The light component spectrum in the energy region 1-300 TeV measured by ARGO-YBJ with a bayesian approach

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Abstract: The ARGO-YBJ experiment, located at the Yangbajing Cosmic Ray Laboratory (Tibet, China, 4300 m a.s.l.) was in data taking from November 2007 till January 2013, more than 5×10^{11} events have been collected and reconstructed. ARGO-YBJ is a detector with a total detection area of 6700 m^2 consisting of a full-coverage carpet of Resistive Plate Chambers, surrounded by a guard ring designed to improve the reconstruction of events with core falling on the central carpet. Each RPC is equipped with a digital readout system, consisting of 80 copper strips, thus providing a high resolution space-time image of the shower front. The high altitude location and the segmentation of the experiment offer the possibility of measuring the cosmic ray light component spectrum down to the TeV region, where direct balloon-borne measurements are available. An analog readout system, consisting of two large electrodes (big-pad) was also implemented in order to extend the measurement of the cosmic ray flux up to PeV energies. In this work the measurement of the light component (proton plus helium nuclei) spectrum of cosmic rays in the 1-300 TeV energy range is performed by using the data sample collected between January 2008 and December 2011. The analysis has been carried out by applying an unfolding method based on the Bayes Theorem. The light component flux measured in this work is in excellent agreement with the previous ARGO-YBJ measurement obtained in a narrower energy region with a smaller data sample, and with direct measurements in this energy region.

Keywords: Cosmic ray, EAS, light spectrum.

1 Introduction

Cosmic rays are ionized nuclei coming from outside the solar system and reaching the Earth's atmosphere. The interaction between charged particles and the galactic magnetic field randomize the arrival direction, making difficult the identification of the cosmic ray sources. The supernova remnants, however, are able to provide the necessary amount of power in order to accelerate charged particles up to energies of the hundreds TeV. The acceleration in the shock waves of a supernova remnant also provide a simple power–law energy spectrum, in agreement with measurement obtained by different experiments. Despite a great experimental effort several questions about the origin and propagation mechanisms of cosmic rays are still under discussion. A detailed measurement of the energy distribution of cosmic rays could provide several information about production and acceleration mechanisms. Balloon–borne detectors designed to measure the energy and the mass are able to investigate the low–energy region of the spectrum. Due to their reduced acceptance and exposure time, the maximum detectable energy is limited up to few hundreds TeV. Ground–based experiments are designed to detect the extensive air showers produced by the interaction of cosmic rays with Earth's atmosphere and they have a large collecting area in order to investigate the highest energies. Due to large fluctuations in the development of the shower and a lack of a model–independent energy calibration, they rely on Monte Carlo simulations in order to unfold the relevant quantities from the collected data. The extension towards the low energy region of the measurements obtained by ground–based detectors can provide a better understanding of the properties of the cosmic ray spectrum and a cross–calibration between the two different experimental techniques. One of the main scientific goal of the ARGO–YBJ experiment is the measurement of the cosmic ray energy spectrum in the energy range $1 - 5 \times 10^3$ TeV. Due to its characteristics (high altitude, high segmentation, low energy threshold) the ARGO–YBJ experiment can detect showers produced by primaries down to a few TeV, where only direct measurements are available. In this work we present the measurement of the light component spectrum of primary cosmic rays in the energy range $1 - 300$ TeV obtained by using a large data sample collected between Jan. 2008 and Dec. 2011.

2 The ARGO-YBJ experiment

The ARGO–YBJ experiment [1, 2] (Yangbajing International Cosmic Ray Observatory, Tibet, P.R. China. 4300 m a.s.l.) is a full–coverage detector made of a single layer of Resistive Plate Chambers (RPCs) with $\sim 93\%$ active area, surrounded by a partially instrumented guard ring ($\sim 64\%$ active area). The basic detector element is a cluster ($7.6 \times 5.7\,\mathrm{m}^2$) of 12 RPCs ($1.23 \times 2.85\,\mathrm{m}^2$ each). Each RPC is read out by 80 strips ($6.75 \times 61.80\,\mathrm{cm}^2$ each) logically arranged in 10 pads ($55.6 \times 61.8\,\mathrm{cm}^2$). The signals of the 18360 pads and 146880 strips are the experimental output of the detector. The central carpet is made of 130 clusters and the full detector is composed of 153 clusters for a total active area of about $6700\,\mathrm{m}^2$. The RPCs are operated in streamer mode with an overall efficiency of about 96 % and a time resolution of about 1.8 ns [2]. A simple trigger logic requiring a number of fired pads $N_{Pad} \geqslant N_{Trig}$ within a time window of 420 ns was implemented. The detector

