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Observation of a knee in the p+He energy spectrum below 1 PeV by using a bayesian technique for the data analysis of the ARGO-YBJ experiment

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The measurement of the cosmic ray (CR) spectrum plays a fundamental role in the understanding of the production and acceleration mechanisms of high energy CRs. Moreover the determination of the CR composition at energies > 100 TeV could provide a better understanding of the origin of the knee in the all-particle CR spectrum. The ARGO-YBJ experiment is a full coverage air shower detector operated at the Yangbajing international cosmic ray observatory (Tibet, P.R. China, 4300 m a.s.l.) and has been in stable data taking in its full configuration since November 2007 to February 2013. The detector has been designed in order to detect showers produced by primaries of energies down to few Tev up to the PeV region. The high segmentation of the detector allows a detailed measurement of the lateral particle distribution, that can be exploited in order to identify showers produced by light primaries. In this work the measurement of the CR p+He energy spectrum is presented in the energy range 10-3000 TeV. In particular, a bayesian technique has been used for the statistical measurement of the energy spectrum. A deviation from a single power law is clearly evident at energies below 1 PeV. This is in agreement with other two independent analysis of ARGO-YBJ data (one of them also using the Cherenkov signal as measured by a LHAASO telescope prototype), and provides new important inputs to acceleration/propagation models for galactic cosmic rays.

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1. Introduction

Cosmic rays (CRs) are ionized nuclei coming from outside the solar system and reaching the Earth's atmosphere. The sources of CRs cannot be unambiguosly identified since their arrival directions are continously randomized by the interaction with the galactic magnetic field. Supernova Remnants (SNRs), however, are the best candidate sources of galactic CRs, since they can provide the necessary amount of power needed in order to accelerate charged particles up to the highest energies. The CR energy spectrum spans several orders of magnitude both in energy and intensity and it can be roughly described as a single power law with a *knee* at energies of about 3.5 PeV. Despite a great experimental and phenomenological effort, the origin of the knee is still subject of a great debate. In the most common scenario the knee is essentially related to a decrease of the flux of light elements. A detailed measurement of the CR energy spectrum and composition at energies around the knee would therefore be of fundamental importance. All the information about the CR energy spectrum and elemental composition at energies greater than 100 TeV comes from large–area ground–based extensive air shower (EAS) arrays, which are able to detect the cascade of particles produced by the interaction of CRs with the Earth's atmosphere. The determination of the elemental composition of CRs is limited to only large mass groups due to the intrinsic fluctuations of the shower. The energy determination, moreover, relies on the hadronic interaction model used in simulations due the lack of a model–independent energy calibration. The ARGO–YBJ experiment is a full–coverage air shower array which was in stable data taking from November 2007 to February 2013. The detector is equipped with two independent readout systems (digital and analog charge readout) designed in order to detect showers in a very wide range of particle density thus exploring the CR energy spectrum in a wide energy range from few TeV up to $\sim$ 5 PeV. The full–coverage technique, combined with the high segmentation and spacetime resolution, allows a detailed measurement of the lateral distribution of the shower that can be used in order to discriminate events produced by light primaries. In 2012 a first measurement of the CR proton plus helium spectrum has been obtained by analyzing the digital information of a small data sample collected during the first period of data taking with the detector in its full configuration [1]. An extension of this measurement in the energy range 3–300 TeV, obtaned by analyzing the full data sample, has been recently presented [2], demonstrating the great stability of the detector during a long period. Several analysis are under way in the ARGO–YBJ experiment in order to measure the CR energy spectrum by using different approaches: the Analog–Bayesian analysis, the Analog analysis and the Hybrid analysis. In this work we present the measurement of the proton plus helium spectrum in the energy range 10-3000 TeV based on the analysis of the analog charge readout information. In particular a bayesian unfolding technique has been used for the statistical measurement of the CR energy spectrum. A deviation from a single power–law is clearly evident at energies less than 1 PeV.

