Selection and 3D-reconstruction of gamma-ray-induced air showers with H.E.S.S.

M. Lemoine-Goumard* and B. Degrange*
for the H.E.S.S. collaboration

*LLR, Ecole Polytechnique, 91128 Palaiseau Cedex, France

Abstract. H.E.S.S. (High Energy Stereoscopic System) is an array of four large imaging Cherenkov telescopes devoted to gamma-ray astronomy above 100 GeV. It has been fully operational since December 2003. Here, we report on a new analysis method based on a simple 3D-modeling of an electromagnetic air shower. This method allows to separate gamma-rays from background events in the field of view without any assumption on the morphology of the source or on the background distribution. This is a crucial point in the study of extended sources (e.g. Supernova Remnants) or in the search for unexpected sources in a sky survey. The performance and results of this method on galactic sources are presented.

INTRODUCTION

An important goal in the new phase of TeV gamma-astronomy opened with H.E.S.S. is the search for extended sources — e.g. supernova remnants — or for unexpected sources in a sky survey. In such a study, the hadronic background cannot be subtracted on the basis of the angular distribution (e.g. the classic θ^2 or α plots) used for point-like objects whose celestial coordinates are known. Here, we present an analysis method based on two steps. The first step reconstructs each event, using stereoscopy and a simple model of electromagnetic shower. The second step extracts *and separates* gamma-ray and background distributions in a given field-of-view *without any assumption on the morphology of the source or on the background distribution* by using a maximum-likelihood method.

THE 3D-MODEL

The most important characteristics of electromagnetic showers considered here is that the spatial distribution of the emission points of Cherenkov photons, and the angular distribution of these photons with respect to the shower axis, are on average rotationally symmetric with respect to the shower axis. The 3D-model of γ-ray showers presented here is based on two simplifying assumptions :

1. The emission points of Cherenkov photons are distributed according to a 3-dimensional Gaussian law with rotational symmetry with respect to the shower axis; it is thus characterized by the following parameters : the direction of the

shower in the reference frame of the telescope, the position of the core on the ground, the altitude of shower maximum, the longitudinal (σ_L) and transverse (σ_T) standard deviations of the Gaussian distributions, referred to as "3D-length" and "3D-width" respectively and the total number N_c of emitted Cherenkov photons. The preceding quantities, referred to as "shower parameters", will be determined by a maximum likelihood fit.

2. The angular distribution of Cherenkov photons with respect to the shower axis is assumed to scale with the maximum Cherenkov angle at a given altitude and to be independent of other variables. This average distribution is derived from simulations.

The preceding 3D-model enables us to work out the expected number of Cherenkov photons q_{th} collected by a given pixel of a given telescope as a function of the shower parameters listed above, by an integration along the line of sight of each pixel. The quantities q_{th} for all pixels, calculated for a set of shower parameters, are further used to build up a likelihood function for each event including at least two images of a given shower. The likelihood function for each event is then maximized with respect to the 8 shower parameters defined above. Thus, for each event, we obtain a complete description of the shower (see reference [1] for more details on the performance of the 3D-model). These informations can then be used to subtract the background with the following "weighting method".

IMPLEMENTATION OF THE WEIGHTING METHOD

The proposed method [2] assumes that the distributions of σ_T are known both for gamma-rays and hadronic showers. Some calibration work is thus necessary, e.g. from data taken on point-like sources at different locations in the field-of-view, at different zenith angles. The σ_T distributions can of course be independently obtained from simulations. For reasons of clarity, we shall assume here that the σ_T distributions for each population (gamma-rays and hadrons) in a given field-of-view are independent of the shower directions and energies. These assumptions can be easily relaxed, at the expense of a more complex calibration procedure, the only important constraint of the method being that the σ_T distributions are "a priori" known as functions of the relevant parameters. In the simple case considered here, we call $g(x)$ and $b(x)$ the probability distribution functions of $x \equiv \sigma_T$ for gamma-rays and hadrons respectively.

