SF2A 2006
D. Barret, F. Casoli, T. Contini, G. Lagache, A. Lecavelier, and L. Pagani (eds)

ULTRA HIGH ENERGY NEUTRINOS WITH THE PIERRE AUGER OBSERVATORY

P. Billoir[1] and O. Blanch Bigas[1] for the Pierre Auger Collaboration

Abstract. The Pierre Auger Observatory was designed to observe cosmic rays of ultra-high energy. It has also the capability to observe rare neutrino-induced showers. An evaluation of the sensitivity of the Surface Detector is presented and a procedure to discriminate them from the background is described.

1 Introduction

The observation of a cosmic ray spectrum that extends up to 10^{20} eV has stimulated the development of theoretical hypothesis for the mechanisms generating particles with energies near or above 10^{21} eV. High energy Cosmic Ray production mechanisms are basically of two types, namely acceleration models and "top-down" scenarios. The former involve very powerful astrophysical objects, mainly Active Galactic Nuclei or Gamma Ray Burst, where protons and nuclei could be accelerated close to those energies by conventional acceleration mechanisms. In the latter, new physic processes, such as collapse of Topological Defects, are the responsible for the nucleon production. For different models, different fluxes of neutrinos in the EeV range are expected, although their predicted levels are uncertain (Waxman 2004). The proton and nucleon interactions with the Microwave Background Light along their path from the source to earth produce the so-called *cosmogenic* neutrinos (Beresinsky & Zatsepin 1969). Therefore, neutrinos are distinctive signatures of the nature and distribution of the potential sources of Ultra High Energy Cosmic Rays.

Standard acceleration processes in astrophysical objects as well as "top-down" models produce mainly neutrinos of electronic and muon flavour. The τ neutrinos are heavily suppressed at production. In the scenario of neutrino flavour oscillation (Fakuda et al. 2001) and a maximal Θ_{23} mixing, the situation has changed when neutrinos reach the earth. After travelling cosmological distances, approximately equal flux levels for each flavour are obtained (Athar et al. 2000). Moreover, it has been shown that the prospective of detecting ν_τ fluxes increases for neutrinos that enter the earth just below the horizon (Bertou 2002). In the EeV energy range, neutrinos traversing a relatively small earth matter depth are very effective in producing a τ emerging from earth. The decay of the τ may produce a shower detectable with the Pierre Auger Observatory. They are the so-called skimming neutrinos.

2 Discrimination of neutrino-induced showers

Any UHE particle, if its interaction length is small compared to the atmosphere, gives rise to a shower with an electromagnetic component reaching its maximal development after a depth of the order of 1000 g/cm^2, and extinguish gradually within the next 1000 g/cm^2. After a few atmosphere depth, only high energy muons can survive. As a consequence, showers induced by nuclei (or possibly photons) in the upper atmosphere under a quasi-horizontal incidence, reach the ground as a thin and flat front of hard muons. On the contrary, if a shower begins deeply (a neutrino interaction in air, or a tau decay), its electromagnetic cascade can hit the ground and gives a broad signal. The digitisation of the signal in each of the surface detector stations through FADCs allows to unambiguously distinguish the narrow signals from the broad ones, then to discriminate stations with and without electromagnetic component. This is illustrated on Fig.1 with FADC traces from real events.

[1] Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3-CNRS-Universités Paris VI et Paris VII, 4 place Jussieu, Tour 33 RdC, 75252, Paris Cedex 05, France

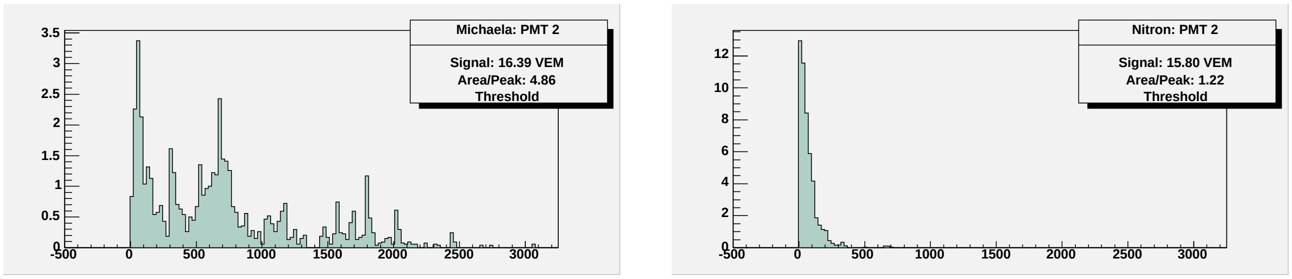

Fig. 1. FADC traces from a station of two different real showers after subtraction of baseline and calibration. Left: moderately inclined (40 deg); right: quasi-horizontal (80 deg). The horizontal scale is in nanoseconds.

