Gamma-hadron discrimination using time profile in the ARGO-YBJ experiment

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Abstract: The ARGO-YBJ experiment is an extensive air shower array located at YBJ, Tibet (4300 m a. s. l.). One of its main goals is to search for very high energy gamma ray sources, for which the huge background comes from charged cosmic rays. Basing on its full coverage measurement of the shower front, a new method using the shower time profile is developed to discriminate gamma initiated showers from hadronic ones. Applying this method to the ARGO-YBJ data, the resulting significance of Crab Nebula is obviously improved, especially at higher energies.

Keywords: Extensive air showers, Gamma-hadron discrimination, Crab Nebula

1 Introduction

Very high energy (VHE) gamma rays are usually detected by ground-based Extensive Air Shower (EAS) experiments. Separating γ showers from hadronic ones becomes a key issue in high-energy gamma-ray astronomy which, together with a good angular resolution, allows the reduction of the background composed of isotropic charged cosmic rays.

Different development mechanism of electromagnetic (the primary particle is γ or electron) and hadronic (the primaries are hadrons) showers indicate possible characteristics of the secondary particles. The IACT (imaging atmospheric Cerenkov telescope) experiments have successfully developed some gamma-hadron discrimination methods [1] [2][3] based on the image parameters, such as the Hillas ones. The MILAGRO experiment has got a significant improvement of the sensitivity after adopting effective gamma-hadron discrimination methods [4][5] based on the shower muon and multiple core information.

The ARGO-YBJ experiment [6], located at Yangbajing Cosmic Ray Observatory (Tibet, P. R. China, 4300 m a.s.l.), consists of a single layer of RPCs (Resistive Plate Chambers) operated in streamer mode. Each RPC ($2.8\times1.25\,m^2$) is read by 80 strips of $6.75 \times 61.8\ cm^2$ defining the space granularity, logically organized (ORed) in 10 independent pads of $55.6 \times 61.8\ cm^2$ defining the detector pixel size as far as the arrival time measurement is concerned (digital readout) . Twelve RPCs are grouped into a so-called cluster ($5.7\times7.6\,m^2$). The central part of the detector, 5600 m^2 in area, is fully covered by 130 clusters, while 23 additional clusters surrounding the central carpet form a guard ring. The whole array covers a total area of about 10,000 m^2. One of the main goals of the ARGO-YBJ experiment is to search for VHE gamma ray sources. Effectively rejecting the hadronic background is the crucial point of the experiment in order to enhance the sensitivity. At higher energies (e.g. >10 TeV), limited by the effective area of the array, the sensitivity of the ARGO-YBJ experiment is much poorer than that at lower energies. Furthermore, the poor measurement of source spectrum at higher energies limited its physical capability. Benefiting from its high altitude and full coverage, the ARGO-YBJ experiment accurately measures the front structure of each detected shower. Thanks to this advantage, a new parameter is proposed to separate gamma-initiated showers from hadronic ones by using the time profile of the shower front. The method is checked in detail by a full Monte Carlo simulation. A much higher significance of VHE gamma ray emission from Crab Nebula (the standard candle) is observed once this method is used in data analysis, showing that this method greatly improves the sensitivity of the ARGO-YBJ experiment and more physical results are expected.

2 Event generation

The first stage in simulating the response of the ARGO-YBJ detector to EAS is the simulation of the production and propagation of EAS through the atmosphere. This is done using the CORSIKA (version 6616) software package[7]. All the simulated showers were thrown over a zenith angle range of 0° to 45° following a power law spectrum with index of 2.5 for γ-rays, 2.75 for protons and 2.68 for iron nuclei. The energy range for γ-ray showers is [0.1 - 100] TeV, while that of protons and iron nuclei is [1.0 - 10^4] TeV.

The simulation of the detector's response to EAS is done using G4Argo V2.1 developed by the ARGO-YBJ collaboration [8] supported by GEANT4 software package[9]. The core positions are randomly sampled over a large enough area centered on the central carpet of the ARGO-YBJ experiment. For each RPC hit, the G4Argo output includes the number of fired pad (N$_{hit}$), their time of arrival and position etc.