The skymap obtained after reconstruction is divided into pixels in celestial coordinates and the following procedure is applied separately to each pixel. Therefore, no correlation between different parts of the field-of-view is induced by the method and no assumptions are made on the signal or background morphology. For each event, the reconstruction procedure described above provides the original direction (thus the relevant pixel in the field-of-view) and the 3D-width. We now consider a given pixel containing N events with 3D-widths x_1, x_2, ... , x_N. We call n_g and n_b the expectation values of the number of gamma-ray and background events respectively. The probability to get the observed configuration (up to differentials dx_1, dx_2, ... , dx_N) is :

$$\frac{\exp(-n_g - n_b)}{N!} \prod_{i=1}^{N} [n_g g(x_i) + n_b b(x_i)] \; dx_1 dx_2 ... dx_N \; . \tag{1}$$

This formula can be easily obtained, starting from Poisson distributions for the event numbers, then considering the different partitions between gamma-ray and background events leading to the values x_1, x_2, ... , x_N, while taking care of the normalization. The likelihood function is then minimized with respect to n_g and n_b, which yields the following equations allowing an iterative calculation of n_g and n_b, as shown below: $n_g = \sum_{i=1,N} \frac{n_g g(x_i)}{n_g g(x_i) + n_b b(x_i)}$ and $n_b = \sum_{i=1,N} \frac{n_b b(x_i)}{n_g g(x_i) + n_b b(x_i)}$. Once the convergence is achieved, for each event, the following quantities:

$$w_{gi} = \frac{n_g g(x_i)}{n_g g(x_i) + n_b b(x_i)} \text{ and } w_{bi} = \frac{n_b b(x_i)}{n_g g(x_i) + n_b b(x_i)}$$

can be interpreted as the weights of event i in the gamma-ray and hadron hypotheses respectively since $n_g = \sum_{i=1,N} w_{gi}$ and $n_b = \sum_{i=1,N} w_{bi}$; furthermore $n_b + n_g = N$. By repeating the preceding procedure for each pixel of the field-of-view independently, one gets two maps, one for gamma-rays and the other for the hadronic background. The method also provides a consistency check, since the histograms of the 3D-width of all events weighted according to w_{gi} and w_{bi} respectively should be compatible with the original distributions $g(x)$ and $b(x)$.

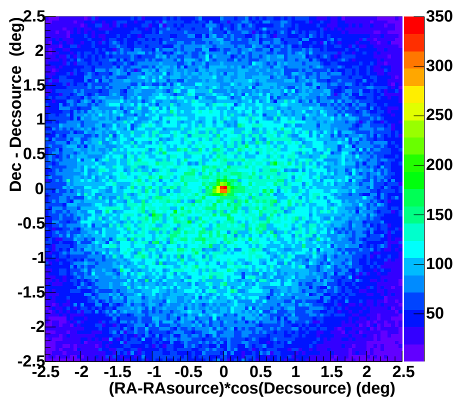

FIGURE 1. Distribution of the direction of the primary particles (gamma-rays and hadrons) in the field-of-view. The map is centered on the position of the Crab nebula. The pixel size is $0.05° \times 0.05°$

CALIBRATING AND TESTING THE METHOD ON THE CRAB NEBULA

The Crab nebula is a point-like source which has been well studied by H.E.S.S. The 3D-reconstruction procedure described above has been applied to a data set representing 2.7

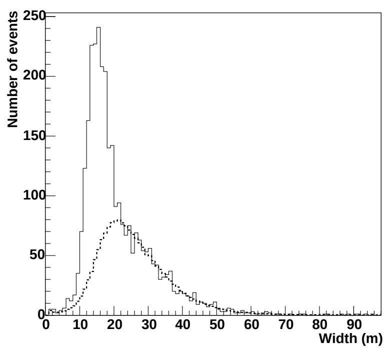

FIGURE 2. *3D-width distributions from Crab data. (a) Solid-line histogram: events for a region close to the source ($\theta < 0.05$ deg^2). (b) Dotted-line histogram: events in a region that excludes the source ($\theta^2 > 0.2$ deg^2). Both histograms are normalized to the same number of events with widths greater than 40 m.*

