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Model analysis for the MAGIC telescope

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Abstract: The MAGIC Collaboration operates the 17 m imaging Cherenkov telescope on the Canary island La Palma. One of the goals of the experiment is to achieve an analysis threshold energy below 100 GeV for primary γ-rays. The new analysis technique (model analysis) takes advantage of the good angular and time resolution of the telescope by fitting the average expected shower images in the camera to the measured ones. This approach allows to recognize and reconstruct images just above the level of the night sky background light fluctuations. Preliminary results show a significant improvement compared to the standard analysis of the MAGIC data.

Introduction

With Imaging Atmospheric Cherenkov Telescopes (IACTs) one measures Cherenkov light from air showers. The telescopes have fine pixelized, high resolution (both in space and time) cameras to catch the Cherenkov flashes of the showers, which last only a few ns. The image of the air shower against the background of the night sky (NSB) is used then to derive the energy and direction of the incoming particle, which caused the air shower, as well as to distinguish between γ-ray and hadron induced showers.

The model analysis is based on the idea to create expected averaged photon distributions from air showers for each energy, sky direction, and impact point of the shower. The expected photon distributions on the camera plane (hereafter templates) are created for γ-induced showers only. Every measured event is then compared with these templates and via a fitting procedure the best template for the particular event is determined.

Template generation

The templates are generated using a simulation of γ-ray air-showers (CORSIKA [1]) and the reflector simulation of the MAGIC telescope [2]. In this way, averaged photon distributions on the camera plane (just before the light enters the photomultipliers of the camera) are created. The templates are generated in a grid of energy (E), impact parameter (I), shower maximum position in the air (Tmax), zenith (Zd) and azimuth (Az) angles. Typically, 2000 showers are used to produce a single template with a given set of parameters. The following quantities are stored for each pixel: 1) Mean and 2) RMS of the number of photons, 3) Mean and 4) RMS of the arrival times of the photons. In Fig. 1 templates for $E = 100$GeV, $I = 100$m are shown. An image dependency of the impact point of the showers is demonstrated in Fig. 2. It is clearly visible that the shape of the image, its distance from the center of the camera and its time structure are changing.

Fitting with templates: likelihood function

The fitting is performed on the calibrated data of the MAGIC telescope. The number of photoelectrons (S) per pixel (i) is compared with the model predictions stored in the templates (m). The prob-

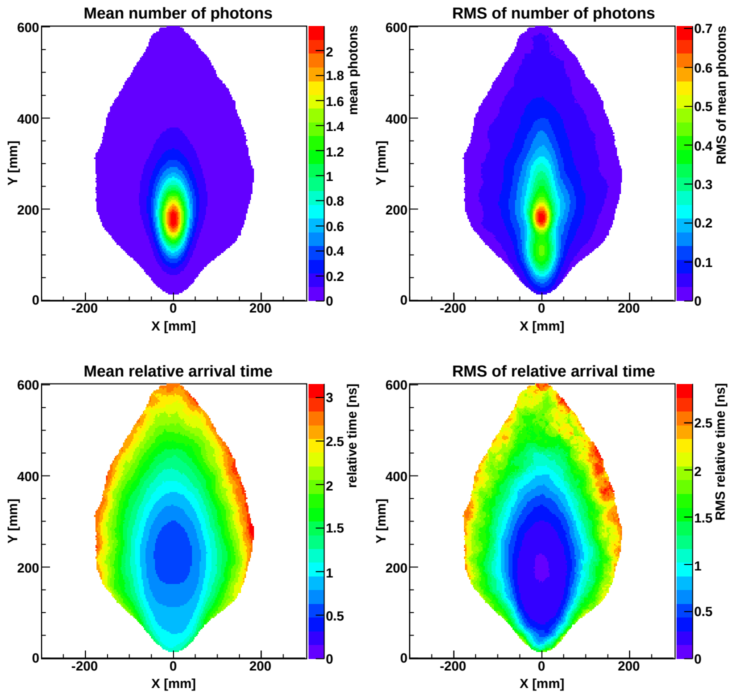

Figure 1: Template example for 100 GeV γ-ray showers at 100m impact distance from the telescope. The source position is at (0, 0) in the camera coordinates. *Top left*: Mean photon density per MAGIC camera pixel. *Top right*: RMS of the number of number of photons. *Bottom left*: Mean relative arrival time of the photons. *Bottom right*: RMS relative arrival time of the photons. Head-Tail asymmetry is clearly visible.

