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Study of the performance of the new ultra-fast 2 GSample/s FADC data acquisition system of the MAGIC telescope

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Abstract

In February 2007 the MAGIC Air Cherenkov Telescope for gamma-ray Astronomy was upgraded with an ultra fast 2 GSamples/s digitization system. Since the Cherenkov light flashes are very short, a fast readout can minimize the influence of the background from the light of the night sky. Also, the time structure of the image is an additional parameter to reduce the background from unwanted hadronic showers. An overview of the performance of the new system and its impact on the sensitivity of the MAGIC instrument will be presented.

The MAGIC Cherenkov telescope

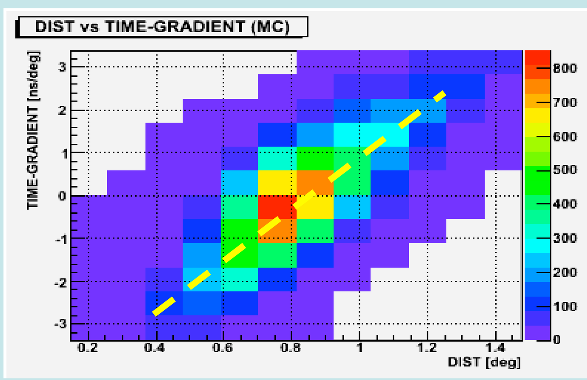
MAGIC (Major Atmospheric Gamma Imaging Cherenkov) is the largest Cherenkov telescope for VHE-γ-ray Astronomy (see [2] for details). It exploits the Imaging Air Cherenkov Technique (IACT) to detect atmosferic showers started by energetic Cosmic Rays (CR). Selection of γ-ray events and reduction of the isotropic background originated by charged CR is possible through the standard analysis of the shape and orientation of the shower images. Further background suppression can be achieved through the analysis of the timing characteristics of the image.

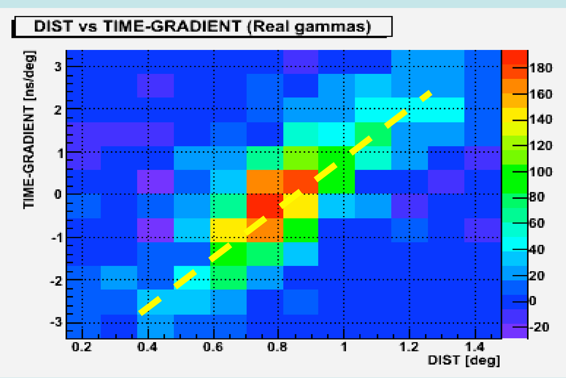
Signal extraction and Image Cleaning

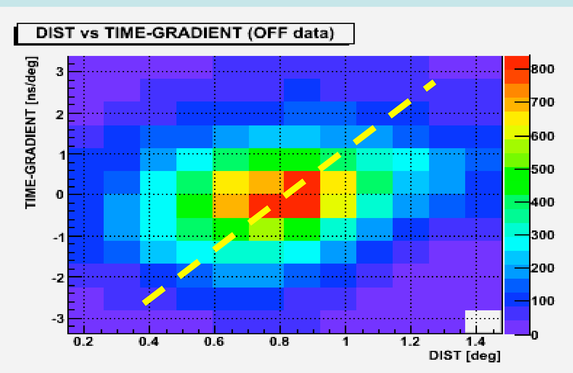
The new MAGIC data acquisition system [4] enhances the telescope performance basically for two reasons: a reduction in the amount of NSB (Night Sky Background) light integrated with the real signal (due to a smaller integration window), and the reconstruction with a good time resolution of the timing characteristics of the showers. The time resolution of each pixel has been estimated to be ~390 ps RMS for a 35 phe signal (calibration pulse).
The pixels which belong to the shower image are selected from the whole camera picture by the so-called Image Cleaning (IC) algorithm. The procedure consists in setting a threshold signal value to select the so called "core pixels" and a second threshold to select or reject their neighbors as "boundary pixels". Timing can be use to further constrain the selection of boundary pixels: a pixel is taken if its charge is above the boundary threshold, at least one of its neighbors is a core pixel and its arrival time is within $\pm\ \Delta t$ of that of the core pixel. This avoids to confuse NSB signal with real image tails (since Cherenkov pulses are very short in time).
Relaxing the cleaning levels results in a larger number of pixels per image and accordingly a lower analysis energy threshold. On the other hand, the inclusion of pixels containing just noise, unrelated to the shower, would degrade the image parameters and worsen the performance of the subsequent analysis. For the present work, a good compromise was reached at cleaning thresholds of 6 and 3 phe, and a time constrain of Δt = 1.5 ns.

