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The sensitivity of the surface detector of the Pierre Auger Observatory to UHE Earth-skimming and down-going neutrinos

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Abstract: The Pierre Auger Observatory is sensitive to ultra-high energy neutrinos in the EeV range and above. In this work we describe the complete chain needed to compute the neutrino acceptance of the surface detector. We firstly address the computation of the probability that an ultra-high energy neutrino produces an air shower. Subsequently we present the simulations to deduce the detector response to those showers. Finally, we discuss the identification of neutrinos based on searching for highly-inclined showers with a significant electromagnetic component at ground.

Introduction

With the Pierre Auger Observatory surface detector (SD) [1] we can detect and identify UHE neutrinos (UHEνs) in the EeV range and above. Neutrinos are expected to be produced in the sources where UHECRs are thought to be accelerated, as well as during the propagation of UHECRs through the cosmic microwave background radiation. Additionally "top-down" mechanisms, proposed as alternatives to explain the production of UHECRs, are expected to produce harder fluxes of UHEνs [2].

The main experimental challenge for the Pierre Auger Observatory is to identify neutrino-induced showers in the background of showers initiated by nucleonic cosmic rays. In principle the concept for neutrino identification is very simple: while hadrons and photons interact soon after entering the atmosphere, neutrinos can penetrate large amounts of matter and generate a shower close to the SD array. By examining inclined showers the differences between showers developing close to the detector ("young") and those produced early in the atmosphere are enhanced. Young showers are expected to exhibit a significant electromagnetic (EM) component at ground, while the EM component of nucleonic cosmic ray showers is largely suppressed due to attenuation in the atmosphere. Young, deep, inclined showers having a significant EM component can be initiated by down-going neutrinos of all flavors interacting through charged or neutral-currents, or by tau neutrinos skimming the Earth and producing an emerging tau lepton which in turn decays in flight over the SD.

In this contribution we show that the SD of the Pierre Auger Observatory is sensitive to upcoming and down-going neutrinos in the EeV range and above. We describe criteria to identify such showers and the procedure that lies behind the effort to search for a diffuse flux of UHE neutrinos with the SD of the Pierre Auger Observatory.

Earth-skimming tau neutrinos

Earth-skimming ν_τs are expected to be observed through the detection of showers induced by the decay products of the emerging τ lepton after propagation and interaction of ν_τs inside the Earth. The efficiency of this conversion and the computation of the emerg-

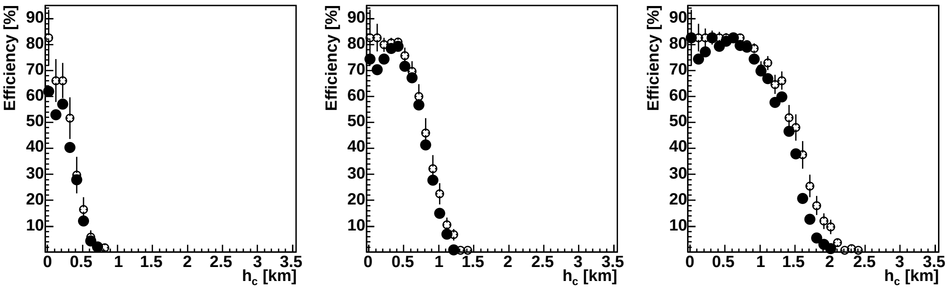

Figure 1: Trigger (open symbols) and identification (closed symbols) efficiencies of τ induced showers as a function of $h_{\rm c}$ (see text), for $\log_{10}(E_\tau/{\rm eV})$ =17.5 (left panel), 18.5 (middle panel), and 19.5 (right panel).

ing flux of τ leptons for an incident ν_τ flux, are therefore two key elements in the calculation of a limit on the diffuse neutrino flux using upcoming showers. The emerging τ flux has been computed using both detailed Monte Carlo simulations and analytical methods, accounting for the charged and neutral-current interactions of the ν_τ inside the Earth, energy loss, weak interactions and decay of the τ leptons. The energy spectrum of the emerging τs peaks at a characteristic energy that depends on the zenith angle due to the different column depths that the injected ν_τs and the produced τs have to cross to reach the detector. Modelling of the τ induced shower in the atmosphere is done by injecting the decay products of τ leptons in the AIRES Monte Carlo shower propagation code at different energies E_τ, zenith angles θ and heights of the decay point of the τ. The QGSJET01 model was used in these simulations. The systematic uncertainty due to the hadronic model is evaluated in [3]. To evaluate the response of the SD of the Pierre Auger Observatory, the particles reaching the ground are stored and injected into a detailed simulation of the tank [4]. Finally the global trigger condition [5] is applied to the local triggers.

