Event selection to improve ARGO-YBJ sensitivity to gamma sources using Crab as a standard candle

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***Abstract*. Since the end of 2007 the ARGO-YBJ experiment has been observing the Crab Nebula with a duty cycle larger than 90%. Crab is a well known source of gamma rays in the TeV region. The data sample of events coming from the source contains a fraction of gamma rays with a known energy spectrum. Using this data sample we implemented selection criteria that increase the sensitivity of the experiment to point-like gamma ray sources. In this work the results of more than one year of Crab observation and the selection method used to improve the ARGO-YBJ sensitivity are presented.**

***Keywords*: Crab, Gamma-Ray, EAS**

I. Introduction

The brightest and best known gamma rays source detected at TeV energies is the Crab Nebula. This plerion is the remnant of a supernova exploded in 1054. At its center there is a young optical pulsar surrounded by about 4 pc extended nebula. Since the Crab Nebula flux is strong and stable, it is defined as the *standard candle* of the Gamma Ray astronomy. Its detection, therefore, plays a crucial role for ground based detectors that can calibrate their sensitivity and energy scale using the well known flux of gammas coming from the Nebula.

II. The ARGO-YBJ detector

ARGO-YBJ is located near the YangBaJing village in Tibet (China) 4300 $a.s.l.$ It is an air shower array exploiting the full coverage approach at very high altitude, with the aim of studying the cosmic radiation with a low energy threshold (a few hundreds GeV).

The detector consists of a full coverage array made of a 78×74 m^2 single layer of RPCs operated in streamer mode. The central carpet is surrounded by a sampling ring with other 1000 m^2 equipped with RPCs.

The basic DAQ unit is the cluster, a set of 12 RPCs, read out by a single local station. The detector is logically divided into 153 clusters, 130 in the central carpet while the remaining 23 in the sampling ring. Each RPC is read out using 10 PADs (62×56 cm^2), each divided into 8 strips (62×7 cm^2). The PAD is the minimal unit that defines the time granularity of the detector while the strip area defines the space granularity of the detector. All the events giving a number of fired pads $N_{PAD} \geq N_{trig}$ in the central carpet in a time window of 420 ns are recorded. Since November 2007 the detector has been in stable data taking with a trigger multiplicity threshold $N_{trig} = 20$ and a duty cycle of about 95% with a event trigger rate of 4 kHz.

The shower direction is reconstructed using the time of the first particle detected by each PAD while the position of the shower core and the lateral density profile of the shower are reconstructed using the number of fired strips in each PAD.

III. Sensitivity to a point gamma ray source

Assuming that the Crab Nebula is a point source, all the events detected from the source come from its nominal position, while their reconstructed directions are distributed around the source position because of the finite angular resolution of the detector. To detect the source and to study its flux, as in the analysis of other ground based detectors, an angular bin $\Delta\Omega$ is selected in the sky, centered on the source position. Its optimal size must be determined to retain as little of the background as possible while keeping the largest fraction $\epsilon(\psi_b)$ of signal events associated with the source. In the case of round bin $\Delta\Omega = 2\pi(1 - cos\psi_b)$ where ψ_b is the optimal half-opening of the bin and depends on the angular resolution of the detector.

Therefore, the sensitivity to a point like source can be defined as:

$$S = \frac{N_\gamma}{\sqrt{N_{bck}}} G(\psi_b)$$

where N_γ is the number of signal events observed per time unit and N_{bck} is the number of background events per steradians per time unit.

The angular resolution of the detector appears in the expression of the sensitivity through the factor:

$$G(\psi_b) = \frac{\epsilon(\psi_b)}{\sqrt{2\pi(1 - cos\psi_b)}}$$

It can be demonstrated [1] that, if the Point Spread Function (PSF) of the detector is a two-dimension Gaussian with standard deviation σ, then the optimal half-opening of the bin is $\psi_b = 1.58\sigma$ and $\epsilon(\psi_b) = 0.715$.

To increase the sensitivity can be useful to select events better reconstructed. An event selection can improve the detector PSF but does not necessarily imply an increase of the detector sensitivity. In fact, assuming that the PSF of the detector is still a two-dimension Gaussian even after the cuts, and that the cut rejects the same fraction of signal and background events, the detector sensitivity after the cuts, compared to the unperturbed one is given by:

$$\frac{S^{cut}}{S} = \sqrt{\epsilon^{cut}} \frac{G(\psi_b^{cut})}{G(\psi_b)}$$

where ϵ^{cut} is the fraction of the events passing the selection and the best half-opening of the bin (ψ_b) for selected and un-selected events is not the same. Because $\sqrt{\epsilon^{cut}}$ is smaller of 1 by definition this quantity just shows the improvement of the angular resolution due to the selection criterion with respect to the unperturbed one.

