A new analysis strategy for Imaging Atmospheric Cherenkov Telescopes

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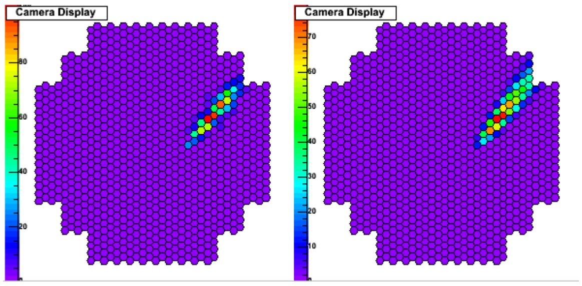
***Abstract*. Tremendous progress has been achieved in the field of VHE γ-ray astronomy in recent years, thanks to the new generation of Imaging Atmospheric Cherenkov Telescopes (IACT). The major keys to this success have been the better angular resolution and the much improved discrimination power against the abundant cosmic-ray background, especially in the case of stereoscopic arrays which offer a multi-dimensional view of the atmospheric showers. The detection of sources at the level of 1% of the Crab Nebula flux requires several tens of hours with arrays such as H.E.S.S. or VERITAS, given their nominal sensitivity. As the sensitivity is affected by the aging of the mirrors and the subsequent increase in threshold energy, the observation time needed for detection of very low-flux sources or new classes of γ-ray emitting sources, or that for detailed morphological studies of extended sources can become prohibitive. A new and powerful rejection strategy, based on a multi-variate combination of previously-known and newly-derived discrimination variables, using the physical shower properties as well as its multiple images will be presented. The performance and the stability of the method will be discussed through application to data on published H.E.S.S. faint sources.**

***Keywords*: Multi-variate analysis, γ/hadron discrimination, weak γ-ray sources.**

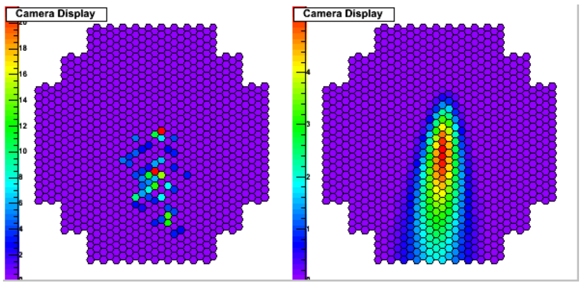
I. Introduction

A new analysis procedure has been developed for atmospheric Cherenkov telescopes optimised for the detection of *weak* sources i.e. sources having a flux level of the order of less than 1% of the Crab Nebula. The new analysis is based on a multi-variate discrimination procedure, where we a set of nine γ/hadron discrimination parameters have been used. All the defined parameters take advantage of two different reconstruction algorithms, the first being the Hillas procedure [1] which parametrises the detected γ-ray images as ellipses, and the second being a 3-dimensional γ-ray model minimisation (Model3D) [2] which parametrises the shower properties.

The Hillas procedure allows to define a *Mean Scaled Length* (MSCL) and a *Mean Scaled Width* (MSCW) [3] for a given shower, but does not take into account the correlations between images of the same shower in different telescopes. On the other hand, the γ-ray model minimisation does include that information, and allows the definition of some intrinsic shower parameters: for instance its physical width, the error on the latter and the shower maximum depth. In addition to the above variables, four new ones have been defined and will be presented hereafter.



(a) γ-ray



(b) hadron

Fig. 1. Detected cleaned images are shown on the left for a simulated γ-ray (a) and for a real hadron (b). The predicted image given by the γ-ray model minimisation is shown on the right panels.

II. A new set of γ/hadron discrimination variables

The main aim for developing new robust discrimination variables is to take advantage of the differences between γ-ray and hadronic showers without recourse to χ^2/likelihood-type discrimination methods which tend to be dependent on the Night Sky Background (NSB) level and hence need detailed calibration.

