The light component spectrum measured by the ARGO-YBJ experiment in the energy region 1–300 TeV.

S. M. MARI[1,2], P. MONTINI[1,2] ON BEHALF OF THE ARGO-YBJ COLLABORATION
[1]*Università degli studi Roma TRE - Dipartimento di Fisica*
[2]*INFN - Sezione di Roma TRE*
montini@fis.uniroma3.it

Abstract: The ARGO-YBJ experiment is taking data at the Yangbajing International Cosmic Rays Observatory located at an altitude of about 4300 m a.s.l. (Tibet, P.R. China). The detector consists of an EAS array made of a full coverage RPCs carpet. In this paper the light component cosmic ray spectrum in the energy region 1–300 TeV is presented, these results allow the comparison between satellite and balloon–borne data with ground based measurements. The measured intensities obtained in this work are in good agreement with the recent CREAM measurements and show a spectrum flatter than the low energy measurements.

Keywords: Cosmic ray, EAS, energy spectrum

1 Introduction

The cosmic ray spectrum spans a huge energy interval, up to 10^{20} eV or more. Taking into account the very low intensity of the cosmic ray flux at energies $\geq 10^{14}$ eV, only ground–based experiments can provide the necessary large collecting area. Ground–based experiments detect showers of secondary particles (EASs) produced in the interaction between cosmic rays and atmospheric nuclei. Measurements made with ground–based experiments rely on the Monte Carlo simulations necessary to unfold the primary energy spectrum and composition from the EASs data. Direct measurements with balloon–borne and satellite detectors can provide informations about the spectrum and composition. Due to small detector size and reduced exposure time this kind of experiments are not suitable to investigate cosmic rays with energy $> 10^{15}$ eV. The extension of the ground–based measurements in the low energy region can provide a better understanding of the comparison between direct and indirect data.
Cosmic ray physics in the energy range $1 - 300$ TeV is one of the main goals of the ARGO–YBJ experiment [1, 2, 3]. The experiment is located in the Yangbajing International Cosmic Ray Observatory (Tibet, P.R. China) at an altitude of about 4300 m a.s.l., corresponding to an atmospheric depth of about 606 g cm^2. The experiment consist on a single layer of RPC detectors arranged in a full coverage configuration. The detector is logically divided into 130 clusters (5.72×7.64 m^2) each made by 12 RPCs. Additional 23 clusters forms a guard ring surrounding the central full coverage carpet in order to improve the core reconstruction for external events. Each RPC is read out by using 10 pads (55.6×61.8 cm^2) divided into 8 strips (6.75×61.80 cm^2). This system can provide a single hit time resolution of about 1.8 ns [4], allowing a complete and high resolution reconstruction of the shower front. In order to extend the detector operating range up to energies of about 1 PeV, a system for the analog charge readout of RPCs has been implemented.
In this work the previous measurement [5] of the light component spectrum has been extended to the energy range 1–300 TeV.

2 Data analysis

Since atmospheric showers present large fluctuations in their development, the energy distribution of cosmic rays must be evaluated by using an unfolding procedure that can be dealt with the Bayesian method [6, 7].
The Monte Carlo data sample used in this analysis was produced by the CORSIKA (v 6.9) code including QGSJETII and FLUKA hadronic interaction models. The electromagnetic component was treated by EGS4 routines. The sample was produced in the energy range ($0.1 \div 10^4$) TeV with an energy distribution given by a power law. Showers were sampled at an atmospheric depth of 606 g cm^2, the same of the ARGO-YBJ experiment site. A full detectors simulation was applied. The detector simulation code, based on GEANT3, takes into account backgrounds, calibrations, trigger and RPC's efficiency. Monte Carlo data were processed, reconstructed and analyzed with the same code used for data. The Monte Carlo data sample contains

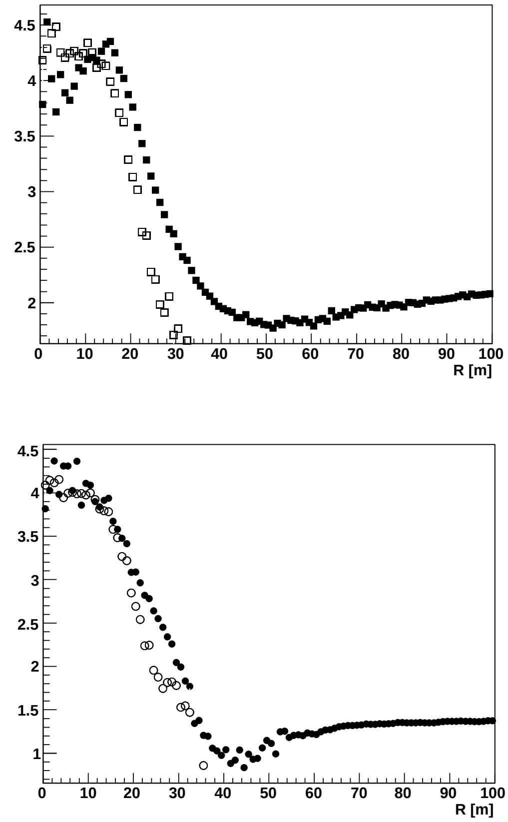

Figure 1: Ratio ρ_{in}/ρ_{out} as a function of the radius R from the detector center for Monte Carlo (filled squares) and data (filled dots). The values of ρ_{in}/ρ_{out} for Monte Carlo (empty squares) and data (empty circles)surviving the selection cuts used in this analysis.

