - \langle \mathrm{AoP} \rangle_{late}$) as the function of zenith angle.

performed including the geographic conditions of the site (e.g. geomagnetic field) for different zenith angles $\theta = 75°, 80°, 85°, 87°, 88°$ and $89°$ and random azimuth angles between $0°$ and $360°$ and different hadronic models: QGSJET II [14] and Sibyll [15]. The secondary particles are injected at different slant depths measured from the ground up to a maximum value depending on θ. Finally the response of the SD array is simulated in detail using the Offline simulation package [18]. In total about 20,000 showers induced by down-going decaying τ leptons were simulated and about 36,000 events for electron induced showers. These neutrino simulations were used to estimate the expected neutrino signal and efficiency of detection of the neutrinos.

The criterion to identify young, inclined, down-going showers consists of looking for broad time signals as in the case of up-going neutrinos, at least in the early region, i.e. in those stations triggered before the shower core hits the ground [12]. The physical basis for this criterion is the large asymmetry in the time spread of signals that one expects for very inclined young showers, in which the late front of the shower typically has to cross a much larger grammage of atmosphere than the early front, and as a consequence suffers more attenuation, see Fig. 2 (upper panel). This has been confirmed by simulations of ν-induced showers as is shown in Fig. 2 (bottom panel). The time signal for ν-showers is expected to be broader around the position of the maximum of the shower development. Broader signals are expected to last about 1000 ns, while the duration decreases to a value of about 150 ns downstream in the latest stations which are hit by the muonic tail of the shower development. For hadronic showers with $\theta > 60°$, the expected duration of the signals is almost constant with an average value of about 150 ns. From Fig. 2 (bottom panel) we can see that a good identification criterion is to require broad signals in the first triggered stations of an event.

In the case of down-going neutrinos the general procedure to extract a neutrino induced shower from real data is similar to the procedure used for Earth-skimming neutrinos, i.e. the inclined events are extracted from real data using the apparent velocity and L/W cut and the criterion for looking for events with broad signal in time are applied. However, there are some differences. The selection criteria cannot be the same as for up-going ν_τ, because in case of down-going neutrinos we are sensitive for a larger zenith angle range (about 15° above the horizon instead about 5° below horizon for up-going ν_τ), which also means a larger background contribution and thus a more demanding selection procedure [10].

In Fig. 3 (left upper panel) the zenith angle distribution of real data and simulated neutrino events is shown. The $\langle V \rangle$ and the ratio L/W cut can extract inclined events from real data, see also Fig. 3 (right upper panel). To extract young showers with broad signals, the area over the peak (AoP) of the first four stations its square (AoP^2), their product (AoP$_1$*AoP$_2$*AoP$_3$*AoP$_4$) and a global early-late asymmetry parameter of the event $(\langle \text{AoP} \rangle_{early} - \langle \text{AoP} \rangle_{late})^2$ can be used. These observables were used to discriminate neutrino showers by using the Fisher method, see [10] for more details. As an example in Fig. 3 (middle panels) distributions of AoP$_1$ and AoP$_1^2$ for the first triggering station are shown. In Fig. 3 (lower panels) we also show the product AoP$_1$*AoP$_2$*AoP$_3$*AoP$_4$ (left panel) and the global early-late asymmetry parameter $\langle \text{AoP} \rangle_{early} - \langle \text{AoP} \rangle_{late}$ (right panel) for real data and MC simulated neutrinos. The good separation is clearly visible between neutrino simulated showers and measured inclined events. The separation is better at large zenith angles where the background signal (real data events) is less abundant. This example demonstrates that the SD array has a satisfactory discriminating power against the larger background of nucleonic showers at zenith angles larger than about 75°.

In Fig. 4 the neutrino identification efficiency, ϵ (the fraction of ν-induced showers triggering SD array and passing the neutrino identification criteria [10]) is shown. It is clear that ϵ depends on the zenith angle and type of interactions. The efficiency as well as the range of slant depth grows as the zenith angle increases. Only for showers very close to the SD array does it drop dramatically since the shower does not cross sufficient grammage to develop in the direction transverse to the shower axis. The efficiencies for NC are much lower than for CC for the same neutrino energy and zenith angle. This is due to the fact that in NC reactions the fragments of a target nucleus induce a pure hadronic shower with a small fraction (about 20%) of energy transfered to the EAS while in CC ν_e reaction the rest of the energy goes to an additional EM shower. The identification efficiency depends also on the neutrino

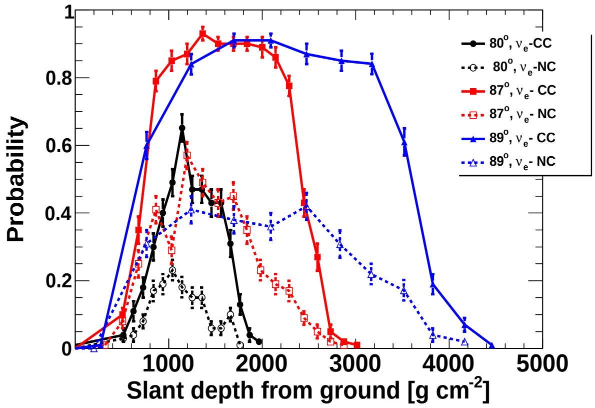

Fig. 4. The ν_e identification efficiency as a function of the neutrino interaction point for different zenith angle and energy 1 EeV.

flavour due to different energy fractions transferred to the induced shower. In CC ν_τ interactions, if the lepton tau decays in flight, only a fraction of its energy is converted into a τ-induced shower. In a ν_μ CC interaction, the produced muon induce a shower which is in general weaker, with a small energy transfer to an EAS with very low probability to trigger the SD array. Thus the ν_e CC induced showers give the main contribution to the expected event rate.

IV. Conclusions

To conclude we have shown that neutrino induced shower can be identified by the SD of the Auger Observatory. The key to for ν identification is the presence of a significant EM component. By means of Monte Carlo simulations we have identified the parameter space where the efficiency of neutrino identification is significant.

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[2] The global early-late asymmetry parameter is defined as the difference between average value of AoPs calculated for the first triggered stations and the last triggered stations of the event. If the number of stations is odd the station in middle is ignored. If the event multiplicity is larger than 8 stations only the first/last four stations are used.