Geomagnetic Field Effects on the Imaging Air Shower Cherenkov Technique

MAGIC Major Atmospheric Gamma Imaging Cerenkov Telescope

S.C.Commichau[1],A.Biland[1],D.Kranich[1],R.de los Reyes[2],A.Moralejo[3],D.Sobczynska[4] for MAGIC*

[1]ETH Zurich, Switzerland [2]UCM Madrid, Spain [3]IFAE Barcelona,Spain [4]U Lodz,Poland *http://wwwmagic.mppmu.mpg.de

commichs@phys.ethz.ch

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Abstract

Imaging Air Cherenkov Telescopes (IACTs) detect the Cherenkov light flashes of Extended Air Showers (EAS) triggered by very high energy (VHE) γ-rays impinging on the Earth's atmosphere. Due to the overwhelming background from hadron induced EAS, the discrimination of the rare γ-like events is rather difficult, in particular at energies below 100 GeV. The influence of the Geomagnetic Field (GF) on the EAS development can further complicate this discrimination and, in addition, also systematically affect the γ efficiency and energy resolution of an IACT. Here we present the results from dedicated Monte Carlo (MC) simulations for the MAGIC telescope site. Additionally, we show that measurements of sub-TeV γ-rays from the Crab nebula are affected even for a low GF strength of $|\vec{B}_\perp| \approx 33\,\mu$T.

Introduction

- Charged secondary particles of the EAS are deflected by the GF resulting in a broadening of the EAS. The east-west separation of electrons and positrons in EAS due to the Lorentz force can be non negligible compared to the displacement due to Coulomb scattering [1].
- The Cherenkov images on ground can be affected in a way that the threshold energy of an IACT increases [2] as well as its γ/hadron separation capability is expected to be deteriorated.
- The effect on γ-ray induced EAS is expected to be more visible than on hadron induced EAS, as their shape is initially more regular and the scattering angles occurring in nuclear interactions are typically larger than that produced by the deflection of secondary charged particles due to the influence of the GF.

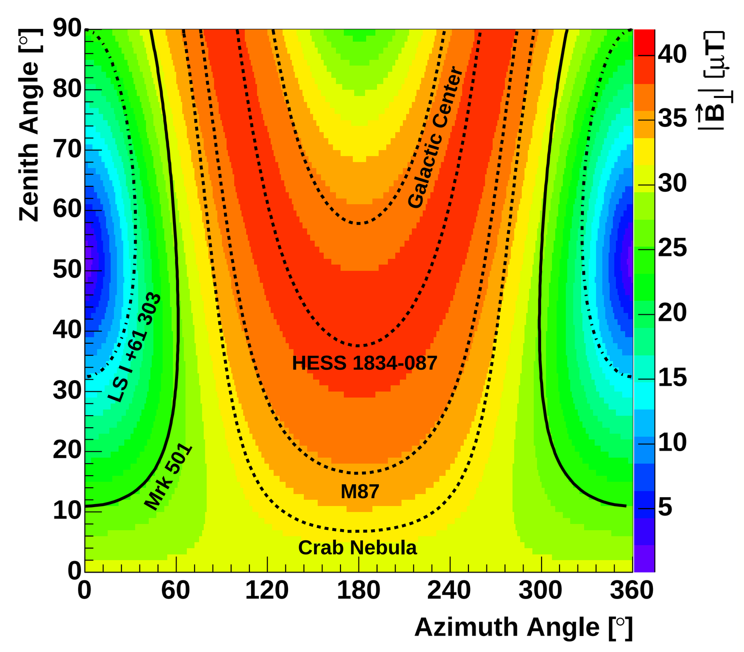

Figure 1: The absolute value of the vertical component (orthogonal to the particle's trajectory) of the GF strength at the site of the MAGIC telescope [3] on the Roque de los Muchachos observatory on La Palma (28.8° N,17.9° W) for 10 km a.s.l. as a function of the azimuth angle and zenith angle (ZA), calculated for the epoch 2005 International Geomagnetic Reference Field (IGRF) model [4]. The trajectories of some established and potential VHE γ-ray sources are indicated. For all sources, the field strength changes very little along the source trajectory. The maximum influence is expected to occur for ZA $\approx$ 40° and 180° azimuth angle, i.e. for EAS oriented perpendicular to the direction of the GF lines.

