Selection of Surviving Primary Protons at 4300 m a.s.l. with the ARGO-YBJ experiment

G. DI SCIASCIO[1] FOR THE ARGO-YBJ COLLABORATION
[1] *INFN, sez. di Napoli, Italy*
giuseppe.disciascio@na.infn.it

Abstract: The primary proton spectrum up to 100 TeV has been investigated by balloon- and satellite-borne instruments. Above this energy range only ground-based air shower arrays can measure the cosmic ray spectrum with a technique moderately sensitive to nuclear composition. An array which exploits the full coverage approach at very high altitude can achieve an energy threshold well below the TeV region, thus allowing, in principle, the calibration of the proton content in the primary cosmic ray flux.

The capability of the ARGO-YBJ experiment, located at the YangBaJing Cosmic Ray Laboratory (4300 m a.s.l., Tibet, P.R. China), in selecting the surviving primary cosmic ray protons is discussed. A procedure looking for quasi-unaccompanied events with a very steep lateral distribution is also presented.

Introduction

Despite large progresses in operating new multi-component Extensive Air Shower (EAS) experiments and in the analysis techniques to infer energy spectra and chemical composition, the key questions concerning the origin of the "knee" in the cosmic ray energy spectrum are still open. In particular, one of the most important questions to be solved is the position of the proton knee (see for example [1] and reference therein). In fact, different experiments have claimed to see a proton knee at different energies: at 10 TeV the MUBEE collaboration [2], at a few hundreds TeV the TIBET-ASγ experiment [3] and at a few PeV the KASCADE [4] and EAS-TOP [5] experiments. In addition, direct measurements carried out in the 100 TeV region by RUNJOB [6] and JACEE [7] do not exhibit any spectral break up to the highest measured energy ($\sim$ 800 TeV). The knowledge of the primary proton spectrum is of great importance to understand the cosmic rays acceleration mechanisms and propagation processes in the Galaxy. A careful measurement of the proton spectrum over a wide range of primary energies (from 0.1 TeV to 10 PeV) using the same method is one of the main tasks of the future cosmic ray experiments.

The energy region up to about 100 TeV has been investigated by balloon- and satellite-borne instruments, and above these energies only ground-based air shower experiments may provide data which have however poor mass resolution. The detection of single hadrons at ground level, strongly related to the surviving primary cosmic ray protons, has been recognized for a long time as a method to investigate the proton spectrum over a large energy range and to derive the total inelastic cross section [8, 9, 10].

The ARGO-YBJ experiment, an air shower array exploiting the full coverage approach at the YangBaJing Cosmic Ray Laboratory (Tibet, P.R. China, 4300 m a.s.l., 606 g/cm^2), offers the unique opportunity to investigate the cosmic ray spectrum over a large energy range (about 3 decades) because of its ability to operate down to a few TeV, thus overlapping the direct measurements, by measuring small size air showers (strip or digital read-out with high spatial granularity) and up to the PeV region by measuring the RPCs charge (analog read-out [11]). In this paper we will discuss how a direct measurement of the primary proton spectrum could be achieved up to the PeV energies with the ARGO-YBJ experiment.

The ”quasi-unaccompanied” events

The ARGO-YBJ detector is constituted by a single layer of RPCs. This carpet has a modular structure, the basic module being a Cluster (7.6×5.7 m^2), divided into 12 RPCs (1.25×2.80 m^2 each). Each chamber is read by 80 strips of 61.8×6.75 cm^2, logically organized in 10 independent pads of 61.8×55.6 cm^2 [12]. The central carpet, constituted by 10×13 clusters with ∼93% of active area, is enclosed by a guard ring partially instrumented (∼40%) in order to improve the identification of external events. The full detector is composed by 154 clusters for a total active surface of ∼6700 m^2. Due to the small pixel size (the space information comes from strips and the time from the pads) the detector is able to image the shower profile with an unprecedented granularity.

