Observation of Very High Energy Gamma-Rays from the Galactic Center with the MAGIC Telescope, considering Geomagnetic Field Effects on the Imaging Technique

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presented by
Sebastian Caspar Commichau
Dipl. Phys., University of Aachen (TH)
born November 5th 1976
citizen of Germany

accepted on the recommendation of
Prof. Dr. F. Pauss, examiner
Prof. Dr. J. Stenflo, co-examiner
Dr. A. Biland, co-examiner

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“There is a theory, which states that if ever anyone discovers exactly what the universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable. There is another theory, which states that this has already happened.”

Douglas Adams
Abstract

The Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescope, located on the Canary Island of La Palma at the Roque de los Muchachos observatory (ORM), is currently the largest single-dish Imaging Air Cherenkov Telescope (IACT) in operation. MAGIC is a third generation telescope comprising a number of improvements and innovative technologies to reduce the threshold energy for the detections of very high energy (VHE) $\gamma$-ray as much as possible. Among all new generation IACTs currently in operation, MAGIC has the lowest threshold energy. This is of particular interest in the context of various astrophysical questions. Currently, the threshold energy for the detection of $\gamma$-rays is about 50 GeV. IACTs aim at the detection of faint Cherenkov light flashes emitted in Extended Air Showers (EAS) generated by VHE $\gamma$-rays interacting with the Earth’s atmosphere. Facing the overwhelming background from hadron induced EAS, the discrimination of the rare $\gamma$ events is rather difficult. Especially in the low-energy regime at some 50 GeV, the $\gamma$/hadron separation becomes complicated. Geomagnetic Field (GF) effects on the EAS development can further complicate the background discrimination.

Results from dedicated Monte Carlo (MC) simulations indicate that the shape and the orientation of $\gamma$-ray shower images can be significantly altered due to the influence of the GF. As a result, the $\gamma$/hadron separation capability of an IACT may be significantly degraded. Depending on the orientation of primary $\gamma$-rays with respect to the direction of the GF, the pointing of the shower images can be degraded and images get systematically rotated, causing a loss of sensitivity. It is demonstrated that the de-rotation of the affected shower images requires extensive MC simulations. Still, the pointing information can be irrecoverable for some orientations of the $\gamma$-rays. Within the energy range of this analysis (30 GeV - 1 TeV), all $\gamma$-ray energies were affected by the GF. Furthermore, the GF effects can degrade the $\gamma$ efficiency and the energy estimation.

The results from the analysis of a MAGIC dataset from the Galactic Center (GC) are presented. The data were collected at large zenith angles (ZA > 59°) involving a high energy threshold ($\gtrsim 700$ GeV). The GC region is a very interesting target as it contains many objects some of which may also be sources of VHE $\gamma$-rays. All new generation IACTs currently in operation have recently reported on observations from the strongest potential $\gamma$-ray source in the GC, the supermassive black hole (BH) Sgr A*. The results of these measurements exhibit substantial differences.

The results from the MAGIC observations confirm the GC region as a source of VHE $\gamma$-rays. The reconstructed $\gamma$-ray spectrum with spectral index $\alpha = 2.19 \pm 0.19_{\text{stat.}}$ is rather hard, and the $\gamma$-ray flux at energies above 1 TeV amounts to about 10% of the Crab nebula flux. The flux level as well as the differential $\gamma$-ray spectrum derived from the MAGIC dataset are compatible within errors with the H.E.S.S. measurement. MAGIC observations indicate that there is no significant time variability on times scales of hours to years. Furthermore, there is no significant time variability between the measurements of the H.E.S.S. experiment and the results obtained from the MAGIC dataset. Given the limited angular resolution of present IACTs ($\mathcal{O}(0.1^\circ)$) the position of the $\gamma$-ray excess is compatible with emission of Sgr A* as well as other sources around the GC region, like the supernova remnant (SNR) Sgr A East. The reconstructed $\gamma$-ray flux from the GC extending to at least 10 TeV is far above theoretical expectations from DM annihilation. Such a scenario is disfavored by particle physics where a sub TeV-scale neutralino/KK photon is the preferred option. The analysis of the MAGIC dataset was performed considering GF effects.
Zusammenfassung

Das Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) Teleskop, Teil des „Roque de los Muchachos Observatoriums“ auf der Kanarischen Insel La Palma, ist weltweit das größte Teleskop seiner Art, das gegenwärtig in Betrieb ist. MAGIC ist ein sogenanntes abbildendes Cherenkov Teleskop der dritten Generation, das zahlreiche Verbesserungen sowie innovative Technologien ausnutzt, um die Energieschwelle zum Nachweis von hochenergetischer $\gamma$-Strahlung so weit wie möglich zu reduzieren. Nebst anderen Cherenkov Teleskopen der neuen Generation, welche zur Zeit in Betrieb sind, hat MAGIC die niedrigste Energieschwelle. Dies ist von besonderem Interesse hinsichtlich verschiedenster astrophysikalischer Fragestellungen. Die gegenwärtige Energieschwelle zum Nachweis von $\gamma$-Strahlung ist etwa 50 GeV.

Abbildende Cherenkov Teleskope weisen schwache, von ausgebreiteten Luftschauern herrührende Cherenkov-Lichtblitze nach, die von auf die Erdatmosphäre auftreffender hochenergetischer $\gamma$-Strahlung ausgelöst wurden. Angesichts des überwältigenden, von geladenen kosmischen Teilchen induzierten Untergrundes stellt die Diskriminierung $\gamma$-Strahlung eine schwierige Aufgabe dar. Insbesondere im Energiebereich von etwa 50 GeV wird die sogenannte $\gamma$/Hadron-Trennung schwierig. Der Einfluss des Erdmagnetfeldes auf die Entwicklung von ausgedehnten Luftschauern kann die Unterdrückung des Untergrundes zusätzlich erschweren.

Die Ergebnisse von dedizierten Monte Carlo (MC) Studien zeigen, dass die Form und die Orientierung von durch $\gamma$-Strahlung induzierten Schauerbildern durch den Einfluss des Erdmagnetfeldes deutlich verändert werden kann. Daher kann die Qualität der $\gamma$/Hadron-Trennung signifikant verschlechtert werden. In Abhängigkeit der Richtung der primären $\gamma$-Strahlung zur Richtung des Erdmagnetfeldes kann die Orientierung der Schauerbilder gestört beziehungsweise Bilder systematisch verdreht werden, was eine Verringerung der Sensitivität zur Folge hat. Die Korrektur der Verdriftung erfordert umfangreiche MC Simulationen. Zudem kann für gewisse Orientierungen der $\gamma$-Strahlung die Richtungsinformation durch den Einfluss des Erdmagnetfeldes unwiederbringlich verloren gehen. Innerhalb des Energiebereichs dieser Analyse (30 GeV - 1 TeV) sind alle Energien durch das Erdmagnetfeld beeinflusst. Ausserdem kann der Einfluss des Erdmagnetfeldes die Nachweisempfindlichkeit für $\gamma$-Strahlung sowie die Energierekonstruktion beeinträchtigen.

Die Ergebnisse der Analyse von Beobachtungen des Galaktischen Zentrums mit dem MAGIC Teleskop werden präsentiert. Die Daten wurden unter großem Zenitwinkel ($> 59^\circ$) genommen, was mit einer hohen Energieschwelle verbunden ist ($\gtrsim 700$ GeV). Das Galaktische Zentrum ist ein interessantes Ziel, da es viele Objekte beherbergt, die für die Erzeugung hochenergetischer $\gamma$-Strahlung verantwortlich sein könnten. Alle zur Zeit betriebenen abbildenden Cherenkov Teleskope haben kürzlich über den Nachweis von hochenergetischer $\gamma$-Strahlung aus Richtung der stärksten potentiellen Quelle, dem supermassiven schwarzen Loch Sgr A*, berichtet. Die Ergebnisse dieser Messungen weisen starke Diskrepanzen auf.

Die Auswertung der von MAGIC durchgeführten Messungen bestätigt das Galaktische Zentrum als Quelle hochenergetischer $\gamma$-Strahlung. Das rekonstruierte Spektrum der $\gamma$-Strahlung ist hart und hat einen spektralen Index von $\alpha = 2.19 \pm 0.19_{\text{stat.}}$. Der Fluss der $\gamma$-Strahlung oberhalb von 1 TeV beträgt etwa 10% des Krebsnebel-Flusses. Innerhalb statistischer Fehler ist der Fluss sowie das differenzielle Energiespektrum kompatibel mit dem Ergebnis der Messungen des H.E.S.S. Experimentes. Die Beobachtungen durch MAGIC weisen darauf hin, dass die Quelle der $\gamma$-Strahlung auf einer Zeitskala von Stunden bis Jahren stabil ist. Insbesondere weisen die Messungen von MAGIC und H.E.S.S. nicht auf eine signifikante Veränderung des Flusses hin. Durch die begrenzte Winkelauflosung heutiger Cherenkov Teleskope ($\Theta(0.1^\circ)$) ist die Position der $\gamma$-Quelle vertraglich mit der Position von Sgr A* sowie mit der von anderen Objekten im Galaktischen Zentrum, wie zum Beispiel mit der des Supernovaüberrestes Sgr A East. Der rekonstruierte Fluss liegt mit Energien von bis zu 10 TeV weit oberhalb den theoretischen Erwartungen, falls die Annihilation von Dunkler Materie als Quelle angenommen wird.
Dieses Szenario wird in der Teilchenphysik nicht favorisiert, sondern sub-TeV Neutralinos beziehungsweise KK-Photonen werden bevorzugt. Die Analyse der MAGIC Daten wurde unter Berücksichtigung der Effekte des Erdmagnetfeldes durchgeführt.
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Introduction

In the few past decades high energy astro-particle physics, a rather new, fast-growing field of research, has been subject to rapid changes. Astro-particle physics is to be considered as a combination of astronomy, one of the oldest sciences, and experimental and theoretical particle physics. Astro-particle physics can be defined as follows: observations of extraterrestrial radiation and astronomical objects and phenomena through passive collection of data, which are analyzed and interpreted by means of techniques commonly used in particle physics. Due to the recent progress made in the development of improved instruments, incorporating very advanced technology and analysis techniques, the field of astro-particle physics has evolved fast.

Astrophysical processes are mostly not reproducible on Earth as they incorporate processes occurring at highest energies which cannot be generated in terrestrial particle physics laboratories. Thus, observations of astrophysical objects and phenomena provide an excellent playground to study properties and interactions of fundamental particles that constitute our own world, at highest energies. Furthermore, astrophysical observations at highest energies, which we believe were involved at the early stage of the universe, may help to elucidate the fundamental structure of the entire material world.

The majority of astrophysical observations are carried out using the electromagnetic spectrum, which is almost entirely covered by today’s existing detector types each of which is optimized to a certain wavelength range. Observations involve radio, infrared, ultraviolet, X-ray and $\gamma$-ray astronomy, while optical astronomy is the oldest kind of astronomy. To date, there seems to be no limitation for the $\gamma$-ray energy.

Objects emitting radiation via thermal processes are most frequently to occur in the universe. This radiation mostly follows the blackbody spectrum. The most prominent example is the remainder of the Big Bang, the Cosmic Microwave Background (CMB), which was discovered by chance in 1965 by Penzias and Wilson. Electromagnetic radiation from the sun and stars or from the accretion disks around neutron stars and other massive objects follow the blackbody spectrum as well.

The so-called non-thermal, relativistic universe is of particular interest as it involves physical processes that are difficult or even impossible to emulate in terrestrial laboratories. The relativistic universe is locally represented by the cosmic rays (CRs), whose observed power-law spectrum is related to the non-thermal origin. The CR energies cover more than thirty orders of magnitude, and the highest energies exceed those achievable in particle physics accelerators by about 9 orders of magnitude, which points at the strength and scope of the processes that power the non-thermal universe. The detailed study of the non-thermal universe is of general interest as it allows us to attain knowledge about the development of stars, galaxies, and other astrophysical objects and to draw conclusions on the origin and evolution of our universe.

As also in the case of CRs, very high energy (VHE) $\gamma$-rays can be indirectly observed by hitting the Earth’s atmosphere. The indirect detection of VHE $\gamma$-rays offers some advantages compared to the measurement of VHE CRs, which will be discussed in the introductory part of this thesis. Techniques whereby $\gamma$-rays of energy around 100 GeV and above can be indirectly studied from ground at high sensitivity are relatively new. The variety of exciting results from this new field of research includes GeV to TeV detections from supernova remnants (SNRs), pulsar wind nebula, from relativistic jets in active galactic nuclei (AGN), microquasars and other sources.

This work can be divided into two topics. One part of this thesis summarizes results from
Monte Carlo (MC) simulations performed to investigate the impact of the Earth’s magnetic field on the development of extended air showers (EAS) and its impact on the reconstruction techniques used in the analysis of Imaging Air Cherenkov Telescope (IACT) data. As one of the prime design goals of the MAGIC telescope was the detection of EAS induced by low-energy $\gamma$-rays around 50 GeV, it is important to know the influence of the Earth’s magnetic field on $\gamma$ showers. Especially in the low-energy region, where the discrimination between signal and background is expected to be weak, the Earth’s magnetic field may deteriorate the discrimination power of $\gamma$-ray induced EAS against the huge background caused by charged CRs.

The second and main part of this thesis is dedicated to results from the analysis of a certain dataset from the Galactic Center (GC) that was observed with the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope in September 2004, and consecutively over three months in May and July 2005. MAGIC observations are particularly interesting, since previous observations in direction of the strongest source in the GC region, Sgr A*, show substantial differences in the observed VHE $\gamma$-ray flux. As the MAGIC telescope is located in the northern hemisphere, observations of the GC region have to be conducted at high zenith angle (ZA), which confines the spectral energy range accessible to the instrument. Nevertheless, although the GC region represents an unfavorable region for the MAGIC telescope, MAGIC observations of the GC region allow to discriminate between previous measurements. Furthermore, the precise knowledge of the VHE $\gamma$-ray flux and spectrum respectively from the direction of the GC region is important, if the $\gamma$ signal is interpreted in the framework of dark matter annihilation. The analysis was performed considering Geomagnetic Field effects on the Imaging Technique.

The thesis is structured as follows:

- **Chapter 1** summarizes the general features of CRs, their energy distribution and chemical composition.

- **Chapter 2** gives a short introduction to $\gamma$-ray astronomy and summarizes its present status. An attempt to show the importance of ground-based VHE $\gamma$-astronomy is made.

- **Chapter 3** reviews the properties of the GC region. Recent VHE $\gamma$-ray observations of the GC region with present IACTs are reviewed and compared. The DM interpretation of the $\gamma$-ray signal as well as alternative production scenarios are discussed.

- **Chapter 4** describes the basic ideas of the imaging technique based on the detection of Cherenkov radiation emitted from EAS. Furthermore, the development, growth and evolution of EAS is discussed.

- In **chapter 5** the new generation IACTs currently in operation are briefly presented. The key elements of the MAGIC telescope are presented in more detail, and its physics program is concisely reviewed.

- **Chapter 6** focuses on the description of the analysis methods and interpretation of IACT data. The extraction of the $\gamma$ signal is explained as well as the determination of the differential $\gamma$-ray flux.

- **Chapter 7** summarizes the results from MC simulations that have been conducted to investigate the impact of the Earth’s magnetic field on EAS.

- In **chapter 8** the analysis results from the MAGIC observations of the GC region are presented and discussed. The results are compared to previous observations that have been carried out so far by the other new generation IACTs.
Chapter 1

Cosmic Rays

CRs, energetic particles coming from outer space, were discovered by Viktor F. Hess in 1912. During balloon flights he had discovered the phenomenon of increasing electric conductivity of the atmosphere with increasing height. It was an indirect discovery since the CRs were not directly detected, but Hess interpreted the raise in electric conductivity by the ionizing effect of an energetic radiation from outer space.

![Differential energy spectrum of galactic CRs](image)

**Figure 1.1:** Differential energy spectrum of galactic CRs (adopted from [198]). The plot summarizes data from several experiments.

In the thirties, the nature of CRs have been studied in greater detail. By measuring the dependency of the CR flux level on the Earth’s magnetic field and through direct detection, it was discovered that the radiation is mainly composed of positively charged particles.
The primary CR energies cover a huge energy range extending from some keV to more than $10^{20}$ eV. Over this wide range of energies, the intensity drops by more than 30 orders of magnitude. Figure 1.1 shows the differential energy spectrum of CRs. The primary energy spectrum is very steep, i.e. the number of CR particles drastically decreases with increasing energy. At energies of $\sim 10^{12}$ eV, the flux is about 10 particles per square meter and minute and at energies beyond $10^{20}$ eV the flux has decreased to about 1 particle per square kilometer and 200 years.

Charged primary CRs are composed of two main components. About 98% of all CR particles are nucleons, only 2% are electrons. The nucleon component is composed of 87% hydrogen, i.e. protons, 12% helium and about 1% heavy ions, in which all elements from hydrogen up to the actinoids have been detected. Neutral CR particles consist of $\gamma$-rays, neutrinos and antineutrinos. $\gamma$-rays contribute with a tiny fraction of only $\sim 10^{-4}$ to the overall CR flux.

While the CR flux at low energies is large enough to perform measurements directly by means of balloon-born or satellite-born experiments, the detection of CRs at higher energies ($\sim 10^{14}$ eV) requires ground-based detectors. Above a few $10^{15}$ eV, the flux drops to only 1 particle/m$^2$ yr, thus measurements at higher energies require huge detection areas and long observation times. The high energies make containment within a space-born detector a serious problem, thus, direct measurements at such high energies are not feasible because of lack of statistics. Experiments have to be ground-based and are usually realized by huge detector arrays which detect CRs indirectly through the detection of secondary particles created in so-called air showers in the Earth’s atmosphere.

To date, one of the largest array designed to indirectly detect primary CRs is the Akeno Giant Air Shower Array (AGASA) in Japan [199], covering an area of about 100 km$^2$. The Pierre Auger Observatory [1, 22, 209] in Argentina is even larger. The array is designed to cover an area of about 3000 km$^2$ and aims at providing much higher statistics in particular at energies beyond $10^{20}$ eV.

Below energies of 30 GeV, the influence of the sun’s and the Earth’s magnetic field becomes important. The 11-year period of the sunspot cycle modulates the intensity of low-energy primary CRs. Furthermore, depending on their arrival direction, low-energy charged CR particles can be deflected by the Earth’s magnetic field. Above these energies the CR flux appears to be quite isotropic, which is expected, since any initial anisotropy would be destroyed due to interactions with galactic magnetic fields. For primary CRs with energies below $10^{14}$ eV, the level of observed anisotropies lies below 0.5% [105].

The primary CR spectrum can be described by a power law $dN/dE \propto E^{-\alpha}$, where the spectral index changes depending on the considered energy range. At energies of about $10^{15}$ eV, the so-called ‘knee’ region, the energy spectrum steepens and the spectral index changes from 2.7 to about 3.0. The so-called ‘ankle’ appears at energies of about $10^{18}$ eV, where there is an indication for a flattening of the differential energy spectrum. The detection of CRs of energies greater than $10^{20}$ eV has been reported by the AGASA experiment [64, 108, 200]. So far, these measurements have not been excluded by another experiment, although the Auger Observatory has recently reported that the CR flux at energies around $10^{20}$ eV seems to be significantly lower [209]. Nevertheless, the sharp suppression of CRs at an energy of $6 \cdot 10^{19}$ eV [202], as reported by the HiRes Fly’s Eye experiment [50], has not yet been confirmed by any other experiment.

The extension of the CR energy spectrum to energies beyond some $10^{20}$ eV would be in contradiction to the so-called Greisen-Zatsepin-Kuzmin (GZK) cutoff, which limits the mean free path of extreme high energy (EHE) CR particles to less than some tens of mega-parsecs, i.e. the universe should become opaque beyond particle energies of $\sim 10^{20}$ eV. The GZK-limit for the mean free path is quite small compared to typical extragalactic scales, which suggests that the most energetic CR particles observed in the outer space are produced in the local cluster. The local cluster still contains a number of galaxies, but none of the known sources or mechanisms could generate such extremely high energies. Although the interaction with the intergalactic magnetic field is negligible at such high energies, there is no indication for localized sources.
As the energy range covered by the CRs exceeds any energy accessible to today’s accelerator experiments by several orders of magnitudes, cosmic accelerators will constitute the most powerful particle accelerators in the foreseeable future. Although CRs have been studied ever since their discovery, future investigations will provide valuable information on elementary particles and their fundamental interactions at highest energies.

The existence of CRs poses a number of questions: Where do the CRs come from? What are the sources of CRs and what kind of mechanisms can accelerate elementary particles to such high energies? How do the CRs evolve through the interstellar medium and how does this interaction affect the properties of the CRs? What are the highest energies of CR particles? To answer these questions, a number of experiments are in operation throughout the world and a variety of experimental techniques are in use.

The origin of CRs remains an open question. More than 90 years after their discovery, CRs cannot be clearly assigned to any of the known astrophysical objects. Even though Active Galactic Nuclei (AGN), quasars, or supernova explosions are excellent source candidates for HE CRs, there is not direct evidence for this assumption.
Chapter 2

Gamma-Ray Astronomy

A wide range of the electromagnetic spectrum shown in figure 2.1 is used for astronomical observations. Observations in the optical spectral range belong to the field of classical astronomy, while radio astronomy, infrared and ultraviolet astronomy as well as X-ray astronomy and γ-ray astronomy are rather young research fields. Electromagnetic radiation with energies above the ultraviolet range and below about 100 keV, is referred to as X-rays, whereas γ-rays have energies greater than 100 keV. There is no limitation for the γ-ray energy.

The origin of CRs is one of the unresolved problems in astro-particle physics. As mentioned in the previous chapter, charged cosmic rays cannot be used to answer this question since they do not point back to their origin. Interactions with intergalactic, irregular magnetic fields cause them to appear isotropically distributed over the sky. At very high energies, i.e. energies above \(10^{19}\) eV where the interaction with the magnetic field becomes weak, charged CRs could be used as tracers to find out their origin. However, at such high energies the CR flux is very low and one would need huge detectors and exposure times. In addition the GZK cutoff limits the accessible energy range.

Contrary to charged CRs, X-rays and γ-rays are not deflected by magnetic fields on their way through space and therefore pointing back to their origin. But, even though they do not interact with magnetic fields, X-rays and γ-rays may be disturbed since they can be subject to time dispersions, and in addition, astronomical objects nearby the line of sight of these sources may distort the trajectory through gravitational lensing.

Figure 2.1: Cutout of the electromagnetic spectrum with several scopes of applications indicated (adopted from [105]).
It is expected that whatever the sources of CRs are, the production of CRs is associated with the production of electromagnetic radiation in terms of energetic $\gamma$-rays. Based on this assumption, the development of space-born and ground-based detectors was started and has made impressive progress in the last 30 years.

Observations in the energy range from soft X-rays (keV - MeV) up to hard X-rays and very low-energy $\gamma$-rays (MeV - GeV) have to be performed in space since in the keV to GeV range the Earth atmosphere completely shields the CRs.

The launch of the COS-B satellite [72] in 1975 triggered a successful era of X-ray astronomy. Sensitive in the energy range between 2 keV and 5 GeV, it provided the first detailed views of the universe in $\gamma$-rays. It was operated until 1982. The launch of the Compton Gamma Ray Observatory (CGRO) [57] in 1991 was another milestone of X-ray astronomy. The EGRET telescope, part of the CGRO, was the most sensitive HE $\gamma$-ray space telescope flown to date [106, 201]. EGRET was operated from 1991 to 2000, and it was sensitive from 30 MeV to 30 GeV with an energy resolution of about 20%. The field of view (FOV) was $\pm 20^\circ$. Figure 2.2 shows the Third EGRET catalog based on the first four years of observations of the CGRO mission.\footnote{The data of the third EGRET catalog can be found at http://vizier.cfa.harvard.edu/ftp/cats/J/ApJS/123/79/3eg.dat.}

![THIRD EGRET CATALOG (E > 100 MeV)](image)

**Figure 2.2:** The Third EGRET catalog of point-like $\gamma$-ray sources of energy $100 \text{ MeV} < E < 10 \text{ GeV}$. The catalog is based on the first four years of observations of the EGRET experiment on board the CGRO satellite [106].

The majority of the 271 sources found are unidentified, i.e. due to the limited angular resolution of the telescope they cannot be associated with an established photon-emitter in the X-ray or $\gamma$-ray energy range. All sources have a statistical significance of more than 4 standard deviations. For sources lying within $10^\circ$ of the galactic plane, the significance level was increased to 5 standard deviations to reduce the uncertainty of a detection. More than 50 sources with $\gamma$ energies greater than 1 GeV are listed in the GeV EGRET catalog. The majority of these GeV sources coincide with the 100 MeV EGRET sources, but their positions are determined with higher precision.

Next generation space telescopes are already under construction. The light imaging detector for $\gamma$-ray astronomy (AGILE), an Italian mission, to be launched beginning of 2007 covers hard X-rays and the energy band from 30 MeV to 50 GeV with good angular resolution and very wide
FOV [2]. Its sensitivity is comparable to that of EGRET. Since it makes use of the silicon strip technology, it mainly acts as a precursor experiment for the Gamma-ray Large-Area Space Telescope (GLAST) [96]. The general design of GLAST will be similar to that of EGRET, but it uses several hardware-improved detector elements and more recent technologies like particle trackers based on the silicon strip technology that has been used in high-energy particle accelerator experiments for several years. GLAST covers the energy range from 20 MeV to 300 GeV and it outperforms EGRET in most parameters [211]. The Alpha Magnetic Spectrometer (AMS) [8] will be installed on the International Space Station [120]. The main prospects of this detector are anti-matter searches with unprecedented sensitivity, studies of the CR isotopes, but also studies of HE $\gamma$-rays with a sensitivity similar to that of EGRET, but with an angular resolution better than the one of GLAST.

The effective aperture, which is in general only a small fraction of a space-born $\gamma$-ray detector, is rarely greater than a few tenth of a square meter, mainly because the costs dramatically increase with size and weight of the detector. To detect $\gamma$-rays beyond $\sim$ 10 GeV, it is necessary to enlarge the effective aperture by some orders of magnitude since the cosmic $\gamma$-ray flux is small. For example, the Vela pulsar, one of the strongest source in the sub-GeV energy range, gives a flux of only one photon per minute at 100 MeV in present day space telescopes. Therefore, very large exposure times are necessary to obtain enough statistics for a significant detection at higher energies.

![VHE Gamma-Ray Sources (E > 100 GeV)](image)

**Figure 2.3:** Galactic coordinates of point-like VHE $\gamma$-ray sources as observed by various Cherenkov telescopes around the world. The source positions are given in galactic coordinates. Active Galactic Nuclei are shown as filled triangles, pulsars as filled squares, Super Nova Remnants as filled asterisks and unidentified sources as filled circles. The flipped triangles represent Radio Galaxies. The observability border for MAGIC for source culmination at 30° zenith angle (ZA) is indicated as a light gray line, the one for 60° ZA as a dark gray line. 30° ZA and 60° ZA correspond to a threshold energy of some 100 GeV and about 1 TeV, respectively.

To keep the costs at a reasonable level, one has to use ground-based detectors for the detection of energies beyond some 100 GeV. Since the Earth’s atmosphere is opaque to $\gamma$-rays at these energies, as it is to photons in many other bands of the electromagnetic spectrum, it is necessary to use an indirect detection technique. One of these methods, the so-called atmospheric Cherenkov imaging technique detects the Cherenkov radiation from charged particles in
2.1. \(\gamma\)-RAY SOURCES

EAS caused by VHE \(\gamma\)-rays and charged cosmic rays (chapter 4).

The first large optical reflector for \(\gamma\)-ray astronomy, a so-called Imaging Air Cherenkov Telescope (IACT), was the Whipple observatory installed 1968 in Arizona [181]. The diameter of its mirror dish was 10 m, but the effective collection area of such a detector is greater than some \(10^4\) m\(^2\) (section 4.3), thus potentially offering a much higher detection probability for \(\gamma\)-rays as compared to space-born telescopes. After several hardware upgrades the threshold energy for \(\gamma\)-rays was about 250 GeV.

Since \(\gamma\)-rays only contribute with a tiny fraction to the overall CR spectrum (in the order of \(10^{-4}\)), it is a challenge to extract the faint \(\gamma\) signal. Although the large effective collection areas provided by IACTs lead to a significant improvement in energy threshold and flux sensitivity, it is just as well important to develop efficient analysis techniques to statistically distinguish between \(\gamma\)-ray induced and hadron induced EAS to be able to discriminate the weak photon signal from a source against the dominating background (section 6).

Although today’s IACTs are about to close the unexplored gap between 30 - 100 GeV, and, in addition provide high-sensitivity measurements of established VHE \(\gamma\)-ray sources and a number of discoveries, next generation IACTs are already being planned and designed. The principal object of the next generation projects is to achieve a higher sensitivity over at least the whole energy range covered by the IACTs currently in operation.

2.1 \(\gamma\)-Ray Sources

In this section possible sources of VHE \(\gamma\)-rays are briefly introduced. There is a variety of candidate sources for VHE \(\gamma\)-ray emission of which some are already established. Recently, several new sources have been discovered, especially along the galactic plane. Figure 2.3 shows point-like and extended candidate sources as well as confirmed sources for VHE \(\gamma\)-ray emission, as of December 2006. Candidate sources or sources which are not yet confirmed by two independent experiments are drawn in red, confirmed sources in green.

Source candidates for VHE \(\gamma\)-rays are Active Galactic Nuclei (AGN), quasars, microquasars, binary systems, Supernova Remnants (SNR), Pulsars, Gamma Ray Bursts (GRBs), unidentified EGRET sources and so on. More information on potential sources for VHE \(\gamma\)-rays can be found elsewhere [3, 105, 211].

2.2 VHE \(\gamma\)-Ray Production Mechanisms

Although several processes are to be considered for the production of VHE \(\gamma\)-rays, it is still unclear by what mechanism \(\gamma\)-rays are actually created and accelerated to the observed energies. The observed energies in \(\gamma\)-ray astronomy cover at least 14 decades in frequency. While the lower bound corresponds to the electron-positron annihilation line and also to the region of nuclear \(\gamma\)-ray lines, the second bound can be associated to the highest energies observable in CRs. So far no CR particles with energies beyond \(\sim 10^{20}\) eV have been observed.

The most important processes that are very likely involved in the production of VHE \(\gamma\)-rays, are:

- **\(\pi^0\)-decay**: The production of VHE \(\gamma\)-rays can be associated with inelastic collisions of relativistic protons with ambient stationary hydrogen gas. These inelastic collisions lead to the production of secondary pions, kaons and hyperons. The production of kaons and hyperons is less likely, due to the smaller production cross sections. \(\pi^0\) mesons provide an important channel to convert the kinetic energy of protons to high-energy \(\gamma\)-rays as the branching ratio for \(\pi^0\) into \(\gamma\gamma\) is 98.78\% [176], whereas the one for \(\pi^0\) into \(e^+e^-\gamma\) is only 1.19\% [176]. The relevant reactions for the pion production are \(p + N \rightarrow p' + N' + \kappa(\pi^+ + \pi^-) + l\ \pi^0\) and \(p + N \rightarrow n + N' + (k + 1)\pi^+ + k\ \pi^- + l\ \pi^0\), where \(k\) and \(l\) are integers, i.e. multiples.
of the produced particle species, \( n \) represents a neutron and \( N \) the target nucleon. The production of one \( \pi^0 \) meson in inelastic proton-proton collisions \((k = 0, l = 1)\) requires the kinetic energy of the proton to exceed the limit \( E_p \approx 2m_p + 2m_\pi^0 / 4m_p \approx 280 \text{MeV} \), where \( m_{\pi^0} = 134.97 \text{MeV}/c^2 \) denotes the mass of the \( \pi^0 \) meson and \( m_p = 938.27 \text{MeV}/c^2 \) the mass of the proton [176]. At higher proton energies \( \mathcal{O}(1 \text{GeV}) \), the production of \( \pi^0 \) mesons and charged pions is nearly equiprobable.

Photo-meson production is yet another possible mechanism to produce high-energy photons. Protons interacting with low-energy (LE) \( \gamma \)-rays can produce mesons by photoproduction, i.e. close to the threshold single-pion production \( p + \gamma_{\text{LE}} \rightarrow p + \pi^0 \) or \( n + \pi^+ \) prevails. The subsequent decay of \( \pi^0 \) mesons may result in high-energy \( \gamma \)-rays. In case of head-on collisions, the kinetic energy of protons must exceed the limit \( E_p \approx (2m_p m_{\pi^0} + m_{\pi^0}^2) c^4 / 4E_{\gamma,\text{LE}} \) (\( E_p \gg m_p c^2 \)) to produce a \( \pi^0 \) meson, where \( E_{\gamma,\text{LE}} \) denotes the energy of the soft \( \gamma \)-ray. For example, the \( \pi^0 \) meson production due to inelastic proton collisions with X-rays \( (E_{\gamma,X} \approx 1 \text{keV}) \) requires the proton energy to be in excess of \( 10^{14} \text{eV} \).

As the decay of the charged mesons will produce energetic neutrinos, simultaneous detections of VHE \( \gamma \)-rays and associated energetic neutrinos would provide a good case for hadronic acceleration mechanisms. Models describing the production of VHE \( \gamma \)-rays by proton-initiated acceleration cascades can be found elsewhere [94, 95].

- **Bremsstrahlung**: Whenever a charged particle is accelerated or decelerated in an electric field it emits electromagnetic radiation which is referred to as Bremsstrahlung. For instance, electrons or protons deflected in the electric field of a nucleus or ion produce Bremsstrahlung.

  It is noteworthy that \( \gamma \)-rays resulting from Bremsstrahlung of cosmic electrons due to interactions with a gas have energies of the same order as the initial electron. The production rate of \( \gamma \)-rays of course depends on the density of the gas. Moreover, if the electron energy distribution obeys a power law with a certain spectral index, the resulting \( \gamma \)-ray spectrum has the same spectral index.

- **Inverse Compton Scattering**: The inverse Compton (IC) scattering process, i.e. the collision of a high-energy electron with a low-energy photon, is presumably important for the generation of high-energy \( \gamma \)-rays. Relativistic electrons may up-scatter low-energy photons to higher energies.

- **Synchrotron Radiation**: While a non-relativistic electron moving through a homogeneous magnetic field \( B \) radiates like a dipole with frequency \( \omega_L = eB/m_e \) (frequency of Larmor precession), a relativistic electron produces synchrotron radiation which is strongly beamed into a narrow cone of angle \( \theta \approx m_e c^2 / E \) around the current direction of motion of the electron. Therein \( m_e \) is the electron mass and \( E \) its energy. The emission of synchrotron radiation follows a continuous spectrum centered around the so-called critical energy \( E_C = (3/2)(eBh/m_e)\gamma^3 \sin \varphi \), where the maximum power is emitted [121]. \( \varphi \) denotes the pitch angle between the direction of the magnetic field and that of the direction of motion of the electron, \( \gamma \) the Lorentz factor of the electron and \( h \) the reduced Planck constant.

  The typical energies of synchrotron photons are generally much lower than the energies of the parent electrons. The production of high-energy photons requires relativistic electrons and strong magnetic fields. For instance, an electron of 500 GeV energy \( (\gamma \approx 10^6) \) moving perpendicular to the direction of a homogeneous magnetic field of field strength 0.1 G, which is typical for shock wave-accelerated electrons in relativistic jets of AGN, produces a synchrotron spectrum peaking at \( E_C \approx 1.7 \text{keV} \). However, the multitude of low-energy photons due to synchrotron emission from electrons may provide a gaseous target for high-energy electrons (inverse Compton scattering) or high-energy protons.
Synchrotron radiation from relativistic protons is possible, but less efficient. The synchrotron cooling time \( t = E/P = E/(dE/dt) \) of protons is much higher than the one of electrons of the same energy, as their energy loss rate \( P = dE/dt \sim \gamma^4 \) \cite{121} is \((m_e/m_p)^4 \approx 10^{13}\) lower than the energy loss rate of electrons.

- **Synchrotron Self-Compton Model**: The IC effect is believed to be the dominant process by which \( \gamma \)-rays are produced in VHE \( \gamma \)-ray sources like plerions or AGN, especially in the framework of the synchrotron self-Compton (SSC) model \cite{188}. According to the SSC, synchrotron photons are Compton scattered on shock-accelerated electrons, producing an additional IC \( \gamma \)-ray component at higher energies. Both, the synchrotron photons and the \( \gamma \)-ray component are due to the same population of electrons. Electronic SSC models have two attractive features: the required TeV electrons can be explained through the relatively well understood shock acceleration mechanism and the synchrotron and inverse Compton radiation channels have a high efficiency \cite{3}.

- **WIMP Annihilation**: The annihilation of hypothetical massive relic particles, respectively Weakly Interacting Massive Particles (WIMPs) is considered as a possible origin of VHE \( \gamma \)-rays. In particular annihilation of cold, non-baryonic Dark Matter (DM) has been considered as a potential source for VHE \( \gamma \)-rays \cite{27}. The production of energetic \( \gamma \)-rays due to pair-annihilation of DM is discussed more detailed in chapter 3.
Chapter 3

The Galactic Center Region

This chapter reviews the properties of the GC region. The phenomena observed in the radio, infrared (IR), x-ray and HE-VHE $\gamma$-ray domain are mentioned. VHE $\gamma$-ray observations of the GC region, recently carried out by the IACTs currently in operation are reviewed as the results from these observations were the decisive factor for MAGIC observations of the center of our Galaxy. Finally, the origin of VHE $\gamma$-rays from the GC region is discussed.

3.1 The Center of our Galaxy

The center of our Galaxy is a very interesting region where a number of high-energy phenomena occur. The wealth of sources around the GC region made it an interesting target for astronomical observations at many wavelengths, as it is active in the radio, IR, x-ray and HE-VHE domain. Figure 3.1, reproduced from GC observations of the NRAO Very Large Array (VLA) observatory [167], reveals the complexity and shows the multitude of sources in the GC region. The GC region extends to about 600 pc size which corresponds to approximately 4° in projection [98, 101].

Observations of the central region of the GC can be carried out only from radio to near infrared frequencies and in the HE-VHE range. Optical, UV and soft x-rays are strongly attenuated through absorption by galactic dust which intercepts the line of sight [98].

The GC contains about 10% of the galactic interstellar medium concentrated in dense molecular clouds like Sgr B1, Sgr B2, Sgr C and those of the Sgr A complex. The interstellar medium is heated through the interaction with the expanding shells of shell-type SNR [98, 101].

Nowadays it is known that the dynamical center of our Galaxy is located in the Sgr A complex, at a distance of about 8 kpc from the sun, in the middle of the Milky Way [75, 189]. The Sgr A complex extends to some 30 pc ($\sim 0.2^\circ$). It contains molecular clouds, an expanding SNR, Sgr A East and the bright radio source Sgr A* which is surrounded by a HII region. Figure 3.2 shows an x-ray image of the Sgr A complex taken by the Chandra observatory [60]. The compact radio source Sgr A* is associated with a hypothetical supermassive BH of mass $3 - 4 \cdot 10^6 M_\odot$ [189] which would be the closest of such extreme objects.

Star kinematic studies based on stellar dispersion and rotation velocities were initiated almost 30 years ago. These studies were aiming at finding out the relation between the enclosed mass and the distance from the GC. The great velocities of the molecular clouds and stars observed in the vicinity of the dynamical center imply the presence of a point-like mass or BH. To properly describe the enclosed mass for lower radii than some 0.5 - 1 pc, it is necessary to assume a point mass (BH hypothesis) or to adopt the presence of a dense cluster made up of dark stellar objects, like low-mass stars, neutron stars and stellar-mass BHs with a density of $4 \cdot 10^{12} M_\odot pc^{-3}$ [189]. Some of these options can be ruled out as they imply greater orbital periods of the stars than the ones observed in the in the vicinity of Sgr A* [166]. Moreover, the instability of such dark clusters strongly corroborates the hypothesis in favor of a massive BH at the center of our
Galaxy. For example, a cluster of stellar BHs would not be stable for more than $10^7$ yr [98]. The BH mass is deduced from ten years of high-resolution near infrared imaging of the orbit of the star currently closest to the compact radio source Sgr A* [189].

The SNR candidate Sgr A East (figure 3.2) is indicated as a large, dotted ellipse. Sgr A East represents a non-thermal radio source with diffuse emission ($3' \times 4'$), offset from Sgr A* by about $50''$ west [98, 101]. Sgr A West, indicated by the smaller, solid ellipse, is a thermal diffuse nebula with the characteristic shape of a mini-spiral rapidly rotating around Sgr A*. A cluster of hot young and massive stars centered at $2''$ from Sgr A* ionize the spiral-shaped gas streamers that form Sgr A West. Some of these stars are responsible for the emission of powerful stellar winds that interact with the surrounding medium and probably feed the BH candidate Sgr A*.

![Wide-Field Radio Image of the Galactic Center](image)

**Figure 3.1:** A wide-field radio image of the GC region (adopted from [140]). The image is derived from GC observations of the Very Large Array (VLA) at the National Radio Astronomy Observatory (NRAO) [167]. Centered on Sgr A, the image covers an area of $4^\circ \times 2.5^\circ$.

