Hadronic Interaction Studies with the ARGO-YBJ Experiment

I.DE MITRI[1,2], G.MARSELLA[3,2], L.PERRONE[3,2], A.SURDO[2], AND G.ZIZZI[4]
(ON BEHALF OF THE ARGO-YBJ COLLABORATION)
[1] *Dipartimento di Fisica, Università del Salento, I-73100, Lecce, Italy*
[2] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Lecce, I-73100, Lecce, Italy*
[3] *Dipartimento di Ingegneria dell'Innovazione, Università del Salento, I-73100, Lecce, Italy*
[4] *Istituto Nazionale di Fisica Nucleare, CNAF, I-40127 Bologna, Italy*

Abstract: Cosmic ray physics in the $10^{12} - 10^{16}$ eV primary energy range is among the main scientific goals of the ARGO-YBJ experiment. The detector, located at 4300 m a.s.l., is a full coverage Extensive Air Shower array consisting of a carpet of Resistive Plate Chambers of about 6700 m^2. The apparatus layout, performance and location offer a unique possibility to make a deep study of 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. In particular, the proton-air cross section has been measured in the 1-100 TeV energy region and total proton-proton cross section has been estimated at center of mass energies where no accelerator data are currently available. The recently implemented analog readout of the RPC signal allows extending these studies towards higher energies. The lateral distribution of particle density down to few meters from the core and the shower time structure are currently observed with unprecedented resolution, thus giving new tools for the study of hadronic interactions at these energies.

Keywords: Cross Section, Hadronic Interactions, Extensive Air Showers

1 Introduction

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 is located in the village of YanBaJing (Tibet,China) at an altitude of 4300 m above sea level (corresponding to a vertical atmospheric depth of about 606 g/cm^2) and it is running in its full configuration from november 2007. It is organized in 153 clusters of 12 RPCs. Each RPC is read out by ten 62×56 cm^2 pads, which are further divided into 8 strips, thus providing a larger particle counting dynamic range [1, 2]. The 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, which allows a complete and detailed three-dimensional reconstruction of the shower front with unprecedented space-time resolution. A system for the RPC analog charge readout [3] from larger pads, each one covering half a chamber (the so called *big pads*), has also been implemented. This actually extends the detector operating range from about 100 TeV up to PeV primary energies. Moreover RPC charge information allows maesuring particle density values up to $\sim 10^4$/m^2 without the saturation at about 20/m^2 otherwise present by using the detector in *digital mode*, i.e. by counting the number of fired strips (see Fig.1). Previous ARGO-YBJ results on hadronic interactions (obtained by using the strip digital information only) concern the measurements of the proton-air cross section in the energy range 1-100 TeV (see [4] and references therein). 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. 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. Improvements in the analysis are 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 RPC readout that will allow extending these studies to collisions with center-of-mass energies up to the TeV region. In this paper we report on the first results of the analysis of RPC analog data with particular interest on hadronic interaction studies.

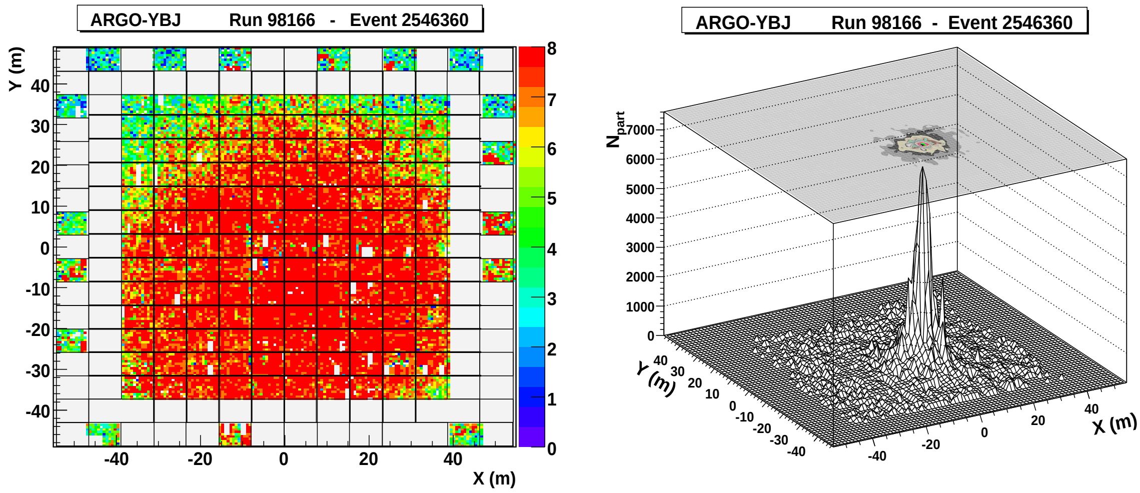

Figure 1: Particle distribution detected by ARGO-YBJ in a real event. *Left* : The hit map with the color code representing the strip multiplicity of each fired pad. Since this is a large energy event, the strip information is saturated around the core. *Right*: Particle density measured on the same shower with the analog RPC information without saturation.