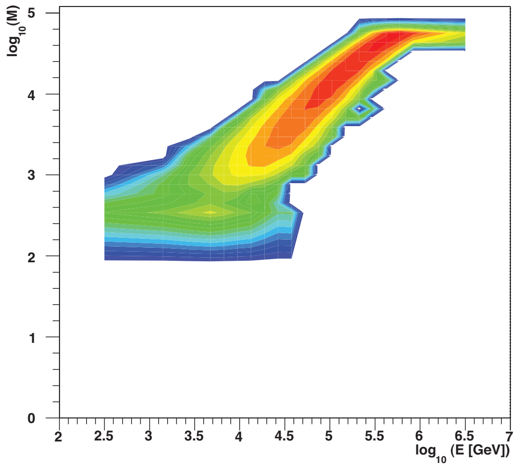

Figure 2: The conditioned probability $P(M|E)$ used in the bayesian unfolding procedure.

only showers produced by protons and helium nuclei because the contribution of the heavier nuclei can be considered negligible [8, 9, 10] and is strongly suppressed by the selection cuts used in this analysis. The data sample used in this analysis was collected by the detector in its full configuration, requiring an inclusive trigger of 20 fired pads in the full coverage area within a time window of 420 ns. The sample was collected in the first 2011 months. A first selection based on the data quality was applied. In order to estimate with good accuracy the probabilities needed in the bayesian unfolding procedure, both data and Monte Carlo events were selected by the following selection criteria.
The events were required to have a reconstructed zenith angle ϑ between 0° and 30°, the Monte Carlo data sample was generated in the range $0^{\circ} - 45^{\circ}$. A selection criteria based on the shower size requires that the strip multiplicity M of each event is in the range $300 \leqslant M \leqslant 65000$. This cut allows the selection of events in an energy range internal to the range $(0.1 \div 10^{4})$ TeV used in the Monte Carlo simulations. The rejection of events with core localized far away from the detector center was obtained by using the following criteria. In the multiplicity range $300 \leqslant M < 500$ a constraint on the particle number measured in the outermost clusters of the detector was required. In the multiplicity range $500 \leqslant M < 50000$ the rejection of external events is achieved by comparing the particle number measured in the outermost clusters (ρ_{out}) with the one measured in the innermost ones (ρ_{in}) and requiring that $\rho_{in} > K \cdot \rho_{out}$ with $K \sim 1.65$. In the multiplicity range $50000 \leqslant M \leqslant 65000$ the reconstructed core position (x_{core}, y_{core}) must be located within a circle of radius $R = 28$ m measured from the detector center. These cuts allow the selection of events with core localized in the central area of the detector. In figure 1 the values of the ratio ρ_{in}/ρ_{out} as a function of the radius R from the detector center are reported for both data and Monte Carlo samples. The selected events are located in a circle of radius $R \approx 30$ m. The plots are obtained with the events selected by using all the cuts described previously.

2.1 The unfolding procedure

According to the bayesian unfolding scheme the selected Monte Carlo data sample was used to compute the conditioned probability. This probability was used in the bayesian unfolding scheme through an iterative procedure. Details on the unfolding procedure can be found in [7, 11]. In figure 2 the values of the conditioned probability $P(M|E)$ are reported. The plot shows a regular behavior of the conditioned probability as expected. In order to unfold the light component spectrum the Monte Carlo events were sorted in 23 multiplicity bins and 10 energy bins. The same multiplicity bins were used to analyze the data. The unfolding procedure was performed on the multiplicity distribution extracted from the data.