The strong, compact, non-thermal radio source Sgr A* was discovered in 1974 at the National Radio Astronomy Observatory (NRAO) [25]. The radio emission from Sgr A* follows an inverted power law with low and high frequency cutoffs. Great flux variability of 30 - 100% around a value of 1 Jy on timescales of few months is observed. The upper limit of the source proper motion of 20 km s$^{-1}$ and the great velocities (500 - 1000 km s$^{-1}$) of the stars in its vicinity indicate that the radio source is static and massive. The lower limit for the mass of the central compact object was derived to be 1000 $M_\odot$ [101].

The first real X-ray images of the GC region were obtained with the Einstein observatory in the beginning of 1980 [210]. These images revealed not only diffuse emission but also point
sources within 20′ of the GC region [191, 210]. Although during these and during follow-up observations a number of transient sources have been detected, Sgr A* appeared always rather faint. In the following decade, the GC region was observed in soft and hard X-rays. In the 2-10 keV X-ray band the GC has been monitored extensively by the Chandra and XMM-Newton X-ray observatories [60, 218]. According to these observations, the transient X-ray binaries 1E1740.7-2942 and 1E1743.1-2843 are probably not associated with the GC [101]. A number of point-like persistent and transient sources, several SNR, non-thermal filaments and star clusters have been detected as well as diffuse emission of X-rays. While the central part of about 20 pc is dominated by Sgr A East, Sgr A* appears to be rather weak, even in the hard X-ray domain. Chandra observations of the GC region, carried out regularly since 1999, providing a high angular resolution of 0.5″, indicated the existence of a weak point-like X-ray source that lies within 0.35″ from Sgr A* [24], which could be the X-ray counterpart of the radio source.

![Figure 3.2: The Chandra full-field image of Sgr A*, color coded by intensity, shows X-rays from 3.3-4.7 keV [60]. The image covers an area of 17.5′ × 14.5′.](image)

The Chandra observations confirm the very low X-ray luminosity measured by previous instruments. The observed X-ray luminosity in direction of Sgr A* amounts to about $2 \cdot 10^{33}$ erg s$^{-1}$ in the 2-10 keV band [24]. The total luminosity from radio to X-rays is $L_{\text{Sgr } A^*} \lesssim 5 \cdot 10^{36}$ erg s$^{-1}$, thus indicating the presence of very inefficient accretion flows onto the BH candidate Sgr A*. In order to explain the low radiative efficiency being orders of magnitudes below the expected one, so-called advection-dominated accretion flow (ADAF) models have been developed [156]. But, unless the accretion rate from stellar wind is much lower than assumed, the data are inconsistent with standard ADAF models [24, 156]. In 2001, Chandra discovered an intense X-ray flare in direction of Sgr A*. The X-ray flux increased by a factor of 50 and reached luminosities of up to $10^{35}$ erg s$^{-1}$ [23]. The XMM-Newton observatory confirmed the intense X-ray outburst [99]. Although modified ADAF models can account for the observed spectral shapes, they predict different correlations between sub-mm, near-IR and X-ray activity. Simultaneous observations of flares at several wavelengths in direction of Sgr A* may help to find the right model and possible correlations between different wavelength bands.

The Chandra and XMM-Newton surveys have also provided results on the observation of diffuse X-ray emission. Diffuse X-ray emission was observed within an elliptical shape of size $1^\circ \times 1.8^\circ$, elongated along the galactic plane and centered at the GC [98, 101]. Further information on the diffuse X-ray emission can be found elsewhere [24, 98, 101].

Although the GC region, especially Sgr A*, is a faint source in X-rays, it is known to be a source for hard X-rays and HE γ-rays. Extreme objects like BHs are known to emit very hard
3.2 VHE $\gamma$-Ray Observations of the GC Region

So far, the GC region has been observed by all new generation IACTs currently in operation. The energy spectrum of VHE $\gamma$-rays from the GC, as measured by the H.E.S.S., Whipple and CANGAROO collaborations, is shown in figure 3.3 [4]. The spectrum determined by the H.E.S.S. experiment is much harder than the one measured by CANGAROO and extends up to 10 TeV.

![Figure 3.3](image_url)  
**Figure 3.3:** VHE $\gamma$-ray flux in direction of the GC, as measured by the H.E.S.S., Whipple and CANGAROO collaborations (adopted from [4]). The spectrum determined by the H.E.S.S. experiment is much harder than the one measured by CANGAROO and extends up to 10 TeV. The measurement of the Whipple telescope provides only one point significantly above the H.E.S.S. flux level. The inset shows the MeV-GeV flux measured by the EGRET detector (previous section) as well as the ones measured by the H.E.S.S. (solid line) and the CANGAROO experiment (dotted line). The scaling of the axes is the same for both plots. Due to the limited angular resolution of the EGRET detector, which is $\mathcal{O}(1^\circ)$ [106, 153], the observed $\gamma$-ray flux may not only be ascribed to the GC.

The results reported by the Whipple collaboration are based on 26 hours of data collected.
between 1995 and 2003 at an average zenith angle (ZA) of $61^\circ$, resulting in a significance of 3.7 standard deviations [133]. The integral flux above $\gamma$-ray energies of 2.8 TeV is reported to be $(1.6 \pm 0.5_{\text{stat.}} \pm 0.3_{\text{sys.}}) \cdot 10^{-8} \text{ph m}^{-2} \text{s}^{-1}$, which corresponds to about 40% of the flux level of the Crab nebula.\(^1\) Furthermore, the Whipple detection of VHE $\gamma$-rays in direction of the GC is compatible with the emission from a point-like source [133].

The CANGAROO collaboration reports on the detection of a statistically significant excess for $\gamma$-ray energies greater than 250 GeV [204]. The spectrum obtained from a fit to the flux data points reported by the CANGAROO collaboration yields a rather soft spectrum:

$$\frac{dF_\gamma}{dE} = \left(3.4 \pm 3.8_{\text{stat.}}\right) \cdot 10^{-12} \left(\frac{E}{1 \text{ TeV}}\right)^{-(4.4 \pm 1.1_{\text{stat.}})} \text{ph cm}^2 \text{s TeV}^{-1}.$$  \hspace{1cm} (3.1)

The results reported by the CANGAROO collaboration are based on $\sim 121$ hours observation time at about $30^\circ$ ZA carried out in July 2001 as well as between July and August 2002. The $\gamma$-ray angular resolution of the CANGAROO-II instrument is reported to be $0.32^\circ$ for a soft energy spectrum $\propto E^{-4.6}$. The significance map obtained by the CANGAROO measurements is compatible with a point-like emission of VHE $\gamma$-rays. Moreover, no statistically significant rate variations of the VHE $\gamma$-ray flux are reported [204].

The H.E.S.S. collaboration accumulated 16.5 hours data between June and July 2003 as well as between July and August 2003 [4]. The observations were carried out with the first two telescopes at moderate ZA around $20^\circ$, with an analysis threshold between 165 and 255 GeV. The differential $\gamma$-ray flux, as determined for energies between 200 GeV to 10 TeV, can be described by a power law:

$$\frac{dF_\gamma}{dE} = (2.50 \pm 0.21_{\text{stat.}} \pm 0.06_{\text{sys.}}) \cdot 10^{-12} \left(\frac{E}{1 \text{ TeV}}\right)^{-(2.21 \pm 0.09_{\text{stat.}} \pm 0.15_{\text{sys.}})} \text{ph cm}^2 \text{s TeV}^{-1}. \hspace{1cm} (3.2)$$

Within statistics, the $\gamma$-ray flux reported by the H.E.S.S. collaboration is stable and compatible with the emission from a point-like source, although extended emission is not excluded. The stereoscopic reconstruction of the shower geometry provides an angular resolution of about $0.1^\circ$ [4]. During subsequent observations of the H.E.S.S. experiment carried out between March and September 2004 with the full four-telescope array, $\sim 48$ h data were collected [7, 186] resulting in a detection significance level of 35 standard deviations. The analysis of this dataset together with a dataset of 15.2 h obtained during a Galactic plane survey provided compatible results. The energy spectrum between $\gamma$-ray energies of 160 GeV and 30 TeV is compatible with a simple power law with a spectral index of $2.25 \pm 0.04_{\text{stat.}} \pm 0.10_{\text{sys.}}$. The integral $\gamma$-ray flux above 1 TeV was found to be $(1.87 \pm 0.10_{\text{stat.}} \pm 0.30_{\text{sys.}}) \cdot 10^{-12} \text{ph cm}^{-2} \text{s}^{-1}$. There is no significant variation of the $\gamma$-ray flux between 2003 and 2004 and the data are found to be consistent with a constant flux. Furthermore, the search for quasi-periodic variations on scales between 1 mHz and 16 $\mu$Hz did not reveal any periodicity [7, 186].

The results from the GC observations as reported by the Whipple, CANGAROO and H.E.S.S. experiments show substantial differences. The flux measurement of Whipple provides only one point significantly above the H.E.S.S. flux level, when converted to a differential flux at the peak detection energy assuming a Crab-like spectrum [4] (figure 3.3). The energy spectrum of VHE $\gamma$-rays reported by the CANGAROO collaboration is much softer than the one published by the H.E.S.S. collaboration.

\(^{1}\)The unit of the $\gamma$-ray flux is photons per square meter per second and the abbreviation “ph” stands for photon.
3.3. THE ORIGIN OF VHE $\gamma$-RAYS FROM THE GC REGION

The reasons that gave rise to MAGIC observations of the GC region are obvious:

- A matter of particular interest was the investigation of the discrepancy between the results from GC observations that have been carried out by the new generation IACTs currently in operation. At La Palma, the GC culminates at comparatively large ZA of about 58° between April and late August, which results in a high threshold energy for VHE $\gamma$-ray observations of about 700 GeV. For this reason, the GC region is not a favorable target for the MAGIC telescope as it can access only a limited energy range within reasonable observation time. But, in order to help resolving the flux discrepancies between the H.E.S.S. and CANGAROO instruments at $\gamma$-ray energies above some 700 GeV, extended MAGIC observations of the GC were planned and conducted between May and August 2005 after initial observations in September 2004 which were carried out during the commissioning phase of the experiment.

- Simultaneous observations by several IACTs provide the possibility for inter-calibration of the instruments, which is important because the absolute energy calibration of an IACT represents a difficult task (section 6.6).

- More general interests involve the investigation of time variability of the VHE $\gamma$-ray emission within the MAGIC observation period as well as the investigation of possible flux variations between the two-year time span of the H.E.S.S. and the MAGIC observations. Furthermore, VHE $\gamma$-ray observations may help to gain information about the nature and acceleration mechanisms of the source.

Although the angular resolution of MAGIC is limited to some 0.1°, observations may help to make an assertion on the source location and extension.

If the $\gamma$-ray flux is interpreted as to originate from Dark Matter (DM) particle annihilation, GC observations may allow to set constraints on models for DM particle annihilation and DM halo profiles.

3.3 The Origin of VHE $\gamma$-Rays from the GC Region

A number of mechanisms have been proposed to explain the production of VHE $\gamma$-rays at the GC region, some of which consider DM annihilation as a possible origin of the VHE $\gamma$-ray emission. Within the numerous theoretical frameworks the super-symmetric (SUSY) extension of the standard model (SM) [76, 125], Kaluza-Klein (KK) theories involving universal extra-dimensions (UED) [39, 190] are frequently discussed in the literature. Both theories provide candidate DM particles. The pair-annihilation of these DM particles are believed to produce a detectable VHE $\gamma$-ray flux [36]. Alternative scenarios try to explain the production of HE-VHE $\gamma$-rays in regions close to the event horizon of the massive BH candidate Sgr A*.

In the next two sections possible scenarios for the production mechanisms taking place at the GC are summarized and discussed.

3.3.1 VHE $\gamma$-Rays from hypothetical Dark Matter Annihilation

Astro-physical observations indicate that most of the matter in the universe is dark. Recent measurements of the Cosmic Microwave Background (CMB) anisotropy performed by the satellite-born Wilkinson Microwave Anisotropy Probe (WMAP) [217] suggest a flat universe in which about 27% of the energy density is due to non-relativistic matter and, out of this, only 4% is due to baryons [35, 194]. Thus, most of the matter in the universe is not only dark but also takes some non-baryonic form. The non-baryonic contribution to the overall matter density
ΩM is referred to as DM. The remaining ~ 73%, required to explain observations indicating that the universe is presently accelerating and spatially flat, are thought to be due to an even more exotic component called “Dark Energy”. The nature of Dark Energy is totally unknown.

To date it is believed that hypothetical DM accounts for the most part of the mass contained in galaxies. The distribution of this unseen matter within the Galaxy, the so-called DM halo where nearly all of the Galaxy’s dark matter is located, is largely unknown. However, recent developments in the theory of DM halo formation made good progress, because the DM halo parameters, such as total mass, peak rotation speed and concentration parameter are correlated to their proximity both the Milky Way and the M31 galaxy provide observational constraints for the structure parameters of the DM halos. Apart from that, the nature of DM is still unknown.

Numerous theoretical frameworks have been developed some of which provide DM candidate particles. A particle must fulfill several requirements to represent DM [220]. To be able to contribute to the structure formation, it must be stable with a long lifetime compared to the age of the universe. Furthermore, the existence of a production mechanism is required to create the right amount of DM in the early universe. DM must be non-relativistic during structure formation, i.e. it must be “cold” to permit galaxies to form. Moreover, it must be only weakly interacting (weak interactions in the order of the electro-weak cross sections) to have escaped detection, electrically neutral and colorless.

In the Minimal Super-symmetric extension of the Standard Model (MSSM), the lightest super-symmetric particle (LSP), the neutralino χ0 j, is an excellent representative for cold DM (CDM). The symmetry which guarantees the stability of the LSP is called R-parity.iii The spectrum of γ-rays from pair-annihilation of the LSP is composed of a continuum and two emission lines [36, 77]. The relevant processes are χ1 + χ0 → f + f, χ1 + χ1 → γ + γ and χ1 + χ1 → Z0 + γ, where f and f denote a fermion-antifermion pair. The former process corresponds to a continuous γ-ray energy distribution. In case the fermion-antifermion pair represents a quark-antiquark pair, the hadronization of the quark-antiquark pair results in an approximately equal amount of π0, π+ and π− mesons. The π0 mesons in turn decay all but almost into two γ’s with a continuous energy spectrum.

The neutralinos may also annihilate, producing a lepton-antilepton pair. For some regions in the super-symmetric parameter space, the largest amount of γ-rays arises from the annihilation of neutralinos into τ leptons [195, 196]. The most important decay channel for the production of VHE γ-rays is the process τ± → π± + π0 + [176], because the π0 mesons subsequently decay to γ’s with continuous energy spectrum.

Instead, the LSP pair-annihilation with two final-state γ’s as well as the Z0,γ process result in γ-ray lines at

\[ E_γ = m_{χ_1} c^2 \text{ and } E_γ = m_{χ_1} c^2 \left(1 - m_{Z_0}^2 / 4 m_{χ_1}^2 \right), \]  

where \( m_{χ_1} \) is the mass of the neutralino and \( m_{Z_0} \) the mass of the Z0 boson. The direct production of γ-rays has a low probability because loop-processes are involved. Therefore,

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iUsually, the total matter density ΩM is expressed in terms of the DM density and the baryon density, i.e. \( Ω_M = Ω_{DM} + Ω_B \), where \( Ω_M = 0.27 ± 0.04 \) and \( Ω_B = 0.044 ± 0.004 \) [35, 194] are the densities expressed as a fraction of the critical density for a flat universe [176].

iiThe WMAP satellite [217] yields a total density of \( Ω_{tot} = 4Ω_0 \), which is consistent with spatial flatness [35, 194]. The contribution ΩL to the total density Ωtot is interpreted as due to a cosmological constant or to a more general “Dark Energy” component.

iiiIn the MSSM, baryon number and lepton number are no longer conserved by all of the renormalizable couplings appearing in theory. Experimentally baryon number and lepton number conservation have been thoroughly tested. Thus, in order not to be in conflict with experimental data, the renormalizable couplings violating baryon respectively lepton number need to be very small. R-parity, defined as \( R = (-1)^{2j+3B+L} \), forbids these couplings [176]. Therein, j denotes the spin, B the baryon number and L the lepton number. SM-particles have R-parity of 1 while super-symmetric particles have R-parity −1.
pair-annihilation predominantly proceeds into continuum \( \gamma \)-rays from jet-fragmentations and hadronization of the quark-antiquark pair.

DM candidate particles are also provided by KK models involving UED, in which all SM fields propagate in extra dimensions, including fermions [39, 190]. In the KK DM scenario, possible candidates for the lightest stable KK particle (LKP) are the first KK excitation of the photon, the hypercharge gauge boson \( B^{(1)} \) as well as the first KK excitation of the neutrino \( \nu^{(1)} \). These KK modes are stable provided KK parity is preserved [190]. While the \( B^{(1)} \) can self-annihilate, the \( \nu^{(1)} \)'s can both annihilate among themselves as well as with their anti-particles (\( \bar{\nu}^{(1)} \)). In case the neutrino \( \nu^{(1)} \) is the LKP, the calculation of the annihilation cross section requires some assumptions, such as a certain asymmetry between particle and antiparticle before freeze-out. Furthermore, the number of possible annihilation processes is greater. The LKP is likely to be associated with the \( B^{(1)} \) [61]. Similarly to the MSSM DM scenario, the process \( B^{(1)} + B^{(1)} \to \gamma + \gamma \) is loop-suppressed. Instead, high-energy \( \gamma \)'s are mostly produced indirectly from decay of \( \pi^0 \) mesons generated in the hadronization of quarks that are produced through \( B^{(1)} + B^{(1)} \to q + \bar{q} \). \( \gamma \)-rays can also be produced in terms of synchrotron radiation of \( e^+e^- \) pairs (originating from the decay of \( \pi^+ \) and \( \pi^- \) mesons) in the galactic magnetic field.

The continuum energy spectrum of \( \gamma \)-rays due to \( \chi_1^0 \) or \( B^{(1)} \) pair-annihilation extends up to the mass of the annihilating particle. The annihilation of the hypothetical DM particles (the \( \chi_1^0 \) in case of SUSY DM annihilation and \( B^{(1)} \) for KK annihilation) in an isothermal halo results in a \( \gamma \)-ray flux of [116, 205]

\[
\frac{dF_\gamma}{dE_\gamma} = \frac{1}{4\pi m_{\chi_1^0 B^{(1)}}^2} \frac{dN_\gamma}{dE_\gamma} \langle \sigma_{\chi_1^0 \chi_1^0 B^{(1)} B^{(1)}} \times v \rangle \times \int \rho_{\chi_1^0 B^{(1)}}^2(r) d\psi \). \hspace{1cm} (3.4)
\]

Therein, \( \psi \) denotes the angle between the line of sight (l.o.s.) and the GC, \( \langle \sigma_{\chi_1^0 \chi_1^0 B^{(1)} B^{(1)}} \times v \rangle \) is the thermally averaged DM annihilation cross section, \( m_{\chi_1^0 B^{(1)}} \) the mass and \( \rho_{\chi_1^0 B^{(1)}}(r) \), in short \( \rho_{\text{CDM}}(r) \), the density of the hypothetical DM particles at a distance \( r \) from the GC. \( dN_\gamma/dE_\gamma \) denotes the \( \gamma \)-ray multiplicity per annihilation above the threshold energy \( E_T \) of the detector. The \( \gamma \)-ray flux is usually decomposed into two factors, where the first one depends on the physical properties of the CDM particles, like mass, cross section and fragmentation spectrum and the second one depends on the characteristics of the CDM spatial distribution \( \rho_{\text{CDM}}(r) \). The shape of the \( \gamma \)-ray spectrum is exclusively determined by the factor in front of the integral derived from particle physics. The second factor, normalized to the distance to the GC and the local halo DM density, can be written as

\[
J(\psi) \equiv \frac{1}{8.5 \text{kpc}} \left( \frac{1}{0.3 \text{GeVcm}^{-3}} \right)^2 \int \rho_{\chi_1^0 B^{(1)}}^2(r) d\psi. \hspace{1cm} (3.5)
\]

Its average over the solid angle \( \Delta \Omega \) (centered on \( \psi = 0 \), \( J(\Delta \Omega) \), can be used to introduce the quantity \( \langle \sigma_{\text{DM}} J \rangle \), defined as [172]

\[
\langle \sigma_{\text{DM}} J \rangle \equiv \left( \frac{\langle \sigma_{\text{DM}} \times v \rangle}{3 \cdot 10^{-26} \text{cm}^3\text{s}^{-1}} \right) J(\Delta \Omega). \hspace{1cm} (3.6)
\]

Together with equation 3.5 and 3.6, the expected \( \gamma \)-ray energy spectrum can be rewritten as

\[
\frac{dF_\gamma}{dE_\gamma} = 5.6 \cdot 10^{-12} \text{cm}^{-2}\text{s}^{-1} \frac{dN_\gamma}{dE_\gamma} \left( \frac{m_{\chi_1^0 B^{(1)}}^2}{1 \text{TeV}} \right)^{-2} \langle \sigma_{\text{DM}} J \rangle \Delta \Omega. \hspace{1cm} (3.7)
\]
As the factor $J(\psi)$ linearly scales with the square density of the CDM distribution, the $\gamma$-ray flux level is very sensitive to the configuration of the CDM halo. Therefore, the central region of the $r \lesssim 200$ pc of our Galaxy expected to harbor an enhanced DM concentration is a favored place to search for DM signatures in terms of high-energy $\gamma$-rays [36].

Extensive $N$-body simulations have been carried out to simulate the evolution of DM halos in their cosmological context [107, 161, 162, 163, 168, 197]. The parameters of DM density profiles can be deduced from observations, i.e. from the virial mass of the halo or from rotation curves. In the vicinity of the GC, the DM spatial density is expected to follow a cuspy profile with $\rho(r) \propto r^{-\alpha}$, where $\alpha$ ranges between 1 and 1.5 [161, 162, 168]. The largest $\gamma$-ray flux is predicted by profiles describing a point-like accumulation of DM at the very center [161, 179]. By contrast, recent $N$-body simulations suggest a DM density profile which flattens inwards to the center [107]. However, there are claims that very steep DM density profiles are required to produce a detectable $\gamma$-ray flux both detectable for IACTs and satellite-born experiments with sensitivities comparable to GLAST [83].

Depending on the DM profile, the quantity $J(\psi)$ varies by several orders of magnitudes. For instance, the Navarro Frenk and White (NFW) profile [168] yields $J(\Delta \Omega) \approx 6 \cdot 10^3$ while a Moore profile [163] yields $J(\Delta \Omega) \approx 2 \cdot 10^6$ [116]. Therein $\Delta \Omega \approx 5 \cdot 10^{-5}$ sr denotes the solid angle corresponding to the angular resolution of the CANGAROO-II experiment, which is $\sim 0.2^\circ$ [204]. Baryonic compression has been considered as a possible effect boosting the $\gamma$ signal by a factor of 1000 compared to the NFW profile [179]. The shape of the DM density profile determines whether source extension may be observed or not, provided the PSF of the detector is good enough (small enough).

![Figure 3.4: Spectral energy density of VHE $\gamma$-rays from the GC as measured by the H.E.S.S. experiment together with typical spectra expected from hypothetical DM annihilation (adopted from [7]). The open points correspond to the 2003 data and the full points to the 2004 data. Upper limits are 95% confidence level. The power-law fit is indicated by the gray-shaded area. The dashed line shows a spectrum of phenomenological MSSM DM annihilation for best fit neutralino masses of 14 TeV, and the dotted line shows the one expected for KK DM annihilation with a mass of 5 TeV. The solid line represents the predicted spectrum of a 10 TeV DM particle annihilating into $\tau^+\tau^-$ (30% branching ratio) and $b\bar{b}$ (70% branching ratio).](image)

Apart from its sensitivity to the DM density profile, the $\gamma$-ray flux depends on the theoretical framework predicting $m_{\text{DM}}$ and $\sigma_{\text{DM}}$ as well as $dN_\gamma/dE_\gamma$. Although data from WMAP impose limits on the CDM relic density $\Omega_{\text{DM}}h^2$ [35, 194], which significantly reduces the SUSY parameter space, both the shape and the level of the predicted $\gamma$-ray flux from neutralino annihilation are still sensitive to variations of the free SUSY parameters [195, 196]. Even a combination of WMAP constraints on the SUSY parameter space with particle physics predictions still leaves
open a broad scope for the SUSY parameters. Therefore, predictions for the γ-ray flux from annihilation of the LSP in the GC can vary over orders of magnitude when exploring the SUSY parameter space.

Figure 3.4 [7] shows the spectral energy density of VHE γ-rays from the GC as measured by the H.E.S.S. experiment together with typical spectra expected from hypothetical DM annihilation. Both, the 2003 and the 2004 H.E.S.S. GC dataset (preceding section) yield comparable results within errors. The position of the VHE γ-ray signal and the absence of temporal variability allow for the possibility of DM annihilation from a DM halo centered at Sgr A*. However, if the observed γ-ray flux is attributed completely to DM annihilation, the extension of the energy spectrum (figure 3.4) to energies above 10 TeV demands for a DM candidate particle mass of at least 10 TeV, which is very close to the unitarity limit [104]. Such massive LSPs are disfavored by particle physics [79, 176]. Lower limits of 9 TeV and 7 TeV were derived assuming an exponential cutoff and a sharp cutoff ($E^2_v dF_\gamma/dE_\gamma = 0$ above the cutoff energy) respectively, at a confidence level of 95% [7]. In the framework of phenomenological MSSMs, the γ-ray spectrum due to neutralino pair-annihilation depends on the gaugino and higgsino mixing [77, 172]. Nevertheless, in the $E^2_v dF_\gamma/dE_\gamma$ versus $E_\gamma$ representation, all spectra exhibit a curved shape rising for energies $E_\gamma \ll m_{\chi^0}$, followed by a plateau at $E_\gamma/m_{\chi^0} \approx 0.01 - 0.1$ with a fast decay for γ-ray energies approaching $m_{\chi^0}$ [7].

Figure 3.5: Confidence level contours from spectral fits to the CANGAROO-II and the H.E.S.S. 2003 and 2004 dataset separately on the plane spanned up by the neutralino mass $m_{\chi^0}$ and the quantity $\langle \sigma, v \rangle J$, which is proportional to the annihilation cross section $\langle \sigma, v \rangle$. For every $m_{\chi^0}$ and a given set of branching ratios, the quantity $\langle \sigma, v \rangle J$ is analytically determined from a fit to the data points of the γ-ray energy spectrum [172].

(b) Confidence level contours on the $\langle \sigma_{\chi_1^0} \times v \rangle - J(\Delta \Omega)$ plane, for the full 2003 and 2004 H.E.S.S. dataset. The upper abscissa indicates the boost factor $J(\Delta \Omega)/J(\Delta \Omega)_\text{NFW}$, where $J(\Delta \Omega)_\text{NFW}$ denotes the solid angle-averaged integral over the DM density calculated for the NFW halo profile. The red arrows indicate values of $J(\Delta \Omega)$ for the most common Milky Way halo profiles. The inset shows the confidence level regions on the $(\sigma_{\chi_1^0} J) - m_{\chi_1^0}$ plane for the combined H.E.S.S. 2003/2004 dataset obtained from spectral fits to the γ-ray energy spectrum.

Albeit all predicted spectra shown in figure 3.4 were obtained for best-fit neutralino masses, they are inconsistent with the measured spectrum following a power law. Apart from this, no indications for a monoenergetic γ-ray line were found [7].

It is shown that an alternative MSSM scenario of a mixed final state with a branching ratio of 25% into $\tau^+ \tau^-$ and 75% into $b\bar{b}$ better describes the experimental data [172]. The resulting
spectra tend to be harder, resulting in a better agreement with the experimental spectrum at \( \gamma \)-ray energies approaching \( m_{\chi_1^0} \). In this scenario, the neutralino mass range allowed at 90 \% confidence level is given by \( 6 < m_{\chi_1^0}/\text{TeV} < 30 \) for the combined 2003/2004 H.E.S.S. dataset. Again, this is well beyond the neutralino mass range favored by particle physics.

Figure 3.5 (a) shows the iso-confidence level contours obtained from spectral fits to the CANGAROO-II and the H.E.S.S. 2003 and 2004 dataset separately on the plane spanned up by the neutralino mass \( m_{\chi_1^0} \) and the quantity \( \langle \sigma_{\chi_1^0} \times v \rangle \), which is proportional to the annihilation cross section \( \langle \sigma_{\chi_1^0} \times v \rangle \) (equation 3.6) [172]. For every \( m_{\chi_1^0} \) and a given set of branching ratios the quantity \( \langle \sigma_{\chi_1^0} \times v \rangle \) is analytically determined from a fit to the data points of the \( \gamma \)-ray energy spectrum. As can be seen from the figure, the 2004 H.E.S.S. dataset significantly reduces the range of allowed values for the neutralino mass. Furthermore, the corresponding confidence level contours are compatible with the ones derived for the 2003 dataset. The iso-confidence level contours derived for the CANGAROO-II [204] \( \gamma \)-ray spectrum and the one for the 2004 H.E.S.S. spectrum are clearly inconsistent. The disagreement can be attributed to the different spectral indices of the energy spectra. Figure 3.5 (a) restricts the range of the quantity \( \langle \sigma_{\chi_1^0} \times v \rangle \) at a certain confidence level and therefore narrows the allowed interval on the \( \langle \sigma_{\chi_1^0} \times v \rangle \) plane, which is shown in figure 3.5 (b) [172]. The calculations were performed for a solid angle \( \Delta \Omega \) corresponding to the angular resolution of the H.E.S.S. experiment. The upper abscissa indicates the boost factor \( \frac{J(\Delta \Omega)}{J(\Delta \Omega)_{\text{NFW}}} \), where \( J(\Delta \Omega)_{\text{NFW}} \) denotes the solid angle-averaged integral over the DM density calculated for the NFW halo profile. The red arrows indicate values of \( J(\Delta \Omega) \) for the most common Milky Way halo profiles.

The inset in figure 3.5 (b) shows the confidence level regions in the \( \langle \sigma_{\chi_1^0} \times v \rangle - \frac{J(\Delta \Omega)}{J(\Delta \Omega)_{\text{NFW}}} \) plane derived for the combined 2003/2004 H.E.S.S. dataset. For a certain confidence level, together with the value for \( \frac{J(\Delta \Omega)}{J(\Delta \Omega)_{\text{NFW}}} \) derived for a given DM halo profile, the figure allows to determine a confidence interval for the thermally averaged DM annihilation cross section \( \langle \sigma_{\chi_1^0} \times v \rangle \). For example, the cuspiest profile at \( J(\Delta \Omega) \approx 10^7 \), which accounts for baryonic compression of the central DM distribution due to infall of baryons to the GC, yields a 90 \% confidence level interval for the cross section given by

\[
3.0 \cdot 10^{-26} < \langle \sigma_{\chi_1^0} \times v \rangle < 1.3 \cdot 10^{-25}.
\]

If the annihilation cross section is independent of the velocity of relic neutralinos, the relation between annihilation cross section and neutralino relic abundance can be approximated by [104]

\[
\langle \sigma_{\chi_1^0} \times v \rangle \cdot \Omega_{\chi_1^0} h^2 \approx 3.0 \cdot 10^{-27} \text{ cm}^3\text{s}^{-1}.
\]

Therein \( \Omega_{\chi_1^0} h^2 = 0.113 \pm 0.009 \) denotes the neutralino relic abundance and \( h = 0.71 \pm 0.04 \) the Hubble constant in units of 100 km s\(^{-1}\) Mpc\(^{-1}\) [35, 194]. For a velocity dependent annihilation cross section, which is generally the case, its velocity dependence must be modeled such that it can explain the measured DM density.

On the assumption that there is no other DM component beside the neutralino, i.e. \( \Omega_{\chi_1^0} h^2 = \Omega_{\text{DM}} h^2 \approx 0.113 \), equation 3.9 yields a value for the annihilation cross section which is conform to the requirement imposed by equation 3.8. In other words, only a very cuspy DM halo profile may explain the \( \gamma \)-ray flux observed from the GC. If the neutralino is not the only constituent of the DM relic abundance, i.e. \( \Omega_{\chi_1^0} < \Omega_{\text{DM}} \), the \( \gamma \)-ray flux will be rescaled by a factor \( \Omega_{\chi_1^0}^2 / \Omega_{\text{DM}}^2 \). In turn, this would require more cuspy halo profiles or a larger annihilation cross section. However, it is shown that equation 3.9 can fail, because both the MAGIC measurement reported in [11] and this thesis as well as the H.E.S.S. [7] measurements can have a super-symmetric interpretation with models allowing for values of the annihilation cross section \( \langle \sigma_{\chi_1^0} \times v \rangle \) implying less cuspy DM profiles with boost factors \( \frac{J}{J_{\text{NFW}}} \) of \( \mathcal{O}(10) \) [172].
Apart from the above considerations, it cannot be ignored that there is a considerable disagreement between the measured and the predicted γ-ray spectrum from the GC (figure 3.4). None of the theoretically predicted spectra reasonably fits to the observed power law over the entire γ-ray energy range. Nevertheless, there is still the possibility that the DM γ-ray signal is hidden under a dominating γ-ray component of astrophysical origin [184], which is discussed in the next section. The search for a hidden DM contribution to the γ-ray spectrum did not reveal a significant component [7]. Instead, an upper limit for the DM contribution of about 10% of the observed γ-ray flux was derived.

In summary, the observed γ-ray spectrum with the MAGIC and the H.E.S.S. IACTs is very likely not dominated by DM annihilation. There is a variety of alternative scenarios proposed to explain the production of VHE γ-rays in the GC region some of which are discussed in the next section.

3.3.2 Alternative Scenarios for the Production of VHE γ-Rays in the GC Region

The production of VHE γ-rays in the immediate vicinity of the BH has been taken into consideration as the very low bolometric IR and optical luminosity of Sgr A* result in a weak attenuation of γ-rays due to internal photon-photon pair production dominated by the interaction of HE-VHE γ-rays with the radiation of the compact IR source. Internal absorption is expected to become significant only at energies above some 10 TeV if the production region is assumed to be limited to $2R_G$. Furthermore, the near-IR and X-ray flares, with variability time scales $\mathcal{O}(10^4\text{s})$ [189] and $\mathcal{O}(10^2 - 10^3\text{s})$ [23] suggest that the VHE γ-rays are produced close to the event horizon of the BH [5].

Synchrotron radiation and curvature radiation of protons in strongly magnetized regions near the gravitational radius of the BH is considered as a possible mechanism for the production of VHE γ-rays [5]. Even for a very efficient proton acceleration and in case proton energy losses are dominated by synchrotron cooling, the energy of the produced γ-rays is limited to a fraction of TeV's, independent of the magnetic field strength. The spectrum of γ-rays from proton curvature radiation can extend up to some 10 TeV if the magnetic field strength is in the order of $10^6$ G. The mean free path of γ-rays decreases with increasing magnetic field strength. For magnetic fields greater than $10^6$ G, the source becomes opaque already for 1 TeV γ-rays [5]. Thus, the GeV-Tev γ-ray flux observed in direction of the GC is most likely not due to proton synchrotron radiation.

Photo-meson production, discussed in section 2.2, chapter 2, is considered as another possible scenario for the production of VHE γ-rays. At energies of $\sim 10^{18}$ eV, proton interaction with far-IR and mm photons becomes dominant [5]. Although protons interact with ambient photons through the pair production, only a small fraction of the proton energy is transferred into electromagnetic secondaries. Since the mean free path of protons through the photon field exceeds the linear extension of the IR source by two orders of magnitude, only a fraction of $\sim 1\%$ of the proton energy is expected to be transferred into secondary particles. Therefore, such a scenario requires a great injection power of HE protons in order to explain the observed luminosity of VHE γ-rays [5]. Simultaneous detection of VHE γ-rays and energetic neutrinos would substantiate the assumption that the observed γ-rays are due to photo-meson production.

The so-called proton-proton scenario is believed to become efficient if the magnetic field in the vicinity of the BH is weak ($B \ll 10^4$ G in a few $R_G$) [5]. In this case, γ-rays and electrons from the GC region are due to proton-proton interactions or interactions of protons with nuclei of ambient plasma. Protons may be accelerated to TeV energies by strong shocks developed in the accretion flow of the accretion disk around the BH. The production efficiency for VHE

\[ R_G = \frac{2GM}{c^2} \approx 10^{19} \text{m} \] denotes the gravitational radius of the BH at the GC, i.e. the boundary at which the escape velocity meets the speed of light in vacuum.
\( \gamma \)-rays depends on the ratio of accretion time and cooling time for proton-proton interactions, which depends on the cross section for proton-proton interactions as well as on the density of the ambient plasma. The efficiency for the production of VHE \( \gamma \)-rays is estimated to be about \( 10^{-4} \). Furthermore, it is concluded that the proton acceleration rate has to be orders of magnitudes above the total electromagnetic luminosity (\( O (10^{39} \text{ erg s}^{-1}) \)) if the process is considered to be responsible for the observed TeV \( \gamma \)-ray flux [5]. A strong case against the proton-proton scenario would be a X-ray flux being orders of magnitudes below the TeV \( \gamma \)-ray flux, as the proton acceleration beyond energies of 10 TeV is accompanied by the production of secondary \( e^+ e^- \) pairs whose synchrotron radiation extends to the hard X-rays. On the contrary, the proton-proton scenario would be supported if a correlation between TeV and X-ray flares was found. The flux of \( \gamma \)-rays with hadronic origin is expected to exhibit sub-hour time variability. However, to date no indication for a significant time variability of the VHE \( \gamma \)-ray flux has been found [4, 11, 133, 204]. The presence of GeV - TeV neutrinos would make a good case for the hadronic origin of the VHE \( \gamma \)-rays.

The curvature radiation-inverse Compton (CIRC) model is another possible scenario for the production of VHE \( \gamma \)-rays [5]. CIRC models describe the emission of curvature and inverse Compton photons by means of electrons accelerated in regular magnetic and electric fields. As the radiative energy loss rate of electrons is much higher than the one of protons, the production of VHE \( \gamma \)-rays through electron acceleration is more efficient. In order to explain the VHE \( \gamma \)-ray flux, electrons have to be accelerated to multi-TeV energies. The balance of the acceleration and synchrotron energy loss rates requires the chaotic component of the magnetic field in the region of acceleration to be below some 10 G. Depending on the configuration of the magnetic field in the acceleration region and whether there is isotropic or anisotropic emission of electrons into the acceleration region, the VHE \( \gamma \)-ray spectrum is expected to exhibit peaks at some GeV (curvature radiation) and some TeV’s (IC scattering) [5]. To what extent the peaks appear in the spectrum of GeV - TeV \( \gamma \)-rays depends also on the viewing angle with respect to the electron acceleration zone. In the CIRC scenario, the absence of neutrinos is expected.

Another mechanism which could account for the production of VHE \( \gamma \)-rays at the GC region involves electron and proton acceleration in stellar wind shocks [173]. The inner parsec of the GC region harbors a multitude of massive stars with an overall mass-loss rate of \( \sim 10^{-3} M_\odot \text{ yr}^{-1} \). The mass is lost to stellar winds that are gravitationally bound by the BH candidate Sgr A*. Shocks among these stellar winds are believed to efficiently accelerate electrons and protons to relativistic energies. The relativistic electrons in turn produce, through inverse Compton scattering with the ambient UV and far-IR radiation field, GeV - TeV \( \gamma \)-rays with constant luminosity. The model discussed in [173] predicts a cooling break at around 4 GeV, lying well within the measurement range of GLAST [96]. Furthermore, the model predicts a detectable keV emission due to synchrotron radiation from the same electrons, extending to the hard X-ray range. The level of this emission depends on the magnetic field strength in the inner parsec of the GC region. The models discussed in [173] requires the field strength to be below some 300 \( \mu \)G. Future measurements of the synchrotron background are expected to provide more accurate limits for the magnetic field strength and thus further constraints for stellar wind accretion models.

Stochastic acceleration in the GC region could also be responsible for the production of VHE \( \gamma \)-rays [145, 146]. This model explains both the millimeter and shorter wavelength spectrum as well as the observed TeV emission from the GC. While the millimeter and shorter wavelength spectrum of Sgr A* is supposed to be due to stochastic acceleration of electrons interacting resonantly with turbulent magnetic fields in a small accretion torus, the TeV \( \gamma \)-ray luminosity is explained with proton-proton induced pion decay. According to the model presented in [145], the proton-proton scattering does not occur in the acceleration region but in the vicinity of the BH, within \( \sim 3 \) pc. The ambient proton density in the acceleration region is supposed to be low, which in turn enables the accelerated protons to diffuse out and scatter with interstellar matter. The model also explains why the TeV \( \gamma \)-ray emission is steady on timescales of a year
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and less. The steady emission is attributed to the fact that the proton-proton scattering time is $O(10^5 \text{ yr})$, which is longer than the time required for the wind-injected interstellar matter to achieve equilibrium. The authors infer that any variability of the TeV $\gamma$-ray emission would be due to density fluctuations of the interstellar matter rather than due to changes in the source [145]. The cascade of secondary particles generated in the proton-proton interactions is responsible for additional spectral components. Below some 100 MeV, most of the radiative emission is proposed to be due to the decay products of charged pions. The secondary leptons radiate through synchrotron, Bremsstrahlung and inverse Compton scattering with the dense UV and IR field in the central few parsecs of the Galaxy. The $\sim 100 \text{ MeV} - 100 \text{ GeV}$ part of the broadband spectrum, the counterpart of the TeV $\gamma$-ray source, is presumed to be detectable by the GLAST project [96].

