ARGO-YBJ Experiment: hadronic interaction studies

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1. Introduction

One of the main scientific goals of the ARGO-YBJ experiment (see [1] and references therein) is the study of Cosmic Ray physics in the $10^{12} - 10^{16}$ eV primary energy range. The apparatus layout, performance and location allow to deeply investigate several characteristics of the hadronic component of the cosmic ray flux in an energy window marked by the transition from direct to indirect measurements. In this energy region the primary cosmic ray composition is sufficiently well known in order to make unbiased studies on the hadronic interactions.

The ARGO-YBJ data analysis using only the strip digital information already produced the measurement of the proton-air cross section in the energy range $1 - 100$ TeV [2]. The analysis is based on the flux attenuation for different atmospheric depths (i.e. zenith angles) and exploits the detector capabilities of selecting the shower development stage by means of hit multiplicity, density and lateral profile measurements at ground. For a given primary energy interval and once X_{dm} (distance between the detector and the shower maximum in the atmosphere) has been fixed, the shower rate exponentially falls when the zenith angle increases. The slope of the exponential behaviour is related to the primary interaction length (i.e. the inverse of proton-air inelastic cross section) through a parameter, k. Such a factor, which depends on hadronic interactions, the shower development in the atmosphere and its fluctuations, the detector response, etc., is evaluated with a full Monte Carlo (MC) simulation.

In that analysis, different hit (i.e. strip) multiplicity windows were used to select showers corresponding to different primary energies, while the information on particle density, lateral profile and shower front extension were used to constrain X_{dm} in a range that made possible the observation of the exponential falling of shower rates.

Several systematic uncertainties affecct such a measure, mainly that arising from the presence in the primary cosmic ray flux of nuclei heavier than protons and the dependence from the hadronic interaction model adopted in the MC simulation. These uncertiainties have been evaluated and taken into account in the final result on proton-air inelastic cross section.

The results have been also used to estimate the total proton-proton cross section at center of mass energies between 70 and 500 GeV not yet reached by p-p colliders and so far unexplored by p-$\bar{\text{p}}$ experiments. The ARGO-YBJ result is consistent with the general trend of experimental data, favouring an asymptotic $ln^2(s)$ rise of the cross section, $\sqrt{s}$ being the total energy in the center of mass reference system.

Significant improvements in the analysis are now expected to come from the use of the detailed information on the shower front that ARGO-YBJ is able to record with very high precision, and by the use of the "analog readout system". That system, presently installed on the whole central detector ($\sim 5700\,m^2$), is intended for the RPC analog charge readout [**?**, 4] from larger pads, each one covering half a chamber (the so called *big pads*). It actually extends the detector operating range from about 100 TeV up to ~PeV primary energies and permits to measure particle densities up to $10^4/m^2$, without the saturation at about $20/\text{m}^2$ given by the strips (Fig.1), thus allowing to study collisions with center-of-mass energies up to the ~TeV region. Here, some preliminary results of this study is reported [5].

2. Simulation and experimental results

The correlation between the experimental observables and several physics quantities of the showers (primary energy, mass, etc.) was studied by means of simulated data samples produced through Corsika code and processed by the detector response simulation program including the detector geometry, performance, trigger logic, electronics noise, etc. Moreover, in order to have a better evaluation of systematics, we produced independent samples by using two different hadronic interaction models, namely QGSJET-

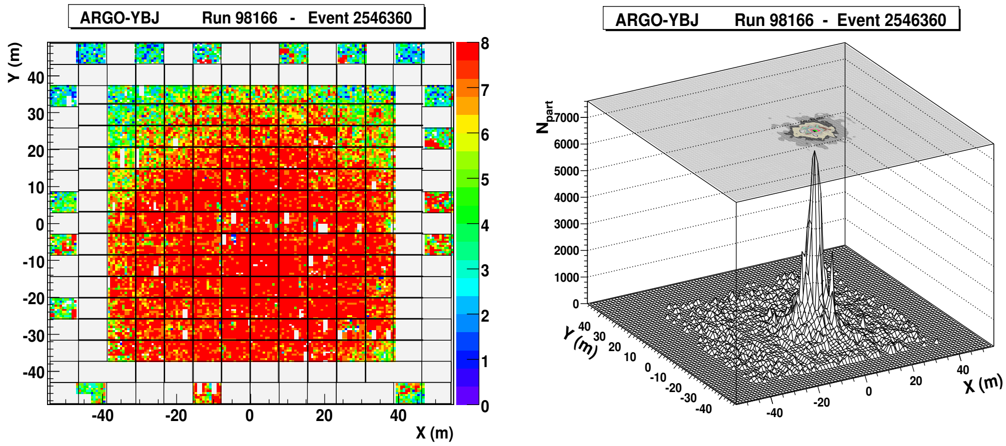

Figure 1. Particle distribution detected by ARGO-YBJ in a real high energy event. *Left* : The digital hit map showing the saturation of the strip pattern around the core. *Right*: Particle density measured on the same shower with the analog RPC information without saturation.

