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Monte Carlo studies on the MAGIC clone

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Abstract

A brief summary of status of the MC studies regarding the MAGIC clone is presented. We foucus mainly in the optimization of the distance between MAGIC and its clone, and on the estimate of the flux sensitivity gain by performing stereo observations, i.e., the simultaneous recording of showers by both telescopes when observing the same source.

Contents

1 Introduction

The aim of this study is to determine the optimal distance between 2 MAGIC-like telescopes. On evaluating the performance of a Cherenkov telescope (either a single one or an array of them), the key parameter is the flux sensitivity, which can be defined as the minimum flux of gamma rays that can be detected in a given observation time at a certain level of statistical significance. We have studied the case of a point-like gamma-ray source, and determined which distance results in the best sensitivity (or smallest detectable flux).

2 The Monte Carlo sample

We have produced a special MC sample for this task, consisting of 10^6 gamma showers of energies between 10 GeV and 10 TeV, following a $E^{-2.6}$ differential spectrum, and 10^7 protons between 100 GeV and 10 TeV ($E^{-2.75}$ diff. spectrum). Showers have been simulated using CORSIKA 6.019. All primary gammas, assumed to come from a point source, had a zenith angle of 20 degrees and an azimuth corresponding to the direction orthogonal to the line along which the telescopes are placed (that is, gammas are paralel to vector $\vec{p}$ in fig. 1). Primary protons were isotropically generated in directions within 5 degrees of the same direction. The cores of the showers were scattered on the plane perpendicular to the vector $\vec{p}$, in a 350 m radius circle for the case of gammas and a 450 m radius for protons. We recorded the showers with 7 aligned MAGIC-like telescopes set at different distances of the center between -70 and 70 m (fig. 1). By selecting different pairs of telescopes we can study their combined performance at different distances between 20 and 140 meters. Larger distances are not convenient because for the MAGIC site height, the Cherenkov light density on ground decreases fast beyond $\simeq 120$ m (distance from the shower axis), which implies a drastic reduction in the number of coincident events for too distant telescopes.

The seven simulated telescopes are equal to the current MAGIC telescope, except for the use of a high quantum efficiency camera, with peak QE around 45% for $\lambda \simeq 500$ nm (compared to the 30% peak of present MAGIC photomultipliers). The MAGIC collaboration has already started testing a developmental HAMAMATSU hybrid PMT of these characteristics, with the aim of equipping the clone telescope with this kind of photosensors. The rest of the simulated characteristics, like mirror size and reflectivity, trigger electronics, DAQ electronics (300 MHz FADCs for the sampling of the signals), etc, are the same of the existing MAGIC.

We have added a diffuse background light noise of 1.7×10^{12} photons $\mathrm{m}^{-2}\ s^{-1}\ sr^{-1}$ between 300 and 600 nm, which is the flux measured on a dark patch of the sky at the MAGIC site [1]. As trigger condition for each telescope we have set a loose one (3 close-compact next neighbours with signal above 4 mV, which corresponds to 6-7 photoelectrons), and an event is registered in all telescopes whenever any of them fulfills the trigger condition. However, the actual gamma energy threshold will be determined by offline cuts which we will perform on the triggered events to select "good" images. These are the ones which can be reconstructed with the methods currently available in the standard MAGIC analysis software (namely a Hillas-like analysis).

3 Reconstruction of the events

To obtain the signal in each single pixel, we integrate 5 samples of the FADC readout. This range is where most of the Cherenkov pulse (originally $\simeq 2-3$ ns long), is contained after the stretching which is performed to allow the sampling with 300 MHz FADCs. In the following analysis we will

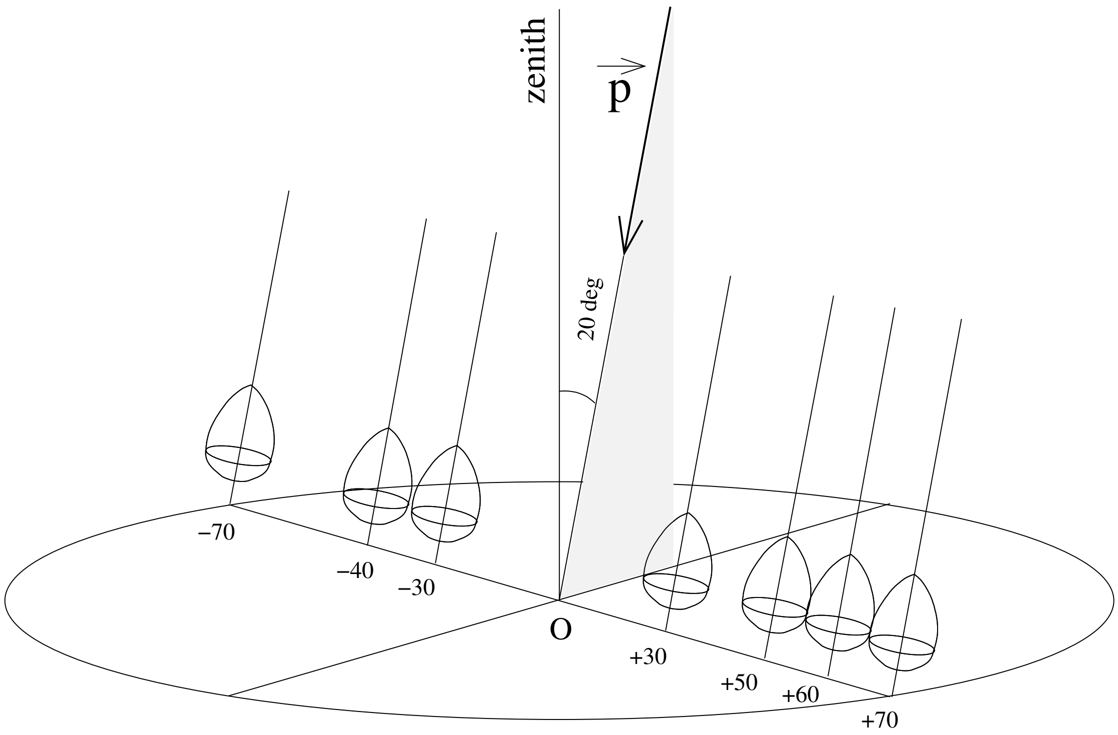

Figure 1: *Position of the telescopes considered in the present simulation, and relative orientation of gamma showers. Distances are in meters.*