The capturing of stars by the GC BH has been discussed as a potential scenario to explain the VHE $\gamma$-ray emission at the GC [62]. The GC region is a region with a high concentration of stars and a star capture may take place from time to time. A captured star, forcibly disrupted when accreted into the BH, could be the source of relativistic protons. The relativistic protons, injected into the ambient matter, undergo proton-proton collisions which are associated with the production of secondary particles some of which produce secondary $\gamma$-rays. The $\gamma$-ray flux is supposed to be almost constant during the lifetime of the protons. But, the exceedance of the proton lifetime is expected to be followed by an exponential decay of the $\gamma$-ray flux, whose characteristic time is dependent on the ambient gas density. A feature of the star-capturing scenario is the extended appearance of the positron annihilation flux around the GC. The positrons effectively annihilate only if they are cooled down to energies of some eV. Within the corresponding cooling time, they are able to propagate away from the central source and to fill an extended region around the GC ($\gtrsim 100 \text{ pc}$). However, high-energy $\gamma$-rays are supposed to be produced rather shortly after the injection of protons into the ambient matter and appear as a point-like source. The calculations in [62] show that it is rather unlikely that the $\gamma$ emission lines and the VHE $\gamma$-rays observed in direction of the GC belong to the same eruption process. Instead it is assumed the VHE $\gamma$-rays are generated by a recent capture, while the diffuse $\gamma$-ray lines from the positron annihilation are generated by a previous capture of a much more massive star. The TeV $\gamma$-ray emission from the GC suggests that the characteristic capture time scale is $\sim 10^5 \text{ yr}$. The protons responsible for the the diffuse $\gamma$-ray lines must be ejected by Sgr A* much earlier than the protons responsible for the TeV $\gamma$-rays, because their spatial extension appears to be different. Assuming the positron cooling time ($\sim 10^6 \text{ yr}$) is longer than the proton-proton collision time the calculations in [62] yield a positron annihilation rate that is more or less constant. The current VHE $\gamma$-ray flux may be measured somewhere between two star captures, which naturally explains why the positron annihilation rate is about 2 orders of magnitude higher than the emission rate of VHE $\gamma$-rays. The positron annihilation emission was measured by the INTEGRAL telescope [118].

It has been put forward that also SNR Sgr A East could be a source of HE- VHE $\gamma$-rays [145]. The EGRET source 3EG J1746-2851 as well as the TeV $\gamma$-ray source at the GC [4, 11, 133, 204] could be associated to Sgr A East. However, the EGRET source 3EG J1746-2851 and the TeV $\gamma$-ray source are very likely two separate sources. The EGRET source 3EG J1746-2851 is excluded at the 99.9% confidence level as to be located at the GC [117]. Instead, the TeV $\gamma$-ray source is coincident with $\sim 1'$ of Sgr A*, although its centroid is displaced eastwards by $\sim 10''$. Furthermore, the extrapolation of the EGRET GC source spectrum into the range covered by the IACTs over-predicts the TeV flux by about a factor of 20 [145]. Because of the limited angular resolution of to date IACTs ($O(0.1')$), it is not yet possible to unambiguously discriminate between the BH candidate Sgr A* and the SNR Sgr A East as a source for VHE $\gamma$-rays.
Chapter 4

Detection Methods for VHE $\gamma$-Rays from Ground

For the detection of $\gamma$-rays above some 10 GeV, ground-based instruments are needed, as the low flux of CRs requires large detection areas. The ground-based instruments use indirect methods to detect extended air showers (EAS) induced by $\gamma$-rays as well as charged cosmic particles.

The imaging air Cherenkov technique aiming at the detection of the faint Cherenkov light flashes emitted in VHE $\gamma$-ray induced EAS has been developed over the past 50 years. Since $\gamma$-rays represent less than 0.01% of the CRs, the imaging air Cherenkov technique involves sophisticated identification methods based on the intrinsic differences in the development of $\gamma$-ray and hadron induced EAS, to efficiently suppress the unwanted background of hadron induced EAS.

The first part of this chapter is dedicated to the development, growth and evolution of EAS, the second part discusses the emission of Cherenkov light in EAS and its detection. The last part explains the basic ideas of the imaging air Cherenkov technique.

4.1 Shower Development, Growth and Evolution

A VHE primary CR particle impinging on the Earth’s atmosphere interacts with the nuclei of the atmosphere molecules at a height of typically 20 - 25 km above sea level. While the CR itself does not survive, the secondary products of its interaction with the atmosphere can be detected by ground-based detectors. The absorption of the primary CR particles can be explained by means of their small interaction length compared to the atmospheric column density. The radiation length of photons, electrons and positrons in air is $X_0 = 36.66 \text{g/cm}^2$ [105] and the relevant absorption length for hadrons in air amounts to $\lambda \approx 90.0 \text{g/cm}^2$ [86, 105]. Together with the total atmospheric column density of about 1000 g/cm$^2$, this corresponds to a depth of about 27 radiation lengths for photons, electrons and positrons and a depth of about 11 absorption lengths for hadrons, respectively.

There are distinct differences in the development of $\gamma$-ray and hadron induced EAS:

- $\gamma$-ray induced EAS: the three relevant processes in the development of $\gamma$-ray induced EAS are pair production, Bremsstrahlung and photoproduction.

  * **Pair production:** in presence of a Coulomb field of an atmospheric nucleus, a $\gamma$-ray is transformed into an electron-positron pair ($\gamma \rightarrow e^+ + e^-$).

\[^1\]High-energy electrons predominantly lose energy in matter by Bremsstrahlung. $X_0$ is the mean distance over which a high-energy electron loses all but 1/e of its energy. The absorption length $\lambda$ is the characteristic length scale for hadron-induced ($p, \pi, \ldots$) cascades [105].
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- **Bremsstrahlung**: secondary charged particles can lose their energy by the interaction with the Coulomb field of an atmospheric nucleus or ion.

- **Photoproduction**: the photoproduction process produces hadronic final states, mostly pions ($\gamma + \text{nucleus} \rightarrow \text{hadrons}$).

Pair production typically occurs after the $\gamma$-ray has traversed one radiation length of atmosphere at an altitude of about 20-25 km. The mean free path for pair production $X_{\text{pp}}$ is related to the radiation length like $X_{\text{pp}} = \frac{9}{7}X_0$. The resulting electron-positron pair will share the energy of the primary $\gamma$-ray and will be emitted in forward direction, i.e. the initial $\gamma$-ray is replaced by two charged particles traveling almost in the same direction. Both the electron and positron predominantly lose their energy mostly by Bremsstrahlung. After having covered a distance of one radiation length $X_0$, the Bremsstrahlung photons may also pair produce and so on. If the average energy of the secondary particles in an EAS drops to a level where the radiation losses and losses due to ionization processes become equal, the EAS has reached its maximum. Below a certain energy, the so-called critical energy $E_C \approx 83$ MeV [85], electrons and positrons lose their energy more likely by ionization of air molecules. Below some MeV, photons lose their energy mainly due to the Compton scattering process, which becomes dominant over the pair production process. At this stage, the EAS dies out.

![Figure 4.1: An illustration of a $\gamma$-ray induced EAS.](image-url)

If the primary $\gamma$-ray interacts with an atmospheric nucleus through photoproduction, the initiated EAS cannot be distinguished from a hadron induced shower. Although the cross section for photoproduction increases with increasing energy, it is about 300 times smaller than the cross section for pair production [136]. The muon pair production process is negligible compared to the one for electron-positron pair production because the relevant cross section is comparatively small.

All processes mentioned above occur in the atmosphere accompanied by a rapidly increasing number of secondary electrons, positrons and $\gamma$-rays. The angle of emission in all these processes is proportional to the ratio $\frac{m_e}{E}$ (measured in radians), where $E$ denotes the electron energy and $m_e$ its rest mass. Thus, the resulting electromagnetic cascade will be tightly beamed around the direction of the initial $\gamma$-ray. Figure 4.1 illustrates the
development of a $\gamma$-ray induced EAS.

The number of electrons and positrons $N_e$ above the critical energy $E_C$ as a function of the atmospheric slant depth $X$ and the primary $\gamma$-ray energy $E$ is given by [102]:

$$N_e(t, E) = \frac{0.31}{\sqrt{\ln \left( \frac{E}{E_C} \right)}} e^{t(1-\frac{3}{2}\ln(s))},$$  \hspace{1cm} (4.1)

where $t$ denotes the slant depth in units of the radiation length $X_0$, i.e. $t = X/X_0$, and $s(t, E) = 3t/(t + 2\ln(E/E_C))$ the shower age, a dimensionless quantity.

The shower age $s$ describes the longitudinal evolution of the number of electrons and positrons $N_e$. As long as $0 < s < 1$, $N_e$ increases with $s$. At $s = 1$ the shower has reached its maximum, i.e. $dN_e/ds = 0$ and $N_e = N_{\text{max}}$. For $s > 1$, the number of electrons and positrons decreases with increasing $s$, i.e. $dN_e/ds < 0$, and the shower dies out. Depending on the primary $\gamma$-ray energy, this can be well before the shower reaches sea level.

The depth of the shower maximum depends only on the primary energy: $t_{\text{max}} = \ln \left( \frac{E}{E_C} \right) / X_0$.

Figure 4.2 shows the number of electrons and positrons above the critical energy $E_C$ as a function of the atmospheric depth $X$ for different primary energies and vertical impact on the Earth’s atmosphere. The location of the shower maxima is given by the intersection points of the curves describing the number of electrons and positrons and the straight gray line.

**Figure 4.2:** The number of electrons above the critical energy $E_C$ as a function of the atmospheric depth $X$ for different energies $E_0$ of the primary $\gamma$-ray. The straight gray line crosses the curves for $N_e(X, E_0)$, where they reach their maximum ($s = 1$). The altitude of the Roque de los Muchachos observatory in La Palma corresponds to an atmospheric slant depth of about 800 g/cm$^2$.

For increasing energies of the primary $\gamma$-ray, the shower maximum $X_{\text{max}} = \ln \left( \frac{E}{E_C} \right) / X_0$ is shifted to lower elevations. The shower maximum of an EAS initiated by a 10 TeV primary
4.1. SHOWER DEVELOPMENT, GROWTH AND EVOLUTION

The so-called NKG-formula describes the lateral development of the number of electrons and positrons in an EAS [103, 170]. According to this formula, the electron and positron density as a function of the distance $r$ from the shower axis is given by

$$
\rho_e(r, t, E) = \frac{\Gamma(4.5 - s)}{2\pi \Gamma(s) \Gamma(4.5 - 2s)} \frac{N_e(t, E)}{r_0^2} \left(\frac{r}{r_0}\right)^{s-2} \left(1 + \frac{r}{r_0}\right)^{s-4.5},
$$

where $r_0$ denotes the Molière radius, $\Gamma$ the Gamma function and $s$, $N_e$ are defined as before. The Molière radius depends on the height above sea level. At sea level $r_0$ is about 79 m.

- Hadron induced EAS: charged CRs, mostly protons, interact in the upper Earth atmosphere and initiate a cascade rather similar to that induced by $\gamma$-rays. But there are substantial differences in the shower development of hadron and $\gamma$-ray induced EAS. Interactions of high-energy protons or heavier nuclei with atmospheric molecules are associated with a large number of secondary particles, i.e. the average multiplicity of charged secondary particles is approximately given by $1.97 \cdot (E_{\text{lab}}/\text{GeV})^{0.25}$ [55], is significantly higher. While 90% of the secondary particles are pions, only 10% kaons and anti-protons are created. The most important difference compared to an electromagnetic shower is the high transverse momentum of the secondary particles in the order of 0.3 GeV/c [85], which is in first order independent of the energy of the primary hadron.

![Figure 4.3: An illustration of an EAS induced by a charged cosmic nucleus.](image)

Primary protons typically interact at lower altitudes than $\gamma$-rays, as the absorption length for protons of 1 TeV energy in air is about $\lambda_p(1 \text{ TeV}) \approx 90 \text{ g/cm}^2$ [86, 105]. As long as the energy of the secondary particles is greater than around 1 GeV, they interact again with the atmosphere and the hadron induced EAS evolves. For secondary energies below about 1 GeV, ionization processes become dominant and the EAS starts to die out.
Secondary pions decay into muons ($\pi^\pm \rightarrow \mu^\pm + \nu^\mu$), which subsequently decay into electrons ($\mu^\pm \rightarrow e^\pm + \nu^e$), whereas $\pi^0$ mesons immediately decay into photons before any hadronic interaction. Due to their short lifetime, decays are more likely than interactions. For example, $\pi^0$ mesons of 100 GeV energy have a flight path of about $2 \cdot 10^{-3}$ cm and their average interaction length in air is $\lambda_{\pi^0}(1 \text{ TeV}) \approx 10^7 \text{ g/cm}^2$ [86]. The decay photons of the $\pi^0$ mesons initiate electromagnetic sub-showers. Although a great proportion of the energy in a hadron induced cascade goes into $\pi^0$ mesons, the typical Cherenkov light yield in $\gamma$-ray induced EAS is two to three times higher than in hadron induced EAS if the primary hadron is of the same energy.

Muons and neutrinos from the decay of charged mesons are penetrating particles and thus able to reach the ground level. The relatively long lifetime of muons amounting to about $2.2 \cdot 10^{-6}$ s and their small interaction cross section enables many of them to reach the detector level without any interaction. Although muons and neutrinos remove some of the shower energy from the atmosphere, the decay of low-energy muons into electrons may transfer a fraction of the muon energy back into electromagnetic sub-showers. Figure 4.3 illustrates the development of a hadron induced EAS.

Hadron induced EAS appear to be broader and more scattered, as the scattering angles of nuclear interactions result in a lateral displacement much larger than that occurring in electromagnetic interactions. The secondary particles which can reach ground level as well as the larger fluctuations in the development of hadron induced EAS lead to increasing fluctuations in the Cherenkov light distribution on ground.

Moreover, since penetrating particles such as Cherenkov light emitting muons arrive slightly earlier, the time spread of the Cherenkov light pulse from hadron EAS induced is considerably longer than that from $\gamma$-ray induced EAS.

Lateral distribution, time spread and differences in the angular distribution of the Cherenkov light on ground may provide a basis to discriminate the weak $\gamma$ signal from a source under study against the hadronic background. The most effective approach to discriminate the $\gamma$ signal against the overwhelming background due to charged CRs is based on the differences in the angular distribution of $\gamma$-ray and hadron induced EAS.

$\gamma$-ray induced EAS may be indistinguishable from hadron induced EAS: depending on the orientation of the primary $\gamma$-ray trajectory with respect to the field lines of the Earth’s magnetic field, the lateral broadening of the shower due the deflection of the charged component in EAS can be significant (chapter 7). As the charged component in EAS is responsible for the emission of Cherenkov light, the Cherenkov light distribution from $\gamma$-ray induced EAS can be very similar to the one from background showers. Especially at low energies it might be important to consider the effect of the Earth’s magnetic field on the development of EAS.

Another background is due to cosmic electrons, because electrons induced EAS behave exactly like $\gamma$-ray induced EAS. Although their energy spectrum is very steep (spectral index of $\alpha_e \approx 3.3$ [214]), they represent a small, but virtually irreducible background for IACTs. Cosmic electrons give rise to EAS which are indistinguishable from $\gamma$-ray induced ones. They are isotropic and cannot be eliminated using traditional $\gamma$/hadron separation methods (section 6.3), but rather by means of an improved angular resolution [69]. Therefore, in extended $\gamma$-ray source searches and diffuse $\gamma$ flux estimations, cosmic electrons represent an irreducible background. For the MAGIC telescope (section 5), the raw rate of electrons triggers was estimated to be in the order of 2 Hz, which is a few percent of the hadronic contribution to the trigger rate [69]. Furthermore, since the threshold energy of an Imaging Air Cherenkov Telescope (IACT) rises with increasing ZA (section 4.3.1) and the cosmic electron spectrum falls off faster than that of the charged CRs or than those of most of the $\gamma$-ray sources, the electron background can be considered to be less significant at large ZA ($> 30^\circ$) [69].
4.2 Cherenkov Light Emission in Extended Air Showers

4.2.1 Generation of Cherenkov Light

Charged particles traversing a dielectric medium at a velocity greater than the velocity of light in that medium emit Cherenkov radiation [63, 84]. The Cherenkov radiation emitted from relativistic charged particles occurs over a wide range of wavelengths.

The threshold velocity $v$ for emission of Cherenkov radiation with angular frequency $\omega$ determined by the index of refraction of the dielectric medium $n(\omega)$, can be obtained from [121]

$$v > \frac{c}{\sqrt{\varepsilon(\omega)}} = \frac{c}{n(\omega)},$$

where $c$ denotes the speed of light in vacuum, $\varepsilon$ the dielectric constant, $\omega$ the angular frequency of the Cherenkov radiation and $n(\omega)$ the index of refraction of the dielectric medium.

Cherenkov radiation is emitted at an angle that depends on the refractive index of the medium, as well as the velocity $v$, and it is beamed in forward direction as shown in figure 4.4. At each point of the trajectory of a particle traveling at $v > c/n$, electromagnetic pulses in the form of spherical waves are radiated. In general, all these wavelets interfere destructively, but in the forward direction the wavefronts from each point of the particle trajectory will interfere constructively, according to the Huygens principle of wavelet reconstruction.

![Figure 4.4: Charged particles traversing a dielectric medium of index of refraction $n$ at a velocity $v$ greater than the velocity of light in that medium $c_n = \frac{c}{n}$ emit Cherenkov radiation (adopted from [105]).](image)

From figure 4.4 it is seen that the angle $\theta$, referred to as Cherenkov angle under which the Cherenkov radiation is emitted with respect to the direction of motion of the charged particle, is determined from the index of refraction $n$ and the velocity $v$ of the particle, according to

$$\cos \theta = \frac{1}{\beta \cdot n(\omega)},$$

where $\beta = v/c$. The maximum Cherenkov angle is given by $\beta \approx 1$, thus restricting the frequency range where Cherenkov light is emitted. The frequency range of the Cherenkov light is confined by the condition $n(\omega) > 1$.

Figure 4.5 illustrates the generation of Cherenkov radiation in a dielectric medium. A fast
charged particle traversing the medium induces small dipole elements along its trajectory and therefore local polarization of the medium in its immediate vicinity. In case of a slow moving particle \( v < c/n \), figure 4.5 (a)), the polarization is symmetrical around and along its trajectory, while the symmetry along the trajectory will not be preserved for a superluminal particle (figure 4.5 (b)). As a result, a dipole remains along the trajectory made up of small dipole elements each of which radiates an electromagnetic pulse. The superposition of these Cherenkov light pulses results in a Cherenkov light cone, whose opening angle is determined by the velocity of the charged particle.

Figure 4.5: A fast charged particle traversing a dielectric medium causes local polarization in its immediate vicinity. For a slow particle (a), the polarization is symmetrical around and along its trajectory. In case of a superluminal particle (b), the radial symmetry will be preserved, while the time-dependent dipole made up of small dipole elements cancels the symmetry along the trajectory. Each of the small variable dipole moments radiates an electromagnetic pulse and thus contribute to the resulting cone of Cherenkov light.

The energy per track length emitted by a particle of charge \( Ze \) is given by

\[
\frac{dE}{dh} = \frac{Z^2e^2}{4\pi\varepsilon_0c^2} \int_{n(\omega)\beta > 1} \left( 1 - \frac{1}{n(\omega)^2 \beta^2} \right) \omega d\omega, \tag{4.5}
\]

where \( e \) denotes the electron charge magnitude, \( \varepsilon_0 \) the permittivity of the vacuum and the integrand defines the differential frequency spectrum of the emitted Cherenkov light [124]. According to equation 4.3, the emission of Cherenkov light is only possible, if \( n(\omega)\beta > 1 \). Therefore, the emission of Cherenkov light in air is confined to the wavelengths of the visible and near visible range of the electromagnetic spectrum, where the condition \( n(\omega)\beta > 1 \) is fulfilled.

The threshold energy \( E_T \) for a charged particle of rest mass \( m_0 \) to emit Cherenkov light can be derived from equation 4.3:

\[
E \geq E_T = \frac{m_0c^2}{\sqrt{1 - \left( \frac{1}{n(\omega)} \right)^2}}. \tag{4.6}
\]
4.2.2 Cherenkov Light Production in Air

As the index of refraction of air, \( n(h) \), increases with decreasing height \( h \), the threshold energy for emission of Cherenkov radiation decreases with decreasing height. The threshold energy for electrons and positrons amounts to about 21 MeV at sea level and about 38 MeV at an altitude of about 10.4 km above sea level corresponding to the shower maximum of an EAS initiated by a 100 GeV primary \( \gamma \)-ray, i.e. \( X \approx 250 \text{ g/cm}^2 \) (figure 4.2). Due to their greater mass, muons have a much higher threshold of about 4.6 GeV at sea level and about 8 GeV at 10.4 km height. Furthermore, EAS contain orders of magnitudes more electrons and positrons than muons. Thus, the main contribution to the Cherenkov light yield within EAS is due to electrons and positrons.

Most of the Cherenkov light is generated at heights around the shower maximum, where the number of electrons and positrons reaches its maximum. At the height of the shower maximum, the threshold energy for Cherenkov light production has decreased compared to the one at high altitudes, where the primary particles impinges on the Earth’s atmosphere.

![Figure 4.6](image)

**Figure 4.6:** The radial spread of the Cherenkov light cone and Cherenkov angle as a function of the atmospheric slant depth \( X \) for \( \gamma \)-ray induced EAS as it is seen from the MAGIC telescope at 2200 m above sea level.

As the index of refraction of air is close to 1 at any height above sea level, charged particles must be highly relativistic, i.e. \( \beta \approx 1 \), to fulfill the condition imposed by equation 4.3. For \( \beta \approx 1 \), the Cherenkov angle in air can be obtained from equation 4.4:

\[
\theta(X) = \arccos \left( \frac{1}{n(X)} \right) \approx \sqrt{2(n(X) - 1)},
\]

since \( (n(X) - 1) \ll 1 \) [182]. Figure 4.6 shows the Cherenkov angle as a function of the atmospheric slant depth. The Cherenkov angle increases with decreasing atmospheric slant depth \( X \), as the index of refraction increases with decreasing altitude.

The relation between radial spread \( r(X) \), Cherenkov angle \( \theta \) and index of refraction \( n(X) \), is given by
\[ r(X) = h(X) \tan(\theta) = h(X) \tan \left( \arccos \left( \frac{1}{n(X)} \right) \right). \tag{4.8} \]

According to [182], the scale height \( h(X) \) above sea level for a given atmospheric slant depth \( X \) can be obtained from
\[
h(X) = \left( 6740 \text{ g/cm}^2 + 2.5 \cdot X \right) \ln \left( \frac{1030 \text{ g/cm}^2}{X} \right), \tag{4.9} \]

and the index of refraction, \( n(X) \), of air is
\[
n(X) = 1 + \eta(X) = 1 + 0.0002926 \cdot \frac{X}{1030 \text{ g/cm}^2} \cdot 273.2 \text{ K}. \tag{4.10} \]

The corresponding temperature at a given atmospheric slant depth \( X \) is calculated according to [182] from
\[
T(X) = (204 + 0.091 \cdot X \text{ g}^{-1} \text{cm}^2) \text{ K}. \tag{4.11} \]

Figure 4.6 shows the radius of the Cherenkov cone for a \( \gamma \)-ray induced EAS for a height of about 2200 m above sea level in case of vertical impact of the primary \( \gamma \)-ray on the Earth’s atmosphere. From the slope of the curve \( r(X) \), it can be seen that most of the Cherenkov light is emitted within a circle of about 120 m radius, while the main fraction of Cherenkov light is emitted at radii of around \( r \approx 60 - 120 \text{ m} \).

Although the Cherenkov light is emitted in a narrow cone, it has to be taken into account that the Cherenkov light distribution on ground is further broadened due to Coulomb scattering of the electrons and positrons in the EAS, i.e. the mean scattering angle of electrons and positrons increases with increasing shower age. The light pool on ground is composed of the superposition of the Cherenkov light cones from all electrons and positrons of which all suffer from multiple scattering and deflection by the Earth’s magnetic field.

The number of emitted Cherenkov photons per atmospheric depth \( X \) in the wavelength range \( \lambda_1 \) to \( \lambda_2 > \lambda_1 \) can be obtained from equation 4.5:
\[
\frac{dN_{\text{ph}}}{dX} = \frac{\lambda_2}{\lambda_1} \int_{\lambda_1}^{\lambda_2} \frac{1}{\hbar \omega} \left( \frac{d^2E}{dX d\lambda} \right) d\lambda = \frac{1}{\rho_{\text{air}}(h)} \cdot \frac{2\pi\alpha}{\lambda_1} \int_{\lambda_1}^{\lambda_2} \left( 1 - \frac{1}{(n(X, \lambda)\beta)^2} \right) \frac{1}{\lambda^2} d\lambda, \tag{4.12} \]
\[
\frac{dE}{dX} = \frac{dE}{dh} \frac{dh}{dX} = -\frac{1}{\rho_{\text{air}}(h)} \frac{dE}{dh}. \tag{4.13} \]

Therein, \( \alpha = \frac{e^2}{4\pi\varepsilon_0 h c} \) denotes the fine-structure constant. According to equation 4.12, the number of emitted photons per unit depth is inverse proportional to the wavelength, i.e. most of the photons are emitted at short wavelengths, in the UV wavelength range. Although the Cherenkov photon density decreases very fast, their wavelengths extend up to the optical range. Furthermore, the amount of Cherenkov light emitted is sensitive to the index of refractive \( n(X(h), \lambda) \) and density of the air \( \rho_{\text{air}}(h) \) at any altitude.

Equation 4.12 allows to estimate the number of produced Cherenkov photons per atmospheric
4.2. CHERENKOV LIGHT EMISSION IN EXTENDED AIR SHOWERS

depth $X$. The quantity $\eta(X)$ (equation 4.10) changes by only 5% over the wavelength range 300-600 nm [38], i.e. $n(X, \lambda) \approx n(X)$. A wavelength range of 300-600 nm corresponds to the range typically covered by photomultipliers. At wavelengths below $\sim 300$ nm, Cherenkov light is predominantly absorbed by ozone [38] (next section). According to equation 4.9, a scale height of $h_0 = 2200$ m above sea level corresponds to an atmospheric depth of $X \approx 800$ g/cm$^2$. Equation 4.10 yields $\eta(800 \text{ g/cm}^2) \approx 2.2 \cdot 10^{-4}$, and the corresponding density of air is about $\rho_{\text{air}}(2200 \text{ m}) \approx 1.0 \cdot 10^{-3}$ g/cm$^3$. Together with equation 4.12, the approximation $n(X, \lambda) \approx n(X)$ yields

$$
\frac{dN_{\text{ph}}}{dX} \approx 4\pi \alpha \frac{\eta}{\rho_{\text{air}}} \left( \frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \approx 336 \left( \text{g/cm}^2 \right)^{-1}, \quad (\lambda_1 = 300 \text{ nm}, \ \lambda_2 = 600 \text{ nm}).
$$

(4.14)

Thus, every electron and positron emits in the order of $10^4$ Cherenkov photons per radiation length in the wavelength range between 300 nm and 600 nm [135].

4.2.3 Attenuation of Cherenkov Light

The main part of the Cherenkov light of GeV - TeV $\gamma$-ray initiated EAS is generated in the upper atmosphere, at some 10 km (figure 4.2). On their way down to the ground, the Cherenkov photon flux is attenuated through interactions with the molecules of the Earth’s atmosphere.

Figure 4.7: The differential Cherenkov photon spectrum in arbitrary units. The Cherenkov photons produced at 10 km a.s.l. suffer from absorption and scattering on their way down through the atmosphere, and the initial spectrum appears to be clearly attenuated at 2.2 km a.s.l., especially at smaller wavelengths. Wavelengths below some 300 nm are completely suppressed.

Figure 4.7 shows the differential spectrum of Cherenkov photons before and after extinction at an altitude of 10 km and 2.2 km a.s.l., respectively. The most important absorbers and scattering processes are taken into account. The transmission coefficient was taken from [38]. Together with the approximation $n(X, \lambda) \approx n(X)$ (the index of refraction is assumed to be independent of the wavelength) and $\beta \approx 1$ (highly relativistic shower particles), the differential Cherenkov photon density can be obtained from equation 4.12. The most dominant absorption processes are the following:
• Below wavelengths of around 340 nm, the absorption of Cherenkov photons due to ozone is very important. The relevant process is $\gamma + O_3 \rightarrow O_2 + O$. Even though the highest concentration of ozone occurs at around 20 km altitude [38], the low concentration near ground is sufficient for strong extinction of Cherenkov photons. Below wavelengths of around 290 nm, almost all Cherenkov photons are absorbed due to interactions with ozone. The $O_2$ and $N_2$ absorption is unimportant for IACTs as the photomultipliers typically used in these experiments are insensitive below 290 nm.

• A large fraction of the Cherenkov light in the wavelength range between some 300 nm and 500 nm is lost due to molecular scattering (Rayleigh scattering). As the typical scattering angle of Rayleigh scattering is large compared to the Cherenkov angle, the scattered light is lost for the Cherenkov detector. Rayleigh scattering is relevant to particles being significantly smaller compared to the photon wavelength $\lambda$. The cross section for Rayleigh scattering is proportional to $\lambda^{-4}$.

• The scattering due to aerosol particles in the atmosphere, described by the Mie scattering theory, has the smallest impact on the overall extinction at high altitudes ($> 1500$ m). The Mie scattering theory describes the scattering of electromagnetic waves on a spherical molecule whose diameter is comparable to the wavelength of the light. As in case of Rayleigh scattering, the Mie-scattered Cherenkov light is lost for a Cherenkov detector in consequence of the large scattering angles. The cross section for Mie scattering scales like $\lambda^{-a}$, with $1 \lesssim a \lesssim 1.5$ [185].

While aerosol (Mie scattering) and ozone absorption are site-dependent and variable, both molecular (Rayleigh) scattering and $O_3$ absorption are predictable and almost constant at any high altitude site [38].

According to equation 4.1, the height of the shower maximum in EAS increases with decreasing primary $\gamma$-ray energy, while the number of particles that emit Cherenkov light gets smaller (figure 4.2). Because of this, Cherenkov photons have to cover a greater distance to ground and the probability to suffer from the absorption processes mentioned beforehand gets larger. Therefore, IACTs aiming at the detection of sub-TeV EAS will perform better at higher altitudes, as the threshold energy will be higher at low altitudes, and at the same time the sensitivity for the $\gamma$-ray flux is expected to be deteriorated.

### 4.2.4 Detection of Cherenkov Light

Figure 4.8 shows the typical Cherenkov light distribution at 2200 m altitude from a MC simulated $\gamma$-ray induced EAS of 100 GeV energy (a) and the one from a MC simulated proton induced EAS of 400 GeV energy (b). Both particles vertically impinge onto the Earth’s atmosphere. The apparent differences of both Cherenkov light distributions are due to the intrinsic differences of the shower development in $\gamma$-ray and hadron induced EAS, as described in section 4.1. The Cherenkov light distribution of the $\gamma$-ray initiated EAS appears to be rather uniformly and symmetric around the center while the one from the proton initiated EAS appears to be diffuse, which is due to the large transverse momentum of the secondary particles and the large number of electromagnetic sub-showers that may contribute to the overall Cherenkov light yield.

As visible from figure 4.8 and elucidated in section 4.2.2, the radius of the Cherenkov light pool on ground from $\gamma$-ray induced EAS is in the order of some 120 m. Within this radius, the light pool is rather uniformly illuminated. As long as a Cherenkov detector is located somewhere in the Cherenkov light pool, it can detect the event. Therefore, a single Cherenkov detector can detect Cherenkov light from EAS of up to $\sim 120$ m impact distance. As a result, such a detector can have an effective collection area in the order of $10^4$ m$^2$, which is much higher than for typical satellite-born instruments.
4.3 Principle of the Imaging Air Cherenkov Technique

The Imaging Air Cherenkov Technique allows to identify $\gamma$-ray induced EAS that develop in the atmosphere and to separate them from the much more abundant hadronic cascades. The separation of $\gamma$-ray induced EAS is based on the different Cherenkov light pattern on ground of $\gamma$-ray induced and hadron induced cascades.

An Imaging Air Cherenkov Telescope essentially consists of three components: a (parabolic) reflector of large aperture $O(10\,\text{m})$, a wide FOV $O(4^\circ)$ camera composed of a matrix of photo-multipliers recording the Cherenkov light collected at the focal plane of the mirror, and a fast pulse counting electronics system.
Figure 4.9: Distribution of Cherenkov light in EAS (adopted from [112]). The red-hashed area indicates the region of maximum Cherenkov light emission for γ-ray showers. Around 25% of the total amount of Cherenkov light is emitted in the region below and above this area. The region of maximum Cherenkov light emission is centered at a height of around 8 km a.s.l. for primary γ-rays of around 1 TeV. 50% of the total Cherenkov light is radially emitted within this area. For proton induced EAS, the corresponding area is indicated as a green trapezoid. Small secondary showers can make the intensity distribution of Cherenkov photons on ground non-uniform.

Figure 4.10 illustrates the principle of an Imaging Air Cherenkov Telescope (IACT). The big reflector of the telescope collects a certain amount of the Cherenkov light from an EAS, if it is physically located somewhere in the Cherenkov light pool on ground. The Cherenkov light is then focused onto the photomultiplier camera located on the optical axis of the telescope, at the focal plane of the reflector. The photomultiplier camera converts the Cherenkov light into electrical signals which are then processed by the pulse counting electronics. The recorded images are analyzed off-line. Since the Cherenkov light from an EAS arrives at the camera as a short burst of a few nanoseconds, it is possible to detect the light clearly without ambiguity against the Poisson fluctuation dominated night sky background (NSB). The NSB is composed of several components, such as star light, fluorescent light from the ionosphere, moonlight, airglow light and light from terrestrial sources. Because the Cherenkov image of every EAS has to be captured in real time, the integration time of the electronics has to lie between some 5 ns and 20 ns, which also reduces the impact of the NSB.
4.3. PRINCIPLE OF THE IMAGING AIR CHERENKOV TECHNIQUE

Figure 4.10: Illustration of an Imaging Air Cherenkov Telescope (IACT). A VHE $\gamma$-ray interacts with nuclei of the Earth’s atmosphere and generates an EAS. Charged particles in the EAS emit Cherenkov light if their velocities exceed the speed of light in air. The reflector of the Cherenkov telescope collects a certain amount of the Cherenkov light and reflects it onto the camera. The camera, composed of several pixels, finally converts the Cherenkov light into electrical signals in a way that the information on the geometrical and temporal structure of the EAS is preserved.

Due to the height dependence of the Cherenkov angle (section 4.2.2), there is a direct relation between the height of the emission and the light distribution in the camera plane. In case of cascades oriented parallel to the telescope optical axis, the Cherenkov light emitted at the upper part (dark blue region of the EAS shown in figure 4.10) is mapped close to the camera center, while Cherenkov light from the lower parts of the EAS (light blue region of the EAS) is mapped to the outer part of the camera. Thus, the imaging technique provides the possibility to take both space and time resolved pictures from EAS if a certain segmentation of the camera is given. An adequate segmentation allows for an efficient identification of $\gamma$-ray induced EAS based on the topological differences between $\gamma$-ray and hadron induced images in the camera plane. Together with an appropriate (fast) processing of the photomultiplier signals, the identification of $\gamma$-ray
induced EAS based on the topological differences can be enhanced using the differences in the temporal structure of the Cherenkov light flashes, as mentioned beforehand.

For $\gamma$-rays originating from a point source located at the center of the telescope FOV, the shower axes are aligned parallel with the telescope optical axis, and the recorded image of the Cherenkov light in the camera will be oriented so as to point radially to its center. All $\gamma$-ray induced EAS whose core impact distances are in the order of some 100 m will be recorded by the telescope. Their images will appear to be more elliptical in shape than those with smaller impact distances and at the same time strongly oriented towards the camera center. As hadron cascades arrive isotropically distributed within the telescope FOV, without any preferred orientation with respect to the telescope optical axis, their image orientations appear to be isotropically distributed within the camera. The major axes of their less elliptical-shaped images exhibit no preferred radial pointing direction like images from $\gamma$-ray induced EAS originating from a source at the center of the telescope FOV. In addition to that, hadronic shower images are mostly rather broad and may consist of several smaller fragments distributed over a large section of the camera. Thus, based on the differences in shape and orientation of the shower images, a statistical distinction between $\gamma$-ray induced and hadronic EAS is feasible.

Today’s IACTs represent complicated instruments. As well as in other fields of research, considerations of costs and feasibility play a decisive role in the design and realization of an IACT. In addition, environmental conditions often impose especially rigorous requirements on the design and construction of the main telescope sub-systems, like mounting system, reflector assembly and imaging camera.

4.3.1 The Features of an Imaging Air Cherenkov Telescope

This section is dedicated to a short discussion of the key elements, features and drawbacks that make up an IACT. The following list itemizes the most important hardware parameters of an IACT.

- **Reflector:** the mirror design is of great importance for the performance of an IACT, as the threshold energy is directly related to its physical mirror size $A_M$. The larger the mirror, the more Cherenkov photons are collected, which in turn results in a larger photon density in the focal plane of the mirror and therefore larger signals in the camera segments. As a result, the threshold energy of the instrument is pushed downwards to lower energies. The threshold energy $E_T$ can be expressed in terms of the flux sensitivity (equation B.5) and the mirror area $A_M$:

$$
E_T \sim S(ZA, E, t)^{-1} A_M^{-\frac{1}{2}} \sim E^{-\left(\frac{\alpha_{CR}}{2} - \alpha_{\gamma}\right) \frac{\sqrt{A_{CR}(ZA, E)}}{A_{\gamma}(ZA, E)} \frac{1}{\sqrt{LDE}} A_M^{-\frac{1}{2}}}, 
$$

(4.15)

where $A_{CR}(ZA, E)$ denotes the effective collection area for CRs and $A_{\gamma}(ZA, E)$ the one for $\gamma$-rays. $\alpha_{CR} \approx 1.7$ denotes the spectral index of the integral energy spectrum of CRs and $\alpha_{\gamma} \approx 1 \ldots 3$ the one of a typical VHE $\gamma$-ray source at sea level. The effective collection areas for CRs and $\gamma$-rays not only depend on the primary energy $E$, but also on the ZA. Although the ZA-dependency of the effective collection areas may be different for CRs and $\gamma$-rays, their magnitudes can vary by more than one order of magnitude over a ZA range of $60^\circ$ (measured with respect to zenith). The so-called light detection efficiency (LDE) depends not only on the mirror reflectivity $R$ ($R < 1$), but also on the hardware parameters of the photomultiplier camera (next item). Today’s IACTs comprise mirror diameters of some 10 m, exclusively constructed in a tesselated design, whereby small, usually spherical shaped mirror elements are mounted on a single structure and focused to a common focal plane. The shape of the reflector defines
whether a distant point source appears as a small spot in the focal plane over the entire FOV, as it is the case for a spherical mirror, or if the time structure of the Cherenkov light from an EAS is preserved, which is a characteristic feature of a parabolic mirror. At diameters greater than $\sim 15$ m, parabolically shaped mirrors are preferred.

- **Camera:** the careful design of the imaging camera in the focal plane of the mirror is essential for the imaging air Cherenkov technique. On the one hand, the camera is required to have a certain segmentation in order to capture high resolution images of the Cherenkov light distribution on ground, on the other hand, the number of pixels is limited due to cost considerations and dead area losses.

Each camera segment, called pixel, usually consists of a high-sensitive photomultiplier tube. Quantum efficiency (QE) and photoelectron (Phe) collection efficiency (CE), both of which are characteristic features of a photomultiplier, have an impact on the threshold energy of an IACT:

$$E_T \sim \frac{1}{\sqrt{\text{LDE}}} = (R \cdot \text{QE} \cdot \text{CE})^{-\frac{1}{2}},$$ \hspace{1cm} (4.16)

where the quantity LDE denotes the light detection efficiency and $R$ the reflectivity of the mirror. QE and CE respectively are the quantum efficiency of the photocathode and the photon collection efficiency (first dynode) of the photomultiplier tubes.

Today’s IACTs are exclusively equipped with photomultiplier tubes, whose mean QEs are presently limited to some 20% in the wavelength range relevant for Cerenkov detectors (300 nm to 650 nm). Since the threshold energy is directly related to the quantum efficiency of the photon detectors of which the camera is made up of, it is important to employ photon detectors with highest sensitivity, especially for blue light. There is a number of promising options for high-granularity and high-sensitivity photon detection currently under development and partially already commercially available. Geiger mode avalanche Photodiodes (APDs) as well as Hybrid Photodiodes (HPDs) represent most promising options for the replacement of the classical photomultiplier tube. So far, the application of such high-sensitivity photon detection devices has not yet been tried, mainly because of cost considerations.

