ARGO-YBJ: hadronic interaction and Cosmic Ray composition studies

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1. Introduction

The scientific goals of the ARGO-YBJ experiment (see [1]) include the study of Cosmic Ray (CR) physics, in particular primary spectrum and mass composition, starting from $\sim 10^{12}$ eV. Indeed, the detector layout, performance and location allow to investigate several characteristics of the hadronic component of the CRs in an energy window beyond the current limits of direct measurements up to the spectrum "knee" region, 10^{15}-10^{16} eV. Previous ARGO-YBJ results on hadronic interactions concern the measurement of the p-air cross section in the energy range 1-100 TeV and, consequently, of the total p-p cross section at center of mass energies $\sqrt{s}$ between 70 and 500 GeV [2]. The ARGO-YBJ result is consistent with the general trend of experimental data, favouring an asymptotic $ln^2(s)$ rise of the cross section. The analysis, based on the flux attenuation at different atmospheric depths (i.e. zenith angles), used the digital information and exploited the detector capabilities of constraining the shower development stage by means of hit multiplicity and spatial concentration.

Significant improvements in such analysis come from the use of the "analog readout system", successively installed on the whole detector and devoted to the RPC analog charge readout [3] from the *BigPads*, each one covering half a chamber. It actually extends the detector operating range from ~100 TeV up to ~PeV primary energies and permits to measure particle densities up to $\sim 10^4/m^2$, without the saturation at 23/m^2 given by the strips (Fig.1), thus allowing to study collisions with $\sqrt{s}$ in the ~TeV region.

The system used a set of dynamic gain scales, with an overlap between digital and analog linearity ranges, thus providing an efficient way to calibrate the system itself [4,5]. Some preliminary results of the analysis of a sub-set of the analog system data can be found in [6,7] and have been more extensively presented at the International Symposium on Very High Energy Cosmic Ray Interactions (ISVHECRI) last year [8].

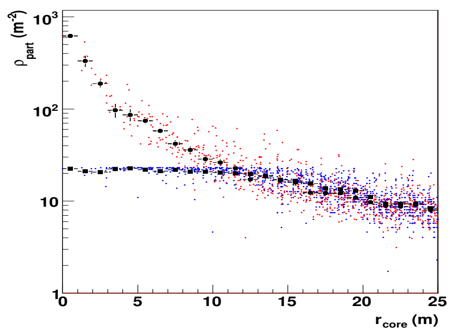

Figure 1. Particle lateral distribution of one ARGO-YBJ event. Strips (blue dots) saturate for ~15m from the core, while the particle density given by the analog RPC charge (red dots) exhibits no saturation also very near to the core.

2. Analysis strategy and Monte Carlo simulation

The peculiar features of the detector, that is full-coverage and charge readout segmentation, joined to the dynamical operating range of the charge readout system allow to study the detailed structure of the particle density distribution for ~30m starting from the core at ground. On the basis of such information, several characteristics of the hadronic interactions could be investigated and different hadronization models compared.

The detailed study of the lateral particle density profile (LDF) at ground is expected to provide information on the longitudinal profile of the showers in the atmosphere, that is to estimate their development stage, or 'age', expressed by X_{max} (g/cm^2), the atmospheric depth at which the cascade reaches its maximum size. If true, this implies the possibility of selecting some intervals of X_{max} or, equivalently, of X_{dm}, the distance between the shower maximum and the detector, crucial for the measurement of p-air cross section using the method of flux attenuation.

For these purposes and to find the possible correlations between the experimental observ-

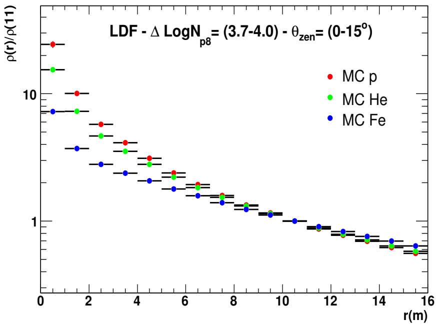

Figure 2. Reconstructed LDF of the detected particles around the core, normalized to the density at 11m of distance, for simulated p, He and Fe initiated showers with $10^{3.7} < N_{p8} < 10^{4.0}$.

