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Astroparticle physics with ARGO-YBJ

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The ARGO-YBJ experiment was installed in the Tibet region of China, 4300 meters above sea level. It run continuously from November 2007 until February 2013, with the goal of observing astronomical γ-ray sources in the energy range between a few hundred GeV and about 100 TeV, and primary cosmic rays in the energy range between about 1 TeV and a few PeV. The unique feature of the ARGO-YBJ detector was its full-coverage layout of Resistive Plate Chambers on an area of (78 x 74) m^2, with a guard ring around and a full area of 11000 m^2. The most important results obtained by ARGO-YBJ will be presented, with specific focus on the observation and monitoring of galactic and extragalactic γ-ray sources and primary light-nuclei spectrum and knee.

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1. Introduction

The ARGO-YBJ experiment [1] was a collaboration between Chinese and Italian research groups. I was installed in Tibet, China, at an altitude of 4300 m a.s.l. in order to reconstruct air showers generated by cosmic rays with energy down to a few hundred GeV. ARGO-YBJ had been designed to investigate a large number of topics in astrophysics and cosmic-ray physics: γ-ray astronomy (search for point-like sources above few hundreds of GeV), search for VHE tails of γ-ray bursts above $\sim$1 GeV, cosmic-ray physics, Sun and heliosphere physics. The ARGO-YBJ detector was based on a full-coverage single layer of Resistive Plate Chambers (RPCs) covering a surface of 74×78 m^2. A group of 12 neighboring RPCs was called a "cluster", and the full-coverage part of the detector included 130 clusters. Around this, 23 additional clusters were placed in order to obtain a better reconstruction of the shower front, which extended the experiment area to 110×100 m^2. The space-time unit of the ARGO-YBJ detector was a "pad", namely a group of 8 neighboring RPC read-out strips. The single-hit time resolution was about 1.8 ns [2]. Air showers were triggered by requiring a number of hits greater than 20 within a 150 ns time window, giving an average trigger rate of about 3.5 kHz with a dead time of 4% and an average duty cycle greater than 86%. ARGO-YBJ had been running almost uninterruptedly with its complete layout since October 2007 with a duty cycle of 90% and an average trigger rate of 3.6 kHz. A selection of its main physics results is presented here, focusing on the monitoring of γ rays from astromomical sources and the "light" cosmic-ray spectrum up to about 1 PeV.

2. Monitoring of galactic and extra-galactic γ-ray sources with ARGO-YBJ

In ARGO-YBJ, the γ-ray flux from point-like or extended sources could only be measured by subtraction from the cosmic-ray background, by using the well-established "time-swapping" and "equi-zenith" methods. The results were carefully checked by monitoring a well known galactic γ-ray source, the Crab nebula, in the energy region above a few hundred GeV, as shown in figure 1 [2].

The analysis of the whole ARGO-YBJ data set gave a statistical significance above 5 standard deviations for 6 γ-ray sources in the above-mentioned energy region. Extremely noticeable results were obtained for the γ-ray emission of two AGN: Markarian 421 (MRK421) and Markarian 501 (MRK501).

Figure 2 shows the integral γ-ray flux from MRK421 over a time span of more than 3 years as measured by ARGO-YBJ and by two other satellite experiments in different energy regions, with the vertical axes suitably rescaled . A few remarkable flares from the AGN MRK421 were observed in the X-ray range by the ASM X-ray telescope in 2006, 2008 and 2010, and ARGO could observe TeV γ emission at the same time for such flares, as shown in figure 2 for the two most recent ones. Concerning the two flares observed on June 4-6 and June 11-13, 2008 [3], ARGO-YBJ investigated the γ emission from the same source on those days [4]. The peak significance for the flare of June 11-13, 2008 was 4.2 standard deviations. The ARGO-YBJ data fully satisfy the relation between the spectral index and the flux resulting from the Whipple measurements of a similar flare of MRK421 [5], suggesting that this relation is an intrinsic property of the source. One more remarkable flare from MRK421 occurred on February 2010. ARGO-YBJ observed