A certain area of the camera, centered to its center, is associated with the trigger system of an IACT. The size of the trigger area also influences the effective collection area for CRs and $\gamma$-rays.

- **Readout electronics:** the readout chain of an IACT typically comprises a large number of channels, each of which is associated with a camera pixel read out by preferably low-noise electronics with large dynamic range and large bandwidth. Since not only the absolute charge of the individual camera pixels is important for the imaging of the Cherenkov light distribution on ground, but also the time information of the fast analog signals from the photomultiplier tubes is essential, a fast digitization is required. Therefore, the electronic readout systems of today’s IACTs are often realized by fast FADC systems.

It is noteworthy that the threshold energy $E_T$ of an IACT also depends on the ZA under which observations are carried out, as the distance to the shower maximum increases with increasing ZA. The ZA-dependency of the threshold energy can be approximately expressed by:

$$d(ZA) \sim \cos^{-1}(ZA).$$

According to [147], the energy emitted as Cherenkov light is linearly related to the energy loss due to ionization processes, i.e. $\frac{dE}{dx} \approx \text{const.} \Rightarrow E \sim d(ZA)$. Thus, the observed $\gamma$-ray flux at sea level behaves like $\Phi_\gamma \sim \cos^{-\alpha_{\gamma}}(ZA)$ and the one from CRs as $\Phi_{CR} \sim \cos^{-\alpha_{CR}}(ZA)$. The relation 4.17 between threshold energy $E_T$ and ZA follows from equation 4.15. However, it has to be kept in mind that the absorption of Cherenkov light by the atmosphere was not taken into account. For a given energy, the distance to the shower maximum scales like $\cos^{-1}(ZA)$. 

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\(^{1}\)The thickness of the atmosphere varies like $d(ZA) \sim \cos^{-1}(ZA)$. According to [147], the energy emitted as Cherenkov light is linearly related to the energy loss due to ionization processes, i.e. $\frac{dE}{dx} \approx \text{const.} \Rightarrow E \sim d(ZA)$. Thus, the observed $\gamma$-ray flux at sea level behaves like $\Phi_\gamma \sim \cos^{-\alpha_{\gamma}}(ZA)$ and the one from CRs as $\Phi_{CR} \sim \cos^{-\alpha_{CR}}(ZA)$. The relation 4.17 between threshold energy $E_T$ and ZA follows from equation 4.15. However, it has to be kept in mind that the absorption of Cherenkov light by the atmosphere was not taken into account. For a given energy, the distance to the shower maximum scales like $\cos^{-1}(ZA)$. 

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\[ E_T \sim \cos(\frac{\alpha_{\text{CR}}}{2} - \alpha_{\gamma})(ZA). \] (4.17)

Due to the large fluctuation in the development of EAS, the threshold energy of an IACT is not sharply defined. A suggestive definition is commonly made in terms of the trigger rate \( R(E) \): the threshold energy is defined as the maximum of the differential trigger rate for a certain energy spectrum (e.g. Crab-like), i.e.

\[ \frac{dR(E)}{dE} \bigg|_{E=E_T} = 0. \] (4.18)

The energy \( E \) at which the condition of equation 4.18 is fulfilled heavily depends on the hardware parameters mentioned beforehand.

### 4.3.1.1 Collection Area

The effective aperture of an IACT extends to \( \sim 240 \text{ m} \) diameter, which is related to the fact that the Cherenkov light of EAS is distributed over a light pool of more than 240 m diameter. Thus, the effective collection area is \( \mathcal{O}(10^4 \text{ m}^2) \), which is far in excess of typical collection areas of space-born instruments where the sensitive area is mainly determined by the dimensions of the detector. A large collection area is essential in the VHE regime, as the cosmic \( \gamma \)-ray fluxes are low.

The effective collection area of an IACT depends both onZA and on the energy of \( \gamma \)-rays and CR particles, respectively. The ZA-dependency of the effective collection area can be expressed by

\[ A_{\text{Eff.}}(ZA) = A_{\text{Eff.}}(0) \cos^{-1}(ZA), \] (4.19)

i.e. the effective collection area increases with increasing ZA. Figure 8.28 (b) shows the effective collection area for large ZAs of around 60°.

### 4.3.1.2 Energy Resolution

As elucidated in section 4.1, over a wide range of energies, the number of secondary particles in an EAS at the shower maximum is proportional to the energy of the primary \( \gamma \)-ray. Although the proportionality between primary \( \gamma \)-ray energy and photon density on ground is partially disturbed, since the height of the shower maximum varies with energy and the Cherenkov light is attenuated, the Cherenkov photon density on ground inside the \( \sim 240 \text{ m} \) diameter is a good measure of the primary energy.

While stand-alone IACTs can only achieve about 20-25% energy resolution, arrays of parallel detectors taking independently pictures of each shower can achieve up to 10-15% energy resolution [211]. The main uncertainty in the determination of the energy is due to the varying distance to the core of an EAS.

### 4.3.1.3 \( \gamma \)-Ray Angular Resolution

IACTs exhibit a reasonable angular resolution, which is related to the nature of the electromagnetic interactions taking place in EAS. The Cherenkov angle of Cherenkov light due to secondary particles is small (\( \mathcal{O}(10^{-3}) \) rad), i.e. the trace of the core of the EAS is very close to the extended trajectory of the primary \( \gamma \)-ray. As the Cherenkov angle increases with increasing slant depth \( X \) and therefore decreases with decreasing primary energy, the angular resolution of an IACT depends on the energy range taken into consideration. In addition, at lower energies,
Coulomb scattering of the secondary electrons becomes dominant. The angular resolution significantly degrades towards lower energies, since Coulomb scattering involves greater scattering angles [211].

The angular resolution of an IACT is typically expressed in terms of the so-called point spread function (PSF). Generally, one has to differentiate between the optical PSF, or optical angular resolution, and the γ-ray angular resolution. The γ-ray angular resolution of an IACT is defined as the intensity distribution of Cherenkov photons in the focal plane of the mirror, generated by a point-like source at infinity. If the intensity distribution can be approximated by a bidimensional symmetric Gaussian distribution, the standard deviation of the Gaussian distribution is referred to as γ-ray angular resolution of the IACT [70]. The γ-ray angular resolution depends not only on the optical PSF, but also on fluctuations in the development of EAS, on the pixel size of the imaging camera and on the reconstruction method used to determine the position of a γ-ray source in the FOV. The typical angular resolution of today’s IACTs is $O(0.1^\circ)$.

To estimate the γ-ray angular resolution, MC simulations are necessary. Instead, the optical PSF can be obtained either from the analysis of the light distribution due to stars in the FOV or by means of muon shower images [157]. A Muon, if its trajectory is parallel to the optical axis of the telescope and if its trajectory crosses the physical area of the mirror, can generate ring-shaped images [82]. The width of these Muon-like images is related to the optical PSF. The term PSF is used throughout this work as a synonym for the γ-ray angular resolution.

The PSF is not necessarily constant over the entire FOV of an IACT. A spherical-shaped mirror is superior to parabolic reflectors for off-axis focusing, since the on-axis PSF is maintained over a large range of the FOV. In case of off-axis observations with a parabolic mirror light from different heights is focused at slightly different planes, none of them corresponds to a single focal plane. As a result, the image may appear blurred. The deterioration of the image finally limits the effective FOV of an IACT that comprises a parabolic mirror. In case the isochronicity of the Cherenkov light front is to be preserved and thus potentially providing the possibility to enhance the γ/hadron separation power based on the arrival time differences in γ-ray induced and hadron induced EAS, a spherical-shaped mirror is disadvantageous.

### 4.3.1.4 Advantages and Drawbacks of IACTs

There are many advantages of IACTs over other types of instruments, which are all mentioned in the preceding sections. The most important assets are:

- Compared to fluorescence light, the Cherenkov light flashes are strongly beamed and thus much more intense. Because the Cherenkov light moves nearly parallel to the shower axis, the light flashes are very short $O(1\text{ ns})$. Both attributes help to reduce the threshold energy and enhance the signal to background ratio.

- IACTs provide a low threshold energy compared to other ground-based detectors. For instance, scintillator detector arrays have significantly higher threshold energies, as they require the secondary particles from cosmic cascades to reach the ground level.

- The Cherenkov light pool from EAS originates from all heights of the cascade, thus containing more information than data from the detection of shower tail particles, which in turn can enhance the ability to efficiently discriminate the background.

---

1Air exhibits a property called luminescence. Luminescent materials, when exposed to certain forms of radiation, for example γ-rays, absorb and reemit the energy in the form of visible light. The process is called fluorescence, if the reemission occurs $O(10^{-8}\text{ s})$ after absorption [142]. For particles exceeding $\sim 10^{17}\text{ eV}$ the fluorescence light of nitrogen is sufficient intense to be recorded at sea level in presence of the diffuse background starlight. The disadvantage of the fluorescence technique is the rather poor duty cycle. Fluorescent detectors can only be operated during cloudless moonless nights.
• IACTs have a higher sensitivity for EAS than scintillator detector arrays because the Cherenkov photon density is typically orders of magnitudes greater than the density of secondary shower particles at ground level.

• IACTs can exploit the possibility to discriminate hadronic background using the arrival time information of Cherenkov photons, because the spread of arrival times is smaller compared to the one from secondary shower particles.

• A small background reduction occurs already at trigger level, as γ-ray induced EAS produce significantly more Cherenkov light than hadrons of the same energy.

The drawbacks of the imaging air Cherenkov technique are:

• IACTs provide a limited observation time as they can observe only during night in the absence of the sun, which reduces the duty cycle compared to scintillator detector arrays. The best observing conditions are given during clear moonless nights, which further reduces the available observation time.

• Worse atmospheric conditions may affect the imaging air Cherenkov technique. The atmosphere is an uncontrollable component of IACTs, as it varies with temperature, pressure and humidity, which can significantly change the characteristics of an IACT. The scattering and absorption of Cherenkov light results in a variable extinction, which in turn affects the observable light distribution on ground. Both, scattering and absorption processes depend on the height. To some extent, the monitoring of the atmospheric parameters may help to account for temporal variations of the atmospheric conditions.

• As the typical FOV of IACTs is $O(4^\circ)$, stand-alone instruments are rather qualified for selective observations but not suited for full sky surveys. An observational network, made up of satellite-born experiments, may provide guidance to change the source under study at short notice.

4.3.1.5 IACT Arrays

Compared to stand-alone IACTs, systems of two or more IACTs provide a number of enhancements, as a potential γ-ray source, respectively their γ-ray induced showers are simultaneously observed by a number of individual IACTs located in the Cherenkov pool of a particular shower. The typical separation between the individual IACTs is in the order of the lateral spread of the Cherenkov light distribution on ground, i.e. $O(100 \text{ m})$. Thus, every IACT of an array of IACTs provides an independent image of each shower, which improves the background rejection capability. Furthermore, improved angular and energy resolution as well as sensitivity improvements are implied.

The Armenian-German-Spanish collaboration, High Energy Gamma-Ray Astronomy (HEGRA), first operated an array of five small telescopes located at the Roque de los Muchachos observatory (ORM) on the Canary Island of La Palma (2200 m a.s.l.) [132].

The numerous improvements of an array of IACTs can be summarized as follows:

• Improved flux sensitivity.

• The threshold energies and sensitivity at low energies may be improved as the γ/hadron separation will be improved.

• Improved energy resolution of better than 20% over a wide range of energies.

• Significantly better angular resolution than stand-alone IACTs: $O(0.05^\circ)$ at 1 TeV for individual γ-rays [26]. The source location capability is expected to be even better.
• Unambiguous location of the origin, i.e. source of the $\gamma$-rays.

A drawback of an array of IACTs are the incremental costs that are associated to its building.
Chapter 5

The MAGIC Telescope

The MAGIC Major Atmospheric Gamma Imaging Cherenkov Telescope which was proposed in 1995, designed and constructed between 1999 and 2001, is currently the largest Imaging Atmospheric Cherenkov Telescope (IACT). The telescope is designed to have the lowest energy threshold so far. The currently achieved analysis threshold for general studies is $\sim 80$ GeV and about 60 GeV for pulsar studies, both at zenith-pointing orientation. MAGIC is located on the Canary Island of La Palma (28.8° N, 17.9° W) at the Roque de los Muchachos observatory (ORM), 2200 m above sea level (figure 5.1).

![MAGIC Telescope](image)

**Figure 5.1:** The MAGIC Telescope on the Canary Island La Palma.

Currently, there exists a number of new generation IACT projects worldwide for VHE $\gamma$-ray astronomy to close the energy gap between 10 GeV and 200 GeV [28]. To improve the sensitivity of $\gamma$-ray detection and to lower the energy threshold, most of the other new generation IACTs use stereoscopic systems of smaller telescopes than MAGIC. Figure 5.2 shows the new generation high-sensitivity IACTs.

- **VERITAS:** USA & England. 4 telescopes, 1275 m a.s.l., 12 m diameter, 80 GeV energy threshold, Montosa Canyon, Arizona (USA) [114, 212].
• MAGIC: Germany, Italy, Spain, Switzerland, Poland, Finland, Armenia, USA. 1 (2) telescope(s), 2200 m a.s.l., 17 m diameter, \( \sim 60 \) GeV energy threshold, Roque de los Muchachos observatory, Canary Islands (Spain) [28].

• H.E.S.S.: Germany, France, England, Ireland, Poland, Czech Republic, Armenia, Australia, Namibia, South Africa. 4 telescopes, 1800 m a.s.l., 12 m diameter, 100 GeV energy threshold, Windhoek (Namibia) [131].

• CANGAROO III: Australia & Japan. 4 telescopes, 165 m a.s.l., 10 m diameter, 100 GeV energy threshold, Woomera (Australia) [165].

It must be emphasized that all threshold energies of the IACTs mentioned above correspond to observations at zenith-pointing orientation. The so-called “analysis threshold” is normally higher, as it depends on the performance of the \( \gamma \)/hadron separation method used to extract the \( \gamma \) signal. Moreover, observations are usually carried out at higher ZAs.

![Figure 5.2: Locations of the new generation IACTs being currently in operation. Altogether, these state-of-the-art instruments cover both the northern and southern hemisphere with high sensitivity.](image-url)

## 5.1 The Physics Case of MAGIC

In this section, some questions in astrophysics and cosmology as well as problems in fundamental physics that MAGIC can help to clarify are briefly itemized. A more detailed annotation of the physics program of the MAGIC telescope can be found elsewhere [9, 28].

• SNRs and plerions: the systematic study of potential galactic \( \gamma \)-ray emitters such as SNRs and plerions, x-ray binaries and unidentified EGRET sources may help to shed light on the main sources for CRs up to energies of about \( 10^{15} \) eV. MAGIC observations in this energy regime may help to discriminate also between the various acceleration mechanisms assumed to be responsible for the production of VHE \( \gamma \)-rays.

• Pulsars: the search for pulsed VHE \( \gamma \)-ray emission from pulsars is one of the prime design goals of MAGIC. As all known pulsars have cutoff energies of their pulsed emission in the few-GeV energy range and since MAGIC provides the lowest threshold energy for the detection of VHE \( \gamma \)-rays among all other new generation IACTs currently in operation, it is best suited for the search of pulsed emission in VHE \( \gamma \)-rays.
• Measurement of the $\gamma$-horizon as a function of the $\gamma$-ray energy (Fazio-Stecker relation [81]): VHE $\gamma$-rays from distant sources interact independently of the acceleration mechanism with low-energy photons from the extragalactic background light (EBL). The EBL is to be considered as a diffuse, isotropic, electromagnetic radiation field evolving with cosmic time. It is in part due to starlight from the first generation of stars and therefore provides information on the phase of early galaxy formation. VHE $\gamma$-rays can produce electron-positron pairs ($\gamma_{\text{VHE}} + \gamma_{\text{IR}} \rightarrow e^+ + e^-$) and thereby disappear. The absorption probability due to electron-positron pair production increases with increasing distance (measured in redshift $z$) and energy, hence defines a maximum observable energy dependent redshift $z_{\text{hor}}(E)$. The relation $z_{\text{hor}}(E)$ describes the so-called $\gamma$-ray horizon, also referred to as Fazio-Stecker relation. As current models for the EBL include substantial uncertainties [123], the optical depth for VHE $\gamma$-rays exhibits large variations depending on the EBL scenario. The measurement of the $\gamma$-rays of some 50 GeV may allow to set stringent limits on the EBL intensity.

• AGN population studies: since only AGN below a certain redshift $z_{\text{hor}}(E)$ are accessible to observations, the low threshold energy possibly enables MAGIC to perform AGN population studies over a much larger redshift range than past instruments. Such studies are needed to understand the VHE $\gamma$-ray emission that occurs in jets of AGN, but also to characterize the EBL, as it may be possible to determine if $\gamma$-rays are absorbed only externally or internally close to their origin. As $\gamma$ astronomy studies processes very close to the BH inside AGN, AGN studies by means of VHE $\gamma$-rays enables us to learn more about the physics processes present in the vicinity of BHs. A reasonably complete understanding of these objects can only be reached by multi-wavelength observations. The Tuorla Observatory, a member of the MAGIC collaboration, is running a Blazar monitoring program which regularly carries out simultaneous observations in the optical wavelength range [46].

• GRBs: due to its short reposition time and its high sensitivity at low energies MAGIC is currently the only IACT suited for GRB observations. More than 8000 triggered GRB events have been recorded by the Burst And Transient Source Experiment (BATSE) [33] during its 9-year mission on board the CGRO [57]. To date, the origin of GRBs is still unclear. Although GRBs have not been detected at VHE $\gamma$-rays yet MAGIC may nevertheless help to uncover the GRB phenomenon.

• Quantum gravity (QG): several models of QG predict an energy-dependent velocity of electromagnetic waves, i.e. $\gamma$-rays of different energy simultaneously produced in a certain source should arrive on Earth at different times [141]. The search for such effects, using time delays as a function of the $\gamma$-ray energy, in a large number of sources may allow to set tighter limits on the effective scale of QG. In respect thereof, VHE $\gamma$-ray observations of transient events like GRBs were proposed [17]. Several measurements have been carried out so far, all of them lead to a lower limits for the effective scale of QG, down to 2 orders of magnitude below the Planck mass [43, 78, 126]. Nevertheless, observations of rapid flaring AGN could provide the possibility to derive more stringent limits for the effective scale of QG.

• Cold Dark Matter (CDM) searches: by systematic searches for CDM annihilation into $\gamma$-rays, the allowed space for the numerous theoretical models of DM may well be restricted. The high sensitivity of MAGIC might help to overcome difficulties due to the low flux in the sharp energy line expected from neutralino annihilations and to possibly identify the continuum signature, which has been proposed in the framework of several DM annihilation schemes.
5.2 Design and Construction of MAGIC

As mentioned before, one of the major goals of MAGIC is to lower the $\gamma$-ray energy threshold as far as possible. MAGIC is a third generation telescope comprising a number of improvements and innovative elements to reduce the energy threshold and diverse backgrounds. Table 5.1 summarizes the main telescope features that are described in greater detail in the following sections.

5.2.1 The Camera

The camera of the MAGIC telescope has in total 577 pixels, 397 inner and 180 outer ones, arranged in a hexagonal geometry. The sampling of the outer region of the 3.5° field of view (1.5 m Ø) camera is coarser. As photosensors, new compact hemispherical six-dynodes photomultiplier tubes (PMTs) from Electron Tubes Inc. 9116A (25 mm Ø) in the inner part and 9117A (39 mm Ø) in the outer part of the camera are used. The average quantum efficiency of the photosensors in the 300-500 nm range is approximatively 25% (enhanced after special coating [174]). The signal rise time is less than 700 ps and the Full Width Half Maximum (FWHM) time spread is less than 1.2 ns [171, 174]. A good single electron response allows for the absolute calibration of the camera. The reduced number of dynodes and a comparatively low gain of around $(1 - 2) \cdot 10^4$ help to minimize the impact of the DC-like NSB and to prevent damage and rapid aging of the PMTs when observations are carried out during partial presence of the moon. Moreover, the low gain assures a small time spread between consecutive dynodes which in turn enhances the time resolution of the camera.

To maximize the active area of the camera, specially shaped light concentrator cones (Winston cones) are arranged in front of the photosensor matrix. The use of the light concentrator cones may also cause the light trajectory of the Cherenkov photons to pass the hemispherical semitransparent photocathode twice. This results in an increase of the effective quantum efficiency of the photomultipliers of around 20% [174].

5.2.2 Trigger and Electronic Readout

The fast analog signals of the PMT camera are transmitted over 162 m long optical fibers to the control house where the readout electronics is located. The optical fibers are driven by Vertical Cavity Surface Emitting Laser Drivers (VCSELs). The use of optical fibers reduces cable weight and allow for electrical decoupling and noise immunity as well as signal transmission with only weak attenuation or pulse deformation. A small and therefore negligible drawback is a slight time dispersion of the signals [175]. To compensate the low gain of the photomultipliers, fast low noise transimpedance amplifiers are used.

Figure 5.3 illustrates the data stream. Before the digitization process by 300 MHz 8 bit Flash ADCs\(^1\) (FADCs) the signal is shaped and split into high and low gain channels to enlarge the dynamical range of the system. Both, the high gain and the low gain channels are limited to a time window of 15 time slices, each of which has a width of 3.3 ns. Additionally, each channel is fed to a discriminator with software adjustable threshold that generates an input signal to the trigger system.

It is envisaged to analyze ultra high-energy (UHE) $\gamma$-ray showers using the time-over-threshold analysis of the FADC information. The FADCs are read out by a multiprocessor PC saving the data to a RAID system and later to a tape library. A data rate of up to 20 MByte/s can be processed. This corresponds to the envisaged maximal trigger rate of around 1 kHz [97].

MAGIC is equipped with a two-level trigger system. The level one trigger (L1T) applies tight time coincidences (2 - 5 ns) and an $n$-fold ($n = 2 \ldots 5$) next-neighbor logic [32]. The trigger

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\(^1\)The 300 MHz FADC system is currently being replaced by a multiplexed 2 GSample/s FADC system with 10 bit amplitude resolution [29]. The exchange will be finished by the end of spring 2007.
region of the camera is divided into 19 hexagonal shaped sub-regions, each of which has 36 channels, partially overlapping. In this way, 325 inner pixels are covered and included in the trigger.

![Diagram of the electronic readout chain of the MAGIC telescope (adopted from [97]).](image)

**Figure 5.3:** The electronic readout chain of the MAGIC telescope (adopted from [97]).

The level two trigger (L2T) is slower (20-50 ns) but allows for a more sophisticated pattern recognition. It is able to analyze the digitized shower images in the trigger region online. Look-up tables containing information about likely patterns may be used to perform a first rough analysis like a fast evaluation of the size of the shower image. Furthermore, the L2T can be used to mask bright stars in the FOV of the camera. This is crucial for the background reduction and to avoid accidental triggers. The data acquisition rate is reduced and kept below some 300 Hz. Moreover, it allows for the reduction of the discriminator thresholds and therefore pushes down the energy threshold of the telescope. However, so far the L2T is not used.

### 5.2.3 The Reflector

The parabolic-shaped mirror dish of the MAGIC telescope has a diameter of 17 m and it is composed of 956 $49.5 \times 49.5 \, \text{cm}^2$ all-aluminum spherical mirror tiles. To ease the fast movement of the telescope, the mirrors are mounted on a light-weight space frame structure made of carbon fiber reinforced plastic tubes (less than 6 tons). Due to the the lightweight construction, MAGIC is able to reposition in any direction in less than 30 seconds. This feature is important for the study of short-time events like GRBs.

The time spread of Cherenkov light hitting the dish is minimized by the parabolic shape of the dish. To fit the parabolic shape of the carbon fiber structure as tightly as possible, the mirror tiles have different radii of curvature. The construction of the mirrors is based on an aluminum honeycomb structure covered with a 5 mm thick plate of AlMgSi1.0 alloy. The shape accuracy is of the order of a micrometer. The aluminum plate of each mirror tile is diamond milled to assure best optical properties. To protect the mirror surface from aging and scratches it is quartz coated. In the wavelength range between 280 nm and 650 nm, the reflectivity of the mirrors (measured after assembly) is well above 80% [40]. The reflectivity was lastly measured to be on average 77% [71].

Apart from the edges of the dish where the mirrors are mounted in groups of three panels, all mirrors are mounted in groups of four on the panels. The position of each mirror on the panels is adjustable via screws. Each panel itself can be re-adjusted during the telescope operation through the so-called active mirror control (AMC) system.

### 5.2.4 The Active Mirror Control

A drawback of the light-weight construction of the MAGIC telescope is the deformability of its frame structure. Due to the large diameter, the requirement of low weight as well as finan-
cial constraints it was not possible to build a completely stiff, non-deformable telescope frame structure. The susceptibility of the frame structure to small residual deformations requires the individual mirror segments to be regularly re-aligned while tracking an object. The deformations of the frame structure, caused by varying gravitational loads depend on the elevation angle of the telescope. In addition, variations of the average ambient temperature, wind etc. can cause a change of the overall geometry of the frame [88].

The active mirror control (AMC) system [41, 87, 88] of the MAGIC telescope allows to maintain a good optical performance during observations, i.e. to minimize the optical PSF of the telescope. The minimization of the optical PSF is important, since a small PSF improves the $\gamma$-ray angular resolution (section 4.3.1.3) and the $\gamma$/hadron separation.

To counteract the deformations of the mirror dish, each of the panels carrying the mirror tiles can be individually re-adjusted. Therefore, two of the three mounting points of each panel are equipped with computer-controlled actuators. In addition to that, each panel is equipped with a computer-controlled laser module located at its center. Each laser module is oriented towards the lids covering the PMT camera of the MAGIC telescope. A CCD camera mounted in the center of the mirror dish allows to monitor the position of each laser spot. The reference point for the alignment of the individual panels is determined with respect to a frame of reference that is defined by four LEDs in the FOV of the CCD mounted onto the camera lids. The bending model of the drive system [52] accounts for the dependence of the frame of reference on the elevation which is caused by the sagging of the camera with respect to the mirror dish.

As the adjustment of the mirror elements using the lasers takes about 4 minutes (including the movement of the camera lids) [88], which is by far too long for GRB observations to be performed on short notice, the AMC provides another adjustment mode based on look-up tables (LUTs). The LUTs contain information on the actuator positions for a certain pointing position of the telescope. Currently, the LUT adjustment of the mirror elements is done every 5° ZA during observations, without interrupting the data acquisition [88]. The LUT adjustment only takes about 10 seconds, as it does not require the lasers.

The LUTs are obtained by means of dedicated laser adjustments being performed every 5° ZA. Once the LUTs are generated, they are valid for a certain period of time. But, to account for residual long-term variations of the telescope frame structure all LUTs have to be regularly updated [88].

The new implementation of the AMC control program significantly speeds up the initial calibration of the AMC as well as the focusing of the telescope during observations. Furthermore, the telescope PSF has improved by $\sim 10\%$ [42].

5.2.5 The Calibration System

The calibration system of MAGIC [89, 90, 91] is equipped with very fast (3 - 4 ns FWHM) and powerful ($10^8 - 10^{10}$ photons/sr) light emitting diodes (LEDs) of three different colors. Situated in the center of the mirror dish, it illuminates the camera uniformly. Light is emitted pulsed or continuously at different intensities (2000 - 3000 photoelectrons (Phe) per pixel and light pulse) at three different colors (370 nm, 460 nm and 520 nm). Therefore, the calibration system allows to calibrate of the whole readout chain of the telescope with respect to wavelength and linearity, i.e. to determine the conversion factor between FADC response and a certain amount of light impinging the camera plane.

To account for short time gain fluctuations of the readout chain, interleaved calibration events are generated at 50 Hz during data taking. In addition, the pedestals and their variances are permanently monitored.

Three different methods are used to determine the absolute light flux incident on the camera:

- The excess-noise factor method [90, 91, 159] allows to deduce the number of Phe from the previously measured excess noise factor (a characteristic PMT dependent quantity) and
the variance of both pedestal and signal. It measures the number of Phe reaching the first dynode of the PMT. In a good approximation, the number of Phe’s is given by

\[
N_{\text{Phe}} = F \cdot \frac{Q^2 - P^2}{\sigma_Q^2 - \sigma_P^2}.
\]

\(\sigma_P\) denotes the electronic noise, \(\sigma_Q\) the measured standard deviation of the signal peak, \(P\) the mean pedestal value and \(Q\) the mean charge. All quantities are measured in FADC counts. Together with the excess-noise factor \(F_i\), these quantities determine the number of Phe \(N_{\text{Phe}}\) that corresponds to the mean charge \(Q\).

![Figure 5.4: Schematics of the calibration system (adopted from [89]).](image)

- The so-called blind pixel method uses a darkened (attenuation factor of 1000), single Phe counting PMT situated in the camera plane. By means of the illumination through a filter, the corresponding pixel is able to resolve single Phe. The conversion factor is then deduced from the single Phe response.

- The comparison of the output of a calibrated PIN diode of known quantum efficiency to the FADC output immediately enables the determination of the conversion factor from FADC output to Phe. The PIN diode measures the absolute light flux from the pulser box at 150 cm distance. A \(^{241}\text{Am}\) source emitting 59.95 keV \(\gamma\)'s is used to calibrate the PIN diode. The PIN diode itself is read out by a charge sensitive pre-amplifier.

5.2.6 Software

5.2.6.1 The Analysis Software

The MAGIC Analysis and Reconstruction Software (MARS) [51, 52, 152, 151] is a ROOT-based [187] collection of C++ classes. It has been developed to process and calibrate raw data and to perform a standard analysis. The modular concept of the software allows for a fast adaption to the current presentation of a problem. A central event loop represents the core of the analysis package. Apart from basic analysis algorithms, the package comprises a number of tools specifically developed for IACTs data analysis, such as refined and enhanced image cleaning algorithms and sophisticated event classification schemes [47, 49] used both for gamma-hadron separation, i.e. background rejection and energy reconstruction of EAS. The development of the MAGIC analysis chain is still ongoing.

\(^1\)A typical value for the excess-noise factor of the PMTs used is \(F \approx 1.15\) [91].
### 5.2. DESIGN AND CONSTRUCTION OF MAGIC

<table>
<thead>
<tr>
<th>Mount</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mount type</td>
<td>alt-azimuth</td>
</tr>
<tr>
<td>Tracking error</td>
<td>0.025°</td>
</tr>
<tr>
<td>Pointing error</td>
<td>0.05°</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Mirror</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror element size</td>
<td>$49.5 \times 49.5 \text{cm}^2$</td>
</tr>
<tr>
<td>Mirror element shape</td>
<td>spherical</td>
</tr>
<tr>
<td>Mirror material</td>
<td>5 mm AlMgSi1.0 alloy plate glued to an aluminum honeycomb structure</td>
</tr>
<tr>
<td>Dish diameter</td>
<td>17 m</td>
</tr>
<tr>
<td>Dish shape</td>
<td>parabolic</td>
</tr>
<tr>
<td>Number of segments</td>
<td>964</td>
</tr>
<tr>
<td>Dish area</td>
<td>$\sim 240 \text{m}^2$</td>
</tr>
<tr>
<td>Focal length</td>
<td>17 m</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>$\sim 0.1^\circ$</td>
</tr>
<tr>
<td>Reflectivity</td>
<td>$\sim 85% \ (280 \text{nm} \leq \lambda \leq 650 \text{nm})$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Camera</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera FOV</td>
<td>3.5°</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>577 (397 inner and 180 outer pixels)</td>
</tr>
<tr>
<td>PMT type</td>
<td>Electron Tubes Inc., 9116A (inner pixels) and 9117A (outer pixels), six dynodes both</td>
</tr>
<tr>
<td>Average QE</td>
<td>$\sim 25% \ (300 \text{nm} \leq \lambda \leq 500 \text{nm})$</td>
</tr>
<tr>
<td>Light concentrators</td>
<td>hollow Winston cones, hexagonal entrance</td>
</tr>
<tr>
<td>Pixel diameter</td>
<td>3 cm Ø (0.1°) inner pixels, 6 cm Ø (0.2°) outer pixels</td>
</tr>
<tr>
<td>Calibration</td>
<td>Multi-wavelength and intensity calibration</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trigger</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0th level</td>
<td>discriminator with software adjustable threshold</td>
</tr>
<tr>
<td>1st level</td>
<td>$n = (2 \ldots 5)$ next-neighbor pixels must coincide within a time window of a few nanoseconds</td>
</tr>
<tr>
<td>2nd level</td>
<td>programmable, can handle rates of up to 1 MHz, provides fast pattern recognition routines for background rejection</td>
</tr>
<tr>
<td>Energy threshold</td>
<td>$\gtrsim 60 \text{GeV}$ (trigger threshold at zenith)</td>
</tr>
<tr>
<td>Nominal trigger rate</td>
<td>$\gtrsim 80 - 250 \text{GeV}$ (analysis threshold, flux and ZA dependent)</td>
</tr>
<tr>
<td>Effective collection area</td>
<td>some $10^4 \text{m}^2$ at zenith</td>
</tr>
<tr>
<td>$f/d$</td>
<td>1.05</td>
</tr>
<tr>
<td>Total weight</td>
<td>$\sim 65 \text{tons}$</td>
</tr>
</tbody>
</table>

**Table 5.1:** The key parameters of the MAGIC telescope [28, 32, 40, 52, 89, 90, 174].

#### 5.2.6.2 Simulation of Extended Air Showers and Detector Performance

Since IACTs use the Earth’s atmosphere as a part of the detector and a testsource or testbeam like in accelerator physics is unavailable, MC simulations of the detector performance are mandatory. Some very important quantities like the detection efficiency, primary $\gamma$-ray energy and energy threshold cannot be determined only from telescope measurements. The simulation takes into account both the hardware behavior and signal reconstruction. The first step involves the simulation of the shower development and the production of Cherenkov light in the Earth’s atmosphere. In the next step, the ray-tracing of the Cherenkov photons is done. Finally, the electronic chain is simulated, i.e. the conversion from Cherenkov light incident on the camera into photoelectrons. From the statistical comparison of MC data and real data, the detector efficiency and the energy of a $\gamma$-ray candidate can be deduced. This is essential for the flux determination.

The simulation of the complete detection process is done in three steps. The MC program CORSIKA (COsmic Ray SImulations for KAscade) [109] simulates the development of extensive
air showers for a given set of input parameters, like primary $\gamma$-ray energy, impact parameter, slope of the energy spectrum, height of the telescope above sea level, pointing direction of the telescope as well as magnitude and direction of the Earth’s magnetic field. CORSIKA uses experimentally determined cross sections and atmospheric models to simulate EAS. The program has been adapted to the requirements of MAGIC [192]. The Earth’s magnetic field is included in the simulation, since it has an impact on the development of EAS (chapter 7). The output of CORSIKA contains information on location and wavelength of each Cherenkov photon on ground, i.e. each Cherenkov photon is individually traced.

A dedicated Reflector program [164] is used to simulate the mirror performance of the MAGIC telescope. It reads the CORSIKA output files and simulates the collection and reflection of the Cherenkov light onto the camera plane. To be able to adapt to different conditions without being forced to rerun CORSIKA, atmospheric absorption as well as mirror degradation is taken into account at this stage. The output of the Reflector program contains information on all Cherenkov photons reaching the telescope focal plane within the camera area.

Finally, the output of the Reflector program is processed by the Camera simulation program [45]. The camera program simulates the behavior of the entire readout chain, i.e. photomultiplier response, trigger and the FADC system including electronic noise. Again, to be able to easily adapt MC data to measurements, the simulation of the optical PSF (section 4.3.1.3) of the telescope is done at this stage. The output of the Camera program can be fed into the standard analysis chain. To account for the influence of stars in the FOV of the telescope, the output of the Starfield simulation program [155] can be read and processed additionally and added to the information obtained from the Reflector program.
Chapter 6

Reconstruction of Extended Air Showers

There are different approaches to describe size, shape and orientation of shower images in the camera plane. Depending on the approach, the preprocessing of data is done differently. The approach described in the next section of this chapter requires a so-called image cleaning procedure.

6.1 Image cleaning

The image cleaning procedure is applied to the reconstructed Cherenkov light distribution in the camera plane after gain normalization (also referred to as flat-fielding) and pedestal subtraction, i.e. applied to calibrated data. The flat-fielding is very important to ensure an equal response of all pixels which in turn helps to avoid camera inhomogeneities.

![Image](image.png)

(a) A potential gamma event after pedestal subtraction and calibration.

(b) The same event after image cleaning.

Figure 6.1: A potential γ-ray event before and after the image cleaning procedure. Only Pixels surviving the image cleaning are used for the following analysis steps.

The basic idea behind the image cleaning is to reject regions of pixels in the camera that presumably do not contain Cherenkov light from the EAS core, i.e. to eliminate uncorrelated background. These regions are supposed to be dominated only by NSB (starlight, fluorescence...
light from the ionosphere, moonlight, airglow light and light from terrestrial sources) and noise of the readout electronics.

The image cleaning procedure uses the pedestal root mean square (RMS) of each individual pixel, which is a measure for the NSB induced noise. The pedestal mean remains unchanged under the influence of the NSB, since an AC-coupling is used to transmit the fast analog signals of the PMTs to the electronic readout. The standard image cleaning procedure is done in two steps: in a first step it is searched for pixels that contain a signal at least a multiple times their pedestal RMS level, the first cleaning level. Pixels that fulfill this condition are then called core pixels if they have at least one neighboring pixel fulfilling the same condition. Pixels surviving the second step of the image cleaning procedure are called boundary pixels. Boundary pixels have to have at least one core pixel as a neighbor and a signal larger than another multiple of their pedestal RMS, the second cleaning level. Pixels that do not fulfill the cleaning are set to zero. The effect of the image cleaning is shown in figure 6.1.

Both cleaning levels have to be chosen very carefully to minimize the introduction of a potential bias. Especially low-energy events with signals close to the noise level of the camera pixels can be biased, i.e. the cleaning may reject not only the background contribution to shower images but also a non negligible fraction of the signal itself. To describe very low-energy events close to the energy threshold of the telescope, other approaches for the image parameterization are being used that do not require this cleaning procedure.

Instead of using real-valued multiples of the pedestal RMS, absolute values for the image cleaning levels in units of photoelectrons (Phe) can be set. In this approach, which is referred to as the “absolute image cleaning”, the cleaning levels are independent of the noise level. The absolute image cleaning was used throughout this work.

Noisy pixels and dead pixels are masked out and then interpolated using the light content of the neighboring pixels.

After the pre-filtration steps described before, the shower images can be processed further.

6.2 Parameterization of Shower Images

To extract the weak signal of γ-ray sources, an efficient γ-hadron separation is mandatory. Mainly hadrons contribute to the huge background one has to overcome. γ-ray induced shower images inside the photomultiplier camera differ from hadron induced showers in shape and orientation. Using this difference, one is able to discriminate between both types of showers. To describe shower images, some form of parameterization is needed. The parameterization is based either on a moment fitting approach or else on a semi-analytical fitting of shower images. To date, most of the experiments using the IACT technique have preferred the former method, because semi-analytical descriptions of the shower images require much more computing power.

Because of the elliptical nature of the shower images, it is natural to perform the image parameterization in terms of a moment analysis using the signals of the camera pixels. The moment analysis is based on the ADC counts of each individual pixel and its coordinate in the camera. The moments of the light distribution in the camera are defined in appendix A.1. In general, the zeroth, first and second order moments of the light distribution are used to describe the shower images. The zeroth order moment is given by the sum of the ADC information of pixels.

The most common set of parameters are the so-called Hillas parameters [111]. These parameters are expressed in terms of the moments and spreads of the images (appendices A.1 and A.2). The geometrical meaning of these parameters is illustrated in figure 6.2 and summarized in table 6.1, while their mathematical definitions are given in appendix A.3. The image parameters SIZE, WIDTH, LENGTH and CONC characterize the shape and light content of the shower images, the parameters DIST and ALPHA describe the position and orientation of shower images in the camera. The image parameters DIST and ALPHA are so-called source-dependent
image parameters, as they are calculated with respect to the source position given by the center of the camera if the instrument is perfectly aligned with the source.

![Diagram](image.png)

**Figure 6.2:** Shower images in the camera are parameterized by the Hillas parameters [111]. The definition of the basic image parameters is illustrated. Light distributions are approximated by an ellipse. Major and minor axis of the ellipse represent the shape of the shower image. Both parameters ALPHA and $\delta$ are related to the orientation of the image. The parameter DIST describes the distance between camera center and centroid of the light distribution.

![Diagram](image.png)

**Figure 6.3:** The relation between the impact parameter $r'$ and the DIST parameter. In direction of the inclination of the telescope, both the impact parameter $r'$ as well as the DIST parameter scale like $\cos(ZA)$.

The value of the parameter SIZE corresponds to the total integrated light of the shower image. After application of the calibration constants determined for each individual pixel, its unit is Phe. As the Cherenkov photon yield on ground is related to the shower energy, the parameter SIZE is a measure for the primary energy, although the dependency is non-linear (section 8.1.8).

