ARGO-YBJ Experiment: review of results on Cosmic Ray Astrophysics

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1. Introduction

The ARGO-YBJ [1] experiment has been the only air shower array with a full-coverage active area operated at high altitude, with the aim of studying the cosmic radiation at an energy threshold of a few hundreds GeV. The large field of view ($\sim 2\,sr$) and the high duty cycle ($> 85\%$) allow a continuous monitoring of the sky in the declination band from -10° to 70° [2]. It stopped operation in February 2013.

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.

ARGO-YBJ also offers a unique chance for a detailed study of several characteristics of the hadronic component of the Cosmic Rays in the $10^{12}-10^{15}$ eV energy range. Indeed, the analog readout of the RPC (Resistive Plate Chamber) signals provides a powerful tool to study, with unprecedented resolution, the distribution of the charged particles of extensive air showers (EAS) down to few meters from the axis, thus allowing to describe its shape in detail and to estimate the shower age at the detection level.

These features make feasible, for the first time, mass composition studies with an EAS detector in an energy region where the comparison with direct measurements is now possible. Moreover, new inputs to the hadronic interaction models, currently used for the analysis of the cosmic ray flux and origin up to the highest energies, can be obtained.

The geomagnetic field causes not only the East-West effect on the primary cosmic rays but also affects the trajectories of the secondary charged particles in the showers, causing their lateral distribution to be stretched along certain directions. Thus both the density of the secondaries near the shower axis and the trigger efficiency of a detector array decrease. The effect depends on age and direction of the showers, thus introducing modulation in the measured azimuthal distribution. Here the non-uniformity of the azimuthal distribution of the showers with the core inside the ARGO-YBJ detector is investigated for different zenith angles on the light of this effect.

2. Study of the time structure of EAS particles with ARGO-YBJ

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 studied.

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

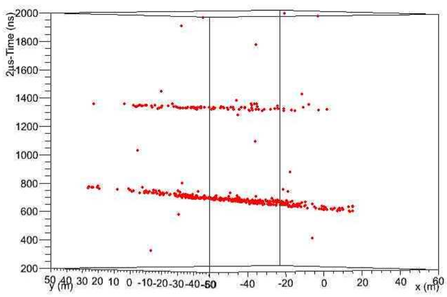

Figure 1. Multiple-Front Shower example. The three-dimensional view of a MFS is shown. On the z axis the arrival time is plotted. It is defined as the time diffence between the starting of TDC counting, when a particle hits the detector, and the common stop signal stated by the occurency of the trigger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

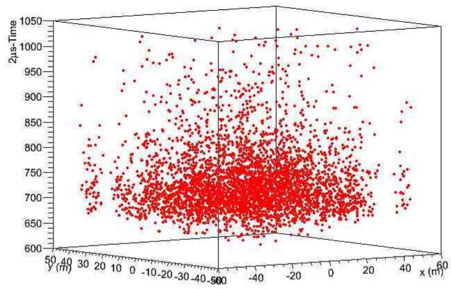

Figure 2. Wide-Front Shower example. The shower has more than 4000 hits uniformly distributed on the carpet and with a time distribution more than 100 ns wide.

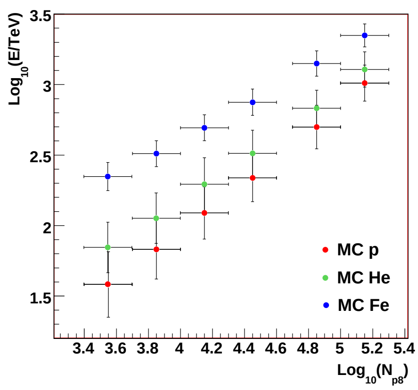

Figure 3. Average primary energy for p, He, Fe initiated MC showers and several N_{p8} intervals.

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.

3. Hadronic interactions and Cosmic Ray mass composition studied by ARGO-YBJ

An EAS array by itself cannot measure directly the shower development stage, but simply the particle density distribution at ground as a function of the core distance (LDF). Anyway, the detailed LDF study is expected to provide information useful to select intervals of X_{max} (depth of the cascade maximum size), important for measuring p-air cross section by the flux attenuation method [4]. In turn, the shower development stage as observed at detection level, depends on the energy E of the interacting primary, while, for fixed E, it depends on the primary type. Then, the combined use of shower E and age estimations ensures a sensitivity to the primary nature.

To perform this analysis, several samples of simulated showers by different primaries (p, He and Fe nuclei) were generated and submitted to a full detector simulation. Monte Carlo (MC) events triggering the analog RPC readout (with reconstructed core in a $64 \times 64\,\mathrm{m}^2$ detector internal area and $\theta_{zenith} < 15°$) were then analyzed to find a suitable estimator of the primary CR energy E. The number of particles detected within $8\,\mathrm{m}$ from the shower axis (N_{p8}) resulted well correlated to E, not biased by the finite detector size and lightly affected by shower to shower fluctuations. In Fig.3, such correlation is shown for p, He and Fe initiated showers.

4. Evidence of geomagnetic effect on extensive air showers in the ARGO-YBJ data

The path of charged primary cosmic rays (CR) is deflected by magnetic fields. The galactic magnetic field randomizes the CR directions. The geomagnetic field (GeoMF) restrains low-rigidity CR's from reaching the terrestrial atmosphere and causes that the CR flux is lower from East than from West. The GeoMF acts also on the charged particles of the extensive air showers (EAS) during their travel in the atmosphere. Cocconi [10] suggested that the lateral displacement induced by the Earth magnetic field is not negligible with respect to the Coulomb scattering when the shower is young. According to Cocconi model the effect could increase for high altitude measurements. Moreover if the trigger efficiency of an array is sensitive to the shower lateral extension, the GeoMF can change the acquisition rate as a function of zenith and azimuth angles.

An azimuthal modulation was observed at the Yakutsk array for EAS with energy above 50 PeV [11]. The GeoMF effect in the ARGO-YBJ data has been already foreseen and observed [12]. Here those studies are updated and the GeoMF effect appears evident in a very large data sample.

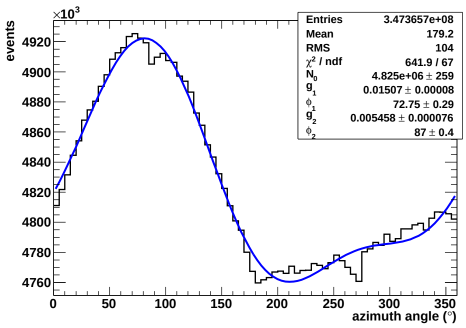

Figure 4. Real data: azimuthal distribution and relative fit.

4.1. Conclusions

The effect of the geomagnetic Lorentz force on EAS charged particles has been observed in a data sample collected by the ARGO-YBJ experiment. The shower extension is enlarged depending on the arrival direction with respect to the GeoMF and the different density of charged particles reduces the trigger efficiency for EAS with the core on the detector. The GeoMF origin and the features of the trigger efficiency decrease are fully understood by means of a toy model complemented by MonteCarlo simulations.

The non-uniform azimuthal distribution has been deeply studied. It is well described by two harmonics, the first one of the order of 1.5%, the second one of the order of 0.5%. The first harmonic is due to the GeoMF, the second one is the sum of magnetic and detector effects. The measurement of the geomagnetic phase ($\phi_1 = 72.22° \pm 0.28°$) is fully compatible with the expected value ($\phi_B = 71.89°$). Other measurements confirm the geomagnetic origin of the modulation.

The phase of the first harmonic (ϕ_1) can be used as a marker of the absolute pointing accuracy of EAS arrays.

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