Study of the time structure of EAS particles with ARGO-YBJ
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Abstract: The ARGO-YBJ experiment is an Extensive Air Shower array located at the high altitude Yangbajing Cosmic Ray Laboratory in the Tibet region. The detector consists of a layer of Resistive Plate Counters (RPCs) covering a total area of about 11000 m². Detector features allow studying the shower front structure with unprecedented space-time resolution. Besides the study of the shape of the shower front, events with peculiar particle time distribution can be selected and analyzed. Two main categories have been identified: Multiple-Front and Wide-Front Showers (MFS and WFS). MFS events might be produced by exotic particle decay, while WFSs are expected to be due to EAS with the core position well outside the detector carpet. Preliminary results of these analyses, also in terms of the Linsley parametrization of the shower thickness, will be presented.

Keywords: Cosmic Rays, Astroparticle Physics, Time Structures.

1 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 greater than few hundred 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 153 units called clusters (5.7 × 7.6 m²), each made of 12 Resistive Plate Counters (RPCs) operating in streamer mode. Each RPC is read out using 10 pads (55.6 × 61.8 cm²) which are further divided into 8 pick-up strips providing a larger particle counting dynamic range. The signals 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 ∼ 1.8 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 110 × 100 m².

ARGO-YBJ was operated in its complete layout from November 2007 to February 2013, allowing a complete and detailed three-dimensional reconstruction of the shower front with unprecedented spatial and time resolution. A system for the RPC analog charge readout was also implemented and operated from December 2010 in order to extend the detector operating range from about 100 TeV up to PeV allowing measuring particle density up to 10⁴ m⁻² avoiding the limits due to the digital saturation which occurs at about 20 m⁻² [1,2,3,4].

This work 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 [5, 6], 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 mass 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, but Multiple-Front Showers (MFS) and Wide-Front Showers (WFS) cases will be discussed.

Figure 1: Multiple-Front Shower example. The three-dimensional view of a MFS is shown. On the z axis the arrival time is plotted. It is defined as the time difference between the starting of TDC counting, when a particle hits the detector, and the common stop signal stated by the occurrence of the trigger condition in a time window of 2µs. The two subshowers are evident and distant more than 300 µs.

2 Multiple-Front Showers

Among showers with large RMS time residual with respect to a plane front, MFS have been detected. In Fig the three-dimensional view of a MFS is shown. On the z axis 2µs minus the arrival time is plotted. The shower time is defined as the time difference between the starting of TDC counting, when a particle hits the detector, and the common stop signal stated by the occurrence of the trigger condition in a time window of 2µs. In [7,8] a detailed description on the technique to select those events and the efficiency
of the method were presented. It has been demonstrated that they are mainly due to accidental coincidences. Rate and other observable distributions are compatible with the expected one from pure accidental coincidences between different showers. In this work we define a phase-space in order to detect possible “exotic” decays or interaction in Cosmic Ray Shower development, for which ARGO-YBJ is a particularly well fit detector.

In the past, many experiments detected anomalous delayed showers\[9\][10\] [11\] [12\]. As a possible explanation many phenomena have been considered such as heavy particle production in the interaction of high energy particles on atmospheric nuclei and relative decay and the existence of tachyons\[14\] [13\]. In order to put some constraints with our data, reconstructing the subshower events in detail, we can select events whose subshower axis has an impact parameter within a restricted area and height. The impact parameter is defined as the shorter distance within the maximum first interaction height allowed for showers. For these selected events is possible to estimate the total multiplicity, the multiplicity of each subshower, the opening angle and the time delay between the subshowers. Those values could give hints on the mass of a decaying particle and characterize hypothetical tachyons. Due to the relatively small area, around 5800 m\(^2\) partially extended to 11000 m\(^2\) with the guard ring, and assuming a mean first interaction height of about 20 km, the angular difference expected between two subshowers of common origin is less than 0.2°. In this case the two subshowers should have approximately the same development and no delay is expected. Late interactions of a leading heavy particle could originate secondary showers with a wider angular difference, with a difference in the multiplicity distribution (late produced particle should develop showers with lower multiplicity) and “large” arrival time delay. In case of production of a massive particle with rest mass M and laboratory energy E, produced at the top of the atmosphere, it will arrive at detector level after traveling a distance \(L\) with a time delay \(\Delta t\) given by:

\[
\Delta t = L \left( \frac{1}{\gamma} - \frac{1}{c} \right) \approx \frac{L}{2c\gamma^2}
\]

