VHE γ-ASTRONOMY OBSERVATIONS WITH THE ARGO-YBJ DETECTOR

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Very High Energy (VHE) γ-astronomy and cosmic ray physics are the main goals of the ARGO-YBJ experiment. The detector is located in Tibet (People's Republic of China) and is a full coverage Extensive Air Shower array consisting of a carpet of Resistive Plate Chambers (RPCs). Altitude and full coverage ensure an energy threshold of few hundreds of GeV for primary photons detected in shower mode, while the RPC time resolution gives a good pointing accuracy, thus allowing a high sensitivity to γ-ray sources. The large field of view and the high duty-cycle allow the continuous monitor of the Northern sky in the declination band ($-10°$, $+70°$). The detector operates also in scaler mode in order to look for Gamma Ray Burst (GRB) signals in the range 1-100 GeV in coincidence with GRB detection by satellites. The performances of the detector and the present results concerning γ-astronomy will be presented.

1 Detector features and performance

The ARGO-YBJ (Astrophysical Radiation Ground-based Observatory at YangBaJing) experiment is located in Tibet at an altitude of 4300 m and is supported by an Italian-Chinese scientific collaboration. The detector consists of a single layer of RPCs operated in streamer mode [1], on a total area of about 110×100 m^2 (Fig. 1). The central part (78×74 m^2) is fully active and surrounded by a sampling ring with other 1000 m^2 (20% of the outer ring) equipped with RPCs. The detector is logically divided in 153 clusters, each made by 12 RPCs with a dedicated Local Station for the DAQ. The digital read-out of the RPCs is performed by means of inductive strips (6×62 cm^2) well suited to detect small air showers. The fast-OR of 8 strips is called "pad" and defines the space-time pixel of the detector, with a time resolution of ~ 1.7 ns [2]. The timing calibration of the detector has been properly performed by means of an innovatory software method [3,4]. In order to extend the measurable energy range, each RPC will be equipped also with two large electrodes, called "big pads", which provide an analog signal proportional to the deposited charge.

ARGO-YBJ collects data in shower and scaler mode. The first one works when the number of pads fired in a time-window of 420 ns exceeds the multiplicity (typically 20) required by the trigger condition. The event (arrival direction, core position and so on) is fully reconstructed looking at the space-time pattern (Fig. 2, left). The scaler mode does not require any trigger, it records the rate for four multiplicities (≥ 1, ≥ 2, ≥ 3 and ≥ 4) on each cluster in a time window of 0.5 s. The scaler mode allows the detection of low energy transient phenomena (e.g. GRBs and solar flares) observed as non-statistical fluctuations of the background [5].

The high altitude location, the full coverage with high space-time granularity, and the RPC time resolution allow an excellent angular resolution and reduce the energy threshold in shower mode to few hundreds of GeV. The continuous sky survey in the declination band from $-10°$ to

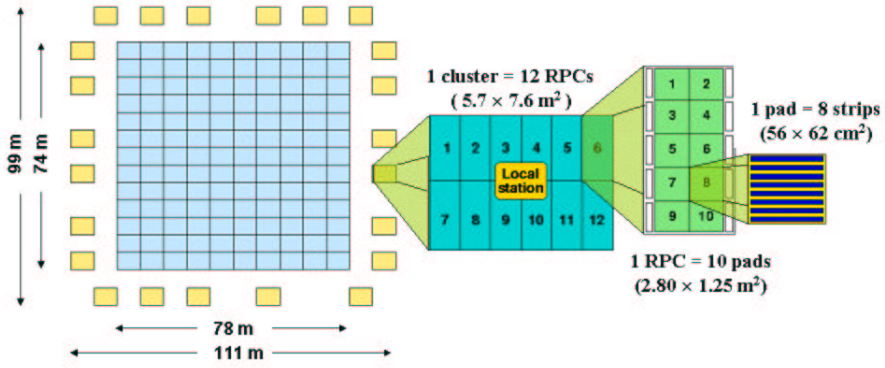

Figure 1: The set-up of the experiment.

+70° is possible thanks to the duty-cycle close to 100% and the field of view greater than 2 sr. The experiment is in data-taking with the central carpet since June 2006, with the ring since November 2007.

