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Study of cosmic ray shower front and time structure with ARGO-YBJ

A.K. Calabrese Melcarne[1,3], I.De Mitri[1,3], G. Marsella[2,3], L. Perrone[2,3], G. Petronelli[1,3], A.Surdo[3], G.Zizzi [1,3] on behalf of ARGO Collaboration
[1]*Dipartimento di Fisica Università del Salento, Lecce, Italy*
[2]*Dipartimento di Ingegneria dell'Innovazione Università del Salento, Lecce, Italy*
[3] *INFN (Istituto Nazionale di Fisica Nucleare, Lecce, Italy*
giovanni.marsella@le.infn.it

Abstract: ARGO-YBJ is a full coverage Extensive Air Shower array located by the high-altitude cosmic rays laboratory of Yangbajing (4300 m a.s.l., Tibet, China). The detector consists of a layer of Resistive Plate Counters covering an area of about 6600 m^2 with 56× 62 cm^2 unit cells. This design allows a detailed characterization of cosmic ray showers. A set of well reconstructed data has been used in order to study the shower phenomenology and front structure with high time resolution ($\sim$ 1 ns accuracy) and fine granularity. Simulated showers have been used and the detector response is taken into account in detail for this analysis. Several observables have been investigated in both real and simulated data and compared, aiming to derive hints on cosmic ray shower age, energy and mass composition.

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 detector consists of a single layer of Resistive Plate Counters (RPCs) covering an area of 74×78 m^2. 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 100×110 m^2. A thick lead converter will cover uniformly the RPC plane in order to increase the number of charged particles by conversion of shower photons. The detector is structured in clusters, each consisting of twelve RPCs of 280×125 cm^2. A cluster is the basic detection and Data Acquisition logical unit. Pads of 56×62 cm^2 are the time elemental units ("pixels") for measuring the pattern of the shower front with time resolution better than 1 ns. Ten pads cover one RPC and each pad contains 8 pick-up strips of 6×62 cm^2, which provide a large particle counting dynamic range. A "shower mode" trigger for the cosmic ray shower detection is implemented. ARGO is operating the full central carpet (130 cluster) since July 2006. A detailed description of detector performance is given in [1].

Shower Reconstruction

The ARGO-YBJ digital readout allows detecting shower secondary particles down to very low densities (0.03 particles/m^2 in the present configuration). The time profile of the shower front can be reconstructed by the time of fired pads. Each pad time resolution is determined by the intrinsic performance of the RPC and its electronics and by signal propagation along the strips. Relative time offsets among different pads are corrected by a proper 'timing calibration' [2]. The overall time resolution is of about 1 ns [3]. 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, space-time coordinates (positions and times of fired pad in the event) can be fitted to a cone. A Maximum Likelihood based algorithm is used to perform a reliable reconstruction of the shower core position up to the edge and slightly beyond the active carpet [4]. The pad signals are shaped to 90 ns and the overall design allows detection of 'multiple hits' by several particles hitting the same pad within a short time window. On the other hand, very delayed particles in the cascade can be recorded, up to a maximum of about 1.3 μs with respect to the shower front, so that the complete time development of the cascade can be widely inspected.

Time structure of extensive air shower front

Time and space structure of extensive air showers depend 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 sketch illustrating the technique for studying an extensive air shower front with a surface detector is shown in Fig. 1. A flat array can measure the particles arrival times and their densities at ground. Detailed studies on the structure of shower front have been carried out by several groups and presented for example in [5, 6, 7] and related references.

The high space-time granularity of the ARGO-YBJ detector allows a fine sampling of the shower front close to the core. The time structure of the shower disk has been studied as a function of distance to shower axis (i.e the distance to shower core computed on the shower plane) up to 40 m in intervals of 1 m. The following observables have been studied in the energy range between few TeV up to 20 TeV as a function of distance to shower axis:

- **the curvature** of the shower front as the mean of time residuals with respect to a planar fit (T_d in Fig. 1)
- **the thickness** of the shower front as the root mean square (RMS) of time residuals with respect to a conical fit (T_S in Fig. 1).

