ARGO-YBJ Experiment: Shower front time structures

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1. Introduction

ARGO-YBJ is operating in its complete layout since 2007 allowing a complete and detailed three-dimensional reconstruction of the shower front with unprecedented spatial and time resolution.

The space-time structure of extensive air showers depends on primary mass, energy and arrival direction and on the interaction mechanisms with air nuclei. Measurements of shower parameters with several detection techniques would be required for a detailed knowledge of the shower front. A flat array like ARGO-YBJ can measure the particles arrival times and their densities at ground. The digital readout allows detecting shower secondary particles down to very low density and the high space-time granularity is able to provide a fine sampling of the shower front close to the core. The time profile of the shower front can be reconstructed by the time of fired pads. Particles within several tens of meters from the shower core are expected to form a curved front. Indeed, to reconstruct the primary particle arrival direction, the space-time coordinates (position and time of fired pads in the event) can be fitted to a cone whose axis crosses the core position at the ground. The arrival times of the particles are fitted by minimizing the following quantity:

$$S^2 = \frac{1}{W}\sum_{i=1}^{N_{hit}} w_i \left(t_i - t_0 - \frac{x_i}{c}l - \frac{y_i}{c}m - \frac{R_i}{c}\alpha\right)^2 \quad (1)$$

The reconstructed parameters are the direction cosines l,m and the time t_0. The sum is over the fired pads, $W = \sum_{i=1}^{N_{hit}} w_i$ being w_i the number of strips fired in the i-th pad, t_i is the measured time, x_i, y_i are the pad coordinates and c is the light velocity. The conicity correction depends on the conicity coefficient (α) and on the pad distance (R_i) to the core in the plane perpendicular to the shower axis. A Maximum Likelihood based algorithm, using a NKG-like [1] lateral distribution function [2] is used to perform a reliable reconstruction of the shower core position and arrival direction up to the edge of the active carpet and slightly beyond. The time structure of the shower disc has been studied as a function of the distance to the shower axis. It is identified by the zenith angle θ and the azimuth angle ϕ of the primary particle arrival direction. Following the approach described in detail in[3], the curvature of the shower front, defined as the mean of time residuals with respect to a planar fit, is investigated in the energy range between 300 GeV and 100 TeV and its features are employed to characterize the standard surface array observables.

2. Temporal and spatial structure of air showers

The analysis uses a data sample of about 3.5×10^8 events satisfying the trigger condition of at least 20 fired pads in a time window of 420 ns[4]. The reconstructed core positions are required to be within the central carpet and a quality cut on the S^2 of the fit has been applied in order to reject mis-reconstructed events. Under these conditions, a Monte Carlo study has shown that the fraction of mis-reconstructed events with true core position external to the central carpet is about 10% at the lowest multiplicity and decreases down to the few percent for increasing multiplicities. This analysis is restricted to events with reconstructed zenith angle $\theta < 15°$.
The spatial and time structure of the shower disc has been studied as a function of the distance to shower axis, in intervals of 1 m between 10 m and up to a maximum distance of 70 m. Fig.1 (top) shows the mean of time residuals with respect to a planar fit for different pad multiplicities. The arrival time delay from planar fit increases with distance up to 10 ns for particles landing further than 50 m from the core. No significant dependence on pad multiplicity is observed. Fig.1 (bottom) shows a comparison of data to simulation (proton) for pad multiplicity between 200 and 400.

Shower-by-shower fluctuations play a key role for the understanding of EAS morphology. The design of the ARGO-YBJ detector offers a unique

