# Selection and reconstruction of very inclined air showers with the Surface Detector of the Pierre Auger Observatory

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**Abstract:** The water-Cherenkov tanks of the Pierre Auger Observatory can detect particles at all zenith angles and are therefore well-suited for the study of inclined and horizontal air showers ($60^\circ < \theta < 90^\circ$). Such showers are characterised by a dominance of the muonic component at ground, and by a very elongated and asymmetrical footprint which can even exhibit a lobular structure due to the bending action of the geomagnetic field. Dedicated algorithms for the selection and reconstruction of such events, as well as the corresponding acceptance calculation, have been set up on basis of muon maps obtained from shower simulations.

## Introduction

The Pierre Auger Observatory [9] is sensitive to inclined extensive air showers, at energies above $\sim 5.10^{18}$ eV, with a high efficiency and unprecedented statistical accuracy. The characteristics of inclined showers, observed with a surface array of detectors, are quite different to their vertical counterparts and require different reconstruction techniques and these characteristics offer new opportunities to study the properties of the primary cosmic ray.

A cosmic ray, typically, initiates an air shower within the first few hundred grams of atmosphere, achieving shower maximum at $\sim 800\,\mathrm{g\,cm^{-2}}$. In the case of vertical showers this results in a large electro-magnetic component at the ground. Beyond $60^\circ$ , the atmospheric slant depth increases from $1,740\,\mathrm{g\,cm^{-2}}$, to $\sim 31,000\,\mathrm{g\,cm^{-2}}$ at $90^\circ$ at the altitude of the Auger array, and the electro-magnetic component of the shower is rapidly absorbed - although below $\sim 65^\circ$ a significant fraction survives at the ground. Once the primary electro-magnetic component has been absorbed, the muons which arrive at the ground are accompanied only by an electro-magnetic halo due, mainly, to muon decay which contributes $\sim$ 15% of the total signal in an Auger surface detector. This absorption of the electro-magnetic component significantly affects the Lateral Distribution Function (LDF) of particles, which is used to measure the size of vertical air showers, and this makes the vertical reconstruction algorithm unsuitable for analysing inclined showers. Instead maps of the muon ground density, based on simulations, are used to fit the core location of the shower and the total number of muons. For highly inclined showers the path length of the muons is sufficiently large that the geomagnetic field significantly affects the muon distribution on the ground, separating the positive and negative muons and forming a lobed structure which is replicated in the muon maps. With the aid of the maps, the 'size parameter', $N_{19}$, is measured for each shower. $N_{19}$ gives the total number of muons, relative to a shower initiated by a proton primary with an energy of $10^{19}$ eV. The hybrid capability of the Auger Observatory (using events observed simultaneously with the surface array and fluorescence detectors), allows an independent cross-check of the geometrical reconstruction algorithm, and also allows the relationship between $N_{19}$ and the energy of the primary particle to be measured [7].

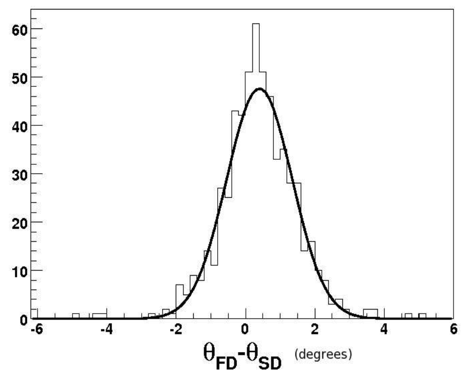


Figure 1: A comparison of the reconstructed zenith angle, $\theta$, found using the horizontal reconstruction and the hybrid reconstruction [2] for 596 hybrid events. The residuals have a mean of 0.45° and a spread of 0.95°.

