Application of an analysis method based on a semi-analytical shower model to the first H·E·S·S· telescope.

M. de Naurois[1], J. Guy[1], A. Djannati-Ataï[2] , J.-P. Tavernet[1] for the H·E·S·S· collaboration[3].
(1) LPNHE-IN2P3/CNRS Universités Paris VI & VII, Paris, France
(2) PCC-IN2P3/CNRS Collège de France Université Paris VII, France
(3) `http://www.mpi-hd.mpg.de/HESS/collaboration`

Abstract

The first H·E·S·S· telescope has been in operation on-site in Namibia since June, 2002. With its fine-grain camera (0.16° pixelization) and large mirror light-collection area (107m^2), it is able to see more detailed structures in the Cherenkov shower images than are characterized by the standard moment-based (Hillas) image analysis. Here we report on the application of the analysis method developed for the CAT detector (Cherenkov Array at Themis) which has been adapted for the H·E·S·S· site and telescopes. The performance of the method as compared to the standard image analysis, in particular regarding background rejection and energy resolution, is presented. Preliminary comparisons between the predicted performance of the method based on Monte Carlo simulation and the results of the application of the method to data from the Crab Nebula are shown.

1. Introduction

In order to take advantage of the fine pixelization of the CAT camera, a new analysis method for Imaging Atmospheric Cherenkov Telescopes was developed [3]. The comparison of the shower images with a semi-analytical model was used to successfully discriminate between γ-ray and hadron-induced showers and to provide an energy measurement with a precision of the order of 20%, without the need for stereoscopy. The H·E·S·S· experiment, in operation in Namibia since June 2002, combines the advantages of the different previous-generation telescopes: large mirror, fine-pixel camera and stereoscopy. In this paper, we present the improvements made to the CAT analysis in the framework of H·E·S·S· (operating in single telescope mode).

2. Model generation

Hillas [2], studied the mean development of electromagnetic showers. We used his parametrization to construct a model of shower development, which we feed into a detector simulation to take into account instrumental effects. After

pp. 1–4

this procedure, we obtain for each zenith angle θ, primary energy E and impact parameter ρ the predicted intensity in each pixel of the camera. Model images have been generated for 30 values between 50 GeV and 10 TeV, zenith angles up to 60°, and impact parameters up to 300 m from the telescope. A multi-linear interpolation method is used to compute the pixel intensity for intermediate parameters. The model generation has been extensively tested against simulation and agrees within 10% up to 10 TeV.

3. Event reconstruction

The event reconstruction is based on a maximum likelihood method which uses all available pixels in the camera. The probability density function of observing a signal S, given an expected amplitude μ, a fluctuation of the pedestal σ_p (due to night sky background and electronics) and a fluctuation of the single photoelectron signal (p.e.) $\sigma_s \approx 0.4$ (PMT resolution) is given by

$$P(S|\mu,\sigma_p,\sigma_s) = \sum_{n=0}^{\infty} \frac{e^{-\mu}\mu^n}{n!\sqrt{2\pi(\sigma_p^2+n\sigma_s^2)}} \exp\left(-\frac{(S-n)^2}{2(\sigma_p^2+n\sigma_s^2)}\right) \tag{1}$$

The likelihood

$$\mathcal{L} = 2\sum_{\text{pixel}} \log\left[P_i(S_i|\mu,\sigma_p,\sigma_s)\right] \tag{2}$$

is then maximized to obtain the primary energy, the target direction T and the impact point I. This five parameter fit can be reduced to four parameters E, ρ, ϕ (azimuthal angle in the camera) and d (angular distance of the shower barycenter to the primary direction, see fig. 1), using the alignement of the image centre of gravity with TI.

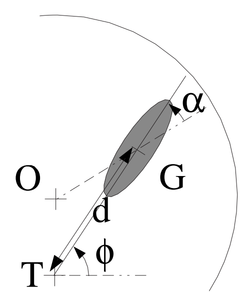

Fig. 1. Definition of geometrical parameters used for the shower reconstruction. O is the center of the camera, G the image barycenter and T the reconstructed target direction.