where \(L\) is the distance from the detector at which the particle has been produced, \(\gamma\) is the velocity of the massive particle, \(c\) is the light velocity and \(\gamma = E/M\). Assuming that the particle is early produced \((L \sim 30\ km\) \(\gamma\) ranges from 30 to 3 for time delay \(\Delta t\) ranging from 50 ns to 1 \(\mu s\), which is the range of sensitivity to this analysis with ARGO-YBJ detector. Thus a particle of mass \(M = 10\ GeV\) with energy \(E = 100\ GeV\ (\gamma = 10)\) produced 10 km above the detector would arrive 160 ns behind the leading shower. If it produces a shower, this could be detected as a secondary delayed shower. So geometrical and kinematic considerations allow to use the time difference \(\Delta t\) between the arrival time of the subshowers to define constraints on heavy mass production in cosmic ray interactions\[15\][16].

In this work we present the method and the first distributions on a small sample of data. As stated in previous works\[17\][18], the observed double coincidences are about 9 Hz. To reduce the background of accidental coincidences the events are selected when the angular distance between the subshowers is less than 5°. This value has been used instead of 0.2° in order to detect also late produced (less than 1 km above the detector) and partially scattered particles. Also a quality selection is applied on the reconstruction of each subshower. For this analysis, events with both the subshowers being reconstructed with a the quality parameter, defined in \[5\], \(s^2 < 100\ m^2\) and the multiplicity of the first subshower greater than 100 and of the second subshower greater than 50. This difference in multiplicity is due to the fact that the first subshower must satisfy the trigger conditions. All this selection cuts reduce the sample to the 0.074 % of the initial value. In Fig 2 the time difference distribution of the selected subshowers is shown. The statistic actually is poor, but this has been obtained using only 3 days of data.

\[\text{Figure 2: Time difference distribution between two subshowers. A quality selection is applied on the reconstruction of each subshower.}\]

![Figure 2: Time difference distribution between two subshowers. A quality selection is applied on the reconstruction of each subshower.](image)

3 Wide-Front Showers

WFS are characterized by a high number of hits distributed on all the carpet and with a time distribution width that can reach several hundreds of ns as shown in Fig. 3. These showers, as stated in literature\[9\][17][18][19][20], could be very energetic showers with the core distant hundreds of meters from the carpet. ARGO-YBJ detector features allow a very detailed study of these rich showers and make possible the study of the atmospheric development of them through the space-time structures of the shower front. In this work we used Linsley parametrization\[18\] to determine the core distance from the time dispersion of the shower front, and we defined a particle space density in order to evaluate the shower energy using an adequate Lateral Distribution Function (LDF).

\[\text{Figure 3: Wide-Front Shower example. The shower has more than 4000 hits uniformly distributed on the carpet and with a time distribution more than 100 ns wide.}\]

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From his studies on the shower time dispersion, Linsley derivated the following empirical equation:\[18\]:

$$\sigma_t = \sigma_0 \left(1 + \frac{r}{r_1}\right)^b$$ \tag{2}$$

where $r$ is the distance from the core, $\sigma_0 = 1.6$ ns, $r_1 = 30$ m and $b \approx 1.65$, while $\langle \sigma_t \rangle$ is the average time dispersion with respect to a planar fit, which also gives the shower direction, once a correction factor has been applied in order to take into account the shower conicity (or sphericity) and that only a side of the front is detected. In Linsley’s work a more precise definition of $b$ has been given:

$$b = (2.08 \pm 0.08) - (0.4 \pm 0.06) \sec(\theta) + b_3 \log\left(\frac{E}{10^{17} \text{eV}}\right)$$ \tag{3}$$

where the dependence from energy has been evaluated as $b_3 = (0.00 \pm 0.06)$, for $\theta < 60^{\circ}$ and $10^{17}$ eV $< E < 10^{20}$ eV. The value $b = 1.65$ used is the average value. $\sigma_t$ has been calculated assuming that the arrival time of the particles of the shower front is distributed as a $\Gamma$ function. In particular he used the following probability distribution:

$$p(t) = \frac{t}{\mu^2} \times \exp\left(\frac{-t}{\mu}\right)$$ \tag{4}$$

where $\mu$ is a scale parameter of the distribution. In this work, as a first approximation, the RMS of the time residual with respect to a shower plane will be used. The time residual is defined as the difference between the time of the particle and the time of the fit ($t_{\text{res}} = t_{\text{part}} - t_{\text{fit}}$). In Fig. 4 the residual distribution of an event is presented. In Fig. 5 the residual of the arriving time of the particles with respect to a planar fit of the shower front vs the core distance of a single event are plotted. Here the core position has been reconstructed using the space topology of the hits and applying a Likelihood method, fitting the data with a Mexican hat function\[21\]. From these two plots the large amount of information present in ARGO-YBJ data is evident.

