PROCEEDINGS OF SCIENCE

Highlights on Cosmic Ray Physics from ARGO-YBJ

G. Di Sciascio* **on behalf of the ARGO-YBJ Collaboration**
INFN - Roma Tor Vergata, Roma, Italy
E-mail: disciascio@roma2.infn.it

The primary cosmic ray (CR) energy spectrum extends up to about 10^{20} eV showing different features, the most important one being the so-called "knee", a small downwards bend at about 3×10^{15} eV. Despite large progresses in building multi-component Extensive Air Shower (EAS) experiments and in the analysis techniques to infer energy spectra and chemical composition, the experimental results in the knee energy region are still conflicting and the key questions concerning its origin are still open. The key component for understanding the origin of the knee, the Galactic CRs acceleration mechanisms and to investigate the transition from Galactic to extra-galactic CRs, is the determination of the maximum energy at which protons are accelerated in CR sources, i.e. the *'proton knee'*. A large number of theoretical papers discussed the highest energies achievable in SNRs and the possibility that protons can be accelerated up to PeVs (for a recent review see [1] and references therein).
The origin of the all-particle knee can be investigated also with the study of diffuse gamma-ray emission. This radiation is the sum of contributions from several components: the truly diffuse Galactic gamma-rays produced by the interaction of CRs, the extragalactic background and the contribution from undetected and faint Galactic γ-ray sources. The spectrum of this radiation may provide insight into the propagation and confinement in the Galaxy of the parent CRs, their source distribution and their spectrum at the acceleration sites. In particular, it provides direct information on the CR spectrum in various locations in the Galaxy which is needed to understand the origin of CRs in the knee energy region.

Aiming to face the open problems in Galactic cosmic ray physics through a combined study of photon- and charged particle-induced EASs with the same detector, ARGO-YBJ has been in stable data taking for more than 5 years at the YangBaJing Cosmic Ray Observatory (Tibet, P.R. China, 4300m a.s.l., 606 g/cm^2). In this paper we report on a measurement of the CR primary energy spectrum (all-particle and light component) in the energy range few TeV – 10 PeV and a study of the diffuse gamma-rays in different locations of the Galactic Plane.

XI Multifrequency Behaviour of High Energy Cosmic Sources Workshop,
25-30 May 2015
Palermo, Italy

*Speaker.

1. The ARGO-YBJ experiment

The ARGO-YBJ detector is constituted by a central carpet $\sim$74$\times$78 m^2, made of a single layer of resistive plate chambers (RPCs) with $\sim$93% of active area, enclosed by a rectangular 'guard ring' partially instrumented ($\sim$20%) up to $\sim$100$\times$110 m^2. The apparatus has a modular structure, the basic data acquisition element being a cluster (5.7$\times$7.6 m^2), made of 12 RPCs (2.85$\times$1.23 m^2 each). Each chamber is read by 80 external strips of 6.75$\times$61.80 cm^2 (the spatial pixels), logically organized in 10 independent pads of 55.6$\times$61.8 cm^2 which represent the time pixels of the detector [2]. The readout of 18,360 pads and 146,880 strips is the experimental output of the detector (the *'digital'* readout). Because of the small pixel size, the detector is able to record events with a particle density exceeding 0.003 particles m^{-2}, keeping good linearity up to a core density of about 15 particles m^{-2}. In order to extend the dynamical range up to PeV energies, each chamber is equipped with two large size pads (139$\times$123 cm^2) to collect the total charge developed by the particles hitting the detector [3]. The RPC charge readout allows to study the structure of the particle density distribution in the shower core region up to particle densities of about 10^4 m^{-2} (the *'analog'* readout). With a duty-cycle greater than 86% the detector collected about 5$\times$10^{11} events acting simultaneously as a wide aperture ($\sim$1.5 sr), continuosly-operated γ-ray telescope at sub-TeV – TeV photon energies and as a high resolution cosmic ray detector in the broad energy range between 4 TeV and 10 PeV.

2. Measurement of the Cosmic Ray Energy spectrum

A measurement of the CR primary energy spectrum (all-particle and light nuclei component) is under way with ARGO-YBJ in the wide energy range from few TeV up to about 10 PeV exploiting different approaches:

- *'Digital-Bayes' analysis*, based on the strip multiplicity, i.e. the picture of the EAS provided by the strip/pad system, in the few TeV – 300 TeV energy range. The selection of light elements (i.e. p+He) is based on the particle lateral distribution. The energy is reconstructed, on a statistical basis, by using a bayesian approach [4, 5].