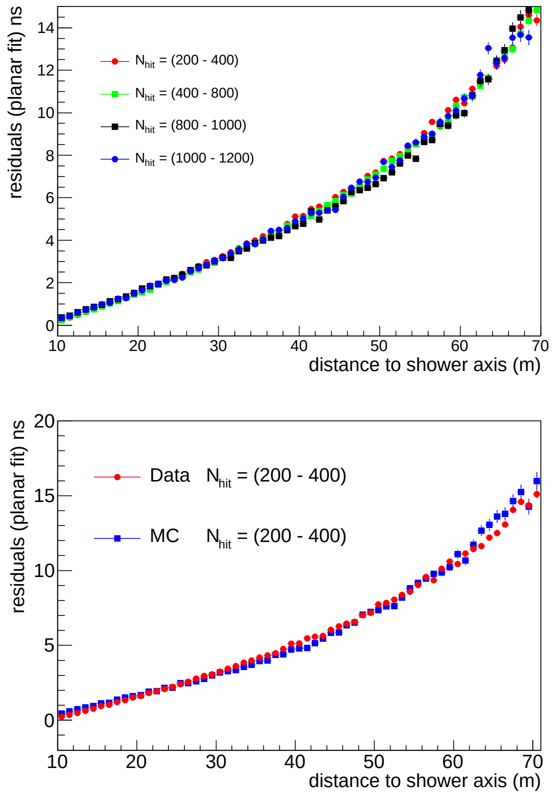

Figure 1. Mean of time residuals with respect to a planar fit (top), data. Comparison to simulation (proton) for pad multiplicity between 200 and 400 (bottom).

chance to have high-resolution pictures of shower footprints at the ground. Each observed event keeps track of the propagation through the atmosphere. This factor can influence the shape of time front and the sequence of arrival times. For primaries interacting deeper in the atmosphere, (originating "young showers"), due to geometrical reasons, the arrival of particles at a given lateral distance is expected to be more delayed compared to primaries that have interacted higher (originating "old" showers). Young showers will then exhibit a steeper time profile with respect to a planar fit. A study of the correlation between the conicity parameter α assigned to each reconstructed event and the atmospheric depth at shower maximum stage, Xmax, has been performed using CORSIKA[5] simulations. Results are shown in Fig 2 for proton primaries with zenith angle below 15°. The conicity increases (decreases) for deeper (shallower) Xmax and this feature suggests to adopt this observable as an estimator of the shower development stage. A third degree polynomial fit to the profile shown in Fig. 2 is used to parametrize the correlation between the

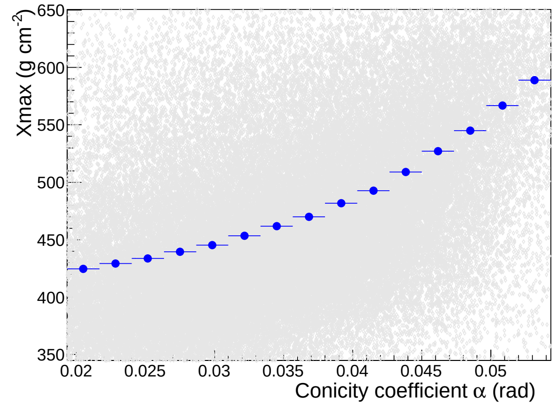

Figure 2. The atmospheric depth at shower maximum (true value from simulation) as a function of the (reconstructed) conicity parameter α (statistical uncertainties only).

observed α and the corresponding mean Xmax. For a sample of data selected with the same criteria used for the simulation, this method provides an estimate of the mean Xmax consistent with the true value within a ten gcm^{-2}. Despite not exaustive, this test gives an encouraging indication to be further exploited.

The potential of the knowledge of the shower front shape has been also investigated by splitting the simulated data set in two sub-samples, on the basis of the conicity. Events with reconstructed α less or larger than 0.035 ns/m are classified as "old" or "young" and the reconstructed multiplicity of fired strips at the ground is studied as a function of true energy (see Fig.3).

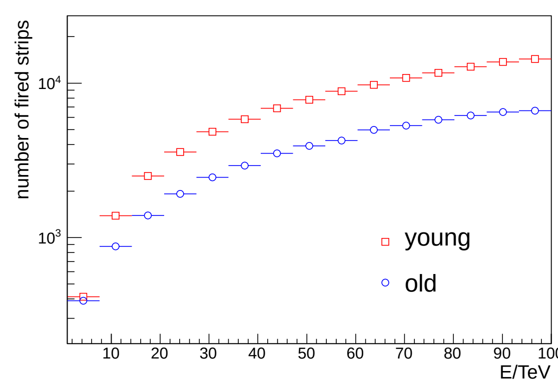

Figure 3. Strip numerosity as a function of true energy between 10 and 100 TeV, for "old" and "young" showers with zenith angle less than 15°.