4. Signal extraction

The following cuts are used in signal extraction

- A cut on the ratio of the shower length L to its amplitude S, designed to reject small muon images : $L/S \leq 1.6\times10^{-2}$mrad p.e.$^{-1}$
- A geometrical cut of the distance mismatch $|\delta D| \leq 5$ mrad, where $\delta D = |\mathrm{TG}| - |\mathrm{OG}|$. This cut selects γ-rays originating from the center of the field of view and is orthogonal to the commonly used α orientation angle.
- A goodness of fit $\mathcal{G} < 0.07$ defined from the likelihood distribution as function of the number of operating pixels N_{dof} as $\mathcal{G} = (\langle\mathcal{L}\rangle - \mathcal{L})/N_{\text{dof}}$, where the

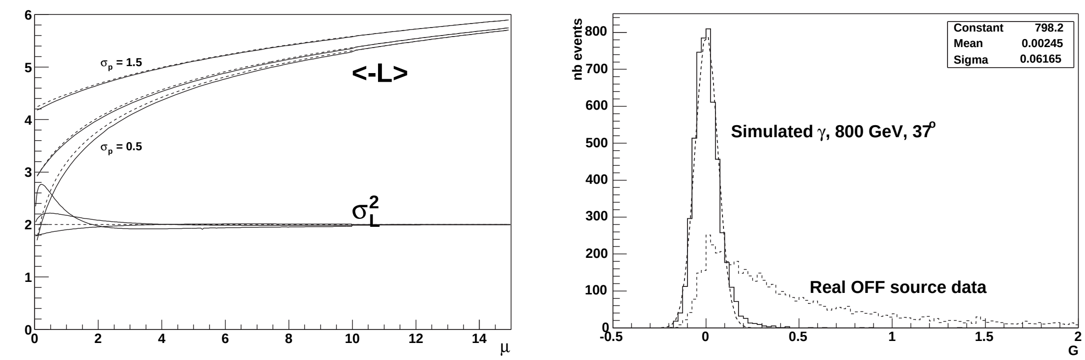

Fig. 2. Left: Likelihood curves for different night sky backgrounds. Solid curves are numerical integrations, dashed curves are simple analytical approximations (eq. 3). Right: Goodness of fit ($\mathcal{G}$) distribution after L/S and D cuts, for simulated γ and real OFF source events.

average likelihood and its RMS are obtained by integration of an analytical approximation of eq. 1:

$$\langle \mathcal{L} \rangle = -\sum_{\text{pixel}} \left(1 + \log 2\pi + \log\left(\mu(1+\sigma_s^2) + \sigma_p^2\right)\right), \quad \sigma_{\mathcal{L}}^2 = 2 \qquad (3)$$

The distribution of $\mathcal{G}$ for simulated γ-rays and real hadrons is shown in fig. 2 together with the likelihood's average and RMS. The distribution for γ-rays is compatible with an expected mean of 0.0 and has a slightly larger RMS than the expected value $\sqrt{2/N_{\text{dof}}} \approx 5 \times 10^{-2}$. A cut $\mathcal{G} \leq 0.07$ keeps 77% of the γ-rays and rejects 82% of the hadrons.

5. Results

We have analysed 20 pairs on the Crab Nebula, corresponding to 4.65 hours (live-time corrected) of data. Fig. 3 shows the comparison between the standard H·E·S·S· analysis [4] and this work. The model analysis alone produces an α plot extending up to 180°. The significance in the $\alpha < 9°$ is better in the hillas analysis ($21\,\sigma$ against $16.9\,\sigma$), mainly because the hadron rejection is not yet fully optimized for the model analysis, but the α resolution is much better in the Model analysis (2.7° against 4.2°), thus providing a better signal to background ratio in the first bins.