1.1 The ARGO–YBJ experiment

The ARGO–YBJ experiment [3, 4] is an air shower detector operated at the Yangbajing International Cosmic Ray Observatory (Tibet, P. R. China, 4300 m a.s.l.). The detector takes data by means of a full–coverage ($\sim$ 93% active area) array of 1836 Resistive Plate Chambers (RPCs), logically arranged in 153 clusters of 12 chambers each. Each RPC is equipped with a digital and an analog readout systems working independently in order to explore the CR properties in a wide energy range. The highly–segmented digital readout consists of 146,880 strips and allows the detection of small size showers. The whole system provides a high resolution reconstruction of showers up to $\sim 23\,\mathrm{particles/m^2}$, corresponding to a primary energy of few hundreds TeV. The analog readout system has been designed in order to detect showers produced by primaries of higher energies. Each RPC has been equipped with two large size electrodes each providing a signal proportional to the number of charged particles impinging the detector surface [5, 6]. The whole system can be operated at eight different gain scales (G0, ..., G7) thus extending the detector operating range up to $\sim 5\,\mathrm{PeV}$. Data from the highest gain scale (G7) have been used for calibration purposes. The intermediate gain scale (G4) overlaps with the digital readout data in a wide energy range between 10 and 100 TeV, providing a cross–calibration of the two techniques. Data from lowest gain scales (G1 and G0) allow the detection of showers with more than 10^4 particles/m^2 in the core region. A dedicated calibration procedure has been implemented for each gain scale. The high segmentation of the whole system allows a detailed measurement of the lateral distribution of particles, which can be exploited in order to discriminate among showers produced by primaries of different masses.

2. Data analysis

The determination of the relation between the primary energy and the distribution of the charged particles at ground–level can be easily determined by means of a bayesian unfolding technique [7, 8]. A detailed simulation of the EAS development and the detector response is needed in order to compute the relevant quantities needed in the unfolding procedure. A sample of shower produced by protons, helium, CNO and Iron nuclei has been generated in the energy range (0.316–31600) TeV by using the CORSIKA code [9], including the QGSJET and FLUKA routines in order to respectively describe high and low energy hadronic interactions. Showers were sampled at the Yangbajing altitude and randomly distributed over an area of $250 \times 250\,\mathrm{m}^2$. A full detector simulation based on GEANT3 was then applied on the resulting showers, including noise, RPC efficiency, time resolution effects, etc. As the first step the simulated showers have been analyzed in order to identify an energy estimator and a suitable set of discrimination parameters. The number of particles within 8 m from the core (N_P^{8m}) appears to be a robust energy estimator, not affected by bias effect due to the finite detector size. As described in section 1.1, the analog readout system can be operated at different gain scales. In this work we present the analyses of the data collected by using G4 and G1 gain scales, corresponding to the energy ranges 10-200 TeV and 100-3000 TeV respectively. In order to obtain an unbiased estimation of the relevant quantities used in the unfolding procedure, the following fiducial cuts have been applied to both Monte Carlo and experimental data samples:

1. reconstructed zenith angle within the range $0-35$ degrees
2. reconstructed core position within an area of $40 \times 40\,\mathrm{m}^2$ around the detector center
3. N_P^{8m} within the range $10^3 - 10^5$ and $10^4 - 10^6$ for G4 and G1 respectively

In figure 1 the distribution of N_P^{8m} of the selected events is reported for both G4 and G1 Monte Carlo and experimental data samples. The plot shows a good agreement between experimental data

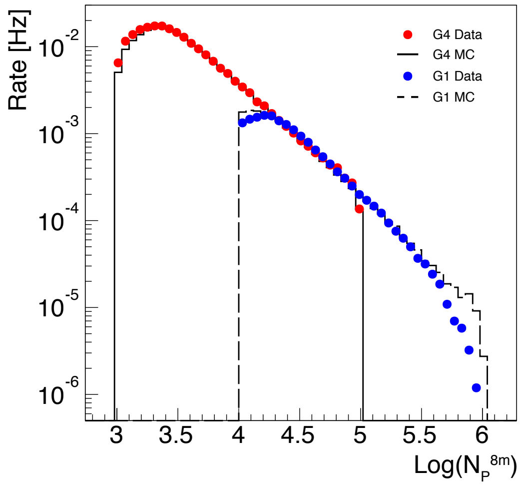

Figure 1: Distribution of N_P^{8m} for G4 and G1 datasets.

and simulations, therefore demonstrating the reliability of the simulation of the detector response. Events of the G4 data sample surviving these selection criteria have been analyzed in order to measure the all–particle spectrum. The high segmentation of the detector allows a high–precision study of the lateral particle distribution at several distances from the core. In showers produced by protons and helium nuclei the highest fraction of particles is localyzed at small distances from the core, while showers initiated by elements heavier than helium have a considerable fraction of particles even at large distance from the core. The ratio between the particle density measured at several distances from the core and the one measured around the core can therefore be exploited in order to identify light primaries. The quantity $\beta = \rho_5/\rho_0$, where ρ_5 and ρ_0 are respectively the particle density measured at $\sim 5\,$m from the core and in a region of $\sim 1\,\text{m}^2$ around the core, has been used as discrimination parameter. In figure 2 the distribution of β is reported for different primaries. The plot shows that a large fraction of protons and helium nuclei have small values of β, demonstrating the possibility of selecting a sample of showers mainly produced by light primaries. A selection criteria based on β was therefore applied to both Monte Carlo and experimental data samples. In figure 3 the energy distributions of events simulated according to the spectra reported in [10] are illustrated. The plot shows that showers surviving the fiducial cuts and the selection criterion based on β described above are essentially produced by light elements.

