

Mass composition and hadronic interaction studies with ARGO-YBJ

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Abstract: The ARGO-YBJ detector layout (a full coverage Resistive Plate Chamber, RPC, carpet), features (high resolution space-time pixels) and location (about 600 g/cm^2 of atmospheric depth) offer a unique opportunity for a detailed study of several characteristics of the hadronic component of the cosmic ray flux in the 10^{12} - 10^{15} eV energy range. The analog readout of the RPC signals indeed provides a powerful tool to study, with unprecedented resolution and without saturation, the extensive air shower space-time structure very close to its axis. The distribution of charged particles at ground and the time structure of the shower front allow estimating the shower age at the detection level independently from the primary mass. Furthermore the truncated size, measured within few meters from the core, gives a reliable energy measurement without biases introduced by finite detector effects. Fluctuations are also reduced thanks to the proximity of the shower maximum to the high altitude detection level. These features allows mass composition studies with an EAS detector in an energy region where a comparison with space or balloon born experiments are now possible for the first time, thus giving a further cross checks on the systematics of the adopted analysis procedures. Moreover, measurements of the proton-air cross section, of the particle distribution close to the shower axis, etc., give new inputs, in the very forward region, to the hadronic interaction models currently used for the study of the cosmic ray flux and its origin up to the highest energies.

Keywords: Extensive Air Showers, Mass Composition, Hadronic Interactions, ARGO-YBJ experiment

1 Introduction

The ARGO-YBJ experiment, with its detector features and location, can offer a unique chance for a detailed study of several characteristics of the hadronic component of the primary cosmic rays (CRs), in an energy range beyond the current limits of direct measurements. A fundamental quantity of all CR interaction models is the total hadronic cross section σ_{tot} and its elastic and inelastic (in particular, diffractive) components. Previous ARGO-YBJ results on hadronic interactions concern the measurement of the proton-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 [1]. The ARGO-YBJ measurements are 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 only (see next section) and exploited the detector capabilities of constraining the shower development stage by means of hit multiplicity and space pattern at ground.

The work presented here is based on the data taken with the RPC analog charge readout that allows measuring the particle densities at ground very close to the shower core, thus extending the analysis sensitivity up to collisions with \sqrt{s} in the TeV region. Several characteristics of the hadronic interactions could be investigated and different models compared to check their validity. In particular, the distribution and physical properties of secondary particles produced in the very forward kinematic region of the primary interaction can be in principle inspected. Even if the lateral distribution of particles at ground is rather

determined by multiple Coulomb scattering and by the transverse momentum spectra of secondaries at much lower energies, such a measurement is important for checking the overall physics consistency of soft and hard interaction mechanisms implemented in the models.

2 The ARGO-YBJ experiment

The ARGO-YBJ detector is a full coverage extensive air shower array made by a single layer of Resistive Plate Chambers (RPCs) operated in streamer mode. The array, located in the YanBaJing (Tibet, China) Cosmic Ray Laboratory, at an altitude of 4300m above sea level (corresponding to a vertical atmospheric depth of $\sim 606\text{ g/cm}^2$), has been in stable data taking in its full configuration since November 2007 until February 2013. It is organized in 153 clusters, each made of 12 RPCs. Each RPC is read out by ten $62 \times 56\text{ cm}^2$ pads, which are further divided into 8 strips, thus providing a larger particle counting dynamic range [2, 3]. Signals coming from all the strips of a given pad are sent to the same channel of a multihit TDC. The whole system provides a single hit (pad) time resolution of 1.8 ns, that, together with the size of space pixels and the full-coverage layout, allows an event imaging and reconstruction with very high details.

A system for the RPC analog charge readout [4] from larger pads (BigPads), $124 \times 140\text{ cm}^2$, each one covering half a chamber, was implemented and took data since January 2010. This actually extended the detector operating range from about 100 TeV up to PeV primary proton energies. Moreover, the RPC charge information allowed measuring very high particle densities, without

the saturation at $\sim 20/\text{m}^2$ otherwise present by using the detector in *digital mode*, i.e. by simply counting the number of fired strips.

The system uses a set of eight dynamic gain scales (defined as G0,...,G7, with increasing gains), with an overlap between digital and analog linearity ranges, thus providing an efficient way to calibrate the system itself [5, 6, 7]. The different scales of operation also define the ranges of the maximum number of particles measured by each BigPad with sufficient overlaps. The measurable maximum density of particles, in each single event, covers more than two decades while the detection rate spans over five decades. Apart from the data of the largest gain scale G7, useful for inter-calibration purposes with the *digital mode*, for this analysis we used two sets of analog data collected with G4 and G1 scales, thus accessing particle density values up to $\sim 10^4/\text{m}^2$. Further details can be found in [6, 8].

