# Study on Multicore Extensive Air Showers in the ARGO-YBJ Experiment

**Xinhua Ma*** **on behalf of the ARGO-YBJ Collaboration**

* *Institute of High Energy Physics, Chinese Academy of Science*

***Abstract*. Multicore events are detected in Extensive Air Showers (EAS) since ′50s and are characterized by the multiple structure in the electro-magnetic component near the shower core. They have been usually interpreted as the jet production with high transverse momentum $p_T$ generated by the EAS leading particle-Air interactions at intermediate altitudes.**
**The ARGO-YBJ experiment, a full coverage array of Resistive Plate Chambers (RPC) with an active area of 6700 $m^2$, provides a unique opportunity to investigate these anomalies in the lateral distribution function (l.d.f.) near the shower axis allowing the main and sub cores separation up to 50 m in the fiducial area.**

**In this paper a preliminary study of the EAS core structure at primary energy $E_o \geq 50$ TeV performed by the ARGO-YBJ detector is presented.**

***Keywords*: EAS; Multicore;Hadronic Interactions**

## I. INTRODUCTION

In the last half century, multicore events in EAS were observed and investigated by different detectors: firstly by ionization chambers and scintillator arrays, and later with mountain emulsion chambers (MEC) and hadronic calorimeters [1], [2], [3], [4], [5], [6], [7], [8], [9]. Such a phenomenon can be explained by hadronic interactions with high transverse momentum ($p_T$) production. Results on jet production cross section in p-Air interactions at $\sqrt{s} \approx 500$ GeV in EAS multicore events agree with the expected one obtained by $p - \bar{p}$ collider data [9] at lower energy in the center of mass.
Emulsion chambers data show that some multicore events have high values for the physical parameter $\chi = \sqrt{E_1 E_2} r_{12} > 1000\ TeV\ cm$ , where $E_1, E_2$ are the energies of two cores and $r_{12}$ is distance between them. Such high $\chi$ events can not be explained properly by the present hadronic interaction models [11], [12] and certainly deviates from Monte Carlo simulations [13]. In the case of the MEC experiments, which have the best spatial resolution, the multicore events were observed only in limited active area of typically 1 $m^2$ so that the events with higher $\chi$ value (or $p_T$) at larger distance can not be investigated.

## II. THE ARGO-YBJ DETECTOR

The ARGO-YBJ experiment is made by a single layer of Resistive Plate Chambers (RPCs) [10] housed in a large building (100×110 $m^2$). The detector has a modular structure: the basic module is a cluster (5.7×7.6 $m^2$), made of 12 RPCs (2.8×1.25 $m^2$ each). 130 of these clusters are organized in a full coverage carpet of 5600 $m^2$ with active area ∼93%; this central detector is surrounded by 23 additional clusters with a coverage of ∼40% ("guard ring") to improve the core location reconstruction. The detector installation has been completed in 2007.
Each RPC is read via 80 strips (6.75×61.8 $cm^2$), logically organized in 10 pads of (55.6×61.8 $cm^2$) that are individually recorded and that represent the high granularity pixels of the detector. The RPC carpet is connected to two different DAQs, working independently, corresponding to the two operation modes, shower and scaler. In shower mode, for each event the location and timing of every detected particle is recorded, allowing the lateral distribution and arrival direction reconstruction; in scaler mode the total counts are measured every 0.5 s: for each cluster, the signal coming from the 120 pads is added up and put in coincidence in a narrow time window (150 ns), giving the counting rates of ≥1, ≥2, ≥3, ≥4 particles, that are read by four independent scaler channels. The corresponding measured counting rates are ∼ 40 kHz, ∼ 2 kHz, ∼ 300 Hz and ∼ 120 Hz. In addition the signal of each RPC chamber is picked out by two large size pads ($1.4 \times 1.25\ m^2$), called BigPads, in analog read-out mode with a 12 bits ADC. This makes possible to extend the measurement range of particle density up to $10^4\ particles/m^2$ [15], [16] and the primary cosmic ray energy from some tens of TeV up to several PeV.
In this paper we present a preliminary study of multicore events observed in the ARGO-YBJ data from February to May 2007.

