Time structure of the extensive air shower front with the ARGO-YBJ experiment

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***Abstract*. The ARGO-YBJ experiment is an Extensive Air Shower array currently operating at the high altitude Yangbajing Cosmic Ray Laboratory (Tibet, P.R. China 4300 m a.s.l.). The detector consists of a layer of Resistive Plate Counters (RPCs) covering an area of about $5800\ m^2$. Its fine granularity, full coverage design and high time resolution provide a detailed characterization of cosmic ray showers. Curvature, thickness and shape of the shower front have been investigated up to 100 TeV. Detailed Monte Carlo simulations of the detector response have been performed using CORSIKA showers and results are compared to data. Finally, correlations of measured observables with the nature of the primary are discussed.**

***Keywords*: Time structure, curvature, thickness**

I. Introduction

The ARGO-YBJ experiment (Astrophysical Radiation with Ground-based Observatory at YangBajing) has been designed to study cosmic rays and cosmic γ-radiation at energy larger than few hundreds GeV, by detecting air showers at high altitude with wide-aperture and high duty cycle. The apparatus is a single layer detector logically divided into 154 units called clusters (7.64×5.72 m^2), each made by 12 Resistive Plate Counters (RPCs) operating in streamer mode. Each RPC is read out using 10 pads (62×56 cm^2), which are further divided into 8 pick-up strips providing a larger particle counting dynamic range. The signal coming from all the strips of a given pad are sent to the same channel of a multi-hit TDC. Pads are the time elemental units for measuring the pattern of the shower front with time resolution of $\sim$ 1 ns. The percentage of active area in the central array is 92%. To improve the reconstruction capability, the surrounding area has been partially instrumented with a guard ring of RPCs extending the detector layout up to 99×111 m^2.

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

II. Shower Reconstruction and definition of the observables

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 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 (shower plane, see Fig. 1) 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 disk has been studied as a function of the distance to shower core computed on the shower plane. It is identified by the zenith angle θ and the azimuth angle ϕ of the primary particle arrival direction. The following observables have been investigated in the energy range between 300 GeV and 100 TeV:

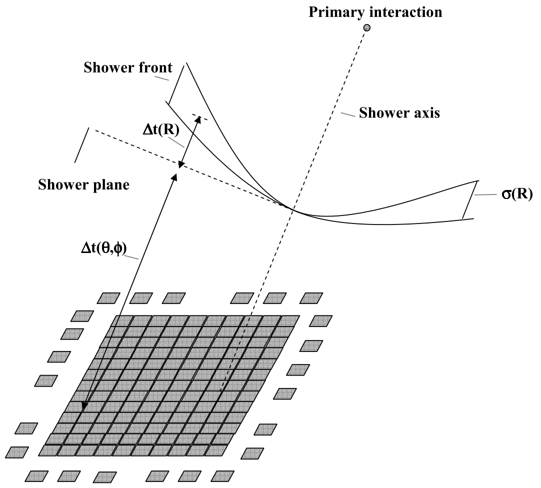

Fig. 1. Sketch of shower front geometry and observables.

- **Curvature** of the shower front as the mean of time residuals with respect to a planar fit ($\Delta t(R)$ see Fig. 1)
- **Thickness** of the shower front as the root mean square (RMS) of time residuals with respect to a conical fit ($\sigma(R)$, see Fig. 1).

III. Data Selection and Results

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. 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. 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 space and time structure of the shower disk has been studied as a function of the distance to shower axis, in intervals of 1 m up to a maximum distance of 80 m. Fig.2 (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 giving time delays larger than 10 ns for particles landing further than 50 m from the core. No significant dependence on pad multiplicity is observed. Fig.2 (bottom) shows the RMS of time residuals with respect to the conical fit (see Eq. 1) as a function of distance to shower axis for different pad multiplicities. The thickness of the shower front increases with distance and it tends to become thinner for increasing multiplicities.

IV. Monte Carlo Simulation and Comparison with Data

About 10^7 proton showers have been generated with the CORSIKA code [3] with an energy spectrum ranging from 300 GeV to 100 TeV according to a differential power-law function with spectral index -1 (properly reweighted to -2.7 when comparing data to simulation). The showers have been generated using SIBYLL [4] and FLUKA [5] as high and low energy hadronic interaction models. A full simulation of the detector response, based on the GEANT package [6], has been performed, including the effect of time resolution, trigger logic and electronics noise. Simulated events have been produced in the same format used for data and are processed through the same reconstruction chain. Fig.3 (top) shows the time residuals with respect to planar fit for data and simulation (pad multiplicity between 200 and 400). Data and simulation show a very good agreement at the level of this observable. The agreement remains good for higher pad multiplicities and larger zenith angles. The measured shower thickness has been found to be systematically larger than expected from simulation and