In figure 1 is reported the increase of the detector sensitivity when applying a selection based on the time spread of the shower front. The estimator used for it is $< FT^2 >$, defined as:

$$< FT^2 >= \frac{\sum_i (time_i^{PAD} - f(x_i, y_i))^2}{N_{PADs}}$$

where $time_i^{PAD}$ is the time of the first particle crossing the i-th PAD, $f(x, y)$ is the fitted time front of the shower, $x_i,\ y_i$ are the coordinate of the center of the i-th PAD and N_{PADs} is the total number of fired PADs in the event.

The increase of the sensitivity shown in Figure 1 is mainly due to the improvement of the Point Spread Function (PSF) induced by the event selection. As an example, the optimal half-opening of the bin in the sky (ψ_b) in the energy range $1.5 - 5\ TeV$ is 1.2^o if events with $< FT^2 >< 100$ are selected and becomes 0.85^o if the selection criterion used is $< FT^2 >< 10$. Figure 1 shows that the same cut works in different way on showers induced by primaries of different energy.

Among the experimental observables investigated to increase the detector sensitivity, the best results has been obtained using a selection based on $< FT^2 >$ and on the distance of the reconstructed shower core from the detector center.

IV. Energy estimation

As shown, the effectiveness of a criterion enhancing the sensitivity depends on the energy of the primary particle inducing the shower. Therefore, a good estimation of the energy is essential to implement an event selection criterion.

The simplest parameter related with the primary energy is the number of particles detected that, for ARGO-YBJ, is well correlated with the total number of fired strips ($nStrips$). But the large fraction of showers with

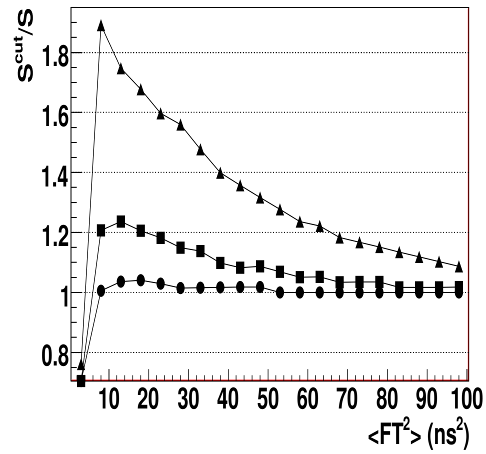

Fig. 1. Increase of the sensitivity due to a cut on the average square time width of the shower front ($< FT^2 >$). The values of sensitivity amplification factor has been obtained selecting showers with $< FT^2 >$ less than the corresponding value in the x-axis. (triangles primary Monte Carlo energy greater of $5\ TeV$, squares $1.5 - 5\ TeV$, circles less than $1.5\ TeV$. Events are simulated with a Crab-like spectrum)

the core outside the detector that pass the trigger condition produces a large uncertainty in the $nStrips$ - energy correlation. On the other hand, selecting only internal showers could be not always convenient in the study of gamma ray source because this cut reduces the effective area of the detector and, therefore, its sensitivity.

A better method to estimate the total number of particles at detector level is to use the theoretical information about the shape of the lateral density distribution of the charge particles. The widely used Nishina-Kamata-Greisen (NKG) function is the approximate analytical solution of the cascade equation [2] and provides a prediction about the expected density distribution.

According to Monte Carlo simulations, the particle density at a distance R from the shower axis can be described as:

$$\rho(R) = f(\frac{R}{R_M}) \frac{\eta}{(R_M)^2}$$

where R_M is the modified Moliere radius, η is the shower size at detector level and f is a fixed function obtained from Monte Carlo simulation that has been adopted to describe the lateral distribution of the showers regardless of their energy([3]).

