Detection of inclined and horizontal showers in the Pierre Auger Observatory

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Abstract. The Pierre Auger Observatory can detect with high efficiency the air showers induced by ultra-high energy cosmic rays incident at large zenith angles $\theta > 60^\circ$. We describe here the specific characteristics of inclined and horizontal showers, as well as the characteristics of their signal in the surface detector. We point out their relevance both to extend the potential of the detector, and in the context of the detection of high-energy cosmic neutrinos.

INTRODUCTION

The Pierre Auger Observatory (PAO) [1] is a hybrid detector designed for the study of the energy spectrum, direction and composition of cosmic rays above $10^{19}$ eV. The surface detector uses water Cherenkov tanks to detect the footprint of the extensive air showers induced by the interaction of the cosmic rays in the atmosphere. This technique makes the PAO suited for the detection of inclined showers, with zenith angle $\theta > 60^\circ$.

The region of zenith angle $60^\circ \leq \theta \leq 90^\circ$ contributes half the total solid angle and 25% of the total geometrical acceptance of the detector. It thus significantly extends its field of view and provides an opportunity to complement the studies of extensive air showers realised in the range $0^\circ \leq \theta \leq 60^\circ$.

Moreover, the possibility of detecting deeply penetrating, very inclined showers could also enable the PAO to operate as a high energy neutrino detector [2, 3, 4]. Neutrino induced showers would have to be identified and separated from a background of inclined showers produced by protons or nuclei. The study of this background has lead to the development of new techniques to analyze this type of showers [5].

CHARACTERISTICS OF INCLINED AIR SHOWERS

Normal cosmic rays initiate an air shower in the first few $100 \text{ g cm}^{-2}$ of the atmosphere. The composition and time structure of the shower at ground depend on the distance between the shower production point and the detector position, which increases with the zenith angle. Studies of the development of inclined showers from nucleonic primaries show that their electromagnetic component from $\pi^0$ production and decay dies out before reaching the ground [6]. The only particles arriving at the detector are energetic muons (typically of $10 – 1000 \text{ GeV}$), accompanied by an electromagnetic halo which
is constantly regenerated by muon decay, bremsstrahlung and pair production, and contributes less than 15% to the overall Cherenkov signal in the tank. Those muons arrive at the ground in a thin front with small curvature, resulting in short FADC pulses in the tanks (see fig. 1).

The trajectories of the muons are extended enough to be affected by the geomagnetic field, which leads to a separation between positive and negative muons. In the plane perpendicular to the shower axis, the muon pattern gets extended and can even assume a lobed form for very inclined showers. This results in very elongated footprints in the ground plane, leading to events with high tank multiplicity.

This effect, together with the difference in evolution of the shower along the footprint on the ground, imply that for very inclined, old showers the cylindrical symmetry around the shower axis is lost, as shown in fig. 2. A specific technique of reconstruction is required, based on the search for the best fit to the muon pattern on the ground, using an average shower characterized by the map of muon densities at ground and by the average response of a tank to incident muons. The knowledge of the best fitting muon map provides us with a characterisation of the shower which is, in good approximation, independent of the composition of the nuclear primary. On the contrary, the scale of the muon density, which can be used to infer the primary energy, changes with the composition; the details of this dependance is obtained using Monte Carlo simulations which are affected by our incomplete knowledge of interactions at high energies.

In this context, hybrid events reconstructed by both the surface and the fluorescence detector will play an important rôle in understanding inclined showers, and in particular their relation with the primary composition, since they allow independant measurements of the electromagnetic and muonic components of the shower [7].

**NEUTRINO INDUCED SHOWERS**

Due to their small cross-section, neutrinos can penetrate the atmosphere deeply and initiate showers at all possible depths, contrary to nuclear or electromagnetic primaries. In particular, showers originating less than $\approx 2000\,\text{gcm}^{-2}$ away from the detector will
reach it before their electromagnetic component attenuates completely. The corresponding signal is that of a young shower: short, peaked FADC traces close to the core position, and extended traces far from it, reflecting the large curvature of the shower front and the presence of an electromagnetic component. At large zenith angles, with these criteria it is in principle possible to separate a young, neutrino induced shower from an old shower induced by a nuclear primary (see fig. 1). The aperture of the PAO for neutrino induced showers should be comparable to that for contained events in conventional neutrino telescopes [2].

CONCLUSIONS

Through the study of inclined air showers, the PAO significantly extends its detection potential and becomes sensitive to another component of cosmic radiation, the neutrinos. The specific phenomenology of those showers also opens new ways for other analyses, like mass composition studies.

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