not consider timing information, but only the light intensity registered by each pixel. Whenever any FADC slice of the the high gain branch saturates, which for the settings used here occurs at around 120 photoelectrons, the low gain branch (which registers a signal 10 times smaller) is taken instead.

To select pixels which will be used in the image analysis, we apply a standard 2-step cleaning procedure, first selecting all pixels above 4 times the RMS of the fluctuations of the background light noise. Of these pixels, we reject those not having at least one neighbour fulfilling the same condition. These are called *core* pixels. Finally, we also keep pixels above just 3 times the RMS of the noise if they have one or more *core* neighbours. We will proceed with the image analysis for those events having at least 5 *core* pixels in the two telescopes we are considering. The reason for this cut is twofold: on one hand, we must require a minimum number of pixels, because the moments of the light distribution do not make much sense if calculated with too few points (for instance 2 or 3 pixels). This does not mean of course that a finer analysis could not extract any information from small events, but we will not consider them in this work. The second reason is a practical one: we have limited the energy range of the MC proton sample to between 100 GeV and 10 TeV. This has been done for practical reasons, to achieve a reasonable statistics with the available CPU power in a short time. Producing protons at lower energies has the problem of the very low trigger efficiency, which means one has to generate many thousands of showers to get just a few usable events. By applying the cut on the number of core pixels, we have estimated that the fraction of proton showers below 100 GeV would be just a 10% (fig. 2), so our sample contains the bulk of the relevant proton background.

In the right pad of figure 2 we show the energy distribution for the MC gammas surviving the cut in the number of core pixels. As we can see, the peak energy, which is often used as a measure of the threshold of a Cherenkov telescope, is around 40 GeV. This will not be the real absolute threshold of the 2-telescope system. We estimate that two MAGICs equipped with the high QE cameras here simulated can have a *trigger* threshold as low as 20 GeV without running into trouble with random triggers from the night sky background light. Of course, such low energy showers will produce very small images, and as mentioned above, a different kind of analysis will be needed, as well as a proton MC sample below 100 GeV. For the present work we will hence concentrate on the defined sample with threshold around 40 GeV.

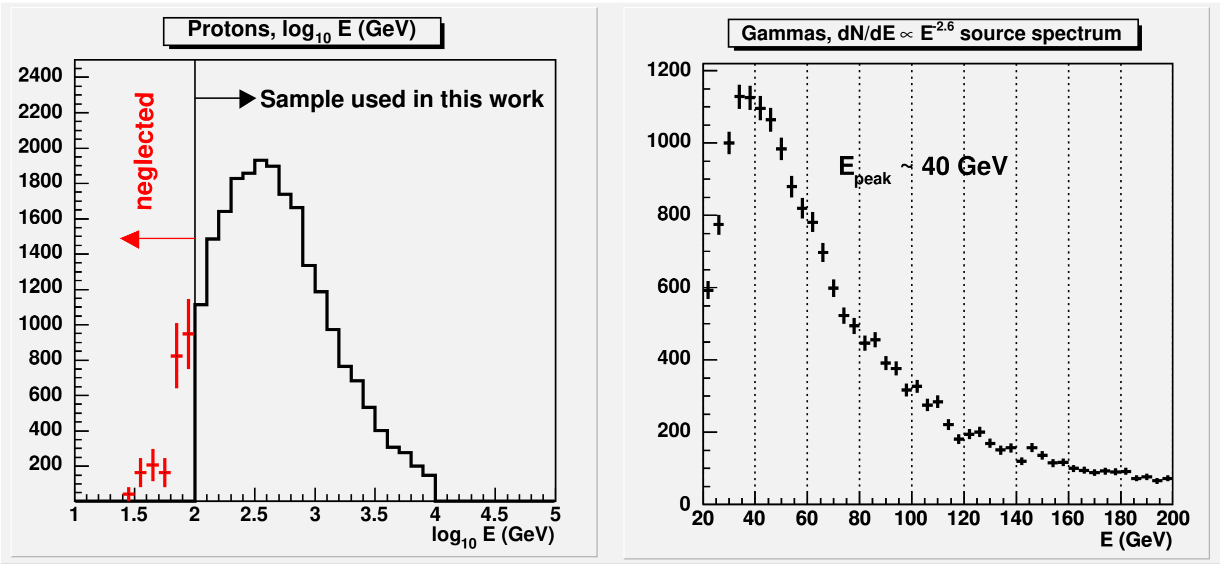

Figure 2: *Energy distribution of protons and gammas which fulfill the quality cut (>5 core pixels) in both telescopes. The case for telescopes placed at 90 m distance is shown. Using a lower energy small MC sample we have estimated the fraction of (neglected) protons below 100 GeV to be about 10 % of the total proton rate.*

With the pixels which survive the image cleaning we calculate the moments up to third order of the light distribution on the camera. From them we derive the well known image parameters defined by Hillas (SIZE, DIST, WIDTH, LENGTH, ALPHA), and some others like CONC (ratio between the sum of signal in the two brightest pixels and SIZE) and the third moment along the major axis, whose sign is defined positive if the narrowest part of the image points towards the source, as expected for gammas (in the following called M3LONG). To improve their background discrimination power, we have scaled WIDTH and LENGTH, dividing them by the mean value expected for the corresponding SIZE of the image. This scaling allows also to average WIDTH and LENGTH for the two telescopes, to obtain for each event the so called *Mean Scaled Width* (MSW) and *Mean Scaled Length* (MSL) [2]. In fig. 4 the distributions of these two parameters for gammas and protons are shown.