3. The cosmic ray spectrum

The G4 and G1 data sets have been analyzed in order to measure the N_P^{8m} distribution and the particle densities at different distances from the shower axis, while the Monte Carlo data sample has been used in order to evaluate the probabilities needed in the unfolding procedure. The resulting spectra are shown in figure 4. The all–particle energy spectrum spans the 40–800 TeV energy range, showing a good agreement with the results of other experiments and therefore demonstrating the reliability of the method. The p+He energy spectrum obtained by analyzing the G4 data sample

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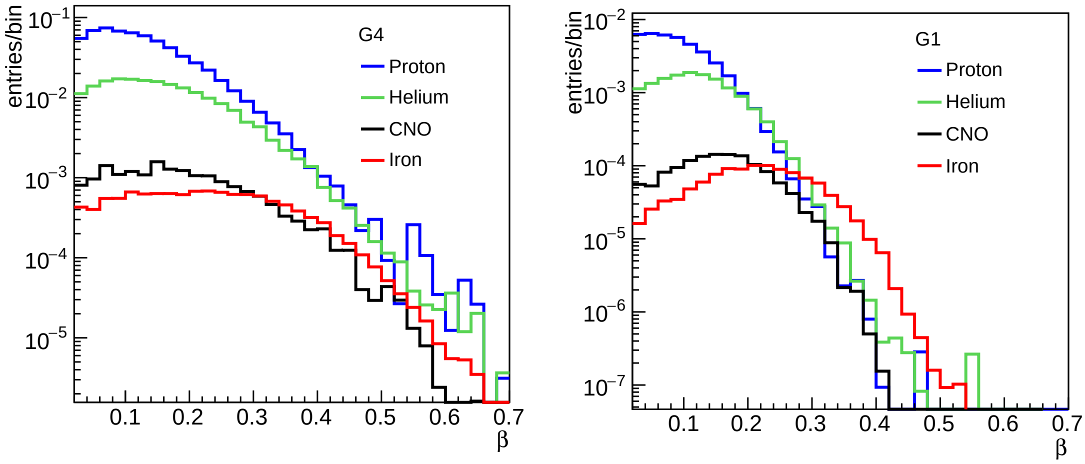

Figure 2: The distribution of the discrimination parameter β for G4 (left) and G1 (right) datasets according to [10]

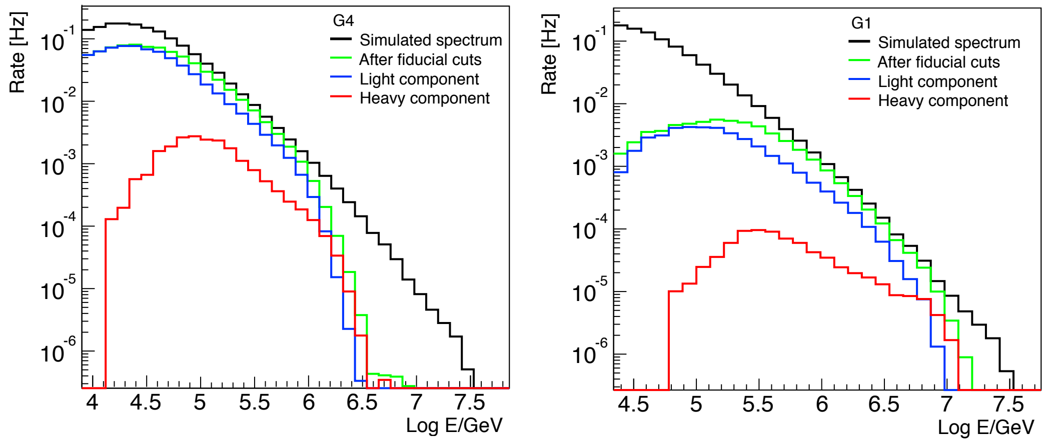

Figure 3: Energy distribution of Monte Carlo events surviving the selection criteria described in section 5 for both G4 (left) and G1 (right) datasets.

spans the energy range between 10 and 150 TeV, overlapping the results obtained by analyzing the digital readout data sample. These results are fairly consistent between each other, both concerning the spectral index and flux intensity, demonstrating the reliability of the response of the analog readout system. The analysis of the G1 dataset extends the energy range of the p+He spectrum up to 3 PeV and shows a deviation from a single power law at energies of about 700 TeV. Both the G4 and G1 results are affected by a systematic uncertainty of about 10%. The G1 results is affected also by a contamination of elements heavier than helium not larger than 10%. This result is consistent with another analysis of the ARGO–YBJ analog data based on an event–by-event energy reconstruction [13]. Moreover this result is also consistent with an *hybrid* analysis combining the information coming from the ARGO–YBJ detector and a wide–FOV Cherenkov telescope [14].

