Study of gamma-hadron discrimination for the ARGO-YBJ experiment

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Abstract: Very High Energy Gamma Astronomy is one of the scientific aims of the ARGO-YBJ experiment (YangBaJing, P.R. China), an extensive air shower detector made of a single layer of Resistive Plate Chambers (RPC's) covering a surface of about 6700 m^2. The exploitation of the full coverage approach (93% of active area) together with the very high altitude location (4300 m a.s.l.) allows to put the energy threshold as low as few hundreds of GeV. ARGO-YBJ can detect showers within a primary energy range partially overlapping that of Čerenkov Telescopes, with the advantages of a larger field of view and a duty cycle close to 100%; this means, for example, that the observation of variable sources (e.g. the AGN's Mrk-421 and Mrk-501) is feasible also when Čerenkov detectors are blind due to the relative position of the source with respect to the Sun.

A gamma ray source is revealed if a statistically significant excess of events is detected from a certain direction above the huge and isotropically distributed background due to the charged cosmic rays. A technique for sorting out the showers induced by gamma primaries from the hadron-induced ones, combined with a good angular resolution, is a crucial issue for increasing the sensitivity of the detector, allowing to reject as much background as possible. In this paper we discuss the capability of ARGO-YBJ to perform gamma-hadron discrimination on the basis of the very detailed information available -thanks to the high granularity of the detector- on the space pattern of the electromagnetic component of the shower.

Introduction

The ARGO-YBJ experiment is designed to detect galactic and extra-galactic gamma ray sources with an energy threshold of a few hundreds of GeV. A gamma source is revealed if an excess of events coming from a certain direction is detected with statistical significance above the overwhelming cosmic ray isotropic background, so the sensitivity of a ground based gamma-ray detector can be expressed in units of standard deviations of the cosmic rays (CR's) background:

$$S = \frac{N_\gamma}{\sqrt{bkg}} = \frac{\int_{E_{th}} J_\gamma(E)\cdot A^\gamma_{eff}\cdot T\cdot\epsilon(\Delta\Omega)\cdot dE}{\sqrt{\int_{E'_{th}} J_{bkg}(E)\cdot A^{bkg}_{eff}\cdot T\cdot\Delta\Omega\cdot dE}}\cdot Q_f$$

where J_γ and J_{bkg} are γ and CR's differential fluxes, A^γ_{eff} and A^{bkg}_{eff} are the effective areas to reveal γ and CR-induced showers, T is the effective observation time of the source, depending on the real time of observation, on the duty cycle of the detector and on the time spent by the source within the detector field of view, $\Delta\Omega$ is the solid angle of observation, related to the angular resolution σ_θ [1], and Q_f is the so-called quality factor (see below). The integral has to be computed above the energy thresolds to reveal γ and CR-induced showers, and it has to be averaged on the different zenith angles on the source path. The quality factor Q_f is defined as:

$$Q_f = \frac{\epsilon_\gamma}{\sqrt{1-\epsilon_{bkg}}}$$

where ϵ_γ is the fraction of showers induced by photons correctly identified as signal by some discrimination criterion and $(1-\epsilon_{bkg})$ is the background contamination, i.e. the fraction of events

1. If the point spread function of σ_θ is gaussian, the opening angle maximizing the $signal/\sqrt{noise}$ ratio is given by $\Delta\theta = 1.58\cdot\sigma_\theta$ and the fraction of events coming from the direction of the source within the solid angle $\Delta\Omega$ is $\epsilon = 0.72$, so $\frac{\epsilon(\Delta\Omega)}{\sqrt{\Delta\Omega}} = \frac{0.45}{\sigma_\theta}$.

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induced by hadrons erroneously identified as γ-induced ones. Both the angular resolution and the quality factor enlarge the detector sensitivity allowing to reject part of the background: a good reconstruction of the arrival direction reduces the sky region contributing to the background level and produces a more narrow spatial distribution of the signal, while the quality factor is related to the capability of discriminating signal from background on the basis of the differences between showers induced by photons and by hadrons. Atmospheric Čerenkov Telescopes have brilliantly solved the problem of background rejection with a discrimination technique based both on shape and orientation of the image of the shower on the instrument [6]. Extensive Air Showers (EAS) arrays (e.g. CASA and CYGNUS experiments), instead, have developed rejection techniques tipically based on the very different muon content in the cascades initiated by gammas and by hadrons, mainly evident in showers generated by primary particles of energy above some tenths of TeV. The MILAGRO collaboration has definded a γ-hadron discrimination method based on the different lateral distribution of the energy deposited in the detector [2].

