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Detection of Very Inclined Showers with the Auger Observatory

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The Pierre Auger Observatory can detect air showers with high efficiency at large zenith angles with both the fluorescence and surface detectors. Since half the available solid angle corresponds to zeniths between 60 and 90 degrees, a large number of inclined events can be expected and are indeed observed. In this paper, we characterise the inclined air showers detected by the Observatory and we present the aperture for inclined showers and an outlook of the results that can be obtained in future studies of the inclined data set.

1. Introduction

The study of very inclined air showers, at zenith angles $\theta > 60^\circ$, provides an opportunity to examine aspects of extensive air showers that complement and extend the studies possible in the range of zenith angles $0^\circ \leq \theta \leq 60^\circ$.

The Pierre Auger Observatory [1, 2] is particularly well suited for the detection of inclined showers because the water Cherenkov tanks used for the surface detector act like volume detectors. For completely horizontal showers the transverse area reaches its minimum value of $4.3\,\mathrm{m}^2$, sufficient to detect particle fluxes at relatively large distances from the shower axis. Moreover the number of stations within a given distance to shower axis rapidly increases as the zenith angle rises above 60°.

It was suggested in the late 1960s [3, 4] that neutrinos could be identified by searching for deeply penetrating, highly inclined showers. It was noted in [5, 6, 7] that the Auger Observatory could operate as a high energy neutrino detector. Neutrino induced showers would have to be identified and separated from a background of inclined showers induced by protons or nuclei. The study of this background has lead to the development of techniques to analyse these showers on an event by event basis [8]. Such analysis has shown to be of great interest both to increase the aperture and the sky coverage of surface detectors but also as a new tool to study composition. From studies of this type with the Haverah Park data a competitive bound on photon composition has been obtained [9].

2. Morphology of very inclined air showers

The surface array of the Pierre Auger Observatory, with its ≈ 1600 water Cherenkov detectors, is sensitive to very inclined air showers of zenith angles up to and beyond 85°. The total depth of the atmosphere increases from $1740\,\mathrm{g\,cm^{-2}}$ at 60° zenith angle to $31,000\,\mathrm{g\,cm^{-2}}$ at 90° (see fig. 1). The shape of a signal produced by very a inclined air showers depends on the depth in the atmosphere where the first interaction occurs.

2.1 Nucleonic showers

Normal cosmic rays initiate a shower at the top of the atmosphere, in the first few $100\,\mathrm{g\,cm^{-2}}$. Due to the large slant depth, only the muons in the shower survive (see fig.2). The muons travel accompanied by an electromagnetic halo which is regenerated mainly by muon decay. The halo is proportional to the muons in the shower and contributes less than 15% to the overall Cherenkov signal in the tank.

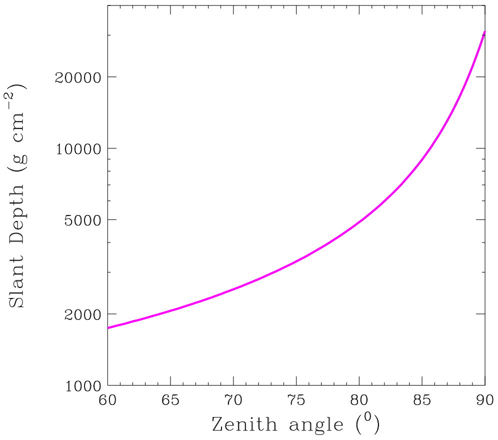

Figure 1. Slant depth for very inclined showers at the southern site of the Pierre Auger Observatory, ranging $1740\,\mathrm{g\,cm^{-2}}$ at 60° zenith angle to $31,000\,\mathrm{g\,cm^{-2}}$ at 90°

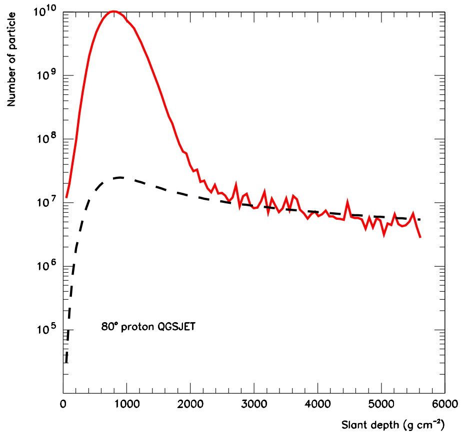

Figure 2. Shower development of an inclined proton shower. From about $2000\,\mathrm{g\,cm^{-2}}$, the electro-magnetic component (red, continuous) dies out and only a halo, induced by and accompanying the muon component (black, dashed) survives [10].

