3D Reconstruction of Extensive Air Showers from Fluorescence Data

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Abstract: A new method to reconstruct the 3-dimensional structure of extensive air showers, seen by fluorescence detectors, is proposed. The observation of the shower is done in 2-dimensional pixels, for consecutive time bins. Time corresponds to a third dimension. Assuming that the cosmic ray shower propagates as a plane wave front moving at the speed of light, a complex 3D volume in space can be associated to each measured charge (per pixel and time bin). The 3D description in space allows a simultaneous access to the longitudinal and lateral profiles of each shower. In the case that several eyes observe the same shower, the method gives a straight-forward combination of all the information. This method is in an early phase of development and is not used for the general reconstruction of the Auger data.

Introduction

The Pierre Auger Observatory will provide a large set of cosmic ray data to be analysed in multiple perspectives, ranging from particle physics to cosmology. A detailed understanding of the data is crucial.

The method proposed in this contribution aims at reconstructing fine-details of the individual shower structure and being sensitive to both lateral and longitudinal profiles simultaneously, from the fluorescence light emission. It is not the standard reconstruction method used in Auger, but is built on top of the existing methods that provide the geometry of the shower line and of the longitudinal profiles with great accuracy.

The Auger Fluorescence Detector (FD) is composed of four eyes, each with six telescopes, observing the atmosphere over the centre of the Surface Detector array from different directions, with each eye covering elevations 2° to 32° and 180° in azimuth. The data comprises cosmic ray events up to the highest energies, at very different distances from the detector eyes - ranging from 1 to above 30 km.

The Auger FD data are collected in pixels of approximate angular dimensions of 1.5° and in 100 ns time bins. The standard reconstruction is based first on the pixel angular information, to find the plane that contains the shower axis and the observing eye (the Shower-Detector Plane, SDP). The centroid time found for each pixel is then used to find the axis line within this plane, the minimum approach distance to the detector, and the reference time at which it occurred (T_0). The shower geometry is simply given by this line (details of the calculation are given in [1], the reconstruction can also use several eyes and the surface detector, as explained in [4]). In the above procedure pixels which do not observe the SDP cannot be used for the geometry reconstruction and the time structure of the signal inside each pixel is neglected. Although for distant showers the line approach is clearly sufficient, for close-by showers relevant information can be lost.

To measure the energy deposited by the primary cosmic ray, a Gaisser-Hillas function is then fitted on this line. To include the effect of non-perfect optics and the fact that the shower in not only a line, the contribution of near-by pixels is considered at this stage, by summing signals for each time bin. Some of the information important for the longitudinal profile and energy reconstruction is restored in this procedure.

However, the information that can be present in the lateral profile of the shower, in possible asymmetries or local fine structures is lost in the standard reconstruction – this is the main motivation to find another reconstruction method that takes all the available information into account. The method described below is under test in simulation (and laser data), and will soon be tested in real data.

The 3D method

Geometry Reconstruction

The basic idea of the method is to propagate the available 3D information - binned in two angular dimensions and one time dimension - into 3D volumes in space. These volumes contain the points from which the observed fluorescence photons were emitted.

The cosmic ray shower is assumed to propagate as a plane wave front, moving at the speed of light. For each direction observed in the detector, there is a line in space that in general does not intercept the shower axis. The observation time, on the other hand, is a sum of the emission time of the photon and its propagation time to the detector. The emission time is characteristic of all the particles in a disk moving coherently along the shower axis at constant velocity c.

Starting from a given hypothesis for the shower axis and core distance, each observation direction at each time corresponds to a unique point in space. The axis and core coming from the standard reconstruction (being it mono, stereo or hybrid when available) are used as a first hypothesis, and, with the geometry fixed, the time of closest approach between the shower line and the detector, T_0, is found using the pixel centroids and directions within the SDP, as before.

The position of the centre of each volume (corresponding to θ_j, ϕ_j of the pixel centre and t_i

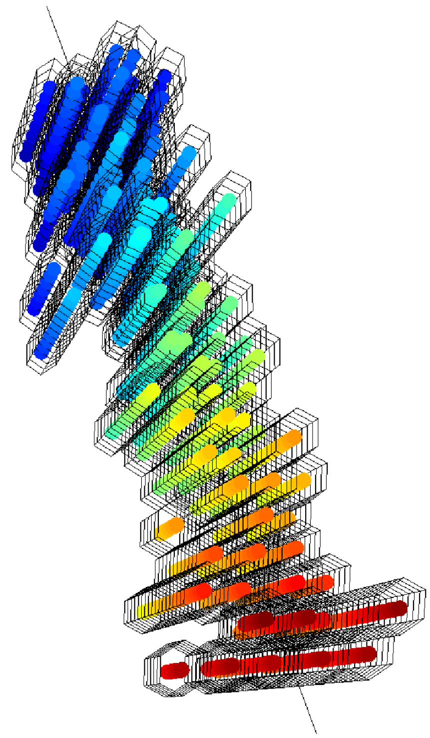

Figure 1: 3D view of a simulated event of $10^{18.5}$ eV seen at 2 km from the telescope. The shapes of the 3D volumes are shown and the color code corresponds to the detection time. The visualisation is done with the map3d package [3].

for each time bin) is then found for

$$r_{ij} = \frac{c \cdot (t_i - T_0)}{(1 + cos(\alpha_j))}, \qquad (1)$$

being α_j the angle between the observation direction and the shower axis.