Due to the difference in the shower development, especially regarding its azimutal symmetry/asymmetry, the fit of a hadronic shower with a γ-ray model (as for instance [2]) leads to incoherences between the predicted shower images and the observed or absent ones in the telescopes (see Fig. 1). These can be exploited both at the level of the 3-dimensional shower reconstructed properties and through information carried by each image in the different telescopes.

The images predicted by the γ-ray model minimisation can be used to define Hillas ellipses (here called *HillasModel* images) and scaled parameters as in the standard reconstruction, but in addition introduce the correlation information within the discrimination procedure.

The first variable is based on the expected difference in the space angle between the two reconstructed shower directions when using *Hillas*$_{57}$ and the *HillasModel*$_{57}$[1] ellipses:

$$\Omega_{57} = \mathrm{acos}(\overline{\mathrm{v}}_{\mathrm{Hillas}_{57}} \cdot \overline{\mathrm{v}}_{\mathrm{HillasModel}_{57}}) \qquad (1)$$

The shift in the mean value of the Ω_{57} distributions (see Fig. 2) is due to the fact that the difference in the major axes of the two ellipses is small for a well-fitted γ-ray and larger for a bad-fitted hadron.

The second and third new parameters take advantage of the variation in the shape of the *Hillas*$_{57}$ and *HillasModel*$_{57}$ ellipses. The lengths ℓ_i and widths w_i of the *HillasModel*$_{57}$ ellipses are then used to define a *Mean Scaled Model Length* (MSCML)

$$\frac{1}{\mathrm{N_{Tels}}} \sum_{\mathrm{i=1}}^{\mathrm{N_{Tels}}} \frac{\ell_{\mathrm{i}} - \overline{\ell}}{\sigma_\ell} \qquad (2)$$

and a *Mean Scaled Model Width* (MSCMW):

$$\frac{1}{\mathrm{N_{Tels}}} \sum_{\mathrm{i=1}}^{\mathrm{N_{Tels}}} \frac{\mathrm{w_i} - \overline{\mathrm{w}}}{\sigma_{\mathrm{w}}} \qquad (3)$$

where $\mathrm{N_{Tels}}$ is the number of telescopes having a predicted image, and $\overline{\ell}$, σ_ℓ and $\overline{\mathrm{w}}$, σ_{w} are obtained from MC simulations (as usual) and represent the mean values and the deviations of the standard Hillas length and width, respectively. The two scaled parameters are shown in Fig. 2: their discrimination power is clearly visible (especially for MSCMW). It should be noted that as opposed to classical scaled parameters, the model-based ones include the correlation information between telescopes.

The last new parameter is based on the idea that hadron images are made up of distinct clusters corresponding to the development of subshowers and to the presence of muon rings. For the cleaned image a core (or a *biggest cluster*) can be defined as the part of the image having the largest charge. The *biggest clusters* of the images detected in each telescope are then used to reconstruct an additional shower direction called *Hillas*$_{BC}$, and the angle formed by this shower and the standard reconstructed Hillas shower *Hillas57*

$$\Omega_{\mathrm{BC}} = \mathrm{acos}(\overline{\mathrm{v}}_{\mathrm{Hillas}_{57}} \cdot \overline{\mathrm{v}}_{\mathrm{Hillas_{BC}}}) \qquad (4)$$

can be used as an additional discriminant parameter (see Fig. 2d).

III. Validation of discrimination variables

The robustness of the discrimination variables has been validated through a careful comparison between real data and MC. In order to do so, γ-rays with a

[1]The index 57 denotes the image cleaning level of 5 p.e. for the boundary threshold and 7 p.e. for the picture threshold [3].