ability P to measure the signal S is then:

$$P(S,\mu)_i = \sum_n \frac{\lambda}{n!}\, e^{-\lambda}\, \frac{1}{\sqrt{2\,\pi}\,\sigma_n}\, \exp\left(-\frac{(S-(\mu+n))^2}{2\sigma_n^2}\right)$$
$$\text{with } \sigma_n^2 = \sigma_\mu^2 + \sigma_{el}^2 + \sigma_{cal}^2 + n\,(F^2-1)$$

λ is the mean of the night sky background (NSB) contribution, measured per pixel during the calibration of the MAGIC data. The Gaussian error σ_n has several contributions: error of the model prediction (part of the templates), σ_μ; electronic noise, σ_{el}; calibration error, σ_{cal}; error coming from the F-factor method, $\sqrt{n\,(F^2-1)}$. The overall likelihood function L for an event is then a product of individual probabilities per pixel:

$$L = \prod_i P(S,\mu)_i \tag{1}$$

And, finally, the loglikelihood function Ln_L is used to be minimized during the fitting routine:

$$Ln_L = -2\,\ln(L) \tag{2}$$

Method performance

A typical fitting result is shown for a MC g-event (Fig. 3). Left: MC event, Right: the result of the fit. The starting parameters are obtained from a simple parametrization using image parameters from the standard analysis. The true position of the γ-ray source in the camera coordinates is marked by a filled black circle. The reconstructed source position is marked by the yellow star.

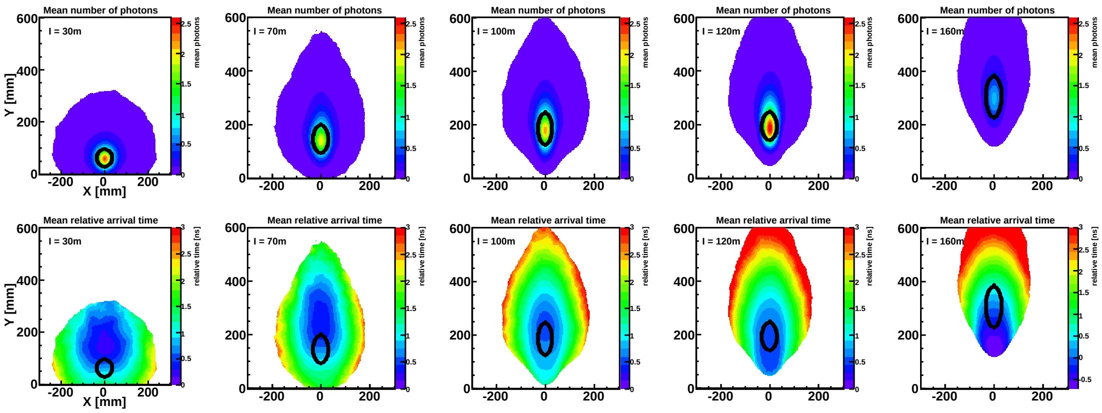

Figure 2: Templates for E=100GeV, Zd=0, and different impact parameters from the telescope, from left to right: I=30 m, 70 m, 100 m, 120 m, and 160 m. *Upper panels*: mean number of photons. *lower panels*: mean arrival times. The time spread is within 2 ns at the FWHM of the signal (marked by the black ellipse) but the time gradient is nicely visible. The gradient changes sign at around 120 meters impact distance.