II.03 and SIBYLL-2.1. The comparison of the Lateral Distribution Function (LDF) by the two MC samples gives a difference within few percent (Fig.2), as expected in this energy range.

Several quantities were analyzed in order to find a suitable estimator of the primary energy E. The number of particles, N_{p8}, detected at ground within a distance of 8 meters from the shower core, resulted to be both well correlated with E and not biased by effects due to finite detector size. In Fig.3 the dependency of N_{p8} on E is shown for simulated proton and iron initiated showers. Different N_{p8} intervals can be chosen in order to select event samples corresponding to different primary energies.

The simulated data samples have then been used to identify the proper cuts for the selection of well reconstructed events and to investigate possible observables useful in the hadronic interaction studies. A relevant correlation has been found between the LDF slope at small distance from the core and the shower age, separately for proton and iron initiated showers, as shown in Fig.4. This gives a hint to use the LDF slope values to select shower ages in a given interval, thus providing a useful tool for the extension of the proton-air cross section measurement to larger energies.

In order to select proton enriched samples in the experimental data, an observable quantity related to the the primary mass has been searched for. Useful information to this purpose come from the time structure of the shower front. For instance, the front curvature quantified in terms of a conicity angle α, when plot as a function of R_{q70} (the radius of the circle around the core lying in the detector plane and including 70% of the detected particles deduced by the RPC charge readout), shows the behaviour in Fig.5. As can be seen, mass separation could be feasible on the basis of these variables.

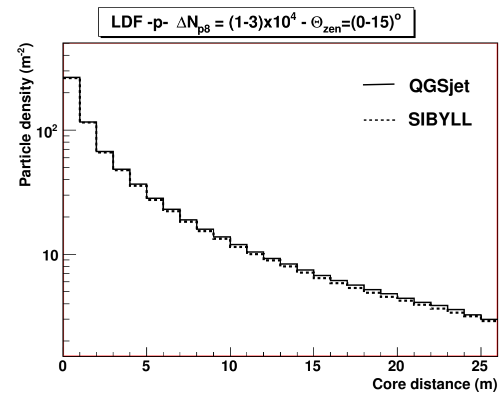

Figure 2. LDF of the detected particles around the core at ground for simulated proton showers with $10^4 < N_{p8} < 3 \cdot 10^4$. The particle densities by QGSJET-II and SYBILL differ by few percent.

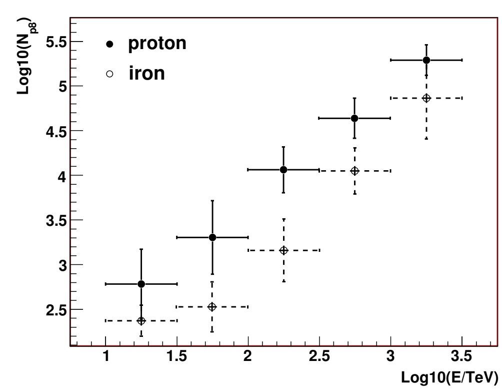

Figure 3. Number of particles detected at ground within a distance of 8 meters from the shower core vs primary energy for proton and iron initiated simulated showers. Vertical error bars show the r.m.s. values of the N_{p8} distributions, while horizontal ones refer to the adopted energy bins.

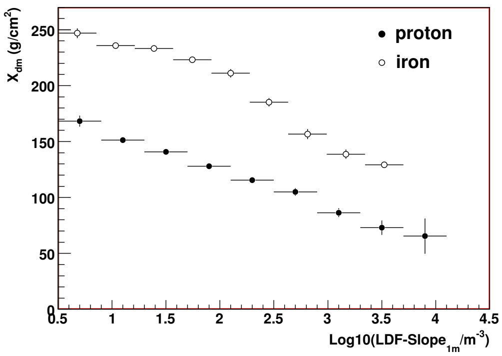

Figure 4. Distance (grammage) of the shower maximum from the detection level, X_{dm}, as a function of the LDF slope at 1 m from the core for proton and iron initiated showers with $N_{p8} > 10^3$.