The parameters WIDTH and LENGTH characterize the spread of a shower image along the minor and major axis of the so-called Hillas ellipse, i.e. the lateral and longitudinal shower development. The compactness of the shower maximum region of an EAS is described by the
image parameter CONC. For γ-ray induced EAS the region of the shower maximum is more compact than in case of hadron induced EAS. Thus, the compactness of γ-ray induced EAS results in larger CONC values.

The parameter ALPHA depends on the relative orientation of the telescope axis and the shower axis. If the direction of the primary particle is aligned with the telescope optical axis, the shower image has a small ALPHA value. Although inclined hadronic showers lying in the same plane spanned up by the direction of the primary particle and the telescope optical axis may have small ALPHA values, they can be distinguished by means of their WIDTH/LENGTH ratio. The main uncertainties of the ALPHA parameter are due to fluctuations in the shower development and the finite pixel size of the imaging camera.

<table>
<thead>
<tr>
<th>Image Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIZE</td>
<td>The total integrated light of a shower image, usually given in units of number of Phe. As the photon yield on ground is directly related to the shower energy, this parameter is a measure for the energy of the primary γ-ray.</td>
</tr>
<tr>
<td>WIDTH</td>
<td>The spread of a shower image along the minor axis of the ellipse and a measure for the lateral development of the EAS. The common unit is degree.</td>
</tr>
<tr>
<td>LENGTH</td>
<td>The spread of a shower image along the major axis of the ellipse and a measure for the vertical development of the EAS. The common unit is degree.</td>
</tr>
<tr>
<td>CONC</td>
<td>The ratio between the two pixels with the largest signals to the sum of all pixels.</td>
</tr>
<tr>
<td>DIST</td>
<td>The distance between the center of the camera to the center of gravity of the image. The common unit is degree.</td>
</tr>
<tr>
<td>ALPHA</td>
<td>The angle between the major axis of the shower image and the straight line from the center of gravity of the image to the center of the camera.</td>
</tr>
<tr>
<td>DELTA (δ)</td>
<td>The angle between the major axis of the shower image and the x-axis of the camera coordinate system.</td>
</tr>
<tr>
<td>ASYM</td>
<td>The asymmetry of the shower image along the shower major axis. The common unit is degree.</td>
</tr>
<tr>
<td>M3LONG</td>
<td>The 3rd moment of the Cherenkov light distribution along the shower major axis. The common unit is degree.</td>
</tr>
</tbody>
</table>

Table 6.1: The definitions of the most common shower image parameters. The image parameters DIST and ALPHA are referred to as source-dependent image parameters. All image parameters are expressed in terms of the moments and spreads of the light distribution (app. A.1 and A.2).

Normally, only moments up to the second order are taken into account for the calculation of the image parameters. In this case, the range of the parameter ALPHA is confined to the interval \(-90^\circ\ldots+90^\circ\). The distribution of the signed parameter ALPHA is symmetric, it is common to show its absolute value.

The parameter DIST, measured in degrees, corresponds to the angle to the telescope axis under which the shower maximum is seen. It is related to the impact parameter of the primary particle with respect to the telescope optical axis (figure 6.3). EAS that develop close to the telescope axis have small DIST values (\(\lesssim 0.2^\circ\)), and the main contribution to the collected Cherenkov light is due to strongly scattered electrons of the shower tail region (figure 4.9). In case of large DIST values (\(\gtrsim 0.9^\circ\)), the instrument detects only Cherenkov light emitted from shower halo particles. In the first case, for small values of the DIST parameter, the shower
images become all roundish, and γ-ray induced shower images are indistinguishable from hadron induced shower images. In the latter case, only high-energy γ-rays are recorded, because, at large impact parameters (∼120 m at 0° ZA), the intensity of the Cherenkov light on ground falls off steeply (figure 4.8).

Figure 6.4 shows the distributions of the shower image parameters introduced afore, for SIZE > 300 Phe and an average ZA of around 60°. MC simulated γ-ray showers are indicated as blue histograms, hadronic as red histograms. The ALPHA distribution for hadron induced showers appears to be rather flat, as there is no prime orientation of the shower axis like for γ-ray induced EAS. Deviations from a flat distribution may be due to the finite size of the imaging camera and also due to the limited trigger area (section 5.2.1 and 5.2.2). For example, ALPHA values that are assigned to shower images only partially contained in the trigger area, are preferentially shifted to larger values.

![Image parameter distributions for MC simulated γ showers (blue) and real hadronic background (red), for SIZE > 300 Phe and an average ZA of around 60°. The MC showers were generated with a spectral index of 2.6.](image)

As the difference between γ-ray and hadron induced EAS is expressed in the image parameters, they can be used to discriminate between γ-rays (signal) and hadrons (background). The most powerful discrimination between γ-rays and hadrons seems to be possible on the basis of the image parameter ALPHA. However, strong discrimination is also given by other parameters like WIDTH, LENGTH and CONC. The discrimination power depends heavily on the energy range taken into account. At very low energies, i.e., at low values of the parameter SIZE, the γ-hadron separation worsens. This is what eventually adds up to the energy threshold of an IACT, apart from the intrinsic energy threshold given by the design and hardware parameters of an IACT. It is worth mentioning that, for geometrical reasons, most of the image parameters scale with increasing ZA and energy (section 4.1), which has to be taken into account when
analyzing IACT data.

The 3rd moment image parameter M3LONG used throughout this work describes the asymmetry of shower images. The parameter M3LONG makes use of the fact that γ-ray induced shower images should exhibit tails which preferentially point away from the source position, whereas hadron induced shower images should not have such a preferred direction. Another parameter describing the asymmetry of shower images along the shower major axis is the image parameter ASYM.

It is important to preferentially select shower images that are fully contained in the camera. Otherwise, high-energy EAS truncated due to incomplete sampling may be wrongly reconstructed as low-energy showers. The relevant image parameter describing the containment of a shower image in the camera is called LEAKAGE. It is defined as the ratio of photons collected in the outer ring of pixels of the camera to the SIZE parameter. Another parameter, LEAKAGE2, is similarly calculated from the photons collected in the two outer rings of pixels of the camera.

There are several successful strategies for the γ/hadron separation, some of which are based on the shower image parameters mentioned before. The γ/hadron separation method used in this work is briefly explained in the next section.

6.3 γ/hadron Separation

In general, IACT data consist of two classes of events: γ-ray induced images (signal) and hadron-like images (background). As hadron induced EAS are much more abundant than γ-ray induced EAS, it is crucial to develop and to apply γ/hadron separation strategies that are based on the differences in shape and orientation of the shower images.

Once the shower images are described by a certain set of parameters, one can use these image parameters to statistically distinguish between γ-like and hadron-like events. Not all image parameters described in the previous section are equally well suited for the background discrimination. The most powerful image parameters to extract the γ signal are ALPHA, WIDTH and LENGTH (section 6.2 for the image parameter definition). The space spanned up by the image parameters is multi-dimensional, hence one has to deal with a nontrivial cut optimization and event classification problem.

For the moment, two different γ/hadron selection strategies for event classification are implemented in the software package MARS used for the data analysis [51, 52, 151, 152]:

- The so-called Supercut method takes into account the energy dependence, i.e. the SIZE-dependence of the Hillas parameters, which describe shape and orientation of the shower images, as well as their dependence on the impact parameter and ZA. Supercuts are cuts in the different image parameters. They are therefore one- and not multi-dimensional. The Supercuts can be constant or parameterized by simple polynomials up to 3rd order in energy, ZA and DIST. A training sample consisting of γ showers (signal) and hadrons (background) serves for the optimization procedure by which the SIZE-, ZA- and energy-dependence of the image parameters is determined. The parameters comprised in the Supercut method are optimized on MC data in the view of maximum significance.

- The Random Forest (RF) method [47, 49] is based on a somewhat different idea. In a simplified view, the multi-dimensional space spanned up by the image parameters is randomly divided into a predefined number of hyper-cubes in which each cube constitutes a node of a RF classification tree. In this way, an ensemble of uncorrelated trees is produced which are then combined to form the RF, a generalized classifier that, in our case, aims at distinguishing γ-ray induced shower images from hadron induced ones.

For the generation of the RF, two training samples are needed, one of which is a pure MC sample of γ-ray induced showers representing the signal. The hadronic shower sample, representing the background, can be obtained either from MC simulations or real data.
6.4 Extraction of the $\gamma$ Signal

In case of stand-alone IACTs, the image parameter ALPHA is commonly used to extract the $\gamma$ signal from the data. As mentioned in the previous section, the ALPHA distribution appears to be rather flat for hadron induced showers, which is related to the isotropy of charged CRs. The presence of a $\gamma$-ray signal shows up in an excess at small absolute values of the parameter ALPHA, typically at $|\text{ALPHA}| \lesssim 10^\circ - 15^\circ$, which is dependent on both energy and ZA. At low energies close to the analysis threshold, the ALPHA distribution appears to be broadened.

Although it is sufficient to carry out only ON-source observations, OFF-source observations can be helpful to monitor and study the background. OFF-source observations are usually carried out in a region of the sky with similar background conditions, under similar ZA, with no $\gamma$-ray source in the FOV. The ALPHA distribution obtained by OFF-source observations appears to be rather flat, as there is no prime orientation of the shower axis with respect to the telescope optical axis (figure 6.4).

After optimization of the cuts on all image parameters besides ALPHA, it is possible to derive both the number of excess events, i.e. $\gamma$-ray candidates and the residual background events from the ALPHA distribution. The number of background events which contribute to the peak in the signal region at small values of ALPHA can be estimated either by extrapolating the background far from the peak to the region of the peak or by subtraction of the dedicated OFF data after its normalization to the ON data in the region of large ALPHA values. The normalization of
the dedicated OFF data may be problematic, as large differences in observation times result in large normalization factors which in turn amplify statistical fluctuations. Thus, large differences in observation times may complicate the extraction of the $\gamma$-ray signal from the distribution of the ALPHA parameter. In case of insufficient OFF data, it is generally better to determine the hadron induced background by extrapolation of the ON distribution from large to small values of ALPHA.

The ALPHA distribution is usually approximated by a simple, empirically determined polynomial function. The number of ON events is then determined from the histogram entries, while the number of background events is derived from the fit and its error. The number of excess events is obtained by subtracting the background from the ON events. As the distribution of the parameter ALPHA depends up to some extent on the cuts applied to the image parameters, there is no standard way to assemble the polynomial function. But, comparisons of dedicated OFF data and extrapolated background always gave satisfactory results.

The significance of a signal, i.e. the probability that an excess in the ALPHA distribution is due to a real source rather than to a spurious background fluctuation, can be calculated according to Li and Ma [143] from

$$S = \sqrt{2} \left\{ N_{\text{ON}} \ln \left[ \frac{1 + \alpha}{\alpha} \left( \frac{N_{\text{ON}}}{N_{\text{ON}} + N_{\text{OFF}}} \right) \right] + N_{\text{OFF}} \ln \left[ (1 + \alpha) \left( \frac{N_{\text{OFF}}}{N_{\text{ON}} + N_{\text{OFF}}} \right) \right] \right\}^{1/2}, \quad (6.1)$$

where $N_{\text{ON}}$ denotes the number of $\gamma$-ray candidates measured during the time $t_{\text{ON}}$ in direction of a suspected source and $N_{\text{OFF}}$ the number of background events from a background measurement during $t_{\text{OFF}}$, or determined from an extrapolation as described afore. $\alpha$ is defined as the ratio of the observation times dedicated to ON-source and OFF-source measurements, i.e. $\alpha = t_{\text{ON}}/t_{\text{OFF}}$.

6.5 Reconstruction of the $\gamma$-Ray Arrival Direction

Sometimes there are uncertainties in the a priori knowledge of the position of the source under study. In the standard observation mode, the IACT is supposed to point in direction of the source, which is not necessarily the case when observing unidentified EGRET sources or even GRBs whose exact coordinates may be afflicted with a certain unknown error. In case of extended objects, potential sources of $\gamma$-rays are presumably not associated with the very center of the FOV. Furthermore, observations of point-like sources at some offset to the camera center may require to follow a different strategy than the standard ALPHA analysis.

There are many similar, empirical methods to estimate the $\gamma$-ray arrival direction from IACT data. The so-called DISP method [73] makes use of the shape of a reconstructed shower image to estimate the position of the source located on the major axis of the Hillas ellipse at a certain distance (DISP) from the COG of the Cherenkov light distribution in the camera. The main ingredient to the DISP method is the ellipticity $\text{WIDTH}/\text{LENGTH}$ of the shower images, which is related to the distance of the COG of the shower image to the source position. The DISP parameter, as proposed by [73], is defined as

$$\text{DISP} = A(\text{SIZE}) + B(\text{SIZE}) \cdot \frac{\text{WIDTH}}{\text{LENGTH} + C(\text{SIZE}) \cdot \text{LEAKAGE}^2}. \quad (6.2)$$

This approach accounts for the SIZE-dependence of the image parameters WIDTH and LENGTH. The SIZE-dependent parameters $A$, $B$ and $C$ in equation 6.2 can be obtained either from MC simulated $\gamma$-ray showers or from data collected on a well known point-like $\gamma$-ray source. Normally, the determination of the DISP parameters is obtained from the minimization
of the average angular distance between the real and estimated source position in the camera.

Because of the head-tail ambiguity in the 2nd moment analysis, the DISP method provides two possible solutions for the location of the source along the major axis of the Hillas ellipse. A possibility to overcome the head-tail ambiguity is to make use of the asymmetry parameter M3LONG. Together with the M3LONG parameter, the DISP parameter can be used to estimate the true location of a \(\gamma\)-ray source. But, it has to be kept in mind that the M3LONG parameter does not always help to identify the true source position. The achieved ratio of correct head-tail assignment is in the order of 70\%, which strongly depends on the considered energy range. Very low-energy showers appear to be widely spread in the camera, which may deteriorate the head-tail assignment significantly. Low-energy \(\gamma\)-rays are strongly affected by limited Cherenkov photon statistics. Hence fluctuations in the shower development have a greater influence on the head-tail assignment.

The outcome of the DISP analysis is usually displayed on a sky map. At ZAs below 30\(^\circ\), the DISP method yields an angular resolution of about 0.1\(^\circ\), for energies greater than 150 GeV [73, 160]. The achieved \(\gamma\)-ray angular resolution at 60\(^\circ\) ZA is comparable [160].

### 6.6 Energy Estimation

As there is no possibility to calibrate an IACT at an accelerator or other laboratory, the absolute energy scale of an IACT must be determined through MC simulations. Correspondingly, the energy estimation of the recorded showers is entirely based on MC simulations. For the detection of a \(\gamma\)-ray source, the knowledge about the absolute energy scale is of minor importance, while for the determination of the shape and absolute level of the differential \(\gamma\)-ray energy spectrum it is of great importance to estimate the primary \(\gamma\)-ray energies as precisely as possible.

In first order, the integral of the Cherenkov photon density on ground is directly related to the shower energy and therefore to the primary energy. The energy of the air showers is estimated using the intensity of the images, which is compared to the one reconstructed from MC generated \(\gamma\) showers in terms the image parameter SIZE. Since the intensity of the recorded shower images also depends on the distance to the EAS maximum, it is important to incorporate additional image parameters related to the shower geometry like DIST, WIDTH and LENGTH. From MC simulations, the dependence of the image parameters on the true energy is known, as the true energy is one of the input parameters of the simulation.

There are two approaches commonly used for the energy estimation. Both of them comprise a certain set of the image parameters. On one hand, the energy is estimated using a MC-based parameterization including the parameters SIZE, DIST, WIDTH, LENGTH and ZA. On the other hand, the energy of the showers can be estimated using the RF method based on a similar set of image parameters.

The implementation of the RF estimation works as follows: for each energy bin \(i\) of all \(N\) energy bins (logarithmic binning), a classifier is generated. Each classifier \(i\) is then constructed by training the contents of its associated energy bin against the others, i.e. all events of energy bin \(i\) have the class label 1 and all other bins have class label 0. In this way, each classifier corresponds to a certain energy range. After application of all \(N\) classifiers to an event, the estimated energy is calculated from

\[
E_{\text{Est.}} = \frac{\sum_{i=1}^{N} w_i E_i}{\sum_{i=1}^{N} w_i}, \tag{6.3}
\]

where the real-valued variable \(w_i = 0 \ldots 1\), obtained from each classifier \(i\), is a measure for the probability that the energy of a given event is \(E_i\).
The input variables for the training of the RF energy estimator are typically ZA, \( \log_{10}(\text{SIZE}) \), WIDTH, LENGTH, \( \log_{10}(\text{SIZE})/(\text{WIDTH} \cdot \text{LENGTH}) \), DIST, CONC and LEAKAGE and naturally \( E_{\text{True}} \).

As for the \( \gamma \)/hadron separation, it is essential to use properly simulated MC showers with matching ZA range, since the reconstructed shower intensity SIZE and the other image parameters being important for the energy estimation depend on the ZA.

### 6.7 \( \gamma \)-Ray Flux Determination

For the \( \gamma \)-ray flux estimation MC simulations are indispensable. The \( \gamma \)-ray flux measured by an IACT depends on the telescope efficiency, also referred to as \( \gamma \) detection probability. The \( \gamma \) detection probability in turn defines the effective collection area of the detector needed for the flux estimation. MC simulations provide the detector efficiency and, in addition, the estimated energy of the recorded showers.

The differential \( \gamma \)-ray flux \( \frac{dF_{\gamma}(E, ZA)}{dE} \) is defined by

\[
\frac{dF_{\gamma}(E, ZA)}{dE} = \frac{dN_{\gamma}(E, ZA)}{dE \cdot A_{\text{Eff.}}(E, ZA) \cdot t_{\text{Eff.}}},
\]

where \( E \) denotes the \( \gamma \)-ray energy, \( A_{\text{Eff.}}(E, ZA) \) the effective collection area and \( t_{\text{Eff.}} \) the effective observation time, i.e. the dead time-corrected exposure time (section 6.7.1). \( dN_{\gamma}(E, ZA) \) denotes the number of showers recorded from the observed source in a certain energy bin \( dE \).

The number of recorded showers during the time \( t_{\text{Eff.}} \) depends on the \( \gamma \) detection efficiency \( \varepsilon_{\gamma} \), which can be defined as

\[
\varepsilon_{\gamma}(E, ZA, r) = \varepsilon_{\text{Trigger}}(E, ZA, r) \cdot \varepsilon_{\text{Cuts}}(E, ZA, r) = \frac{N_{\gamma}^{\text{MC, Post Cuts}}(E, ZA, r)}{N_{\gamma}^{\text{MC}}(E, ZA, r)}.
\]

\( N_{\gamma}^{\text{MC}} \) denotes the number of simulated showers, \( N_{\gamma}^{\text{MC, Post Cuts}} \) the number of MC simulated \( \gamma \)'s surviving the entire image analysis chain. All quantities depend on the energy \( E \), the ZA and the impact parameter \( r \).

The detection efficiency depends on the telescope performance parameters like trigger efficiency and detection efficiency of the Cherenkov light and the probability to survive all cuts.

The effective collection area can then be obtained as follows:

\[
A_{\text{Eff.}}(E, ZA) = \pi \int_{0}^{2\pi} \int_{r_{\text{Min.}}}^{r_{\text{Max.}}} \varepsilon_{\gamma}(E, ZA, r) \cdot r \, dr \, d\varphi,
\]

where \( \varphi \) denotes the azimuth angle. Thus, the effective collection area completely describes the telescope sensitivity. \( r_{\text{Min.}} \) is normally set to zero and \( r_{\text{Max.}} \) extends to a finite value where the \( \gamma \) detection efficiency \( \varepsilon_{\gamma} \) is negligible.

In practice, the data is divided into bins of the energy \( E \), ZA and impact parameter \( r \). The effective collection area is then determined from a discrete calculation:

\[
A_{\text{Eff.}}(E_i, ZA_j) = \pi \sum_{k=1}^{N} \frac{N_{\gamma}^{\text{MC, Post Cuts}}(E_i, ZA_j, r_k)}{N_{\gamma}^{\text{MC}}(E_i, ZA_j, r_k)} \left( r_{k,\text{Max.}}^2 - r_{k,\text{Min.}}^2 \right).
\]

The differential \( \gamma \)-ray flux is then given by

\[
\frac{dF_{\gamma}(E, ZA)}{dE} = \frac{\Delta N_{\gamma}^{\text{Post Cuts}}(E, E+\Delta E; ZA)}{t_{\text{Eff.}}(ZA) \cdot A_{\text{Eff.}}(E, ZA)}. \]
The determination of the differential $\gamma$-ray flux involves several steps. In a first step, the differential $\gamma$-ray flux (equation 6.8) is determined as a function of the estimated energy, based on the analysis of the ALPHA distributions. In a next step, the so-called unfolding of the energy spectrum is done. The unfolding procedure [16, 216] converts the differential $\gamma$-ray flux as a function of the estimated energy $E_{\text{Est.}}$ ($dF_{\gamma}(E_{\text{Est.}}, ZA)/dE_{\text{Est.}}$) into the differential $\gamma$-ray flux as a function of the true energy $E_{\text{True}}$ ($dF_{\gamma}(E_{\text{True}}, ZA)/dE_{\text{True}}$). The so-called unfolding is required because of the limited energy resolution of the detector. The unfolding procedure accounts for migration between different energy bins that have been chosen for the spectrum calculation. In order to minimize correlations between the data points of the unfolded distribution and to limit the fluctuations of the result, the unfolding procedure incorporates regularization algorithms [16, 216]. The number of bins in $E_{\text{True}}$ is chosen to be less than the number of bins in $E_{\text{Est.}}$. Normally, the unfolding is applied in a recursive manner.

### 6.7.1 Effective Observation Time

To extract the true $\gamma$-ray flux of a source, one has to know the effective observation time $t_{\text{Obs.}}$. In general, a real detector has a finite dead time, i.e. the detector may not be always available for data acquisition. This can result in a loss of a certain fraction of events that would be recorded by an ideal detector with vanishing dead time $t_{\text{Dead}}$. The dead time is due to the fact that the readout chain of a detector may be busy with processing the data of an event while another event has occurred. The time differences of successive CR events follow a poissonian distribution, and the probability distribution for the time differences should therefore exhibit an exponential behavior according to

$$P(t) = \lambda \cdot e^{-\lambda t}, \quad (6.9)$$

where $\lambda$ denotes the average event rate and $t$ the time difference between successive events. At best, in case of an ideal detector with zero dead time, the total observation time is given by the time for which a source has been observed.

In the more general case, as it is done for the MAGIC data analysis, the dead time of a detector can be obtained from the data by means of an exponential fit to the part $t > t_{\text{Dead}, \text{Max.}}$ of the distribution of event time differences which is not affected by the dead time [215]. The effective observation time is then given by

$$t_{\text{Eff.}} = \frac{N}{\lambda_{\text{Eff.}}}, \quad (6.10)$$

where $\lambda_{\text{Eff.}}$ denotes the effective event rate as obtained from the exponential fit. The time $t_{\text{Eff.}}$ can be understood as the time interval within which $N$ events would be recorded by an ideal detector. The fraction of lost observation time can be calculated from the average observed event rate $\lambda_{\text{Obs.}}$ and effective event rate as obtained from the exponential fit as follows:

$$r_{\text{Dead}} = \left(1 - \frac{\lambda_{\text{Obs.}}}{\lambda_{\text{Eff.}}}\right). \quad (6.11)$$

The above mentioned method is reliable as long as the dead time of the detector is constant and the observed event rate stays rather constant. The latter is the case if the main contribution to all recorded events is due to CR events and if the covered ZA range is small.
6.8 Cut Optimization

As already pointed out in the previous sections, successful detections of GeV - TeV γ-ray sources require efficient γ/hadron separation strategies to discriminate the weak γ-ray signals against the overwhelming hadron induced background. All selection strategies are based on intrinsic differences of the shower images from γ-ray and hadron induced showers, which on their part are expressed in differences of the preferred image parameters that are used to describe the shower images. The discrimination between γ-like and hadron-like events is done by means of cuts on the relevant image parameters (sections 6.2 and 6.3).

As the differences between γ-like and hadron-like showers may become washed-out, which is known to be the case especially at primary γ-ray energies below 100 GeV, an efficient γ/hadron separation is very difficult to achieve. Therefore, one is left with the choice between efficient background reduction and keeping the fraction of selected γ-ray events high.

The effectiveness of a particular strategy is usually defined by the so-called quality factor $Q$ [82]:

$$Q = \frac{\varepsilon_\gamma}{\sqrt{\varepsilon_h}},$$  \hspace{1cm} (6.12)

where $\varepsilon_\gamma$ denotes the fraction of γ-ray induced showers surviving the γ/hadron selection and $\varepsilon_h$ the corresponding number for hadronic showers. The value of the quantity $Q$ can be understood as the factor by which the significance of a data signal is enhanced, but also as a measure for the γ purity of a data sample after application of a certain γ/hadron selection.

The generation and optimization of γ/hadron selection cuts can be either done using a MC simulated reference sample of γ-ray and hadron images or real data. Both approaches exhibit advantages and disadvantages. The first approach relies on the assumption that the MC simulated events perfectly describe real showers, including their detection by the IACT. Although MC simulation input parameters may be adjusted in a way that MC simulated events resemble real data very well, the agreement between MC simulated showers and real showers will never be perfect. Another drawback of the first approach is the large time consumption of MC simulations that are required to obtain hadron data of enough statistics. On the other hand, MC simulations are essentially required to estimate both the collection area and the energy response of an IACT (sections 6.7 and 6.6).

Both approaches may suffer from variations of the telescope performance during and in between observational periods. Thus, the reference sample used for the development of γ/hadron selection cuts may significantly deviate from the data sample of the source under study and may therefore lead to a poorer performance of the γ/hadron separation. However, the second approach requires data with a strong γ-ray signal which is not available for all ZAs and observation periods etc.. But, in case of simultaneously taken reference data, these data provide the possibility to monitor the telescope performance and to account for significant variations in the time evolution of the image parameters.

A common approach in the standard MAGIC analysis is to use MC simulated γ-ray showers and real hadronic showers from dedicated OFF observations. Furthermore, it is required that the data sample used for the cut optimization covers the same ZA range as the data from the source under study, as the threshold energy and the effective collection area as well as the distributions of the most important image parameters depend on the ZA.

As the quality factor $Q$, defined by equation 6.12, is directly related to the significance of a detection, it is well suited for the optimization of γ/hadron separation cuts.
Chapter 7

Geomagnetic Field Effects on the Imaging Technique

Among all IACTs being currently in operation, the MAGIC telescope aims at the detection of very low-energy $\gamma$-rays in the order of 60 GeV [28]. Since $\gamma$/hadron separation becomes more and more complicated at primary $\gamma$-ray energies close to the threshold energy of MAGIC, it is crucial to investigate the impact of the Geomagnetic Field (GF) on EAS.

The influence of the GF on EAS was already qualitatively discussed in 1953 [67]. Charged secondary particles in EAS are deflected by the GF which causes a broadening of the EAS. It was pointed out that 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. The effect on $\gamma$-ray induced EAS is expected to be bigger than on hadron induced EAS, as their shape is initially more regular and the scattering angles occurring in nuclear interactions are typically much larger than that produced by the deflection of secondary charged particles due to the influence of the GF [67]. The Cherenkov images on ground can be affected in a way that the threshold energy of an IACT increases [48] as well as its $\gamma$/hadron separation capability is expected to be deteriorated.

The goal of the MC studies carried out in this work is to find out about the impact of the GF on the analysis methods that are used to extract the $\gamma$-ray signal from a VHE $\gamma$-ray source. The first part of this chapter contains some general information on the origin and features of the GF. The influence of the GF on the development of EAS as well as on the Cherenkov light distribution on ground is briefly reviewed and discussed. Furthermore, details on the MC dataset generated for this studies are given. Finally, results from the analysis of the MC data are presented, together with a discussion of the influence of the GF on the analysis of MAGIC data.

7.1 The Geomagnetic Field

In the most simple model, the GF in space can be approximated by the magnetic field that is generated by a dipole magnet located at the center of the Earth. Figure 7.1 shows a simplified representation of the GF. In reality, the magnetic field lines do not strictly follow those of a dipole magnet. Furthermore, the dipole center does not coincide with the center of the Earth and the dipole axis is not parallel to the spin axis of the Earth, i.e. north and south geographic poles and north and south magnetic poles are not located in the same plane. The geographic north of the Earth is close to the magnetic south, but the dipole axis is tilted from the spin axis by $\sim 11^\circ$ [54].

The solar wind, a stream of charged particles that are ejected from the upper atmosphere of the sun, modifies the GF. Field lines going toward the sun get compressed, while the field lines on the opposite side form the so-called Earth’s magnetotail. In this way, the solar wind determines
the overall shape of the GF. The solar wind mostly consists of high-energy electrons and protons that are able to overcome the sun’s gravitational attraction. To date, the mechanism by which the particles attain the high kinetic energy of $O(1\text{ keV})$ is not well understood [31]. Although a fraction of the kinetic energy can be attributed to the high temperature of the corona, there is another process required, being able to provide additional energy. This process may involve strong magnetic fields in the solar atmosphere. The solar wind not only temporarily deforms the GF (on timescales hours and days) due to coronal mass ejections, but also modulates the GF according to the eleven-year cycle of the solar activity of the sun. Coronal mass ejections are believed to be caused by a temporary release of magnetic energy at the sun. The sudden disturbances of the GF induced by the solar wind, also called magnetic storms, can last from hours to several days. These locally occurring disturbances of the GF can reach some 500 nT [54].

The main part of the GF is generated by internal sources. The intensity of the generated field ranges from 20 $\mu$T to 70 $\mu$T. External sources, related to ionized currents in the upper atmosphere, have a small share on the GF, which is in the order of some 100 nT [54]. Although the magnetic properties of iron and its abundance in the Earth suggest that the Earth represents a big magnet, the high temperature existing in the inner core rebuts this assumption. It is known that all materials lose their magnetism at the so-called Curie temperature, and the Curie temperature of iron is already reached at an average depth of 25 km [54]. The Curie temperature increases with increasing pressure, but the change is small compared to the average increase in temperature towards the Earth’s interior.

Figure 7.1: A simplified representation of the GF [18]. In first order, the GF closely resembles a dipole magnet situated at the center of the Earth. On closer inspection, the GF appears to be variable in time and position. The axis of the GF dipole component is not only offset from the center of the Earth, but also tilted with respect to the Earth’s spin axis by $\sim 11^\circ$ [54].

The Earth’s crust by itself, i.e. the outer layer of some 20 km thickness, cannot account for the GF observed in space. The complete magnetization of the material in the outer layer of the Earth would contribute only marginally to the dipole field [54]. Furthermore, time variations of the dipole location as well as the evidence for an ancient dipole reversal indicate that the GF is probably generated by liquid motion of material in certain layers deep inside the Earth. To date, the liquid outer core at depths between about 2900 km and 5200 km is believed to hold a massive ring of current whose flow may generate the dipole field of the Earth. There is a number of so-called current-source models that explain the occurrence of the GF by means of a “self-excited dynamo” model [54]. These models comprise time constants that are probably
much larger than the period of reliable observations of the GF field, which have been carried out to this day. The occurrence of dipole reversals as well as the relation between the change in the Earth’s spin and the secular change of the dipole declination is described by these self-excited dynamo models, however. Nowadays, dipole reversals are expected to happen every 200 thousand years.

Given its irregularity and temporal variability, the GF must be measured in many places all around the world to get a satisfactory and comprehensive picture of its orientation and strength. The surveying and mapping of the GF is done by means of satellites as well as by a large number of Earth-based and satellite-born geomagnetic observatories throughout the world, such as the International Real-time Magnetic Observatory Network (INTERMAGNET) [119], which measures the magnitude of the GF components and their change over time down to time-scales of hours. Because the orientation and strength of the GF continuously changes, it is impossible to make an accurate prediction of the GF components at any point in the very distant future. But, from the information collected on the GF over period of years, it is possible to introduce a mathematical representation of the GF, a so-called main field model. There are two global main field models, the World Magnetic Model (WMM) and the International Geomagnetic Reference Field Model (IGRF), which are constantly updated and distributed by the National Geophysical Data Center (NGDC) [169]. While the WMM is the standard navigation model for the U.S. and U.K. Departments of Defense and National Air Transportation Association (NATA), the IGRF is the international research reference model, providing the most accurate estimate for the GF components all around the world. Based on the measurements of the geomagnetic observatories, the WMM and the IGRF are updated every five years.

**Figure 7.2:** Definition of the geographic coordinate system. The $z$-axis is aligned with the Earth’s spin axis and the $x$-axis points towards the Greenwich meridian at $(b = 52^\circ, \lambda = 0^\circ)$.

It is common to express the GF by the gradient of a magnetic scalar potential $V$. Then, the GF can be obtained from

$$\vec{B} = -\nabla V.$$  \hspace{1cm} (7.1)

The spherical symmetry of the problem allows to perform the harmonic analysis of the scalar
potential $V$ of the GF in terms of the following expansion [54]:

$$V(r, \lambda, b) = r_E \sum_{n=1}^{N} \sum_{m=0}^{n} \left( \frac{r_E}{r} \right)^{n+1} (g_{n,m} \cos(m \lambda) + h_{n,m} \sin(m \lambda)) P_n^m(\sin b).$$  \hspace{1cm} (7.2)

$(r, \lambda, b)$ is a system of spherical coordinates. The polar axis of the corresponding spherical coordinate system coincides with the $z$-axis of a Cartesian coordinate system situated at the Earth’s center. The $z$-axis of the Cartesian coordinate system is aligned with the Earth’s spin axis, and the $x$-axis is oriented towards the Greenwich meridian (figure 7.2). $r_E$ denotes the mean radius of the Earth (6371.2 km), $r$ the radial distance from the center of the Earth, $\lambda$ the longitude eastwards from Greenwich, $b$ the geographic latitude, and $P_n^m(\sin b)$ the associated Legendre function of degree $n$ and $m$. The associated Legendre functions are normalized according to the convention of Schmidt [53]. $N$, the maximum spherical harmonic degree of the expansion, defines the precision of the approximation. The most accurate model for the GF, the IGRF, describes the GF in terms of a series expansion like the one in equation 7.2. The spherical harmonic coefficients $g_{n,m}$ and $h_{n,m}$ are adjusted to best fit the GF measurements. The maximum degree of the expansion is usually set to $N = 5$. The spherical harmonic coefficients are updated every five years. Coefficients for dates lying between neighboring five-year epochs are interpolated using the coefficients as well as their first time derivations of the corresponding neighboring intervals. So far, coefficients are available back to the year 1900.

The main contribution in the spherical harmonic expansion, defined by equation 7.2, comes from the terms with $n = 1$. The contributions of higher-order terms of the series expansion are considered as a perturbation of the dipole-like component of the GF. In the so-called centered dipole model, the terms with $n = 1$ can be identified with the magnetic potential produced by a dipole situated in the center of the Earth whose axis is inclined with respect to the Earth’s spin axis. For $n = 1$, the magnetic scalar potential of the GF, approximated by the first term of the resulting series expansion, reads

$$V(r, \lambda, b) = r_E \left( \frac{r_E}{r} \right)^2 B_0 \sin b, \quad B_0 = \sqrt{g_{1,0}^2 + g_{1,1}^2 + h_{1,1}^2}. \hspace{1cm} (7.3)$$

The coordinates $b$ and $\lambda$ are now measured in a spherical coordinate system with its center situated at the Earth’s center and the polar axis coinciding with the direction of the dipole [134]. The coordinate system, whose polar axis is aligned with the dipole, is referred to as the geomagnetic system. The geomagnetic coordinate system is connected to the geomagnetic reference system through a rotation around the $y$-axis and a rotation around the $z$-axis. $B_0 \approx 3 \cdot 10^{-5} \text{T} = 0.3 \text{G}$ denotes the mean value of the GF on the geomagnetic equator at the Earth’s surface. Thus, in the centered dipole approximation, the main component of the GF is given by

$$\vec{B}(r, \lambda, b) = -\nabla V(r, \lambda, b) = \left( \frac{r_E}{r} \right)^3 B_0 \left( \cos b \, \vec{e}_b + 2 \sin b \, \vec{e}_r \right). \hspace{1cm} (7.4)$$

Another approach, the so-called eccentered dipole model, is used to approximate the GF with a magnetic dipole that is not necessarily located at the center of the Earth [54]. The eccentric dipole has the same moment as the centered dipole and the same orientation of its axis, but in terms of the geographic Cartesian coordinate system. The dipole is placed in a way that the quadrupole term is made to vanish, maximizing the dipole term. The eccentered dipole model is somewhat more appropriate for studies of magnetospheric particle dynamics, as charged particles, arriving from space, are guided by the eccentered dipole field.

Usually, the GF is described by seven parameters [54]. The total intensity $F$, the inclination $I$, the declination $D$, the horizontal intensity $H$, the north and the east components, $X$ and $Y$, respectively, and the vertical component $Z$. All components are provided by both the IGRF model and the WMM. Nevertheless, at any point of the Earth, the direction and intensity of the GF is completely determined by only three parameters. The values for $F$, $I$, $X$ and $Y$,
respective, can be derived from $D$, $H$ and $Z$. Figure 7.3 shows the decomposition of the total intensity $F$ of the GF in a Cartesian coordinate system whose $x$-axis is aligned with the spin axis of the Earth. The $y$-axis points eastwards and the $z$-axis points inwards into the Earth. The vertical intensity $Z$ is the $z$-component of the GF, which is considered positive when pointing down. The horizontal intensity $H$ points to the magnetic south, while its projection on the $x$-axis, $X$, points to the geographic north. The declination $D$, sometimes called magnetic variation, is the difference between the true meridians and the magnetic meridians, i.e. $D$ is determined by the angle between the magnetic and the geographic north pole. $D$, usually measured in degrees, is considered positive east of the geographic north and negative when being west of the geographic north. The inclination $I$ is the angle under which the magnetic field lines dip into the surface of the Earth. The magnetic inclination varies from $+90^\circ$ (perpendicular to the surface) at the magnetic poles to $0^\circ$ (parallel to the surface) at the magnetic equator. The total GF $F$ intensity can be expressed in terms of the horizontal intensity $H$ and the vertical intensity $Z$:

$$ F = \sqrt{Z^2 + H^2}. \quad (7.5) $$

The relation between inclination $I$, horizontal intensity $H$ and vertical intensity $Z$ reads

$$ \tan(I) = \frac{Z}{H}. \quad (7.6) $$

The north and the east components, $X$ and $Y$ respectively, can be calculated from $H$ and $D$:

$$ X = H \cos(D), \quad Y = H \sin(D). \quad (7.7) $$

Up-to-date values for the components of the GF can be found at the web pages of the NGDC [169]. The NGDC web pages also provide a collection of programs to estimate the components of the GF based on either the WMM or the IGRF model. The errors on the field components are very small. For example, the errors on the components $D$ and $I$ are $O(500 \text{ nT})$ and $O(30^\prime)$, respectively.

Figure 7.4 shows the main field isomagnetic contours in geographic coordinates (Mercator projection) at 10 km a.s.l., calculated for November 2006 according to the epoch 2005 WMM.

**Figure 7.3:** Decomposition of the total intensity $F$ of the GF in a Cartesian coordinate system, whose $x$-axis is aligned with the spin axis of the Earth. The $y$-axis points eastwards and the $z$-axis points inwards to the center of the Earth. $H$ points to the magnetic south, while its $x$-component, $X$, points to the geographic north. The declination $D$ is given by the angle between the magnetic south and the geographic north pole. The inclination $I$ is the angle under which the magnetic field lines dip into the surface of the Earth.
The locations of the new generation IACTs being currently in operation are indicated. Of all the four observatory sites, the one of the CANGAROO experiment exhibits the highest value for the absolute GF strength. Instead, the H.E.S.S. observatory site shows the lowest value, although the global minimum in the total GF, called South Atlantic/South American anomaly, is located at about (30° S, 50° W).

Figure 7.4: Iso-contours of the absolute value of the GF in geographic coordinates (Mercator projection) for 10 km a.s.l., calculated for November 2006 according to the epoch 2005 WMM [169]. The locations of the new generation IACTs being currently in operation are indicated. Of all four observatory sites, the one of the CANGAROO experiment exhibits the highest value for the absolute GF strength. Instead, the H.E.S.S. observatory site shows the lowest value. The minimum in the total GF at about (30° S, 50° W) is called South Atlantic/South American anomaly.

Table 7.1: Present values (November 2006) as well as the annual change of the GF components at the Roque de los Muchachos observatory on the Canary Island of La Palma (28.8° N, 17.9° W) at 10 km a.s.l., calculated according to the epoch 2005 IGRF model [169].

<table>
<thead>
<tr>
<th>Main Field</th>
<th>Secular Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$ (declination)</td>
<td>$-7.021°$ (west)</td>
</tr>
<tr>
<td>$I$ (inclination)</td>
<td>$38.631°$ (down)</td>
</tr>
<tr>
<td>$H$ (horizontal intensity)</td>
<td>$30130.57$ nT</td>
</tr>
<tr>
<td>$X$ (north component of the horizontal intensity)</td>
<td>$29904.63$ nT</td>
</tr>
<tr>
<td>$Y$ (east component of the horizontal intensity)</td>
<td>$-3683.00$ nT</td>
</tr>
<tr>
<td>$Z$ (vertical intensity)</td>
<td>$24079.34$ nT</td>
</tr>
<tr>
<td>$F$ (total intensity)</td>
<td>$38570.27$ nT</td>
</tr>
</tbody>
</table>

Table 7.1 lists the values as well as the annual change of the GF components. The regular changes of the components are also called secular variations. The estimation of the values was done for November 2006 according to the epoch 2005 IGRF model.