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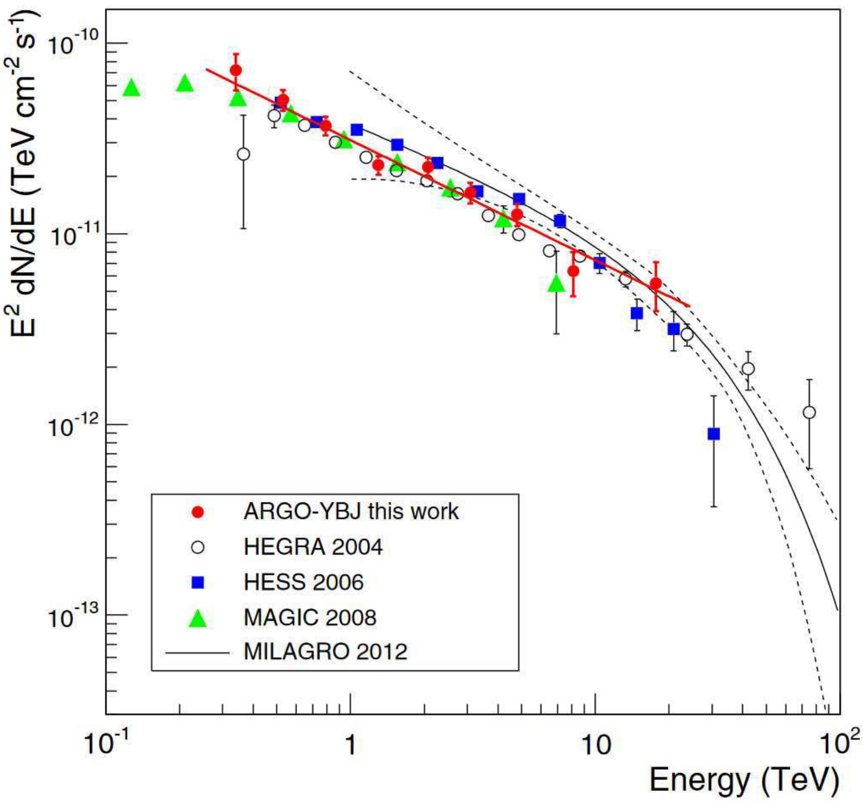

Figure 1: Crab Nebula differential energy spectrum multiplied by E^2, measured by ARGO-YBJ and other experiments. The thick red solid line represents the best fit of the ARGO-YBJ data. The dotted lines delimit the 1 sigma error band of the Milagro spectrum.

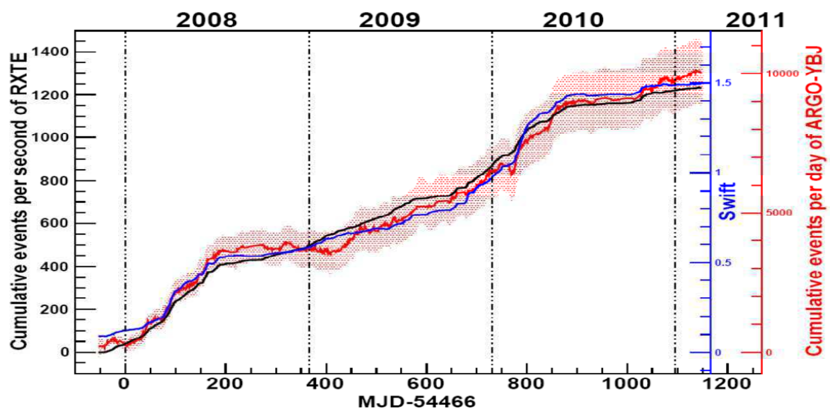

Figure 2: Comparison of the cumulative counting rates for the γ-ray emission from MRK421 as measured by ARGO-YBJ (red), RXTE/AMS (black) and SWIFT (blue). The vertical coordinates have been rescaled suitably in order to obtain a direct visual comparison of the three experimental results.

it between February 16th and February 18th at a 6 s.d. significance level. The measured flux exceeded 3 Crab units for the duration of the observation. The importance of this measurement by ARGO-YBJ lies in the fact that for the first time a ground-based experiment could detect a flare with a 5 standard-deviation significance level on a daily basis.

An X-ray flare from the AGN MRK501 was detected by the RXTE/ASM telescope in October 2011 after a long "quiet" period (the previous intense X-ray flare dated back to 1997). This flare was associated to a strong emission in the TeV energy range detected by ARGO-YBJ [6]. During the flaring period, the TeV emission was observed in 36 days with a significance greater than 6 standard deviations.