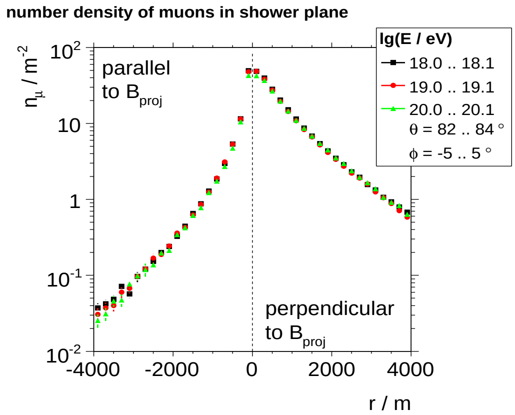


Figure 2: Averaged number density of muons measured in the shower plane. For each primary energy, ten CORSIKA proton showers were used. All individual showers were scaled to the equivalent density of $10^{19}$ eV. The right (left) hand curve shows the distribution perpendicular (parallel) to the projected magnetic field.

The inclined shower reconstruction algorithm has been developed to select genuine events from the background of atmospheric muons, and to provide a robust measurement of the arrival direction and size of the air shower.

## Event Selection

The trigger hierarchy, for the horizontal reconstruction, follows an identical format to that chosen for the vertical reconstruction [3]. The Central Trigger (T3) records all candidate events, the Physics Trigger (T4) selects stations which are compatible with a shower front moving at the speed of light, and a Quality Trigger (T5) is applied, to ensure the validity of the reconstruction.

The first step is to select physical shower events (T4) from the N stations with a signal that were identified by the Central Trigger (T3). The timing of each triggered station is checked for compatibility with a shower front and the projection of the footprint on the ground plane is required to be compact. These tests are applied to an initial configuration of N selected stations, then successive trials with N-1, N-2, ... stations are performed until a satisfactory configuration with four or more stations is found. The conditions to accept a configuration depend on its zenith angle (the shower front is better defined at large zenith angles) and the multiplicity (the variance of the start times increases with the distance to the core).

## Angular Reconstruction

Initially the station start times are corrected for differences in the station altitude and to compensate for the curvature of the Earth. This gives a significant improvement for very inclined, highly energetic events. Of the stations selected by the T4 trigger, no more than seven (those with the highest signals), are used in a plane front fit to the corrected start times. The result of this fit is used to select the appropriate muon map, which are produced in discrete steps of 2° in zenith angle and 5° in azimuth. With this map the core location and shower size, $N_{19}$, are provisionally determined (section 4). Once an assumed core location has been found, a more sophisticated angular reconstruction is made which includes timing corrections to describe the curvature of the shower front. The result from this angular reconstruction, is compared with the result of the original plane fit, and if necessary a more appropriate muon map is selected, and the angular reconstruction is re-iterated with the new muon map. This process is repeated until the results converge (typically one iteration is sufficient). A comparison of the reconstructed zenith angles with the hybrid reconstruction for 596 events is shown in figure 1.

## Core Location and Size Determination with Muon Maps

Inclined showers have a broken radial symmetry caused primarily by the muon component, which is long-lived and is polarised by the Earth's magnetic field. A generalised lateral distribution function is used to reconstruct these showers, which includes magnetic field effects. Such a function can be studied and derived from Monte Carlo simulations to model the lateral number densities of the muons at the ground. These parameterisations are called muon maps.

The shape of the muon maps are dependent on zenith and azimuth angle only, with no significant dependence on the energy (figure 2) and composition of the primary particle . This invariance is due, in part, to their strong dependence on the shape of the muons energy distribution, at their production point, coupled with the large distance from this production point to the ground. Once the muons are produced their trajectory to the ground can be described by well-understood physical processes.

To derive the muon maps from the Monte Carlo simulations three independent algorithms were developed, all using proton showers. The different methods involved AIRES and CORSIKA simulations (using both QGSJET I and QGSJET II), with and without the geo-magnetic field. For the studies without the magnetic field, geo-magnetic corrections were applied using one model which tracks the muons from their production point to the ground, and a second model which applies a correction to the ground distributions. The resultant ground densities, for each of the three methods, were then parameterised to produce the final muon maps. An analysis of the different muon maps shows a good agreement between all three, with the differences far smaller than the Poisson fluctuations expected for a shower initiated by a primary of energy $10^{19}$ eV. The $sin^2\theta$ distribution [7] for reconstructed events, suggests there is no significant zenith-dependent bias between the muon maps and the data.

