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Observation of a knee in the Cosmic Ray p+He energy spectrum below 1 PeV by ARGO-YBJ

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The Cosmic Ray spectrum has been studied by the ARGO-YBJ experiment in a wide energy range energy (from few TeV up to several PeV). This study is particularly interesting since it allows a better understanding of the so called "knee" of the energy spectrum and of its origin and also provides a powerful cross-check among very different experimental techniques. The unique detector features (full coverage, time resolution, large dynamic range) and location (4300 m a.s.l.) allowed both lowering the energy threshold down to the region covered by direct measurements and reaching the knee of the all-particle spectrum where data from many ground based experiment are available. In addition, the possibility of a detailed study of the distribution of particles detected in the first few meters from the shower axis provided a new and efficient way of selecting events initiated from light mass primaries (i.e. protons and alpha particles), without relying on the muon signal. On the other side, such a study could give new inputs, in the very forward region, to the hadronic interaction models currently used for the investigation of the cosmic ray flux and origin at the highest energies. The resulting all-particle spectrum (measured by ARGO-YBJ in the energy range 80 TeV - 20 PeV) is in good agreement with both theoretical parametrizations and previous measurements, thus validating the selection and reconstruction procedures. The light-component (i.e. p+He) spectrum, measured from 30 TeV up to about 5 PeV, while being consistent with highest energy direct measurements, shows a clear indication of a bending 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

The all-particle cosmic ray (hereafter CR) energy spectrum in the knee region (few PeV) has been investigated by several experiments with different approaches [1]. Below the knee, recent measurements carried out by the balloon-borne CREAM experiment [2,3] show that the proton and helium spectra from 2.5 to 250 TeV are harder compared to lower energy measurements. The structure of the proton and helium spectra and their subtle differences could be clues of the presence of different populations of CR sources contributing to the overall flux and operating in environments with different chemical compositions, as pointed out by several authors [4, 5]. Diffusion effects during CR propagation in the Galaxy might also play an important role.

Towards higher energies, including the knee region, the CR primary spectrum is measured by means of EAS arrays. In this case, mass composition studies are difficult and often affected by large systematic uncertainties. The average composition at the knee is considered to be dominated by light elements, and the knee itself is interpreted as the steepening of the p and He spectra [6]. However, several experimental results suggest a heavier composition at knee energies [7–12].

A measurement of the CR primary energy spectrum (all-particle and light-component) in the $10^{12} \rightarrow 10^{16}$ eV energy range is under way with the ARGO-YBJ experiment (see [13]). In order to cover this very wide energy range, different approaches have been followed:
- *'Digital'* analysis. It is based on the RPC digital readout system (i.e. on the strip multiplicity), and is sensitive in the 3 TeV - 300 TeV range [14, 15].
- *'Analog-LDF'* analysis. It uses the information coming from the RPC analog readout, thus exploring the 30 TeV-20 PeV energy range. The energy is reconstructed on an event-by-event basis by measuring the particle densities (and their lateral distribution) close to the shower axis [16, 17].
- *'Analog-Bayes'* analysis. Same as above but the energy is reconstructed in a complete different way, on a statistical basis, by using a bayesian approach. The selection of light elements (i.e. p+He) is also different, even if based (as in the previous analysis) on the particle lateral distribution [18].
- *'Hybrid'* analysis. It is carried out by combining the data coming from ARGO-YBJ and a wide field of view Cherenkov telescope, exploring the 100 TeV - 3 PeV region [19, 20].

The results concerning the all-particle and the light-component (i.e. p+He) spectra, so far obtained by the aforementioned analyses (in particular the *'Analog-LDF'* one), will be here described.

2. Event reconstruction and measurement of the all-particle spectrum

The RPC charge readout system of the ARGO-YBJ detector allows studying the structure of the particle density distribution in the shower core region up to values of about 10^4/m^2 [28, 29]. The study of the particle lateral distribution, through a lateral density function (LDF), is expected to provide information on the shower longitudinal profile in the atmosphere, that is to estimate its development stage, or the so-called *age*, which is related to X_{max}, the atmospheric depth at which the cascade reaches its maximum size. When observed at a fixed altitude (the detection one), the shower development stage depends on the energy of the interacting primary, while, for fixed energy, it depends on the nature of the primary itself. For this reason, the combined use of the shower energy and age estimations can ensure a sensitivity to the primary mass, thus giving the possibility of selecting a light (p+He) event sample with high efficiency.