3 Gamma-hadron discrimination

The front of an EAS is actually not a flat plane, but is approximately a parabolic shaped disk [10] with apex at the intersection of showers axes and detector plane. Figure 1 shows the arrival time as a function of the distance to the shower core position for γ and proton primaries with almost same N$_{hit}$ range (e.g. here the number of fired pads N$_{hit}$ is 2078 for γ and 2079 for proton). It can be seen that the arrival time of the secondary particles increases with the increase of their distance from the shower axes both for γ-ray and proton, and the time delay is more evident for γ-ray than proton with almost same N$_{hit}$ range. Using this time feature, a new parameter called conical factor α is proposed to separate γ-ray showers from hadronic ones. The conical factor α is defined as the slope of the cone measured from the shower core which is also used as a fitting parameter applied to the direction reconstruction. Least square method is used in the direction reconstruction, during which the χ^2 equation is defined as

$$\chi^2 = \sum_{i=0}^{N} (t_i - \frac{lx_i + my_i + \alpha R_i + ct_0}{c})^2 \qquad (1)$$

Here $l = sin\theta cos\phi$, $m = sin\theta sin\phi$, $c = 29.98cm/ns$, α is the fitting parameter (i.e. conical factor). For the ith hit, its positon is (x_i, y_i) and t_i is the arrival time while R_i is the distance from the hit position to the axes of the showers. Since the core position reconstructed acts as fixed vertex when fitting the parabolic shaped shower front, the accuracy of the shower core affects the reconstruction accuracy of α. So only events with N_{hit} >500 (median energy above 8 TeV) undergo the following gamma-hadron discrimination method.

3.1 Event analysis

The analysis has been realized in the shower plane, using the core position and direction reconstructed by MEDEA++[11], while the conical factor α acts as a fitting parameter during the direction reconstruction. Only events meeting the following requirements are selected in data analysis:

- N$_{hit}$ >500
- Zenith angle θ <50°
- Distance of the core reconstructed from the detector's center R < 40 m

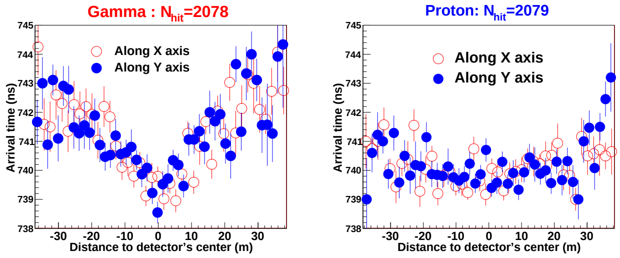

Figure 1: Arrival time of secondary particles in a vertical shower initiated by γ-ray (left) and proton (right) with core located at the center of the ARGO-YBJ detector as a function of the distance from the core position along X-axis and Y-axis.

Figure 2 gives the fitted conical factor α as a function of N$_{hit}$. Firstly, the conical factor increases synchronously with the increase of N$_{hit}$; Secondly, there is an obvious difference of α between γ-ray and proton at the same N$_{hit}$ ranges, which indicates its ability to separate γ-ray showers and proton ones. Finally, the conical factor of data (cosmic rays with all the compositions) lies between proton's and iron's as expected, ant it leaves the proton curve with increasing N_{hit}, hinting that this parameter is also sensitive to cosmic ray composition.

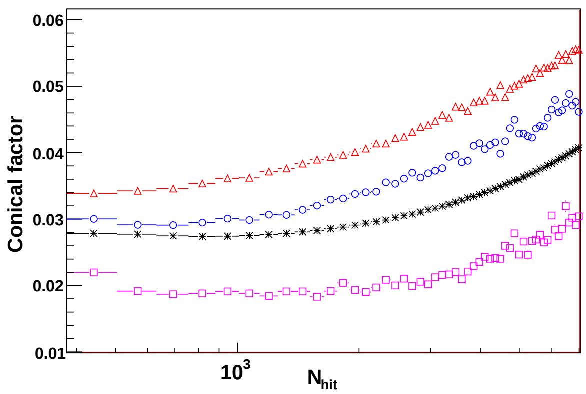

Figure 2: The conical factor as a function of N$_{hit}$ for γ-rays (red hallow triangular), protons (blue hallow circle dot) , iron nuclei (pink hallow diamonds) and data (black solid star).

3.2 The quality factor

The conical factor α is firstly corrected to α_{norm}

$$\alpha_{norm} = \alpha - (P0 + P1 * N_{hit} + P2 * N_{hit} * N_{hit})$$

Here P0, P1 and P2 are the fitted parameters of the γ-ray line in Figure 2 using a quadratic function, which are same for γ-ray and data. The events have been grouped into 5 multiplicity bins according to N_{hit}: [500-1000], [1000-1500], [1500-3000], [3000-6000] and [500-]. Figure 3 shows the distribution of α_{norm} of primary γ-ray and data at five different N_{hit} ranges. Looking at the α_{norm} distribution for data and gamma-rays their separation appears to grow steadily as N_{hit} increases. A cut value of α_{norm} (α^{cut}_{norm}) for background (abbr. bkg) rejection is got in each N_{hit} bin to maximize the quality factor, which is defined as $Q = \frac{\varepsilon_\gamma}{\sqrt{1-\varepsilon_{bkg}}}$, where ε_γ is the acceptance of γ-ray and ε_{bkg} is the rejection of background. Table 1 lists ε_γ and ε_{bkg} for the best Q factor.