2 Data Simulation and Experimental Results

In order to better understand the meaning of several observables and the correlations among them and with physics parameters of the shower (e.g. primary energy, mass, etc.) several samples of simulated data were produced and studied. About $3 \cdot 10^6$ proton-initiated (and $2 \cdot 10^6$ iron-initiated) showers were produced with the CORSIKA code with zenith angle up to 30°, energy range between 1 TeV and 3000 TeV and spectral index as given in [5], resulting from a global fit of existing experimental data. In order to have a better evaluation of systematics, we produced independent samples by using two different hadronic interaction models, namely QGSJET-II.03 [6] and SIBYLL-2.1 [7]. In the following text, if not differently stated, the results referring to QGSJET-II will be shown. A full simulation of the detector response, based on the GEANT package, was performed, including also the effects of time resolution, trigger logic, electronics noise, etc. Simulated data have been produced in the same format used for the real ones and they have been analyzed by using the same reconstruction code. The reliability of the simulation procedure was successfully checked in several ways by comparing simulated and measured quantities.

Events that triggered the analog RPC readout (i.e. producing at least 73 fired pads in a given RPC cluster) were subsequently selected by requiring the reconstructed core position 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 (actually less than 10^{-3}) the fraction of events with true core outside the detector but misreconstructed inside. In this preliminary work the analysis was also restricted to events with reconstructed zenith angle $\theta < 15°$.

As a first step, several quantities were analyzed in order to find a suitable estimator of the primary energy E. Among

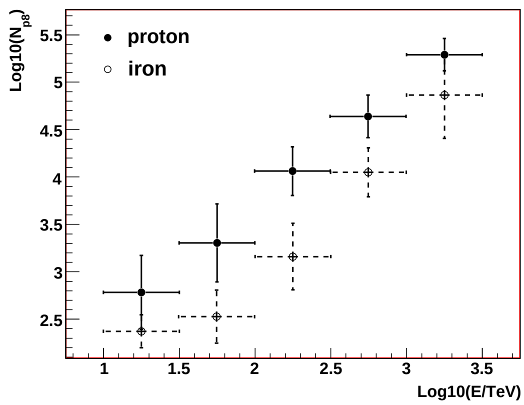

Figure 2: Number of particles detected at ground within a distance of 8 meters from the shower core vs primary energy for proton and iron initiated simulated showers. Vertical error bars show the r.m.s. values of the N_{p8} distributions, while horizontal ones refer to the adopted energy bins.

them N_{p8}, the number of particles 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.2 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.

Given the full coverage and the high granularity offered by the experimental setup, a unique opportunity is given for the study of the Lateral Distribution Function (LDF) of the detected particles near the core position at ground. A first check has been made that the LDF is not affected by the systematics introduced by the used hadronic interaction models. As can be seen in Fig.3, the reconstructed LDF obtained with QGSJET-II and SIBYLL-2.1 are quite similar,

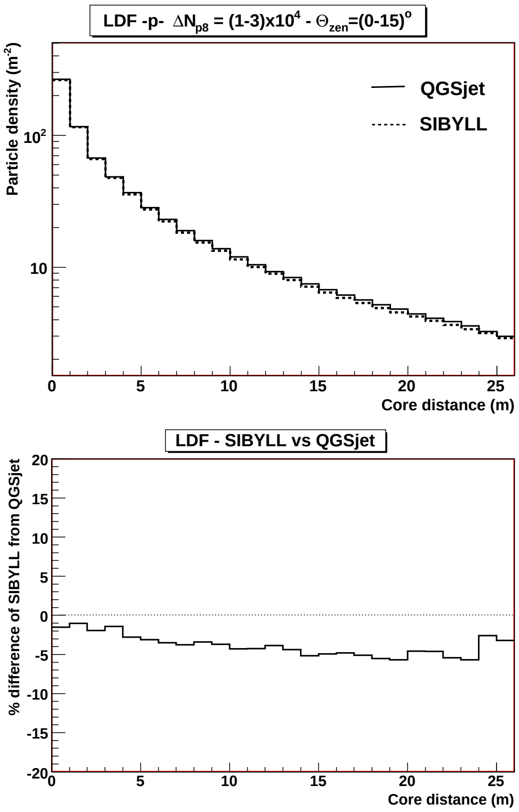

Figure 3: Reconstructed LDF of the detected particles around the core position at ground for simulated proton initiated showers with $10^4 < N_{p8} < 3 \cdot 10^4$. The particle densities obtained with QGSJET-II and SYBILL are shown in the upper panel, while the percentage deviation among the two models is given in the lower one.

