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# FIRST RESULTS FROM THE H.E.S.S. EXPERIMENT WITH AN ANALYSIS METHOD BASED ON A SEMI-ANALYTICAL SHOWER MODEL

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**Abstract.** An analysis method based on an analytical model is described. The longitudinal and transverse light distribution in the focal plane of every camera results from the developement of a $\gamma$-ray initiated shower in the atmosphere. The method simultaneously determines the energy of the initiating $\gamma$-ray the position of the shower axis with respect to the detector, and the source location ($\gamma$-ray origin) on a shower-by-shower basis. Results of this method applied to H.E.S.S. experimental data and a preliminary spectrum from Crab Nebula are shown.

## 1 Introduction

The H.E.S.S. (High Energy Stereoscopic System) detector (1) is an array of four Imaging Atmospheric Cerenkov Telescopes, located in Namibia at 1800 meters altitude, designed to study very high energy ($> 100$ GeV) $\gamma$-rays. Each telescope is composed of a $107\,\mathrm{m}^2$ mirror (2), (3) and a $5^\circ$ diameter field of view camera (4). The $\gamma$-rays are detected indirectly via Cerenkov light emitted by the charged particles producted in induced air-shower. Images of the shower are analysed to provide background suppression and to reconstruct primary $\gamma$-ray parameters.

The standard analysis is based on a fit of the image by an elliptical shape. An other method based on an analytical model giving the light distribution resulting from a $\gamma$-ray initiated shower in the focal plane of the cameras, has been recently developped for stereoscopic H.E.S.S. observations. After a short description of the method, it is applied to the 2003 Crab nebula data. The spectrum reconstruction method is briefly described.

## 2 Semi-analytical model

The principle of the semi-analytical model-based analysis is to compare actual shower images to analytical images, and derive from this comparison the primary

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shower parameters: energy $E_\gamma$, impact parameter D and $\gamma$-ray direction (zenith and azimuth angle).

This model is based on the results from Hillas (6) where the mean development of electromagnetic showers is described and parametrized. Parametrisations of the number of charged particles ($e^{\pm}$) at a given atmospheric depth, their energy spectrum, angular distribution with respect to the shower axis and lateral distribution ans spread around the shower axis are included in the model. The parametrisations are fitted with our Monte-Carlo simulations. The atmospheric characteristics such as density profile, optical absorption and Cerenkov emission properties are also taken into account. The detector features such as the mirror anisochronism, reflectivity and average point spread function, the photomultiplier tubes quantum efficiency, and the charge integration window width are included in the model. In practice, the shower is divided into 'slices' perpendicular to its axis at different depths. The contribution of every slices to the image is calculated. The output of the model is the mean number of photo-electrons in every pixels of the cameras for a shower of given energy, impact parameter observed at a given zenith angle.

The comparison between the mean images generated with the model and the data images is performed using a likelihood method. The likelihood is defined as the product over all the pixels i of the probability density function:

$$\mathrm{P_{DF}}(\mathrm{x_i}, \mu_\mathrm{i}, \sigma_\mathrm{i}) \;=\; \sum_\mathrm{n} \frac{\mu_\mathrm{i}^\mathrm{n}\,\mathrm{e}^{-\mu_\mathrm{i}}}{\mathrm{n}!\,\sqrt{2\pi(\sigma_\mathrm{pi}^2 + \mathrm{n}\sigma_\gamma^2)}} \exp\left(\frac{-(\mathrm{x_i}-\mathrm{n})^2}{2(\sigma_\mathrm{pi}^2 + \mathrm{n}\sigma_\gamma^2)}\right)$$

The $\mathrm{P_{DF}}$ describes the probability of measuring $x_i$ photo-electrons in pixel i when the theoretical signal is $\mu_\mathrm{i}$. The individual pedestal widths $\sigma_\mathrm{pi}$ take into account the fluctuations due to electronic noise and night sky background. The photomultiplier tube resolution is described by $\sigma_\gamma$. n is the number of photo-electrons.
The sum is performed on every pixel of the cameras, and the NSB in every individual pixel is taken into account in the fit. Therefore, the model-based analysis does not need any prior image cleaning, lowering the energy threshold with respect to standard analysis. The relevant parameter is the goodness of fit:

$$\mathrm{g} = \frac{\ln(\mathcal{L}) - <\ln(\mathcal{L})>}{\mathrm{Ndof}} \tag{2.1}$$

From an analytical calculation, one can show that the distribution of this parameter should be centered on 0 with a width of $\sqrt{2/\mathrm{Ndof}}$, where Ndof is the number of pixels used in the fit.

In contrast to other analysis, only one cut is used to select the gamma-like events: the maximum goodness of fit is set to 0.02. It gives a hadron rejection factor of the order of 50 with good flat $\gamma$-ray efficiency of the order of 80%. An additionnal cut on the $\gamma$-ray direction is used for point-like source analysis: the maximum square of the angular distance of the reconstructed $\gamma$-ray to the expected source position ($\theta^2$) is set to $0.03^{\circ^2}$. No dependence of these cuts on photon index and zenith angle are used.