The first step of the discrimination is the identification of "young" showers. An event is tagged as a "young" shower if most of its stations show an electromagnetic component and three of them are in a close configuration. The latter is to ensure that the shower fulfils the trigger conditions of the Surface Detector.

The next step is to define from the set of local stations included in the global trigger: first, the tensor of inertia of the positions (weighted by the signals) defines a "length" (along the main axis) and a "width" (along the minor axis); then, for each pair (i,j) of tanks, a "speed" is defined as $d_{i,j}/|\Delta t_{i,j}|$, where $d_{i,j}$ is the distance between them (in projection onto the main axis) and $|\Delta t_{i,j}|$ is the difference between the start times of their signals (Fig.2).

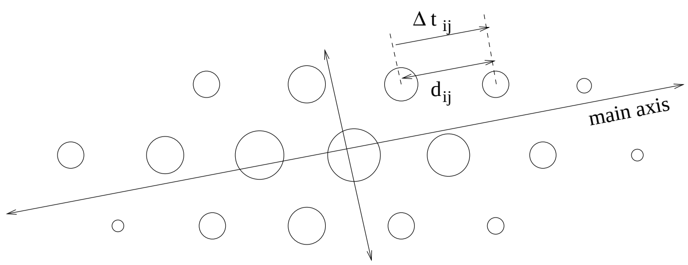

Fig. 2. Footprint of a shower on the surface array. Each circle is represents the position of a station and their sizes are proportional to the station signal.

An horizontal shower is long-shaped (large value of length/width) and it has speeds tightly concentrated around the speed of light. Fig.3 shows the distributions of these discriminating variables for real events and simulated tau showers. The following cuts are applied:

- length/width > 5
- $0.29 <$ average speed < 0.31 m/ns
- r.m.s.(speed) < 0.08 m/ns

This procedure is simple and robust, may be applied to any footprint and does not require any global reconstruction.

Monte Carlo simulations of the surface detector response to extended air showers generated by the decay of a τ have been done to estimate the trigger and selection efficiencies. The selection cuts are satisfied by almost all simulated neutrino events, which pass the trigger condition, while they are expected to be free of background. To compute the Pierre Auger Observatory sensitivity to skimming neutrinos, an incident flux of ν_τ is injected in the earth at energies ranging from 10^{17} to 10^{20} eV, n.c. and c.c. interactions are simulated with cross sections according to CTEQ4-DIS parton distribution (Gandhi et al. 1998), allowing for multiple steps and accounting for the energy loss of the τ. The characteristics of the emerging τ (energy, direction and decay point) are folded with the trigger and identification efficiencies to compute the expected sensitivity of the Pierre Auger Observatory (see Fig.4).

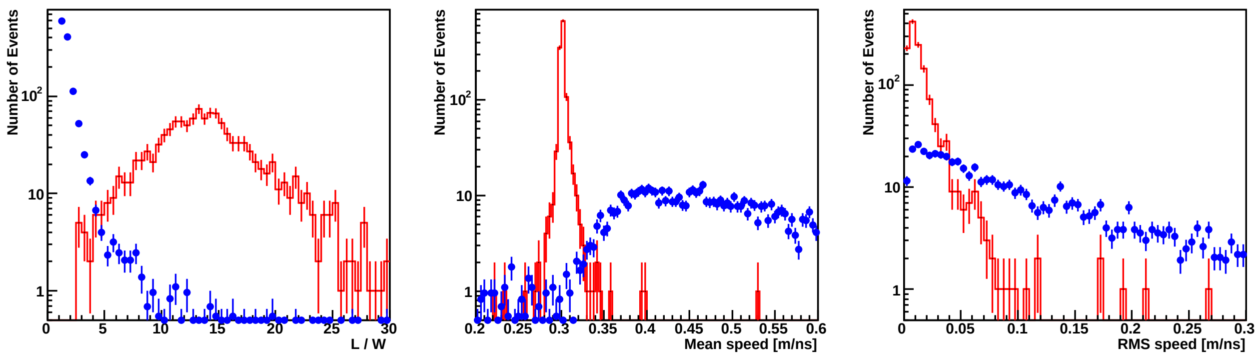

Fig. 3. Distribution of discriminating variables between neutrinos (histogram) and real events passing the "young shower" selection (points). Left: length/width ratio; medium: average of the speed between pairs of stations; right: r.m.s. of the speeds.