3. Cosmic-ray physics and light-component knee with ARGO-YBJ

Several results in cosmic-ray physics with ARGO-YBJ were already reported in the past, with particular emphasis on the cosmic-ray flux anisotropy at TeV energies [7], the study of the moon shadow [8] and the corresponding limit on the $\bar{p}-p$ flux ratio [9], the proton-air interaction cross section [10] and the light-component spectrum up to 200 TeV [11].

Subsequently, a joint analysis of the data collected by ARGO-YBJ and the WFCT-02 Cherenkov telescope placed close to the ARGO-YBJ experimental hall was performed . The data collected by the two detectors from December 2010 and February 2012 were considered, requiring a coincidence within an 8-μs time window using the GPS event time stamps of the two detectors. The event-selection requirements for ARGO-YBJ were the following: well reconstructed shower-core position, shower direction within 6° of the telescope axis, more than 6 fired pixels in the telescope PMT matrix, more than 1000 fired pads in the ARGO-YBJ central carpet; the coincident events for the light-component selection were chosen according to the number of charged particles in the shower core and the shape of the Cherenkov-light image.

Figure 3 shows the ARGO-YBJ light-component spectrum (both at lower energy [13] and higher energy [14]) in comparison with the results of other experiments. A steepening of the light-component energy spectrum is observed, starting at about 700 TeV. This is compatible with the results previously obtained by Tibet AS-γ, CASA-MIA and MACRO. This result strongly encourages further investigation in future experiments (e.g. LHAASO), in order to improve our understanding of proton acceleration by SNRs up to energies approaching 1 PeV.

4. Conclusions

The ARGO-YBJ experiment ran data almost uninterruptedly with its complete layout for more than 5 years, from November, 2007 till February, 2013. Its results in galactic and extragalactic γ-ray astronomy, and in cosmic-ray physics as well at the energy scale from a few hundred GeV up to a few PeV, strengthened our knowledge about the γ-ray emission of AGN and prepared the path for future, deeper investigations of cosmic-ray physics around the knee.

References

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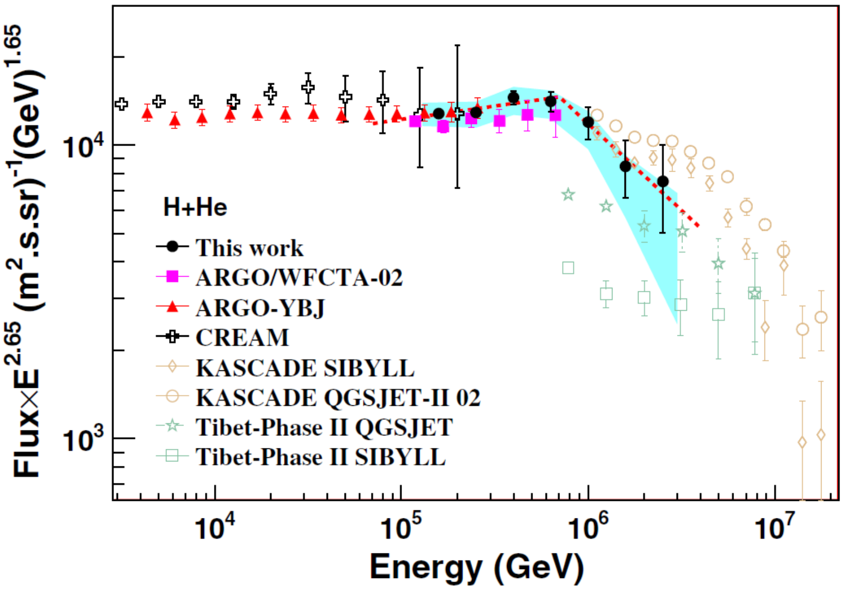

Figure 3: Light-component cosmic-ray spectrum obtained by the hybrid experiment with ARGO-YBJ and the imaging Cherenkov telescope [12]. A clear knee structure is observed around 700 TeV. The light-component spectra by CREAM, ARGO-YBJ and the hybrid experiment below the knee, the spectra by Tibet AS-γ and KASCADE above the knee are shown for comparison. In our result, the error bar is the statistical error, and the shaded area represents the systematic uncertainty.

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