The performances of the ARGO-YBJ detector as a gamma-telescope have been checked looking at the Moon shadow [6]. Indeed the cosmic rays (CR) are hampered by the Moon and a deficit in its direction is visible. The same effect has been observed in the direction of the Sun [7] and the studies on the Moon shadow allow also to investigate the presence of antiprotons in the CR flux [8]. The Point Spread Function (PSF) of the detector is related to the shape of the Moon shadow. The westward angular shift ($\Delta\psi$) of the shadow is due to the propagation of CR in the geomagnetic field and allows to calibrate the scale of the primary energy (E) according to the formula $\Delta\psi \sim \frac{1.7^\circ}{E\ (TeV)}$. Finally the deficit position for events with high rigidity (that is energy) allows to estimate the pointing accuracy. The analysis of the data (Fig. 2, right) confirms the MC simulation, making us confident in the detector performaces and in the reconstruction algorithms. The measured angular resolution is less than 0.6° for CR events with a strip multiplicity higher than 300. For γ-induces showers we expect a 30% improvement due to the better defined time profile.

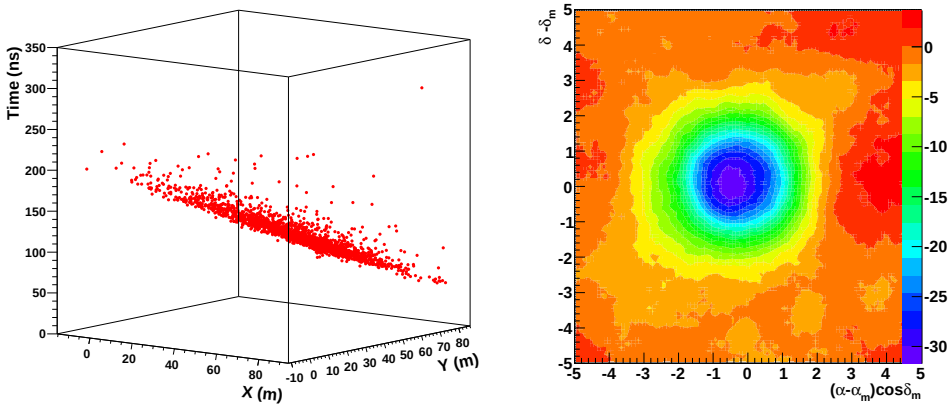

Figure 2: Left: Space-time view of an extensive air shower. Right: Moon shadow significance map for a 1-year sample. The events are selected requiring more than 60 fired strips and a zenith angle lower than 50°.

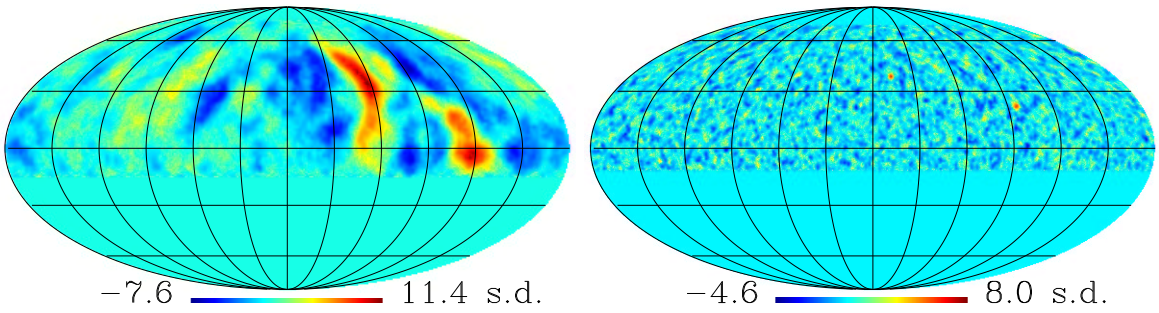

Figure 3: The sky map for a data sample collected in 424 days (the color scale gives the statistical significance). Left: The map before the correction introduced to take into account large excess area. Anisotropies in the CR flux are present. Right: The map after the correction. The statistically significant sources are the Crab Nebula and the Mrk 421.

2 Gamma astronomy

The data collected in shower mode have been analysed searching for γ-sources. In Fig. 3 the result of this search is shown in celestial coordinates. In the left map two large hot spots are visible, already reported by the Milagro experiment [9]. These regions have been interpreted as CR excesses ($\sim 0.1\%$), but their origin is not yet understood. Other studies about the features of these hot spots are in progress [10,11]. A correction procedure [10] has been adopted in order to normalize the background eliminating all features of large angular size. After this correction two point sources are visible in the right map: Crab Nebula and Markarian 421 (Mrk 421). The ARGO-YBJ measurement of the Crab spectrum (Fig. 4, left) is fully compatible with those of other experiments. No statistically significant excess has been observed up to now at the positions of 48 galactic and 86 extragalactic MeV-GeV γ-sources.