- *'Analog-Bayes' analysis*, based on the RPC charge readout, covers the 30 TeV – 10 PeV energy range. The selection criteria used below 300 TeV have been adapted to this energy range. The energy is reconstructed (as in the previous analysis), on a statistical basis, by using a bayesian approach [6].

- *'Analog' analysis*, based as above on the RPC charge readout. The energy is reconstructed on an event-by-event basis by measuring the particle densities (and their lateral distribution) in the shower core region. The selection of light elements is different, also if based (as in the previous analyses) on the particle lateral distribution [7].

- *'Hybrid measurement'*, carried out by ARGO-YBJ and a wide field of view Cherenkov telescope, in the 100 TeV - 3 PeV region. The selection of (p+He)-originated showers is based on the shape of the Cherenkov image and on the particle density in the core region measured by the ARGO-YBJ central carpet [8, 9].

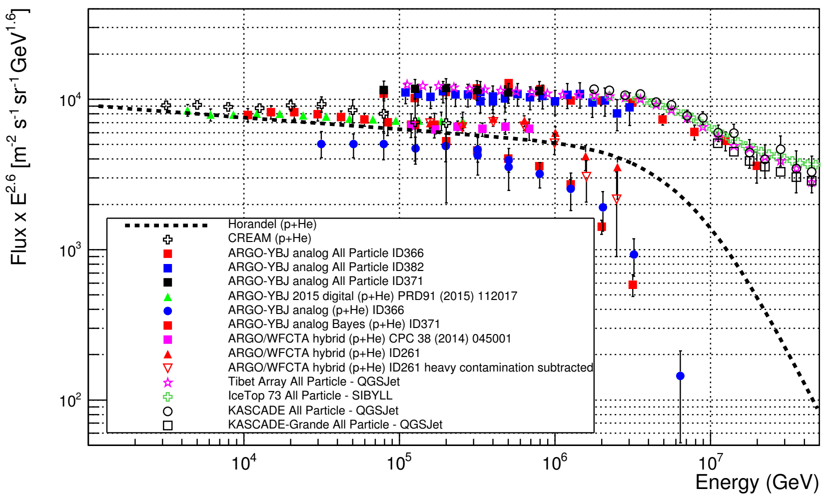

Figure 1: All-particle and light (p+He) component energy spectra of primary CRs measured by ARGO-YBJ. Data analyzed with different techniques are compared. The statistical uncertainty is shown by the error bars. For comparison all-particle spectra measured by other experiments (Tibet Array, IceTop 73, KASCADE, KASCADE-Grande) are shown. Light component data are compared with the results obtained by the CREAM satellite and with a widely used parametrization of the experimental data (dashed line) [13].

In the ARGO-YBJ experiment the selection of (p+He)-originated showers is performed not by means of an unfolding procedure after the measurement of electronic and muonic sizes, but on an event-by-event basis exploiting showers topology, i.e. the lateral distribution of charged secondary particles. This approach is made possible by the full coverage of the central carpet (92% active area), the high segmentation of the read-out and the high altitude location of the experiment that retains the characteristics of showers lateral distribution in the core region.

2.1 All-particle spectrum of Cosmic Rays

The measurement of the energy spectrum of the CR total flux (the so-called all-particle spectrum) up to about 10 PeV has been carried out exploiting the RPC charge readout [3]. The all-particle energy spectra measured by ARGO-YBJ by reconstructing showers with three different approaches [6, 7, 10] are shown in the Fig. 1. The statistical uncertainty is shown by the error bars. A systematic uncertainty, due to hadronic interaction models, selection criteria, unfolding algorithms, aperture calculation and energy scale, of $\pm 15\%$ is estimated. The ARGO-YBJ all-particle spectrum clearly shows a knee-like structure at few PeVs in fair agreement with the results obtained by Tibet Array, IceTop-73, KASCADE and KASCADE-Grande experiments.

2.2 Light component (p+He) energy spectrum of Cosmic Rays

As described in [4, 5], by using the read-out provided by the strip/pad system and applying a selection criterion based on the particle density to quasi-vertical showers ($\theta < 35°$), a sample of events induced by p and He nuclei, with the shower core well inside the ARGO-YBJ central carpet, has been selected. The contamination by heavier nuclei is found negligible. An unfolding technique based on the bayesian approach has been applied to the strip multiplicity distribution in order to obtain the differential energy spectrum of the light component.

The spectrum measured by ARGO-YBJ with the digital read-out in the few TeV – 300 TeV energy range is shown in Fig. 1 (green triangles). Data agree remarkably well with the values obtained by adding up the p and He fluxes measured by CREAM both concerning the total intensities and the spectral index [11]. The value of the spectral index of the power-law fit to the ARGO-YBJ data is -2.64±0.01 [5]. ARGO-YBJ is the only ground-based experiment that overlaps with the direct measurements for more than two energy decades.