- It was shown elsewhere [5] that IACT measurements of TeV γ-rays from the Crab nebula were not significantly affected when the GF strength was below $35\,\mu$T.
- The sensitivity of an instrument to the influence of the GF depends on the imaging performance, i.e. optical point spread function (PSF) and pixel resolution. Current IACTs and future high resolution instruments will be more sensitive to GF effects.

Monte Carlo Simulation

- Dedicated MC data were produced to study the influence of the GF on the performance of the MAGIC telescope. The MC data were produced following the standard MC production of the MAGIC telescope, doing three steps [6]:
  1. The CORSIKA program (version 6.019) [7] is used to simulate the delevopment of γ-ray as well as hadron induced extensive air showers (EAS) for a given set of input parameters, like the primary γ-ray energy, the magnitude and direction of the GF, etc. The GF components were set to the values for La Palma (28.8° N,17.9° W) according to the IGRF model [4].
  2. The output of CORSIKA, containing information on the location and wavelength of each Cherenkov photon on ground, is processed with a dedicated Reflector program, which does the ray-tracing of the Cherenkov photons.
  3. The Camera program reads the output of the Reflector program and simulates the entire readout chain, i.e.the photomultiplier response, the trigger and the FADC system including electronic noise.
- The calibration and the image parameter calculation (Hillas analysis [8]) was done using the MAGIC Analysis and Reconstruction Software (MARS) [9].

Results & Discussion

Only few selected results can be discussed here and a more detailled analysis can be found in [10].

Influence of the GF on the Image Orientation

- Due to the influence of the GF on the development of EAS the major shower image axes can be rotated and do not point any more towards the camera center as expected for γ-rays coming from a point-like source pointed at by the telescope.
- The extent of the rotation depends on various parameters, like the γ-ray energy, the impact parameter, and the position of the impact point with respect to the telescope.

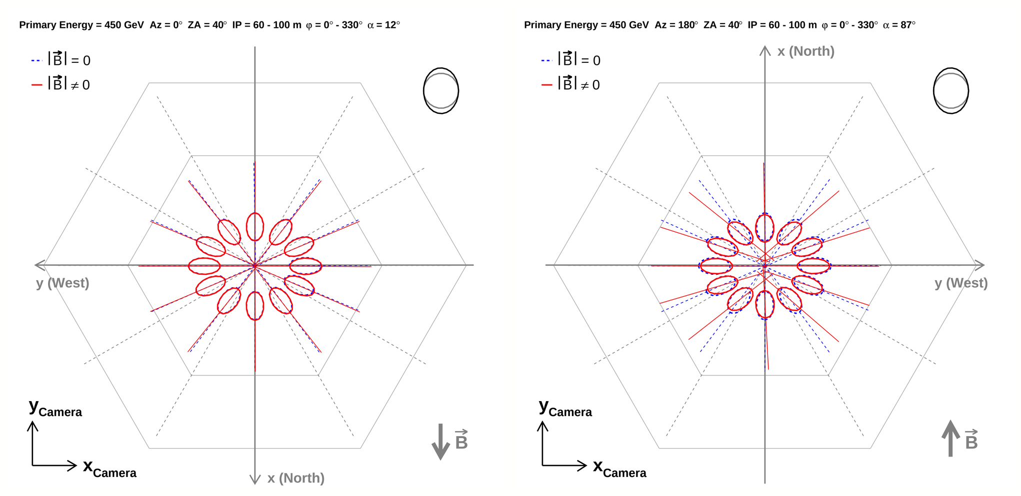

Figure 2: Hillas ellipses in different regions of the camera for primary γ-rays of 450 GeV energy, impact parameters between 60 m and 100 m, 40° ZA, azimuth angle 0° (left), 180° (right). The red ellipses were obtained with, the blue ones without GF. For 40° ZA and 180° azimuth angle (right) the GF effects are rather strong because the EAS evolves nearly vertically to the direction of the GF lines.