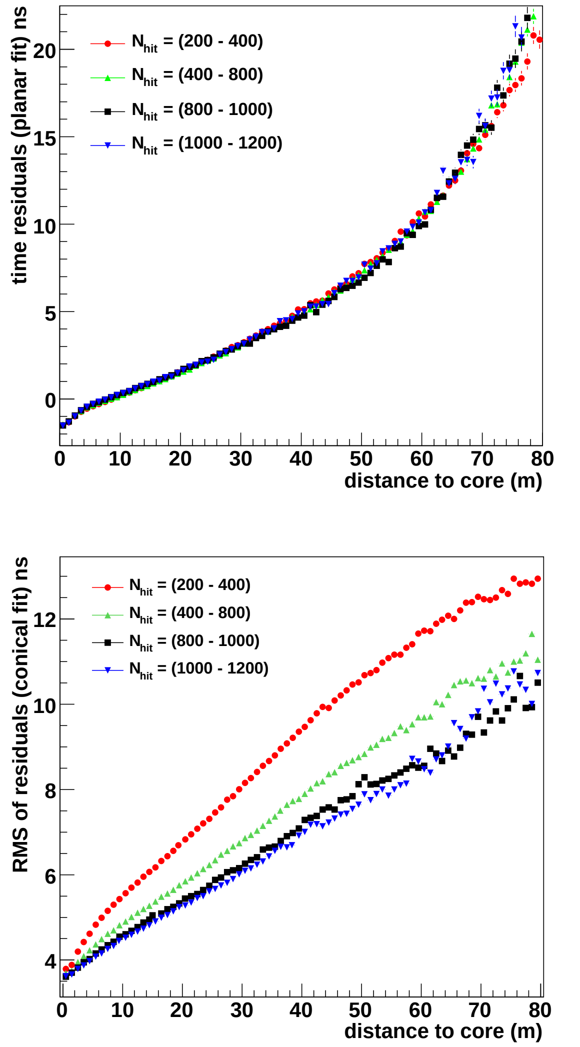

Fig. 2. Mean of time residuals with respect to a planar fit (top) and RMS of time residuals with respect to a conical fit (bottom) as a function of distance to the shower axis for different pad multiplicities and for zenith angles less than 15°. Data are shown (statistical uncertainties only).

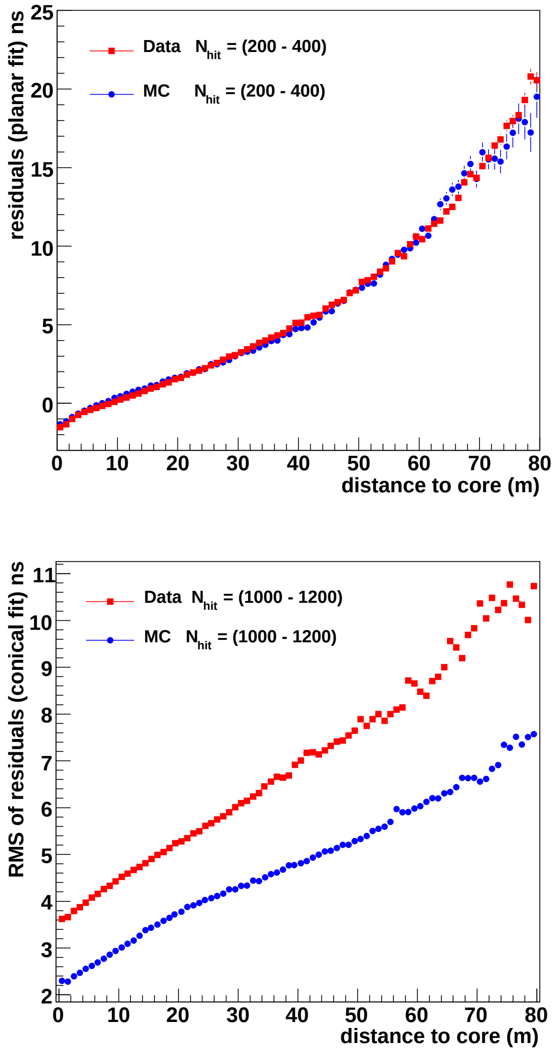

Fig. 3. Time residuals with respect to a planar fit (top) and RMS of time residuals with respect to a conical fit (bottom) for data and simulation. Pad multiplicity between 200 and 400 (top) and between 1000 and 1200 (bottom). Zenith angle less than 15° (statistical uncertainties only).

this feature doesn't change with multiplicity, even, as shown in Fig.3 (bottom), for the highest multiplicities at which the quality of reconstruction is enhanced. A further check has performed by applying additional quality cuts (i.e. density and compactness cuts as used for the analysis of hadronic cross-sections, see [8]). Results remain unchanged. However, due to temperature and pressure variations occuring in real operating conditions, data suggest a lower time resolution [7], [9] than assumed for this study (~1 ns). Besides that, the simulation doesn't include the contribution of heavier primaries. These facts may account for part of the observed discrepancy.

