The Energy Resolution of The MAGIC Telescope

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Abstract

In the field of gamma-rays Astrophysics in the $\mathrm{GeV}-\mathrm{TeV}$ energy domain, the understanding of spectra of detected gamma rays is necessary in developing models for acceleration, emission, absorption and propagation of very high energy particles in their sources and in space. Therefore, high precision in the measurement of the energy of observed gammas is important. On the example of the $17\,\mathrm{m}$ ø MAGIC telescope, we study in this paper the energy resolution of an imaging Cherenkov telescope operating in stand-alone mode in the $\mathrm{GeV}-\mathrm{TeV}$ energy range.

1 Introduction

A good knowledge of the spectra of detected gamma-rays is necessary in developing models for acceleration, emission, absorption and propagation of very high energy particles in their sources and in space. One of the most important parameters of any given detector is its the energy resolution. In the case of Imaging Atmospheric Cherenkov telescopes (IACTs), the evaluation of this parameter has to be done by using Monte Carlo methods. The energy of the primary particles is not measured directly: primary particles entering the atmosphere initiate a shower of secondary particles, e.g. Cherenkov photons, which can be used to estimate the energy of the former. Measurement with IACTs is a calorimetric one, where the atmosphere serves as a calorimeter.

Currently, existing IACTs have a lower detection energy of $\geq 200\,\mathrm{GeV}$. In our earlier works ((González, 1997) and (González, 1997b)) we have shown for the first time that one can design large IACTs which allow us to dramatically lower the energy threshold and to measure successfully at energies above $10\,\mathrm{GeV}$ (Barrio, 1998). The MAGIC Telescope is dedicated to Gamma-ray Astrophysics in the entire energy range $10\,\mathrm{GeV}$ – $50\,\mathrm{TeV}$ (see (Martinez, 1999), in these proceedings). It is scheduled to see the first light with the beginning of the new millennium, its primary goal being to investigate the unexplored energy range between the upper energy detection limit of satellite born experiments and the lower detection threshold of the current ground-based Cherenkov telescopes, i.e. 20–$200\,\mathrm{GeV}$. In this contribution we report the results from our studies about the energy resolution of The MAGIC Telescope.

2 Simulations

2.1 Monte Carlo data: A new library of Monte Carlo events based on several improvements compared to the one used in (González, 1997) has been generated using the version 4.52 of CORSIKA air shower simulation program (Knapp & Heck, 1995), with some modifications to make it suitable for our purposes. The simulations include the atmospheric absorption and scattering processes: Rayleigh scattering, Mie scattering and Ozone absorption (Gaisser, 1990). The effect of the Earth magnetic field is also included. In addition, since the atmospheric model used in CORSIKA is plane-parallel, we have modified it using a local-plane atmosphere model in each point of the development of the shower. We used the wavelength range 290–$600\,\mathrm{nm}$ to simulate Cherenkov light from air showers, saving the position, direction, relative time of arrival and the wavelength of each single photon hitting the reflector. The showers where simulated with a primary energy from $1\,\mathrm{GeV}$ up to $30\,\mathrm{TeV}$. We simulated our events using differential spectral index of 1.5 for gammas (in order to provide enough statistics for high energies), 2.75 for protons and 2.62 for Helium, according to

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the compilation given in (Wiebel, 1994). Our events were generated continuously in the zenith angle range 5°–25°.

For this paper, a total of 80 000 gamma showers has been processed. Since most of the sub-100 GeV hadronic showers did not fulfill the trigger condition, we had to simulate a huge amount of them, but without leaving out the high energy ones. This is achieved naturally by using a realistic spectral index over the whole energy range.

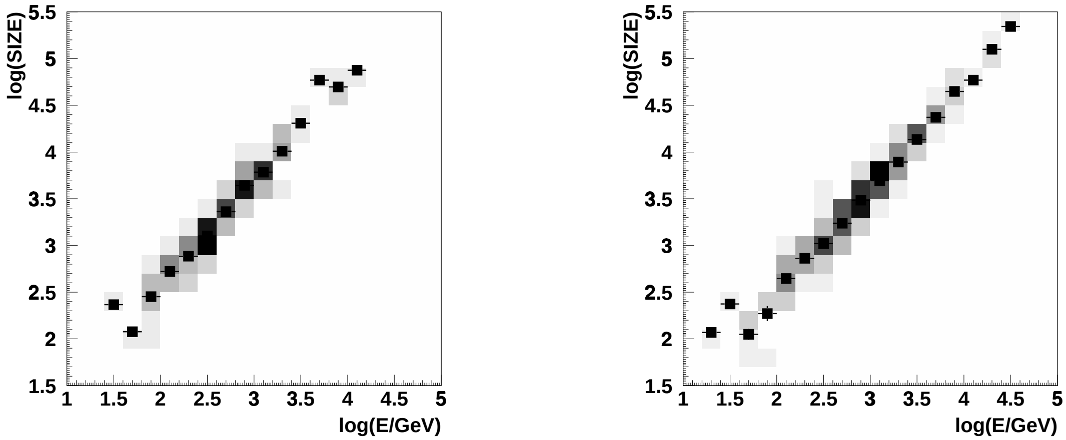
2.2 Data processing: All the showers were processed through a ray-tracing simulation of the reflector and a camera simulation program. We apply the atmospheric attenuation of Cherenkov light prior to the reflector simulation. In this simulation, the effects of reflectivity, possible misalignment, irregularities of the mirrors and differences in the focal lengths of the 920 square spherical-shaped mirrors (due to design and to possible imperfections) are all taken into account. Also, by using a ray-tracing method we ensure all aberration effects produced by the segmented reflector of MAGIC.

