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Monte Carlo Simulation for the MAGIC-II System

E. Carmona[1], P. Majumdar[1], A. Moralejo[2], V. Vitale[3], D. Sobczynska[4], M. Haffke[5], C. Bigongiari[6], G. Cabras[3], M. De Maria[3], F. De Sabata[3] for the MAGIC Collaboration
[1]*Max-Planck-Institut für Physik*
[2]*Institut de Física d'Altes Energies*
[3]*Dipartimento di Fisica dell'Università di Udine and INFN sez. di Trieste*
[4]*Division of Experimental Physics, University of Lodz*
[5]*Universität Dortmund*
[6]*IFIC - Instituto de Física Corpuscular*
carmona@mppmu.mpg.de, pratik@mppmu.mpg.de

Abstract: Within the year 2007, MAGIC will be upgraded to a two telescope system at La Palma. Its main goal is to improve the sensitivity in the stereoscopic/coincident operational mode. At the same time it will lower the analysis threshold of the currently running single MAGIC telescope. Results from the Monte Carlo simulations of this system will be discussed. A comparison of the two telescope system with the performance of one single telescope will be shown in terms of sensitivity, angular resolution and energy resolution.

Introduction

The MAGIC telescope, currently the largest (17 m diameter mirror) single dish imaging atmospheric Cherenkov telescope, has been in scientific operation since summer 2004. A second 17 m telescope equipped with advanced photodetectors and ultra-fast readout is under construction and is expected to be ready in 2007 [1]. MAGIC-II, the two telescope system, is designed to lower the energy threshold and simultaneously achieve a higher sensitivity in stereoscopic mode.

In order to determine the optimal baseline distance between the first and the second telescope and estimate the performance of the system, detailed Monte Carlo simulations have been carried out [2]. The Monte Carlo simulation of the MAGIC-II system is divided into three stages. The *CORSIKA* [3] program simulates the air showers initiated by either high energy gammas or hadrons. In this simulation we have used the CORSIKA version 6.019, the EGS4 code for electromagnetic shower generation and VENUS and GHEISHA for high and low energy hadronic interactions respectively. We have also introduced new atmospheric models for MAGIC on the basis of studies of total mass density as a function of the height. The second stage of the simulation, *Reflector* program, accounts for the Cherenkov light absorption and scattering in the atmosphere and then performs the reflection of the surviving photons on the mirror dish to obtain their location and arrival time on the camera plane. Finally, the *Camera* program simulates the behaviour of the MAGIC photomultipliers, trigger system and data acquisition electronics. Realistic pulse shapes, noise level and gain fluctuations obtained from the MAGIC real data have been implemented in the simulation software.

For the present study a total of 1.14×10^8 protons between 30 GeV and 30 TeV have been produced, as well as and 2.0×10^6 gammas between 10 GeV and 20 TeV. The energy distribution of primary gamma rays is a pure power law with a spectral index of -2.6, whereas charged primaries follow the power law of -2.78. The telescope pointing direction is 20° in zenith, with the directions of protons scattered isotropically within a 5° semi-aperture cone around the telescope axis. Maximum impact parameters of 350 and 450 m have been simulated for gammas and hadrons respectively.

Analysis of stereo events

The two telescopes in the MAGIC-II system can be independently operated by observing two different sources or sky regions. However, the best performance of the system is achieved with the simultaneous observation of air showers by the two telescopes. The stereoscopic observation mode allows a more precise reconstruction of the shower parameters as well as a stronger suppression of the hadronic showers and other background events.

The analysis of stereoscopic events is performed by individually analyzing the images from the two telescopes. A set of parameters (Hillas parameters [4]) is obtained from each image and they are combined to obtain the shower parameters. Only showers triggering both telescopes are considered under the stereo analysis. The images are combined following the first algorithm in [5]. The intersection point of the two major axis of the ellipses recorded in the telescope cameras, provides the location of the source of a particular shower (figure 1). The θ^2 parameter is defined as the square of the angular distance from the real source image in the camera and the reconstructed one for each event. The location of the shower core on ground is obtained by intersecting the image axes from the telescope positions on the ground. In addition, the height of the shower maximum (H_{max}) can also be obtained. Having only two telescopes, the quality of the reconstruction of these parameters depends on the amplitude ($Size$) of the recorded images and the angle between the axes.