V. Shower Morphology

Shower by shower fluctuations play a key role for the understanding of EAS morphology. The design of the ARGO-YBJ detector offers a unique chance to have high-resolution pictures of shower footprints at 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 showers interacting deeper in the atmosphere, ("young showers"), due to geometrical reasons, the arrival of particles at a given lateral distance is expected to be more delayed compared to showers that have interacted higher in the atmosphere ("old" showers). Young showers will then exhibit a steeper time profile with respect to a planar fit. Additionally, secondary muons, more abundant in hadron-induced showers, originate at even higher altitudes and their contribution further reduces the time delay leading to a flattening of the arrival time profile. 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 simulations. Results are shown in Fig 4 for proton and photon primaries. More than 10^7 photon-induced CORSIKA showers have been produced with the same hadronic interaction models as for proton and used for this analysis. As shown in

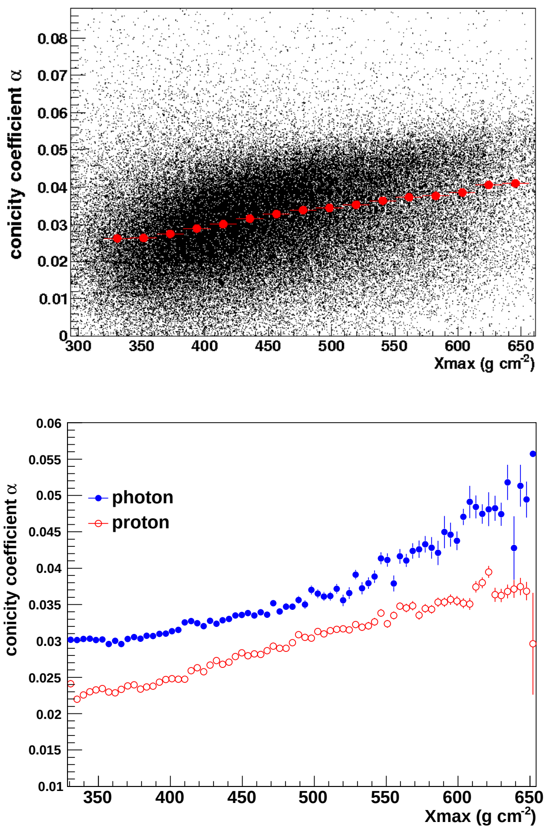

Fig. 4. The conicity parameter α as a function of the atmospheric depth at the shower maximum Xmax for proton (top) and compared to photon (bottom) (statistical uncertainties only).

Fig. 4, the average value of α tends to increase for deeper Xmax. Indeed, on an event by event basis, the true value of Xmax is associated to the reconstructed conicity and

a deep Xmax, independently of multiplicity, is expected to give a younger shower with larger α.
Photon-induced showers behave similarly but they have a higher average conicity reflecting their intrinsic structure dominated by a pure electromagnetic component with a much smaller muon content with respect to hadronic showers.
Though very challenging from the experimental point of view, a measured conicity can be correlated with an average Xmax, providing and indication of the stage of shower development. This study is still in progress (i.e heavier primaries have to be added, the impact of detector systematic uncertanties has to be considered) but several analyses, including the calculation of hadronic cross-sections (see [8]), might benefit from a positive outcome of this work.
Finally, Fig. 5 shows the ratio $RMS_{proton}/RMS_{photon}$ from conical fit. Proton showers tend to have a slightly larger thickness than photon close to the core and further away.

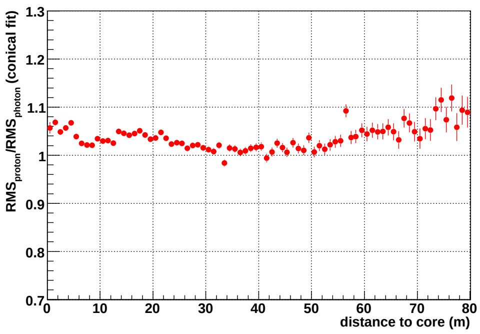

Fig. 5. $RMS_{proton}/RMS_{photon}$ from conical fit as a function of distance to shower axis (statistical uncertainties only).

VI. CONCLUSIONS

The unique design of the ARGO-YBJ detector providing fine granularity and high resolution time measurements has been used to characterize cosmic ray showers with energies up to 100 TeV. The shape and the thickness of the observed shower front have been measured as a function of distance to reconstructed axis and for different signal multiplicities. A full simulation using CORSIKA showers in combination with a GEANT-based detector simulation has been found to be a powerful tool for exploiting the information potential contained in the available observables.

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