The detector is not able to discriminate between different charged particles and to identify charged hadrons. Anyway, the detector granularity and the large continuous area allows to reconstruct in great details small showers produced deep in the atmosphere a few g/cm^2 above the carpet. The idea is to select surviving primary protons that interact only into the last interaction length above the detector, thus producing small showers (”quasi-unaccompanied” events) with a very steep lateral distribution. In fact, a very collimated hadronic jet is produced and the electromagnetic cascade originated by π^0's is at very early stage of development.

The surviving protons arriving at the YangBaJing atmospheric depth suffer an attenuation given by $N_S = N_0 \cdot e^{-606/\lambda(E))}$, where $\lambda(E)$ is the nuclear interaction mean free path. The number of expected events per 1000 m^2·year·sr in the energy range 1 TeV - 1 PeV is shown in Fig.1 compared with the primary protons flux [7]. The flux of protons interacting in the last interaction length above the detector is also reported for comparison. As it can be seen from the figure, about $3 \cdot 10^4$ (500) events/year are expected above 10 (100) TeV.

In order to investigate the phenomenology of small EAS a number of vertical proton-induced showers has been simulated by the Corsika/QGSJet code [13] with the first interaction height fixed at the following value: 4350, 4400, 4500, 4600, 4800, 5000, 5500, 6000, 6500, 7000, 7500, 8000, 9000 m asl, for energies ranging from 1 TeV to 1 PeV. We note

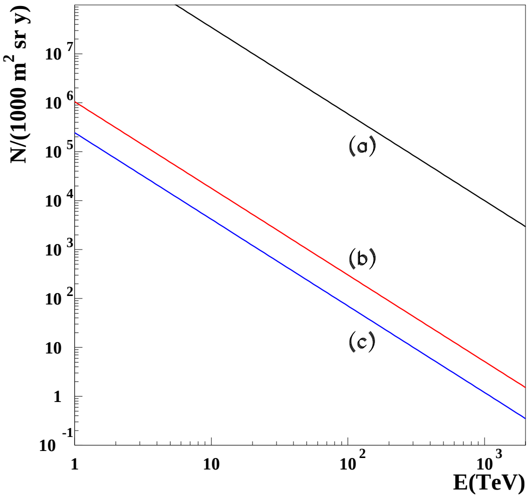

Figure 1: The integral spectrum of surviving primary protons at the YBJ atmospheric depth (c), of protons interacting into the last interaction length (b) and of primary proton flux (a), for 1000 m^2·year·sr.

E	4350	4400	4500	4800	5500
10 TeV	41	57	94	257	1011
10^2 TeV	76	111	203	691	3632
10^3 TeV	139	225	464	1919	13786

Table 1: Mean shower size N_{ch} (= $e^{\pm}+\mu^{\pm}+h^{\pm}$) as a function of the proton energy for different first interaction heights (m asl).

that 4350 m asl corresponds to 603 g/cm^2, 4400 m asl to 599 g/cm^2, 4500 m asl to 591 g/cm^2 and 4800 m asl corresponds to 568 g/cm^2. The shower core positions have been uniformly sampled on a 100×100 m^2 area centred on the detector.

The mean shower sizes for showers induced by vertical protons of different energies are reported in Table 1 as a function of the first interaction height. From these values we can conclude that a first interaction height higher than about 4500 m asl (591 g/cm^2) produces showers too big, indistinguishable from the bulk of extensive showers.

In order to investigate the ”compactness” of the events, the distributions of R_{70}, i.e., the ra-

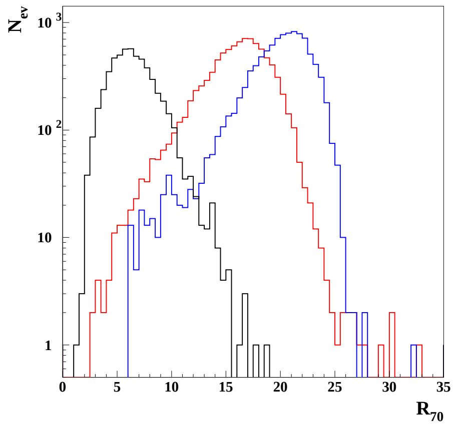

Figure 2: Distribution of the R_{70} parameter for different first interaction heights: 4350 (black), 4800 (red), 5500 (blue) m asl. The proton energy is 100 TeV.