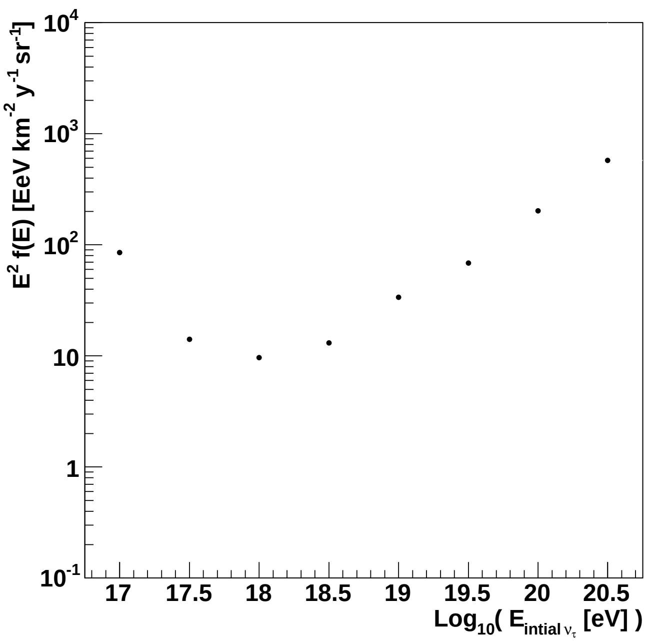

Fig. 4. Sensitivity of the Auger Surface Detector defined as 1 event per year per decade of energy, medium estimation of systematic errors.

3 Energy reconstruction

Once a neutrino induced shower is identified, the aim will be its characterisation. The reconstruction of the energy E_i of the incident neutrino is not straight forward:

- The energy of the emerging τ may be much less than E_i, in particular for high energies, where many intermediate interactions may have occurred while travelling through the earth.
- An arbitrary fraction of the τ energy goes into the extended air shower when the τ decays, since part of the energy is carried out by neutrinos. Moreover, the hadronic to electromagnetic ratio of the products, which changes the shower characteristics, is very dependent on the decay mode.
- Usual estimators of the shower energy from the ground signal rely on the position of the shower core, which

is no well defined for τ induced showers. The signal of the shower of a given energy depends strongly on the altitude where it develops and, hence, the energy cannot be estimated without an estimation of the altitude, which is a priori unknown.

In this scenario, the best we can hope is an approximate lower bound of the initial ν_τ energy.

4 Systematic errors

Computing the acceptance in real conditions of data taking, especially during the deployment of the array, will require to use the monitoring of its status at every time. This has been done for normal events, and the procedure should not suffer from a large systematic error.

Moreover, the earth was assumed to be an homogeneous sphere. Some corrections would be needed, for example the presence of water (Pacific Ocean) in a part of the interaction volume or the non flatness of the earth (Andes). Those correction has been estimated to be below 20 %.

Modelling the tau decay (e.g. neglecting the polarisation effects) and the shower development may contribute for 30 to 40 % to the error on the sensitivity.

Large uncertainties arise from the Monte Carlo simulations of the neutrino interactions inside the earth. Despite the neutrino cross-section estimations based on the standard model may differ upto an orther of magnitude at 10^20 eV, this leads only to a 5% systematic. The dominant source of uncertainties is, by far, the energy loss of the tau in matter. The radiative effects (pair production, bremsstrahlung) may be rescaled from the muon values. The contribution of deep inelastic scattering is much more controversial and it may change the penetrating power of the τ by a factor 5.

With such uncertainties, there is almost one order of magnitude between the lower and the upper estimation of the sensitivity.

5 Conclusions

The Pierre Auger Observatory, designed to observe the cosmic rays around and above 10^{19} eV, may also detect neutrino induced showers and distinguish them unambiguously under quasi-horizontal incidence, above 10^{17} eV. The ν_τ generated by ν_μ though oscillations is the most promising case, through the earth skimming mechanism, despite of very large theoretical systematic errors (mainly the energy loss of the tau through the earth). Within a few years (ten in a pessimistic scenario), the full array of the Surface Detector will, either detect clear neutrino candidates, or put strong limits on the predictions of both bottom and top-down models.

References

Athar, H., et al. 2000, Phys. Rev. D, 62, 103007

Beresinsky, V.S., & Zatsepin, G.T. 1969, Phys Lett B, 28, 423

Bertou, X., et al. 2002, Astropart. Phys., 17, 183

Fakuda, S., et al. 2001, Phys. Rev. lett., 86, 5656

Gandhi, R., et al. 1998, Phys. Revf. D, 58, 093009

Waxman, E. 2004, New J.Phys, 6, 140