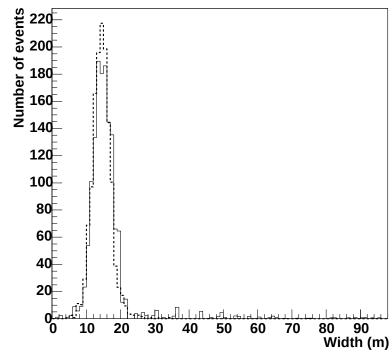

FIGURE 3. *3D-width distribution of gamma-rays. (a) Solid-line histogram: experimental distribution obtained from figure 2 after background subtraction (see text). (b) Dotted-line histogram: distribution obtained from simulated gamma-rays.*

hours of observation taken at zenith angles close to 46° with 3 telescopes. For each event, the method provides the direction of the primary particle; its distribution in the field-of-view is shown in figure 1. Our goal is now to separate the respective contributions of gamma-rays and hadrons.

First of all, the data have been used to determine the functions $g(x)$ and $b(x)$. Figure 2 shows the 3D-width distributions obtained from the data in two different regions of the field of view. The solid-line histogram corresponds to a region close to the source ($\theta^2 < 0.05$ deg^2), θ being the angle between the reconstructed direction of the shower and that of the source, whereas the dotted histogram, referring to a region with no significant gamma-ray contribution ($\theta^2 > 0.2$ deg^2) yields the 3D-width distribution of the background. Since gamma-rays are not expected to contribute to large widths, the two histograms have been normalized to the same number of events with 3D-widths greater than 40 m, which allows a straightforward subtraction of the background, yielding the 3D-width distribution for gamma-rays, shown by the solid-line histogram in figure 3. Gamma-ray events with a Crab-like spectrum were also simulated in the same conditions of observation and submitted to the same reconstruction procedure; the corresponding 3D-width distribution, shown by the dotted histogram in figure 3, is very similar to the experimental one.

In order to determine the functions $g(x)$ and $b(x)$, the solid-line histogram of figure 3 and the dotted histogram of figure 2 were fitted.

The method was then applied to the Crab nebula 2003 data set, yielding the two sky maps shown in figure 4, one for gamma-rays and the other for background events. On the first map, the signal is actually distributed according to the point-spread function expected from simulations. Figure 5 shows the 3D-width distributions in which each event contributes according to its weight w_{gi} (as a gamma-ray) and w_{bi} (as a hadron) respectively ("a posteriori" distributions). As a consistency check of the method, the

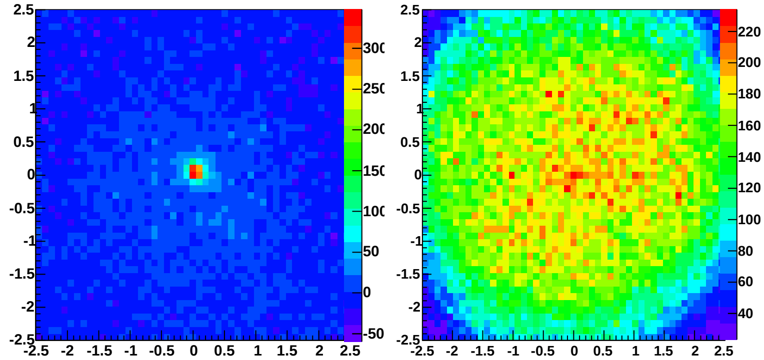

FIGURE 4. *Separated distributions of events in the field-of-view of the Crab nebula. (a) Gamma-rays. (b) Background events.*

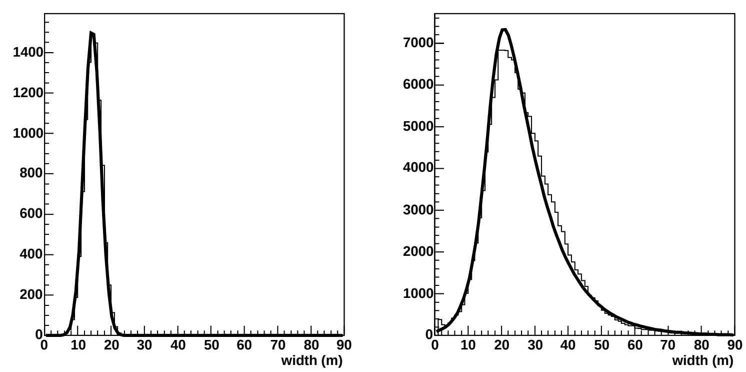

FIGURE 5. *"A posteriori" 3D-width distributions for gamma-rays (left) and hadrons (right), compared to functions $g(x)$ and $b(x)$ used in the method.*