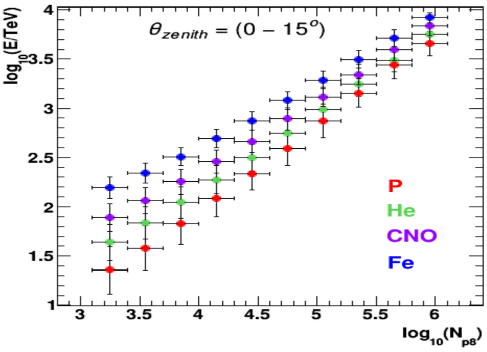

Figure 1: The primary energy as a function of the reconstructed truncated size N_{p8} (within 8 m from the axis) for simulated showers initiated by different primary nuclei.

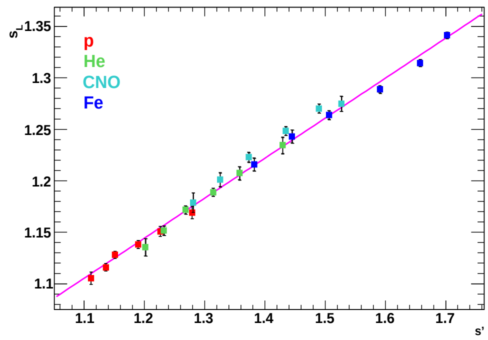

Figure 2: The longitudinal age parameter s_{long} vs the lateral age s' resulting from the fit of the reconstructed LDF, for simulated showers initiated by different primary nuclei (see text).

For the analyses here presented, several air shower samples induced by different primary kinds have been simulated, for a total amount of several millions events in the (10^{12}-10^{16}) eV energy range. The simulated showers were produced by using the *CORSIKA* code [21], with *QGSJET-II.03* [22] as hadronic interaction model, and following the spectra as given in [23], with zenith angle $\theta < 45°$. Randomly sampled in a larger area than the detector surface, such showers were given in input to a *GEANT* [24] based program fully simulating the detector structure and response (including the effects of time resolution, trigger logic, electronics noise, etc.). The Monte Carlo (MC) events triggering the digital and analog readout systems have then been processed by the same reconstruction program used for real data. The events were subsequently selected having the core in a fiducial area contained in the central detector, thus ensuring a good shower reconstruction.

The study of these MC events allowed to identify the truncated size N_{p8}, defined as the number of particles detected within a distance of 8 m from the shower axis, as a suitable estimator of the primary CR energy, since well correlated with E, not biased by effects due to finite detector size, nor dominated by shower to shower fluctuations. Clearly, as shown in Fig.1, the N_{p8} quantity is a mass dependent primary energy estimator parameter. In order to have a mass-independent parameter we fitted the lateral particle distribution of individual showers (up to ten meters from the core) event-by-event, for different N_{p8} intervals and different shower initiating primaries, with a suitable NKG-like LDF [25, 26] to get the shape parameter s' (see [16] for details).

The LDF slope parameter s' plays the role of the so-called *lateral age* [27], as proven by Fig.2, where the average value of the longitudinal shower age parameter $s_{long} \equiv 3X_{det}/(X_{det} + 2X_{max})$, for each simulated primary type and N_{p8} interval, is plotted as a function of the s' value obtained from the fit of each reconstructed event. That figure also expresses an important universality property of the LDF of detected EAS in terms of the lateral shower age, i.e. the shape parameter s' depends only on the development stage of the shower, independently from the nature of the primary particle. Then, the LDF slope s' is a mass-independent estimator of the average s_{long} (or X_{max}).

Moreover, s' from the LDF fit close to the shower axis, together with the measurement of N_{p8}, can give information on the primary particle nature, thus making possible the study of mass composition and the selection of a light-component data sample (see below).