The Lorentz force exerted on charged particles in an EAS depends both on $Z_A$ and azimuth angle that correspond to the direction of the primary particle. For a particle of charge $q$, traveling at a velocity $\vec{v}$ through a magnetic field of strength $\vec{B}$, the Lorentz force $\vec{F}$ reads

$$\vec{F} = \frac{d\vec{p}}{dt} = q \left( \vec{v} \times \vec{B} \right) = q \frac{m}{m} \left( \vec{p} \times \vec{B} \right) \propto \vec{B}_\perp. \quad (7.8)$$

Therein $\vec{p}$ denotes the momentum of the particle and $\vec{B}_\perp$ the component of the magnetic field strength perpendicular to the direction of movement of the particle. For sake of simplification,
the reference frame is usually chosen such that the $y$-component of the magnetic field strength vanishes.

\[
\vec{B}(\theta, \phi) = -\sin \theta \sin \phi B_z \vec{e}_x + (\sin \theta \cos \phi B_z - \cos \theta B_x) \vec{e}_y + \sin^2 \theta B_x \vec{e}_z.
\] (7.9)

Therein the $\vec{e}_i$, $i = \{x, y, z\}$ denote the unit vectors of the tilted reference frame, and the angles $\phi$ and $\theta$ correspond to the azimuth angle and the ZA under which the particle is traveling.

In a reference frame rotated clockwise by the angle $D$ around the $z$-axis, the magnetic field reads $\vec{B} = (B_x, B_y, B_z)^T = (H, 0, Z)^T$. In such a reference frame, the magnetic field strength perpendicular to the direction of movement of the particle can be written as

\[
\vec{B}_\perp(\theta, \phi) = -\sin \theta \sin \phi B_z \vec{e}_x + (\sin \theta \cos \phi B_z - \cos \theta B_x) \vec{e}_y + \sin^2 \theta B_x \vec{e}_z.
\] (7.9)

---

**Figure 7.5:** The angle between the shower axis and the direction of the GF versus azimuth angle (for La Palma). The ZA was varied between $0^\circ$ and $60^\circ$ in steps of $10^\circ$.

**Figure 7.6:** The absolute value of the vertical component of the GF strength for alt-azimuth coordinates. (a) The absolute value of the vertical component of the GF strength for equatorial coordinates and $0^\circ \leq \text{ZA} \leq 90^\circ$. (b) The absolute value of the vertical component of the GF strength at the Roque de los Muchachos observatory on La Palma ($28.8^\circ$N, $17.9^\circ$W) for 10 km a.s.l., together with the trajectories of some established and potential VHE $\gamma$-ray sources. The GF components were calculated for November 2006 according to the epoch 2005 IGRF model [169].
The angle $\alpha$ between the shower axis and the direction of the GF can be expressed in terms of the azimuth angle and the ZA:

$$\alpha \equiv \angle(\vec{B}, \vec{p}) = \arcsin \left( \frac{|\vec{B}_\perp(\theta, \phi)|}{|\vec{B}|} \right).$$

(7.10)

Figure 7.5 shows the angle $\alpha$ between the shower axis and the direction of the GF versus azimuth angle (for La Palma). The ZA was varied between $0^\circ$ and $60^\circ$ in steps of $10^\circ$. Depending on the ZA, the angle $\alpha$ takes values between $\sim 0^\circ$ and $90^\circ$. For each ZA, the maximum Lorentz force coincides with the maximum angle $\alpha$. For instance, at about $40^\circ$ ZA the maximum Lorentz force is reached at $180^\circ$ azimuth angle.

Another representation of the relation between maximum Lorentz force, azimuth angle and ZA is shown in figure 7.6. The vertical component $|\vec{B}_\perp|$ of the GF strength at the Roque de los Muchachos observatory on La Palma ($28.8^\circ$ N, $17.9^\circ$ W) is shown for 10 km a.s.l., calculated for November 2006 for the epoch 2005 IGRF model [169].

Figure 7.6 (a) shows the absolute value of the vertical GF component for local, i.e. alt-azimuth coordinates. The trajectories of several selected sources at different declination angles are indicated. It is remarkable that the absolute value of the vertical GF component is symmetric in azimuth. The minimum influence of the GF is expected to occur at the magnetic north at $\text{ZA} = (90^\circ - I) \approx 51^\circ$, where the angle $\alpha$ between the shower axis and the GF lines becomes smallest. $I$ denotes the inclination angle under which the GF lines dip into the surface of the Earth (table 7.1). The maximum influence of the GF on EAS occurs in direction of the magnetic south at $\text{ZA} = I \approx 39^\circ$.

Figure 7.6 (b) shows the absolute value of the vertical GF component for equatorial coordinates. The figure was obtained for $0^\circ \leq \text{ZA} \leq 90^\circ$. The trajectories of several selected sources at different declination angles are indicated. For all sources, the field strength changes very little along the source trajectory. That is, if there is a non negligible systematic GF effect on the reconstruction methods, this effect can be expected to stay approximately constant along the trajectory of a certain source. Moreover, large ZA observations are not necessarily more affected by the GF than observations carried out at low ZA.

Except for M87, MAGIC has detected VHE $\gamma$-ray emission from all sources whose trajectories are indicated in figures 7.6 (a) and (b) [10, 11, 12, 13, 207]. Observations of the source HESS 1834-087 should be more affected by the GF compared to observations of LSI +61 303. The maximum effect is expected to occur for sources at declinations between $-20^\circ$ and $+10^\circ$.

Figure 7.7 shows the absolute value of the vertical component of the GF strength at the $\gamma$-ray observatories MAGIC, H.E.S.S., VERITAS and CANGAROO. While the GF strength at the H.E.S.S. site exhibits the lowest maximum value among all observatory sites, the one of the CANGAROO experiment exhibits the highest maximum field strength. Furthermore, the GF strength at the CANGAROO site varies by up to 90%. For low-ZA observations below $\sim 10^\circ$, the MAGIC and VERITAS sites exhibit the same GF strength over the entire range of the azimuth angle. In comparison to the other observatory sites, the H.E.S.S. site exhibits the lowest GF strength for observations carried out at $\text{ZA} \lesssim 10^\circ$. Thus, with regard to possible GF effects, the H.E.S.S. observatory site exhibits most favorable conditions for observations of the GC, while the VERITAS observatory site, apart from the large ZA under which GC observations have to be carried out, provides rather bad conditions for observations of the GC. For GC observations carried out under $\sim 60^\circ$ ZA at the MAGIC observatory site, the absolute value of the vertical GF component is $\sim 37 \mu$T, which is comparable to the GF strength for Crab nebula observations carried out under similar ZA. Therefore, if there is a significant GF effect on the image analysis, the effect should be comparable. It was shown elsewhere [139] that IACT measurements of TeV $\gamma$-rays from the Crab nebula were not significantly affected when the GF strength was below $35 \mu$T. However, the sensitivity of an instrument to the influence of
7.1. THE GEOMAGNETIC FIELD

the GF depends on the imaging performance, i.e. PSF and pixel resolution. IACTs currently in operation as well as future instruments may be more sensitive to GF effects.

![Graphs showing the absolute value of the vertical component of the GF strength at the \(\gamma\)-ray observatories MAGIC, H.E.S.S., VERITAS and CANGAROO, together with the trajectories of the Crab nebula and the Galactic Center. The GF components at 10 km a.s.l. were calculated for November 2006 according to the epoch 2005 IGRF model [169].](image)

**Figure 7.7:** The absolute value of the vertical component of the GF strength at the \(\gamma\)-ray observatories MAGIC, H.E.S.S., VERITAS and CANGAROO, together with the trajectories of the Crab nebula and the Galactic Center. The GF components at 10 km a.s.l. were calculated for November 2006 according to the epoch 2005 IGRF model [169].

To study the influence of the GF on the reconstruction methods using real MAGIC data will be complicated for several reasons. First of all, the source needs to be strong and stable, preferably without any time variability. Secondly, the change of the telescope performance must be as small as possible in order to be able to disentangle a possible influence of the GF from all other influences which may mimic and look like a GF effect. As already pointed out, the change of the intensity of the GF along a source trajectory is very little. For example, in case of the MAGIC site, Crab nebula observations restricted to \(\text{ZA} < 60^\circ\) involve changes of the GF intensity of at most 5%. In addition, the influence of the GF on the reconstruction methods for the VHE \(\gamma\)-ray signal is expected to be energy dependent. Because the energy threshold of an IACT strongly depends on the ZA under which observations are carried out (section 4.3.1), it is not trivial to extract a possible GF effect just from the comparison of observations carried out at different ZA intervals. Beside the Crab nebula, all other sources are either faint or variable in time. Therefore, it is much more straightforward to carry out MC simulations to investigate
possible GF effects on the reconstruction methods. Nevertheless, in case of MAGIC, the source HESS 1834-087 could be best suited to study a possible influence of the GF on the reconstruction methods for EAS (figure 7.6).

The impact of the GF on EAS as well as on the Cherenkov light distribution on ground is briefly discussed in the next two sections. Rather detailed reports on the GF effects on EAS and on the Cherenkov light distribution on ground can be found elsewhere [183, 193, 213].

7.1.1 The Influence of the Geomagnetic Field on EAS

Figure 7.8: The two-dimensional projection of the trajectories of secondary particles from a MC simulated $\gamma$-ray induced EAS. The energy of the primary $\gamma$-ray was set to 10 GeV and the GF was disabled. The EAS was simulated for very large ZA of 70$^\circ$. Electron trajectories are colored green, whereas the ones of positrons are colored red. Apart from differences due to intrinsic fluctuations of the EAS development, there is no systematic difference between the shape of the electron and the positron component in the EAS (adopted from [213]).

The Lorentz force acts on the movement of secondary charged particles in EAS. As the Lorentz force exerted on oppositely charged particles in a magnetic field points at diametrically opposed directions, the GF is expected to laterally broaden the EAS. It was discussed firstly in 1953 that the displacement from the rectilinear path due to the Lorentz force on electrons and positrons in EAS can be of the same order as the displacement due to Coulomb scattering [67].
7.1. THE GEOMAGNETIC FIELD

The magnetic deflection modifies the electron and positron distribution around the core of a γ-ray induced EAS rather than that of the low-energy electrons and positrons being more offset from the core. Below the critical energy $E_C \approx 83$ MeV, electrons and positrons lose their energy predominantly by ionization of air molecules as well as Compton scattering, i.e. low-energy electrons and positrons are carried away by single large-angle scatterings (section 4.1).

**Figure 7.9:** The two-dimensional projection of the trajectories of secondary particles from a MC simulated γ-ray induced EAS. The energy of the primary γ-ray was set to 10 GeV. The EAS was simulated for very large ZA of 70°. Electron trajectories are colored green, whereas the ones of the positrons are colored red. Both the electron and the positron component of the EAS are clearly separated, which is due to their (opposite) deflection by the GF (adopted from [213]).

Figure 7.8 shows the two-dimensional projection of the trajectories of secondary particles from a MC simulated γ-ray induced EAS, color coded by the particle species [213]. The energy of the primary γ-ray was set to 10 GeV and the GF was disabled. Even though a value of 10 GeV is well below the threshold energy of all IACTs currently in operation, the figure obtained with this somewhat extreme input parameter allows to illustrate the influence of the GF on EAS. The ZA was set to 70° and the azimuth angle was set to 90° to obtain a front view on the shower. Positron trajectories are colored red, while electron trajectories are colored green, and secondary photons (not Cherenkov photons!) are indicated as blue traces. Within statistical fluctuations,
the shapes of the electron and positron components are comparable. Apart from differences due to intrinsic fluctuations of the EAS development, there is no systematic difference between both components.

Figure 7.9 was generated under the same conditions, except for the GF, which was enabled. The overall shape of the EAS (upper left figure) is different from the one in figure 7.8. The influence of the GF becomes more obvious when comparing both the electron and the positron component, which are now clearly separated due to their opposite deflections by the GF. At the beginning, just after the interaction of the primary $\gamma$-ray with one of the atmospheric molecules, the deflection of the positive and the negative components is rather small. At this stage, the primary energy is distributed over a small number of secondary particles. During the development of the EAS downwards, the number of secondary particles increases fast and the primary $\gamma$-ray energy is distributed over a large number of secondaries. The charged secondary particles, carrying only a fraction of the energy of the primary $\gamma$-ray, are deflected stronger. The influence of the GF on both the electron and positron component in $\gamma$-ray induced EAS was studied in detail in [213].

The photon component (blue) of the EAS in figure 7.9 appears to be modified too. The modification of the neutral component in $\gamma$-ray EAS is indirectly related to the GF, since most of the secondary photons are produced in pair production processes involving secondary electrons and positrons, which are subject to deflection. Provided that most of the positrons and electrons in an EAS have enough energy to emit Cherenkov radiation, the distribution of Cherenkov photons on ground will be significantly modified. The change of the Cherenkov image on ground depends on the angle included by the trajectory of the primary $\gamma$-ray and the field lines of the GF. The largest change of the Cherenkov image is expected to occur for telescope orientations for which the vertical component of the GF strength is maximal (figure 7.6).

In case of hadron induced EAS, the deflection of secondary charged particles, such as nucleons and mesons, is expected to be smaller. Nuclear interactions involved in the development of hadron induced EAS cause a much larger lateral displacement than that due to the GF (section 4.1).

7.1.2 The Influence of the GF on the Cherenkov Light Distribution

As all charged particles in EAS are deflected due to the GF, the distribution of Cherenkov photons on ground will also be changed. Figure 7.10 shows the average distribution of Cherenkov photons on ground as obtained from a MC simulation. For each figure, 15 individual EAS events were averaged. The primary $\gamma$-ray energy was set to 50 GeV and the ZA to 50°. The GF was disabled in both cases.\(^1\) As expected, both images appear to be very similar. Independent of the azimuth angle which was set to 0° and 90°, respectively, the shape and the intensity level of the Cherenkov light distribution is very similar for both orientations. Differences between the images can be attributed to intrinsic fluctuations of the EAS development. The elliptical shape of the images is of geometrical origin, i.e. due to the fact that the Cherenkov cones emanating from the EAS are snipped on ground under an angle that corresponds to the ZA. For 0° ZA the Cherenkov images on ground look like a circle (figure 4.8, section 4.2.4).

To demonstrate the influence of the GF on the Cherenkov light distribution on ground, the MC simulation was rerun with enabled GF. Figure 7.11 shows the average distribution of Cherenkov photons on ground for a primary $\gamma$-ray of 50 GeV energy. Again, 15 events were averaged for each figure. The ZA was fixed to 50° and the azimuth angle was set to 0°, 45°, 90° and 135°. While figure 7.11 (a) is very similar to figure 7.10 (a), all other images appear to have significantly altered. As can be seen from figure 7.6 (section 7.1), at ~ 50° ZA, the vertical component of the GF strength is maximal at azimuth angles of ~ 135° and ~ 225°.

\(^1\)Because the CORSIKA simulation program requires non-zero input values for the GF components, the field components were set to the thousandth part of their nominal values.
respectively. At 45° azimuth angle and 50° ZA, the GF strength has already increased by more than a factor four with respect to 0° azimuth angle, resulting in a significant change of the Cherenkov light distribution (figure 7.11 (b)). The image appears to be rather faint compared to that obtained for 0° azimuth angle. Furthermore, the Cherenkov photons are widely spread along the secondary diagonal. The attenuation of the intensity of the Cherenkov images becomes even more pronounced for increasing azimuth angles. For 50° ZA, the maximum field strength is reached at \( \sim 135° \) azimuth angle. As can be seen from figure 7.11 (d), the corresponding intensity distribution of Cherenkov photons appears to be strongly attenuated compared to that obtained for 0° azimuth angle. Moreover, the distribution of Cherenkov photons is widely dispersed along the \( y \)-direction.

\[
\alpha_T \approx 0.04 \quad B \quad ZA = 50° \quad \text{Primary Energy} = 50 \text{ GeV} \quad Az = 0.00
\]

\[
\alpha_T \approx 0.04 \quad B \quad ZA = 50° \quad \text{Primary Energy} = 50 \text{ GeV} \quad Az = 90.00
\]

**Figure 7.10:** MC simulated distributions of Cherenkov photons on ground for \( \gamma \)-ray induced EAS. The primary \( \gamma \)-ray energy was set to 50 GeV, the ZA to 50° and the azimuth angle to 0° (a) and 90° (b), respectively. The GF was disabled in both cases. Both images appear to be very similar. Differences can be attributed to intrinsic fluctuations of the EAS development.

Obviously, there is a strong correlation between the angle \( \alpha \) and the Cherenkov density. The Cherenkov density decreases with increasing angle \( \alpha \), which is given in the title of the figures. Therefore, depending on the energy of the primary \( \gamma \)-ray and the orientation of its trajectory, the GF is expected to significantly reduce the performance of an IACT at those low energies. The decrease of the Cherenkov photon density at the telescope level reduces the number of Cherenkov photons that are collected by the mirror. As a result, the threshold energy of the detector will be increased as well as the effective collection area of the IACT will be affected [48, 122, 127, 139, 183, 192]. Furthermore, if the influence of the GF is not properly taken into account, the energy of a \( \gamma \)-ray may be significantly underestimated. The thinned distribution of Cherenkov photons can make a primary \( \gamma \)-ray of certain energy look like a \( \gamma \)-ray of much lower energy. The angular dispersion of the images will also have an effect on the angular resolution of an IACT. It was shown elsewhere that the distortions of the Cherenkov images on ground not only depend on the orientation of the trajectory of the primary \( \gamma \)-ray with respect to the GF lines, but also strongly depend on its energy [122, 127, 183, 192, 213].

### 7.1.2.1 Lateral Cherenkov Light Distribution

The figures 7.12-7.15 show the average lateral Cherenkov distribution of MC simulated \( \gamma \)-rays on ground as a function of the impact parameter \( r \) for several energies of the primary \( \gamma \)-ray. The energy was set to 50 GeV, 100 GeV, 300 GeV and 1 TeV, respectively. The ZA was varied...
between 20° and 60° in steps of 20°, and the azimuth angle between 0° and 180° in steps of 90°. Up to 100 events were averaged for each orientation and energy of the primary γ-ray.

As mentioned in the previous section, Cherenkov images on ground have, for a geometrical reason, an elliptical shape for ZA greater than zero. While the left column corresponds always to the semi-major axis of the Cherenkov ellipse on ground, the right one corresponds to the semi-minor axis. The angle between the direction of the momentum of the primary γ-ray and the direction of the GF lines is given in brackets behind the value of the azimuth angle in the legend.

The average lateral Cherenkov density significantly decreases with increasing ZA. For example, the comparison of the intensity of Cherenkov photons at the hump for 20° ZA and 60° ZA (in 7.12 (a) at about 120 m and in 7.12 (e) at about 400 m impact parameter) shows that the intensity decreases from ∼ 8 photons/m² to only ∼ 0.7 photons/m². The Cherenkov photons

**Figure 7.11:** MC simulated distributions of Cherenkov photons on ground for γ-ray induced EAS. The primary γ-ray energy was set to 50 GeV, the ZA to 50° and the azimuth angle to 0° (a) 45° (b) 90° (c) and 135° (d), respectively. The GF was enabled in all cases. Differences between the Cherenkov images can be attributed to the influence of the GF on the EAS development.
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originating from a $\gamma$-ray impinging at large ZA propagate longer through the atmosphere and therefore suffer from absorption. Furthermore, at large ZA, Cherenkov photons are distributed over a wider area resulting in a lower intensity.

The average lateral Cherenkov distribution shown in figure 7.12 exhibits some dependence on the azimuth angle. While the change of the intensity between $0^\circ$ and $180^\circ$ azimuth angle (solid black line and dash-dotted blue line) is less than 10\%, the change between $0^\circ$ and $90^\circ$ azimuth angle (solid black line and dashed red line) is greater, especially for large impact parameters $r$. For $90^\circ$ azimuth angle, the lateral distribution of Cherenkov photons is clearly broadened along the semi-major axis, which is aligned in east-west direction, i.e. perpendicular to the GF lines.

Even though the opposite way around, the same effect occurs for the Cherenkov distribution along the semi-minor axis (figures 7.12 (b), (d) and (f)). For $20^\circ$ ZA (figure 7.12 (b)), the Cherenkov distributions described by the solid black line and the dash-dotted blue line, i.e. the ones obtained for $0^\circ$ and $180^\circ$ azimuth angle, respectively, appear to be enhanced with respect to the one described by the dashed red line, especially at large impact parameters $r$. At larger ZA, the solid black curve is of similar shape as the dashed red curve, which can be explained by the decrease of the angle between the GF lines and the direction of the primary $\gamma$-ray.

At higher ZA, the influence of the GF becomes more pronounced. For $40^\circ$ ZA, depending on the azimuth angle, the Cherenkov photon intensity changes by up to 30\% (figure 7.12 (c) and (d)). For $60^\circ$ ZA and for the azimuth angles taken into consideration, the change of the Cherenkov photon intensity on ground is of the same order of magnitude as for $40^\circ$ ZA (figure 7.12 (e) and (f)).

At higher energies of the primary $\gamma$-ray, the influence of the GF on the shape of the lateral distribution of Cherenkov photons becomes smaller. For 100 GeV $\gamma$-rays (figure 7.13) at ZA up to $40^\circ$, there is almost no difference between the intensity of Cherenkov photons up to the hump at some 100 m impact parameter. At larger impact parameters beyond the hump of the Cherenkov distribution, the difference of the Cherenkov distributions is more pronounced.

At 300 GeV (figure 7.14) and 1 TeV energies (figure 7.15) of the primary $\gamma$-ray, respectively, the influence of the GF on the lateral distribution of Cherenkov photons gets smaller and smaller. Because high-energy EAS contain more charged particles with higher momentum, which are deflected less by the Lorentz force, the influence of the GF becomes lower with increasing energy of the primary $\gamma$-ray. The influence of the GF on the Cherenkov light distribution originating from low-energy $\gamma$-rays of energies between 10 GeV and 100 GeV was studied in [183, 193].
Figure 7.12: Average lateral distributions of Cherenkov photons on ground for $\gamma$-ray induced EAS. The primary $\gamma$-ray energy was set to 50 GeV, the ZA was set to 20°, 40° and 60°, and the azimuth angle to 0°, 90° and 180°, respectively. The left column corresponds to the semi-major axis of the Cherenkov ellipse on ground, while the right one to the semi-minor axis.
Figure 7.13: Average lateral distributions of Cherenkov photons on ground for $\gamma$-ray induced EAS. The primary $\gamma$-ray energy was set to 100 GeV, the ZA was set to 20°, 40° and 60°, and the azimuth angle to 0°, 90° and 180°, respectively. The left column corresponds to the semi-major axis of the Cherenkov ellipse on ground, while the right one to the semi-minor axis.
Figure 7.14: Average lateral distributions of Cherenkov photons on ground for γ-ray induced EAS. The primary γ-ray energy was set to 300 GeV, the ZA was set to 20°, 40° and 60°, and the azimuth angle to 0°, 90° and 180°, respectively. The left column corresponds to the semi-major axis of the Cherenkov ellipse on ground, while the right one to the semi-minor axis.
7.2. MC Production

The MC data used for the GF studies carried out in this work were produced following for most instances the standard MC production chain described in section 5.2.6.2. Showers were generated...
with the CORSIKA MC simulation program (MMCS version 6.19) [109, 192], processed further with the Reflector program (program version 0.6) [164] and the Camera program (program version 0.7) [45].

Figure 7.16: The telescope positions (green) and the primary $\gamma$-ray impact point (red) on the ground. The simulations were done for fixed impact parameters $r = 20\,\text{m}, \ldots 220\,\text{m}$ and fixed angles $\varphi = 0^\circ, 30^\circ, \ldots 330^\circ$.

To investigate the extent of the GF effect on the EAS development in greater detail, the EAS were simulated for fixed impact positions $(r, \varphi)$, i.e. in the range $r = 20\,\text{m}, \ldots 220\,\text{m}$ and $\varphi = 0^\circ, 30^\circ, \ldots 330^\circ$, which is illustrated in figure 7.16.\(^1\) The telescope position (green) was varied within the limits mentioned before, and the impact point of the primary $\gamma$-ray (red) was always fixed at the origin of the coordinate system. In this way, for not too big impact parameters, the telescope is always located somewhere in the Cherenkov pool on ground. The telescope is always oriented in the direction of the primary $\gamma$-ray. The impact parameter was varied in steps of 20 m and the angle $\varphi$ in steps of 30°.

By the choice of the arrangement for the telescope position and the $\gamma$-ray impact point $r$, the true impact parameter $r'$ varies between $r \cos(ZA)$ and $r$. Thus, in direction of the inclination of the telescope the DIST parameter scales like $\cos(ZA)$ (figure 6.3). For some arrangements $(r, \varphi, ZA, Az)$ the average DIST of the shower images lies below a lower cut usually applied to the data, e.g. $\text{DIST} > 0.2^\circ - 0.3^\circ$.

About $10^5$ events were generated per impact position at fixed primary $\gamma$-ray energies of 30, 50, 70, 120, 170, 300, 450 and 1000 GeV, respectively.

As the production of MC data is rather time consuming, the generation of $\gamma$ showers with a continuum energy distribution as well as continuum impact parameter distribution was omitted. Furthermore, the choice of discrete values for the primary $\gamma$-ray energy allows to investigate the energy dispersion of the showers due to the GF. Since the energy estimation of showers is based on the image parameter SIZE (section 6.2), it is important to know how its value depends on the GF.

As the absolute value of the vertical component of the GF is symmetric in azimuth (figure 7.6), the azimuth angle was varied in steps of 30°, from 0° to only 180°. The ZA was changed in steps of 20° in the range between 0° and 60°.

The simulation of the electronic noise as well as NSB was done as in the standard MC production. The diffuse NSB level for the inner pixels was set to 0.183 Phe/\text{ns}.

The optical PSF of the telescope was set to 1.4 cm (each axis) and the reflectivity of the mirrors was set to 73%, which is a rather conservative value, as the mirror reflectivity was lastly measured to be about 77% [71]. The MC simulations for this work were performed before that

\(^1\)For the production of standard MC data the EAS core location is randomly placed somewhere in a circle on the plane perpendicular to the direction of the EAS.
7.3 Analysis and Results

The trigger condition simulated in the MC is the one that is commonly used for data acquisition as well as for the standard MC production. Normally, a so-called four next-neighbor coincidence is required: at least 4 neighboring pixels are required to trigger, and, if any of the 4 pixels is taken out of the group, the remaining pixels are still neighbors.

Figure 7.17: The coordinate system of the CORSIKA MC simulation program [109]. The coordinate system is in line with the geomagnetic system such that the GF has only two components. The angle $\theta$ corresponds to the ZA and the angle $\phi \neq \varphi$ to the azimuth angle.

Figure 7.17 shows the coordinate system of the CORSIKA simulation program. The coordinate system is in line with the geomagnetic system such that the GF can be locally described by only two components, i.e. $\vec{B} = (B_x, 0, B_z)^T$ (section 7.1). The values used for the MC simulation are $B_x = 29.5 \mu T$ and $B_z = 23.0 \mu T$, respectively.

As a reference, MC data were produced with disabled GF. This was done only for $0^\circ$ azimuth angle, but in the same ZA range as the MC dataset for which the GF was enabled. In case of disabled GF, the MC generated $\gamma$ showers should not exhibit a dependency on the azimuth angle.

7.3 Analysis and Results

The MC generated $\gamma$ showers were calibrated using the MARS package (version 0.11.2) [51, 152, 151]. To find out about the influence of the image cleaning, the calculation of the image parameters was done for two image cleaning levels. The cleaning levels were set to 4.0 Phe (core pixels) and 2.0 Phe (boundary pixels) as well as to 10.0 Phe (core pixels) and 5.0 Phe (boundary pixels), respectively. The first set of image cleaning levels (in the following referred to as soft image cleaning) is rather low compared to the latter ones (in the following referred to as hard image cleaning), which are the default values used in the standard analysis for $\gamma$-ray energies above 100 GeV.

The image cleaning levels have to be chosen carefully (section 6.1) so as to keep a potential bias at a minimum. Too high image cleaning levels will reject not only uncorrelated background but may also remove a non negligible fraction of the signal itself. Especially in the low-energy regime, at primary $\gamma$-ray energies below $\sim 100$ GeV, a relaxed image cleaning is important to keep as much low-energy events as possible, i.e. to obtain a reasonable detection efficiency for low-energy $\gamma$-rays and to minimize the analysis threshold for data. Moreover, due to the influence of the GF on low-energy $\gamma$-ray induced EAS, some of the corresponding shower images may look more hadron-like, which may cause them to be removed if the image cleaning levels are chosen too high.
7.3.1 GF Effects on the Image Parameters

For this work, all image parameters that are commonly used for the extraction of the γ-ray signal were calculated. As demonstrated in section 7.1.2, the GF affects the shape, the orientation as well as the intensity of the Cherenkov light distribution on ground. Therefore, the GF is expected to affect the reconstructed shower images in the camera plane of the telescope, which was already shown elsewhere [48, 58, 122, 127, 139, 183, 192, 213].

Figure 7.18: The influence of the GF is qualitatively demonstrated in terms of Hillas ellipses obtained from MC generated γ showers. On each camera display, ten Hillas ellipses are superimposed. The primary γ-ray energy was set to 450 GeV and the ZA to 40°. The GF was enabled. While figure (a) contains Hillas ellipses for showers generated at 0° azimuth angle where the GF strength is minimal (figure 7.6), figure (b) is obtained for showers generated at 180° azimuth angle where the GF strength is maximal, i.e. the angle between the GF lines and the direction of the primary γ-ray is about 90° (figure 7.5). In the latter case, the shape and orientation of the Hillas ellipses has clearly changed with respect to the ones plotted in figure 7.18 (a). The Hillas ellipses appear to be more roundish, and the angle of the major image axis enclosed with the y-axis has a much larger spread. As the telescope axis is parallel to the shower axis, the major image axis should enclose small angles with the y-axis, which is the case for 0° azimuth angle (figure 7.18 (a)). The dispersion of the alignment with respect to the y-axis will cause the distribution of the image parameter ALPHA to appear broadened. The broadening of the ALPHA distribution affects the reconstruction of the γ signal, which, in the ideal case, shows up at small values of the image parameter ALPHA (section 6.4). Therefore, the influence of the GF can cause a loss of signal events, i.e. the number of excess events from the ALPHA distribution is lower than the one which could be expected in the absence of the GF.

Apart from that, the influence of the GF on the other image parameters that describe the shape of shower images, like the WIDTH and LENGTH parameters, may affect the γ/hadron separation capability of the analysis. It was already shown that the image parameters WIDTH
and LENGTH, also very important for the background suppression, are subject to changes due to the influence of the GF [59, 122, 127, 183, 192, 213].

In the preceding section it was shown that the GF can thin out the distribution of Cherenkov light on ground. The reduction of the number density of Cherenkov photons will affect the $\gamma$ efficiency. In other words, the detection probability for the primary $\gamma$-ray depends on its arrival direction with respect to the GF lines.

Both the number of $\gamma$-ray candidates derived from the ALPHA distribution as well as the $\gamma$ efficiency derived from MC simulations are used to estimate the differential flux of a VHE $\gamma$-ray source (section 6.7). Provided that the influence of the GF on the image parameters depends on the energy of the $\gamma$ shower [122, 127, 183, 192, 213], the GF can affect not only the level of the

Figure 7.19: MC simulated distributions of Cherenkov photons on ground for $\gamma$-ray induced EAS. The primary $\gamma$-ray energy was set to 100 GeV. The azimuth angle was fixed to 0° and the ZA was set to 0° (a) 20° (b) 40° (c) and 60° (d), respectively. The GF was enabled in all cases. The origin of the coordinate system is placed at the point of intersection of the primary $\gamma$-ray’s trajectory with the ground. The Telescope is placed at fixed positions on the light blue circles.
observed γ-ray flux, but also the shape of the reconstructed differential energy spectrum. The shape of the differential energy spectrum derived for a certain source as well as the absolute flux level is generally used to probe assumptions on the physical processes taking place at the source. It is therefore very important to investigate the effect of the GF on the image parameters in great detail, and to possibly correct the differential energy spectrum for effects of the GF.

![Figure 7.20: Average lateral distribution of MC simulated Cherenkov photons on ground for γ-ray induced EAS. The γ-ray energy was set to 100 GeV. Both the azimuth angle as well as the ZA were set to 0°. The red line would be measured by a telescope situated on the x-axis of the CORSIKA coordinate system, while the black corresponds to a telescope situated on the y-axis.](image)

To clean the MC dataset, weak pre-selection cuts have been applied: for all data, the parameter NUMCOREPIXELS was required to be greater than four, i.e. only showers having a minimum of four core pixels were kept, and the DIST parameter was required to be greater than 0.1° (section 6.2 for the definition of the image parameters). A lower cut on the number of core pixels ensures that the moments used for the image parameter calculation are well defined. The lower cut on the image parameter DIST is motivated by the fact that the image parameter ALPHA is not defined for too small DIST values, since shower images located in the camera center appear to be roundish without any preferential direction.

Because of the strategy which was selected for the MC production (section 7.2), the interpretation of the reconstructed data has to be done carefully. For instance, the positioning of the telescope at fixed radii around the primary γ-ray impact point on ground (figure 7.16) causes the GF effects and geometrical effects on the image parameters to be entangled. For ZA greater than 0°, the maximum intensity of Cherenkov photons, the so-called hump, is not any more located on a circle centered at the intersection point of the primary γ-ray’s trajectory with the ground. Instead, the maximum intensity is located on an ellipse whose semi-minor axis corresponds to the impact parameter r, while its semi-major axis scales like $r \cos^{-1}(ZA)$.

Figure 7.19 shows the MC simulated distributions of Cherenkov photons on ground for γ-ray induced EAS of 100 GeV energy. The azimuth angle was fixed to 0° and the ZA was varied between 0° and 60° in steps of 20°. The GF was enabled in all cases. About 150 events were averaged.

In absence of the GF, figure 7.19 (a) would be symmetric with respect to the origin of the gray coordinate system superimposed to the distribution of Cherenkov photons. That is, along the light blue circles that are superimposed to the distribution and centered at the origin of the coordinate system, the average intensity would remain constant. Instead, the distribution
of Cherenkov photons appears to be asymmetric which is due to the fact that positrons and electrons in EAS are deflected to opposite directions. The intensity of Cherenkov photons along the $y$-axis is smaller than the one on the $x$-axis. As a result, the estimated energy of the primary $\gamma$-ray will be underestimated if this effect is not properly taken into account. Thus, by using inappropriate MC produced at wrong azimuth angles, the energy may be systematically under- or overestimated. Another representation of this effect is given in figure 7.20 where the average lateral distribution of Cherenkov photons along the $x$-axis and $y$-axis, respectively, is shown. While the red curve corresponds to the intensity measured by a telescope situated at the $x$-axis ($\phi = 0^\circ$), the black curve would be measured along the $y$-axis ($\phi = 90^\circ$).

Figure 7.21: Frequency distributions of reconstructed image centroids for MC generated $\gamma$-ray showers. The energy was set to 30 GeV. The ZA was fixed to 0°, while the azimuth angle was set to 0° (a) and 90° (b), respectively. The soft image cleaning was applied.

At 0° ZA, the asymmetry of the distribution of Cherenkov photons due to the GF is independent of the azimuth angle, as the angle $\alpha$ stays constant with increasing azimuth angle (figure 7.5). For ZA greater than 0°, the influence of the GF depends on the azimuth angle. The distribution of Cherenkov photons shown in figure 7.19 (b), obtained for 20° ZA, is not only asymmetric in the same way as the one shown in figure 7.19, but in addition, it appears to be elongated along the $x$-axis. In absence of the GF, the average intensity of Cherenkov photons measured along the pink circles would be constant. In the MC data produced for these studies, the telescope is always placed on the light blue circles. Therefore, the GF effects as well as geometrical effects are entangled.

The reconstructed intensity not only changes because of the GF, but also because the telescope is not always located at the hump of the distribution of Cherenkov photons. At 20° ZA, the deviation from a circle is at most 6 m which roughly corresponds to the width of the hump (figures 7.12 (a) - 7.15 (a)). At larger ZA, the deviation of the Cherenkov distribution from a circle becomes greater, i.e. for 40° ZA it extends up to 30 m and for 60° ZA it extends up to 100 m.

Figure 7.19 (d) exhibits an additional south-north asymmetry of geometrical origin. Because of the inclination of the EAS with respect to the $x$-axis, half of all Cherenkov photons cover a greater distance through the atmosphere, which results in a certain attenuation (section 4.2.3). The path difference $\Delta s$ depends on the impact parameter $r$ and the ZA. For instance, at 40° ZA and $r = 120$ m it amounts to $\Delta s = 2r \tan(ZA) \approx 200$ m, and for 60° ZA it is $\Delta s \approx 420$ m.
Figure 7.22: Depending on the orientation of the telescope, one is confronted with a different situation. The circles correspond to the position of the maximum intensity (the hump in the lateral distribution at \( r \approx 120 \) m) of Cherenkov photons. The telescope positions are indicated as green spots and the primary \( \gamma \)-ray impact point is indicated as a red spot.

Figure 7.21 shows the frequency distributions of the reconstructed image centroids of MC generated \( \gamma \)-ray showers of 30 GeV energy for two different azimuth angles. The ZA was fixed to \( 0^\circ \) ZA and the azimuth set to \( 0^\circ \) and \( 90^\circ \), respectively. For \( 0^\circ \) azimuth angle (figure 7.21 (a)), the \( x \)-axis of the camera reference system is aligned with the \( y \)-axis of the CORSIKA reference system (figure 7.17). Due to the influence of the GF, the number of showers above the analysis threshold reconstructed along the \( x \)-axis of the camera reference system is lower than the one reconstructed along the \( y \)-axis. A comparable distribution of centroids, even though rotated anti-clockwise, is obtained for \( 90^\circ \) azimuth angle (figure 7.21 (b)). The latter is expected, because for \( 0^\circ \) ZA the lateral component of the GF stays constant with increasing azimuth angle.

According to the relation between the coordinate system of the CORSIKA MC program and the one of the Reflector program [164], the image parameter \( \delta \), the azimuth angle and the angle \( \varphi \) are related through

\[
\delta = 90^\circ + \text{azimuth angle} - \varphi.
\]  

(7.11)
Therein \( \delta \) is defined as the angle between the major axis of the shower image in the camera and the \( x \)-axis of the camera coordinate system (figure 6.2).

As already pointed out, for fixed impact parameters \( r \) as well as fixed angles \( \varphi \) and \( ZA > 0^\circ \) the telescope is not always located at the hump of the Cherenkov distribution on ground. Therefore, to disentangle both the geometrical effect and the influence of the GF, it is appropriate to place the telescope always on the hump, i.e. on the semi-minor axis of the ellipses of maximum intensity. To achieve this, the angle \( \varphi \) must be set to \( \varphi = \text{azimuth angle} + 90^\circ \), while the impact parameter \( r \) can be kept constant. Figure 7.22 illustrates the situation. The circles and ellipses, respectively, correspond to the position of the maximum intensity (the hump in the lateral distribution at an impact parameter of \( r \approx 120 \text{ m} \)) of the Cherenkov photon distribution. For \( ZA > 0^\circ \), each circle devolves to an ellipse whose orientation is given by the azimuth angle. The telescope positions are indicated as green spots and the primary \( \gamma \)-ray impact point is indicated as a red spot.

### 7.3.1.1 Influence of the GF on Shape and Orientation of the Shower Images

As the \( \gamma \)/hadron separation is based on the shape and orientation of the shower images, it is important to investigate the influence of the GF on the image parameters that are commonly used for the background discrimination (section 6.3).

### 7.3.1.1.1 Influence of the GF on the Image Parameters WIDTH and LENGTH

To investigate the influence of the GF on the image parameters WIDTH and LENGTH, it is helpful to depict the reconstructed \( \gamma \)-ray images in the camera. Furthermore, to disentangle the influence of the GF on the shape of the images and the one on the orientation of the images, it is, for the first instance, suggestive to ignore the information on the distortion of the image parameter DIST and the parameter \( \delta \).