3 Analysis strategy and objectives

An EAS array by itself cannot measure directly the shower development stage, through the direct determination of the depth of the shower maximum. It can only measure the particle density distribution at ground as a function of the core distance (LDF) and, from its slope, information on the longitudinal shower development can be accessed. Historically, it was shown that the LDF, as measured by a traditional sampling EAS array at distances of the order of hundreds meters from the core, can be described by the Nishimura-Kamata-Greisen (NKG) function [9], with parameters reflecting the shower size, the detection altitude and the shower age. The age parameter determined in this way is usually referred to as 'lateral age' [10].

The detailed study of the LDF is expected to provide information on the shower development stage and then on X_{max} (g/cm^2), the atmospheric depth at which the cascade reaches its maximum size. This would give the possibility of selecting some intervals of X_{max} or, equivalently, of X_{dm} the distance between the shower maximum and the detector. The selection of showers with X_{dm} in a given interval for different zenith angles is an important point for the measurement of p-air cross section using the method of flux attenuation, as discussed in [1].

The shower development stage in the atmosphere, as observed at a fixed altitude (the detection one), depends on the energy of the interacting primary. For fixed energy, it depends on the primary nature: heavier primaries interact higher in the atmosphere, thus giving showers which, on average, reach their maximum at a larger distance from the detector than a lighter primary of the same energy. For this reason, the combined use of the shower energy and age estimations can ensure a sensitivity to the primary nature. This would also give the possibility of selecting a proton-enriched event sample, thus allowing a measurement of the p-air cross-section. A possible residual contamination will contribute to the overall systematic uncertainty of the measurement.

4 Monte Carlo simulation

Several samples of simulated data were produced and studied with the aim of correlating the experimental observables to the physics parameters of the showers.

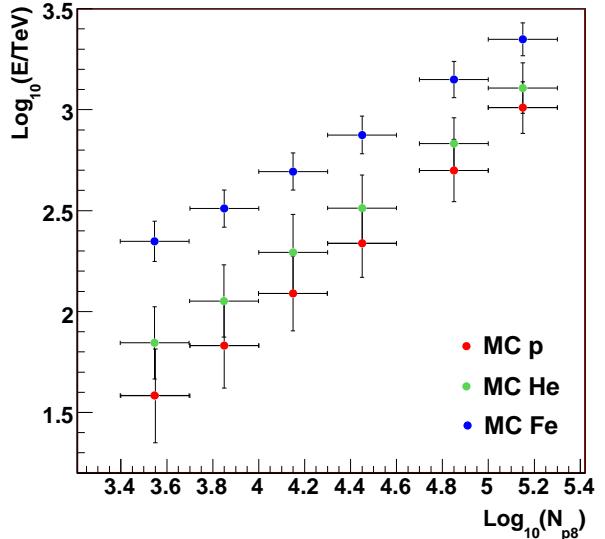


Fig. 1: Average primary energy for p, He and Fe initiated MC showers for various intervals of N_{p8} , the number of detected particles within 8m from the shower axis. Vertical error bars are the RMSs of the energy distributions, while the horizontal ones show the widths of the N_{p8} bins.

About $30 \cdot 10^6$ proton, $7 \cdot 10^6$ helium and $3.5 \cdot 10^6$ iron initiated showers were generated by the CORSIKA [11] code, with zenith angle up to 45° , energy range between 1 TeV and 3000 TeV and energy spectra as given in [12]. In order to have a better evaluation of the systematics, we produced independent samples of proton showers by using two different hadronic interaction models, namely QGSJET-II.03 [13] and SIBYLL-2.1 [14]. If not differently stated, the results described in this work refer to QGSJET-II model. The full simulation of the detector response, based on the GEANT package [15], included the effects of time resolution, trigger logic, electronics noise, etc. 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.

Several quantities, such as the LDF of the detected particles around the core, estimated through the analog system simulation, have been checked in order to investigate the systematics introduced by the hadronic interaction model. The reconstructed LDF obtained with QGSJET-II and SIBYLL-2.1 are quite similar, their difference being within few percent, as expected in this energy range [16].

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

As a first step, various observables were considered and analyzed in order to find a suitable estimator of the primary CR energy E . Among them, N_{p8} , the number of particles detected within a distance of 8 m from the shower axis, resulted well correlated with E , not biased by the finite detector size and not much affected by shower to shower

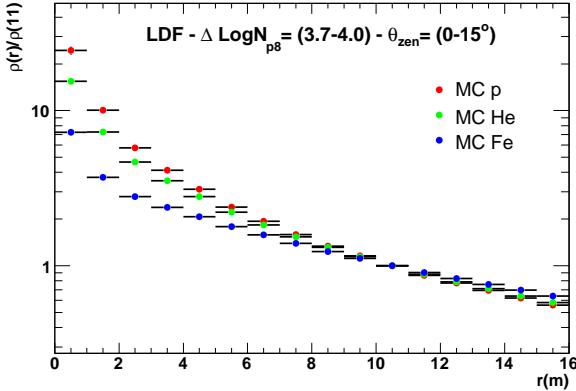


Fig. 2: Reconstructed LDF of the detected particles around the shower axis for simulated p, He and Fe initiated showers with $10^{3.7} < N_{p8} < 10^{4.0}$ and zenith angle less than 15° . The three distributions are here normalized to the particle density at 11 m.

fluctuations. In Fig. 1, the correlation between E and N_{p8} is shown for simulated proton, helium and iron initiated showers. Four N_{p8} intervals have been chosen to select event samples corresponding to different primary energies.