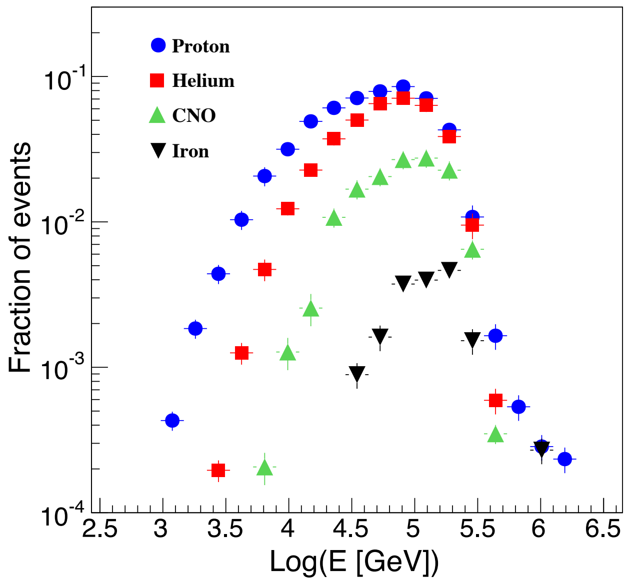

Fig. 1: Fraction of Monte Carlo events selected by the criteria described in sect. 3 as a function of the primary energy. Protons (blue dots) Helium (red squares), CNO nuclei (green triangles) and Iron (black inverted triangles) are shown.

has been in stable data taking in its full configuration from November 2007 to December 2012 with a trigger threshold $N_{Trig} = 20$, corresponding to a trigger rate of about 3.6 kHz and a dead time of about 4%. In order to extend the detector operating range to investigate energies up to the PeV region, each RPC has been equipped with two large size electrodes ($139 \times 123\,\mathrm{cm}^2$) called Big Pads [3], which provide an analog signal whose amplitude is proportional to the number of charged particles hitting the detector. The analog readout system allows a detailed measurement of showers with particle density up to $\sim 10^4\,\mathrm{particles/m}^2$.

3 Shower and detector simulations

The development of the shower in the Earth's atmosphere has been simulated by using the CORSIKA (v. 6980) code [4], including the QGSJET-II.03 model [5, 6] and the FLUKA package [7, 8]. The particular choice of the high energy interaction model, as shown in sect. 5 and in [12], has a negligible impact to the total systematic uncertainty. Showers have been generated in the zenith angle range $(0^\circ \div 45^\circ)$ and in the energy range $(0.3 \div 31600)$ TeV with a power–law distribution ($\gamma = -1$) and sampled at the Yangbajing altitude. The resulting CORSIKA showers have been processed by a GEANT3 [9] based code in order to reproduce the detector response. Showers produced by Protons, Helium, CNO and Iron nuclei have been generated. More than 1.7×10^7 events have been simulated for each primary. The simulated showers have been produced in the same format as data and processed via the same reconstruction code.

4 Data analysis

The ARGO–YBJ experiment measures the space–time distribution of the charged particles of the shower front. For each charged particle belonging to the shower front arrival