For the ARGO-YBJ experiment some gamma-hadron discrimination (GHD) techniques have been developed: a GHD method based on the study of the distribution of the hits and of the fluctuations on the detector by means of a neural network is described in [4], a GHD method based on the multifractal nature of the image of the shower on the detector can be found in [9]. In this paper we present a GHD algorithm based on the study of the compactness and uniformity properties of the lateral disribution of the electromagnetic component of the shower.

Detector layout

The ARGO-YBJ experiment is located at the High Altitude Cosmic Ray Laboratory of YangBaJing (longitude $90.53°E$, latitude $30.11°N$, 4300 m a.s.l.). ARGO-YBJ is a modular detector, the basic module being the cluster ($5.7 \times 7.6\ m^2$), divided into 12 RPC's ($2.8 \times 1.25\ m^2$ each) [1]. Each chamber is read by 80 strips ($6.75 \times 61.8\ cm^2$ each), logically organized in 10 indepenent pads of dimension $55.6 \times 61.8\ cm^2$ which are individually acquired. The full detector is composed by 154 clusters, corresponding to a total active surface of $\simeq 6700\ m^2$: a central full coverage carpet made up of 10×13 clusters is enclosed by a guard ring partially instrumented (40%) in order to enlarge the active area and improve the capability to tag internal and external events. The detector will be covered by a $0.5\ cm$ thick layer of lead to convert some of the secondary gamma rays in $e^+ - e^-$ pairs, reducing the time spread of the shower front and improving the angular resolution. A more detailed description of the detector, of its performances and of the first obtained results can be found in [8] and references therein.

The rejection technique

To perform γ-hadron discrimination, ARGO-YBJ can exploit its great peculiarity of being a full-coverage detector with a very good spatial resolution. Differently from traditional EAS arrays which sample the particle density at different distances from the shower core, ARGO-YBJ detects in a very detailed way the structure of the shower on a large area, thus allowing the study of the region close to the shower core, where the showers induced by gamma and by hadrons show the most evident differences (see fig.1).

The sample of events used in this work has been generated by means of the MonteCarlo simulation program CORSIKA 6.2 [5]: $3.8 \cdot 10^5$ gamma and proton [2] events have been simulated within the energy range $[1, 100]\ TeV$, with a primary energy spectrum generated according to power laws with spectral index -2.7 for protons and -2.5 for γ - according to the CRAB spectrum measured by the WHIPPLE collaboration [7], with azimuth angle between 0 and 40 degrees and core at the detector center. The detector response has been simulated by using ARGOG, a tool developed within the ARGO-YBJ collaboration and based on the GEANT3 package. The analysis has been made in the shower plane, using the arrival direction and the core position reconstructed by the ARGO-YBJ

2. As a first approximation, we assume that the contribution of primary nuclei heavier than protons can be neglected.

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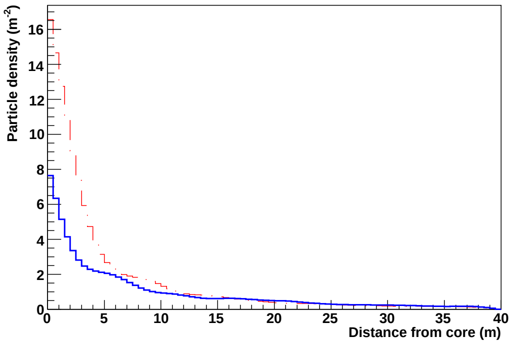

Figure 1: Lateral distributions of the electromagnetic component of two showers producing the same number of hits ($\simeq 1600$) on the ARGO-YBJ carpet (red, dotted-line: primary γ of E=5.12 TeV; blue, continuous line: primary proton of E=10.3 TeV);

collaboration analysis program MEDEA++. Only events with reconstructed $\theta < 35^o$ have been analized, to avoid border effects.

The events have been grouped in 4 multiplicity windows (see table 1) according to the number of fired pads on the detector, requiring at least 100 fired pads on the central carpet.

The GHD method has been tuned on half of the simulated sample and its efficiency has then been checked on the remaining sample.