From the position and orientation of the images in the two considered telescopes we can also estimate the location of the source on the camera (see fig. 3, left), and the impact point on the ground of the shower axis. From the former we can derive the parameter θ^2, the square of the angular distance between the reconstructed source direction and the nominal one (the center of the camera). This parameter will have a sharp peak at zero for gammas coming from the point-like source, while showing a much flatter distribution for an isotropic flux like that of hadronic cosmic rays (fig. 4).

For the calculation of the shower impact point on the ground, we will assume that the shower axis is paralel to the axes of the telescopes, which point to the gamma-ray source. The position of the shower axis can then be estimated as the intersection of the planes P1 and P2 (see fig. 3, right), defined by the pointing direction, the position of each telescope (center of mirror) and the vectors $\vec{v1}$ and $\vec{v2}$ which point from the telescopes to the shower maximum, and which can be obtained from the position of the shower image on the camera. This approach will of course lead to the correct impact parameter only in the case in which the primary is actually coming from the assumed source direction. One could also use in the calculations the estimated direction of the shower (fig. 3, left), but then the uncertainty in the estimate of the core position is much larger, since it is dominated by the angular resolution (given that the shower develops several kilometers above the observation level, even an uncertainty of tenths of a degree translates into a big error in the core position).

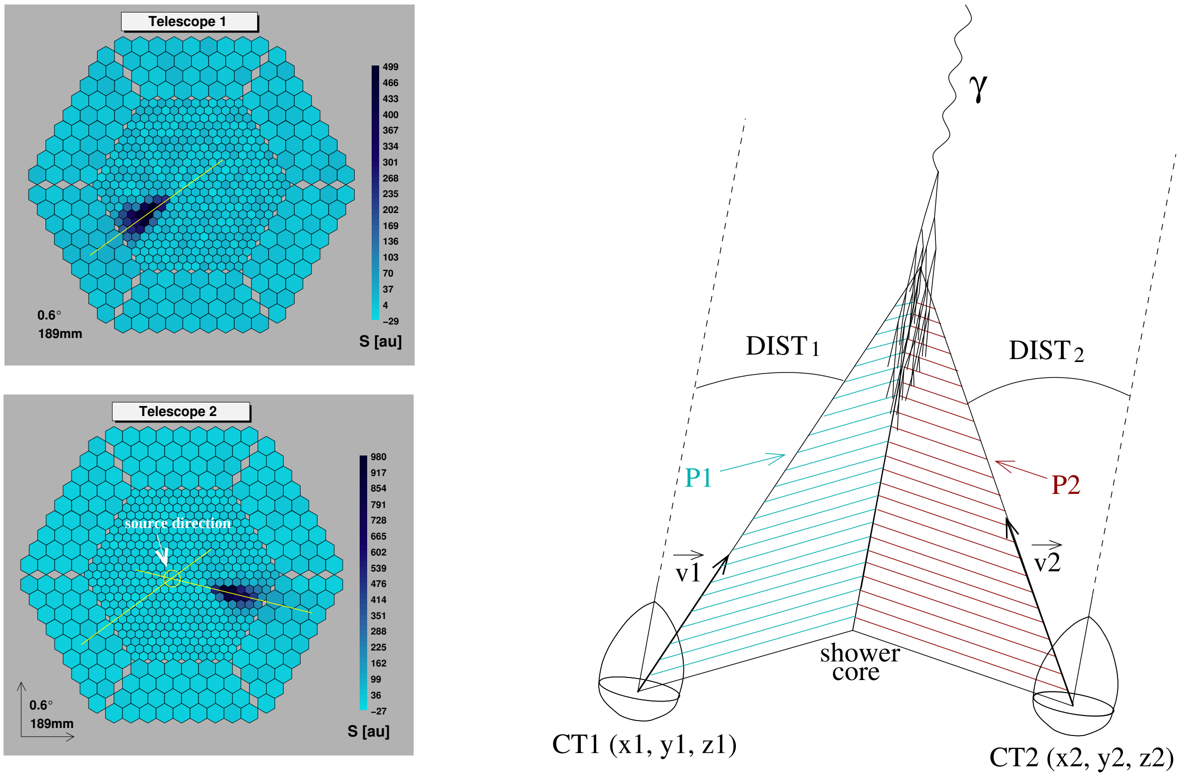

Figure 3: *Left: reconstruction of the shower direction through the intersection of the major axes of the images in both telescopes. Right: reconstruction of the shower core position assuming that the shower axis is paralel to the pointing direction of the telescopes.*

4 Proton background discrimination

For the selection of gamma events we have used the method known as *Random Forest* [3], implemented in the MAGIC standard software by T. Hengstebeck. This method has proved to be the fastest and