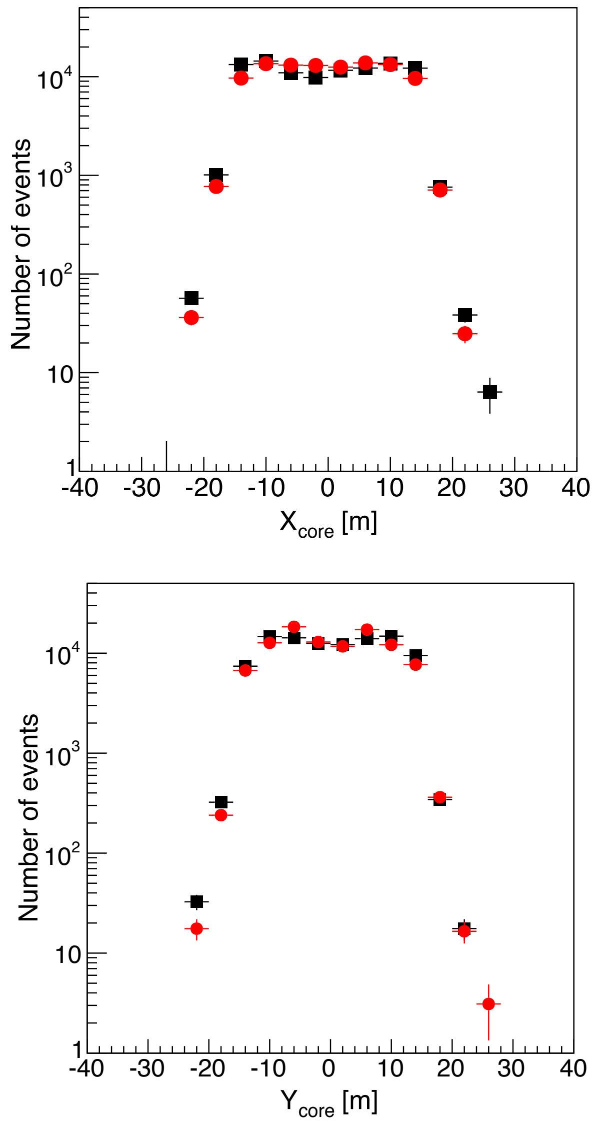

Fig. 2: Distribution of the reconstructed core position coordinates (X_{core}, Y_{core}) for both data (red dots) and Monte Carlo (black squares) samples. For a better comparison, the distributions have been normalized to the same number of events.

time and position are recorded and the main characteristics of the shower are reconstructed. In this work we present the analysis of events collected between January 2008 and December 2011. The measured multiplicity M (i.e. the number of strips fired by charged particles of the detected shower front) cannot be related directly to the primary energy spectrum due to large fluctuations in the development of the shower and in the first interaction point. Extracting the cosmic ray energy spectrum from the observed multiplicity distribution is a classical cause–effect problem that can be dealt by using an unfolding method based on the Bayes theorem. In the Bayesian unfolding method the connection between shower multiplicity and primary energy is achieved by using a probabilistic approach. The conditioned probabilities needed in the unfolding procedure are evaluated by means of a detailed simulation of the shower development and of the detector response. A general description of the procedure is given in [10], a more detailed descrip-

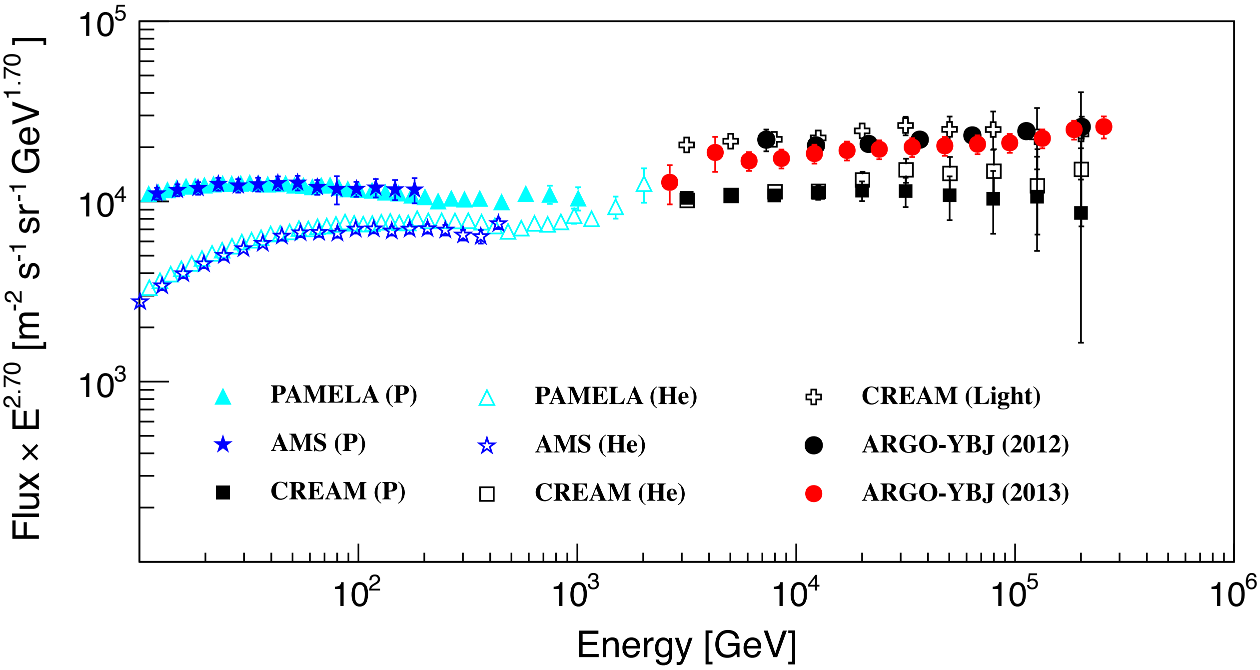

Fig. 3: The light component spectrum measured by the ARGO–YBJ experiment using the 2008–2011 data sample. Results from PAMELA, [14] (blue triangles), AMS[15] (blue stars), CREAM [16] (squares) are shown. The open crosses represent the value of the light component spectrum obtained by combining the proton and helium spectra measured by CREAM. The measurement of the light component spectrum performed by ARGO–YBJ by using a smaller data sample is also reported [12] (black circles).