For on-axis observations, energy resolution is of the order of 15%, angular resolution of the order of 0.06°. The energy threshold in cuts at Zenith is 120 GeV (defined as the maximum differential flux for a $E^{-2}$ spectrum).

## 3 Spectrum reconstruction

The spectral analysis method has been used by the C.A.T. experiment (7), (8). Using the differential flux, it is based on the comparison of the measured and theoretical number of events. The theoretical number of events are given by the convolution of the detector function (effective area and energy resolution as function of energy) and an assumed spectrum shape. The detector function are determined by detailed Monte-Carlo simulations of the H.E.S.S. response.

In practice, the data are divided in bins of energy and zenith angle. In every bin, the number of on-source and off-source (hadronic background) events, and the duration of the observation in the zenith range are stored. The theoretical numbers of $\gamma$-rays in every bin is calculated with Poisson statistics, using the detector function, the duration and the assumed spectum shape. Then a maximum-likelihood estimation of the spectral parameters is performed.

This method has been succesfully applied to the H.E.S.S. data as shown in next section.

## 4 Crab nebula analysis

The model-based analysis has been applied to a Crab nebula dataset of Fall 2003. This dataset consists in 4.0 live hours of 3-telescope observation at mean zenith angle of 46°. The trigger condition is 2.5 pixels above 4 photo-electrons per camera, with telescope multiplicity 2. The observations are in wobble mode, with declination offset of $\pm 0.5°$.
At this zenith angle, the model-based analysis gives an energy threshold of 480 GeV. Using a ring around the assumed source location to estimate the background, the excess is of $63\,\sigma$ (using Li&Ma (9) statistics) as shown in figure 1-Left. The apparent size of $0.063 \pm 0.001°$ is compatible with expectations for a point-like source. The measured energy spectrum is shown figure 1-Right. Data are fit by a power law, $dN/dE = F_0 E_{TeV}^{-\alpha}$, with photon index $\alpha = 2.67 \pm 0.06$ and $F_0 = (34.22 \pm 1.07) \times 10^{-8}\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}$. Systematics errors are estimated to $\Delta\alpha \sim 0.15$ and $\Delta F/F \sim 25\%$. The reconstructed integral flux above 1 TeV is then $(2.05 \pm 0.09) \times 10^{-7}\mathrm{m}^{-2}\mathrm{s}^{-1}$ which is in very good agreement with previous measurements (10) and standard H.E.S.S. analysis results (11) with other spectrum reconstruction methods.

## 5 Conclusion

The model-based analysis is now fully operationnal for stereoscopic H.E.S.S. data analysis. Compared to the standard analysis, its main advantages are a lower

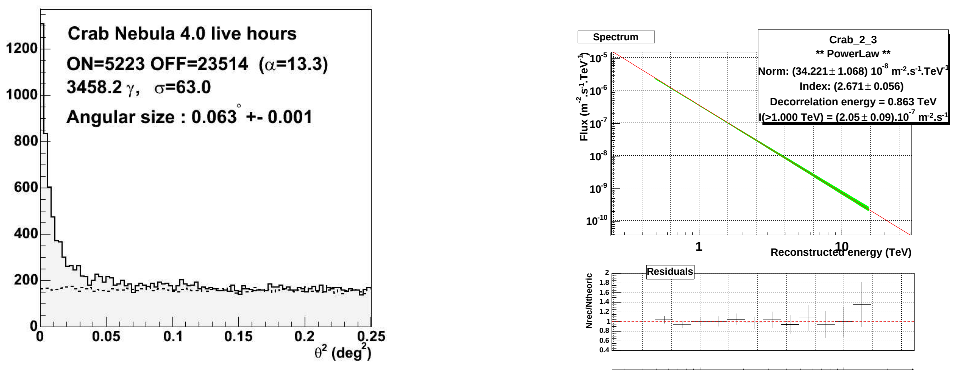


**Fig. 1.** Left: Angular distribution of $\gamma$-raylike events relative to the location of the Crab nebula. $\theta$ is the angular distance between the $\gamma$-ray direction and the Crab nebula. A uniform background results in a flat $\theta^2$ distribution. Dashed line: background region. Continuous line: signal region. Rigth: Crab nebula energy spectrum: $dN/dE$. The line is the best fitted spectrum, the filled region gives the the statistical 1-sigma confidence level flux. The residuals are the ratio of the measured to the theoretical number of gammas in every bin.

energy threshold and a better angular resolution. Moreover, only one cut on the goodness of fit allows to find the gamma-like candidates.

Results of this analysis on the Crab nebula data have proven its efficiency. Position and size of the Crab nebula are in agreement with other H.E.S.S. analysis results. The C.A.T. spectrum reconstruction technics has been used to compute the Crab nebula spectrum. Results are compatible with other H.E.S.S. analysis and spectrum reconstruction methods as well as with previous measurements.

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