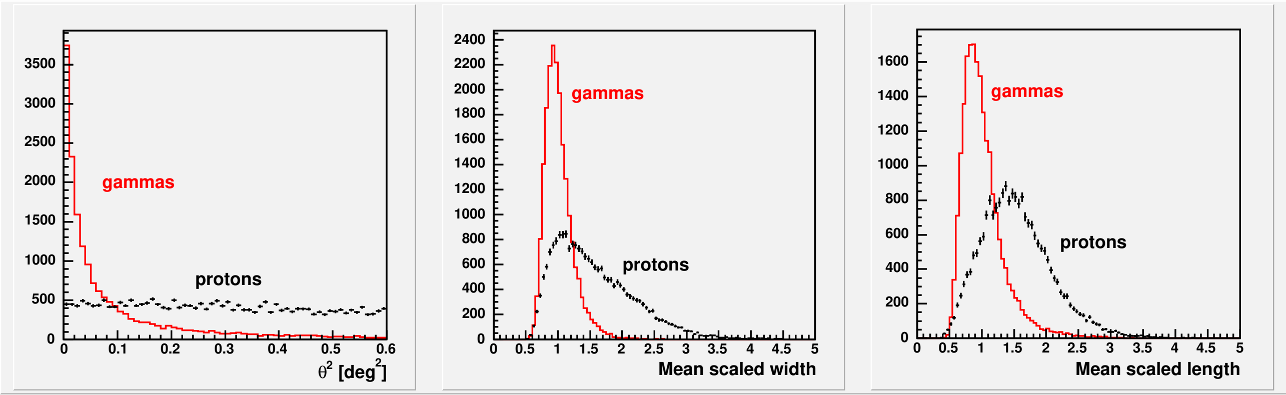

Figure 4: *Some image parameters obtained from the data of 2 telescopes (the case for 90 m distance is shown as an example).*

most efficient in classifying images as gamma-like or hadron-like [4]. A set of variables is fed to the algorithm for every event. In our case we use 15 parameters: SIZE, DIST, CONC, ALPHA and M3LONG of both telescopes, plus θ^2, scaled WIDTH, scaled LENGTH, and reconstructed shower impact parameters with respect to both telescopes. After the *growing* of the random forest (see above references for details) using a training Monte Carlo sample (consisting of half of the produced events, gammas and protons), the rest of the simulated events (test sample) are driven through the forest, the final result being a single number per event, here called *hadronness*, whose value is between 0 and 1. A *hadronness* of 0 means the event is gamma-like, while a value close to 1 indicates the event is very likely not a gamma (see fig. 5, left). Hence the background discrimination reduces now to applying a cut *hadronness* $< H$, which will keep a fraction of gammas ε_γ and a fraction of hadrons (here only protons) $\varepsilon_h < \varepsilon_\gamma$. A very tight cut is generally not convenient because it will reduce too much the number of gammas (and fluxes are usually low!), while a loose cut will result in poor sensitivity. A usual choice is to take the cut which provides the highest *quality factor* $\mathrm{Q} = \varepsilon_\gamma/\sqrt{\varepsilon_h}$ (fig. 5, right). Since the fluctuations of the number of background events (the hadrons) are expected to be poissonian, the statistical significance of the detection of a given gamma-ray source is expected to be increased roughly by a factor Q when applying the cut *hadronness* $< H$.

In order to estimate the sensitivity gain achievable with the addition of a second telescope, we have repeated the whole analysis above using only the image parameters available for one telescope. A first idea of the improvement in the background discrimination when adding a second telescope can be grasped by comparing figures 6 and 5, where the performance of the Random Forest in both cases is shown. For a proper comparison, we have applied am additional preliminar cut, SIZE > 130 phe$^-$, on the single telescope data, so that both samples, single and stereo, have within the uncertainties the same energy distribution for gammas, and in particular the same value of the peak energy $E_{peak} \simeq 40$ GeV. To the gain due to the better reconstruction of showers, we must add a smaller gain due to the fact that the condition of having more than 5 core pixels in both telescopes cuts out more protons than gammas. This effect will be included in the calculation of flux sensitivities which we will explain in the next section.

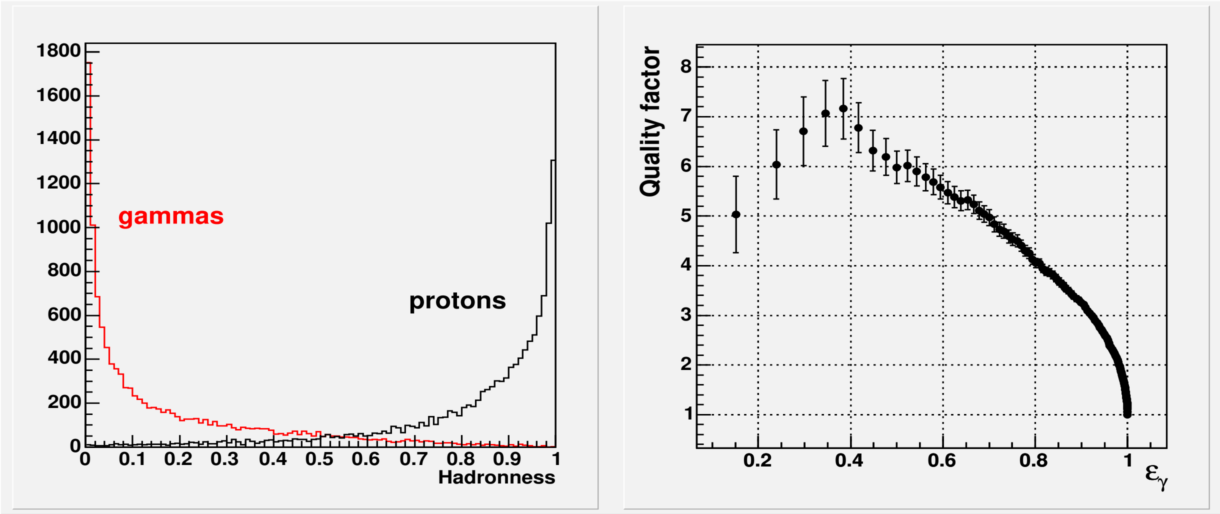

Figure 5: *Outcome of the event classification using the Random Forest for the case of two MAGIC telescopes at 70 m distance. Left: hadronness distribution for gammas and protons. Right: quality factor (see text) as a function of the gamma efficiency for different upper cuts in the hadronness.*