For a given energy of primary particle, the observed multiplicity may be very different for the two classes of events, as it is influenced by the altitude of the first interaction point (i.e. by the shower age). An independent measurement of the stage of the shower development can in principle allow an improvement of the resolution of the multiplicity, leading to a better accuracy in the estimate of the energy.

3. Large rms shower fronts

This section is devoted to the study of events that show particularly wide time distribution. After a study on the shower time profile and on the lateral distribution at different time delay from the shower front, showers with large time residual rms with respect to the shower front have been investigated. The longitudinal time structures in data could help to better define selection criteria for particular analysis, such as γ/hadron separation, composition or "exotic" physics, and allow a better determination of EAS disc structure and correlations between front profile, front thickness and core distance. By this analysis, several structures have been observed. The events are selected requiring a strip multiplicity threshold greater than 120, in order to have a proper multiplicity to reconstruct two separated fronts, and a time residual rms from the conical front greater than 15 ns, which correspond to a cut of $S^2 > 225\, ns^2$. The cut in multiplicity correspond to select the 10% of the events, while the cut in rms reduce the sample to 11% of the total events. The combined cuts select 0.5% of the events. For double shower fronts an additional request has been defined: the time residual from the conical shower front is fitted with two Gaussian distributions. If the two Gaussians are well separated, the two peak distance is greater than the sum of the relative sigmas, the event is selected. In this work only double front showers analysis will be reported.

In order to establish the origin of these events, a detailed analysis has been carried out. First of all the two groups of hits are separated and the shower properties reconstructed separately. After that reconstructed parameters such as subshower multiplicity, direction and arrival time are compared. Requiring good reconstruction parameters on both subshower permits to detect pure coincidence events. The expected number of events have been calculated as the number of coincidences expected in the trigger time window $\tau = 2\mu s$ taking into account the quality selection on subshowers. The expected rate is equal to:

$$\lambda_{exp} = 2 \times \lambda_1 \times \lambda_2 \times \tau = 14.5 \pm 0.5 Hz \qquad (2)$$

where $\lambda_1 = \lambda_2 = 2.69$ kHz is the oberved rate of the showers satisfying the quality requirements for the subshowers in the same sample of data. In case of pure time coincidences the multiplicity distribution should be similar for the two subshowers. The relative delay, defined as the time difference between the two T_0 from the planar fit applied to reconstruct the subshower parameters, are compatible with the expected exponential distribution $e^{-\lambda t}$, with $\lambda \sim 3.5$ kHz, the DAQ acquisition rate. The relative angular distribution have been compared with a similar distribution obtained by a toy Montecarlo. All distributions analyzed show the expected behaviour. The results are fully consistent with the random ditributions of two events distributed with a $cos^2\theta$ zenith angle dependance. At present 3.1×10^8 events have been processed and 1931 results as double coincidences, corresponding to about 6 $\times 10^{-4}$% of the events, three order of magnitude smaller than expected. The actual algorithm, and in particular the request on the shape of the residual distribution, is too hard. New more effective selection criteria are under study. Artificial double events will be produced to calculate the efficiency of the entire procedure and to better define the correct selection parameters.

In order to evaluate also the possibility to find double front showers in single shower development, the same analysis has been applied to a full sample of MC data of several elements (Proton and Helium) at zenith angle ranging from 0^o to 45^o and in an energy range between 100 GeV and 1 PeV. Several Events show interesting delayed time structures, especially in heavy elements and higher energy ranges, but MC events,as expected in analysis of random time coincidences, don't reproduce double shower angular distribution, indicating that eventual interesting events in shower cascade development should be searched at low values of the relative angular distribution. More checks are necessary to understand the origin of such delayed events and to better define observables to be searched in real data.

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