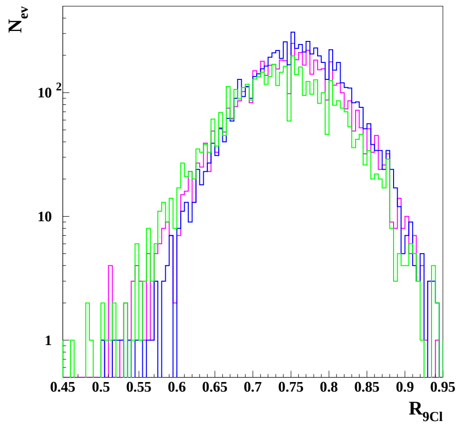

Figure 3: Distributions of the fraction R_{9Cl} of fired strips inside A_{9Cl} for different energies of the primary proton: 10 (green), 100 (red), 1000 (blue) TeV. The first interaction height is 4350 m asl.

dius around the core that contains the 70% of the charged particles, is shown in Fig.2 for 100 TeV proton-induced showers as a function of the first interaction height. As expected, the events produced a few g/cm^2 above the observation level have a lateral extension very reduced being R_{70} <10-15 m. These values show that the radial extension of such a showers is well contained in a matrix constituted by 3×3 Clusters (A_{9Cl} = 22.8×17.1 m^2 ∼390 m^2) around the Cluster which contains the highest strip multiplicity, suggesting to consider the remaining carpet as an anti-coincidence area. In Fig.3 the ratio $R_{9Cl}=N_{9Cl}/N_s$ between the number N_{9Cl} of fired strips inside the 3×3 Cluster matrix and the total number N_s of fired strips is displayed for different energies of protons interacting 4350 m asl. From the figure it results that R_{9Cl} is independent on the primary energy in the range 10 - 1000 TeV. In Fig.4 the distributions of R_{9Cl} for different first interaction heights are shown. As expected, events locally produced consist in very collimated jets with the charged particles totally contained into a few meters around the shower core position. By selecting showers for which R_{9Cl} >0.7 we exclude the contribution of protons interacting above 450 g/cm^2 (∼6500 m asl), i.e. more than about 2 mean free paths above the detector.

The selection procedure

The selection of protons interacting only a few g/cm^2 above the observational level can be performed as follows: (1) selection of events with the cluster with highest particle multiplicity inside the inner 8×11 clusters (A_f ∼3800 m^2) of the central carpet, i.e. we exclude the outer ring constituted by 42 clusters; (2) selection of showers with $R_{9Cl} > 0.7$; (3) the shower core position of the selected events are reconstructed by means of a weighted center of gravity method applied only inside A_{9Cl}; (4) any core lying outside the fiducial area A_f is further rejected. The shower core position resolution of selected events is less than 2 m. In this analysis only events with N_s >30 have been taken into account. From the Table 2 it results that the selection efficiency is rather independent from the energy. With the described procedure only a few percent of protons interacting above 4500 m asl are selected. In Fig.5 the mean particle delays are plotted as a function of the mean fired pad distances from the shower core (a measure of the shower lateral extension) for 100 TeV protons selected with the described procedure. As can be seen, the degree of temporal profile curvature is higher for showers in a earlier stage of development and can be used as a further criterium for the proton selection.