More interesting is the background rejection capability of a *combined analysis*. The lower plot of fig. 3 shows the α distribution of the events passing both the Hillas and Model analysis cuts. The signal over background ratio is increased by a factor of more than 3, reaching the value of 4.8 for $\alpha < 9°$ wheras less than 15% of the γ-rays are lost. This also results in a net increase in significance up to $25.2\,\sigma$. The complementarity of the hadron rejection capabilities of both analyses

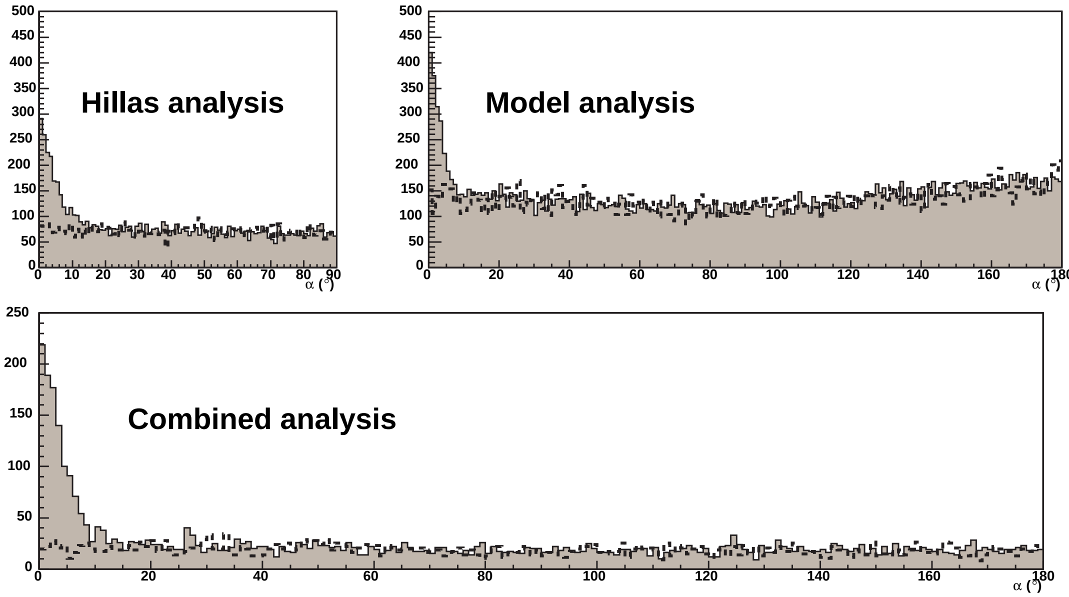

Fig. 3. Results of the model analysis. Solid lines: ON source. Dashed lines: OFF source. *top left:* α plot with standard H·E·S·S· analysis based on hillas parameters. *top right:* Corresponding α plot for the model analysis. *bottom:* Effect of the combination of the cuts on the background.

is a very powerful instrument for finding faint sources, and was successfully used to detect the blazar PKS 2155-304 in October 2002 at the level of $7.4\,\sigma$ [1].

This analysis also provides energy and shower impact measurements with respective resolutions of about 20% and 20 m at 800 GeV.

6. Conclusion

We have developed a powerful analysis for H·E·S·S· based on the comparison of shower images with a semi-analytical model. This analysis provides a better α angle measurement than the standard analysis (base on Hillas parameters), as well as good energy and shower impact resolution. Moreover, the combination of both analysis provides an additional background rejection factor of about 3, which leads to an important increase in significance. This combination method has been successfully used to detect the blazar PKS 2155-304 at the level of respectively $13\,\sigma$ and $7.4\,\sigma$ in July and October 2002. Further results will be presented at the conference.

7. References

1. Djannati-AtaïA, These proceedings
2. Hillas A.M.. 1982, J. Phys. G 8, 1461
3. Le Bohec S *et al.*, NIM A416 (1998) 425
4. Masterson C, These proceedings