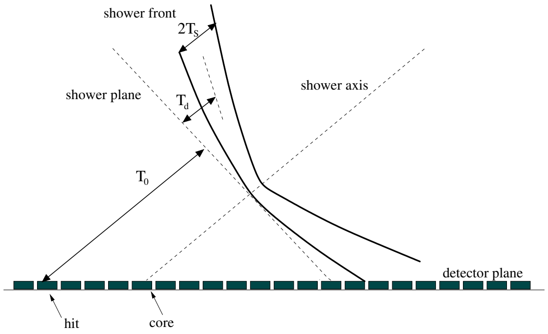

Figure 1: Sketch of shower front geometry and observables

A set of well reconstructed data consisting of about 10^6 events has been selected for this analysis. The reconstructed cores are required to be within an area of 20×20 m^2 centered on the carpet. A hit (pad) multiplicity greater than 200 and a quality cut on the χ^2/dof of the fit has been applied in order to reject misreconstructed events. A Monte Carlo study has shown that the applied cuts select well reconstructed events, mostly landing within the array (contained events). Fig. 2 (left) shows the mean of time residuals with respect to a planar fit as a function of distance to shower axis for different pad multiplicities and for zenith angles less than 15°. It can be derived from simulation that hit multiplicities of 200, 400, 600 and 800 correspond to average primary energies of about 4, 7, 11 and 15 TeV (proton primaries, zenith angle less than 15°). The deviation from a planar fit increases with distance (up to about 8 ns at 40 m) and depends only weakly on hit multiplicity in the considered energy range. Fig. 2 (right) shows the RMS of time residuals with respect to a conical fit as a function of distance to shower axis for different pad multiplicities and for zenith angles less than 15°. The thickness of the shower front (T_S, see Fig. 1) increases with distance (up to about 7 ns at 40 m) without a signifi-

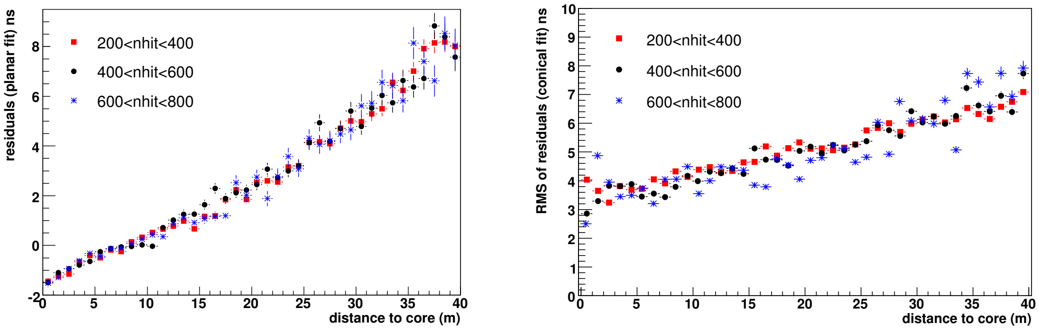

Figure 2: Mean of time residuals with respect to a planar fit (left) and RMS of time residuals with respect to a conical fit (right) as a function of distance to shower axis for different pad multiplicities and for zenith angles less than 15°. Real data shown (statistical uncertainties only).

cant dependence on hit multiplicity in the considered energy range. Finally, no significant dependence on zenith angle has been observed both, for shower curvature and thickness, up to 45°.