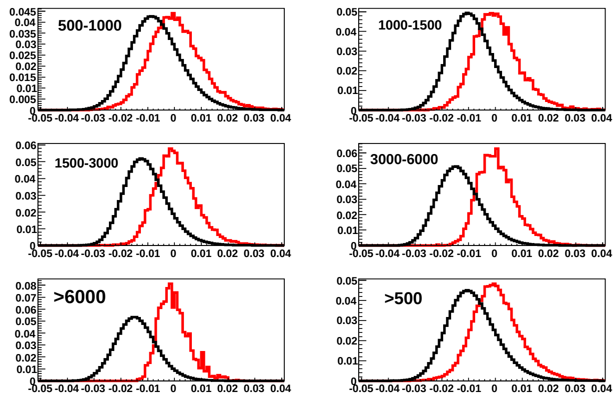

Figure 3: The distribution of α_{norm} (the horizontal (X) axis) at different N_{hit} ranges for γ-rays (red heavy line) and data (black heavy line). All of the histograms have been normalized to have unit entries(see the vertical (Y) axis).

N_{hit}	E_γ	α^{cut}_{norm}	$\varepsilon_\gamma(\%)$	$\varepsilon_{bkg}(\%)$	Q
500-1000	8.4	-0.0085	81.1	47.3	1.1
1000-1500	13.0	-0.0045	68.9	73.5	1.3
1500-3000	20.2	-0.0035	66.6	83.6	1.6
3000-6000	37.2	-0.0035	67.4	89.4	2.1
>6000	66.9	-0.0035	66.8	92.2	2.4

Table 1: The quality factor at different N_{hit} ranges. Here E_γ is the median energy (TeV) of γ.

Further study shows that the optimal cut value of α_{norm} varies with shower zenith angle θ. Table 2 shows the optimal Q factor in different zenith angle ranges. Since the Q factor becomes better for smaller zenith angle ranges than larger zenith angle ranges shown in table. It seems better to normalize the zenith angle of cosmic gamma-ray (simulation) and cosmic ray (data) to the orbit of the sources, like Crab Nebula, thus to get the best Q factor from Monte Carlo simulation and the cut value respectively.

The Crab Nebula acts as a standard candle in gamma-ray astronomy due to its long-term stable emission. The new discrimination parameter is tested on this source. The zenith angles of simulated γ-rays (as signal) and the

θ	N_{hit}	α^{cut}_{norm}	$\varepsilon_\gamma(\%)$	$\varepsilon_{bkg}(\%)$	Q
0-15°	500-1000	-0.0065	80.2	53.1	1.2
	1000-1500	-0.0025	66.2	78.6	1.4
	1500-3000	-0.0005	59.8	98.7	1.9
	3000-6000	-0.0005	59.6	94.3	2.5
	>6000	-0.0035	73.1	95.1	3.3
15-30°	500-1000	-0.0085	82.7	47.0	1.1
	1000-1500	-0.0035	66.0	77.0	1.2
	1500-3000	-0.0035	68.2	83.7	1.7
	3000-6000	-0.0025	63.7	91.4	2.2
	>6000	-0.0045	68.9	91.6	2.4
30-45°	500-1000	-0.0145	89.9	25.2	1.0
	1000-1500	-0.0085	76.3	58.6	1.2
	1500-3000	-0.0055	63.8	78.5	1.4
	3000-6000	-0.0075	78.4	79.3	1.7
	>6000	-0.0035	70.4	89.3	2.2

Table 2: The quality factor at different N_{hit} ranges for three zenith angle ranges.

ARGO-YBJ data (as background) are normalized to the zenith angle distribution of the orbit of the Crab Nebula to determine the cut value of α_{norm} at 5 different N_{hit} ranges. Table 3 lists the optimized Q factor, ε_γ and ε_{bkg}, according to which a Q factor of 1.3 is expected for all of the events with N_{hit} $>$500.

N_{hit}	ε_γ (%)	ε_{bkg} (%)	Q
500-1000	76.7	54.9	1.1
1000-1500	66.7	76.4	1.4
1500-3000	65.6	85.9	1.8
3000-6000	65.9	91.3	2.2
>6000	68.2	93.5	2.7

Table 3: The quality factor for the orbit of the Crab Nebula.