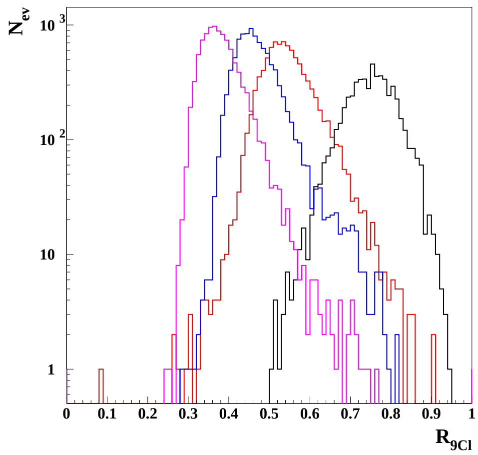

Figure 4: Distributions of R_{9Cl} for different heights of the first interaction point: 4350 (black), 4800 (red), 5500 (blue), 6500 (cyan) m asl. The proton energy is 100 TeV.

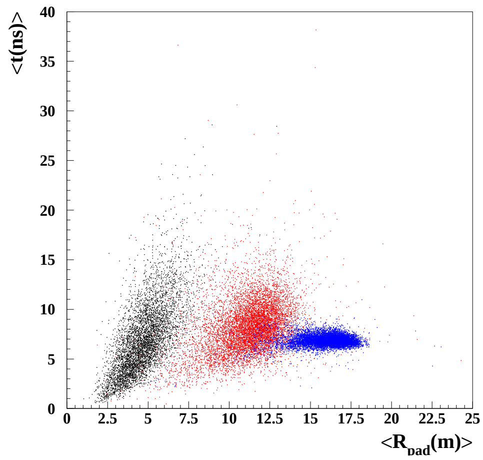

Figure 5: Mean particle delays vs mean fired pad distances from the shower core for 100 TeV protons interacting 4350 (black), 4800 (red), 5500 (blue) m asl.

f.i.h. (m asl)	10 TeV	10^2 TeV	10^3 TeV
4350	72%	80%	84%
4400	34%	41%	42%
4500	12%	12%	11%
4600	6%	6%	4%
4800	3%	2%	2%
5000	2%	1%	0.5%
5500	1%	1%	0.1%

Table 2: Percentage of selected events a function of the proton energy for different first interaction heights (f.i.h.). The values are normalized to the showers with $N_s > 30$.

Conclusions

The selection of surviving primary protons is possible with the ARGO-YBJ experiment by measuring events interacting a few g/cm^2 above the observational level. The granularity of the detector allows to investigate in great details the lateral and temporal features of hadronic jets just produced. Calculations are in progress to evaluate the contribution of heavier primaries and to properly take into account the fluctuations in the shower development. A preliminary data analysis will be presented at the conference.

References

[1] G. Di Sciascio and L. Saggese, ”*Towards a Solution of the Knee Problem with High Altitude Experiments*”, in ”Frontiers in Cosmic Ray Research”, Nova Publishers ed., NY (2007) ch.3, pp. 83-130.

[2] V.I. Zatsepin et al., Proc. 23rd ICRC (Calgary), 2 (1993) 13.

[3] M. Amenomori et al., Phys. Lett. B632 (2006) 58.

[4] H. Ulrich et al., Proc. 27rd ICRC (Hamburg), 1 (2001) 97.

[5] M. Aglietta et al., Astrop. Phys. 21 (2004) 583.

[6] A.V. Apanasenko et al., Astrop. Phys. 16 (2001) 13.

[7] K. Asakimori et al., ApJ 502 (1998) 278.

[8] G.B. Yodh et al., Phys. Rev. Lett. 28 (1972) 1005.

[9] M. Aglietta et al., Astrop. Phys. 19 (2003) 329.

[10] T. Antoni et al., ApJ 612 (2004) 914.

[11] P. Creti et al., 29th ICRC, Pune **8**, 97 (2005).

[12] G. Aielli et al., NIM **A562** 92 (2006).

[13] D. Heck et al., Report **FZKA 6019** Forschungszentrum Karlsruhe (1998).