Image analysis is based on the analysis of the second moments of the images recorded by the telescopes cameras. Among the parameters obtained, *Width* and *Length* (second moments of the light distribution along the major and minor axes of the image) are the more useful ones for signal (gammas) / background (hadrons) separation. *Width* and *Length* depend on the distance from the shower core to the telescope, hence, a correct estimation of the impact parameter is required to properly evaluate these parameters. With a single telescope, the observer can not easily resolve the ambiguity between a close by, low energy shower and a distant, high energy one. With a second telescope, in most cases the ambiguity disappears because of the stereoscopic vision of the showers.

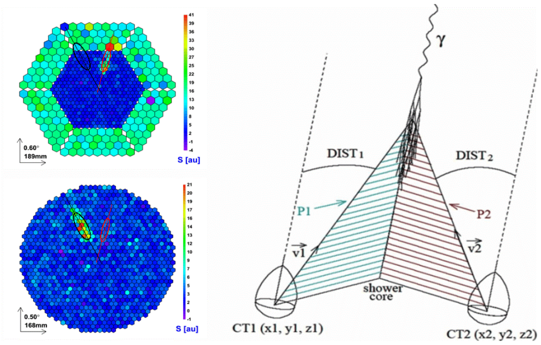

Figure 1: Stereoscopic principle. The incoming direction of the shower and core distance are obtained by combining the information of the images on both telescopes.

In order to combine the parameters from both images, we compute the *Mean Scaled Width*(MSW) and *Length*(MSL) parameters. These new parameters are obtained by subtracting the mean and dividing by the RMS of the parameter distribution (as a function of size) for Monte Carlo gammas. The new distributions have a mean value of 0 and RMS of 1 for gamma showers and are broader for proton showers. The distribution of these parameters for gamma and proton showers are shown in figure 2. A comparison between the single telescope case (MAGIC-I) and two telescopes case (MAGIC-II) is also shown. A higher gamma/hadron separation is achieved when combining the information from the two telescopes, compared with the single telescope case.

In our analysis, the *Random Forest* [6] (*RF*) technique is used for gamma/hadron separation. *RF* is a multidimensional classification tool that, in this case, it is used to determine an average probability of an event to be a hadron induced shower. A set of MC gamma ray events and MC proton events is used to train the *RF*. After training, the test samples can be classified by *RF*, providing a parameter (called $Hadronness$) distributed between 0 and 1. Values closer to 0 mean that the event is more gamma-like and values closer to 1 mean that the event is more hadron-like.

For this study, the parameters that have been used in Random Forest are: average amplitude ($Size$),

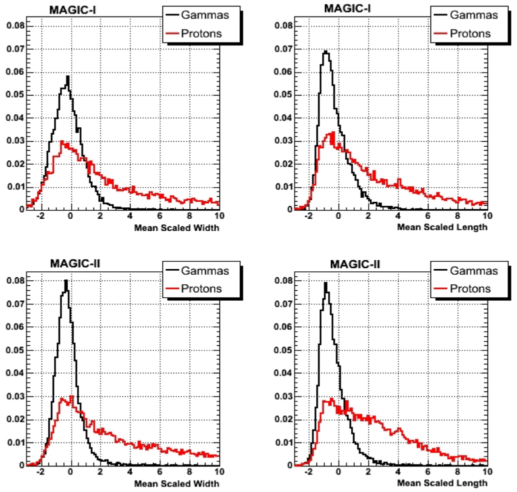

Figure 2: Comparison of the scaled $Width$ (left) and $Length$ (right) parameters between MAGIC-I and MAGIC-II.

average number of islands (N_{island}) [1], core distance, H_{max}, MSW and MSL. This set of parameters, however, should not be considered as optimal and some improvement could be expected with an optimized parameter selection.

In the analysis, gamma/hadron separation is based on the $Hadronness$ and θ^2 parameter is used to extract the signal events.

Finally, energy reconstruction is based on lookup-tables where Monte Carlo energy of gamma showers is tabulated as a function of shower impact parameter, H_{max} and $Size$. For each telescope, a reconstructed energy is obtained by interpolation. The shower energy is obtained as the average of the values from both telescopes.

