Recent highlights from ARGO-YBJ

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Abstract. The ARGO-YBJ experiment has been in stable data taking for more than 5 years at the YangBaJing Cosmic Ray Laboratory (Tibet, P.R. China, 4300 m a.s.l., 606 g/cm$^2$). With a duty-cycle of about 87% the detector collected more than $5 \times 10^{11}$ events in a wide energy range, from few hundreds GeV up to 10 PeV. A number of open problems in cosmic ray physics has been faced exploiting different analyses. In this talk we summarize the latest physics results obtained in gamma-ray astronomy and in cosmic ray physics.

1. The ARGO-YBJ experiment

ARGO-YBJ is an EAS detector located at an altitude of 4300 m a.s.l. (606 g cm$^{-2}$) at the Yangbajing Cosmic Ray Laboratory (30.11 N, 90.53 E) in Tibet, P.R. China. It is mainly devoted to $\gamma$-ray astronomy and cosmic ray physics. The detector consists of a carpet ($\sim 74 \times 78$ m$^2$) of resistive plate chambers (RPCs) with $\sim 93\%$ of active area, surrounded by a partially instrumented area ($\sim 20\%$) up to $\sim 100 \times 110$ m$^2$. Each RPC 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. Details of the detector layout can be found in [1]. 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$^{-2}$. The RPC charge readout allows to extend the measurements up to particle densities of about $10^4$/m$^2$ [2]. Due to the full coverage configuration and the location at high altitude, the detector energy threshold is $\sim 300$ GeV. The detector, in its full configuration, has been in stable data taking since November 2007 to February 2013, with a 4% of dead time and an average duty cycle of about 87%. The detector performance and the analysis techniques are extensively discussed in [3]. The detector angular resolution depends on the number of triggered pads $N_{pad}$, ranging from $1^{\circ}$.7 for $N_{pad} > 20$ to $0^{\circ}$.2 for $N_{pad} > 1000$. The median primary energy of $\gamma$-rays is 0.36 TeV for events with $N_{pad} > 20$ and 8.9 TeV for $N_{pad} > 1000$ [3].

In this paper the latest results obtained in Galactic and extra-Galactic astrophysics are summarized.

2. 4.5 years observations of the blazar Mrk 421

Active Galactic Nuclei (AGNs), one of the most luminous sources of electromagnetic radiation in the universe, are galaxies with a strong and variable non-thermal emission, believed to be the result of accretion of mass onto a supermassive black hole (with a mass ranging from $\sim 10^6$ to $\sim 10^{10}$ M$\odot$) lying at the center of the galaxy. Multi-wavelength observations are of fundamental importance to investigate the mechanisms of high energy emission.
Figure 1. Mrk 421 light curves in different energy bands, from 2008 August 5 to 2013 February 7 [4]. Each bin of the ARGO-YBJ data contains the event rate averaged over 30 days.
Fig. 1 shows the light curves of Mrk 421, as obtained by the data of different experiments, covering the energy range from radio to the TeV band [4]. The time integration is chosen taking into account the sensitivity of the instruments. For ARGO-YBJ each point corresponds to one month (30 days) of data, while for Fermi-LAT, Swift-BAT, RXTE-ASM and MAXI-GSC the data are averaged over one week. Thanks to the ARGO-YBJ and Fermi data, the whole energy range from 100 MeV to 10 TeV is covered without any gap. The main results of the multiwavelength analysis can be summarized as follows [4]:

- Mrk 421 showed both low and high activity phases at all wavebands during the 4.5 year period analyzed. The variability increases with energy for both the Spectral Energy Distribution (SED) components. Concerning the synchrotron component, the variability amplitude increases from 21% in radio and 33% in UV to 71%-73% in soft X-rays and 103%-137% in hard X-rays. For the Inverse Compton component, the amplitude is 39% at GeV energies and increases to 84% at TeV energies.

- The variation of the X-ray flux is clearly correlated with the TeV $\gamma$-ray flux. This result is consistent with many previous observations, supporting the idea that the X-ray and VHE $\gamma$-ray emissions originate from the same zone. For the first time we observed a moderate correlation between GeV and TeV $\gamma$-ray fluxes. On the contrary, X-ray and $\gamma$-ray fluxes are weakly or not correlated with radio and UV fluxes.

- Seven large flares, including five X-ray flares and two GeV $\gamma$-ray flares with variable durations (3–58 days), and one X-ray outburst phase were identified and used to investigate the variation of the spectral energy distribution with respect to a relative quiescent phase.

- During the outburst phase and the seven flaring episodes, the peak energy in X-rays is observed to increase from sub-keV to few keV. The TeV $\gamma$-ray flux increases up to $0.9–7.2$ times the flux of the Crab Nebula. The behavior of GeV $\gamma$-rays is found to vary depending on the flare, a feature that leads us to classify flares into three groups according to the GeV flux variation.

- The one-zone synchrotron self-Compton (SSC) model was adopted to describe the emission spectra. Two out of three groups can be satisfactorily described using injected electrons with a power-law spectral index around 2.2, as expected from relativistic diffuse shock acceleration, whereas the remaining group requires a harder injected spectrum. The underlying physical mechanisms responsible for different groups may be related to the acceleration process or to the environment properties.

3. 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 [5, 6].

- ‘Analog-Bayes’ analysis, based on the RPC charge readout [2], 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 [7].

- ‘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 [8].

- '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 [9, 10].

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.

The all-particle energy spectra measured by ARGO-YBJ by reconstructing showers with three different approaches [7, 8, 11] are shown in the Fig. 2. 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 ±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.

The light component (p+He) energy spectrum measured by ARGO-YBJ with the so-called digital read-out in the few TeV – 300 TeV energy range is shown in Fig. 2 (green triangles) [5, 6]. The value of the spectral index of the power-law fit to the ARGO-YBJ data is -2.64±0.01 [6]. 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 [7, 8]. 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 [9, 10]. The energy of the primary particle is reconstructed both by an unfolding procedure [7] or on an event-by-event basis [8, 9, 10].

The resulting light component energy spectra are shown in the Fig. 2.

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) [14] .

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 and extragalactic CRs has been studied with a combined measurement of photon- and charged particle-induced showers and a number of important issues in Astroparticle Physics has been investigated

- cosmic ray physics (energy spectrum, elemental composition, anisotropy, p-air and pp cross section measurement) starting from TeVs
- gamma-ray astronomy (galactic and extragalactic) starting from few hundreds GeV
- search from GRBs in the full GeV–TeV energy range
- search for antiproton in the cosmic ray primary flux at TeV energies
- study of the solar and heliosphere physics above GeV.

These achievements represent the accomplishment of the aims which motivated the proposal and the design of the experiment. Final analysis with the full statistics of the analog data will give new inputs to the hadronic interaction models currently used to describe particle physics and CRs up to the highest energies.

5. References
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