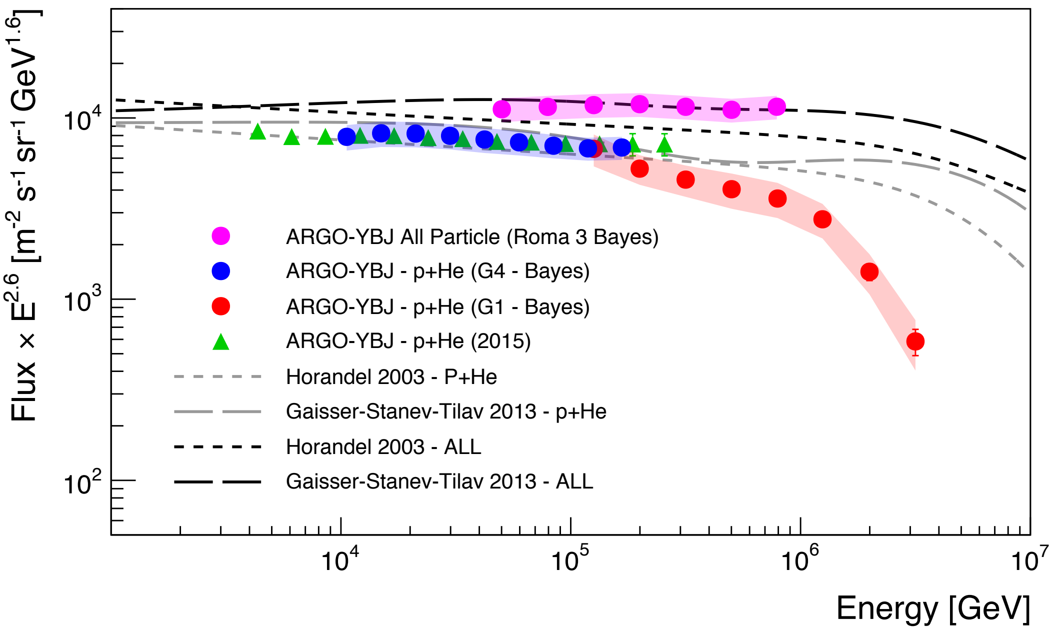

Figure 4: The all–particle and the proton plus helium spectra measured by the ARGO–YBJ experiment. The all–particle spectrum obtained from the analysis of the G4 data sample is shown (pink dots). Values of the p+He spectrum obtained by analyzing the full digital (green triangles), the G4 (blue dots) and G1 (red dots) analog data samples are reported. The shaded area around G4 and G1 values represents the systematic uncertainty. The curves of the proton plus helium spectrum according to the Hörandel (solid line) [10] and GST (dashed line) [12] models are also shown.

4. Conclusions

The ARGO–YBJ experiment has been continuously taking data in its full configuration for more than five years. The detector has been equipped with two independent readout systems in order to explore the cosmic ray energy spectrum in a wide energy range. The analog readout system has been designed and implemented in order to sample showers with about 10^4 particles/m^2 around the core region corresponding to a primary energy up to several PeVs. The analysis of the analog readout data sample has been performed in order to measure the cosmic ray proton plus helium energy spectrum in the (10–3000) TeV energy range and the all–particle spectrum in the 40–800 TeV energy range. The relation between the primary energy and the spacetime distribution of the particles of the shower detected at ground level has been established by using a bayesian unfolding procedure. The discrimination between showers produced by light and heavy primaries has been obtained by using a selection criterion based on the lateral distribution of charged particles in the shower front. The resulting spectrum shows a good agreement with the measurements obtained from the analysis of the digital readout data [1, 2] in a wide energy range between 10 and 150 TeV, thus providing a cross–calibration between the two experimental techniques. A deviation

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from a single power law behaviour of the p+He energy spectrum is clearly evident at about 700 TeV. This is consistent with another two independent analysis of ARGO-YBJ data (one of them using in addition the information coming from a Cherenkov telescope). This result demonstrates the possibility of exploring the cosmic ray properties in a wide energy range with a single ground–based experiment and opens new scenarios about the evolution of the light component energy spectrum towards the highest energies and the origin of the knee.

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