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ARGO-YBJ: Highlights and Prospects

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Abstract

The ARGO-YBJ experiment has been in stable data taking for 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 greater than 86% the detector collected about $5{\cdot}10^{11}$ events in a wide energy range, from few hundreds GeV up to the PeV. A number of open problems in cosmic ray physics has been faced exploiting different analyses. In this paper we summarize the last results in gamma-ray astronomy and in the cosmic ray physics and introduce the LHAASO project, mainly driven by the Chinese community, to study the cosmic ray physics up to 10^{17} eV.

Keywords: cosmic rays - extensive air showers - Gamma-ray astronomy - ARGO-YBJ.

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1 The ARGO-YBJ Experiment

ARGO-YBJ is a full coverage air shower detector located at the Yangbajing Cosmic Ray Laboratory (4300 m a.s.l., 606 g/cm^2, Tibet, PR China) devoted to the study of gamma rays and cosmic rays. Exploiting the high altitude and the full coverage technique, ARGO-YBJ can detect gamma rays with an energy threshold as low as a few hundred GeV.

The detector consists of a $\sim$74×78 m^2 carpet made of a single layer of Resistive Plate Chambers (RPCs) with $\sim$93% of active area, surrounded by a partially instrumented ($\sim$20%) area up to $\sim$100×110 m^2. The detector has a modular structure with a high granularity, that provides a detailed view of the shower front. The smallest space-time unit, called "pad", has a size of 55.6×61.8 cm^2. The time and the location of each fired pad are recorded and used to reconstruct the position of the shower core and the arrival direction of the primary particle. The point spread function (PSF), the pointing accuracy and the energy calibration of the detector have been evaluated using the Moon shadow technique, i.e. the deficit of cosmic rays in the Moon direction. For a detailed description of the detector performance see (Aielli et al., 2006, Aielli et al. 2009, Bartoli et al., 2011).

Since November 2007 to January 2013 the ARGO-YBJ experiment monitored with high duty cycle ($\sim$86%) the northern sky at TeV photon energies. With a cumulative sensitivity ranging from 0.24 to $\sim$1 Crab units, depending on the declination, six sources have been observed with a statistical significance greater than 5 standard deviations (s.d.) in the declination band from -10° to 70°.

In this paper the last results obtained in gamma-ray astronomy and in the study of the anisotropy in the CR arrival direction distribution are summarized.

2 Northern Sky Survey

The ARGO-YBJ data used in this analysis were collected from November 2007 to January 2013, with a total observation time of 1670.45 days. The total number of events selected with a zenith angle less than 50° is about $3{\times}10^{11}$. They are used to fill a map in celestial coordinates (right ascension and declination) with $0.1^\circ{\times}0.1^\circ$ bins, covering the declination band from -10° to 70°.

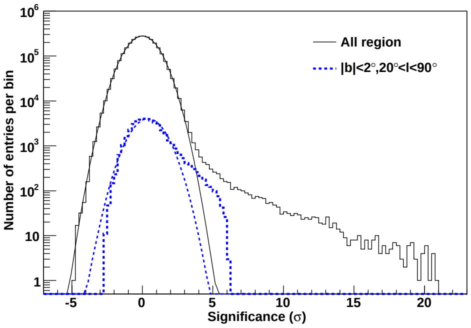

Figure 1: Significance distribution of the whole sky map (thick solid line). The thin solid line represents the best Gaussian fit. The significance distribution of the Galactic Plane region with $\mid b \mid < 2^\circ$ and $20^\circ < l < 90^\circ$ is shown by the thick dotted line. The thin dotted line represents the best Gaussian fit for the same region.