In order to extend the measurement of the light component to PeVs two different read-outs are used. With the analog one the selection of (p+He)-induced showers is carried out on an event-by-event basis exploiting the lateral distribution of charged secondary particles in the shower core region [6, 7]. In the hybrid measurement two mass-dependent parameters are defined to select the light component: the shape of the Cherenkov footprint of showers reconstructed by a wide field of view telescope and the particle density in the core measured by ARGO-YBJ [8, 9]. The energy of the primary particle is reconstructed both by an unfolding procedure [6] or on an event-by-event basis [7, 8, 9].

The resulting light component energy spectra are shown in the Fig. 1. The results are consistent for what concern spectral index and absolute flux with the measurements carried out by ARGO-YBJ below 300 TeV and by CREAM. The flux difference with CREAM is about 10% and can be explained with a difference in the experiments energy scale at level of 5%.

The calibration of the absolute energy scale is one of the main problems of ground-based esperiments. The low energy threshold of ARGO-YBJ allowed to calibrate the relation shower size - primary energy at 10% level below 30 TeV [12], exploiting the measurement of the west-ward displacement of the Moon shadow under the effect of the geomagnetic field as a function of the event multiplicity. Above this energy the overposition with CREAM provides a solid anchorage of the absolute energy scale at a few percent level.

As can be seen, all different analyses show evidence of a knee-like structure in the (p+He) spectrum starting from about 650 TeV, well below the all-particle spectrum knee confirmed by ARGO-YBJ at ∼3 PeV, in disagreement with widely used parametrizations as the Horandel polygonato model (dashed line) [13] .

Table 1: Diffuse gamma-ray emission from the Galactic plane for $|b| < 5°$.

Locations	Statistical Significance	Spectral Index
$25° < l < 100°$	6.9 s.d.	-2.80 ± 0.26
$40° < l < 100°$	6.1 s.d.	-2.90 ± 0.31
$65° < l < 85°$	4.1 s.d.	-2.65 ± 0.44
$25° < l < 65°$ & $85° < l < 100°$	5.6 s.d.	-2.89 ± 0.33

3. Diffuse Gamma-Ray emission from the Galactic Plane

More than $2 \cdot 10^{10}$ showers have been observed by ARGO-YBJ in 5.3 years of data collection

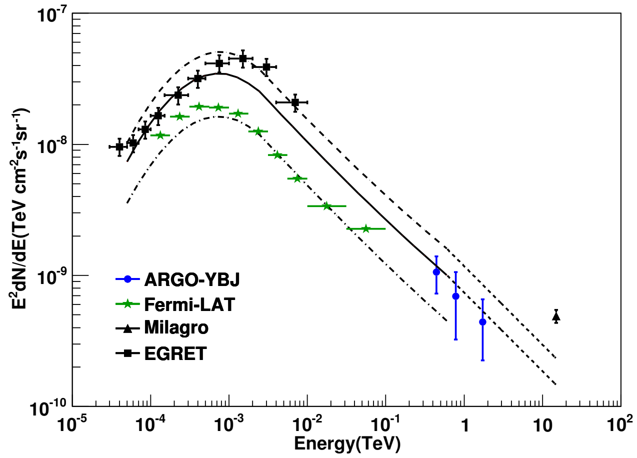

Figure 2: Energy spectrum of the diffuse gamma-ray emission measured by ARGO-YBJ in the Galactic region $65^\circ < l < 85^\circ$, $|b| < 5^\circ$ (dots). The solid line shows the flux according to the *Fermi*-DGE model. The short-dashed line represents its extension following a power law with spectral index -2.6. For details and references see [14].

from the Galactic plane in the Galactic latitude belt $|b| < 5^\circ$ [14]. The energy range covered by this analysis, from ∼350 GeV to ∼2 TeV, allows the connection of the region explored by Fermi with the multi-TeV measurements carried out by Milagro [15, 16]. These data have been used to measure the diffuse emission from the regions of the Galactic plane of longitude $25^\circ < l < 100^\circ$ and $130^\circ < l < 200^\circ$. Indeed the region $100^\circ < l < 130^\circ$ is excluded since in the high declination region $\delta > 60^\circ$ the Galactic plane runs parallel to the right ascension axis and the contribution from the signal could affect the background estimate. The excess of gamma-induced showers is obtained following the procedure of the background estimation applied to the ARGO-YBJ data as reported in [17]. The analysis has been focused on two selected regions of the Galactic plane, i.e., $40^\circ < l < 100^\circ$ and $65^\circ < l < 85^\circ$ (the Cygnus region), where Milagro observed an excess with respect to the model expectations. Great care has been taken in order to mask the most intense gamma-ray sources, including the TeV counterpart of the Cygnus cocoon recently identified by ARGO-YBJ [18], and to remove residual contributions.