In this paper we are interested in the characteristics of the MAGIC telescope with the phase I photomultipliers (PMTs) camera. Therefore, a realistic simulation of the Quantum Efficiency (QE) and other effects have been taken into account. For the PMTs simulation we have used the measurements obtained for the bialkali PMT EMI-9083A. This QE has been used as a basis to generate separated QE curves for each individual PMT in the camera. The Light of the Night Sky (LONS) has been implemented using the measurements given in (Mirzoyan & Lorenz, 1994). The intensity of the LONS was measured in La Palma, at the site of the HEGRA experiment. For a narrow angle detector (acceptance angle less that 1°) in our wavelength range, this intensity was measured to be $I = (1.7 \pm 0.4) \cdot 10^{12}\,\mathrm{ph.\,m^{-2}\,s^{-1}\,sr^{-1}}$. By folding the Cherenkov spectrum (which follows, after atmosphere, an almost inverse-square law of the wavelength of the emitted light) with the QE of our PMTs, we obtained a mean value of 0.5 photo-electrons (ph.e.s) per pixel ans 10 nsec time-window. This value is used as the mean for a poissonian distribution, which describes very well the LONS. A more detailed description of the detector simulation can be found in (González, 1997) or (Barrio, 1998).

The trigger condition for the PMTs camera "*any 4 neighbour channels in a close pack above the pre-set threshold of 4 ph.e.s*" has been applied both for gammas and hadrons. The sub-100 GeV hadrons produce several times less Cherenkov light than gammas of similar energies (Weekes and Turver, 1977). Therefore, we will get triggers from gamma showers below this energy, while only those hadronic showers with their energy well above 100 GeV produce sufficient light to pass the trigger threshold. Also, this trigger condition allows us to reject efficiently hadronic showers, due to their more diffuse distribution of light in the camera, as well as to trigger efficiently on gamma showers, to suppress the accidental triggers due to LONS and after-pulsing, and to lower the trigger threshold. In the camera we have used a trigger area of 0.8°radius. Restricting the trigger area to 0.8°those showers with primary energies above 100 GeV will readily trigger the camera (due to large images and excessive light). On the other hand, since the sub-100 GeV gamma showers develop higher in the atmosphere compared to TeV ones, they are seen by MAGIC at smaller angles, and therefore the restriction in the trigger area will not affect them, while the rate of hadronic showers will be strongly reduced.

2.3 Filtering of data: The image cuts applied to the data where those used before in our analyses (see for example (González, 1997), (González, 1997b) or (Barrio, 1998)). However, these cuts were optimised for the use of hybrid photomultipliers, not for PMTs. In this sense, our results can be taken as conservative.

Our studies where done using the following slices in the DISTANCE parameter: 0.4°– 0.5°, 0.5°– 0.7°, 0.7°– 0.9°, 0.9°– 1.1°. In addition, we mixed some of these slices: 0.5°– 0.9°, 0.5°– 1.0°, 0.6°– 1.0°. Slightly different cuts where used in each slice. The use of several small slices in DISTANCE is necessary because of the different behaviour of the lateral distribution of showers with distinct energies for the primary particle. For 1 TeV showers, for instance, the lateral distribution of light is rather flat from ∼20 meters away from the shower axis till the hump, at our detector level. But this distribution can evolves to an increasing or decreasing tendency depending on the energy of the primary. Small slices on DISTANCE (which is a good estimator for the impact parameter of the shower) provide an almost flat light density profile within a given bin.



a) b)

Figure 1: Total amount of light in the camera of MAGIC as a function of the energy of the primary, for those events passing the cuts applied for the DISTANCE range 0.5°– 0.9°, and for the zenith angle ranges: a) $\cos\theta > 0.96$ (approx. $5^\circ \le \theta \le 16^\circ$); and b) $\cos\theta < 0.96$ (approx. $16^\circ \le \theta \le 25^\circ$).