In the future a more precise study on the time distribution will be done, considering that, with ARGO-YBJ detector, $\sim 6600$ m$^2$ (153 clusters $\times$ the cluster area) of the shower front can be used where the time of each particle out of hundreds of hits is known at the ns precision and whose position is known within about 50 cm (8 cm in one direction if the strip information is used). It is evident that any interaction along the development of the shower should be “recorded” in the time distribution of the electromagnetic cascade. Not only it would be possible, by geometrical constraints, to determine the $X_{\text{max}}$ $(g/cm^2)$ of the shower, but also hints on secondary interactions and, possibly, hints on the nature of the primary cosmic ray. Once the core distance has been evaluated, it is possible to evaluate the energy of the shower by studying the density of particle distribution, using the LDF. Various modifications of the NKG\[22\] have been reported in the dedicated work by ARGO-YBJ collaboration in this conference\[23\]. In particular, in this work we used the so called “scaling formalism”\[24\] that allows to reproduce LDF for primary cosmic rays in the energy range $10^{14} - 10^{20}$ eV and core distance interval $10$ m $- 4$ km depending on the shower age $s$. The density distribution as a function of the core distance is equal to:

$\text{Figure 4:}$ Shower time residual with respect to a planar fit for a single event. The time residual is defined as the difference between the time of the particle and the time of the fit ($t_{\text{res}} = t_{\text{part}} - t_{\text{fit}}$).

$\text{Figure 5:}$ Shower time residual with respect to a planar fit in function of the core distance for a single event as reconstructed by the ARGO-YBJ standard algorithm. Black points are the profile of the time residual in function of the core distance.

$\text{Figure 6:}$ The RMS of the time residual profile with respect to a plane fit of the shower front as a function of the true core position. The data are referred to a MC sample of Protons (red:1000 $-$ 3000 TeV; blue:300 $-$ 1000 TeV; black:100 $-$ 300 TeV; violet:30 $-$ 100 TeV). A fit with the Linsley curve is superimposed where the free parameters were the normalization (P0) and $r_1$ (P1).
$\rho(r) = \frac{N_r}{r_0} C \left( \frac{r}{r_0} \right)^{-\alpha} \times \left( 1 + \frac{r}{r_0} \right) \times \left( 1 + \left( \frac{r}{10r_0} \right)^2 \right)^{-\delta}$.

For electron densities, $C = 0.28$, $\alpha = 1.2$, $\beta = 4.53$, $\delta = 0.6$, while $r_0$ is a free parameter sensible to the age or mass of the primary cosmic ray and $N_r$ is the shower size.

**4 MC studies**

In order to validate the proposed analysis and to calculate the proper parameters for ARGO-YBJ detector that could take into correct account the detailed information of the shower front and the fact that the detector is operating at 4300 m a.s.l., a detailed MC has been used. For the present work $10^7$ protons at energies ranging from 30 TeV to 3000 TeV on an area of about $0.8 \times 0.8$ km$^2$ have been generated.

In Fig.7, the RMS of the time residual with respect to a plane front as a function of the true core position. The data are referred to a MC sample of Protons (red:1000 – 3000 TeV; blue:300 – 1000 TeV; black:100 – 300 TeV; violet:30 – 100 TeV).

**5 Conclusions**

In this work the unicity of ARGO-YBJ detector in studying cosmic ray showers has been presented. Particular attention has been paid to large time residual RMS with respect to the shower front. These events have been divided in two categories: Multiple-Front and Wide-Front Showers. The first type of events has been used to study possible detections or upper limits to the production and decay of massive particles in the cosmic ray interactions with the atmosphere. The method presented here will be developed and applied to the huge mass of data of the ARGO-YBJ experiment. The second type of events are generated by energetic showers with a core impact hundreds of meters far from the detector. Following Linsley’s parametrization example, a parametrization will be searched in order to locate the core distance. Using an adequate modified NKG distribution, it is possible to evaluate the total size of the shower from the local density and from it the energy of the primary cosmic ray. The present work showed how the detailed space-time information available with the ARGO-YBJ detector can be used to reconstruct in detail the characteristic of the shower front, in which the signature of the development and interactions of the EAS along its path in the atmosphere are recorded.

**References**