Time-related image parameters

In order to exploit the better time resolution of the new FADC system, new time-related image parameters have been introduced and characterized.
• The TIME RMS parameter measures the arrival time spread of the Cherenkov photons in the pixels belonging the cleaned image (μ, γ-ray and hadron induced showers may have different characteristic time spread [8]).
• Previous studies [5] determined that along the major axis of a gamma induced Cherenkov image is present a time structure. This can be well approximated by a linear TIME GRADIENT. The magnitude of this gradient is related to the angle between the telescope and the shower axes and moreover, for γ-initiated showers of a given direction, is well correlated with the Impact Parameter (IP) of the shower. In turn, this makes that the TIME GRADIENT is well correlated with DIST (angular distance from the image center of gravity to the source location) for gamma images from a point-like source, whereas no such correlation exists for hadron images (not even after a cut in the ALPHA parameter), as shown in the figures on the bottom. The inclusion of TIME RMS and TIME GRADIENT among the parameters used in background discrimination, must therefore result in an enhancement in sensitivity.

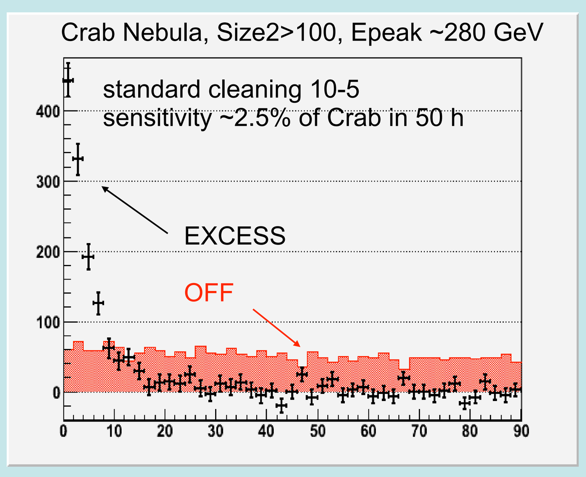


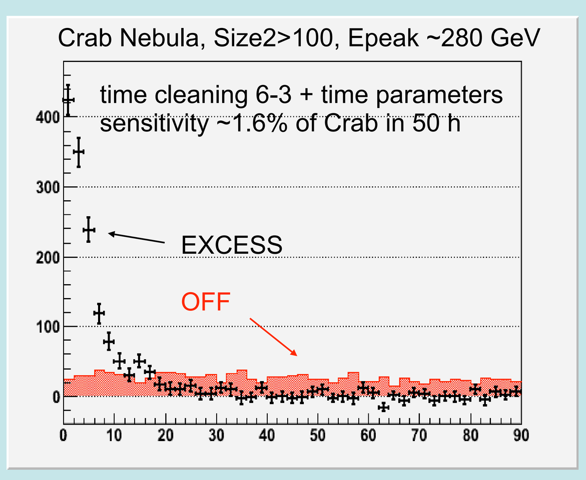


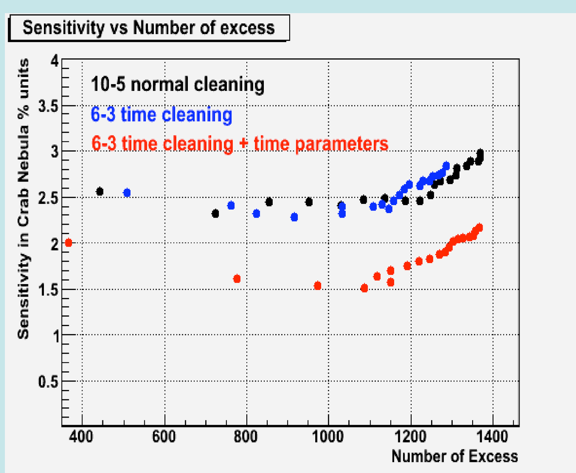


Analysis performance and sensitivity

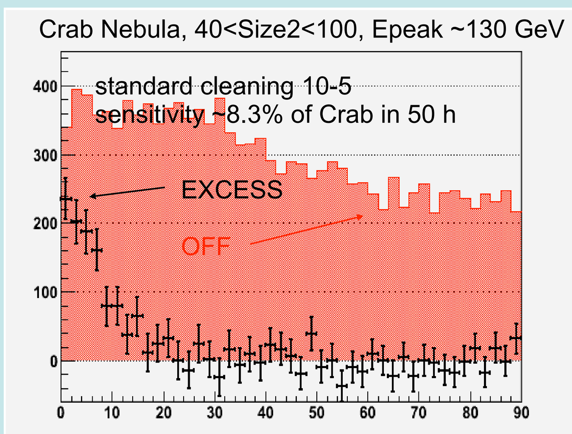
Three different analyses of the same Crab Nebula data sample (5.6 h observed in the so-called "wobble mode") have been performed:
1. Using 10-5 phe IC levels and standard image shape parameters for γ/h separation (reference analysis, the one commonly applied to MAGIC data before the upgrade of the readout).
2. Using 6-3 phe IC levels imposing also the time constrain (level 1.5 ns). The same standard parameters of analysis 1 for γ/h separation.
3. Using the same time IC of analysis 2 and in addition to the standard parameters the TIME RMS and TIME GRADIENT were used for γ/h separation.
In all cases the image parameters were the input of a Random Forest event classification algorithm, which was used to determine the optimal background suppression cuts. In the figures below we compare two ALPHA-plots obtained from analysis 1 and 3. The sum of the signals (in phe) of the two highest pixels (dubbed "size2") has been used as parameter to select event samples of different energies. Like the classical event SIZE, size2 is correlated with energy, but unlike SIZE, it does not depend on the cleaning levels. In this way, the selected samples contain mostly the same events for the different analysis methods (except for events too faint to survive the tougher cleaning).
The time cleaning and the time parameters allow to halve the residual background while keeping the same number of excess events. In the third plot a more general comparison is shown: the flux sensitivity in Crab units (excess = 5 * RMS of background in 50 h) for the three different analyses described is plotted versus the number of excess events in the signal region (α-cut optimized for best significance). The curves are obtained changing the cut in the γ/h separation parameter. The minimum size2 cut applied for the plots below is rather tight, >100 phe, corresponding to an energy distribution peak of ~280 GeV.