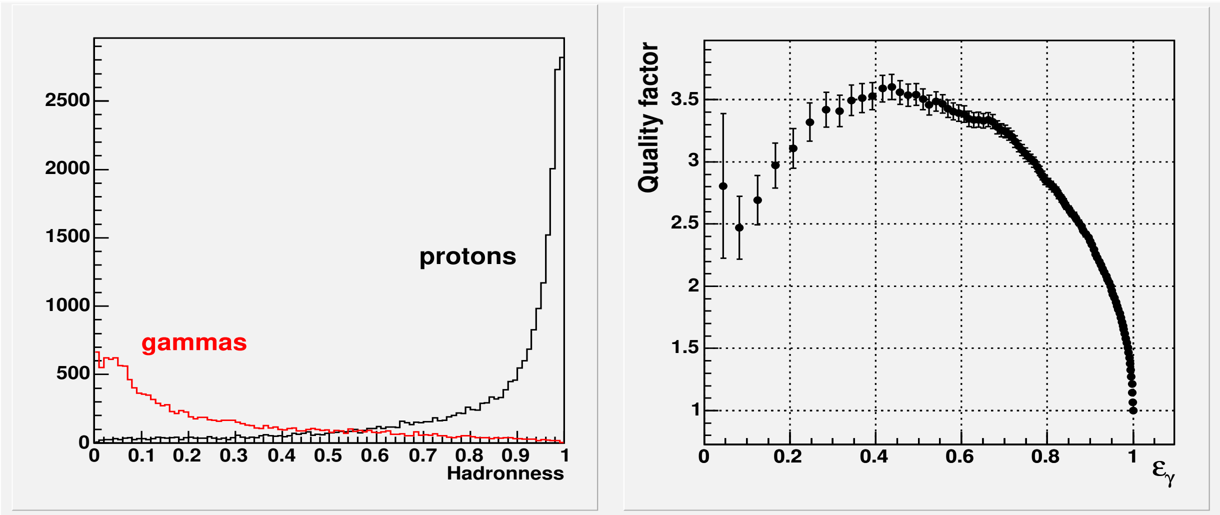

Figure 6: *Outcome of the Random forest for one single MAGIC telescope, and an event sample comparable to that in fig. 5. The maximum achieved quality factor is about half of the one obtained with two telescopes.*

5 Calculation of flux sensitivity

As a definition of flux sensitivity we will use the following: minimum integral flux (events per unit time and unit area) above the gamma peak energy E_{peak} that a source must emmit, so that the number of detected gammas in 50 h is 5 times the standard deviation of the number of detected background events. We assume a power-law spectrum of the gamma rays, $dN/dE \propto E^{-2.6}$. By "detected" in this context we mean the events surviving whatever type of analysis we perform on the data, which in our case means all those verifying the cut *hadronness* $< H$. In terms of event rates:

$$R_\gamma^{min} \cdot t_{50} = 5 \cdot \sqrt{R_h \cdot t_{50}} \tag{1}$$

Here R_γ^{min} and R_h are the gamma and hadron rates after cuts, and t_{50} is 50 hours. The relation between rates and integral fluxes, both for gammas and protons, can be written as:

$$R = \phi \cdot A \cdot \frac{N_{fin}}{N_{prod}} \tag{2}$$

Where ϕ is the integral flux in the MC production energy range, A is the area in which the cores of MC showers have been distributed, and N_{prod}, N_{fin} are the number of produced MC events and the number of MC events after the whole analysis respectively. For the calculation of R_h we have used the proton flux measurements from the AMS-01 experiment (*Alpha Magnetic Spectrometer*) [5]. From (1) and (2) we can obtain an expression for the integral flux sensitivity:

$$\phi_{E>E_{peak}}^{min} = \frac{5}{A_\gamma} \cdot \sqrt{\frac{R_h}{t_{50}}} \cdot \left(\frac{E_{peak}}{10\ \mathrm{GeV}}\right)^{-1.6} \cdot \frac{N_{\gamma,\, prod}}{N_{\gamma,\, fin}} \tag{3}$$

The value of 10 GeV which appears in the formula is the minimum energy simulated for gammas, and is used for scaling down the integral flux from that energy to the peak energy E_{peak}.

We remark once more that the considered hadronic background consists only of protons between 100 GeV and 10 TeV. As already noted, we are neglecting protons outside that energy range, and also the heavier nuclei (alpha particles and others) of the cosmic radiation (which may increase the rates by about 30%). This means that the calculated flux sensitivities will be, in absolute value, slightly better than the actual ones, but accurate enough for the main purpose of the study, which is finding the best distance to place the second telescope and estimating the gain in sensitivity with respect to the single one. That is, we are mainly interested on the relative sensitivities between the single telescope and pairs of telescopes at different distances.

6 Results

Using the methods described above, the flux sensitivity for pairs of telescopes at distances ranging from 20 to 140 m has been estimated. In figure 7 the sensitivity (eq. 3) is plotted versus the proton flux after the gamma / hadron separation cut, which depends on the tightness of the applied cut on *hadronness*. Three different 2-telescope setups are compared to the single telescope. For a very loose cut (high residual rate), the minimum observable flux increases with the distance bertween telescopes, just because the number of coincident events goes down: it would eventually become zero when telescopes are so distant that no shower manages to illuminate both instruments. For tighter cuts, gamma / hadron separation starts to play a role and the better discrimination provided by stereoscopic analysis compensates the loss of statistics: the telescope pairs at 70 and 120 m become both better than the single telescope, and also better than the 20 m combination, since as expected, stereoscopy becomes less efficient when the two telescopes view the shower from nearly the same point. The lowest minimum among the tested arrangements is achieved for two telescopes placed at 70 m (see right pad of fig. 7 and fig. 8).

