
A Study Of Very Inclined Showers In The Pierre Auger Observatory

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Abstract

The Engineering Array of the Auger Observatory has been running successfully since 2001 and inclined showers have been recorded from the start. We have analysed the events with zenith angle $> 70^{\circ}$ recorded between May and November 2002. The different algorithms developed to analyze these showers are also discussed. An preliminary discussion of a reconstructed event having 20 detectors hit is presented. Inclined showers will be detected by the full Auger Observatory and they will allow significant enhancement of the array aperture. High energy events will be seen as spectacular events with 30 or 40 tanks triggered and they will provide alternative information on muon content in air showers.

1. Introduction

Uncovering the origin, composition and energy spectrum of the highest energy cosmic rays is one of the biggest challenges in astroparticle physics. The Pierre Auger project is the next step in the search for answers to intriguing questions about the origin of these particles. Before proceeding to the construction of the full-size observatory, a subset of it, the Engineering Array (EA), has been built and operated. A detailed description of the EA can be found in [1].

Ground arrays of water Čerenkov detectors are very sensitive to extensive air showers at large zenith angles. In these showers the majority of the particles reaching ground level are energetic muons and electromagnetic particles resulting from muon interactions or decay. The rate of these showers is then governed by their muon content and is thus sensitive to primary composition. The understanding of these showers is also important because they constitute the background to search for very inclined showers induced by ultra-high energy neutrinos.

Inclined showers would not be very different from vertical showers except for the fact that they develop in the upper part of the atmosphere. As a result the electromagnetic part of the shower, produced mainly from π^0 decay, is mostly absorbed well before the shower front reaches ground level. However, the muon front propagates through the atmosphere mixed with an electromagnetic halo coming from bremsstrahlung, pair production and muon decays. This halo is

continuously generated and proportional to the number of muons, representing less than 15% of the signal in a Čerenkov tank as long as one is sufficiently far away from the core (a few tens of meters).

The muon energy spectrum at ground has a *low energy* cutoff, caused by muon decay, which increases as the zenith angle rises and the average muon energy at ground level also increases. The *high energy* part of the muon spectrum is also slightly different due to the rise of the pion critical energy (the energy at which the pions are more likely to decay than to interact), caused by the smaller density in the upper part of the atmosphere where inclined showers develop.

These energetic muons travel making small angles to the incoming cosmic ray direction and their trajectories are deflected by the magnetic field of the Earth. These effects start to be important at zenith angles above 70° for the geomagnetic latitude of the Auger Observatory. At these zenith angles the muon density patterns at ground are very different from typical densities measured in vertical showers that show symmetry around the shower axis. The geomagnetic field acts as a “natural magnetic spectrometer” selecting high energetic muons and deforming the symmetric pattern.

Signals of inclined showers in Čerenkov tanks being due to muons differ from those in vertical showers. Since the electromagnetic part is heavily suppressed inclined signals have a sharper time structure, with a higher rise time. The signals are proportional to the muon tracks which increase as the zenith angle rises. Direct light, Čerenkov photons to fall directly onto the PMT without reflection from the tank walls, also increase the signal produced by inclined muons. Finally, inclined muons are more energetic enhancing the probability of muon interactions inside the tank, such as bremsstrahlung, pair production and muon nuclear interactions [2].

In this paper we report the preliminary results of the analysis of the inclined shower events recorded by the EA between May and November 2002.

2. Analysis procedure and results

The analysis of inclined showers is a 3 step procedure. The direction of the events are obtained by fitting the particle arrival times recorded at each station to a plane or curved front.

To reconstruct the energy of inclined events a theoretical prediction of the muon density patterns is required. Geomagnetic field effects must be taken into account. There are 3 independent groups working on this issue: *a)* An analytical approximation of the deflection of muons in the geomagnetic field based on the correlation of the muon energy with the distance to the shower axis, Monte Carlo simulations without magnetic field are required to apply this method [2]. *b)* Parameterizations of the number of muons in a tank based on detailed Monte Carlo simulations with geomagnetic field effects. This is a two step simulation:

first the hadronic shower is simulated in the absence of magnetic field, the position, the energy and the direction of the muons is kept at their production point, and in the second step the muons are propagated in the geomagnetic field. The second step is very fast in computing time, allowing to produce simulations for all possible azimuth angles rapidly [3]. *c)* An analytical approximation of the lateral and longitudinal distribution of muons in the absence of geomagnetic field, with the geomagnetic field effects implemented a posteriori in a similar way to method *a)*, [4].