Mrk 421 flares - The continuous data taking in a large field of view ($\sim$ 2 sr) is a benefit of the EAS technique. Therefore ARGO-YBJ was able to detect Mrk 421 flares in 2006 and 2008, at γ-ray energies above 0.8 TeV. Here we want to stress the results for the strongest flares in March-June 2008. The average emission during that period was about double with respect to the Crab Nebula level (Fig. 4, center) and decreased afterwards. The γ-signal shows a good correlation with x-ray emission. The flares occurred in the first half of June have been studied from optical to 100 MeV γ-rays, and only partially up to TeV energies [12], since the moonlight hampered the Cerenkov telescope observations during the second and most intense part of the emission. ARGO-YBJ data measured the spectra also during this second flare completing the multifrequency observations. The signal intensity is about 7 Crab units on June 11-13, with a significance of 4.2 standard deviations. The measured flux in those days (Fig. 4, right) is consistent with the prediction [12] made in the framework of the Synchrotron Self-Compton (SSC) model, in which the flare is caused by a rapid acceleration of leptons in the jet.

Search for Gamma Ray Bursts - The data collected in scaler mode have been analysed to search for signals from GRBs in coincidence or with some delays with respect to the prompt emission detected by satellites. Presently ARGO-YBJ analysed the largest sample of GRBs on ground in the GeV range. Up to now statistically significant GeV signals of GRB counterpart were not detected and the fluence upper limits reached values as low as 10^{-5} erg cm^{-2} in the 1-100 GeV range [13]. Also the shower mode data have been used in a stacked analysis to put significant upper limits on the GRB fluence up to 1 TeV [14].

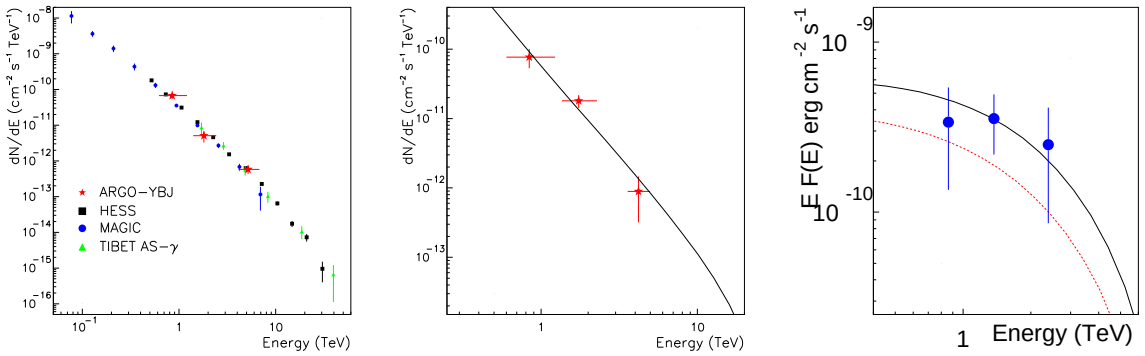

Figure 4: Left: The spectrum of the Crab Nebula measured by ARGO-YBJ and other experiments. Center: The spectrum of Mrk 421 in 2008 (days 41-180). The superimposed fit takes into account the Extragalactic Background Light absorption. Right: Spectrum of Mrk 421 during the June 11-13 flare in 2008. The measurements are compared with the flux (higher curve) predicted by the model by Donnarumma et al. [12] for the same days.

3 Conclusions

The performances of the ARGO-YBJ detector as a γ-telescope have been presented. Remarkable results were achieved analysing about 1-year data. Anisotropies have been observed in the TeV-CR sky. New limits have been put on the fluence from GRBs. The Crab Nebula spectrum has been measured and the continuous monitor of the sky allowed the observation of Mrk 421 flares in 2006 and 2008 with a significant correlation of VHE γ-flux with x-emission. Moreover the ARGO-YBJ measurement favours the SSC mechanism for the Mrk 421 blazar.

Further studies are in progress to increase the experiment sensitivity. These studies are devoted to select better quality data samples and to define γ-hadron separation algorithms, mainly based on the unprecented time-space view of the extensive air showers. Finally, we would like to stress that the continuous γ-sky monitoring is going on with a duty-cycle close to 100% and a field of view limited only by the atmosphere thickness.

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