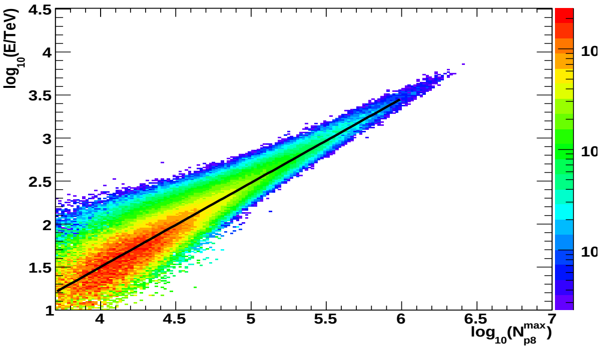

Figure 3: The $log_{10}(E/TeV)$ vs $log_{10}(N^{max}_{p8})$ scatter plot for a simulated mixture of quasi-vertical ($\theta < 15^o$) nuclei, in the assumption of Hörandel composition model. A linear fit is superimposed.

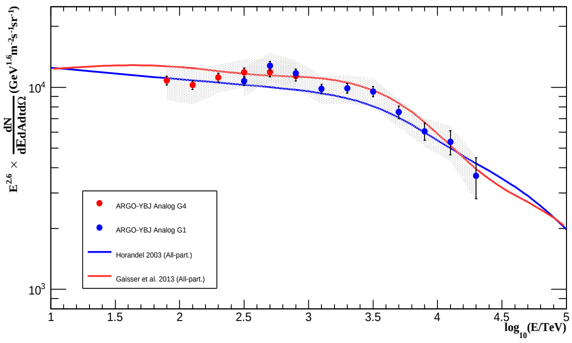

Figure 4: The all-particle energy spectrum of primary CRs resulting from this work. The parametrizations provided by [4] and [23] are shown for comparison.

By assuming an exponential absorption after the shower maximum, we get N^{max}_{p8}, the truncated size at the shower maximum, using N_{p8} and s' measurements for each event and simply correcting with: $N^{max}_{p8} \approx N_{p8} \cdot exp[(h_0 sec\theta - X_{max}(s'))/\lambda_{abs}]$. A suitable choice of the atmosphere absorption lenght λ_{abs} (=100 g/cm^2) allows to get N^{max}_{p8}, a parameter correlated with primary energy in an almost linear and mass independent way (see Fig.3), providing an energy estimator with Log(E/TeV) resolution of 0.10–0.15 (getting better with energy) and Log(E/TeV) bias less than 0.05 [16].

As described in [28], the RPC charge readout system has 8 different and overlapping gain scale settings (G0,....,G7 from smaller to larger gains), in order to explore the particle density range from about 20 up to $\sim 10^4$ particles/m^2. In this analysis, the results obtained with two gain scales (so-called G1 and G4) are presented. The analog system response, for each considered data set and gain scale, has been carefully calibrated by following the procedures fully discussed in [28, 29].

Selecting quasi-vertical events ($\theta < 15°$) with different values of the truncated size N_{p8}, using the above described procedure, we reconstructed the CR all-particle energy spectrum shown in the Fig.4 in the energy range 80 TeV$\rightarrow$ 20 PeV. In the plot the overall systematic uncertainty, due to hadronic interaction models, selection criteria, unfolding algorithms, and aperture calculation, is shown by the shaded area. The statistical uncertainty is shown by the error bars. As can be seen from the figure, spectra obtained by analyzing two different data samples with two different gain settings, actually overlap. The resulting all-particle spectrum is in fair agreement with the parametrizations provided by [4] and [23], showing evidence of a spectral index change at an energy consistent with the knee position. As shown in Fig.7, this result is consistent with previous measurements made by both direct and indirect experiments and is in agreement with another independent analysis of ARGO-YBJ data [30]. It also represents an important check on the absolute energy scale set for this analysis (systematic uncertainty anyhow conservatively estimated at 10%).

3. Measurement of the light-component energy spectrum

For the light-component spectrum measurement, a selection has been made in order to have a sample of p and He initiated showers, with sufficiently high efficiency and low contamination.