Very inclined showers are selected by requiring compatibility of the observed footprint of the shower on the ground with that produced by an almost horizontal shower front travelling at the speed of light along the array. The criterium for identification of deeply penetrating inclined showers produced near the detector requires the presence of a significant number of local Time-over-Threshold (ToT) triggers. ToT local triggers identify broad signals in time that typically reveal the presence of a thick front characteristic of delayed EM particles in the shower. Also a cut on the ratio of the area of the signal over its peak value is applied to reject ToT local triggers produced by consecutive muons hitting a tank. Two similar selections based on these principles have been applied, and one of them has been used to produce a limit on the diffuse flux of UHEνs [3].

In Fig.1 we show the trigger and identification efficiency for upcoming showers induced by τ decays as a function of the height $h_{\rm c}$ reached by the shower at a nominal distance of 10 km along the shower axis from the τ decay. Clearly the higher the energy of the shower the higher in the atmosphere the τ can decay and still be detected and identified. The efficiency can only reach a maximum value of 82.6 % due to the τs decaying into μs which to a first approximation do not produce a detectable shower. Our simulations indicate that for a fixed E_τ, the only relevant parameter determining the efficiency of identification is $h_{\rm c}$. Also, the showers injected at the greatest heights above ground and/or at the smaller nadir angles, do not trigger the array for any of the simulated energies, giving us confidence that the relevant parameter space of E_τ, θ and h has been effectively covered with our simulations. These efficiencies are crucial for the calculation of the acceptance of the surface detector to UHEνs described in [3].

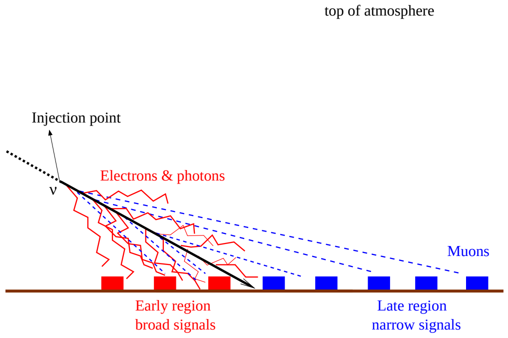

Figure 2: Sketch of a deep inclined shower having broad signals in time due to the EM component in the early part of the shower (before the core), while in the late region the signals are narrow due to the thin muonic shower front.

Down-going neutrinos

Down-going neutrinos of any flavor may interact through both charged and neutral current interactions producing different combinations of hadronic and/or electromagnetic showers. To evaluate the trigger and the identification efficiency for down-going neutrinos, Monte Carlo simulations of shower development and of the tank response are also needed. For this purpose, proton showers at different energies and zenith angles were required to interact at different slant depths. These showers have been simulated using the AIRES propagation code with the QGSJET01 model. The assumption is that the hadronic shower induced in a neutral-current interaction of a neutrino of any flavor, or in the charged-current interaction of a muon or tau neutrino has the same properties as that induced by a proton, except perhaps for a small shift in the depth of development which does not have any implications on the calculation of detection probability. The accuracy of this approximation has been studied by comparing with simulated ν-showers in CORSIKA, and it works well at the $\sim 10\%$ level. Work on modelling the showers produced by electron neutrinos in CC interactions is under development. The response of the tanks is computed in the same way as for Earth-skimming ν_τs [4].