As already stated in the previous section, the basic idea is to get information on the shower development stage from the LDF structure around the core. In a first preliminary study [16], we found a promising correlation between the reconstructed LDF slope in the range $1 \div 2$ m from the core and the distance of the shower maximum from the detection level, X_{dm} , for p and iron initiated showers. In the current analysis, the whole reconstructed LDFs (up to about 10 m 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 (see [8] for details). As an example, Fig. 2 shows the average LDF obtained for a sample of simulated proton induced shower events in the interval $\Delta N_{p8} = 10^{3.7} \div 10^{4.0}$, corresponding to an average energy $E_p \simeq 70$ TeV. In the same plot, the average LDFs for the case of He and Fe primaries in the same ΔN_{p8} (corresponding to an average energy $E_{He} \simeq 100$ TeV and $E_{Fe} \simeq 300$ TeV respectively) are also shown. As discussed in [8], the following NKG-like function

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

has been found to better reproduce, in the above distance interval, the LDF shape for both ARGO-YBJ simulated and real data, with the minimum number of free parameters, normalization (A) and slope (s'), while r_0 is set at 30 m.

5 Results and discussion

The average LDF 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 given in Eq.(1) to get the shape parameter s' (see [8] for details). From these studies we find that, for a given primary, the s' value decreases when N_{p8} (i.e. the energy) increases, this being due to the observation of younger (deeper) showers at larger energies. Moreover for a given range

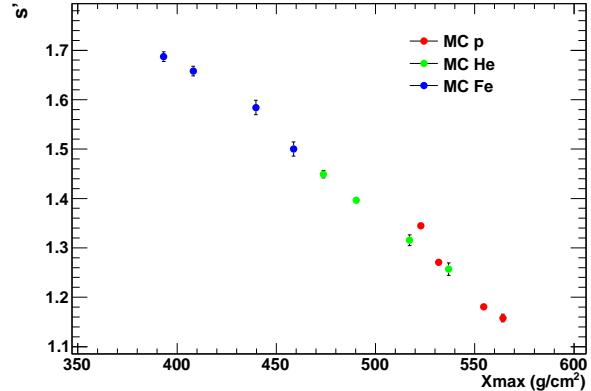


Fig. 3: The age parameter s' resulting from the fits of the average LDF of simulated p, He and Fe samples (in each N_{p8} bin) vs the corresponding X_{max} average values.

of N_{p8} , s' increases going from proton to iron, as a consequence of a larger primary interaction cross section. Both dependencies are in agreement with the expectations, the slope s' being correlated with the shower age, thus reflecting its development stage. This outcome has two important implications, since the measurements of s' and N_{p8} can both (i) help constraining the shower age and (ii) give information on the primary particle nature.

Concerning the first point, we show in Fig.3 the s' values as obtained from the fit of the average LDFs, for each simulated primary type and N_{p8} interval, as a function of the corresponding X_{max} average value. As can be seen the shape parameter s' depends only on the development stage of the shower, independently from the nature of the primary particle and energy. That plot expresses an important universality of the LDF of detected EAS particles in terms of the lateral shower age. This implies the possibility to select most deeply penetrating showers (and quasi-constant X_{dm} intervals) at different zenith angles, an important point for correlating the exponential angular rate distribution with the interaction length of the initiating particle [1]. Obviously shower-to-shower fluctuations (the RMS of X_{max} is of the order of 70 g/cm² for p and helium, and about 30 g/cm² for iron) introduce unavoidable systematics, whose effects can be anyway quantified and taken into account.

The second implication is that s' from the LDF fit very close to the shower axis, together with the measurement of the truncated size N_{p8} , can give information on the primary particle nature, thus making possible the study of primary mass composition and the selection of a proton-enriched CR data sample to be used for p-air cross section measurement.

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 in Eq.(1) has been applied. Also for experimental data, the lateral particle density profiles appear properly described by that function, as shown in Fig.4 where the fit of the average LDF in a particular N_{p8} bin is shown (see [8] for details). The s' values from experimental data are reported in Fig.5 together with the corresponding fit results from MC simulations for different primaries. Even with the preliminary nature of this result, we observe that the data points lie between the expectations from extreme pure compositions.