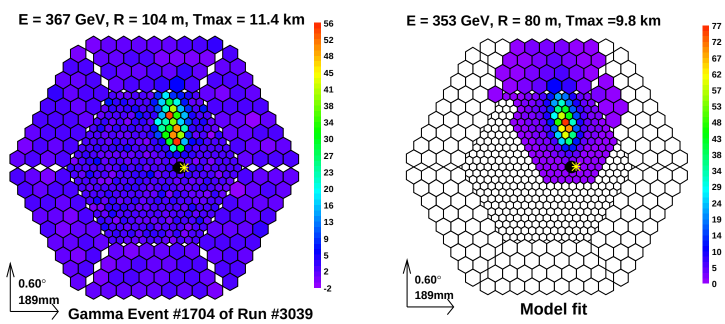

Figure 3: An example of the fit. *On the left*: Simulated γ-ray image in the MAGIC camera, the true shower parameters are listed on the top. *On the right*: Result of the fit, the estimated parameters are listed on the top. The number of photoelectrons per pixel are color coded. The true source position is indicated by a yellow star, the estimated source position from the fit is marked by the filled black circle.

First results

The model analysis has been tested on a MC γ-ray sample with the old 300 MHz FADC configuration. The energy resolution of the model analysis is slightly better at low energies compared to the standard analysis [3], whereas the angular resolution is slightly worse. Since the tails of the measured photon distributions are being better taking into account, the model analysis seems to reconstruct another parameter very well: the head-tail asymmetry. In Fig. 4, the fraction of correct assignment of the head-tail information is shown as a function of the image size (which is proportional to the energy of the γ-ray) for the standard analysis (open blue circles) and for the model analysis (filled red circles). At low size values, the model analysis has a better performance by about 30%.

In Fig. 5, we show the θ^2 distribution for MC γ-events with no γ/hadron separation cuts after the standard and the model analyses. θ is the angular distance between the real source position and

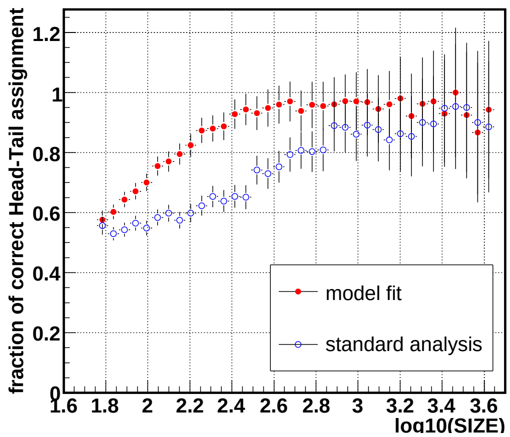

Figure 4: Fraction of the correct Head-Tail assignment for the model fit and for the standard analysis. A better performance of the model analysis at lower SIZE values (i.e. at lower energies) is clearly visible.

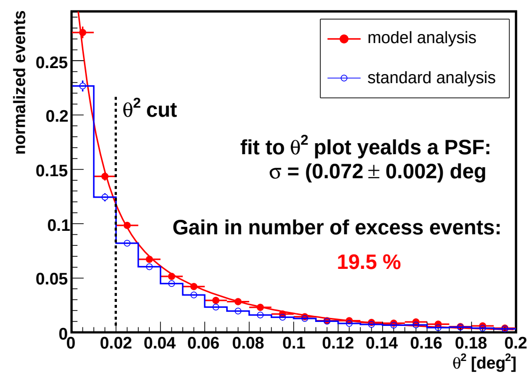

Figure 5: θ^2 distribution of MC γ-events without cuts after the standard and the model analysis. The model analysis achieves a gain of almost 20% of the events in the signal region.

the reconstructed one. The angular resolution (γ-PSF) has a $\sigma = 0.072°$ for the model analysis. The number of g-events with $\theta^2 < 0.02°^2$ (a standard cut corresponding to 2σ of the PSF) is evaluated. The resulting gain in the number of excess events of almost 20% is mainly due to the better head-tail assignment (Fig. 4).

Conclusions

Motivated by a good experience of the CAT [4] and H.E.S.S. [5] collaborations, we have developed and implemented the model analysis for the MAGIC telescope. Our model analysis is based on the averages of the MC simulated events. For the first time, the timing information of the photons is taken into account. Though tuning and testing of the method is ongoing, the model analysis already provides:

- an independent analysis method
- an independent γ/hadron separation
- an independent source position reconstruction
- an independent energy estimation
- a superior Head-Tail assignment

After the first tests, we can already show an improvement compared to the standard analysis. A further improvement is possible by tuning the templates. We expect an additional improvement of the sensitivity of the experiment by combining the model analysis with the standard one.

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