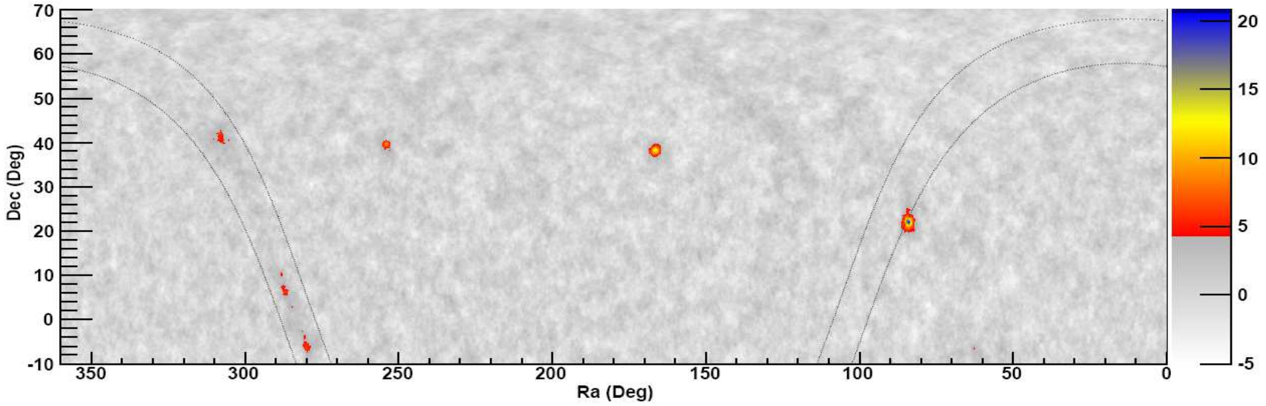

Figure 2: Significance map of the northern sky as seen by the ARGO-YBJ experiment in VHE γ-ray band. The two dotted lines indicate the Galactic latitudes $b = \pm 5°$.

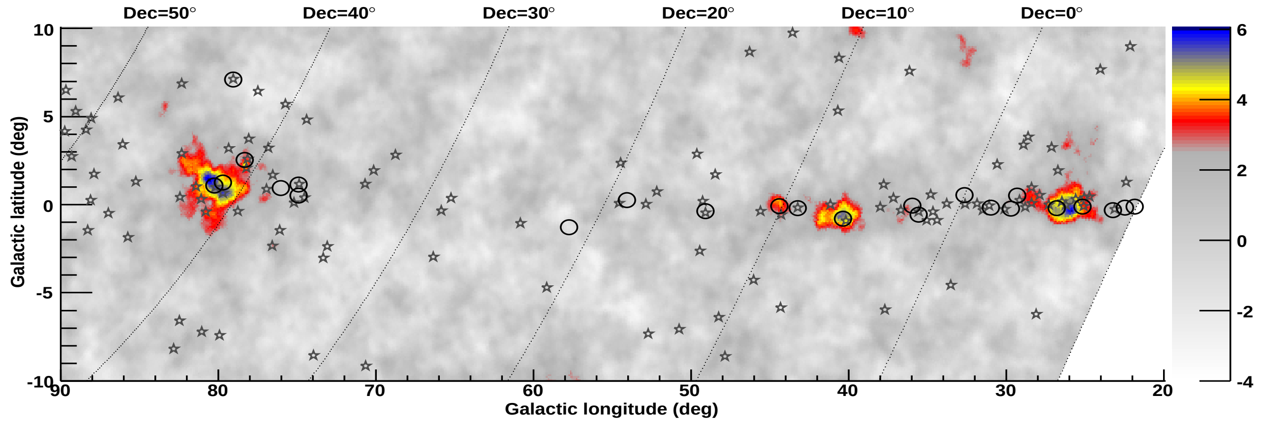

Figure 3: Significance map of the Galactic Plane region with $\mid b \mid < 10°$ and $20° < l < 90°$ obtained by the ARGO-YBJ experiment. The circles indicate the position of all the known VHE sources. The open stars mark the location of the GeV sources of the second *Fermi*-LAT catalog.

The significance distribution of the whole map bins is shown in Fig.1. The distribution, with a mean value of 0.002 and σ=1.02, closely follows a standard Gaussian distribution except for a tail with large positive values, due to the excesses from several gamma ray emission regions, shown in Fig. 2. Table 1 lists the locations of all the regions with pre-trial significance greater than 4.5 s.d. . For each independent region, only the coordinates of the pixel with the highest significance are given. Based on the distribution of negative points (Fig. 1), a significance threshold of 4.5 s.d. corresponds to ~ 2 false sources in our catalog.

The significance distribution of the inner Galactic plane region (longitude $20° < l < 90°$ and latitude $\mid b \mid < 2°$) is also shown in Fig. 1. The Gaussian fit of the distribution has a mean value of 0.40 and σ=1.04. Also in this case a tail of significant excesses is present. The locations of all the excesses with a significance greater than 4.0 s.d. are listed in Table 1. Fig. 3 shows the inner Galactic Plane region in galactic coordinates.

Since the smoothing radius is larger than the bin width, the significances in adjacent bins are correlated, and a Monte Carlo simulation is necessary to correctly evaluate the post-trial probabilities. According to our simulations, the probability to have at least one source with a pre-trial significance $> 5.1\ \sigma$ ($> 4.0\ \sigma$) anywhere in the map (in the inner Galactic Plane) due to background fluctuations is 5%. However, since in the sky region monitored by ARGO-YBJ only $\sim$70 known VHE emitters exist, the post-trial significance increases for the candidate sources associated to a counterpart. Detail about different sources are discussed in Chen S. et al. (2013).