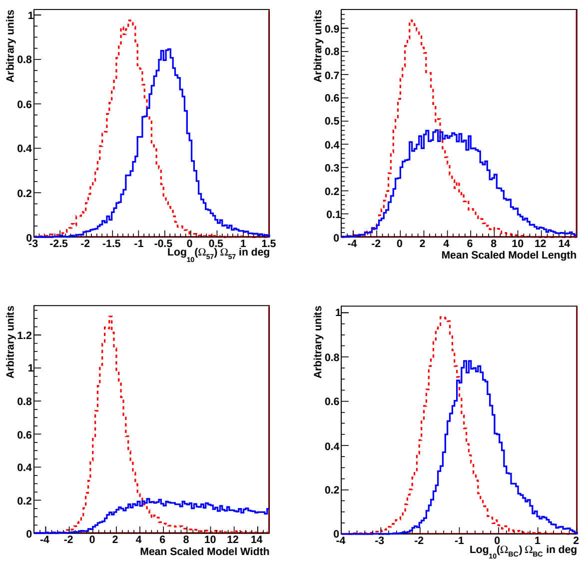


Fig. 2. The four new γ/hadron discriminating variables are shown for γ-ray simulations (red/dashed curves) and real data (blue/full curves). Upper left: Ω_{57}; upper right: Mean Scaled Model Length; lower left: Mean Scaled Model Width; lower right: Ω_{BC}.

spectral index of 2.6 at a zenith angle of 46° have been simulated and their distributions have been compared with the real Crab Nebula γ-rays. The result of the comparisons is shown in Fig. 3: a general good agreement is found on the shape of the distributions, and the small deviations seen for MSCW (Fig. 3b) and Ω_{BC} (Fig. 3i) are probably due to calibration issues.

As our aim is to define and use robust γ-ray/hadron discrimination parameters, their NSB dependence has also been checked: no significant effect in the shape of the distributions is seen for background rate levels of less than 200 MHz.

IV. Multi-variate analysis

In order to achieve the best rejection capability the 4 parameters introduced above together with the five already available ones have been input into a multi-variate training machinery using the *Boosted Decision Trees* (BDT) implemented in TMVA tool-kit [4]. The simulated γ-ray sample and the data used for the training phase both contain 2.1×10^4 events: the γ-ray shower simulation has been chosen to have a hard spectral index of 2.2 and zenith angles in a 0°–70° range; the hadron sample is a mixture of a list of several H.E.S.S. real runs at different zenith angles in which no significant signal has been found. In this paper a very first attempt performed in a rather simple approach is presented, assuming that the BDT algorithm is able to manage the two above-mentioned samples in which all zenith angles and all energy bands are mixed up. As mentioned earlier in this paper this work is aimed at the detection of sources having very low flux levels, therefore specific cuts depending on the absolute flux normalisation have been defined. The γ-ray and background efficiencies,