histograms in figure 5 are superimposed to the functions $g(x)$ and $b(x)$ conveniently renormalized. A perfect agreement is obtained for gamma-rays, whereas a slight difference is detected for hadrons, due to the simplifying assumtpion that $b(x)$ should be independent of the position in the field of view.

THE METHOD AS APPLIED TO THE SUPERNOVA REMNANT RXJ 1713-3946

The satisfactory results obtained on the Crab nebula allow us to consider them as a measurement of the functions $g(x)$ and $b(x)$ which can be applied to other fields of view and in particular to RXJ 1713-3946. The present sample corresponds to 17.8 hours of observation at different zenith angles (from 16° to 46°). The distribution of $\sigma_T \cos\zeta$ was assumed to be independent of the zenith angle ζ [1]. Figure 6 shows the distributions of the origins of gamma-rays. We can clearly see the shell morphology of the supernova

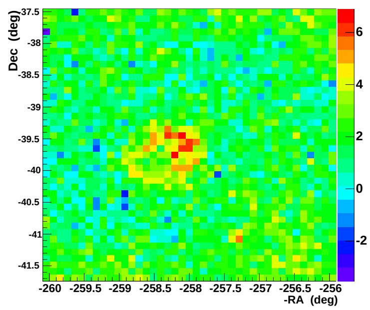

FIGURE 6. *Distributions of gamma-rays in the field-of-view of RXJ 1713-3946 (significance skymap)*

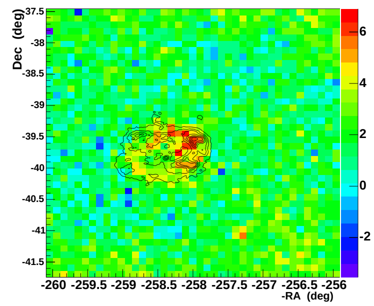

FIGURE 7. *X-ray contours as seen by ASCA in the 1-3 keV range superposed on the TeV skymap of RXJ 1713-3946*

remnant with a significance of nearly 38 sigmas and a threshold of about 200 GeV.

CONCLUSION

By parametrizing the 3D-width distributions for gamma-rays and for hadrons, it is thus possible to avoid using cuts. This contrasts with the classic analysis based on cuts on several Hillas parameters. On the other hand, the present method is as sensitive as the standard one on a point-like source like the Crab and it has the advantage to be directly applicable to extended sources. Even with a rather crude calibration, the method explained above gives satisfactory results on the H.E.S.S. data taken on RXJ 1713-3946 with two telescopes. The weighting method explained above has been applied to H.E.S.S. data taken on RXJ 1713-3946. No restriction to high energy events has been used in the present analysis and the background subtraction is nevertheless satisfactory.

ACKNOWLEDGMENTS

The support of the Namibian authorities and of the University of Namibia in facilitating the construction and operation of H.E.S.S. is gratefully acknowledged, as is the support by the German Ministry for Education and Research (BMBF), the Max-Planck-Society, the French Ministry for Research, the CNRS-IN2P3 and the Astroparticle Interdisciplinary Programme of the CNRS, the U.K. Particle Physics and Astronomy Research Council (PPARC), the IPNP of the Charles University, the South African Department of Science and Technology and National Research Foundation, and by the University of Namibia. We appreciate the excellent work of the technical support staff in Berlin, Durham, Hamburg, Heidelberg, Palaiseau, Paris, Saclay, and in Namibia in the construction and operation of the equipment.

REFERENCES

1. Lemoine-Goumard, M., and de Naurois, M., *these proceedings* (2004).
2. Behr, L., *Thèse de doctorat d'Etat*, Ph.D. thesis, Université de Paris (1965).