Table 1: Location of the excess regions

ARGO-YBJ Name	Ra (deg)	Dec (deg)	S (s.d.)	Associated TeV Source
J0409−0627	62.35	-6.45	4.8	
J0535+2203	83.75	22.05	20.8	Crab Nebula
J1105+3821	166.25	38.35	14.1	Mrk 421
J1654+3945	253.55	39.75	9.4	Mrk 501
J1839−0627	279.95	-6.45	6.0	HESS J1841-055
J1907+0627	286.95	6.45	5.3	HESS J1908+063
J1910+0720	287.65	7.35	4.3	
J1912+1026	288.05	10.45	4.2	HESS J1912+101
J2021+4038	305.25	40.65	4.3	VER J2019+407
J2031+4157	307.95	41.95	6.1	MGRO J2031+41 TeV J2032+4130
J1841-0332	280.25	-3.55	4.2	

2.1 Sky upper limits

Excluding the sources listed in Table 1, we can set upper limits to the γ-ray flux from all other directions in the sky. To estimate the response of the ARGO-YBJ detector we simulated a source located at different declinations, with a power law spectrum in the energy range 10 GeV - 100 TeV and different spectral indices. The number of events is transformed into a flux using the results of the simulation. The 95% C.L. upper limits to the flux of γ-rays with energies above 500 GeV for each bin are obtained.

The upper limits as a function of the declination are shown in Fig. 4 for different photon spectral indices. The limits range between 9% and 44% I_{Crab} and are the lowest obtained so far. The lowest limit for a spectral index -2.0 (-3.0) is 5% (9%) I_{Crab}, where the Crab unit is defined as 5.77×10^{-11} cm^{-2} s^{-1}.

3 Cosmic Ray Anisotropy

The CR arrival direction distribution and its anisotropy has been a long-standing problem ever since the 1930s. In fact, the study of the anisotropy is a powerful tool to investigate the acceleration and propagation mechanism determining the CR world as we know it.

The anisotropy in the CR arrival direction distribution have been observed by different experiments with increasing sensitivity and details at different angular scales. Current experimental results show that the main features of the anisotropy are uniform in the energy range (10^{11} - 10^{14} eV), both with respect to amplitude (10^{-4} - 10^{-3}) and phase ((0 - 4) hr). The existence of two distinct broad regions, one showing an excess of CRs (called "tail-in"), distributed around 40° to 90° in R.A., the other a deficit (the "loss cone"), distributed around 150° to 240° in R.A., has been clearly observed.

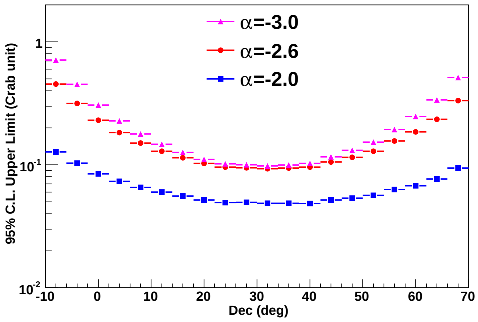

Figure 4: 95% C.L. flux upper limits for energy above 500 GeV, averaged over the right ascension, as a function of the declination. The different curves indicate a different power-law spectral index.

The origin of the CR anisotropy is still unknown. Unlike predictions from diffusion models, the CR arrival distribution in sidereal time was never found to be purely dipolar. Even 2 harmonics were necessary to properly describe the R.A. profiles, showing that the CR intensity has quite a complicated structure unaccountable simply by kinetic models.

In the last years the Milagro (Abdo et al. 2008) and ARGO-YBJ (Di Sciascio, 2013) Collaborations reported evidence of the existence of a medium angular scale anisotropy contained in the tail-in region. The observation of similar small scale anisotropies has been recently claimed also by the Icecube experiment (Abbasi et al., 2011) in the southern hemisphere.

In Fig. 5 the ARGO-YBJ sky map in galactic coordinates as obtained with 4.5 years data is shown. The color scale gives the statistical significance of the observation in s.d. . The map center points towards the galactic Anti-Center. The maps have been smoothed with an angle given by the PSF of the detector for CR-induced showers.

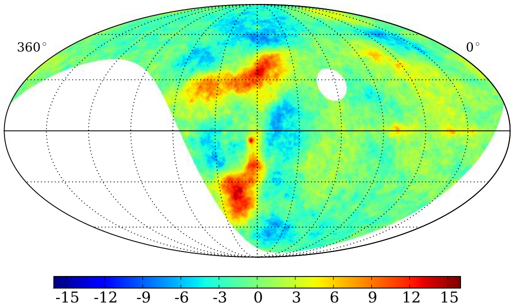

Figure 5: ARGO-YBJ sky-map in galactic coordinates. The statistical significance of the observation in s.d. is shown. The map center points towards the galactic anti-center.