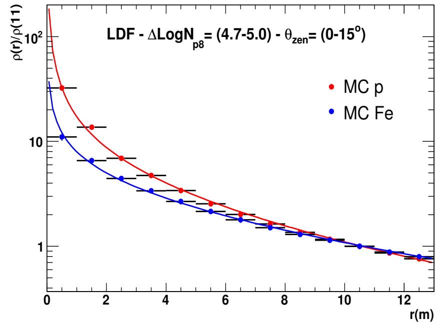

Figure 3. Fits to the reconstructed LDFs of the detected particles around the axis for simulated proton and iron induced showers with $10^{4.7} < N_{p8} < 10^{5.0}$, by the NKG-like function (1).

ables and several shower features (primary energy, mass, etc.), a full Monte Carlo (MC) simulation has been useded, with *CORSIKA* code for the interaction and transport in the atmosphere and a complete ARGO-YBJ detector response.

In order to have a better evaluation of systematics, we produced independent samples by using two different hadronic interaction models, namely *QGSJET-II.03* and *SIBYLL-2.1*. Simulated data have been analyzed by using the same reconstruction code as for real data. The simulation reliability was successfully checked by comparing several simulated and measured quantities.

Events that triggered the analog RPC readout ($\geq$73 fired pads in a cluster) were subsequently selected by requiring the core position, reconstructed with a precision of the order of $\sim$1m or less, in a fiducial area $64\times64\,\mathrm{m}^2$ around the detector center. This cut actually reduces to a negligible value (¡ 10^{-3}) the fraction of events with true core outside the detector but mis-reconstructed inside. This analysis was also restricted to events with reconstructed zenith angle $\theta < 15°$.

As a first step, a suitable estimator of the primary CR energy E was searched for: N_{p8}, the number of particles detected within a distance of 8m from the shower core at ground, showed a good correlation with E, not biased by the finite detector size and only slightly affected by shower to shower fluctuations. Then, since the basic idea is to get information on the shower development stage from the lateral profile structure around the core, the whole reconstructed LDFs (up to $10-15$m of distance from the core), for different N_{p8} intervals and different shower initiating primaries, have been studied in detail by fitting their shape with some proper functions.

As an example, Fig.2 shows the average LDF from a sample of p-induced shower events ('mean event') in the interval ΔN_{p8}=$10^{3.7}$-$10^{4.0}$, corresponding to a typical energy $E_p$$\sim$70 TeV. In the same plot, the LDFs for the 'mean event' induced by He and Fe primaries in the same ΔN_{p8} ($E_{He}$$\sim$100 TeV and $E_{Fe}$$\sim$300 TeV) are shown.

The following function has been found to better reproduce, in the above distance interval, the LDF shape for ARGO-YBJ simulated data:

$$\rho(r) = A \times \left(\frac{r}{r_0}\right)^{s'-2}\left(1-\frac{r}{r_0}\right)^{s'-4.5} \qquad (1)$$

with only two free parameters, normalization (A) and shape parameter (s'), while r_0 is fixed to 32 m. It is clearly a NKG-like function, that is corresponds to the classical NKG lateral distribution function, with $r_0$$\sim$1/4 the Moliere radius at the YBJ altitude and s' candidate to play the role of the 'lateral age' parameter.

3. Analysis results and discussion

The LDF of the 'mean event' for each of the three considered primaries (p, He, Fe) and for each N_{p8} interval (i.e. energy bin) has been fitted by the function (1) to obtain the shape parameter s'. As an example, Fig.3 shows the average lateral distribution and the related fit for the p-primary event sample of ΔN_{p8}=$10^{4.7}-10^{5.0}$ corresponding to a typical energy E_p $\sim$500 TeV. In the same plot, the distribution and fit for the 'mean event' induced by iron-nucleus primaries (E_{Fe} $\sim$1.4 PeV) can also be observed.