Down-going neutrinos can be expected over a large range of zenith angles and a different identification criterium has been developed. Stations belonging to the event are selected using the start time compatibility with a plane front. The arrival direction is then reconstructed. The event is kept if the reconstructed $\theta > 75^\circ$ guaranteeing that there is no remnant EM component due to π^0 decay. The criterium to identify young, inclined, down-going showers consists of looking for broad signals in time as in the case of upcoming neutrinos, but only in the early region, i.e. in those tanks triggered before the shower core hits the ground. The physical basis for this criterium is the large asymmetry in the time spread of the 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 (depending on the zenith angle), and in consequence suffers more attenuation as illustrated in Fig. 2. For example, the particles in a $\theta = 80^\circ$ shower, initiated at $X_{\rm inj} = 800$ g cm^{-2} (as measured in slant from ground) have to cross of the order of 700 g cm^{-2} *additional* atmosphere to hit a tank at a distance of 3 km from the core of the shower when the tank is located downstream from the first tank struck. One expects to have a thin front of shower muons in the late part of the shower and a thick front of EM particles only in the early region of the shower. This has been confirmed by our simulations which suggest that a good identification criterium is to require that there are broad signals in the first two triggered tanks of the event.

In Fig.3 we show the efficiency for identification of neutrinos of any flavor interacting through neutral-currents or of muon neutrinos interacting through charged-currents assuming 20% of the neutrino energy goes into the shower. The energies in the figure correspond to shower energies, not neutrino energies. The simulated events are checked to satisfy the central trigger algorithms, the algorithm to select inclined showers and the criterium to identify deep showers. The efficiency drops for showers produced very close to the array because they have not spread out sufficiently in the transverse plane to trigger. As the neutrinos interact further away from the

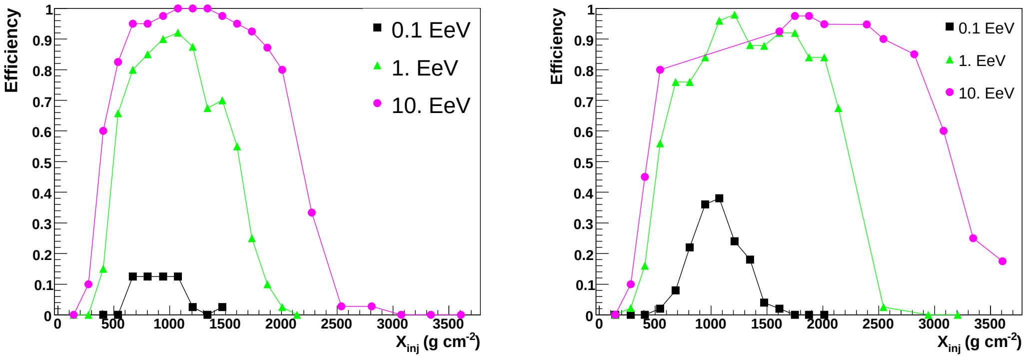

Figure 3: Identification efficiencies (see text) for down-going neutrinos as a function of slant injection depth measured from ground, for different shower energies (not neutrino energies, see text). Note that $X_{\text{inj}} = 0$ g cm^{-2} corresponds to ground level. Left panel: $\theta = 80°$ Right panel: $\theta = 85°$.

surface they are less likely to be identified by this method and the efficiency drops. In this case neutrino identification would require inferring the depth of shower development from the SD alone using the time structure of the muonic signal [6]. One can see in Fig. 3 that the more energetic the shower, the higher the efficiency and also the wider the range of injection depths where the shower can be identified as a young shower [7]. Also for a fixed shower energy, the injection range where identification is possible increases as θ increases. This is due to the combination of two essentially geometrical effects. Firstly, the projection of the array configuration on the shower plane makes tanks look closer to each other from the point of view of the incoming particles, increasing the trigger probability. The second effect is that for a fixed injection in slant depth, the more inclined a shower is the smaller the height above ground of its injection point. As a consequence the EM component of the early part of the shower can reach ground with less attenuation and the shower can be more easily identified as being due to a deeply penetrating particle.

Conclusions

We have shown that upcoming showers initiated by the decay of τs emerging from the Earth after the propagation of a ν_τ flux, and down-going showers produced by a flux of neutrinos of all flavors, can be identified by the SD of the Pierre Auger Observatory. The key to the identification is the presence of a significant EM component. By means of Monte Carlo simulations, we have identified the region in the parameter space in (E_τ, θ, h) for upcoming ν_τ, and in $(E_{\text{shower}}, \theta, X_{\text{inj}})$ for down-going neutrinos where the efficiency of neutrino identification is significant. A search for upcoming showers in the SD data sample is reported in [3]. The search for down-going showers initiated by UHEνs is in progress.

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