## III. THE MULTICORE DEFINITION

Usually the lateral distribution of the electron-magnetic component in the EAS is described by the NKG function [17]:

$$\rho(r) = C(s)\frac{N_e}{r_M^2}(\frac{r}{r_M})^{s-2}(1+\frac{r}{r_M})^{s-4.5} \qquad (1)$$

where $\rho(r)$ is the particle density as a function of the core distance r, $r_M$ is the Moliere radius ($\approx\ 130m$ at

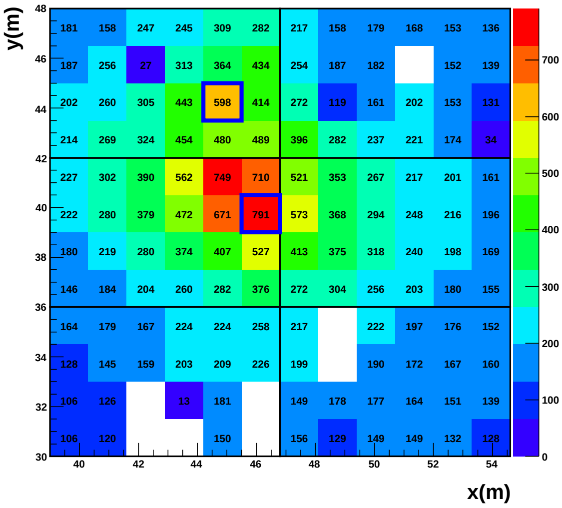


Fig. 1: The particle density distribution of a EAS multicore event observed by the ARGO-YBJ detector. The sampling unit is the BigPad. For each BigPad the particle density is shown. The two BigPads with the maximum densities are indicated. Empty boxes corresponds to bad working BigPads which are not used.

YangBaJing level), $N_e$ the size, s the age of the shower and finally C(s) a normalization factor. Since the core region of the shower is concerned for this analysis, the following simplified but more effective function, which in fact is the close-to-core approximation of the NKG function distribution, is used:

$$\rho(r) = p_1 \cdot r^{p_2} \tag{2}$$

where $p_1$ is a parameter proportional to the EAS size correlated with primary energy, and $p_2$ is linearly correlated with the age parameter of the shower, $p_2 = s - 2$. For each BigPad $\rho(r)$ is the number of detected particles normalized to their area scaled by the cosine of the measured EAS zenith angle $\theta$.

In logarithm scale the values of the shower density fluctuation

$$f = log(\rho_{Meas}(r)) - log(\rho_{Fit}(r)), \tag{3}$$

sampled in different points of the EAS front by the BigPads of the detector, follow a Gaussian distribution with mean value 0 and standard deviation $\sigma$. The $\rho_{Meas}(r)$ is the detected particle density and $\rho_{Fit}(r)$ the expected value at the same point obtained by the best fit of the lateral distribution function using equation 2. A subcore structure is found when the f value exceeds $5\sigma$ and do not coincide with the main EAS core. If one ore more subcores are found the EAS is tagged as multicore.

## IV. The Data Analysis

First of all the arrival direction of each detected shower is reconstructed from the digital pads which record positions and arrival times of particles. The front of the shower must correspond to a single conical shape excluding random coincidence of two independent showers that can simulate multicore anomalies. Particle densities are calculated by using only BigPads measurement. Some quality cuts are applied to BigPads which show unstable behavior and they are not used. BigPads are periodically inter-calibrated with the digital pads over the common particle density range. Details on the method are widely discussed in [15]. A new method of calibration using air showers as beam and propagation from the calibrated one to all BigPads are described in [16].

The EAS core position is fixed as the position of the BigPad with the maximum measured density. If the core position is found at the edge of the active area in the array, the event is discarded since both the core position determination and the fit of the l.d.f. can be affected. Only internal events are therefore considered.

The algorithm to search for multicore EAS follows a 3 steps procedure.

1) The lateral distribution of particle densities is fitted using function 2 to obtain parameters $p_1$ and $p_2$ assuming the initial core position. For the present analysis the fitting range in distance from the core is limited between 3.5 m and 10 m. The lower limit is chosen to avoid the region too close to the core where the NKG function is expected to fail. The higher limit is chosen to set up a common lateral cut for all events.
2) The density fluctuation distribution $f$ is fitted with a gaussian function that must be compatible with a 0 mean value. If this is the case, secondary cores with significance of more than $5\sigma$ are extracted.
3) Finally experimental quality cuts are applied to extract only good multicore events. We require at least a density of 100 particles $/m^2$ in the main EAS core and at least 50 particles$/m^2$ in the secondary cores above the expected $\rho_{Fit}(r)$ values. No BigPads must be saturated in the event.

Figure 1 shows one real multicore event observed in the ARGO-YBJ data. The event has a well defined second core with a density of 598 $particles/m^2$ with an estimated significance of $5.3\sigma$. In figure 2 for the same multicore event the f distribution is presented with its gaussian best fit.