Simulation results

Monte Carlo simulations show that the sensitivity does not vary dramatically with the distance between telescopes, the optimal value being around 90 m [2]. The sensitivity is defined as “integral flux resulting in gamma excess events, in 50 hours of observation, equals to 5 times the standard deviation of the background”. The effective area at trigger level of the MAGIC-II system is smaller than that of any of the two telescopes because of the coincidence requirement. However, at energies above 300 GeV matches the effective area of MAGIC-I which is slightly lower than that of the new second telescope because this is equipped with higher quantum efficiency photomultipliers. The coincidence requirement provides a higher background rejection. As a result a better sensitivity below 100 GeV and also a reduction of the analysis threshold is achieved.

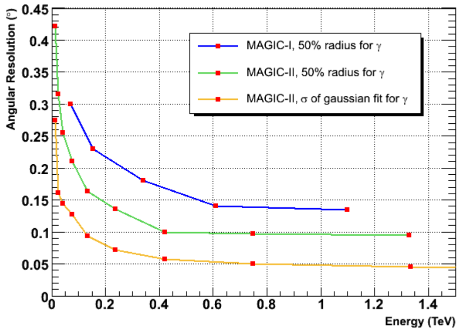

Figure 3: Comparison of the angular resolution between MAGIC-I (1 telescope) and MAGIC-II (two telescopes). Sigma of the fit to a 2-dimensional gaussian is also shown for MAGIC-II.

For a single telescope, the angular resolution is estimated using a modified parametrisation of the so called $DISP$ method [7]. The discrimination of the shower head and tail relies on the shape of the image (asymmetry along the major axis). This often results in a wrong head-tail assignment that degrades the angular resolution. With two telescopes, this drawback is easily overcome since the source direction is obtained as the intersection of major axes of the images in the camera. The angular resolution, here defined as the angle within which 50% of the reconstructed gammas from a point source would be contained, as a function of gamma ray energy is shown in figure 3. The improvement in angular resolution from 1 to 2 telescopes is clearly seen.

The stereoscopic analysis also results in a better energy reconstruction due to better reconstruction

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[1] an island is defined as any cluster of 2 or more pixels surviving the image cleaning.

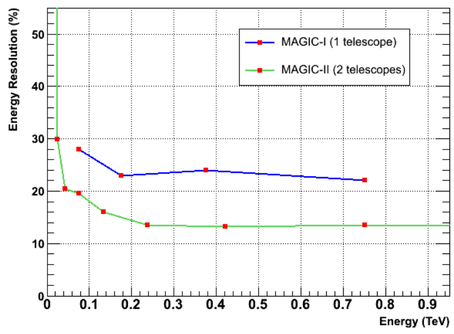

Figure 4: Energy resolution of the MAGIC-II (two telescopes) system compared with MAGIC-I.

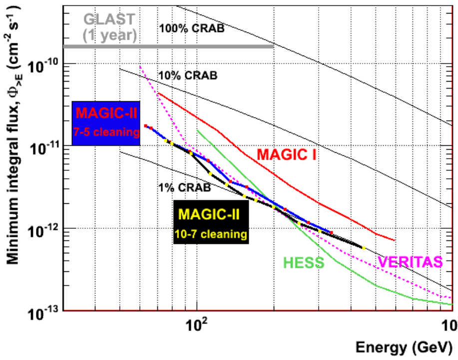

Figure 5: MAGIC-II system sensitivity compared with the Crab flux and other existing experiments (MAGIC-I, HESS and VERITAS).

of the shower axis and also a double sampling of the light pool. The energy resolution for gammas as a function of primary energy is shown in figure 4. For comparison, the energy resolution of MAGIC-I is also shown. An energy resolution for gammas better than 20% is achieved above 50 GeV.

The sensitivity estimate for MAGIC-II is shown in figure 5. The flux sensitivity of the 2-telescope system is between 2 and 3 times better than that of a single telescope (MAGIC-I) and it is significantly improved below 100 GeV. The MAGIC-II system can achieve a sensitivity of 1% Crab in 50 hours above 150 GeV.

Conclusions

The MAGIC-II system of 2 telescopes will perform observations in stereoscopic mode, allowing a more precise reconstruction of the showers and a significant reduction of backgrounds below 100 GeV. This will make possible an improved angular and energy resolution as well as a reduction of the analysis threshold. All together it will increase the current sensitivity of the instrument by a factor between 2 and 3 at different energies.

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