Apart from the extreme cases of very short or very long distances displayed in fig. 7, the dependence of sensitivity with the telescope distance is not very strong. There seems to be a rather flat plateau (fig.

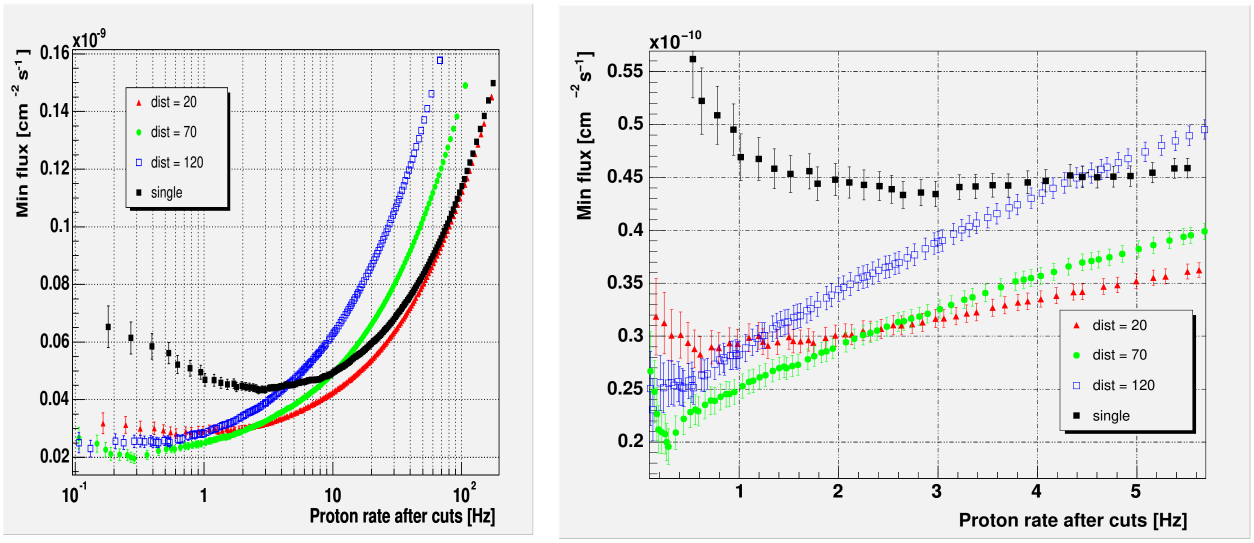

Figure 7: *Integral flux sensitivity for the single telescope and pairs of telescopes at three different distances, as a function of the residual proton flux. The remaining proton flux depends on the tightness of the hadronness cut. A natural choice for the analysis cut would be that which corresponds to the minimum flux, equivalent to the best sensitivity. The right pad shows a detail of the curves in this best sensitivity region. The curve which reaches lowest values is that for a telescope distance of 70 m.*

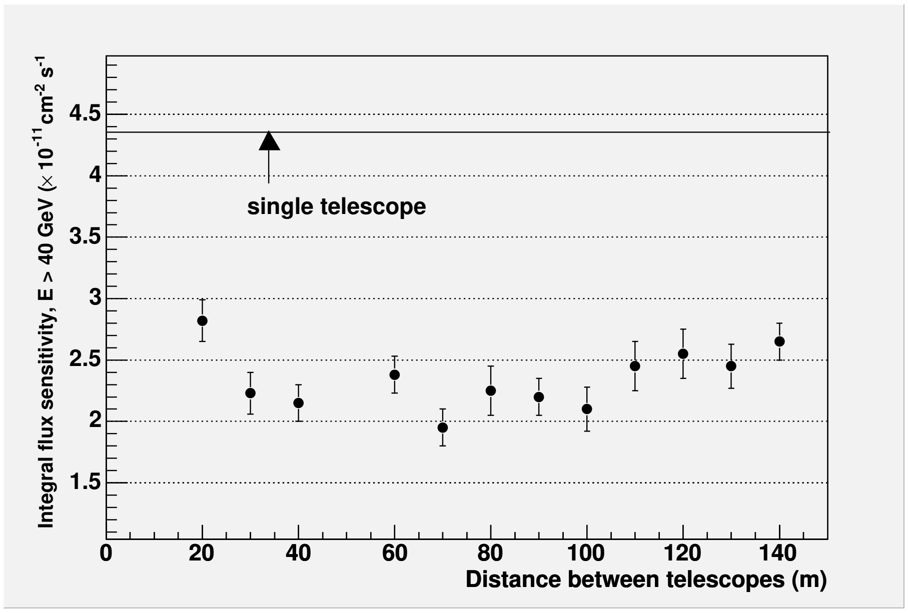

Figure 8: *Integral flux sensitivity above 40 GeV for the two telescope system as a function of the distance between the telescopes. We have chosen in each case the hadronness cuts resulting in the best sensitivity. As expected, at very small and very large distances sensitivity gets worse. Besides, our results seem to indicate that the sensitivity has a rather wide plateau around a distance of 70 m.*

8) spanning from 40 to 100 meters. Although fluctuations are large (after tight cuts, the number of remaining simulated protons in the sample is rather low, of the order of 20), the best sensitivity is very likely somewhere between 60 and 100 m. This is actually rather convenient, since the distance which really matters is not the separation D between the telescopes *on the ground*, but their distance *as viewed by the shower*, that is, on the plane perpendicular to the axes of the observed showers (which is roughly the telescope pointing direction). In the extreme case, for a certain azimuth angle the effective separation of telescopes will be $D' = D \cdot \cos(\theta)$, being θ the zenith angle. For typical observing angles of θ up to 50∘, if we choose for instance $D = 70$ meters, we end up with $D' = 45$ m, which is still in the range where stereoscopy works reasonably well. This means the performance of the system will be rather uniform for different observing directions.