tion of the unfolding of the cosmic ray spectrum is given in [11, 12]. The conditioned probabilities used in the unfolding procedure have been evaluated by using the Monte Carlo data sample described in section 3. A first selection based on the data and reconstruction quality was applied to the full 2008–2011 data sample: the resulting sample of about 7×10^{10} events, corresponding to more than 5000 hours, was analyzed. In order to obtain an accurate estimation of the bayesian probabilities the following selection criteria were applied to both data and Monte Carlo data samples:

- measured multiplicity $300 \leqslant M \leqslant 50000$
- reconstructed zenith angle $\vartheta \leqslant 35°$
- the position of the cluster with highest multiplicity must be inside an area of about $40 \times 40\,\text{m}^2$ centered on the detector.
- the average particle density measured by the innermost clusters must be greater than the density measured by the outermost clusters.

The cut based on the particle density on the detector surface selects showers with well–shaped core, mainly induced by light primaries and discards events induced by heavy nuclei. The effect of the described selection criteria are shown in figures 1 and 2. In figure 1 the fraction of Monte Carlo events surviving the selection cuts is shown as a function of energy. The fraction of selected Iron nuclei is negligible while the fraction of selected CNO nuclei is reduced by a factor ~ 5 if compared with the fraction of selected Protons and Helium nuclei. Moreover elements heavier than Helium give a minor contribution in this energy region [13]. In figure 2, the distribution of reconstructed X_{core} and Y_{core} are shown for events surviving the selection criteria (red dots for data and black squares for simulation). The plot shows that events falling outside an area of $40 \times 40\,\text{m}^2$ give a negligible contribution. In order to evaluate the probabilities required by the unfolding procedure, the Monte Carlo events were sorted in 16 multiplicity bins and 15 energy bins. The same multiplicity bins were used in the analysis of the experimental data. The bayesian unfolding procedure was performed on the multiplicity distribution extracted from the data sample.

5 The light component spectrum

The values of the light component spectrum are reported in figure 3. Statistical uncertainties have been estimated as less than $\pm 0.1\%$. The systematic uncertainties are essentially due to the following effects:

- impact of the selection criteria used in this analysis
- accuracy of the simulation of the detector response

The contribution to the systematic uncertainties due to the selection cuts, estimated by applying large variations on the selection cuts, is about $\pm 5\%$. The accuracy of the detector response has been checked by comparing several distributions obtained by applying the same selection criteria to both data and Monte Carlo samples. In order to evaluate the contribution to the total systematic uncertainty due to the accuracy of the simulation procedure and to effects related to different run conditions of the detector, the whole data sample has been divided into 25 sub–sample taken in different periods. An estimation of the uncertainty has been obtained by analyzing the 25 sub–samples separately, and turns out to be about $\pm5\%$. Moreover it has been shown in [12] that large variations on the fraction of the helium nuclei used in Monte Carlo simulations give a negligible contribution. The particular choice of the high–energy interaction model used in Monte Carlo simulations gives a very small contribution to the total systematic uncertainty [12]. Total uncertainty is about $\pm10\%$, except for the edge bins.

6 Conclusions

The cosmic ray spectrum in the $1-300$ TeV energy range plays a fundamental role in the understanding of propagation and acceleration mechanisms. The ARGO–YBJ experiment was designed in order to investigate the cosmic ray spectrum in the energy range $1-5\times10^3$ TeV. The peculiar characteristics of the detector (high duty cycle, high segmentation and time resolution, high altitude) allow the detection of showers produced by primaries of energy down to ~1 TeV. The high granularity of the detector allows a detailed measurement of the lateral distribution that can be used in order to discriminate showers mainly produced by light primaries. In this work the ARGO–YBJ data sample consisting of about 4×10^{11} events collected between January 2008 and December 2011 has been analyzed in order to select high–quality events. The resulting sample of about 7×10^{10} events has been used to measure the light component spectrum in the energy range $1-300$ TeV by applying an unfolding procedure based on the Bayes theorem. The present analysis does not allow the determination of the individual proton and helium flux, however it shows a discrepancy with the spectra obtained at lower energies. In particular there is the evidence of a hardening of the spectrum in the energy region $1-300$ TeV, which should be taken into account in cosmic ray propagation and acceleration models. The measured spectrum is in good agreement with previous measurements performed by ARGO–YBJ in a narrower energy region, with a data sample of about 7.5×10^7 events. The resulting spectral index obtained in this analysis ($\gamma=-2.61\pm0.02$) remarkably agrees with ARGO–YBJ previous measurements. The measured spectrum covers a wide energy range and is fairly consistent with balloon–borne observations made by the CREAM experiment.

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