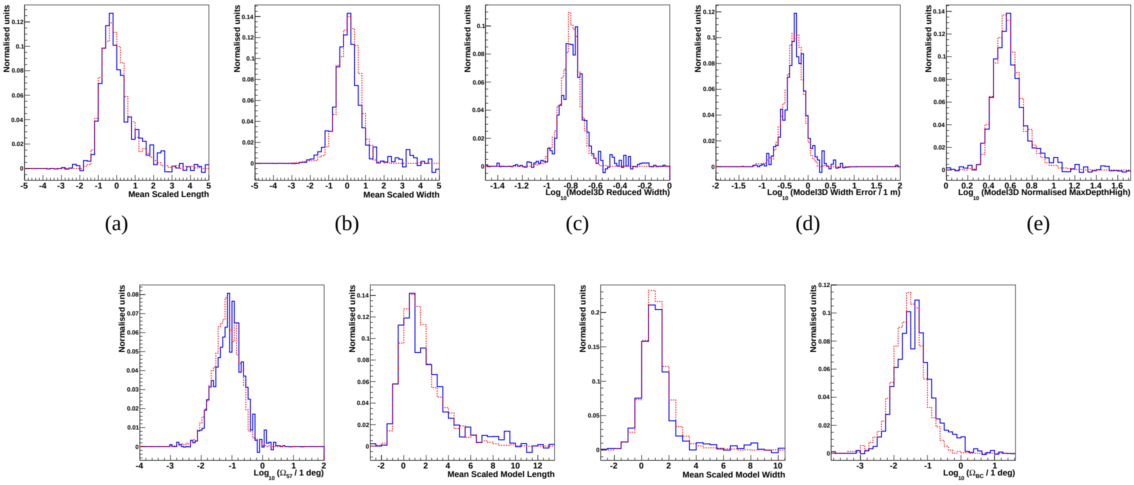


Fig. 3. Comparison between simulated (red/dashed lines) and real γ-rays (blue lines). The real γ-rays are selected from the Crab Nebula runs. (a) Mean scaled length, (b) Mean scaled width, (c) Model3D reduced width, (d) Model3D error on width, (e) Model3D maximum depth, (f) Ω_{57}, (g) Mean Scaled Model Length, (h) Mean Scaled Model Width, (i) Ω_{BC}.

TABLE I
γ AND HADRON EFFICIENCIES

flux (Crab%)	MVA cut	γ eff.	bkg eff.	S/sqrt(S+B)
1%	0.362	0.52	0.007	8.49
10%	0.198	0.79	0.023	15.26
1%–10%	0.187	0.80	2.8	7.2–15.0

together with their associated multi-variate (MVA) cut at the maximum value of signal-to-noise ratio for 10% and 1% Crab flux levels are summarised in Tab. I.

The effective γ-ray detection area, at 26° zenith angle and 1° offset, for the new analysis is shown in Fig. 5 together with the performance of the standard Hillas-based analysis: there is a clear gain for energies greater than about 500 GeV, at the expense of a slight loss at lower energies.

Currently, the performance of the analysis for a more detailed approach where the samples are separated into zenith angle and energy bands is being evaluated.

V. Performance Evaluation and Conclusions

A new analysis strategy for IACT optimised for the detection of *weak* γ-ray sources has been presented. What distinguishes this particular analysis from other works [5] is that it relies on four brand-new robust discrimination parameters and combines relevant reconstruction information from the both well-established Hillas and Model3D algorithms.

The performance of the new MVA analysis has been checked on some previously detected H.E.S.S. sources. The results obtained show that a significantly higher sensitivity is achieved, allowing a gain in observing time by a factor ranging from 2 to 4 depending on the source spectrum. Details will be shown in the oral presentation.

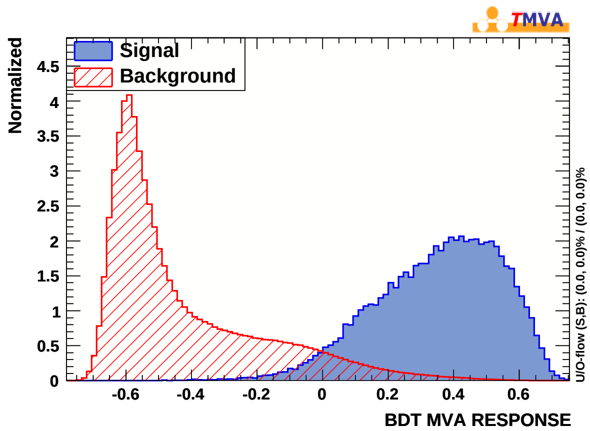


Fig. 4. Boosted Decision Tree response to the nine-variable training and test phases. The distribution of the multi-variate response for the training and test samples are shown for simulated γ-rays (blue, filled) and for real hadrons (red, hatched).

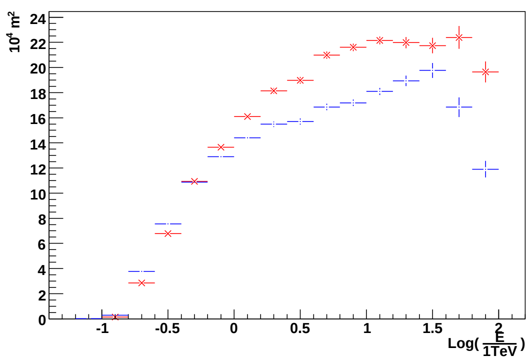


Fig. 5. Effective detection area at 26° zenith angle and 1° offset for the standard Hillas analysis (blue points) and the new MVA analysis (red crosses). With the new MVA analysis the effective area is improved for $E > 500$ GeV at the expense of a small decrease for lower energies.

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