Sensitivity gain with respect to MAGIC I

At the plateau, the improvement in sensitivity with respect to a single telescope is a factor of two. In terms of observation time, this means that an observation of a source at a given level of significance will be possible in a period 4 times shorter with the two telescope system when compared to the current MAGIC. For comparison, the enhancement of sensitivity in the case of two independently working identical telescopes would be of just a factor $\sqrt{2}$ because it would be simply equivalent to doubling the observation time.

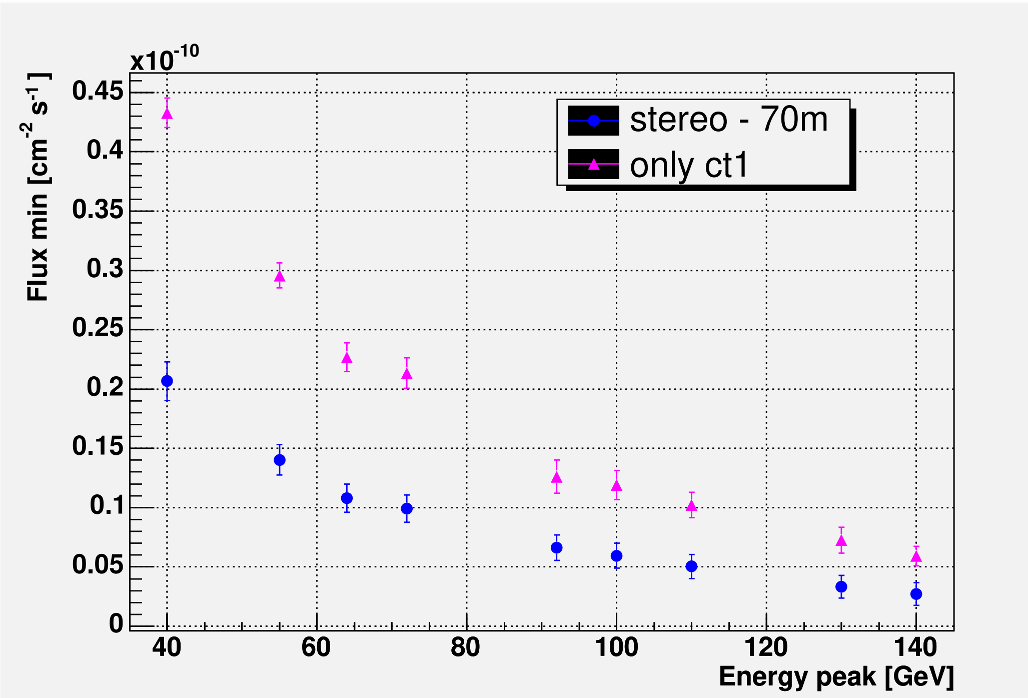

Figure 9: *Comparison of the integral flux sensitivity of a single telescope with a system of 2 telescopes at 70 meter distance as a function of energy. The energy threshold will be lower than 40 GeV, and the curve will extend up to several TeV: the shown range is the one which could be explored with the Monte Carlo sample used in this study. The 2-telescope system is better than a single telescope by a factor of 2. Absolute flux values will be slightly underestimated (by* $\simeq 25\%$*) due to the characteristics of the used MC sample (see text).*

We have repeated this analysis by applying different cuts in the SIZE parameter of the images in both telescopes. This provides us with samples with different peak gamma energies E_{peak} with which the flux sensitivity at higher energies can be obtained. The results for the single telescope and for the system at 70 m distance are presented in figure 9. The factor of 2 gain is kept when moving to higher energies, the last studied point being at $E_{peak} = 140$ GeV due to lack of statistics at higher energies. It must be noted once more that the *absolute* minimum observable fluxes here calculated are somehow lower than they should, because of the background which for technical reasons has been neglected (see section 3 and fig. 2). To correct for this, we have shifted both flux curves up until the one for the standalone telescope matched the MAGIC sensitivity estimated previously using a higher statistics (but single-telescope) Monte Carlo library. The result is shown in fig. 10, compared to the sensitivities of other existing or projected gamma ray observatories.