Influence of the GF on the Image Parameter ALPHA

- Due to the rotation of shower images the distribution of the image parameter ALPHA, commonly used to extract the γ signal in single-dish IACTs, can be significantly degraded.

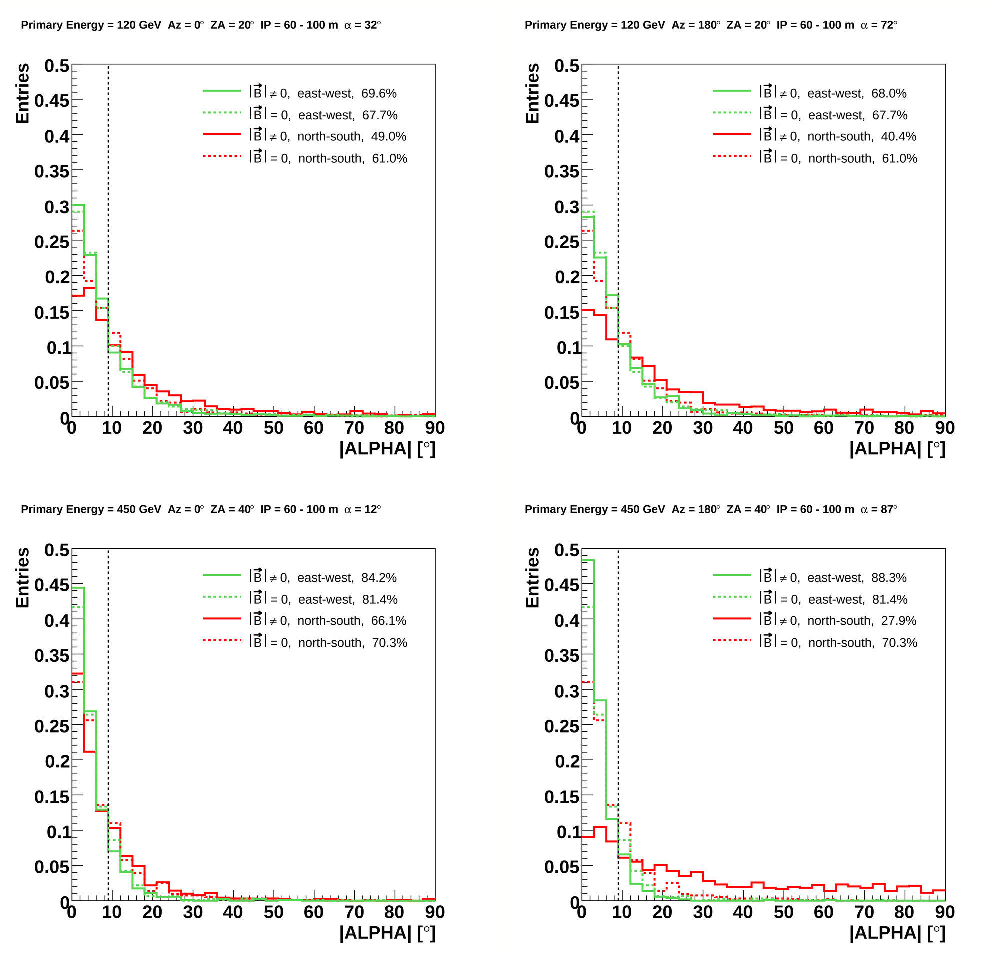

Figure 3: Normalized distributions of the image parameter ALPHA for primary γ-rays of 120 GeV (top) and 450 GeV energy (bottom), impact parameters between 60 m and 100 m, 20° ZA, and azimuth angle 0° (left) and 180° (right), respectively. The red-colored ALPHA distributions correspond to an arrangement where the connecting line between shower axis and telescope optical axis is parallel to the north-south direction and the green distributions correspond to a configuration where the connecting line between shower axis and telescope optical axis is parallel to the east-west direction. The ALPHA distributions for disabled GF in the MC are drawn as red and green dotted lines.