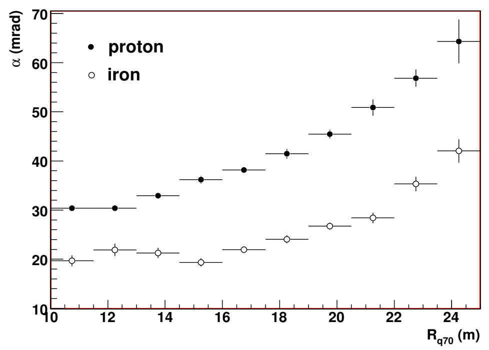

Figure 5. Curvature parameter α as a function of R_{q70} for events with $N_{p8} > 10^3$. Simulated proton and iron initiated showers are compared.

Concerning real data analysis, a set of about $3.5{\cdot}10^6$ events triggering the analog system (at least 73 fired pads in a given RPC cluster, for a trigger rate at level of $\sim 8\,\mathrm{Hz}$) was used. A sample of $5{\cdot}10^5$ events was then selected by requiring a reconstructed zenith angle $\theta < 15°$ and the core position (from charge information) at ground to be in a fiducial region of $64 \times 64\,\mathrm{m}^2$ around the detector center. This cut actually reduces to a negligible value ($< 10^{-3}$) the fraction of true external core events which are misreconstructed as internal. In Fig.6 the experimental distribution of the number of particles detected at ground is shown. Two suitable ranges can be identified, one concerning the strips and the other one related to the analog charge information. It can be seen that the two systems agree fairly well and the estimated particle multiplicity spectra can be fitted with a single power law. This is also a check of the analog charge calibration procedure [6].

The experimental LDF is shown in Fig.7 for events in two N_{p8} intervals and with core in the $48 \times 48\,\mathrm{m}^2$ central area. As can be seen, the two systems (*analog* and *digital*) cover a large dynamic range in particle density and results are in good agreement with MC predictions (see Fig.2).

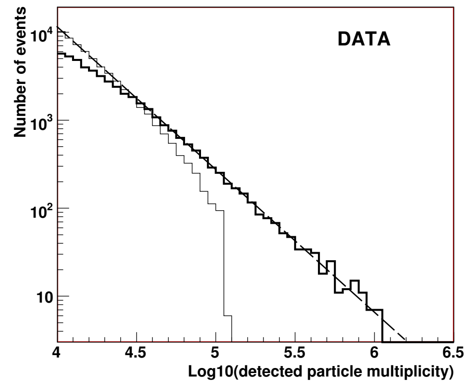

Figure 6. Experimental distribution of the number of particles detected at ground, from strips (thin line) or analog charge (thick line). A power law fit of spectra is superimposed (dashed line).

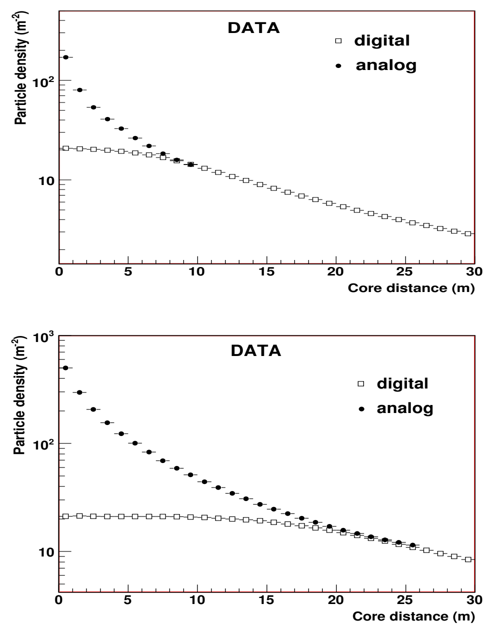

Figure 7. LDF from 2 experimental data samples with $10^4 < N_{p8} < 3 \cdot 10^4$ (*upper*) and $5 \cdot 10^4 < N_{p8} < 10^5$ (*lower*). Particle density is measured in *digital* (up to $\sim 20/\mathrm{m}^2$) and *analog* modes.

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