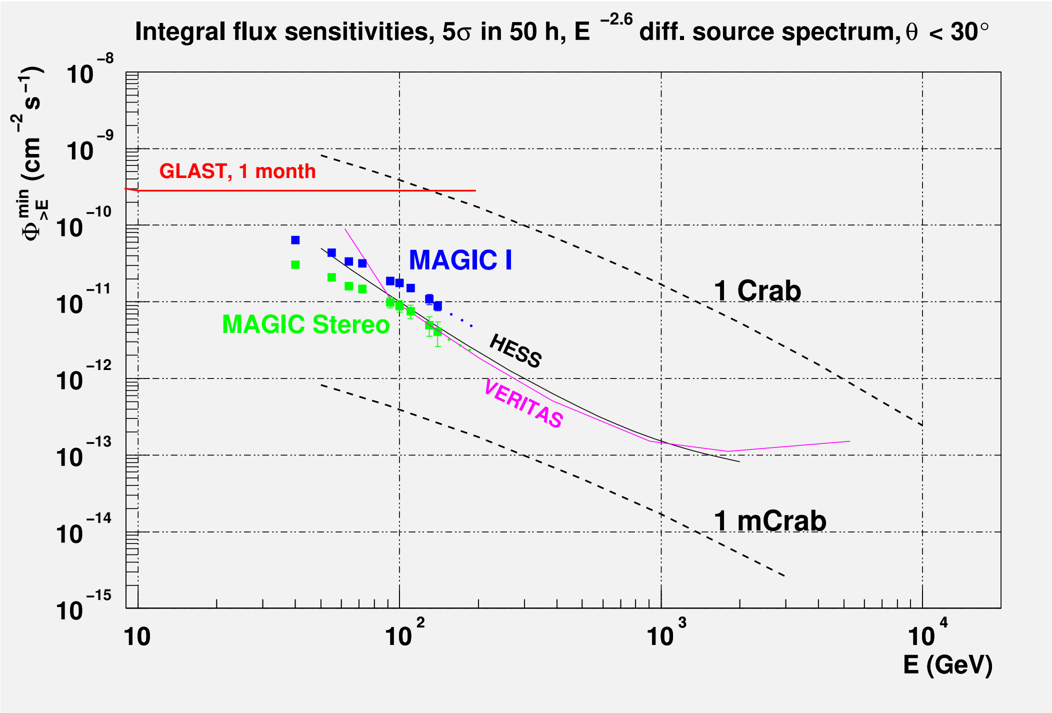

Figure 10: *Estimate of the integral flux sensitivity as a function of energy. The calculated values shown in fig. 9 have been scaled up now, to correct for the "missing background" in the used MC sample (see text). We have shifted up the two MAGIC curves such that the one for the single telescope matches the calculated MAGIC sensitivity obtained with a high statistics (single telescope) MC library. The same comment of fig. 9 about the energy range accesible to MAGIC applies here.*

An additional advantage of stereo reconstruction of showers is the better estimate of the incident direction of primary gamma rays on an event by event basis. The simplest approach is the one explained in fig. 3 (left) where the intersection of the major axes of the images is taken as the source position. As shown in figure 11 angular resolution (defined here as the angular radius of a region centered in the point source, within which 68% of the reconstructed events are contained) becomes better for increasing distances between telescopes, and also for increasing shower sizes, as one would expect from simple geometrical arguments. In fact this is one of the most important factors in the enhancement of sensitivity for point sources when adding a second telescope. The resolutions shown in fig. 11 are very conservative, since they can be improved by making cuts to reject events in which the images are nearly paralel. Work is going on in this direction. Also the better estimate of shower core position provided by the 2-telescope system will benefit the energy resolution, an improvement which still has to be quantified.

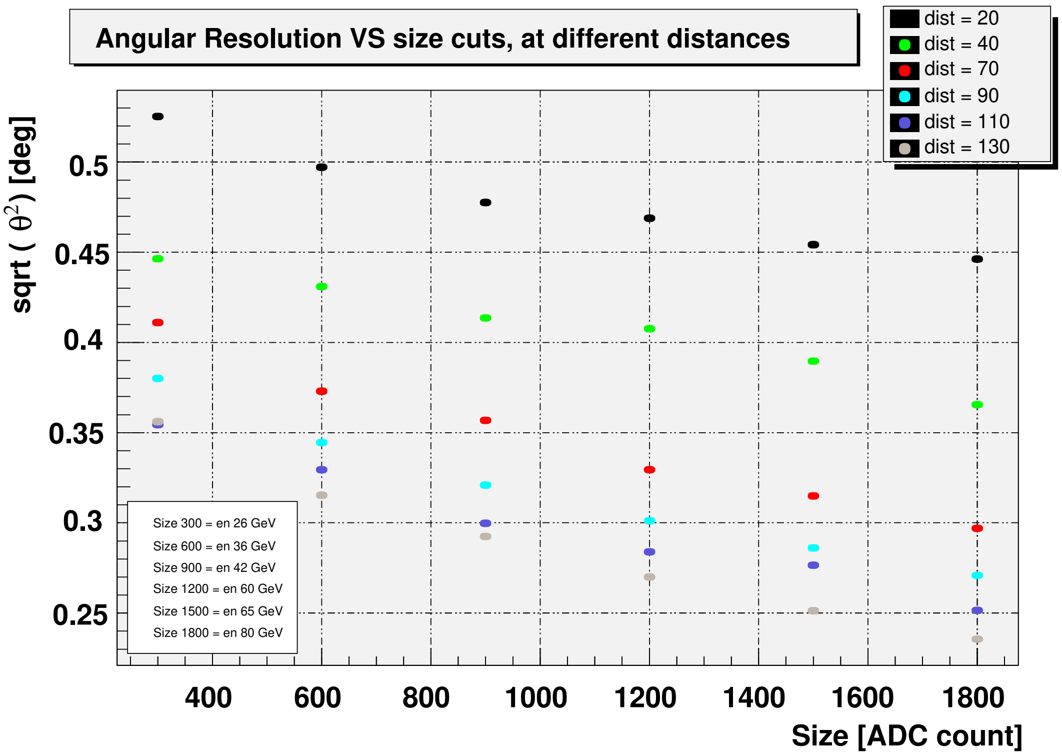

Figure 11: *Angular resolution for different distances between telescopes, from simple major axes intersection. The x axis indicates various cuts in the SIZE of the images, and the approximate correspondence with gamma ray energies is quoted in the box at the bottom left. Since only gamma showers are considered here, we can go down to lower energies than in the case of the sensitivity calculations, where we are limited by the MC proton sample. The angular resolution can be further improved by quality cuts in the relative positions of the images.*

7 Conclusions

The performance of a system of two MAGIC like Cherenkov telescopes has been studied, focusing mainly on the evaluation of the flux sensitivity to gamma ray point-like sources. The first results indicate that best sensitivity can be achieved by placing the second telescope at 70 m distance from the first one. The sensitivity improvement with respect to a single telescope is roughly a factor 2, which would be equivalent to a gain of a factor 4 in effective observation time.

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