Once the arrival direction has been determined, the shower size and core reconstruction proceeds. All the selected stations with a signal are used as well as adjacent stations without a signal. To allow a comparison of the muon maps with the station signals, the signal measured in each tank must be converted into an equivalent number of muons. As a first step, a correction is made to remove the fraction of the signal due to the electro-magnetic component. This correction is based on a study of AIRES simulations, where the ratio of the electro-magnetic signal to the muonic signal has been parameterised as a function of zenith angle and core distance. This ratio tends towards $\sim 15\%$ at large core distances and zenith angles. For any assumed core position the muon maps can be used to predict the number of muons, $N_\mu$, in each tank. The probability density functions (PDF) for an observed signal, $S$, are calculated, based on Geant4 simulations [5] and take into account the shower zenith angle and the mean expected muon energy [1] as well as the number of muons crossing the tank. Finally the differences between the muon maps and the corrected station signals are minimised to find the core location and $N_{19}$, the number of muons in the shower, relative to the appropriate muon map.

## Quality Trigger (T5) and Aperture Calculation

Following the strategy used by the Pierre Auger Collaboration to produce the spectrum for vertical showers [4], the acceptance is calculated geometrically. Two basic T5 configurations are considered: 1) The station closest to the reconstructed core location must be surrounded by an 'active' hexagon (i.e. six functioning adjacent stations, though not necessarily with a signal) and 2) the station closest to the core must be surrounded by two 'active' hexagons (18 functioning stations). In addition the reconstructed core location must be enclosed by a triangle of active stations. Compromises on these criteria are also being considered, allowing for one missing station in the hexagons.

The geometric computation is based on counting the stations that fulfill the requirement imposed by the T5 quality trigger. Moreover, the T3 central trigger condition must be fulfilled by stations involved in the T5 to ensure a uniform response from the array. The central trigger assesses up to four hexagons of stations surrounding the central station to built a T3. For inclined showers, which do not have a compact configuration on the detector plane, the energy at which the T3 efficiency reaches 100% will increase if the T3 condition is required in fewer than four hexagons. If more active hexagons are required in the T5 trigger, the acceptance decreases. With two active hexagons, it decreases to $\sim 50\%$ ($\sim 80\%$ allowing one missing station) of that with one hexagon. A comparison is also underway to compute the acceptance by Monte Carlo, throwing simulated muon maps at a realistic detector array, using a position of the core and a time of occurrence that are randomly selected. This avoids the compromise, between maximising the acceptance and reducing the energy at which the efficiency of the array is 100%, that appears for the geometric computation.

The quality of the reconstruction is currently being assessed under the various T5 conditions. This is done using real showers, hitting the centre of an ideal array in which specific real configurations with holes and edges are forced. Preliminary results suggest the dispersion on the reconstructed size parameter is negligible with the requirement that the closest station to the shower core is surrounded by six active stations. Other configurations with requirements for the next to closest neighbours do not significantly reduce the dispersion of the reconstructed size parameter.

## Outlook

The signals, measured with the surface array, from inclined showers lead to what is essentially a measurement of the muon content of the shower ($N_{19}$). Combined with measurements of the electro-magnetic content and the depth of shower maximum, (with the Auger fluorescence detector), this gives a powerful tool to study the cosmic ray composition [8]. Additionally the detectors are sensitive to both deeply-interacting, and Earth-skimming, inclined neutrinos which can be discriminated from the nucleonic cosmic ray flux [6]. Analysing inclined showers increases the Auger aperture significantly: half the available solid angle corresponds to zenith angles between 60 and 90°. The analysis of inclined showers will offer insights into the cosmic ray composition and their atmospheric interactions, and will also supplement the vertical observations by increasing the available number of events in the measurement of the cosmic ray flux and in anisotropy studies.

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