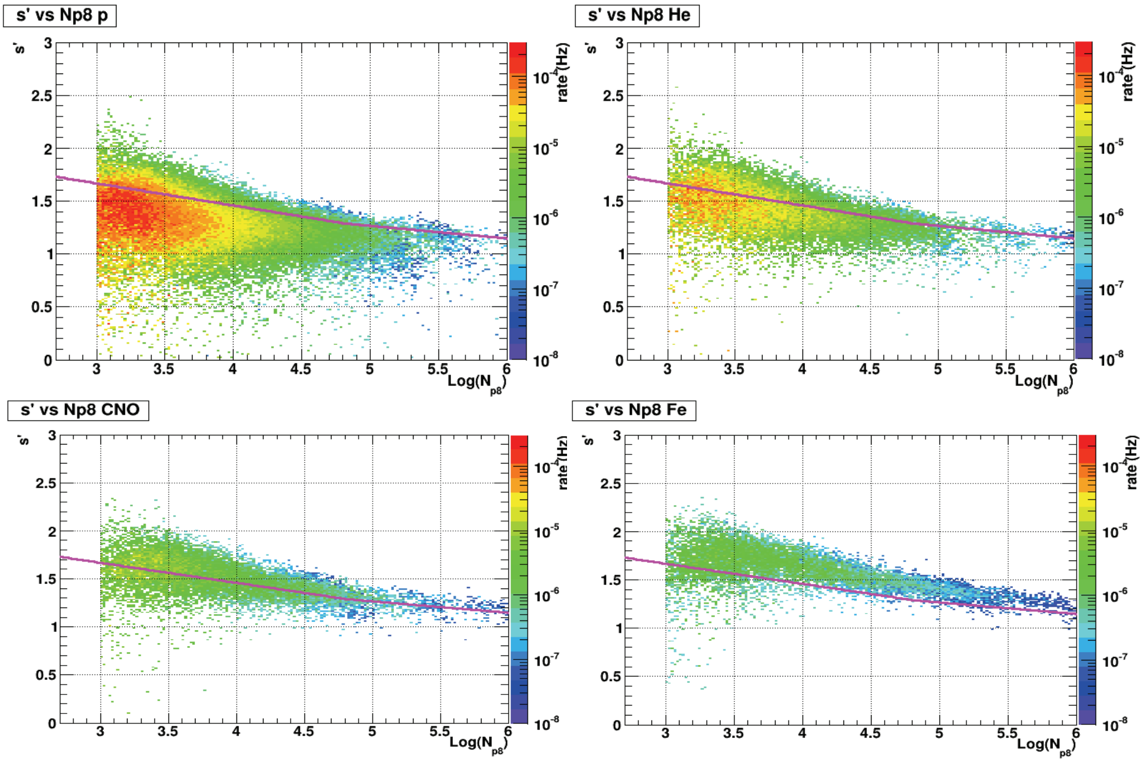

Figure 5: The LDF slope s' as a function of the truncated size N_{p8} as reconstructed for showers initiated by different primaries, as indicated in the upper left labels. The p+He selection cut is shown by the pink line.

In the *'Analog-LDF'* analysis, starting from the initial data set used for the all-particle spectrum measurement, the selection of a sample of showers initiated by light nuclei has been possible on the basis of the simultaneous study of the LDF slope s' and the truncated size N_{p8} (see Sec. 2 and [16]).

In Fig.5 the values of s' are shown as a function of N_{p8}, as reconstructed for different samples of simulated data resulting form EAS initiated by protons, helium, CNO (i.e. Carbon-Nitrogen-Oxigen) group, and iron nuclei. As in the previous plots, the fluxes have been parametrized as in [23], and the full simulation of detector response and analysis procedures has been applied. A different parametrization of the single fluxes, namely [4], gives consistent results within the quoted systematics (see below). The line in the plots shows the cut used in selecting the p+He enriched sample from real data. The efficiency in selecting p and He initiated showers and the heavier elements contamination are at the level of 90% and 10% respectively, with variations of few percent depending on the energy region and the adopted flux parametrizations.

Taking into account these values (and their energy dependence), the p+He flux has been obtained. The result is shown in Fig.6. The systematic uncertainty on the flux is shown by the shaded area and the statistical one by the error bars. A systematic uncertainty on the energy scale at the level of 10% has also been conservatively estimated (not shown in the plots). Moreover we conservatively decided not to subtract the estimated contamination of heavier elements, adding their contribution in the systematic uncertainty on the flux. The parametrizations of the light-component provided by [4] and [23] are shown by the red and blue dashed lines, respectively. A modified version of the fluxes given in [23], with each knee at Z×1 PeV (i.e. about a factor four lower in energy than in the original formulation), is also shown for comparison. As can be seen also from Fig.7, the result is consistent with low energy (direct) measurements and show a clear evidence for a bending at larger energies but starting below 1 PeV.