As can be seen in the Fig. 2, the ARGO-YBJ results do not show any excess at sub-TeV and TeV energies corresponding to the excess found by Milagro, and are consistent with the predictions of the Fermi model for the diffuse Galactic emission [14]. The questions raised by the Milagro observations can be answered by taking into account the emission of TeV photons from the Cygnus cocoon and, at a minor extent, from discrete sources.

The spectral indexes measured by ARGO-YBJ in different regions of the Galactic plane are reported in Table 1. The statistical significance of the observations in standard deviations (s.d.) is shown in the second column. The TeV flux averaged over the Cygnus region $65^\circ < l < 85^\circ$ cover the energy range 400 GeV – 2 TeV and follow a power law with spectral index -2.65±0.44, a value very close to that found for TeV emission from the Cygnus cocoon [18], indicating the possible presence of a factory of young CRs. Future gamma-ray observatories as LHAASO [19] will operate with high sensitivity up to PeV energies thus investigating the characteristics of diffure emission in different locations and providing important clues on the nature of the knee.

4. Conclusions

The ARGO-YBJ detector exploiting the full coverage approach and the high segmentation of the readout imaged the front of atmospheric showers with unprecedented resolution and detail in the wide TeV - PeV energy range. The physics of Galactic CRs has been studied with a combined measurement of photon- and charged particle-induced showers.

The cosmic ray all-particle spectrum has been measured in the 80 TeV – 10 PeV energy region by using different analysis procedures. As shown in the Fig. 1, results confirm the observation of a knee structure around 3 PeV, in agreement with other experiments. The energy spectrum of the light-component (i.e. p and He) has been measured with different techniques and analysis procedures from few TeV up to about 5 PeV. The result, while being consistent with highest energy direct measurements, shows a clear indication that the knee of the proton primary spectrum starts well below 1 PeV, thus being not coincident with the knee of the all-particle spectrum.

More sensitive measurements of the energy spectrum and elemental composition in the range from 10^{12} to 10^{17} eV are required to observe the knees of different nuclei and to investigate in detail the end of the spectrum of Galactic CRs and the tension among different experiments.

References

[1] Blasi P., Astron. Astrophys. Rev., 21, 70 (2013).

[2] Aielli G. et al. (ARGO-YBJ coll.), Nucl. Instr. and Meth. A 562, 92 (2006).

[3] Bartoli B. et al. (ARGO-YBJ coll.), Astrop. Phys. 67 (2015) 47.

[4] Bartoli B. et al. (ARGO-YBJ coll.), Phys. Rev. D 85, 092005 (2012).

[5] Bartoli B. et al. (ARGO-YBJ coll.), Phys. Rev. D 91 (2015) 112017.

[6] Mari S.M. et al. (ARGO-YBJ coll.), in Proc. 34th ICRC (The Hague, 2015) **ID:371**.

[7] D'Amone A. et al. (ARGO-YBJ coll.), in Proc. 34th ICRC (The Hague, 2015) **ID:366**.

[8] Bartoli B. et al. (ARGO-YBJ coll.), Chinese Phys. C **38** (2014) 045001.

[9] S.S. Zhang et al. (ARGO-YBJ coll.), in Proc. 34th ICRC (The Hague, 2015) **ID:261**.

[10] Iacovacci M. et al. (ARGO-YBJ coll.), in Proc. 34th ICRC (The Hague, 2015) **ID:382**.

[11] Y.S. Yoon et al., Astroph. J. **728**, 122 (2011).

[12] Bartoli B. et al. (ARGO-YBJ coll.), Phys. Rev. D 84, 022003 (2011).

[13] J.H. Hörandel, Astroparticle Physics **19**, 193 (2003).

[14] Bartoli B. et al. (ARGO-YBJ coll.), Astroph. J. 806 (2015) 20.

[15] Atkins, R. et al. (Milagro coll.), Phys Rev. Lett., 95, 251103 (2005).

[16] Abdo, A. A. et al. (Milagro coll.), Astroph. J., 688, 1078 (2008).

[17] Bartoli B. et al. (ARGO-YBJ coll.), Astroph. J. 734 (2011) 110.

[18] Bartoli B. et al. (ARGO-YBJ coll.), Astroph. J. 790 (2014) 152.

[19] Z. Cao et al., Chin. Phys. C, 34, 249 (2010).

PoS(MULTIF15)050