The muon spectrum is cut off at lower energies by muon decays. This limit increases with increasing zenith angle, since more muons decay due to the longer distances travelled. At high energies, the spectrum drops rapidly, since, with increasing energies, πs become increasingly more likely to interact than to decay. At large zenith angles, the shower develops in a thinner atmosphere, which favours decay and therefore a higher cut-off in the muon spectrum.

Even more importantly, the trajectories travelled by the muons become sufficiently large to be affected by the geomagnetic field. Positive and negative muons are separated, leading to an extended pattern of the muons in the plane perpendicular to the shower axis. The projection of this pattern on the ground produces a very elongated footprint, leading to events with high tank multiplicity.

For highly inclined showers, the cylindrical symmetry around the shower axis is lost, both due to the evolution of the shower along the footprint on the ground, and due to the distortions induced by the geomagnetic field. This requires a reconstruction technique different from those used at smaller zenith angles. One tries to find the best fit of an average shower, characterised by the map of muon densities $\rho_\mu(\vec{x})$ on the ground and by the average response of a Cherenkov tank to incident muons. To a good approximation, the pattern of muon densities on the ground has been shown to be similar for protons and heavier nuclei. The scale of the density depends on the energy and the type of the primary particle. The details of this relation are established using Monte Carlo simulations and are therefore subject to uncertainties from our incomplete knowledge of interactions at very high energies. The knowledge of the best fitting muon map, therefore, provides us with a composition-independent characterisation of the shower. To deduce the energy from this fit requires a hypothesis about the nature of the primary cosmic ray.

Hybrid events will also play an important rôle in understanding very inclined showers and help to tune the analysis methods. Very inclined hybrid events exist mainly in the range $60^\circ \leq \theta \leq 70^\circ$. At larger zenith angles, the shower maximum tends to be out of the field of view of the fluorescence detector. A few dozen fully reconstructible events of this type have been detected (e.g., fig 3). These events will allow independent measurements of the electromagnetic component with the fluorescence detector and the muon component with