The dependence on the primary energy and on the fluctuation in the first interaction point in the atmosphere is absorbed in the η factor (total size of the shower). This assumption simplifies the calculation of the size that can be shown to be described, from an experimental point of view, as:

$$\eta = \frac{nStrips}{A \sum_k f_k}$$

where A is the surface of a PAD, f_k is the value of the $f(\frac{R}{R_M})$ function calculated in the center of k-th PAD

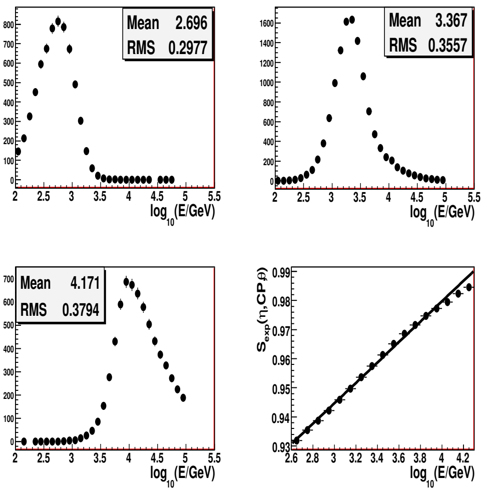

Fig. 2. Distribution of $log_{10}(E/GeV)$ of Monte Carlo showers produced with a Crab like energy spectrum for 3 different cut in $S_{exp}(\eta, CP, \theta)$ (first three panels: top left $S_{exp} < 0.94$, top right $0.95 < S_{exp} < 0.97$, and $S_{exp} > 0.98$) In the last panel the correlation between the Monte Carlo energy and S_{exp} is shown

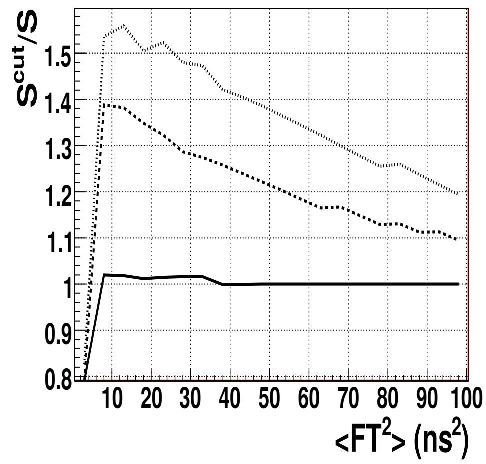

Fig. 3. Increase of the sensitivity due to a cut on the average square time width of shower front ($< FT^2 >$). The values of sensitivity amplification factor has been obtained selecting showers with $< FT^2 >$ less than the corresponding value in the x-axis. (line $E = 500\ GeV$; dash $E = 2\ TeV$; dot $E = 15\ TeV$)

starting from the shower core position and the sum is extended on all the detector PADs (fired and not).

We introduce a Compactness Parameter (CP) to account for the fluctuations introduced by the not correct estimation of the core position for showers with the core outside the detector. CP is defined has:

$$CP = \frac{\sum_k dist(CoG, PAD_k) nStrips_k^{PAD}}{nStrips}$$

where $dist(CoG, PAD_k)$ is the distance of the k-th fired PAD from the Center of Gravity (CoG) and $nStrips_k^{PAD}$ is the number of fired strip of the k-th PAD. CoG identifies the density center of the event as seen by the detector. CP is a kind of average dimension of the shower seen by the detector.

The correction for the attenuation in the atmosphere due to different atmospheric depths seen by the showers for different zenith angle has been take into account by applying a Constant Intensity Cut (CIC) in the observed flux and by parameterizing an attenuation function. The flux has been normalized to the flux seen at a zenith angle of 36^o.

The obtained energy estimator $S_{exp}(\eta, CP, \theta)$ is function of the reconstructed total size η, the Compacteness Parameter (CP) and of the reconstructed zenith angle of the shower θ.

$S_{exp}(\eta, CP, \theta)$ is defined as:

$$S_{exp} = \frac{\eta \times CP}{a + b(cos^2(\theta) - cos^2(36^o))}$$

where a and b are estimated by an empirical fit of the collected data in order to obtain the same flux in different bins of $cos^2(\theta)$ (CIC).

Figure 2 shows the distribution of the energy of Monte Carlo gamma induced showers for different bins in $S_{exp}(\eta, CP, \theta)$ and the correlation between the Monte Carlo energy and the energy estimator. The obtained energy resolution ($\frac{\Delta E}{E}$) is about 70% in the range $500\ GeV$, $10\ TeV$.

V. The event selection

The detector sensitivity, for different event selections and in different bins of S_{exp} can be estimated using the known flux of the Crab Nebula.

$1.4 \cdot 10^9$ showers induced by gamma ray have been simulated using CORSIKA [4], for the development of the shower in the atmosphere, and a GEANT3 based code, for the detector response. The energy distribution of the simulated sample reproduces the Crab Nebula spectrum with a spectral index of -2.49 [5].