4 Results

The ARGO-YBJ data, acquired from the data taking process from day 1, 2008 to day 365, 2010, which continually accumulated to about 7505.7 hours (equivalent to 312.7 days), have been analyzed with the above-mentioned gamma-hadron discrimination method. The background has been calculated by the direct integration method[12]. The event selection is the same as mentioned in section 3.1. The significance of the Crab Nebula is calculated by Li-Ma formula [13]. Fig.4 shows the significance distribution over 4° × 4° around the Crab Nebula before and after applying the gamma-hadron discrimination method to N_{hit} range [500-1000] and [500-]. A clear improvement has been achieved using the selection of α. The significance before and after gamma-hadron discrimination is listed in Table 4. The Q factor is 1.3 (1.2) for N_{hit} range [500-1000] ([500-]) which is consistent with the Monte Carlo expectations.

A further check is done on the signal acceptance and the background rejection. Take N_{hit} range [500-1000] for example, the number of signal events in the window centered in the Crab Nebula position is 944 (831) before (after) applying the gamma-hadron discrimination method. This means that $\sim$88%$\pm$19% of the signal is accepted using this method. Similarly, the number of background events is 26215 (11922) without (with) gamma-hadron separation. This means that $\sim$55% of the background is rejected. Both are consistent with Monte Carlo expectation.

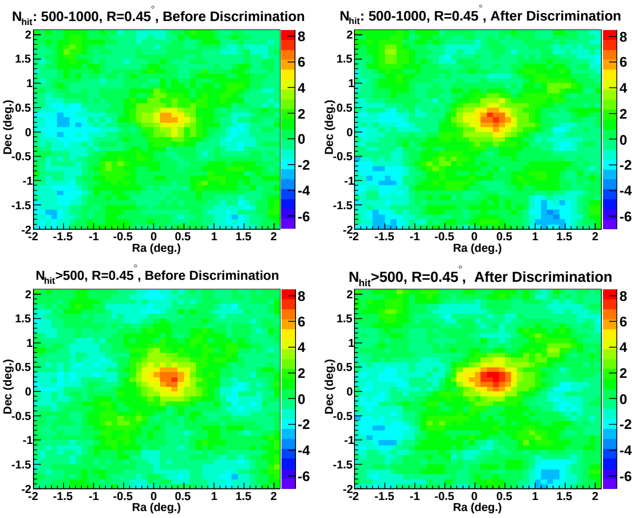

Figure 4: Significance map around the Crab Nebula with the α_{norm} cuts applied (the right two figures) or not (the left two figures). The smooth angle is 0.45° for each figure. The N$_{hit}$ range is [500-1000] for top two figures and [500-] for bottom two ones.

N$_{hit}$	S_{before}	S_{after}	Q
500-1000	5.8	7.5	1.3
> 500	7.1	8.4	1.2

Table 4: The Q factor of the maximal σ for the Crab Nebula data before and after the gamma-hadron discrimination.

5 Conclusion

A detailed information of the shower front measured by the full coverage ARGO-YBJ detector provides possible parameters to discriminate the showers induced by γ-rays and hadrons. Based on the time profile of the shower front, the conical factor α is proposed to separate gamma-initiated from hadron-initiated showers. The resulting Q factor from a detailed Monte Carlo study is about 1.3 for a Crab-like source. The application of the gamma-hadron discrimination method increases the significance 7.1σ of TeV gamma-ray emission from the Crab Nebula to 8.4 σ ($N_{hit} > 500$) for nearly 3 years data taking, which is consistent with the expectations from Monte Carlo simulation. Thus the sensitivity of the ARGO-YBJ experiment is significantly improved, and more physical results are expected. It's worth to point out that the discrimination parameter α is also sensitive to cosmic ray compositions.

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References

[1] Fegan David J., Journal of Physics G: Nuclear and Particle Physics, 1997, **23**(9): 1013-1060

[2] Hillas A. M., Space Science Reviews, 1996, **75**(1-2): 17-30

[3] Br$\ddot{u}$ggemann M., et al., 30th ICRC, 2008, **4**: 207-210

[4] R. Atkins, et al., ApJ, 2003, **595**(2): 803-811

[5] Abdo A.A., ApJ, 2007, **658**(1): 33-36

[6] G. Aielli, et al., Nucl. Instr. and Meth. A, 2006, **562**: 92-96

[7] Heck D., et al., Forshungszentrum Karlsruhe, Report FZKA 6019 (1998).

[8] Y. Q. Guo, et al., Chinese Physics C, 2010, **34**(5): 555-559

[9] http://geant4.web.cern.ch/geant4

[10] G. Di Sciascio, et al., Astropart. Phys., 1997, **6**(3-4): 313-322

[11] C. Bleve, et al. ArgoYBJ-Note, 2003**002**

[12] R. Fleysher, et al., ApJ, 2004, **603**(1): 355-362

[13] T. P. Li and Y. Q. Ma, ApJ, 1983, **272**(1): 317-324