Data have been recorded in 1587 days out of 1656, for a total observation time of 33012 hrs (86.7% duty-cycle). A selection of high-quality data reduced the data-set to 1571 days. The zenith angle cut ($\theta \leq 50°$) selects the dec. region $\delta \sim$ -20°÷ 80°. According to the simulation, the median energy of the isotropic CR proton flux is $E_p^{50} \approx$1.8 TeV (mode energy $\approx$0.7 TeV). No gamma/hadron discrimination algorithms have been applied to the data. Therefore, the sky map is filled with all CRs possibly including photons, without any discrimination.

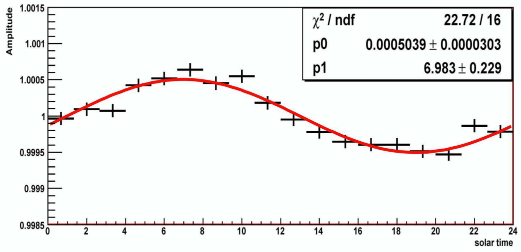

Figure 6: One-dimensional projection in right ascension of the two-dimensional CR sky map in local solar time. The red line shows the best-fit to ARGO-YBJ data (crosses).

In spite of the fact that the bulk of SNR, pulsars and other potential CR sources are in the Inner Galaxy surrounding the Galactic Centre, the excess of CR is observed in the opposite, Anti-Centre direction. As stressed in Erlykin & Wolfendale (2013), the fact that the observed excesses are in the Northern and in the Southern Galactic Hemisphere, favors the conclusion that the CR at TeV energies originate in sources whose directions span a large range of Galactic latitudes.

The right side of the map is full of few-degree excesses not compatible with random fluctuations (the statistical significance is up to 7 s.d.). The observation of these structures is reported by ARGO-YBJ for the first time.

So far, no theory of CRs in the Galaxy exists which is able to explain both large scale and few degrees anisotropies leaving the standard model of CRs and that of the local galactic magnetic field unchanged at the same time.

3.1 The Compton-Getting effect

The origin of CR anisotropies is still unknown therefore, the observation of an expected anisotropy is important to check the reconstruction algorithms, the exposure and background calculations and the stability of the detector performance. A well-known expected anisotropy is the so-called Compton-Getting (CG) effect, a dipole anisotropy in the local solar frame, due to the Earth's motion around the Sun (Compton & Getting, 1935). A significant signal compatible with CG is seen by ARGO-YBJ in solar time above $\sim$ 8 TeV to avoid additional effects due to heliospheric magnetic field and solar activity. In fact, we found that including lower energy events results in much larger modulation amplitudes than those obtained when these events were excluded. Fig. 7 shows the solar variations observed by ARGO-YBJ together with the sinusoidal curve best fitted to the data. The fair agreement between data and calculations (ϕ = 6:00 hr, A = $9.7 \cdot 10^{-5}$) make us confident about the capability of ARGO-YBJ in detecting anisotropies at a level of 10^{-4}.

4 Prospects: the LHAASO Experiment

A new experiment has been proposed by the Chinese community to face the open problems in galactic cosmic ray physics. The LHAASO experiment is a multi-component extensive air shower array constituted by: (1) an array consisting of 5137 scintillators (1 m^2 each) 15 m away from each other (KM2A) and 1200 muon detectors (40 m^2 each). The total effective area of the muon detector is about 48,000 m^2. (2) A Water Cherenkov Detector Array (WCDA) consisting of 4 water ponds, 150 × 150 m^2 each. The pond depth is about 4.5 m. Each pond is subdivided into 30 × 30 = 900 cells sized 5 × 5 m^2 each, separated by black plastic curtains. An 8 inches PMT looks upward at the bottom of each cell to collect Cherenkov photons produced by secondary charged particles in the water pond. (3) 24 Wide Field of view Cherenkov Telescope Array (WFCTA). (4) Shower Core Detector Array (SCDA) with an effective area of 5000 m^2.

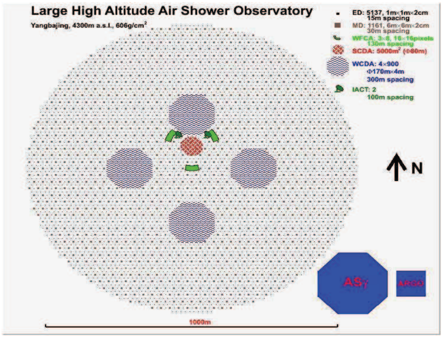

Figure 7: Layout of the LHAASO experiment.