The borders of each volume are given by the same procedures using the θ, ϕ of each vertex and $t_i \pm 50$ ns. Notice that the Auger pixels are regular hexagons layed on a spherical surface – irregular in θ, ϕ – and that the observation times correspond to constant emission times along the bisectrix between the shower axis and the observation line.

As the time differences between pixels give information on the shower axis location, the time duration of the signal within each pixel can also provide the same information. In addition, larger time signals can also correspond to larger lateral dimensions of the shower. To profit from the extra information, the charge observed in each volume is used to refine the shower axis (and core) determination.

This is done by calculating the "centre-of-mass" and "inertia axis" of the 3D object composed by all the volumes, considering the charge to be, in first approximation, proportional the number of particles, and to the "mass".

The main "inertia axis" gives the shower direction, replacing the shower axis (the shower core being fixed by the "centre-of-mass").The two other axes give a first measurement of the average lateral distribution, the fact that they are usually equal shows that there is no significant bias in the use of time as a third dimension.

To a new axis and core hypothesis correspond new SDP and T_0 (the latest to be recalculated from data), and so new positions and shapes for each volume. The procedure can thus be iterated until reasonable stability is obtained for the axis direction and core location. The resolutions on core location and axis directions obtained after the iterations are comparable with the ones from the standard reconstruction used as inputs, no clear improvement is obtained but no information is lost, which again shows that there is no significant bias in the use of time as a third dimension.

Figure 1 shows the 3D view of a simulated close-by event. The different volume shapes with dimensions coming from pixel and time bin size are clearly seen, the color codes show the time bin of detection associated to each volume.

Energy and Profiles Reconstruction

The 3D volumes in space correspond to the regions from which the observed photons were emitted. It is then possible to compare their charges to that given by a hypothesis - a longitudinal and a lateral profile - taking into account the light attenuation from the emission point (P) to the detector and the effective collection area seen by the telescope, as shown in equation 2.

$$Exp_P = GH(\mathbf{X_P}, X_{max}, X_0, \lambda, N_{max}) \cdot GO(\mathbf{X_P}, \mathbf{R_P}, X_{max}) \cdot RS(\mathbf{r_P}) \cdot Y_f \cdot \frac{A}{(4\pi \mathbf{r_P}^2)} \quad (2)$$

where Y_f is the fluorescence yield, GH is the longitudinal profile depending on the slant depth, X_P, and GO is the lateral profile, that depends also on R_P the distance to the axis (the profiles are given, respectively, by a Gaisser-Hillas and a Góra function [2], for example), RS is the Rayleigh Scattering factor, depending on the distance between the emission and detection points r_P (no Mie scattering is considered for now and multiple scattering contributions are neglected), and A represents the effective diaphragm area and may include constant calibration factors.

In addition to the fluorescence light, also direct and scattered Cherenkov are included. Even for showers not directed to the eye, scattered Cherenkov can represent a non-negligible fraction of the detected light. The parameterisation of the angular distribution function given in ref [5] is used for the direct contribution, while for the scattered one the convolution of the Cherenkov light production with Rayleigh scattering is considered.

The light observed in the telescope is spread by the non-perfect optics in the mirror, producing a spot, which depends on the incidence angle and can be parameterised from simulation, including also camera shadow effects. This information can be included to find the exact positions of the photons in the camera. Since the calibration is done by illuminating equally all the camera points, a factor f_m can be found to correct up the sensitive areas, and correct down the Mercedes regions.

The Monte Carlo integration starts by finding a cylinder with the reconstructed shower axis, and enclosing the several reconstructed volumes. The expected number of photons from function 2 is evaluated for each of $N_1 \times N_{vol}$

randomly generated points, to cover all the N_{vol} volumes found for each telescope. Afterwards, N_2 points are spread according to the spot parametrisation and, in each, the function is corrected by f_m. The sum of the function for the final points in each volume, normalised by volume of the cylinder V_{cyl}, gives the expected number of photons per pixel and time bin, to be compared to the observed one:

$$Exp_{vol} = \frac{V_{cyl}}{N_{vol} N_1 N_2} \sum_P Exp_P \sum_{P' \in vol} f_m(P') \quad (3)$$

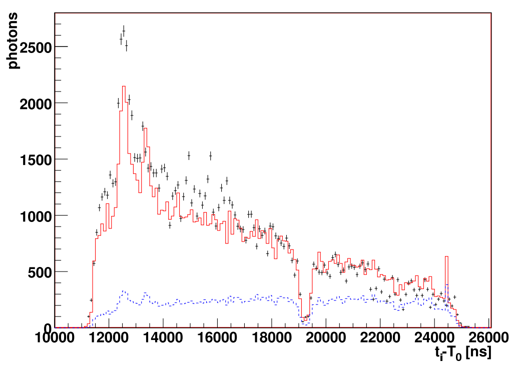

Figure 2: Number of observed photons from a simulated event of $10^{18.5}$ eV, as a function of time. The data points are compared to the total expectations. The Cherenkov contribution is shown separately in the dashed line.

Figure 2 shows the expected and observed number of detected photons as a function of the observed time, for a given simulated event. The simulated values are used for the Gaisser-Hillas and Góra function. Knowing the error on the observed value, one can create a χ^2 function to minimise for the model parameters appearing in both functions. The lateral profile function could be directly tested for close-by events and that might help in the estimation of the total energy and X_{max}, even when X_{max} is out of the field of view.

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