Figure 7.23 shows the Hillas ellipses for primary \( \gamma \)-rays of 30 GeV energy, two different image cleaning levels and two ranges of the impact parameter, i.e. 40-60 m as well as 100-120 m. The ZA was set to 0\(^\circ\). In this case, as the absolute value of the GF strength is symmetric in the azimuth angle (figure 7.6), it is sufficient to consider only one azimuth angle. The minor and major axes of the Hillas ellipses are obtained from the mean values of the distributions of the image parameters WIDTH and LENGTH. For each telescope position \((r, \varphi)\), the ellipses are placed at the average DIST value that was obtained in case of disabled GF in the MC simulation. The nominal orientation \( \delta \) of the ellipses is given by equation 7.11. Compared to the images which have survived the soft image cleaning (figures 7.23 (a) and (c)), the images obtained after application of the hard image cleaning levels appear to be significantly smaller. The latter is expected, as the application of the hard image cleaning levels result in a removal of more boundary pixels which do not contribute any more to the size of the images. Undistorted shower images, which were obtained for disabled GF, are displayed as blue ellipses (dotted lines), whereas distorted shower images, which were obtained for enabled GF, are displayed as red ellipses (solid lines). As indicated by the black curve in the upper right part of the figures 7.23 (a) - (d), for 0\(^\circ\) ZA, the Cherenkov light distributions on ground are circularly shaped. The coordinate system of the MC program CORSIKA (figure 7.17) is centered on the camera display, and the coordinate system of the telescope camera is indicated in the lower left part of the figures 7.23 (a) - (d). The \( x \)-axis of the CORSIKA coordinate system is always in line with the GF whose projection in the camera is indicated in the lower right part of the figures.

As can be seen from figure 7.23 (a) (soft image cleaning), on average, the distortion of the image parameters WIDTH and LENGTH is rather small. In case of larger image cleaning levels (figure 7.23 (b)), the Hillas ellipses obtained for enabled GF appear to be slightly different from the ones obtained for disabled GF. Images lying on the \( x \)-axis of the camera coordinate system
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$(\varphi = 90^\circ, 270^\circ)$ are slightly stretched horizontally with respect to the direction of the GF. Instead, images lying on the $y$-axis of the camera coordinate system appear to be more roundish than the one obtained for disabled GF. This effect was already shown qualitatively in [59]. In both cases, i.e. for $\delta = 0^\circ, 180^\circ$ as well as $\delta = 90^\circ, 270^\circ$, the average pointing of the shower images is expected to be maintained and the parameter ALPHA should remain mostly unaffected. The angle $\delta$ is counted anti-clockwise from the positive $x$-axis of the camera coordinate system (figure 6.2 for the definition of the angle $\delta$). At intermediate angles $\delta \neq 0^\circ, 90^\circ, 180^\circ, 270^\circ$ the shower images are expected to be affected too, although the figures do not allow to draw a conclusion (at least at the $\gamma$-ray energies considered for this plot). At larger impact parameters (figures 7.23 (c)-(d)) the situation is similar, although the average WIDTH and LENGTH of the shower images appear to be slightly less affected than in case of smaller impact parameters.

At $ZA > 0^\circ$, the situation is somewhat different, as the angle $\alpha$ between the shower axis and the direction of the GF is a function of the azimuth angle, i.e. the absolute value of the GF strength changes with increasing azimuth angle (figure 7.6). Figure 7.24 shows the Hillas ellipses for primary $\gamma$-rays of 30 GeV energy, two different image cleaning levels and impact parameters between 100 m and 120 m. The ZA was set to $20^\circ$. The Hillas ellipses depicted in figure 7.24 (a) are similar to the ones in figure 7.23 (a), although the influence of the GF is expected to be smaller, as the angle between the direction of the shower axis and the GF lines is smaller ($\alpha = 32^\circ$). The shapes of the Hillas ellipses obtained for $180^\circ$ azimuth angle are comparable to the ones obtained for $0^\circ$ azimuth angle. The shape of the distorted $\gamma$-ray images does not systematically change as a function of the angle $\delta$. Instead, the variation of the shape of the images is rather due to limited statistics and a significant difference between the images obtained for disabled GF and the ones obtained for enabled GF is hardly visible. At 30 GeV and $20^\circ$ ZA the trigger efficiency is in the order of 10% (section 7.3.1.3). Therefore, at higher energies where much more events survive the image cleaning procedure, the influence of the GF on the image parameters WIDTH and LENGTH is expected to appear more articulated.

Figure 7.25 shows the Hillas ellipses for primary $\gamma$-rays of 450 GeV energy, two different image cleaning levels and two ranges of the impact parameter, i.e. 40 - 60 m as well as 100 - 120 m. The ZA was set to $0^\circ$. As can be seen from the figures, the Hillas ellipses obtained for enabled GF appear to be different from the ones obtained for disabled GF. The distortion of the images occurs at impact parameters 40 - 60 m as well as between 100 m and 120 m, independently of the image cleaning level. Images lying on the $x$-axis of the camera coordinate system $(\varphi = 90^\circ, 270^\circ)$ are slightly stretched horizontally with respect to the direction of the GF. Instead, images lying on the $y$-axis of the camera coordinate system appear to be more roundish than the one obtained for disabled GF. In both cases, i.e. for $\delta = 0^\circ, 180^\circ$ as well as $\delta = 90^\circ, 270^\circ$, the average pointing of the shower images is expected to be maintained, and the parameter ALPHA should remain unaffected. Shower images pointing at intermediate angles $\delta \neq 0^\circ, 90^\circ, 180^\circ, 270^\circ$ are altered compared to the ones obtained for disabled GF. Because these images are neither oriented horizontally nor vertically with respect to the direction of the GF, the sideways extension of these showers images is expected to result in a systematic rotation away from the source position (camera center) [59]. Therefore, at least at intermediate angles $\delta$, the distribution of the parameter ALPHA is expected to be broadened.
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Figure 7.23: Hillas ellipses for primary γ-rays of 30 GeV energy, two different image cleaning levels and two impact parameter windows. The ZA was set to 0° and the azimuth angle to 0°. The angle $\varphi$ was varied over the full range between 0° and 330°. To demonstrate the influence of the GF on the image parameters WIDTH and LENGTH, the distortion of the orientation ($\delta$) and the parameter DIST was ignored. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity (zero for 0° ZA) of the Cherenkov light distribution on ground.
Figure 7.24: Hillas ellipses for primary $\gamma$-rays of 30 GeV energy, two different image cleaning levels and impact parameters between 100 m and 120 m. The ZA was set to 20° and the azimuth angle to 0° and 180°, respectively. The angle $\varphi$ was varied over the full range between 0° and 330°. To demonstrate the influence of the GF on the image parameters WIDTH and LENGTH, the distortion of the orientation ($\delta$) and the parameter DIST was ignored. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
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Figure 7.25: Hillas ellipses for primary $\gamma$-rays of 450 GeV energy, two different image cleaning levels and two impact parameter windows. The ZA was set to 0° and the azimuth angle to 0°. The angle $\varphi$ was varied over the full range between 0° and 330°. To demonstrate the influence of the GF on the image parameters WIDTH and LENGTH, the distortion of the orientation ($\delta$) and the parameter DIST was ignored. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity (zero for 0° ZA) of the Cherenkov light distribution on ground.
Figure 7.26: Hillas ellipses for primary $\gamma$-rays of 450 GeV energy and impact parameters between 100 m and 120 m. The hard image cleaning level was applied. The ZA was set to 20° and 40°, respectively, and the azimuth angle to 0° and 180°, respectively. The angle $\varphi$ was varied over the full range between 0° and 330°. To demonstrate the influence of the GF on the image parameters WIDTH and LENGTH, the distortion of the orientation ($\delta$) and the parameter DIST was ignored. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
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Figure 7.27: Hillas ellipses for primary $\gamma$-rays of 1 TeV energy and impact parameters between 100 m and 120 m. The hard image cleaning level was applied. The ZA was set to 20° and 40°, respectively, and the azimuth angle to 0° and 180°, respectively. The angle $\varphi$ was varied over the full range between 0° and 330°. To demonstrate the influence of the GF on the image parameters WIDTH and LENGTH, the distortion of the orientation ($\delta$) and the parameter DIST was ignored. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.

Figure 7.26 shows the Hillas ellipses for primary $\gamma$-rays of 450 GeV energy, two different image cleaning levels and impact parameter between 100 m and 120 m. The ZA was set to 20° and 40°, and the azimuth angle was set to 0° and 180°, respectively. The Hillas ellipses depicted in figure 7.26 (a) that were obtained for enabled GF are altered slightly less than the corresponding ellipses in figure 7.26 (b), which is due to the fact that the influence of the GF is weaker. In the
latter case, the angle between the direction of the shower axis and the GF lines is $\alpha = 72^\circ$.

At $40^\circ$ ZA, the difference between images obtained for $0^\circ$ azimuth angle (figure 7.26 (c)) and $180^\circ$ azimuth angle (figure 7.26 (d)) is even more pronounced. In figure 7.26 (c), the Hillas ellipses obtained for enabled GF look alike the ones obtained for disabled GF, whereas in figure 7.26 (d) the influence of the GF is clearly visible.

Figure 7.27 shows the Hillas ellipses for primary $\gamma$-rays of 1 TeV energy and impact parameters between 100 m and 120 m. The images were obtained by application of the hard image cleaning. The azimuth angle was set to $0^\circ$ and $180^\circ$ and the ZA to $20^\circ$ and $40^\circ$. Similar to the case of lower energies the GF effect is clearly visible.

From the figures presented beforehand, it can be concluded that, for very low energies, the influence of the GF on the WIDTH and LENGTH of the shower images is, within statistics, in the order of the one presumably resulting from intrinsic fluctuations in the shower development. For higher energies, the influence of the GF on the shape of the Hillas ellipses is clearly visible.

As yet it was not investigated to what extent the alternation of the shape of the shower images degrades the $\gamma$/hadron separation. But, even for very unfavorable orientations of the shower axis with respect to the GF lines (large angle $\alpha$) the standard $\gamma$/hadron separation should be feasible, even though it might be degraded. Apart from the influence of the GF on the shape of the shower images, its influence on the orientation of the images is of major importance, as it directly affects the distribution of the parameter ALPHA commonly used to extract the $\gamma$ signal.

7.3.1.1.2 Influence of the GF on the Orientation of $\gamma$-Ray Shower Images

The investigation of the influence of the GF on the orientation of the shower images is important, as it allows to draw a conclusion to what extent the GF affects the analysis of Cherenkov images, particularly with regard to the $\gamma$/hadron separation, which is partially based on the image orientation.

Figure 7.28 shows the Hillas ellipses for primary $\gamma$-rays of 30 GeV energy, two different image cleaning levels, two impact parameter windows, $0^\circ$ ZA and $0^\circ$ azimuth angle. The angle $\varphi$ was varied over the full range between $0^\circ$ and $330^\circ$. For each position $(r, \varphi)$ of the telescope, the corresponding ellipse is positioned according to the average value of the DIST parameter as well as the average angle $\delta$. The angle $\delta$ is counted anti-clockwise from the positive $x$-axis of the camera coordinate system indicated in the lower left part of the figures (figure 6.2 for the definition of the angle $\delta$). The coordinate system of the MC program CORSIKA, (figure 7.17) is always centered on the camera displays. Furthermore, the $x$-axis of the CORSIKA coordinate system is always in line with the GF whose projection in the camera is indicated in the lower right part of the figures. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
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Figure 7.28: Hillas ellipses for primary $\gamma$-rays of 30 GeV energy, two different image cleaning levels and two impact parameter windows. The ZA was set to 0° and the azimuth angle to 0°. The angle $\varphi$ was varied over the full range between 0° and 330°. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
(a) Soft image cleaning, ZA 20°, azimuth angle 0°, impact parameter 60 - 100 m.
(b) Soft image cleaning, ZA 20°, azimuth angle 90°, impact parameter 60 - 100 m.
(c) Soft image cleaning, ZA 20°, azimuth angle 120°, impact parameter 60 - 100 m.
(d) Soft image cleaning, ZA 20°, azimuth angle 180°, impact parameter 60 - 100 m.

Figure 7.29: Hillas ellipses for primary γ-rays of 30 GeV energy and impact parameters between 60 m and 100 m. The ZA was set to 20° and the azimuth angle to 0°, 90°, 120° and 180°, respectively. The angle ϕ was varied over the full range between 0° and 330°. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
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Figure 7.30: Hillas ellipses for primary $\gamma$-rays of 30 GeV energy. The ZA was set to 20° and the azimuth angle to $0^\circ$, $90^\circ$, $120^\circ$ and $180^\circ$, respectively. The angle $\varphi$ was varied over the full range between $0^\circ$ and $330^\circ$. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
The red ellipses (solid lines) were obtained for enabled GF and the blue ones (dashed lines) were obtained for disabled GF. The Hillas ellipses depicted in figure 7.28 (a) significantly differ from the ones depicted in figure 7.28 (b), which were obtained after application of the hard image cleaning. At these low energies (30 GeV), the application of the hard image cleaning levels results in the removal of many events, which in turn significantly reduces the statistics (section 7.3.1.3). Moreover, the application of the hard image cleaning increases the average distance of the images to the camera center, which is due to the fact that the intensity of Cherenkov light on ground is not flat (figure 7.12). At impact parameters between 60 m and 100 m, the intensity of the Cherenkov light increases towards greater impact parameters. Therefore, at low energies, the trigger probability increases towards greater impact parameters.

The Hillas ellipses obtained for enabled GF, soft image cleaning and impact parameters between 60 m and 100 m (figures 7.28 (a) - (b)) appear to have a preferential direction of rotation, although the rotation angle is rather small. At larger impact parameters (figures 7.28 (c) - (d)), the Hillas ellipses obtained for enabled GF appear to be rotated with respect to the ones obtained for disabled GF and the rotation angle is greater than in figure 7.28 (a). Furthermore, the rotation is symmetric with respect to the direction of the GF. Ellipses situated on the x-axis and the y-axis of the camera coordinate system, i.e. perpendicular and parallel to the direction of the GF, appear to be aligned with the ones obtained for disabled GF.

Figures 7.29 (a) - (d) show the Hillas ellipses for primary $\gamma$-rays of 30 GeV energy, 20° ZA and impact parameters between 60 m and 100 m. The azimuth angle was set to 0°, 90°, 120° and 180°. At 0° azimuth angle (figure 7.29 (a)), where the GF strength is lowest, the average orientation of the shower images obtained for enabled GF resembles the one obtained for disabled GF. At larger azimuth angles (figures 7.29 (b) - (d)), the rotation of the shower images slightly increases. Most of the images are rotated in the right direction. The very large rotation angles of some images (figure 7.29 (d)) can be explained by statistical fluctuations. The decrease of the intensity of the Cherenkov light on ground with increasing ZA further reduces the detection probability and therefore the statistics of the datasets.

Figure 7.30 shows the Hillas ellipses obtained for a similar configuration of input parameters but for impact parameters between 100 m and 140 m. The situation is comparable to the one depicted in the preceding figures, although the average distance of the images to the camera center is greater. The ellipses situated at intermediate angles $\delta$ (not the ones on the x- and y-axis of the CORSIKA coordinate system) are systematically rotated towards the x-axis. However, at higher energies where the statistics are higher, the influence of the GF on the orientation of the GF is expected to be better separable from effects resulting from intrinsic fluctuations in the EAS development.

Figure 7.31 shows the Hillas ellipses for primary $\gamma$-rays of 170 GeV energy, 0° ZA, 0° azimuth, angle two different image cleaning levels and two impact parameter windows. The ellipses obtained for enabled GF and soft image cleaning depicted in figure 7.31 (a), do not exhibit a pronounced rotation like the corresponding images in figure 7.31 (b), where the hard image cleaning was applied. The average pointing of the Hillas ellipses obtained for enabled GF depicted in the latter figure is degraded due to the influence of the GF. While the average pointing is preserved for images oriented either parallel or vertically with respect to the direction of the GF, i.e. at $\delta = 0°, 90°, 180°$ and 270°, images oriented at intermediate angles are rotated. At intermediate angles $\delta$, the pointing is degraded, i.e. the major image axis does not any more point towards the camera center.

At larger impact parameters (figures 7.31 (c) - (d)), the situation is similar, although the rotation of the images obtained for enabled GF appears to be smaller. The orientation of the images in figure 7.31 (d) exhibits the same symmetry as the ones in figure 7.31 (b). The Hillas ellipses depicted in figure 7.32 were obtained for the same telescope orientation, but for larger impact parameters. In case of the hard image cleaning, the images obtained for enabled GF exhibit some rotation with respect to the ones obtained for disabled GF. For impact parameters
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between 100 m and 140 m (figures 7.32 (a) - (b)), only images at intermediate angles $\delta$ are rotated. The rotation appears to be more pronounced for impact parameters above 140 m (figures 7.32 (c) - (d)). Furthermore, compared to figure 7.31 (b) (20 - 60 m impact parameter), the angle of rotation has changed its sign, although the symmetry with respect to the direction of the GF is preserved. The former is probably related to the fact that, for impact parameters greater than $\sim$ 140 m, the intensity of the Cherenkov light on ground decreases with increasing distance to the core of the light pool, while for impact parameters below $\sim$ 100 m the intensity increases with increasing impact parameter (figures 7.12 - 7.15). However, the shower images in figure 7.36 do not exhibit the flip in the sign of the rotation angle.

Figure 7.33 shows the Hillas ellipses for primary $\gamma$-rays of 170 GeV energy, 20° ZA and impact parameters between 20 - 60 m. The azimuth angle was set to 0°, 90°, 120° as well as 180°. The shower images obtained for enabled GF are significantly rotated away from the direction of the GF. The expected increase of the rotation angle with increasing azimuth angle, i.e. increasing angle $\alpha$ between the direction of the primary $\gamma$-ray and the direction of the GF, is hardly visible. At greater impact parameters between 60 m and 140 m (figures 7.34 - 7.35), the influence of the GF appears to be less pronounced. For 0° azimuth angle (figure 7.35 (a)), the angle of rotation is very small. Even for an unfavorable orientation at 180° azimuth angle (figure 7.35 (d), large angle $\alpha$), the average pointing of the images obtained for enabled GF is preserved.

Figure 7.36 shows the Hillas ellipses for primary $\gamma$-rays of 450 GeV, four impact parameter windows, 0° ZA and 0° azimuth angle. The figures obtained for these input parameters exhibit a similar behavior as the figures obtained for 170 GeV $\gamma$-ray energy (figure 7.31). At impact parameters between 20 m and 60 m (figure 7.36 (a)), the average distortion of images at intermediate angles $\delta \neq 0°, 90°, 180°$ and 270° results in a sizeable mis-pointing. At larger ZA, the influence of the GF on the average pointing of the shower images is more pronounced. Figures 7.37 and 7.38 show the Hillas ellipses for $\gamma$-rays of 450 GeV energy, four impact parameter windows, 20° ZA, and two azimuth angles, 0° and 180°, respectively. At 180°, the rotation of the images is more pronounced than for the images obtained for 0° azimuth angle, because the influence of the GF is stronger for the latter telescope orientation. At 40° ZA, the difference between images obtained for enabled GF, 0° and 180° azimuth angle, respectively, is even more pronounced (figures 7.39 and 7.40). For impact parameters below $\sim$ 140 m and 180° azimuth angle (figures 7.40 (a) - (c)), the influence of the GF is very pronounced (the GF strength is maximal, figure 7.6), while for 0° azimuth angle (figures 7.39 (a) - (c)), the influence of the GF is rather small, i.e. the images obtained for enabled GF are nearly oriented like the ones obtained for disabled GF.

It is worth mentioning that for ZA $> 0°$ the major image axes obtained for disabled GF are not any more parallel to the gray dotted lines crossing the camera center. The gray dotted lines correspond to the nominal orientations of the shower images according to the telescope positions ($r, \varphi$). However, the rotation results from the impact parameter definition in the production of the MC datasets (section 7.2) but it does not affect the pointing of the images. For ZA $> 0°$, the true impact parameter $r'$ as well as the DIST parameter scale like cos(ZA), resulting in an elliptical arrangement of the images in the camera display (e.g. figure 7.40).

Figure 7.41 shows the Hillas ellipses for primary $\gamma$-rays of 450 GeV energy, two impact parameter windows, 60° ZA and 0° and 180° azimuth angle. For 0° azimuth angle (figures 7.41 (a) - (b)), the influence of the GF is very small, resulting in a small distortion, while for 180° azimuth angle (figure 7.41 (c) - (d)), the influence is very strong. The Hillas ellipses shown in figures 7.42 - 7.43 were obtained for primary $\gamma$-rays of 1 TeV energy. As for lower energies, the average orientation appears to be altered due to the influence of the GF. Thus, the GF also rotates shower images obtained from primary $\gamma$-rays of at least 1 TeV.

From the figures shown beforehand it is evident that the GF can severely affect both the shape and the orientation of shower images recorded with an IACT. It was demonstrated that
the extend of the influence not only depends on the orientation of the telescope with respect to the direction of the GF, but also on the position of the telescope with respect to the primary \(\gamma\)-ray’s impact point on ground. Shower images are not only rotated away from the projected direction of the GF in the telescope camera plane but can also be rotated towards the latter direction, contrary to what was reported in [58].

(a) Soft image cleaning, ZA 0°, azimuth angle 0°, impact parameter 20 - 60 m.

(b) Hard image cleaning, ZA 0°, azimuth angle 0°, impact parameter 20 - 60 m.

(c) Soft image cleaning, ZA 0°, azimuth angle 0°, impact parameter 60 - 100 m.

(d) Hard image cleaning, ZA 0°, azimuth angle 0°, impact parameter 60 - 100 m.

**Figure 7.31:** Hillas ellipses for primary \(\gamma\)-rays of 170 GeV energy, two different image cleaning levels and two impact parameter windows. The ZA was set to 0° and the azimuth angle to 0°. The angle \(\varphi\) was varied over the full range between 0° and 330°. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
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Figure 7.32: Hillas ellipses for primary $\gamma$-rays of 170 GeV energy, two different image cleaning levels and two impact parameter windows. The ZA was set to 0° and the azimuth angle to 0°. The angle $\varphi$ was varied over the full range between 0° and 330°. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
(a) Hard image cleaning, ZA 20°, azimuth angle 0°, impact parameter 20 - 60 m.

(b) Hard image cleaning, ZA 20°, azimuth angle 90°, impact parameter 20 - 60 m.

(c) Hard image cleaning, ZA 20°, azimuth angle 120°, impact parameter 20 - 60 m.

(d) Hard image cleaning, ZA 20°, azimuth angle 180°, impact parameter 20 - 60 m.

**Figure 7.33:** Hillas ellipses for primary $\gamma$-rays of 170 GeV energy and impact parameters between 20 m and 60 m. The ZA was set to 20° and the azimuth angle to 0°, 90°, 120° and 180°, respectively. The angle $\varphi$ was varied over the full range between 0° and 330°. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
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Figure 7.34: Hillas ellipses for primary $\gamma$-rays of 170 GeV energy and impact parameters between 60 m and 100 m. The ZA was set to $20^\circ$ and the azimuth angle to $0^\circ$, $90^\circ$, $120^\circ$ and $180^\circ$, respectively. The angle $\varphi$ was varied over the full range between $0^\circ$ and $330^\circ$. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
(a) Hard image cleaning, ZA 20°, azimuth angle 0°, impact parameter 100 - 140 m.

(b) Hard image cleaning, ZA 20°, azimuth angle 90°, impact parameter 100 - 140 m.

(c) Hard image cleaning, ZA 20°, azimuth angle 120°, impact parameter 100 - 140 m.

(d) Hard image cleaning, ZA 20°, azimuth angle 180°, impact parameter 100 - 140 m.

Figure 7.35: Hillas ellipses for primary γ-rays of 170 GeV energy and impact parameters between 100 m and 140 m. The ZA was set to 20° and the azimuth angle to 0°, 90°, 120° and 180°, respectively. The angle ϕ was varied over the full range between 0° and 330°. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
(a) Hard image cleaning, ZA $0^\circ$, azimuth angle $0^\circ$, impact parameter 20-60 m.

(b) Hard image cleaning, ZA $0^\circ$, azimuth angle $0^\circ$, impact parameter 60-100 m.

(c) Hard image cleaning, ZA $0^\circ$, azimuth angle $0^\circ$, impact parameter 100-140 m.

(d) Hard image cleaning, ZA $0^\circ$, azimuth angle $0^\circ$, impact parameter 140-200 m.

Figure 7.36: Hillas ellipses for primary $\gamma$-rays of 450 GeV energy and four impact parameter windows. The ZA was set to $0^\circ$ and the azimuth angle to $0^\circ$. The angle $\varphi$ was varied over the full range between $0^\circ$ and $330^\circ$. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
Figure 7.37: Hillas ellipses for primary $\gamma$-rays of 450 GeV energy and four impact parameter windows. The ZA was set to 20° and the azimuth angle to 0°. The angle $\varphi$ was varied over the full range between 0° and 330°. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
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Figure 7.38: Hillas ellipses for primary $\gamma$-rays of 450 GeV energy and four impact parameter windows. The ZA was set to 20° and the azimuth angle to 180°. The angle $\varphi$ was varied over the full range between 0° and 330°. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
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Figure 7.39: Hillas ellipses for primary $\gamma$-rays of 450 GeV energy and four impact parameter windows. The ZA was set to 40$^\circ$ and the azimuth angle to 0$^\circ$. The angle $\varphi$ was varied over the full range between 0$^\circ$ and 330$^\circ$. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
(a) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 20-60 m.

(b) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 60-100 m.

(c) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 100-140 m.

(d) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 140-200 m.

Figure 7.40: Hillas ellipses for primary γ-rays of 450 GeV energy and four impact parameter windows. The ZA was set to 40° and the azimuth angle to 180°. The angle ϕ was varied over the full range between 0° and 330°. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
(a) Hard image cleaning, ZA 60°, azimuth angle 0°, impact parameter 60 - 100 m.

(b) Hard image cleaning, ZA 60°, azimuth angle 0°, impact parameter 100 - 140 m.

(c) Hard image cleaning, ZA 60°, azimuth angle 180°, impact parameter 60 - 100 m.

(d) Hard image cleaning, ZA 60°, azimuth angle 180°, impact parameter 100 - 140 m.

Figure 7.41: Hillas ellipses for primary γ-rays of 450 GeV energy and two impact parameter windows. The ZA was set to 60° and the azimuth angle to 0° and 180°. The angle ϕ was varied over the full range between 0° and 330°. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
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Figure 7.42: Hillas ellipses for primary $\gamma$-rays of 1 TeV energy and two impact parameter windows. The ZA was set to $0^\circ$ and $20^\circ$ and the azimuth angle to $0^\circ$ and $180^\circ$. The angle $\varphi$ was varied over the full range between $0^\circ$ and $330^\circ$. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
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Figure 7.43: Hillas ellipses for primary $\gamma$-rays of 1 TeV energy and two impact parameter windows. The ZA was set to 40° and 60° and the azimuth angle to 0° and 180°. The angle $\varphi$ was varied over the full range between 0° and 330°. While the red ellipses (solid lines) were obtained for enabled GF, the blue ones (dashed lines) were obtained for disabled GF. The black curve in the upper right part of the figure indicates the ellipticity of the Cherenkov light distribution on ground.
It is remarkable that the GF effects not only occur at very low-energies but also at high-energies around 1 TeV, which is presumably linked to a characteristic feature in the development of a γ-ray induced EAS. As described in section 4.1, the process of multiplication in EAS continues until the average energy of the shower particles is insufficient to further produce secondary particles in subsequent collisions. At this stage of the shower development, the shower maximum is reached (largest number of secondary particles) and the average energy of the secondaries is close to the so-called critical energy below which secondary electrons and positrons lose their energy predominantly through ionization of air molecules. At the shower maximum, the average energy of the secondary particles is independent of the primary γ-ray energy and the GF has on average the same influence on the secondary particles.

However, the average slant depth at which the shower maximum occurs logarithmically increases with increasing energy of the primary γ-ray (figure 4.2), and therefore the distance along which secondary electrons and positrons suffer from Lorentz deflection increases, too. Thus, at higher energies, the GF effects can be expected to be at least just as well pronounced as at low energies.

Another point worthy of mentioning is the fact that the threshold energy for a charged particle to emit Cherenkov light decreases with increasing slant depth (section 4.2.1). Hence, in high-energy EAS, even charged secondaries of lower energy suffering strong Lorentz deflection may additionally contribute to the Cherenkov light pool on ground.

### 7.3.1.2 Influence of the GF on the Image Parameter ALPHA

Although it was shown in the preceding paragraph that the GF can strongly alter the average orientation of shower images and therefore the pointing of γ-rays originating from a VHE γ-ray source under study, it remains important to investigate the influence of the GF on the image parameter ALPHA.

**Figure 7.44:** Normalized distributions of the image parameter ALPHA for primary γ-rays of 30 GeV energy, impact parameters between 20 m and 200 m and various orientations of the telescope. The soft image cleaning was applied, and the entire range of the angle φ between 0° and 330° was considered.

The study of the average rotation of γ-ray induced shower images is not sufficient to conclude on the influence of the GF on the parameter ALPHA, which is commonly used to extract the γ signal. In the preceding section it was demonstrated that the GF can only rotate shower images
recorded for a telescope situated at intermediate angles $\varphi \neq 0^\circ, 90^\circ, 180^\circ$ and $270^\circ$. For some pointing directions of the telescope that are unfavorable with regard to the influence of the GF, the average pointing of the shower images remains unchanged, i.e. if the telescope is situated at $\varphi = 0^\circ, 90^\circ, 180^\circ$ and $270^\circ$, while the ALPHA distribution could be significantly broadened anyway. It was shown elsewhere that the ALPHA distribution can be strongly affected by the influence of the GF [48, 58, 59, 122, 127, 139, 183, 192, 213]. However, it has not been investigated so far how the shape of the ALPHA distribution depends on the telescope position in the Cherenkov light pool on ground.

Figure 7.44 (left panel) shows the normalized distributions of the image parameter ALPHA for primary $\gamma$-rays of 30 GeV, various telescope orientations and impact parameters between 20 m and 200 m. The soft image cleaning was applied. To get an impression of the average degradation of the ALPHA distribution with increasing GF strength, all telescope positions between $\varphi = 0^\circ \ldots 330^\circ$ were considered. The angle $\alpha$ (in parentheses) between the direction of the GF and the direction of the EAS, the azimuth angle as well as the percentage of $\gamma$ showers lying within $|\text{ALPHA}| \leq 9^\circ$ are given in the legend. As can be seen from the figures, the ALPHA distributions are rather flat, independent of the azimuth angle. The influence of the GF is hardly visible, even for $20^\circ$ ZA, where the angle $\alpha$ increases with increasing azimuth angle (figure 7.44, right panel).

![Figure 7.45: Normalized distributions of the image parameter ALPHA for primary $\gamma$-rays of 30 GeV energy, impact parameters between 20 m and 200 m and various orientations of the telescope. The hard image cleaning was applied, and the entire range of the angle $\varphi$ between 0° and 330° was considered.](image)

Figure 7.45 (left panel) shows the normalized ALPHA distributions obtained for a similar configuration of MC input parameters as before, but for the hard image cleaning. The application of the higher image cleaning levels results in a stronger peaked ALPHA distribution at around zero, but the influence of the GF is again hardly visible. At $20^\circ$, the situation is similar (figures 7.44 - 7.45, right panels). The ALPHA distributions are rather dominated by fluctuations due to limited statistics of the dataset than by the influence of the GF, as the width of the ALPHA distributions does not exhibit a clear dependency on the strength of the GF.

Figure 7.46 shows the normalized ALPHA distributions for primary $\gamma$-rays of 450 GeV and similar MC simulation input parameters as before. At $0^\circ$ ZA (upper left panel of the figure), the ALPHA distribution obtained for disabled GF is narrower than the ones obtained for enabled
GF. The percentage of γ showers lying within |\(\text{ALPHA}\)\| ≤ 9° is reduced by ~10% compared to the case of disabled GF. The ALPHA distributions obtained for enabled GF and different azimuth angles are compatible to each other, which is expected, as the angle α does not depend on the azimuth angle.

For ZA > 0°, the shape of the ALPHA distribution also depends on the azimuth angle, i.e. on the strength of the GF. Depending on the direction of the primary γ-ray, the influence of the GF on the shower development can result in a significant broadening of the ALPHA distribution. The percentage of γ showers lying within |\(\text{ALPHA}\)\| ≤ 9° decreases with increasing azimuth angle. For 20° ZA (upper right panel in the figure) and enabled GF it decreases by ~10% and for 40° ZA (lower left panel in the figure) it decreases by up to ~15%.

**Figure 7.46:** Normalized distributions of the image parameter ALPHA for primary γ-rays of 450 GeV energy, impact parameters between 20 m and 200 m and various orientations of the telescope. The hard image cleaning was applied, and the entire range of the angle \(\varphi\) between 0° and 330° was considered.
Furthermore, the width of the ALPHA distributions increases with increasing ZA. At 60° ZA, the ALPHA distribution happens to be significantly broadened due to the decrease of the intensity of Cherenkov photons on ground, but also because the angular distance between telescope pointing direction and direction of the the shower (DIST) gets smaller for some positions of the telescope. The ALPHA distributions are rather dominated by fluctuations due to limited statistics of the dataset than by the influence of the GF.

Normally, in case of ON-source observations, the $\gamma$ signal is expected to show up in an excess at small absolute values of the image parameter ALPHA, typically at $|\text{ALPHA}| \lesssim 5^\circ - 10^\circ$ (section 6.4). Therefore, in case of unfavorable pointing directions with regard to the influence of the GF, a certain fraction of the signal may be lost.

**Figure 7.47:** Normalized distributions of the image parameter ALPHA for primary $\gamma$-rays of 1 TeV energy, impact parameters between 20 m and 200 m and various orientations of the telescope. The hard image cleaning was applied, and the entire range of the angle $\phi$ between 0° and 330° was considered.
Figure 7.47 shows the normalized distribution of the image parameter \( \text{ALPHA} \) for primary \( \gamma \)-rays of 1 TeV and similar MC simulation input parameters as before. As can be seen from the \( \text{ALPHA} \) distributions, the GF affects not only low-energy \( \gamma \) showers, but also at higher energies. This was already noticed in the previous section where the influence of the GF on the average shape and orientation was investigated. The full list of normalized \( \text{ALPHA} \) plots for the entire MC dataset generated for the GF studies can be found in [68].

![Figure 7.48: Arrangement 1](image)

**Figure 7.48:** Arrangement 1: for enabled GF in the MC simulation the telescope is situated at \( \varphi = 90^\circ \) (telescope position 2, filled blue circle) as well as \( \varphi = 0^\circ \) (telescope position 1, filled red circle), while for disabled GF the telescope is situated at \( \varphi = 90^\circ - \) azimuth angle (telescope position 2, open blue circles) as well as \( \varphi = 360^\circ - \) azimuth angle (telescope position 1, open red circles). By the choice of this arrangement, the telescope is not always situated at the maximum of the Cherenkov light distribution on ground. However, in case of enabled GF, the connecting line between the impact point of the primary \( \gamma \)-ray (filled yellow circle) and the telescope position is either parallel (telescope position 1) or vertical (telescope position 2) to the direction of the GF.

In section 7.3.1.1.2 it was shown that the influence of the GF can severely affect the average pointing of \( \gamma \)-rays. The extent of the disturbance depends on the position \((r, \varphi)\) of the telescope with respect to the direction of the EAS. The average rotation of the shower images will of course affect the \( \text{ALPHA} \) distribution, but it is unclear if a de-rotation of the images will help to recover events otherwise lost due to their large value for \( \text{ALPHA} \). As mentioned beforehand, the average pointing \((\delta)\) is maintained, i.e. the pointing corresponds to the one of images obtained for disabled GF. However, the \( \text{ALPHA} \) distribution could be significantly broadened. Therefore, to find out about how the shape of the \( \text{ALPHA} \) distribution depends on the position of the telescope with respect to the direction of the EAS, it is suggestive to investigate the dependency of the shape of the \( \text{ALPHA} \) distribution on the angle \( \varphi \).

As mentioned in section 7.3.1, for \( ZA > 0^\circ \), GF effects as well as geometrical effects on the image parameters are entangled. To disentangle both effects, it is helpful to chose a certain arrangement for the telescope position with respect to the direction of the primary \( \gamma \)-ray. Figure
7.48 shows an arrangement (in the following referred to as arrangement 1), where the telescope is not always situated on the maximum of the Cherenkov light distribution on ground. As can be seen from the figure, the distance between the telescope position 2 (filled blue circle) and the maximum of the Cherenkov light distribution on ground (indicated by the dashed, dotted and dash-dotted gray ellipse) increases with increasing azimuth angle. The connecting line between the impact point of the primary γ-ray (filled yellow circle) and the telescope position is either parallel (telescope position 1, located on the x-axis of the CORSIKA coordinate system, filled red circle) or vertical (telescope position 2, located on the y-axis of the CORSIKA coordinate system, filled blue circle) to the direction of the GF. For enabled GF in the MC simulation the telescope is situated at ϕ = 0° (telescope position 2) as well as ϕ = 90° (telescope position 1). For disabled GF in the MC, data were produced only for 0° azimuth angle. Thus, for disabled GF, the telescope has to be placed at equivalent positions ϕ = 90° – azimuth angle (telescope position 2, open blue circles) as well as ϕ = 360° – azimuth angle (telescope position 1, open red circles). Another possible arrangement will be discussed later.

Figure 7.49 shows the normalized distributions of the image parameter ALPHA for primary γ-rays of 30 GeV energy, impact parameters between 20 m and 180 m and various orientations of the telescope as well as different image cleaning levels. The angle ϕ was set to 0° (x-axis of the CORSIKA coordinate system, pointing to the north, figure 7.17) and 90° (y-axis of the CORSIKA coordinate system, pointing to the west), corresponding to δ = 90° and δ = 0°. The angle α between the direction of the GF and the one of the primary γ-ray is given in the figure caption. The ALPHA distributions obtained for enabled GF and ϕ = 0° (telescope position 1) is drawn as a red solid line, while the one obtained for enabled GF but ϕ = 90° (telescope position 2) is drawn as a blue solid line. The ALPHA distributions obtained for disabled GF are drawn as red and blue dotted lines. The black dotted line indicates the region considered being the signal region. To get an impression of the extent of the disturbance due to the influence of the GF, the percentage of γ showers lying within |ALPHA| ≤ 9° was calculated. The corresponding values, calculated for both telescope positions and for enabled as well as disabled GF, are given in the legend.

The normalized ALPHA distributions in figure 7.49 (a), obtained after application of the soft image cleaning, appear to be rather flat and do not show a strong dependence on the strength of the GF. The percentage of events contained within |ALPHA| ≤ 9° is all about the same.

A similar situation is shown in figure 7.49 (b). The ALPHA distributions were obtained for the same MC input parameters, but after application of the hard image cleaning. In case of enabled GF, the percentage of events contained within |ALPHA| ≤ 9° is slightly lower than for disabled GF.

The ALPHA distributions for 20° ZA (figures 7.49 (c) - (d)) look similar to the ones obtained for 0° ZA. In figure 7.49 (d) for enabled GF and telescope position 2 (blue solid line), the percentage of events contained within |ALPHA| ≤ 9° is slightly greater than in case of disabled GF (blue dotted line). But, as mentioned beforehand, the ALPHA distributions at 30 GeV are rather dominated by fluctuations due to limited statistics of the dataset than by the influence of the GF.

Figure 7.50 shows the normalized distributions of the image parameter ALPHA for primary γ-rays of 170 GeV energy and four impact parameter windows. The hard image cleaning was applied. As can be seen from the figures, at 170 GeV energy the ALPHA distributions can be significantly altered depending on the position (r, ϕ) of the telescope. The ALPHA distributions obtained for enabled GF and ϕ = 0° (telescope position 1, red solid lines) are significantly degraded compared to the ones obtained for disabled GF (red dotted line). The percentage of events contained within |ALPHA| ≤ 9° can be reduced by more than 20% (figure 7.50 (b)). However, for impact parameters between 20 m and 60 m, the ALPHA distributions obtained for enabled GF and ϕ = 90° (telescope position 2, blue solid line) appear to be enhanced with respect to the case of disabled GF, where somewhat less shower images are contained within
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Thus, if the telescope is situated on the y-axis of the CORSIKA coordinate system, perpendicular to the direction of the GF, the pointing of γ-ray showers can be enhanced. The latter configuration corresponds to images elongated in direction of the major image axis (figure 7.25, section 7.3.1.1.1).

At 0° ZA, the result is independent of the azimuth angle (figure 7.51), since the distribution of Cherenkov light on ground is, on average, circular. The ALPHA distributions obtained for different azimuth angles are compatible with each other, irrespective of the orientation of the telescope. Furthermore, the ALPHA distributions for telescope position 2 appear to be always enhanced compared to the ones obtained at position 1.

The normalized ALPHA distributions shown in figure 7.52 were obtained for similar MC input parameters, but 20° ZA and two different azimuth angles, i.e. 0° and 180°, respectively. The ALPHA distributions obtained for enabled GF and telescope position 2 are always in excess of the ones obtained for disabled GF. The ALPHA distributions obtained for enabled GF and telescope position 1 appear to be significantly disturbed. In case of telescope position 1, the percentage of γ-ray showers contained within |ALPHA| ≤ 9° can differ by up to ~ 30% (figure 7.52 (d)). For 180°, the influence of the GF on the image parameter ALPHA is apparently more pronounced than for 0° azimuth angle, as the angle α between the shower axis and the direction of the GF is greater. It should be kept in mind that for ZA > 0° and azimuth angle 0° and 180°, the γ-ray showers collected by the telescope located at position 1 have a smaller angular distance (DIST) than the ones collected at position 2 (figure 6.3).