A custom physical observable, proportional to the transverse momentum, has been defined in our analysis as

$$\chi^* = \sqrt{\rho_1 \rho_2} r_{12} \tag{4}$$

following the emulsion chambers technique: $\rho_1$ $(particles/m^2)$ is the first maximum density and $\rho_2$ the second one subtracted by the expected $\rho_{Fit}(r)$ values, and $r_{12}(m)$ is the distance between the two cores. The obtained $\chi^*$ value is scaled to the transverse momentum $p_T$ of the particles (or jets) who generated the cores. The estimated value of the physical

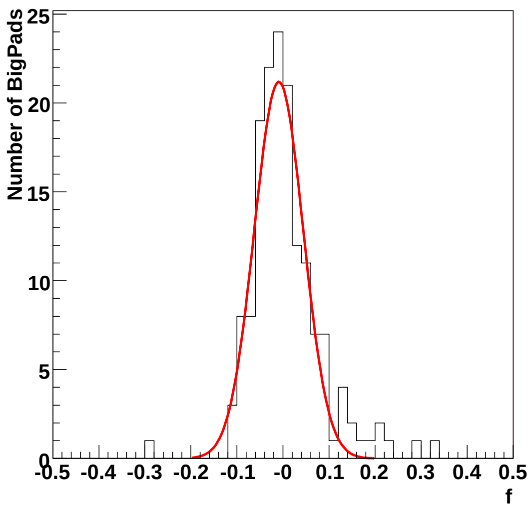


Fig. 2: The fluctuation density distribution $f$ (see the text) for the event in figure 1: the mean value is compatible with 0 and standard deviation is $\sigma$=0.05. The maximum deviation corresponds to the outlined second core.

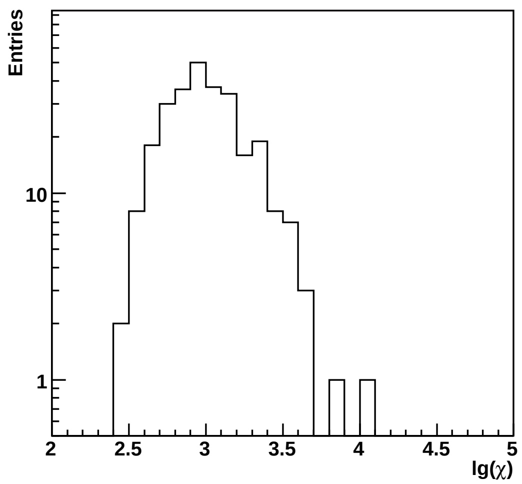


Fig. 3: The $\chi*$ distribution for the selected multicore events.

parameter for the selected event is $log(\chi^{*}) = 3.3$.

Applying the selection procedure on the full data set 270 multicore events are found. The corresponding f distribution for the whole set is shown in figure 3.

## V. The Montecarlo simulation

A preliminary Montecarlo simulation has been performed in order to get the energy threshold of our experimental procedure and to check if multicore events at high $\chi^{*}$ (and so far the $p_T$) values are expected or not in the frame of a fixed hadronic interaction model. EAS have been generated by the Corsika code [18] with QGSJETII as hadronic interaction model. QGSJET (Quark Gluon String model with JETs) [19] is specifically designed to include the nucleon-nucleon, nucleon-nucleus, and nucleus-nucleus scattering at ultra-relativistic energies. QGSJET is an extension of the QGS model and includes hadronic interactions with exchanging single or multiple Pomerons based essentially on the Gribov-Regge theory. Additionally the model includes minijets to describe the hard and half-hard interactions which are important at high energies, where perturbative QCD is available. The model is a typical one of QCD inspired models suitable as an approach for simulating the multicore EAS events.

A set of $1.6 \times 10^{5}$ showers has been simulated corresponding to the equivalent of 10 days of real time acquisition at ARGO-YBJ detector. The primary energy range is $10^{14} - 10^{16} eV$ and composition and primary spectrum are set as in [20]. The zenith angle ranges from $0°$ to $45°$ and azimuthal angle from $0°$ to $360°$. The observation level is fixed at the YangBaJing Observatory, 4300 m a.s.l.. The particle density distribution at the BigPads sampling points are therefore obtained considering only the experimental geometry. The full detector simulation is not yet included at the present stage of the work. Finally the same selection procedure to extract multicore events in the real data is applied to simulated ones.

According to this rough simulation we found an absolute core position resolution of about of 1 m (2m) and an energy threshold of 50 TeV (200 TeV) for primary proton (iron). A total of 10 multicore events at very low $\chi^{*}$ value ($lg(\chi^{*}) \leq 3$) are generated by the simulation at the mean rate of 1 event per day of detector acquisition. Hence the multicore events in the simulated showers are less than the ones we found in the real data and at lower $\chi^{*}$. It infers that the excess of multicore events at high $\chi^{*}$ in the ARGO-YBJ data might not be reproduced by the QGSJET model in the simulation.

## VI. Conclusions

ARGO-YBJ data have been analyzed to search for multicore EAS events. A simple Montecarlo simulation has been made to check properties of real data. More statistics in real data and full simulation of the ARGO-YBJ experiment are expected in the near future to provide more details about the multicore EAS events.

## VII. ACKNOWLEDGEMENTS

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