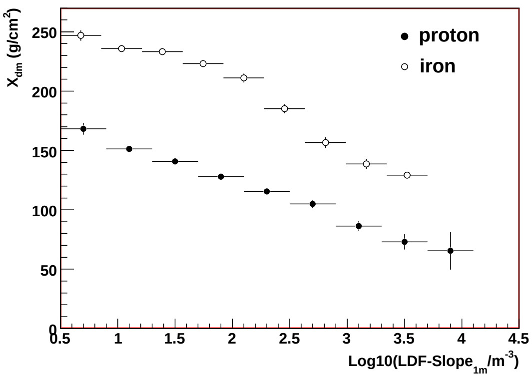

Figure 4: The distance (grammage) of the shower maximum from the detection level, X_{dm}, as a function of the LDF slope at 1 meter from the core for proton and iron initiated showers with $N_{p8} > 10^3$.

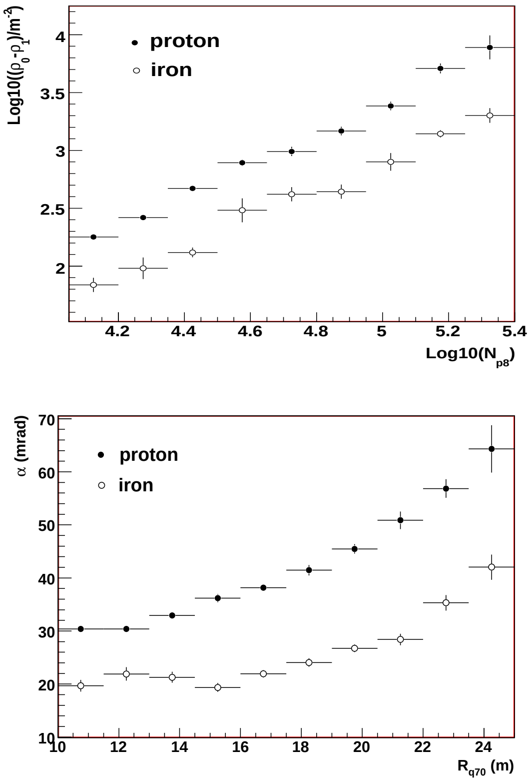

Figure 5: *Upper panel*: Difference between ρ_0 and ρ_1 as a function of N_{p8}. *Lower panel*: The curvature parameter α as a function of R_{q70} for events with $N_{p8} > 10^3$. Both plots refer to simulated proton and iron initiated showers.

their difference being within few percent, as expected in this energy range [8]. A relevant correlation was found between the LDF slope at a given distance from the core and the shower age. The distance (grammage) of the shower maximum from the detection level, X_{dm}, is shown in Fig.4 as a function of the reconstructed LDF slope at 1 meter from the core for proton and iron initiated showers. As can be seen, the LDF slope values can be used to select shower ages in a given interval. This is particularly promising for the extension of proton-air cross section measurement to larger energies [4].

For the same purpose (and of course for composition studies), it is important to find some observable quantities that are related to the primary mass and might be used to select proton enriched samples in the experimental data. In Fig.5 *upper panel*, the difference of the reconstructed particle densities ρ_0 and ρ_1 is reported as a function of N_{p8} for simulated proton and iron initiated showers. Here and in the following, ρ_k is defined as the average particle density at ground as measured between k and $k+1$ meters from the core. Useful information also come from the time structure of the shower front. As discussed in [9] its curvature can be quantified in terms of an angle α, which is equal to zero for a flat front. It is shown in Fig.5 *lower panel* 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

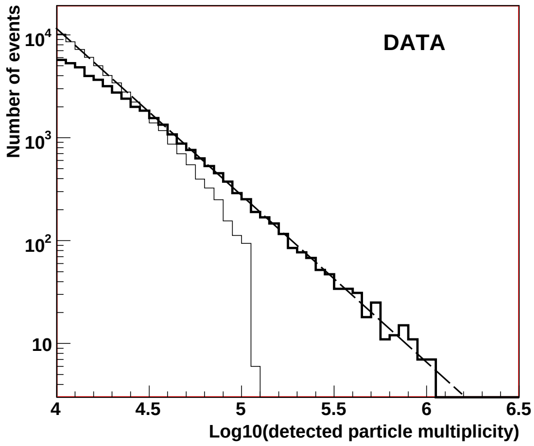

Figure 6: Experimental distribution of the number of particles detected at ground, by using the strip (thin line) or the analog RPC charge (thick line) information. A power law fitting the two spectra in the proper range is also superimposed (dashed line).