The water ponds allow to improve the sensitivity to γ-ray sources down to a percent of the Crab Nebula flux in the TeV energy region. The KM2A array will extend the search for γ-ray sources in the 100 TeV region with an unprecedented sensitivity. In fact, exploiting the shower muon content measurement, the detection of photon-induced showers is basically background free above few tens TeV. The sensitivity of LHAASO-WCDA + LHAASO-KM2A (green line) for detection of point gamma ray sources is compared to other experiments or projects in Fig. 8. The observation times is 1 year and 50 hour for wide field-of-view detectors and IACT, respectively.

The WFCTA and the SCDA will allow, in addition, to study the cosmic ray physics up to the 10^{18} eV region, thus investigating the transition between galactic and extra-galactic CR components and the elemental composition above PeV energies.

The different elements of the experiment (scintillators, water pool, wide field of view cerenkov telescopes, neutron detectors) have been successfully tested at the Yangbajing Laboratory exploiting the CR beam provided by the ARGO-YBJ detector.

The installation of the detectors is expected to start between 2-3 years and finish in about 5 years. The proposed site is located in China, in the Yunnan province, at an altitude of about 4300 m a.s.l. .

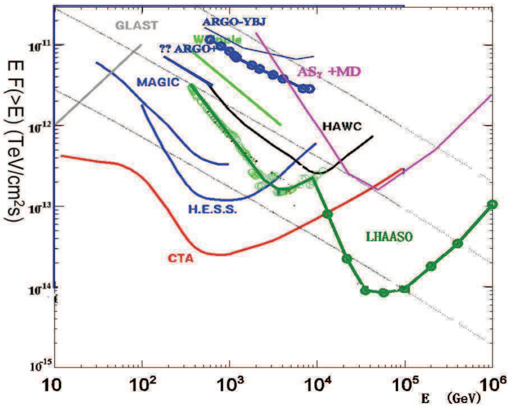

Figure 8: The sensitivity of LHAASO-WCDA + LHAASO-KM2A (green line) compared to other experiments or projects. The observation times is 1 year and 50 hour for wide field-of-view detectors and IACT, respectively.

5 Conclusions

The ARGO-YBJ detector exploiting the full coverage approach and the high segmentation of the readout is imaging the front of atmospheric showers with unprecedented resolution and detail. The digital and analog readout will allow a deep study of the CR phenomenology in the wide TeV - PeV energy range. The results obtained in the low energy range (below 100 TeV) predict an excellent capability to address a wide range of important issues in Astroparticle Physics.

In this paper we summarized the last results in gamma-ray astronomy and in the study of the CR anisotropy. The new experiment LHAASO, mainly driven by the Chinese community, to study the cosmic ray physics up to 10^{18} eV has been introduced.

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DISCUSSION

C. MUNOZ-TUNON: Could you extend a little on the details of the site for the new experiment in China ?

G. DI SCIASCIO: In principle the new project LHAASO will be located in two different high altitude sites. The LAWCA (Large Water Cherenkov Array) experiment is a possible upgrade of the ARGO-YBJ experiment at the Yangbajing Laboratory in Tibet. The detector will consist in a large water pond L-shaped around the ARGO-YBJ building with an area of about 23,000 m^2 and is focused to study gamma-ray astronomy between 100 GeV and 30 TeV. The detector structure is identical to the WCDA of the LHAASO project, therefore this experiment is the phase-0 of the LHAASO project. The data taking is expected to start a couple of years after the start of the construction.

J. BEALL: Will the new facility be at the same altitude ?

G. DI SCIASCIO: Yes, the LHAASO experiment will be located at an altitude of about 4300 m a.s.l. in the Yunnan province, similar to the altitude of the Yangbajing Laboratory where is located the ARGO-YBJ detector.

C. PITTORI: Can you say something more about the possible connection between observed anisotropies and the heliosphere ?

G. DI SCIASCIO: As discussed in (Amenomori et al., 2010), the main regions of the Medium Scale Anisotropy can be described as two intensity enhancements placed along the Hydrogen Deflection Plane, which contains the directions of the interstellar wind velocity and the interstellar magnetic field surrounding the heliosphere, each symmetrically centered away from the heliotail direction. The separation angle between the heliotail direction and each enhancement monotonously decreases with increasing energy in an energy range 4 30 TeV. The MSA being placed along the HDP suggests that it is possibly caused by the modulation of galactic cosmic rays in the magnetic field of the heliotail within ~ 70 AU to ~ 340 AU from the Sun.