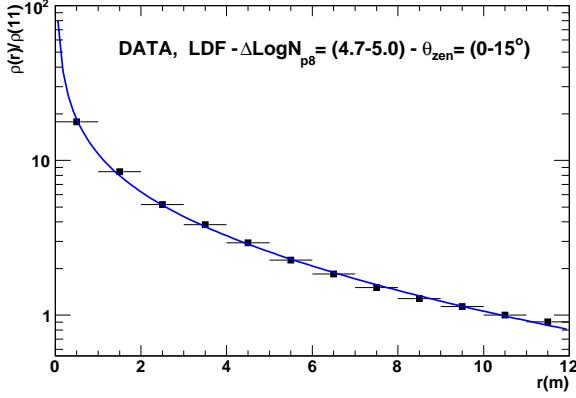


Fig.4: Average LDF for real ARGO-YBJ events with $10^{4.7} < N_{p8} < 10^{5.0}$. The superimposed fit with the NKG-like function is also shown (see text). Particle densities are normalized to the measured value at 11m from the axis.

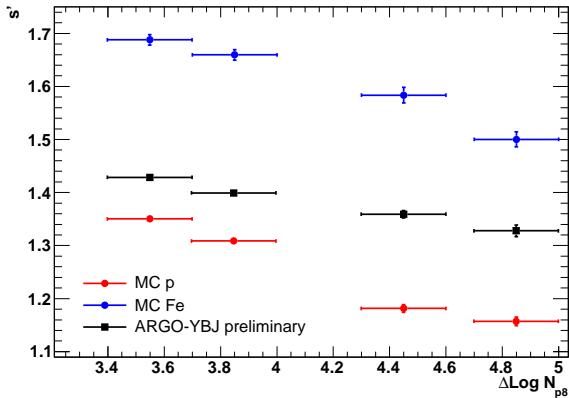


Fig.5: Age parameter s' as resulting from the fits of average LDFs of real ARGO-YBJ data and simulated p and Fe induced showers, in four N_{p8} bins.

The systematics due to intrinsic shower-to-shower fluctuations and their effects on the sensitivity to the mass composition have to be taken into account. In order to evaluate their effects, we have made the fit of LDF on an event by event basis. The result in terms of s' distributions is shown in Fig.6 for real ARGO-YBJ data and simulated proton and iron initiated showers, in one of the N_{p8} bins. As can be seen this type of analysis might also give important tools for the discrimination between light and heavy elements.

Finally the use of the data taken with the smallest gain scale G0 (suitable for the study of events with the largest primary energies) and of the information coming from the shower front time curvature will give a complete picture of the present analysis.

6 Conclusions

The ARGO-YBJ features and setup allow the study of the shower core region with unprecedented details and the measurement, with great accuracy, of the radial particle density distribution. This implies the possibility to investigate several characteristics of the hadronic interactions, to extend the previous p-air cross section measurement up to few PeV proton energies and to get hints on primary mass composition.

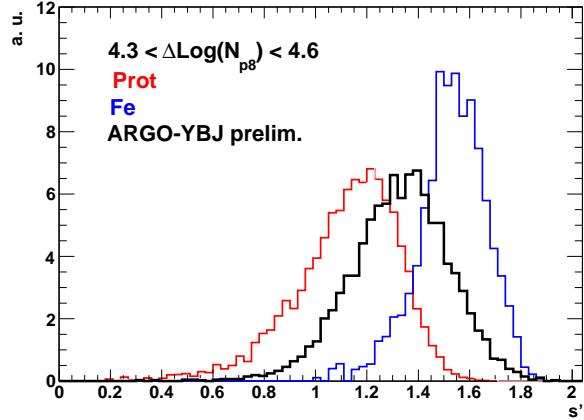


Fig.6: Age parameter s' as resulting from event-by-event LDF fits for real ARGO-YBJ data and simulated p and Fe induced showers, in one of the N_{p8} bins. Each histogram is normalized to its total number of entries.

Preliminary results from a first analysis of analog data indicate the capability of ARGO-YBJ to reliably estimate the primary CR energy and put constraints on the detected shower age from the particle distribution structure near the core, parameterized by the slope of the LDF. This parameter, together with the truncated size within 8 m from the core, is also shown to be sensitive to the primary composition. The effects of its fluctuations and of the correlations with other quantities are currently under investigation. In the preliminary analysis presented here, the lateral age values from LDF fits of ARGO-YBJ real data consistently lie between predictions from extreme pure proton and iron compositions. Moreover the study of the LDF is shown to give important tools for light/heavy mass discrimination on an event by event basis. Further improvements in the analysis will come from the use of the detailed information on the shower front time structure that ARGO-YBJ is able to record with very high precision.

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