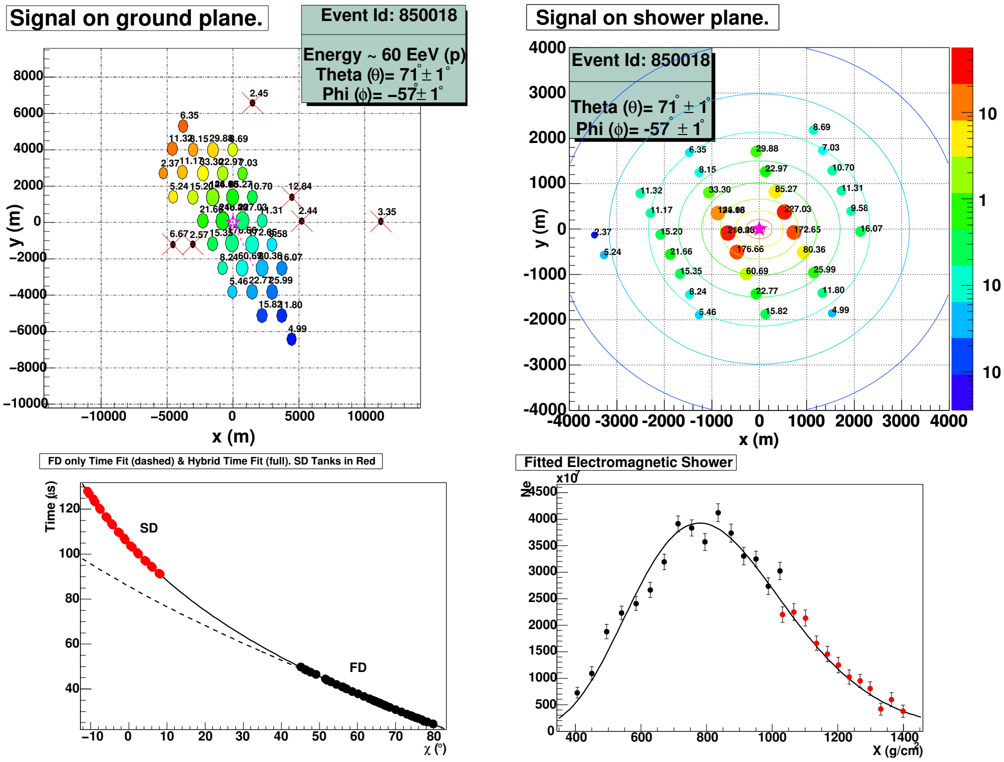

Figure 3. A reconstructed, inclined, hybrid event. In the top row, we have the surface detector data as seen on the ground (left) and in the plane orthogonal to the shower axis (right). One can see the distortions of the iso density lines due to geomagnetic effects. These distortions get larger with increasing zenith angle. In the bottom row, we have the timing fit and the longitudinal profile. The energy assignment of ≈ 60 EeV assumes that the primary particle is a proton and that the hadronic interaction model is QGSJET.

the surface detector. Being able to measure these two components independently is particularly relevant for composition studies [11, 12].

2.2 Neutrino induced showers

Neutrinos, due to their small cross section, can penetrate the atmosphere deeply and interact at all possible slant depths. This means that neutrino induced showers can originate from parts below the region where showers induced by nuclear or electro-magnetic primaries start. In particular, showers originating less than $\approx 2000\,\mathrm{g\,cm^{-2}}$ away from the detector will reach the detector fully developed and before the electromagnetic component attenuates completely. The traces of such a young shower are extended in time (fig. 4, left), compared to that of an old shower (fig. 4, right). Furthermore, the curvature of the shower front is much larger for a young shower than for an old one. With these criteria, it is possible to separate a young, neutrino induced shower from an old shower induced by a nuclear primary. The aperture of the Pierre Auger Observatory for neutrino induced showers has been calculated and is comparable to that for contained events in conventional neutrino telescopes [5].

Earth skimming τ-neutrinos, which convert in the Earth's crust and produce a τ which decays in the atmosphere

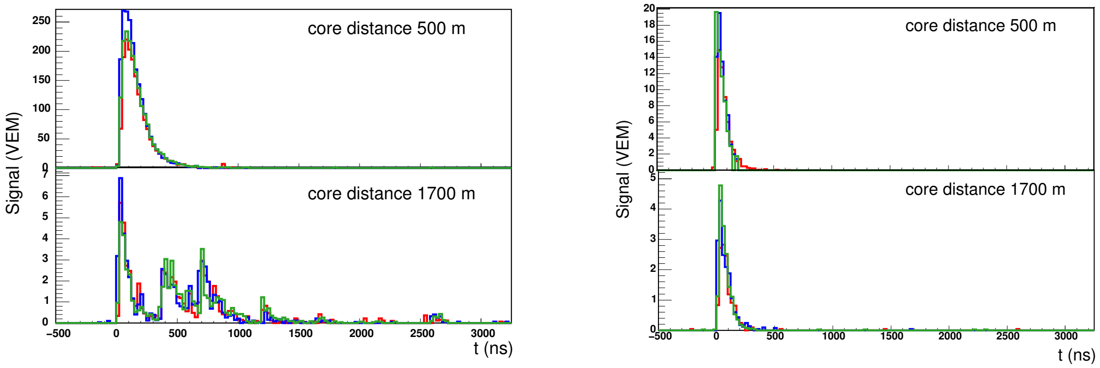

Figure 4. FADC traces of a young (left) and old (right) shower. We see on the left how the signal gets smaller and more extended as the core distance changes from $500\,\mathrm{m}$ (top left) to $1700\,\mathrm{m}$ (bottom left). Old showers have short traces at all core distances (right).

above the detector, provide another channel in which the Pierre Auger Observatory could detect high energy neutrinos. Calculations [6] show that the aperture in this channel is similar to or larger than that in other channels. In principle, such events are also detectable with the fluorescence detector, but expected event rates are not more than 0.25 events per year [7].

3. Conclusions

The study of very inclined air showers extends the potential of the Pierre Auger Observatory. In particular, neutrino detection is possible. The difference in the shower phenomenology of very inclined showers also opens new ways for other analyses, like photon flux and mass composition studies.

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