The parameters used by the GHD algorithm are essentially based on the more evident compactness and smoothness of showers induced by photons respect to the proton-induced ones. For each event a region symmetrical respect to the reconstructed core position and entirely included in the central carpet has been fixed. Let's call R_{spot} the radius of such a region and $Nhits_{in}$ the number of fired strips within R_{spot}. The study of the pattern of the hits in R_{spot} has lead to the definition of 5 discrimination parameters related to the compactness of the shower:

1. the mean distance (R_m) of the fired pads from the reconstructed core position weighted on the strip multiplicity of each pad;

Pad multiplicity	$< E_\gamma >$ (TeV)	γ events
$100 \div 300$	2.3	43829
$300 \div 1000$	4.0	27516
$1000 \div 3000$	9.6	8476
$3000 \div 6000$	25.0	2217

Pad multiplicity	$< E_p >$ (TeV)	p events
$100 \div 300$	3.3	41267
$300 \div 1000$	5.6	26162
$1000 \div 3000$	14.9	6656
$3000 \div 6000$	39.2	1765

Table 1: MonteCarlo sample of events. The mean energy values have been calculated on the simulated sample.

2. the slope of the line fitting the dimension of regions containing different percentages (R_n, where n is the chosen percentage value) of $Nhits_{in}$ as a function of n;

3. the slope of the line fitting the mean distance from the core in R_n as a function of n;

4. the ratio between the number of fired strips in the 10 hottest modules and the number of fired strips in the following 20 hottest modules, where a module is defined as a group of 3 adjacent chambers;

5. the ratio between R_m and $R_{m,20}$, the latter being the mean distance from the core within the region including 20% of $Nhits_{in}$.

A further discrimination parameter connected to the uniformity expectd in the spatial distribution of the electromagnetic component in γ-induced showers has been defined: R_{spot} has been divided in 180 sectors and the total fluctuation has been calculated as the sum of the fluctuations in each sector respect to a uniform distribution.

The chosen set of parameters has been combined by means of Fisher Linear Discmininant Analysis (LDA) [3], a simple and fast parametric method giving the linear combination of parameters which best separetes two classes maximizing the between-classes variance respect to the within-class variance. The method has been implemented so that the cut which maximizes the separation between the two populations is in 0. The position of

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the cut has than been moved in order to maximize the ratio between the signal and the fluctuations of the noise. Fig. 2 shows an example of the obtained discrimination function distribution.

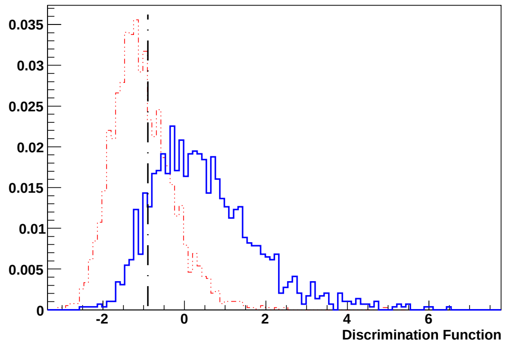

Figure 2: Distributions of the linear combination of the discrimination parameters for γ (red, dotted-line) and proton (blue, continuous line) induced showers with hit multiplicity within the range $[1000, 3000]$ on ARGO-YBJ carpet. In the shown example the cut has been set in Discr.Func.=-0.9 to maximize the$signal/\sqrt{noise}$ ratio.

The obtained results for the 4 pad multiplicity windows are listed in tab 2. The overall discrimination power, obtained calculating the ratio between the detector sensitivity with and without the application of the described GHD method, is $Q \sim 1.7$.

PadMultiplicity	Q	ϵ_γ	ϵ_p
$100 \div 300$	1.45 ± 0.04	0.63	0.81
$300 \div 1000$	1.68 ± 0.11	0.53	0.90
$1000 \div 3000$	1.97 ± 0.26	0.58	0.91
$3000 \div 6000$	1.98 ± 0.28	0.78	0.84

Table 2: Results obtained for the quality factor for different values of the pad multiplicity on the central carpet.

Conclusions

A γ-hadron discrimination method based on the study of the spatial distribution of the electromagnetic component of γ and proton-induced showers has been implemented by means of linear discriminant analysis. The application of such a discrimination techique enlarges ARGO-YBJ sensitivity of a factor ~ 1.7, compatible with the overall previous results in [4] and [9].

The definition of discrimination parameters taking into account the information about the temporal structure, as well as completely different discrimination methods based on the pattern of the hit distribution with techniques typical of image analysis are currently under investigation.

Acknowledgements

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