- For the most unfavorable arrangements of EAS w.r.t. the telescope the ALPHA distribution is significantly degraded even if the images are not rotated.
- The de-rotation of rotated shower images does not help to recover the pointing entirely. At most 10 % of the events can be recovered by de-rotation of the shower images, requiring the knowledge of the γ-ray impact parameter [10].

Influence of the GF on the Energy Reconstruction & Detection Efficiency

- The Cherenkov light distributionon on ground from showers close to the threshold energy can be thinned out such that most of the events do not survive the trigger level, i.e. the detection efficiency for γ-rays can vary by up to 25 % [10].
- For higher energies ($\sim$ 300 - 1000 GeV), the γ efficiency is affected only at very large ZA ($\sim$ 40° - 60°), where the telescope threshold energy is significantly increased.
- The total reconstructed integrated light of shower images can be reduced by up to $\sim$ 20 % [10].

Considering GF Effects in Real Data

- 50 min of low-ZA (7° - 10°) Crab nebula data from February 2007 were analyzed considering GF effects.
- The standard MAGIC analysis was performed to extract the γ-ray signal from the data.
- Due to the influence of the GF the ALPHA plots for distinct camera sectors show substantial differences.
- GF effects are visible in real data even for a very low value of the GF strenth ($|\vec{B}_\perp| \approx 33\,\mu$T).