Finally, a likelihood function is built to fit the energy of each event. Two different likelihood functions are being used: *a)* The signal in VEM is converted to muon numbers dividing it by the average signal produced by a muon at the corresponding zenith angle, Poisson statistics are then used to calculate the probability using the prediction of the number of muons. *b)* The other approach uses a probability density function of the signal produced by k muons, obtained in simulations, and multiplies it by the Poisson probability. Details of the two methods can be found in [3], [7]. In order to account for the tank response to inclined muons with different energies and angles of incidence, simulations were performed using the GEANT [5] and SDSIM [6] packages.

We have analyzed all the events recorded between May and November 2002 with zenith angles larger than 70° and with 5 or more stations triggered. In the present work we have assumed proton primaries and the QGSJET hadronic model [8]. Different assumptions about hadronic models and the mass of the primary particle have a direct impact in the number of muons and give rise to different results.

The left panel of Fig. 1 shows the correlation between the energy as reconstructed in two independent analysis. One combines the parameterization of the muon densities and the likelihood function described as *a)* in the previous section and the other corresponds to different parameterization and likelihood function (*b)*). The agreement is encouraging. We can define ΔE_0 as the distance of each point to the line defined by $E_a = E_b$. Right panel of Fig. 1 shows the distribution of the ratio of ΔE_0 to the mean energy using both algorithms. The spread of this distribution is 20% and no significant offset is present.

The results presented here are preliminary. The agreement between the two algorithms used is encouraging but further checks are in progress. The energy of some events are very sensitive to the shape of the muon density patterns used, specially at high energies, where the EA is small compared to the size of the shower at ground. Fig. 2 shows an example: the density map of a reconstructed event in the plane perpendicular to the shower axis. This result was obtained using method *a)* and displays the signals in each tank (converted to mean number of recorded muons). The position of the best-fit impact point is indicated by a cross. The y -axis is aligned with the component of the magnetic field perpendicular to

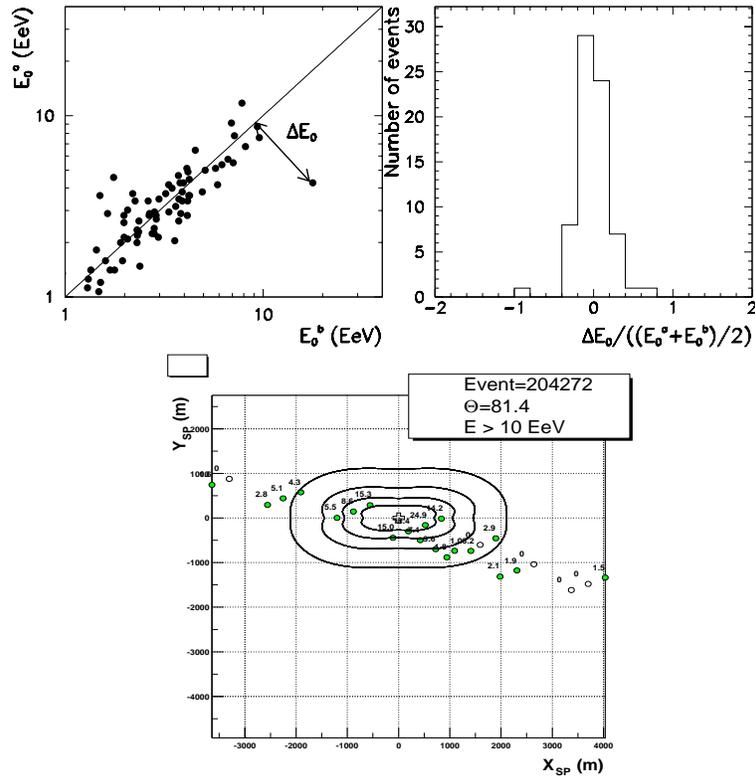


Fig. 1. Top left panel: Correlation of the reconstructed energy by two different algorithms, see text. Top right panel: Distribution of ΔE_0 to the mean energy reconstructed by the two algorithms, see text. Bottom panel: Density map of an event, see text.

the shower axis. Contour levels for 2, 5, 10 and 20 muons per station are shown for the fit. Events like this will be very common in the full array and they will help to check the muon density patterns obtained through simulations or analytical techniques.

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