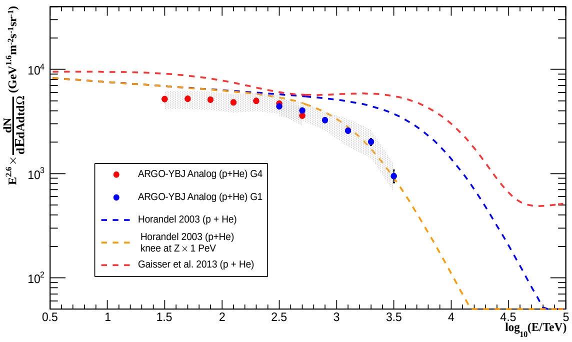

Figure 6: Light (i.e. p+He) component energy spectrum of primary CRs as measured in the analysis of ARGO-YBJ analog data (see text).

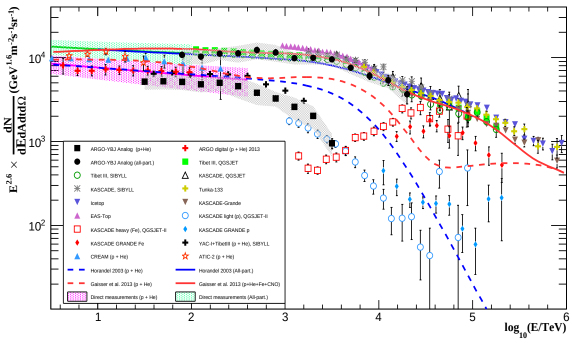

Figure 7: All-particle and light-component energy spectra of primary CRs as measured in this work, compared to several other experimental results.

The evidence for the spectral bending is also given by a different analysis (the *'Analog-Bayes'* one) of the same ARGO-YBJ analog data set, which uses a bayesian unfolding approach for the statistical measurement of the CR energy spectrum, in particular the light-component one (see [15, 18] for the details). Again, the truncated size N_{p8} has been used as shower energy estimator, while the ratio between the particle densities measured respectively at ∼5 m from the axis and in a region of $\sim 1\,m^2$ around the core has been identified as discrimination parameter to select the showers from light primaries. The obtained light component spectrum is shown in Fig.8. Both the G4 and G1 results (separately shown) are affected by a systematic uncertainty of about 10%. The G1 result is also affected by a contamination of elements heavier than helium not larger than 10%.

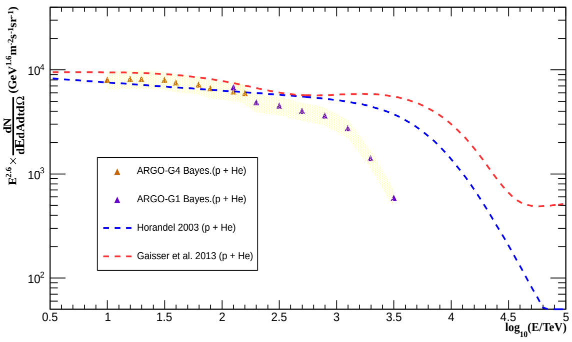

Figure 8: Light component (p+He) energy spectrum of primary CRs as measured from the ARGO-YBJ data using a bayesian unfolding approach.

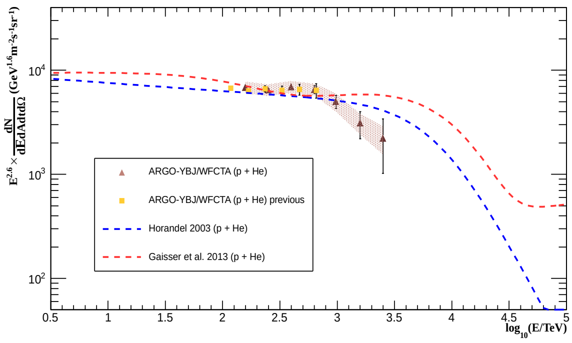

Figure 9: Light component energy spectrum of primary CRs as obtained from a hybrid data set of ARGO-YBJ and a wide FoV Cherenkov telescope.