In order to estimate the energy of the primary of an atmospheric shower, several parameters have to be taken into account, being the most important the impact parameter and zenith angle of the shower, the total amount of light, and the position of the maximum development in the atmosphere, $h_{\max}$:

$$E = E(\text{SIZE}, \rho_{\text{impact}}, \theta_{\text{zenith}}; h_{\max}; \text{WIDTH}, \text{LENGTH}, \ldots) \tag{1}$$

We use the total amount of light in the camera of MAGIC as an observable directly correlated with the total amount of light, and hence with the energy of the shower. In our studies, a simplification of this model has been used:

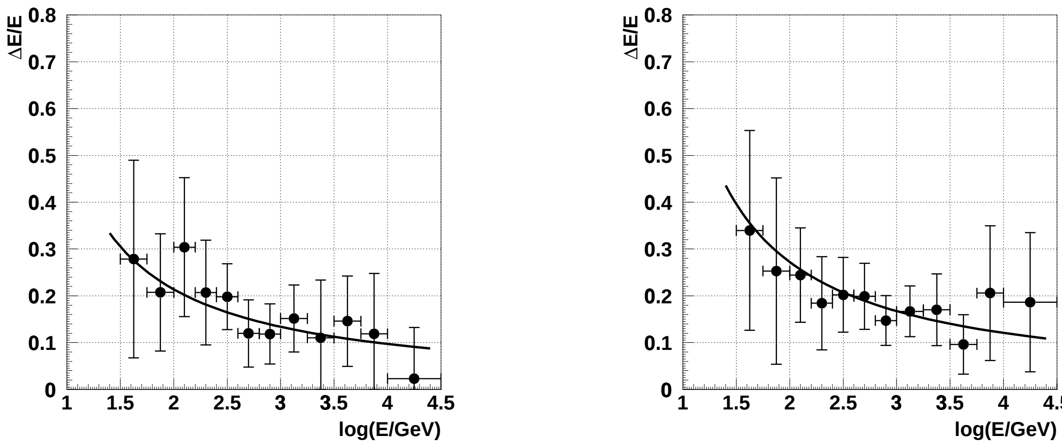
$$E = E(\text{SIZE}, \text{DISTANCE}^{\text{bins}}, \theta_{\text{zenith}}^{\text{bins}}) \tag{2}$$

Additional, second-order parameters are also correlated with the energy of the primary, but these fine effects are not yet taken into account. Further studies are in progress.

3 Results

In Fig. 1 we show the amount of light in the camera of MAGIC for one of the studied slices in DISTANCE, namely 0.5°– 0.9°, after all the cuts were applied. We can see that the amount of light measured is not univocally determined by the energy of the primary. First, the density of light not exactly constant with the impact parameter; second, the binning in zenith angle ($\cos\theta > 0.96$ and $\cos\theta < 0.96$ in this case) affects in the same way; also are important the effects of a restricted trigger region in the camera, and the finite camera size itself; and last, but not least, the fluctuations on the shower itself, which are completely unavoidable: for a fixed impact parameter, zenith angle and energy of the primary, still the shower can develop deeper of earlier in the atmosphere, and this results in a fluctuation in the amount and density of light in the detector level.

As we can see in Fig. 1, however, in the mean the amount of light is strongly correlated over almost three order of magnitude in energy with the energy of the primary (under the necessary restrictions in impact parameter, i.e. DISTANCE, and zenith angle). This correlation allows one to estimate the energy of the primary. The energy resolution, i.e., the mean error that we can make in this prediction of the primary energy, is shown in Fig. 2, were we plot the energy resolution $\Delta E/E$ obtained for the same sets used in Fig. 1. As we see, for the case of $\cos\theta > 0.96$, MAGIC reaches a value of about ≤15% at energies above 300 GeV. This value is worse, around 30%, for low energies, near the threshold (around 30-40 GeV for the PMTs camera),



a) b)

Figure 2: Calculated energy resolution for the cases a) and b) of the Fig. 1.

where we are affected by the trigger bias (events trigger due to positive fluctuations), but improves to less 15% around several TeV, getting close to 10% for energies of tenths of TeV. Our studies indicate that for the case $\cos\theta < 0.96$ a mean value of 20% is easily reachable. Note that these results are obtained with the simple approach expressed by Eq. 2.

4 Conclusions

MAGIC will be a powerful instrument for gamma-ray Astrophysics. In the estimation of the energy of the primary, we get energy resolutions of around 15% over more than two orders of magnitude in energy. This resolution is even better (close to 10%) for the case of near-to-zenith observations and showers in the TeV range. Further studies are needed to perform a better estimation of the dependence of the resolution of MAGIC with the energy of the primary particle, the impact parameter, the zenith angle and the position of $h_{\max}$, as well as to include several second-order parameters in the determination of the energy.

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