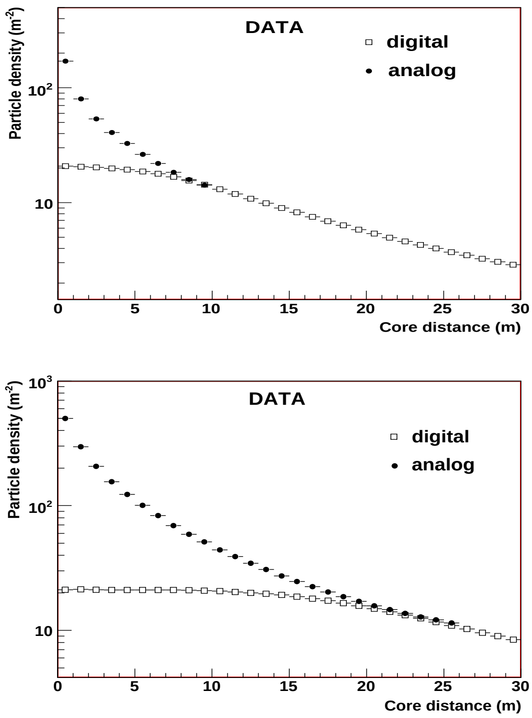

Figure 7: LDF from experimental data sample with $10^4 < N_{p8} < 3{\cdot}10^4$ (*upper panel*) and $5{\cdot}10^4 < N_{p8} < 10^5$ (*lower panel*). The particle density has been measured in *digital* mode up to about 20/m^2 and then by using the analog RPC readout for larger values.

(by using the RPC charge readout). As can be seen mass separation can be feasible on the basis of these variables.

The total trigger rate of ARGO-YBJ working in $digital$ $mode$ is of about 3.5 kHz with a threshold of at least 20 fired pads on the inner carpet. The analog RPC read out system has been conceived and designed to extend the detector sensitivity up to primary energy range in the few PeV region starting from about few tens of TeV. The measured trigger rate of *analog* events is at the level of about 8 Hz. A data sample of about $3.5{\cdot}10^6$ events has been analyzed. The same aforementioned cuts on the reconstructed zenith angle and core position have then been applied to experimental data, resulting in a data sample of about $5{\cdot}10^5$ events. In Fig.6 the experimental distribution of the number of particles detected at ground is shown. In the two corresponding ranges, the information coming from the strips and the analog RPC charge has been used. As can be seen the two systems agree fairly well and the estimated particle multiplicity spectra can be fitted with a single power law. This gives a further check on the analog RPC charge calibration procedure, which accounts for both detector and electronics response and is fully described in [10].

The experimental LDF is then shown in Fig.7 for two data samples in two different N_{p8} intervals and for events with recostructed core position in the 48×48 inner RPC clusters. As can be seen the two systems ($analog$ and $digital$ mode) cover a large dynamic range in particle density and the results, even if preliminary, are in fairly good agreement with MonteCarlo predictions (see Fig.3).

3 Conclusions

The analysis of the Aicrc0754.texRGO-YBJ analog RPC charge system has been shown to give interesting information on the space-time distribution of shower particles at ground. In particular, different observables have been identified to be promising tools for the energy and age determinations of the showers, with some sensitivity also to the primary mass. This will allow the extension of the ARGO-YBJ proton-air cross section measurement by more than one order of magnitude in primary energy. Moreover first experimental results, namely particle multiplicity spectra and lateral density functions, are in fair agreement with expectations. These informations allow hadronic interaction studies up to center of mass energy values in the TeV region, where models start to give sizeable different results.

References

[1] C. Bacci et al., Astropart. Phys., 2002, **17** : 151

[2] G. Aielli et al., Nucl. Instr. and Meth. A, 2006, **562** : 92

[3] P. Creti et al., Proc. of 29th ICRC, Pune, 2005, **8** : 97

[4] G. Aielli et al., Phys. Rev. D, 2009, **80** : 092004

[5] J.R. Hörandel, Astropart. Phys., 2003, **19** : 193

[6] S. Ostapchenko, Nucl. Phys. B, 2006, **151** : 143

[7] R. Engel et al., Proc. of 26th ICRC, Salt Lake City, (1999) vol.1, pag. 415

[8] R.D. Parsons et al., Astropart. Phys., 2011, **34** : 832

[9] A.K. Calabrese et al., Proc. of 31th ICRC, Lodz, (2009), No.1388

[10] M. Iacovacci et al., these proceedings