Comparison of simulation to data

A Monte Carlo study has been performed using a sample of about 6×10^6 CORSIKA showers [8] (protons) with zenith angle less than 45° and energy spectral index of -2.7, in the range between 100 GeV and 1000 TeV. The detector response has been simulated in detailed with a GEANT3-based program [9]. A preliminary comparison between data and simulation is discussed. Fig. 3 shows the distribution of pad multiplicity from simulation in comparison with data, for zenith angle less than 15°. A fairly good agreement is generally found. Fig. 4 shows the time residuals with respect to a planar fit for data (blue bullets) and simulation (red boxes) (pad multiplicity between 200 and 400 and zenith angle less than 15°). An agreement is found up to a distance of 15 m. At larger distances, the measured front curvature tends to be larger than expected by simulation. Similarly, the measured shower thickness has been found to be systematically larger than expected and this effect is larger at small distances to the shower axis. As a final remark, it should be pointing out that this simulation doesn't contemplate the contribution of heavier primary nuclei and doesn't yet reproduce the case of multiple hits on the same pad. This may account for the residual discrepancy observed at large multiplicity (see Fig. 3).

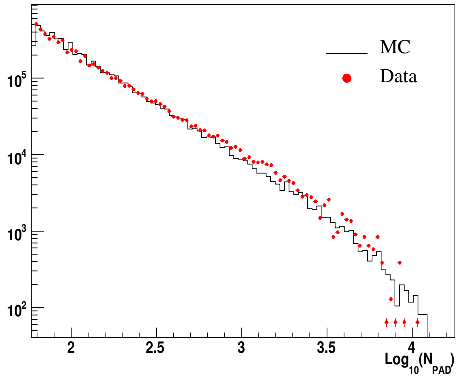

Figure 3: Distribution of pad multiplicity for data (bullets) and simulation (solid line). The histograms are normalized to the same area.

Mass Composition

To inspect the dependence of the studied observables on primary mass, a dedicated simula-

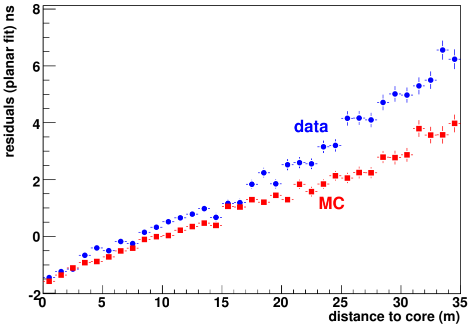

Figure 4: Time residuals with respect to a planar fit for data and simulation, for pad multiplicity between 200 and 400 and zenith angle less than 15°.

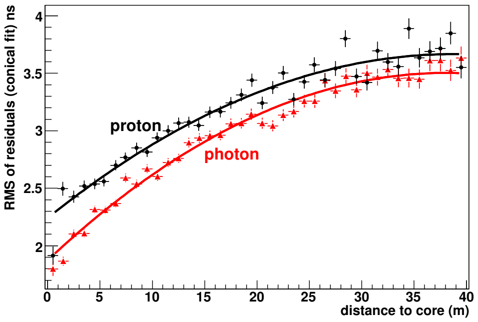

Figure 5: RMS of time residuals with respect to a conical fit for proton and photon primaries, pad multiplicity between 200 and 400 and zenith angle less than 15°

tion has been performed for proton and photon showers. 5000 protons and 5000 photons CORSIKA showers [8] have been generated in the energy range between 3 and 10 TeV with zenith angle between 0° and 15°. The RMS of time residuals with respect to a conical fit is shown in Fig. 5 for proton and photon primaries as a function of distance to shower axis. Events are selected with pad multipliticities larger than 200 and reconstructed core within an area of $40 \times 40\ m^2$ centered on the carpet. Though the measured difference is very small (at the level of the time resolution of the detector), this observable could provide on statistical basis a clue to $\gamma/hadrons$ separation and mass composition studies. Further studies and an extended simulation with heavier primaries are planned.

Conclusions

The space and time high-granularity of the ARGO-YBJ detector provides a powerful tool for the study of time structure of cosmic rays shower front close to the core. Curvature and thickness of the shower front have been measured. The impact of these observables on mass composition studies has been discussed and the potentialities of the method investigated.

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