Moreover, a third analysis (the *'Hybrid'* one) also gives similar results. In this analysis, the energy spectrum of the light component below 3 PeV has been measured using the hybrid data from the ARGO-YBJ detector and a wide field of view Cherenkov telescope. An exhaustive discussion of the analysis method can be found in [19,20]. Here we only outline that in this case the shower energy is reconstructed from the total number of photoelectrons in the shower image recorded by the telescope. The selection of the p+He sample is instead carried out by combining two composition-sensitive parameters: the first is a combination of the number of particles recorded in an event by the most hit RPC of the ARGO-YBJ carpet and the number of photoelectrons in the same event, the other one is related to the geometrical shape of the shower image recorded by the Cherenkov telescope. The light component spectrum of Fig.9 is finally obtained, which also exhibits an evident bending structure with a knee at ∼700 TeV. The overall systematic uncertainty on flux is plotted as a dashed area in the figure. Assuming the Hörandel composition, the contamination of heavy species in this analysis is found to be 13% at ∼1 PeV and gradually increases to 27% around 3 PeV.

The light (p+He) component energy spectra of primary CRs as measured by ARGO-YBJ in three independent analyses are finally summarized and compared in Fig.10. The three analyses are in agreement in revealing a bending of the spectrum below 1 PeV and give consistent results, within the systematic uncertainties and the possible difference in the energy scale of the *'Hybrid'* analysis with respect to the other two.

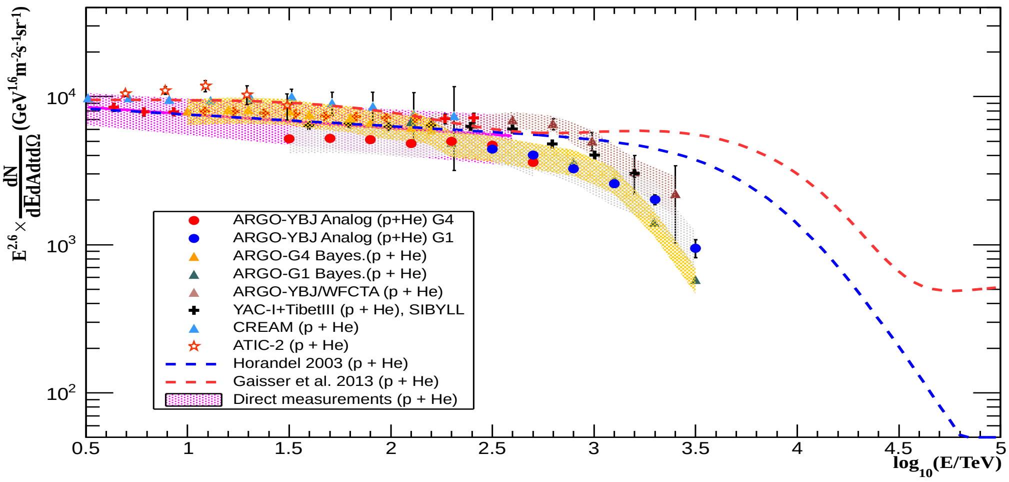

Figure 10: The light (p+He) component energy spectra of primary CRs as measured by ARGO-YBJ in three independent analyses (see text). They are in agreement in revealing a bending of the spectrum below 1 PeV.

4. Conclusions

The CR all-particle and light component (p+He) energy spectra have been measured by the ARGO-YBJ experiment with different approaches. In particular, the results of the analysis technique based on the study of the number of charged particles at ground and the shape of their lateral density distribution within the first ten meters from the shower axis have been reported.

The cosmic ray all-particle spectrum has been measured in the 80 TeV-20 PeV energy region, by using two different data samples taken with two different gain settings of the RPC analog readout system. The results are in agreement with previous observations from both direct and indirect experiments, thus validating the analysis strategy and the event reconstruction procedures.

Suitable selections of the light-component (i.e. protons and helium nuclei) have then been applied and its energy spectrum has been measured from 30 TeV up to 3 PeV. Three independent analyses of ARGO-YBJ data (one of them using in addition the information coming from a Cherenkov telescope) give consistent results: a clear indication of a bending below 1 PeV is observed.

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