From the results concerning the shape fit parameter s', for the different energy intervals and primaries (see Fig.6), we observed that, for a given primary, the s' value decreases when N_{p8} (i.e. the energy) increases, while, for a fixed ΔN_{p8}, it increases with the primary mass: this behaviour is perfectly in agreement with the expectation if s' is correlated to the shower age, thus reflecting its development stage.

This outcome has two important implications: the s' value (a) can help to constrain the shower

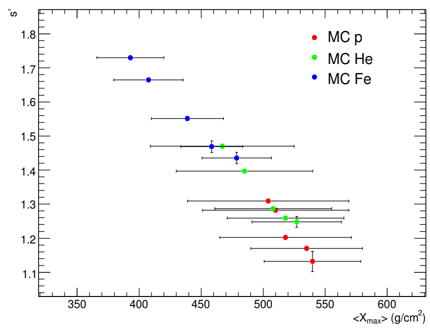

Figure 4. Age parameter s' from the fits to the lateral distributions of p, He and Fe 'mean event' by the NKG-like function vs the averages of X_{max}, for the five N_{p8} considered intervals.

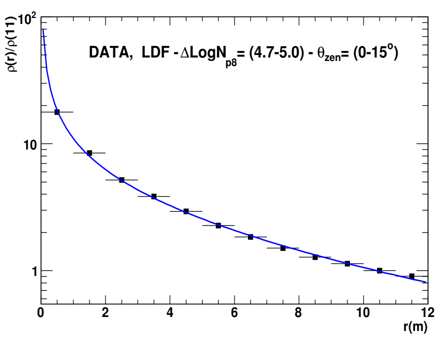

Figure 5. Reconstructed LDF of the detected particles around the core for real ARGO-YBJ events with $10^{4.7} < N_{p8} < 10^{5.0}$. The superimposed fit by the NKG-like function is also shown.

X_{max} position and (b) can give information on the primary particle nature. Concerning the first point, we put in the same plot the s' value as obtained from the LDF fit, for each primary and N_{p8} interval, vs the average value of X_{max} distribution from MC simulation, as shown in Fig.4. The two quantities not only are clearly correlated, but also the shape parameter s' depends only on the development stage of the shower, irrespective of the nature of the primary particle and energy. This expresses the universality of LDF of detected EAS particles in terms of the lateral shower age.

The second implication is that s' from the LDF fit, although in the distance range up to ∼12m of the core distance, is sensitive to the primary particle nature, thus making possible the study of primary mass composition and the selection of a proton-enriched CR primary beam.

Similar LDF distributions, in the same N_{p8} intervals used for MC data, have been obtained from real event samples and the fit with function (1) has been applied. Also for experimental data, the lateral particle density profiles appear properly described by that function, as shown in Fig.5 where the fit to the 'mean event' in a particular ΔN_{p8} is shown as an example.

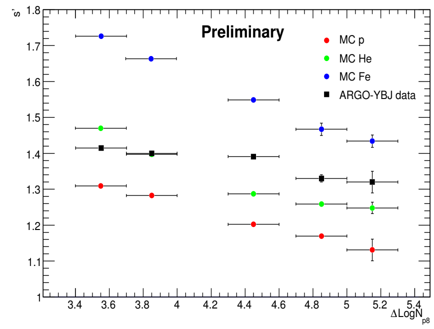

Figure 6. Age parameter s' values from the fits to the 'mean event' lateral distributions from MC simulations (p, He, Fe) and from experimental data, in the five N_{p8} bins.

The preliminary s' values from ARGO-YBJ data are reported in Fig.6 together with the corresponding fit results from the MC samples for different primaries. The errors on the parameter s' shown in the figure, both for MC and real data, arise from the described fit of the 'mean event' distributions, so they don't reflect the spread caused by the shower by shower fluctuations. In a further and more complete analysis, the systematics due to intrinsic shower fluctuations and their effects on the sensitivity to the mass composition study will be carefully evaluated.

Anyway, once stated the preliminary nature of this result, we observe that the lateral age values from LDF fit to ARGO-YBJ data consistently lie between predictions from extreme pure proton or iron-nucleus compositions.

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