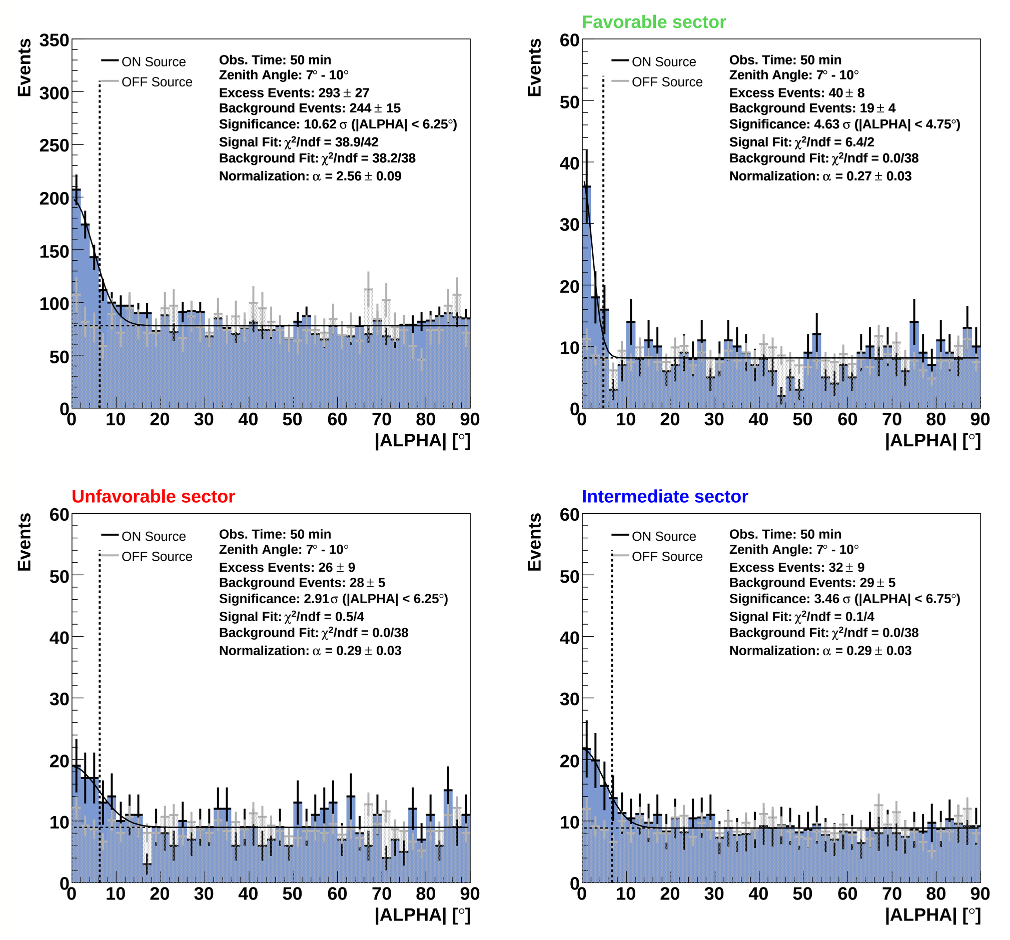

Figure 4: ALPHA distributions for the low-ZA Crab nebula dataset for γ-ray energies above $\sim$ 120 GeV, considering GF effects. The upper left distribution was obtained considering the entire camera (significance of about $10.6\,\sigma$) while upper right figure corresponds to images oriented at favorable directions with regard to the influence of the GF. Instead, the lower left figure corresponds to events oriented at the most unfavorable directions with regard to the influence of the GF. In order to have enough statistics, the opening angles of the most unfavorable and favorable camera sectors were set to 20° (figure 5, left panel). For each ALPHA plot, the cut on the parameter ALPHA used to extract the number of excess events was optimized on MC data in view of maximum significance. The lower right figure was obtained for events oriented at intermediate orientations with respect to the projected direction of the GF in the camera (the distribution was normalized to the area of the favorable and most unfavorable sectors).

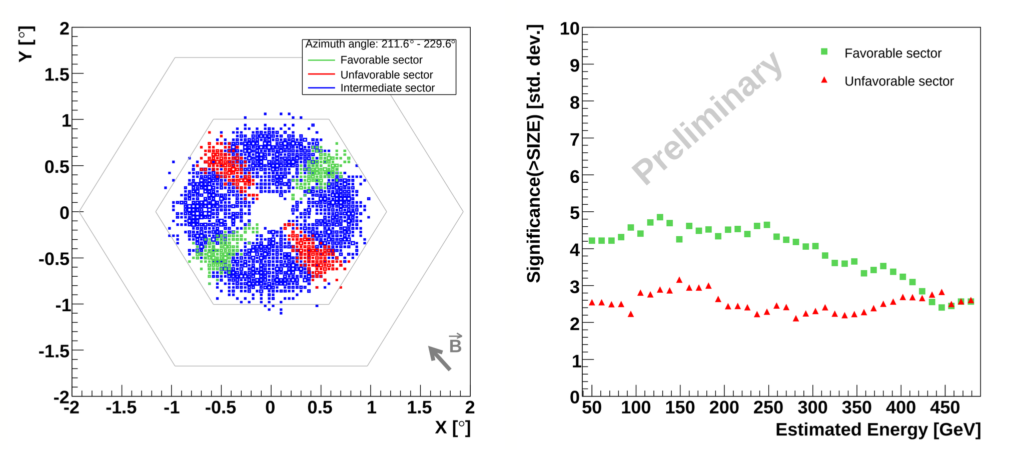

Figure 5: The camera sectors taken into account to extract the γ-ray signal (left) and the significance in terms of standard deviations for the low-ZA Crab nebula dataset as a function of the estimated energy for selected regions in the camera (right). The opening angles of the most unfavorable (red) and favorable (green) camera sectors were set to 20°.

Conclusions

- The results from the MC studies suggest that the influence of the GF can reduce the γ/hadron separation capability, and significantly affect the energy estimation as well as the γ efficiency of an IACT.
- The results from the MC studies indicate also that appropriate MC datasets are not only required for the analysis of low-energy data $\lesssim$ 100 GeV but also for the reconstruction of VHE γ-rays of at least 1 TeV [10].
- The analysis of low-ZA Crab nebula data taken with the MAGIC telescope proofs that the instrument is sensitive enough to demonstrate the influence of the GF even for a very low vertical component of the GF ($|\vec{B}_\perp| \approx 33\,\mu$T).

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