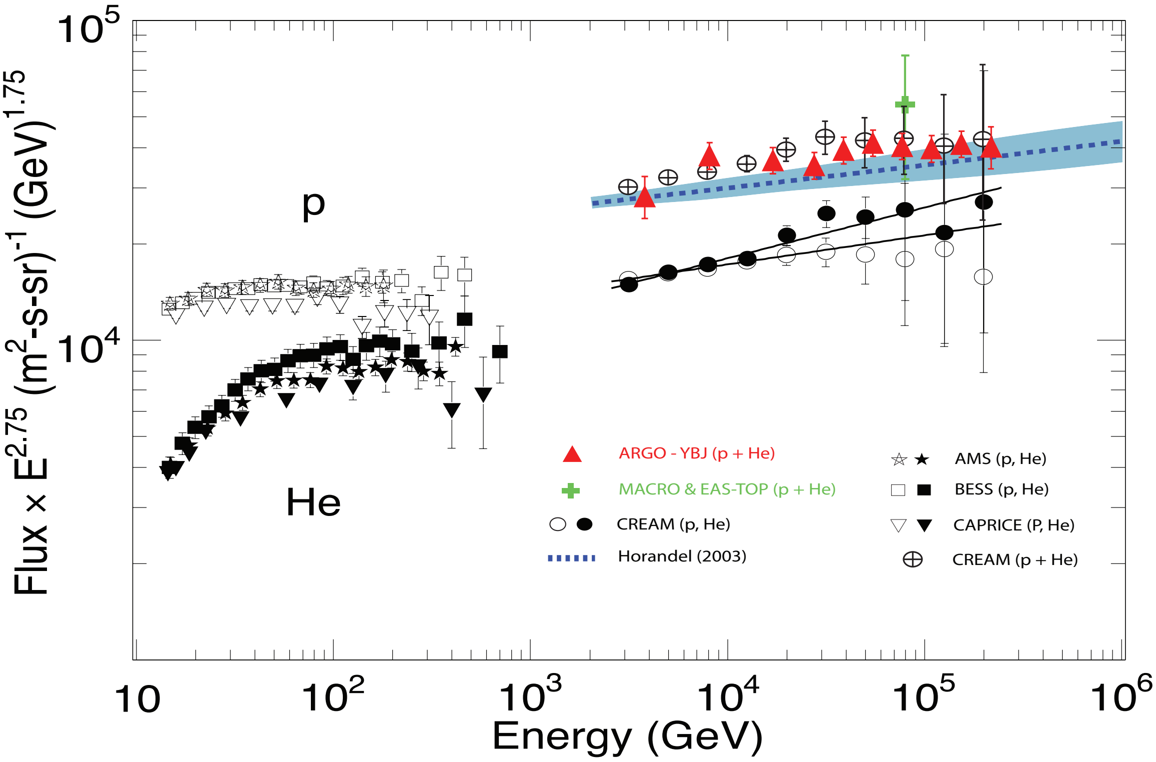

Figure 3: The differential energy spectrum of the light-component (proton and helium) measured by ARGO-YBJ (filled triangles) compared with the proton spectrum (open circles) and helium spectrum (filled circles) measured by the CREAM experiment [12]. The open crosses represent our sum of the proton and helium data measured by CREAM. The dashed line represents the best fit to proton and helium data performed by Hörandel [13]. The spectra measured by AMS (stars), BESS (squares), CAPRICE (inverted triangles) are shown.

3 Results

The results are shown in figure 3. Statistical uncertainties turns out to be less than 1%. The sources of systematical uncertainties considered in this analysis are: effects due to the variation of the selection criteria, reliability of the detector simulation. The uncertainty due to the selection cuts is about 5% for the eight internal bins. An estimate of the uncertainty due to the reliability of the detector response has been estimated by analyzing several runs taken in different detector conditions, it not exceed 4%. The whole result is affected by a systematical uncertainties not exceeding 10%. The measured fluxes at the first energy bin (3,7 TeV) and at the last one (211 TeV) are affected by a systematic uncertainty of about 15% because of the variation of the selection cuts.

4 Conclusions

The ARGO-YBJ experiment is able to sample the front of showers produced by primaries of energy down to a few TeV. In this paper the previous measurement [5] of the intensity of the light component energy spectrum is extended to the energy range $(1 \div 300)$ TeV. A bayesian unfolding technique was applied to the observed multiplicity distribution in order to obtain the values of the spectrum. The whole result is affected by a systematical uncertainties of about 10%. The ARGO-YBJ data are in agreement with recent results from the balloon-borne CREAM experiment.

Acknowledgments

This work is supported in China by NSFC (Contract No. 101201307940), the Chinese Ministry of Science and Technology, the Chinese Academy of Science, the Key Laboratory of Particle Astrophysics, CAS, and in Italy by the Istituto Nazionale di Fisica Nucleare (INFN), and Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR).

References

[1] C. Bacci et al., Nucl. Phys. Proc. Suppl., 1999, **78**: 38
[2] C. Bacci et al., Astropart. Phys., 2002, **17**: 151
[3] G. Aielli et al., Nucl. Instrum. Meth., 2006, **A562**: 92
[4] G. Aielli et al., Nucl. Instrum. Meth., 2009, **A608**: 246
[5] S.M. Mari et al., Proc. ICATPP conference on Cosmic Rays for Particle and Astroparticle Physics, Como, Oct. 2010
[6] G. D'Agostini, Nucl. Instrum. Meth., 1995, **A362**: 487
[7] S. Bussino et al., Astropart. Phys., 2004, **22**: 81

[8] M. Amenomori et al., Ap. J., 2008, **678**: 1165
[9] M. Ave et al, Ap. J., 2008 **678**: 262
[10] A. V. Apanasenko et al., Astropart. Phys, 2001 **16**: 13
[11] S.M. Mari et al. Proc. 31^{st} ICRC, 2009
[12] H. S. Ahn et al., Ap. J. Lett., 2010 **714**: L89
[13] J. R. Hörandel, Astropart. Phys., 2003 **19**: 193