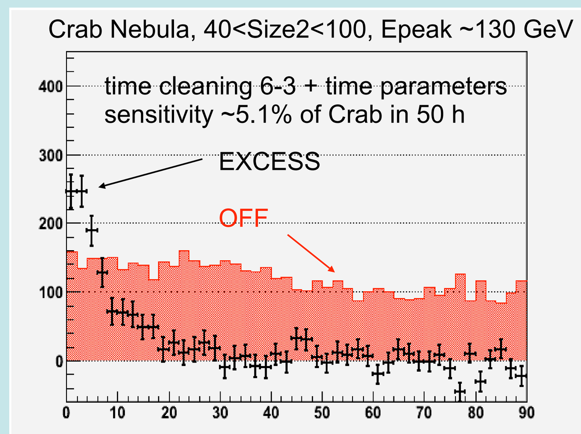


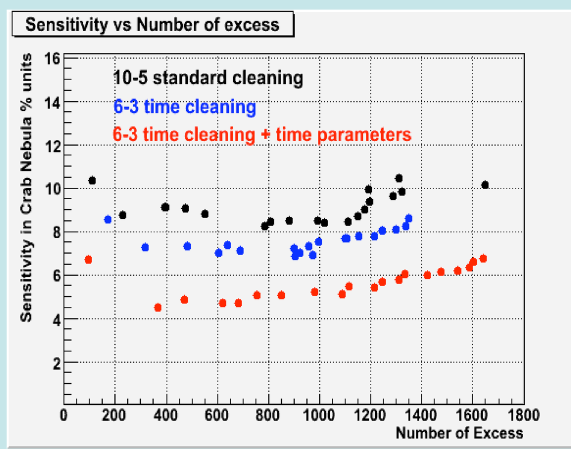




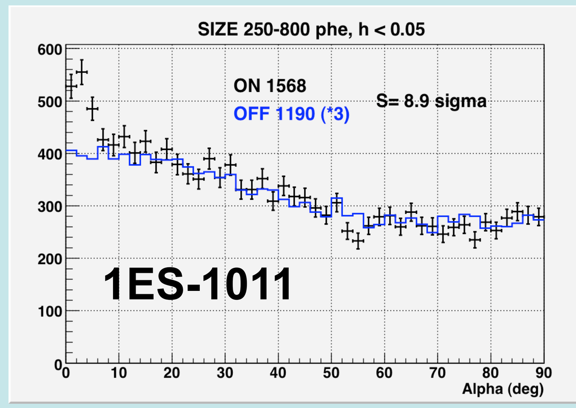
The same comparison has been done for a differential low energy bin (size2 between 40 and 100 phe, corresponding to an energy peak of ~130 GeV). The improvement in background suppression is even clearer in this case.







The method has been also tested on a recently discovered [9] VHE γ-rays source, the far AGN 1ES-1011. The significance obtained with the method here described is 8.9σ. Compared with the 6.2σ of the discovery paper it is in agreement whith the expected enhancement in sensitivity.



Conclusions

The use of timing information in the analysis of the new MAGIC data (after the recent readout upgrade) provides a considerably better background suppression and results in an enhancement of about a factor 1.4 of the flux sensitivity to point-like sources, as tested on real observations of Crab Nebula.
We concentrated here on the α-analysis approach since the major improvement is due to the use of the (source position dependent) TIME GRADIENT timing parameter. How to apply this method in a source position independent framework and how timing could be use to determine the direction of incoming gamma-rays are under investigation. Improvements (of ~15%) have been found also in the event energy reconstruction. In fact the TIME GRADIENT gives information about the real impact parameter of the shower and therefore it helps to distinguish distant high energy showers from closer, low energy ones.
We expect that this type of timing analysis will also be helpful to future Cherenkov telescopes, like HESS-II, which will operate, at least in part of their energy range, in non-stereo mode.

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