Figure 3 shows the increase of the sensitivity obtained after applying a cut on $< FT^2 >$ for three different energy ranges selected by using the S_{exp} (defined in the previous section). The increase in sensitivity due to the $< FT^2 >$ selection is evident. With respect to Figure 1 there is a deterioration of the performance coming from the use of the estimated energy, with its uncertainty, instead of the Monte Carlo one.

VI. The Crab Nebula analysis

The analysis procedure was tested with the Crab Nebula, the standard candle for VHE astronomy.

At the YangBaJing latitude the Crab Nebula culminates at zenith angle $\theta_{culm} = 8.1^o$ and it is observable every day for 5.8 hours with a zenith angle $\theta < 40^o$. The Crab Nebula was observed from 2007 November to 2009 March, for a total of 424 days on source.

The average number of gamma rays detected per day in the observational window centered on the source

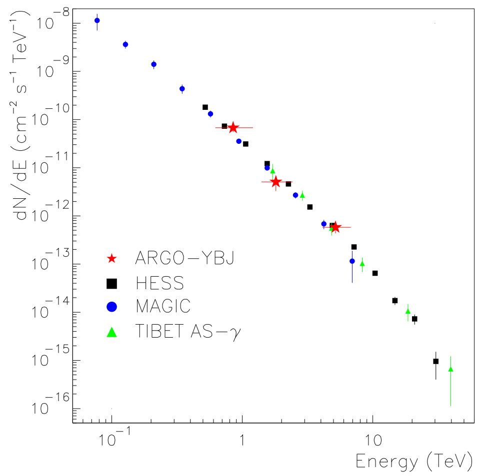

Fig. 4. ARGO-YBJ measured Crab spectrum and comparison with the results of some other detectors

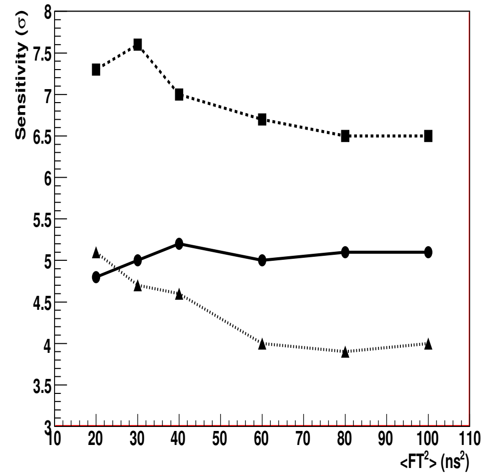

Fig. 5. The values of the obtained statistical significance(S) of the events excess in the direction of the nominal position of Crab is plotted selecting showers with $< FT^2 >$ less than the corresponding value in the x-axis. (circles $E = 500\ GeV$, squares $E = 2\ TeV$ and triangles $E = 15\ TeV$)

position is 128 ± 24 for $N_{pad} > 40$. The data can be fitted to a power law spectrum:

$$dN/dE = (3.7 \pm 0.8) \times 10^{-11} E^{-2.67 \pm 0.25} \\ (\gamma rays\ cm^{-2} s^{-1} TeV^{-1})$$

in fair agreement with other observations (Fig. 4).

To test the selection criteria in the analysis procedure, we divided the collected data in three sub-samples with different ranges of the energy related (S_{exp}) parameter defined in the previous section. The three data subsets correspond to a median primary energy of $500\ GeV$, $2\ TeV$ and $15\ TeV$ respectively.

With no event selection the Crab is visible with a statistical significance of about 4, 5 and 3.5 standard deviations in the three energy bins.

We obtain an increase of the statistical significance of the Crab signal in the three bins of energy applying the $< FT^2 >$ cut (Fig. 5), in good agreement with what expected from the simulation.

Applying cuts on the width of the arrival time distribution of the shower front for events of energy larger than $1\ TeV$ can improve the ARGO-YBJ sensitivity to point-like sources. These improvements, in agreement with Monte Carlo simulation, are mainly due to selection of events better reconstructed. Using the proposed estimator of the showers energy the best results has been obtained for showers of energy of about $2\ TeV$ where the sensitivity of ARGO-YBJ is maximal.

This new approach in data analysis can improve the ARGO-YBJ sensitivity to point like source by a factor $1.2 - 1.4$ and can be used in combination with hadron/gamma discrimination techniques ([6]).

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