For greater impact parameters between 100 m and 200 m (figures 7.53 (a) - (d)) the situation is similar. For impact parameters beyond 140 m, the difference between the ALPHA distributions obtained for enabled GF at the telescope positions 1 and 2 becomes smaller.

Figure 7.54 shows the normalized ALPHA distributions for primary γ-rays of 170 GeV energy and impact parameters between 60 m and 100 m. The ZA was set to 20° and the azimuth angle to 30°, 60°, 90° and 150°. For these azimuth angles, the telescope position 2 is not always located on or close to the maximum intensity of the Cherenkov distribution on ground. The degradation of the ALPHA distribution for telescope position 2 is rather low, while the one for the γ-ray showers collected at telescope position 1 can be greater than 20%.

At 40° ZA the influence of the GF is more pronounced (figures 7.55 - 7.56), and the GF strength strongly increases with increasing azimuth angle. At 180° azimuth angle, the GF strength is almost maximal (α = 87°), while at 0° azimuth angle it is very low (α = 12°). It is noteworthy that the ALPHA distributions obtained for large α at telescope position 2 (figures 7.55 (b) and (d), 180° azimuth angle, strong GF) are significantly enhanced compared to the ones obtained for telescope position 1 and small α (figures 7.55 (a) and (c), 0° azimuth angle, weak GF). Thus, for some orientations of the EAS with respect to the telescope pointing direction, the pointing of γ-ray showers can be significantly enhanced.

Figure 7.57 shows the normalized ALPHA distributions for primary γ-rays of 170 GeV energy and impact parameters between 60 m and 100 m. The ZA was set to 20° and the azimuth angle to 30°, 60°, 90° and 150°. Except for 150° azimuth angle (figure 7.57 (b)) where the telescope position 2 is close to the maximum of the Cherenkov light distribution on ground, the influence of the GF is rather small.

Figure 7.58 shows the normalized distributions of the image parameter ALPHA for primary γ-rays of 450 GeV energy, four impact parameter windows, 0° ZA and 0° azimuth angle. As for lower energies, the ALPHA distributions obtained for telescope position 2 and enabled GF appear to be enhanced compared to the corresponding distributions obtained for disabled GF. The distributions obtained for telescope position 1 and enabled GF appear to be degraded compared to the corresponding distributions obtained for disabled GF. Except for impact parameters beyond 100 m where the ALPHA distributions are narrower, the degradation is in the order of 20%.

The normalized ALPHA distributions shown in figures 7.61 - 7.64 were obtained for 20° as
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well as 40° ZA but intermediate azimuth angles between 30° and 150°. Except for 150° azimuth angle, the ALPHA distributions obtained for enabled GF appear to be significantly degraded compared to the ones obtained for disabled GF. It is noteworthy that the pointing of γ-rays collected at telescope position 1 (close to the maximum of the Cherenkov light distribution on ground) is severely degraded for 90° azimuth angle. The degradation is in the order of 40% (figure 7.64 (d)). The pointing of those events cannot be entirely recovered using the information on the average rotation of the images, as the parameter ALPHA is distributed over a wide range and does not exhibit a piling up at a certain value, i.e. there is no systematic rotation away from the camera center (section 7.3.1.1.2).

At larger ZA (figures 7.59 - 7.60 and 7.62 - 7.63), the influence of the GF becomes more pronounced. For some combinations of MC input parameters, the ALPHA distribution obtained for telescope position 1 and enabled GF is severely degraded. At 40°, ZA 180° azimuth angle (strong GF) and impact parameters between 20 m and 60 m (figure 7.62 (b)), the ALPHA distribution obtained for telescope position 1 and enabled GF is completely disturbed, looking background-like. In contrast to this, the pointing of γ-ray showers collected at telescope position 2 can be significantly enhanced. As mentioned beforehand, the latter configuration corresponds to images elongated in direction of the major image axis (figure 7.26, section 7.3.1.1.1). For greater impact parameters, the pointing of the γ-rays is less affected by the GF.

Figure 7.65 shows the normalized ALPHA distributions for primary γ-rays of 1 TeV energy and impact parameters between 100 m and 140 m. The ZA was set to 40° and 60° and the azimuth angle to 0° and 180°. As can be seen from the figure, even at 1 TeV the pointing of γ-rays can be severely affected by the influence of the GF. In case of enabled GF, the ALPHA distribution obtained for 60° ZA and 180° azimuth angle at the telescope position 1 is completely disturbed.

The full list of plots for the entire set of MC input parameters can be found in [68].
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Figure 7.49: Normalized distributions of the image parameter ALPHA for primary $\gamma$-rays of 30 GeV energy, impact parameters between 20 m and 180 m and various orientations of the telescope. The angle $\varphi$ was set to $0^\circ$ and $90^\circ$, respectively.
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(a) Hard image cleaning, ZA 0°, azimuth angle 0°, impact parameter 20-60 m. (b) Hard image cleaning, ZA 0°, azimuth angle 0°, impact parameter 20-100 m.

(c) Hard image cleaning, ZA 0°, azimuth angle 0°, impact parameter 100-140 m. (d) Hard image cleaning, ZA 0°, azimuth angle 0°, impact parameter 140-200 m.

Figure 7.50: Normalized distributions of the image parameter ALPHA for primary γ-rays of 170 GeV energy, four impact parameter windows, 0° ZA and 0° azimuth angle. The angle ϕ was set to 0° and 90°, respectively.
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Figure 7.51: Normalized distributions of the image parameter ALPHA for primary $\gamma$-rays of 170 GeV energy, impact parameters between 60 m and 100 m, $0^\circ$ ZA and azimuth angles between $0^\circ$ and $90^\circ$. The angle $\varphi$ was set to $0^\circ$ and $90^\circ$, respectively.
Figure 7.52: Normalized distributions of the image parameter ALPHA for primary \( \gamma \)-rays of 170 GeV energy, two impact parameter windows, 20° ZA, 0° and 180° azimuth angle. The angle \( \phi \) was set to 0° and 90°, respectively.
Figure 7.53: Normalized distributions of the image parameter ALPHA for primary γ-rays of 170 GeV energy, two impact parameter windows, 20° ZA, 0° and 180° azimuth angle. The angle ϕ was set to 0° and 90°, respectively.
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(a) Hard image cleaning, ZA 20°, azimuth angle 30°, impact parameter 60 - 100 m. (b) Hard image cleaning, ZA 20°, azimuth angle 60°, impact parameter 60 - 100 m.

(c) Hard image cleaning, ZA 20°, azimuth angle 90°, (d) Hard image cleaning, ZA 20°, azimuth angle 150°, impact parameter 60 - 100 m.

Figure 7.54: Normalized distributions of the image parameter ALPHA for primary γ-rays of 170 GeV energy, impact parameters between 60 m and 100 m, 20° ZA, 30°, 60°, 90° and 150° azimuth angle. The angle \( \varphi \) was set to 0° and 90°, respectively.
7.3. ANALYSIS AND RESULTS

Figure 7.55: Normalized distributions of the image parameter ALPHA for primary γ-rays of 170 GeV energy, two impact parameter windows, 40° ZA, 0° and 180° azimuth angle. The angle \( \varphi \) was set to 0° and 90°, respectively.
(a) Hard image cleaning, ZA $40^\circ$, azimuth angle $0^\circ$, impact parameter 100-140 m.

(b) Hard image cleaning, ZA $40^\circ$, azimuth angle $180^\circ$, impact parameter 100-140 m.

(c) Hard image cleaning, ZA $40^\circ$, azimuth angle $0^\circ$, impact parameter 140-200 m.

(d) Hard image cleaning, ZA $40^\circ$, azimuth angle $180^\circ$, impact parameter 140-200 m.

**Figure 7.56:** Normalized distributions of the image parameter ALPHA for primary $\gamma$-rays of 170 GeV energy, two impact parameter windows, $40^\circ$ ZA, $0^\circ$ and $180^\circ$ azimuth angle. The angle $\varphi$ was set to $0^\circ$ and $90^\circ$, respectively.
7.3. ANALYSIS AND RESULTS

Figure 7.57: Normalized distributions of the image parameter ALPHA for primary γ-rays of 170 GeV energy, two impact parameter windows, 40° ZA, 30°, 60°, 90° and 150° azimuth angle. The angle φ was set to 0° and 90°, respectively.
Figure 7.58: Normalized distributions of the image parameter ALPHA for primary $\gamma$-rays of 450 GeV energy, four impact parameter windows, $0^\circ$ ZA and $0^\circ$ azimuth angle. The angle $\varphi$ was set to $0^\circ$ and $90^\circ$, respectively.
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(a) Hard image cleaning, ZA 20°, azimuth angle 0°, impact parameter 20-60 m.

(b) Hard image cleaning, ZA 20°, azimuth angle 180°, impact parameter 20-60 m.

(c) Hard image cleaning, ZA 20°, azimuth angle 0°, impact parameter 60-100 m.

(d) Hard image cleaning, ZA 20°, azimuth angle 180°, impact parameter 60-100 m.

Figure 7.59: Normalized distributions of the image parameter ALPHA for primary γ-rays of 450 GeV energy, two impact parameter windows, 20° ZA, 0° and 180° azimuth angle. The angle φ was set to 0° and 90°, respectively.
Figure 7.60: Normalized distributions of the image parameter ALPHA for primary $\gamma$-rays of 450 GeV energy, two impact parameter windows, 20° ZA, 0° and 180° azimuth angle. The angle $\varphi$ was set to 0° and 90°, respectively.
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(a) Hard image cleaning, ZA 20°, azimuth angle 30°, impact parameter 60 - 100 m.

(b) Hard image cleaning, ZA 20°, azimuth angle 60°, impact parameter 60 - 100 m.

(c) Hard image cleaning, ZA 20°, azimuth angle 90°.

(d) Hard image cleaning, ZA 20°, azimuth angle 150°, impact parameter 60 - 100 m.

Figure 7.61: Normalized distributions of the image parameter ALPHA for primary γ-rays of 450 GeV energy, impact parameters between 60 m and 100 m, 20° ZA, 30°, 60°, 90° and 150° azimuth angle. The angle φ was set to 0° and 90°, respectively.
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Figure 7.62: Normalized distributions of the image parameter ALPHA for primary γ-rays of 450 GeV energy, impact parameters between 60 m and 100 m, 40° ZA, 0° and 180° azimuth angle. The angle ϕ was set to 0° and 90°, respectively.
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Figure 7.63: Normalized distributions of the image parameter ALPHA for primary $\gamma$-rays of 450 GeV energy, two impact parameter windows, 40° ZA, 0° and 180° azimuth angle. The angle $\varphi$ was set to 0° and 90°, respectively.
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Figure 7.64: Normalized distributions of the image parameter ALPHA for primary $\gamma$-rays of 450 GeV energy, impact parameters between 60 m and 100 m, 40° ZA, 30°, 60°, 90° and 150° azimuth angle. The angle $\varphi$ was set to 0° and 90°, respectively.
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(a) Hard image cleaning, ZA 40°, azimuth angle 0°, impact parameter 100 - 140 m.

(b) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 100 - 140 m.

(c) Hard image cleaning, ZA 60°, azimuth angle 0°, impact parameter 100 - 140 m.

(d) Hard image cleaning, ZA 60°, azimuth angle 180°, impact parameter 100 - 140 m.

Figure 7.65: Normalized distributions of the image parameter ALPHA for primary γ-rays of 450 GeV energy, two impact parameter windows, 40° and 60° ZA, 0° and 180° azimuth angle. The angle \( \varphi \) was set to 0° and 90°, respectively.
Figure 7.66 shows an arrangement (in the following referred to as arrangement 2), where the telescope position 2 is always on or close to the maximum of the Cherenkov light distribution on ground. In case of enabled GF, the telescope is situated at \( \varphi = \) azimuth angle (telescope position 1, open red circles) as well as \( \varphi = 90^\circ + \) azimuth angle (telescope position 2, open blue circles), while for disabled GF the telescope is situated at equivalent positions \( \varphi = 0^\circ \) (telescope position 1, filled red circle) as well as \( \varphi = 90^\circ \) (telescope position 2, filled blue circle). For \( 0^\circ \) ZA, both the arrangement 1 and the arrangement 2 are equivalent to each other, which is also the case for \( \text{ZA} > 0^\circ \) and azimuth angles \( 0^\circ, 90^\circ \) and \( 180^\circ \).

The shower images that correspond to the telescope positions indicated in figure 7.66 may be corrected for their average rotation away from the camera center. For these configurations, the average rotation angles of the images are expected to be non-zero. In section 7.3.1.1.2 it was demonstrated that images being not perpendicular or parallel to the direction of the GF are systematically rotated away from the camera center.

![Arrangement 2](image)

**Figure 7.66:** Arrangement 2: for enabled GF in the MC simulation, the telescope is situated at \( \varphi = \) azimuth angle (telescope position 1, open red circles) as well as \( \varphi = 90^\circ + \) azimuth angle (telescope position 2, open blue circles), while for disabled GF the telescope is situated at \( \varphi = 0^\circ \) (telescope position 1, filled red circle) as well as \( \varphi = 90^\circ \) (telescope position 2, filled blue circle). By the choice of this arrangement, the telescope position 2 is always situated on or close to the maximum of the Cherenkov light distribution on ground. However, in case of enabled GF, the angle enclosed by the direction of the GF and the connecting line between the impact point of the primary \( \gamma \)-ray (filled yellow circle) and the telescope positions (open blue as well as open red circles) changes with increasing azimuth angle.

Figures 7.67 - 7.70 show the normalized ALPHA distributions for primary \( \gamma \)-rays of 450 GeV energy, two impact parameter windows, \( 20^\circ \) and \( 40^\circ \) ZA, as well as \( 30^\circ, 60^\circ, 120^\circ \) and \( 150^\circ \) azimuth angle. As can be seen from the figures, the distortion is maximal at \( 150^\circ \) azimuth angle, \( 40^\circ \) ZA and small impact parameters between 60 m and 100 m. For this orientation of the telescope, the degradation of the ALPHA distribution for \( \gamma \)-rays collected at telescope position 1 is in the order of 40% (figures 7.69 (d) and 7.70 (d)). At \( 20^\circ \) ZA, the corresponding degradation
is about 30%. In case of telescope position 2, the degradation is at most 25% (figure 7.69 (b)).

Figure 7.67: Normalized distributions of the image parameter ALPHA for primary γ-rays of 450 GeV energy, impact parameters between 60 m and 100 m, 20° ZA, 30°, 60°, 120° and 150° azimuth angle. The angle ϕ was set to 0° and 90°, respectively.
Figure 7.68: Normalized distributions of the image parameter ALPHA for primary γ-rays of 450 GeV energy, impact parameters between 100 m and 140 m, 20° ZA, 30°, 60°, 120° and 150° azimuth angle. The angle ϕ was set to 0° and 90°, respectively.
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Figure 7.69: Normalized distributions of the image parameter ALPHA for primary γ-rays of 450 GeV energy, impact parameters between 60 m and 100 m, 40° ZA, 30°, 60°, 120° and 150° azimuth angle. The angle ϕ was set to 0° and 90°, respectively.
(a) Hard image cleaning, ZA 40°, azimuth angle 30°, impact parameter 100-140 m. (b) Hard image cleaning, ZA 40°, azimuth angle 60°, impact parameter 100-140 m.

(c) Hard image cleaning, ZA 40°, azimuth angle 120°, (d) Hard image cleaning, ZA 40°, azimuth angle 150°, impact parameter 100-140 m.

**Figure 7.70:** Normalized distributions of the image parameter ALPHA for primary γ-rays of 450 GeV energy, impact parameters between 100 m and 140 m, 40° ZA, 30°, 60°, 120° and 150° azimuth angle. The angle ϕ was set to 0° and 90°, respectively.
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The shape of the ALPHA distributions suggests that the pointing of the shower images cannot be entirely recovered using the information on the average rotation of the images. The parameter ALPHA is distributed over a wide range and does not exhibit a piling up at a certain value. The shower images are not only systematically rotated away from the camera center but can be strongly scattered around the average orientation resulting in a degradation of the ALPHA distribution.

Apart from the arrangements 1 and 2 discussed beforehand, there exist more possible configurations. For a given azimuth angle and $ZA > 0^\circ$, the telescope could be situated at $\varphi = 120^\circ + \text{azimuth angle}$ and $\varphi = 30^\circ + \text{azimuth angle}$ as well as $\varphi = 150^\circ + \text{azimuth angle}$ and $\varphi = 60^\circ + \text{azimuth angle}$. For azimuth angles $0^\circ$, $90^\circ$ and $180^\circ$, the latter positions are complementary to the first positions, as they arise from a mirroring on the y-axis of the CORSIKA coordinate system.

Figure 7.71 shows the normalized ALPHA distribution for primary $\gamma$-rays of 450 GeV energy, impact parameters between 60 m and 100 m, $40^\circ$ $ZA$, $0^\circ$ and $180^\circ$ azimuth angle. The angle $\varphi$ was set to $30^\circ$ and $120^\circ$, respectively. As for the other arrangements discussed beforehand, the ALPHA distributions that are strongly disturbed by the influence of the GF do not exhibit any piling up at a certain value, and the width of the ALPHA distributions can be significantly increased. It is therefore questionable whether the decrease of the $\gamma$ acceptance due to the influence of the GF can be compensated or not.

In conclusion it can be stated that, for some selected telescope positions on ground the pointing of the $\gamma$-ray showers is not necessarily degraded but can be enhanced instead, even for orientations of the primary $\gamma$-ray corresponding to large angles $\alpha$ (strong influence of the

Figure 7.71: Normalized distributions of the image parameter ALPHA for primary $\gamma$-rays of 450 GeV energy, impact parameters between 60 m and 100 m, $40^\circ$ $ZA$, $0^\circ$ and $180^\circ$ azimuth angle. The angle $\varphi$ was set to $30^\circ$ and $120^\circ$, respectively.
\( \gamma \) showers.

\[ \gamma = 450 \text{ GeV}, \ A = 0^\circ, Z = 40^\circ, \text{Hard Image Cleaning} \]

Table 7.2: The nominal angle \( \delta_n \), average displacement \( \Delta \delta \), average value of the parameter DIST, RMS of the ALPHA distribution for enabled GF and impact parameters between 60 m and 120 m. The RMS of the ALPHA distribution for disabled GF is given parentheses. The primary \( \gamma \)-ray energy was set to 450 GeV, the ZA to 40° and the azimuth angle to 0°.

\[ \gamma = 450 \text{ GeV}, \ A = 180^\circ, Z = 40^\circ, \text{Hard Image Cleaning} \]

Table 7.3: The nominal angle \( \delta_n \), average displacement \( \Delta \delta \), average value of the parameter DIST, RMS of the ALPHA distribution for enabled GF and impact parameters between 60 m and 120 m. The RMS of the ALPHA distribution for disabled GF is given parentheses. The primary \( \gamma \)-ray energy was set to 450 GeV, the ZA to 40° and the azimuth angle to 180°.

For unfavorable orientations of the EAS with regard to the GF, the pointing of shower images is efficiently enhanced only if the direction of the GF is perpendicular to the connecting line of the primary \( \gamma \)-ray impact point on ground and the telescope position (\( \varphi = \pm 90^\circ \)). Furthermore, the pointing of \( \gamma \)-ray showers is significantly enhanced only if the telescope is situated on or close to the maximum of the Cherenkov light distribution on ground. For all other impact positions, the pointing will be degraded.
Table 7.4: The nominal angle $\delta_n$, average displacement $\Delta \delta$, average value of the parameter DIST, RMS of the ALPHA distribution for enabled GF and impact parameters between 60 m and 120 m. The RMS of the ALPHA distribution for disabled GF is given parentheses. The primary $\gamma$-ray energy was set to 1000 GeV, theZA to $40^\circ$ and the azimuth angle to $180^\circ$.

Table 7.5: The nominal angle $\delta_n$, average displacement $\Delta \delta$, average value of the parameter DIST, RMS of the ALPHA distribution for enabled GF and impact parameters between 60 m and 120 m. The RMS of the ALPHA distribution for disabled GF is given parentheses. The primary $\gamma$-ray energy was set to 1000 GeV, theZA to $60^\circ$ and the azimuth angle to $180^\circ$.

In the worst case, the degradation of the pointing of shower images not only causes a loss of events but may cause the $\gamma$-ray source under study to appear as an extended source. For unfavorable pointing directions, the orientations of the $\gamma$-ray images will be blurred and in addition rotated away from the nominal direction. As a result, the reconstructed arrival direction may significantly deviate from the nominal one.

Table 7.2 and table 7.3 list some of the parameters which can be strongly affected by the influence of the GF: the nominal angle $\delta_n$, the average rotation angle $\Delta \delta$, the average value of the parameter DIST, and the RMS of the ALPHA distribution obtained for enabled GF and
four impact parameter windows. The RMS of the ALPHA distribution obtained for disabled GF is given in parentheses. The primary $\gamma$-ray energy was set to 450 GeV, the ZA to 40° and the azimuth angle to 0° (small influence of the GF) and 180° (strong influence of the GF).

The green-colored rows in table 7.2 and 7.3 correspond to arrangements that are favorable with regard to the pointing of the shower images, i.e. the telescope is situated on the y-axis of the CORSIKA coordinate system, pointing to the west, perpendicular to the direction of the GF. For impact parameters below 120 m, the RMS values of the ALPHA distributions obtained for enabled GF are significantly smaller than the ones obtained for disabled GF. This effect is very pronounced for 180° azimuth angle (table 7.3).

The red-colored rows correspond to the most unfavorable arrangements where the telescope is situated on the x-axis of the CORSIKA coordinate system, pointing to the north, parallel to the direction of the GF. Compared to the case of disabled GF the RMS of the ALPHA distribution obtained for enabled GF are significantly increased, while the average pointing remains unchanged. On average, there is only a small rotation $\Delta \delta$ of the shower images.

The intermediate positions (blue-colored rows) at $\delta_n$ around 90° and 270° suffer from large rotations $\Delta \delta$ of the shower images (up to $\sim 17\degree$ for 180° azimuth angle and 60 m impact parameter). The RMS of the ALPHA distribution obtained for enabled GF at intermediate positions is increased but in most cases smaller than the ones obtained for $\delta = 90\degree$ and $\delta = 180\degree$.

Tables 7.4 and 7.5 show the rotation angles $\Delta \delta$ for primary $\gamma$-rays of 1 TeV energy, 40° and $60\degree$ TZA as well as 180° azimuth angle. As for lower energies, the rotation of the shower images can be sizeable for unfavorable directions with regard to the influence of the GF (blue-colored rows). The full list of tables for the entire set of MC input parameters can be found in [68].

Figure 7.72 shows the normalized ALPHA distributions for primary $\gamma$-rays of 450 GeV energy, impact parameters between 60 m and 120 m, 40° TZA and 180° azimuth angle. The angle $\varphi$ was varied between 0° and 330°. While the black distributions were obtained for disabled GF, the red distributions correspond to the case of enabled GF. The green-colored ALPHA distributions show the ones of the de-rotated shower images (enabled GF). The de-rotation was done using the average displacement $\Delta \delta$, which is listed in table 7.3. The ALPHA distributions of the de-rotated shower images are in most cases improved with regard to the original distributions, i.e. the percentage of events lying within $|\text{ALPHA}| \leq 9\degree$ is greater than for the untouched ALPHA distributions. The percentage of recovered events increases for lower impact parameters. But, as expected, the recovery of the pointing by changing the orientation of the images is not possible for all events. The GF changes not only the average pointing of $\gamma$-ray shower images, but significantly disturbs the ALPHA distribution.

The removal of events collected at the most unfavorable orientations with regard to the influence of the GF further enhances the pointing. The normalized ALPHA distributions shown in figure 7.73 were obtained for primary $\gamma$-rays of 450 GeV energy, impact parameters between 60 m and 120 m, 40° TZA and 180° azimuth angle. The most unfavorable orientations with regard to the influence of the GF, $\varphi = 0\degree$ and 180° ($\delta = 90\degree$ and 270°) were not considered. As can be seen from the figures, the removal of events that are disturbed strongest by the influence of the GF further enhances the ALPHA distributions.

Figure 7.74 shows the normalized ALPHA distributions that were obtained for similar MC input parameters as before. The telescope was situated at the most unfavorable positions with regard to the influence of the GF, $\varphi = 0\degree$ and 180°. Apparently, the pointing of the shower images obtained for enabled GF cannot be recovered by the de-rotation. The ALPHA distributions are strongly disturbed, and the pointing information of shower images at around 60 m impact parameter is completely lost due to the influence of the GF. Thus, for unfavorable orientations of the telescope, it is appropriate to remove those events from the data sample.

Figure 7.75 shows the normalized ALPHA distributions for primary $\gamma$-rays of 1 TeV energy, impact parameters between 100 m and 120 m, 40° and 60° TZA and 180° azimuth angle. The angle $\varphi$ was varied between 0° and 330°. At 40° TZA and 100 m impact parameter (figure 7.75 (a)),
the percentage of events recovered by de-rotation is rather low, and for 120 m impact parameter (figure 7.75 (b)) the de-rotation slightly worsens the ALPHA distribution. Table 7.4 was used to de-rotate the shower images.

For 60° ZA (figure 7.75 (c) - (d)), the de-rotation of shower images helps to enhance the percentage of events lying within |ALPHA| ≤ 9°. Similar to the case of lower energies, the ALPHA distributions can be further enhanced by rejecting the most unfavorable orientations with regard to the influence of the GF $\varphi = 0^\circ$ and $\varphi = 180^\circ$ (figure 7.76 (a) - (d)).

Figure 7.77 (a) - (d) shows the ALPHA distributions of events collected at the most unfavorable orientation with regard to the influence of the GF. The pointing of the shower images cannot be recovered by de-rotation, and for 60° ZA the ALPHA distributions obtained for enabled GF look background-like.

In general, for large angles $\alpha$ (strong GF), the most unfavorable arrangements with regard to the influence of the GF are the ones at $\varphi = 0^\circ, 180^\circ$ and the most favorable are the ones $\varphi = \pm 90^\circ$. At intermediate positions $\varphi \neq 0^\circ, 90^\circ, 180^\circ$ and $270^\circ$, the pointing of shower images can be disturbed as well as the average pointing can be significantly altered. According to equation 7.11 this can be transformed to the camera coordinate system: for unfavorable orientations with regard to the strength of the GF $\gamma$-ray, shower images at intermediate angles

$$\delta \neq n \cdot 90^\circ + \text{azimuth angle}, \quad n \in \mathbb{N},$$

are systematically rotated away from the camera center as well as away from the direction of the GF. Provided that the average rotation angle is known, a certain fraction of the $\gamma$ signal can be recovered by de-rotation. The average pointing of shower images at

$$\delta = n \cdot 90^\circ + \text{azimuth angle}, \quad n \in \mathbb{N},$$

remains unchanged. However, depending on the impact parameter, the ALPHA distribution can be significantly disturbed for $n = 1$ as well as $n = 3$.

It is noteworthy that the figures 7.72 - 7.77 were obtained under an optimistic scenario, since the impact parameter is well defined. In reality, the impact parameter is only known with an accuracy of $\sim 20\%$ [135].
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|Entries| |ALPHA| 0 10 20 30 40 50 60 70 80 90 |

Primary Energy = 450 GeV Az = 180° ZA = 40° IP = 60 m α = 87°

(a) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 60 m, ϕ = 0°…330°.

Primary Energy = 450 GeV Az = 180° ZA = 40° IP = 80 m α = 87°

(b) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 80 m, ϕ = 0°…330°.

Primary Energy = 450 GeV Az = 180° ZA = 40° IP = 100 m α = 87°

(c) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 100 m, ϕ = 0°…330°.

Primary Energy = 450 GeV Az = 180° ZA = 40° IP = 120 m α = 87°

(d) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 120 m, ϕ = 0°…330°.

Figure 7.72: Normalized distributions of the image parameter ALPHA for primary γ-rays of 450 GeV energy, impact parameters between 60 m and 120 m, 40° ZA and 180° azimuth angle. The angle ϕ was varied between 0° and 330°.
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(a) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 60 m, \( \phi \neq 0°, 180° \).

(b) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 80 m, \( \phi \neq 0°, 180° \).

(c) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 100 m, \( \phi \neq 0°, 180° \).

(d) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 120 m, \( \phi \neq 0°, 180° \).

Figure 7.73: Normalized distributions of the image parameter ALPHA for primary \( \gamma \)-rays of 450 GeV energy, impact parameters between 60 m and 120 m, 40° ZA and 180° azimuth angle. The most unfavorable orientations with regard to the influence of the GF, \( \phi = 0° \) and 180° were not considered.
(a) Hard image cleaning, $\gamma$ 40°, azimuth angle 180°, impact parameter 60 m, $\varphi = 0^\circ, 180^\circ$.

(b) Hard image cleaning, $\gamma$ 40°, azimuth angle 180°, impact parameter 80 m, $\varphi = 0^\circ, 180^\circ$.

(c) Hard image cleaning, $\gamma$ 40°, azimuth angle 180°, impact parameter 100 m, $\varphi = 0^\circ, 180^\circ$.

(d) Hard image cleaning, $\gamma$ 40°, azimuth angle 180°, impact parameter 120 m, $\varphi = 0^\circ, 180^\circ$.

**Figure 7.74:** Normalized distributions of the image parameter ALPHA for primary $\gamma$-rays of 450 GeV energy, impact parameters between 60 m and 120 m, 40° ZA and 180° azimuth angle. The angle $\varphi$ was set to 0° and 180°, respectively.
7.3. ANALYSIS AND RESULTS

(a) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 100 m, \( \varphi = 0° \ldots 330° \).

(b) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 120 m, \( \varphi = 0° \ldots 330° \).

(c) Hard image cleaning, ZA 60°, azimuth angle 180°, impact parameter 100 m, \( \varphi = 0° \ldots 330° \).

(d) Hard image cleaning, ZA 60°, azimuth angle 180°, impact parameter 120 m, \( \varphi = 0° \ldots 330° \).

Figure 7.75: Normalized distributions of the image parameter ALPHA for primary γ-rays of 1000 GeV energy, impact parameters between 100 m and 120 m, 40° and 60° ZA and 180° azimuth angle. The angle \( \varphi \) was varied between 0° and 330°.
(a) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 100 m, \( \varphi \neq 0^\circ, 180^\circ \).

(b) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 120 m, \( \varphi \neq 0^\circ, 180^\circ \).

(c) Hard image cleaning, ZA 60°, azimuth angle 180°, impact parameter 100 m, \( \varphi \neq 0^\circ, 180^\circ \).

(d) Hard image cleaning, ZA 60°, azimuth angle 180°, impact parameter 120 m, \( \varphi \neq 0^\circ, 180^\circ \).

**Figure 7.76:** Normalized distributions of the image parameter ALPHA for primary \( \gamma \)-rays of 1000 GeV energy, impact parameters between 100 m and 120 m, 40° and 60° ZA and 180° azimuth angle. The most unfavorable orientations with regard to the influence of the GF, \( \varphi = 0^\circ \) and 180° were not considered.
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(a) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 100 m, \( \varphi = 0°, 180° \).

(b) Hard image cleaning, ZA 40°, azimuth angle 180°, impact parameter 120 m, \( \varphi = 0°, 180° \).

(c) Hard image cleaning, ZA 60°, azimuth angle 180°, impact parameter 100 m, \( \varphi = 0°, 180° \).

(d) Hard image cleaning, ZA 60°, azimuth angle 180°, impact parameter 120 m, \( \varphi = 0°, 180° \).

Figure 7.77: Normalized distributions of the image parameter ALPHA for primary \( \gamma \)-rays of 1000 GeV energy, impact parameters between 100 m and 120 m, 40° and 60° ZA and 180° azimuth angle. The angle \( \varphi \) was set to 0° and 180°, respectively.
7.3.1.3 The Influence of the GF on the Image Parameter SIZE and the $\gamma$ Efficiency

In the simplest approach, the estimation of the energy of a $\gamma$-ray candidate can be done using only the image parameter SIZE, which is the total reconstructed integrated light of a shower image (section 6.2). Because the photon yield on ground is directly related to the shower energy, the parameter SIZE is a measure for the energy of a $\gamma$-ray candidate. The energy estimation is done by comparing the SIZE of real shower images with the one of MC simulated $\gamma$-ray events.

In general, the energy estimation incorporates additional image parameters (section 6.6). For instance, the SIZE of an event depends also on the image parameter DIST which is related to the impact parameter of a primary $\gamma$-ray.

The influence of the GF on the Cherenkov light distribution on ground was briefly discussed in section 7.1.2. It was shown that the shape and intensity of the distribution of Cherenkov photons on ground and also in the telescope plane strongly depend on the orientation of the primary $\gamma$-ray with respect to the direction of the GF [213]. The thinning of the Cherenkov light distribution on ground is expected to have an influence on the image parameter SIZE. For unfavorable orientations with regard to the influence of the GF the SIZE parameter presumably takes smaller values than in case of favorable orientations. Thus, if the effect of the GF is not properly taken into account, the reconstructed energy may be underestimated. It is therefore important to investigate the influence of the GF on the image parameter SIZE.

The $\gamma$ efficiency, defined as

$$\varepsilon_{\gamma,\text{Trigger}}(E, r, ZA, Az) = \frac{N^{\text{Trigger,Image Cleaning}}(E, r, ZA, Az)}{N^{\text{Generated}}(E, r, ZA, Az)}$$

(7.14)

is another important impact parameter to look at. Therein, $N^{\text{Trigger,Image Cleaning}}(E, r, ZA, Az)$ denotes the number of MC simulated $\gamma$-rays surviving the trigger level as well as the subsequent image cleaning procedure. $N^{\text{Generated}}(E, r, ZA, Az)$ is the number of MC simulated $\gamma$-rays at a certain energy $E$, impact parameter $r$ and orientation of the telescope. The $\gamma$ efficiency is used to determine the effective collection area, which is in turn used to estimate the flux from a $\gamma$-ray source (section 6.7).

**Figure 7.78:** The mean value of the image parameter SIZE and the $\gamma$ efficiency as a function of the azimuth angle for 30 GeV $\gamma$-rays and ZA between 0° and 20°. The telescope is always placed at angles $\varphi = \text{azimuth angle} + 90°$. The impact parameter was set to $r = 120$ m. The soft image cleaning was applied.
However, the influence of the GF is expected to affect the $\gamma$ efficiency only close to the analysis threshold, where the thinned-out distributions of Cherenkov photons on ground have a lower probability to survive the trigger level as well as the image cleaning procedure.

Figure 7.78 shows the mean value of the image parameter SIZE and the $\gamma$ efficiency as a function of the azimuth angle for a primary $\gamma$-ray of 30 GeV energy. The impact parameter was set to $r = 120$ m and the ZA to $0^\circ$ and $20^\circ$. The soft image cleaning was applied. For the hard image cleaning, the $\gamma$ efficiency is at most $\sim 4\%$. The angle $\alpha$ between the direction of the primary $\gamma$-ray and the direction of the GF is written on top of the abscissa. To disentangle both the geometrical effect and the effect of the GF (figure 7.22, section 7.3.1), the telescope is always placed at angles $\varphi = \text{azimuth angle} + 90^\circ$. Thereby, the telescope is always located on top of the maximum of the Cherenkov light distribution on ground or at the same distance with respect to the latter.

For $0^\circ$ ZA (left panel of figure 7.78), both the mean SIZE and the $\gamma$ efficiency are reduced in case of enabled GF. As expected, there is no dependency on the azimuth angle, as the angle $\alpha$ stays constant. The corresponding values that were obtained for disabled GF are drawn as solid lines, because the MC data was generated only for $0^\circ$ azimuth angle. For $20^\circ$ ZA (right panel of figure 7.78), the mean SIZE as well as the $\gamma$ efficiency decrease with increasing azimuth angle, as the angle $\alpha$ increases, too. The effect on the $\gamma$ efficiency is stronger, which is expected for $\gamma$-rays being close to the analysis threshold. Events lying below the analysis threshold do not survive the trigger level or the image cleaning and therefore do not contribute to the average of the image parameter SIZE.

![Figure 7.78](image.png)

**Figure 7.78**: The mean value of the image parameter SIZE and the $\gamma$ efficiency as a function of the azimuth angle for 30 GeV $\gamma$-rays and ZA between $0^\circ$ and $20^\circ$. The telescope is always located on the maximum of the Cherenkov light distribution on ground or at the same distance with respect to the latter. The telescope was always placed on the maximum of the Cherenkov light distribution on ground or at the same distance with respect to the latter. The telescope was always placed on the maximum of the Cherenkov light distribution on ground or at the same distance with respect to the latter.

Figure 7.79 was obtained for similar MC input parameters as the preceding figure, but the impact parameter range was enlarged to $r = 20 \ldots 200$ m. From the comparison of figure 7.78 and figure 7.79 it can be seen that both the mean value of the parameter SIZE and the $\gamma$ efficiency are smaller if the impact parameter range is enlarged. The latter is expected, as in case of figure 7.78 the telescope was always placed on the maximum of the Cherenkov light distribution on ground. Nevertheless, the influence of the GF on the mean SIZE and the $\gamma$ efficiency is comparable.

Figure 7.80 shows the mean value of the image parameter SIZE and the $\gamma$ efficiency for
170 GeV γ-rays and 120 m impact parameter. The hard image cleaning was applied, and the ZA was set to 0°, 20° and 40°. As for lower energies, the GF affects both quantities. At 20° ZA, the influence of the GF on the average value of the image parameter SIZE is stronger than for γ-ray energies of 30 GeV energy. In case of enabled GF and 20° ZA, the mean value of the SIZE parameter varies by ∼10%. At 40° ZA, the γ-efficiency is strongly affected, while the average SIZE changes very little. The angle α between the direction of the primary γ-ray and the direction of the GF increases faster than for 20° ZA. As a result, the influence on the γ-efficiency is more pronounced. However, the GF affects the average SIZE of shower images only if the events lie above the analysis threshold.

Figure 7.80: The mean value of the image parameter SIZE and the γ-efficiency as a function of the azimuth angle for 170 GeV γ-rays and ZA between 0° and 40°. The telescope is always placed at angles ϕ = azimuth angle + 90°. The impact parameter was set to \( r = 120 \text{ m} \). The hard image cleaning was applied.

Figure 7.81 shows the mean value of the image parameter SIZE and the γ-efficiency for similar MC input parameters as before. The mean SIZE and the γ-efficiency are also reduced if impact parameters between 20 m and 200 m are considered. However, the influence of the GF
is comparable to the one observed for 120 m impact parameter.

For MC simulated $\gamma$-rays of 450 GeV energy and ZA below 60° (figure 7.82 and 7.83), the GF does not affect the $\gamma$-efficiency at all. All MC generated $\gamma$-ray showers lie above the analysis threshold, although their images are fainter, i.e. on average they have a smaller SIZE. For 20° ZA, the average SIZE changes by $\sim 10\%$ with increasing azimuth angle, and for 40° ZA it changes by up to $\sim 20\%$. For 60° ZA, the average SIZE remains largely unchanged, as the trigger efficiency for events having SIZE values below the one at $\sim 0°$ azimuth angle do not survive either the trigger level or the image cleaning procedure.

![Figure 7.81](image)

**Figure 7.81:** The mean value of the image parameter SIZE and the $\gamma$ efficiency as a function of the azimuth angle for 170 GeV $\gamma$-rays and ZA between 0° and 40°. The telescope is always placed at angles $\phi = $ azimuth angle $+ 90°$. The impact parameters were set to $r = 20..200$ m. The hard image cleaning was applied.

Figures 7.84 and 7.85 show the mean value of the image parameter SIZE and the $\gamma$ efficiency for 1 TeV $\gamma$-rays. As can be seen from the figures, at 1 TeV the GF significantly affects the SIZE parameter for ZA > 20°. Instead, the influence on the trigger efficiency is rather low.

It is noteworthy that low-energy $\gamma$-rays are at least as strong affected as high-energy $\gamma$-rays.
$\gamma$-rays oriented at unfavorable directions with regard to the strength of the GF are altered in a way that they do not survive the trigger level or the image cleaning procedure. The influence of the GF on the image parameter SIZE is clearly visible only for those energies and orientations of the primary $\gamma$-ray where the $\gamma$ efficiency is not altered too much. The latter depends of course on the image cleaning levels which are applied to the shower images. The full list of figures for the entire MC dataset can be found in [68].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{The mean value of the image parameter SIZE and the $\gamma$ efficiency as a function of the azimuth angle for 450 GeV $\gamma$-rays and ZA between $0^\circ$ and $60^\circ$. The telescope is always placed at angles $\varphi = \text{azimuth angle} + 90^\circ$. The impact parameter was set to $r = 120\text{ m}$. The hard image cleaning was applied.}
\end{figure}
Figure 7.83: The mean value of the image parameter SIZE and the $\gamma$ efficiency as a function of the azimuth angle for 450 GeV $\gamma$-rays and ZA between 0° and 60°. The telescope is always placed at angles $\varphi = \text{azimuth angle} + 90^\circ$. The impact parameters were set to $r = 20 \ldots 200$ m. The hard image cleaning was applied.
Figure 7.84: The mean value of the image parameter SIZE and the $\gamma$ efficiency as a function of the azimuth angle for 1 TeV $\gamma$-rays and ZA between $0^\circ$ and $60^\circ$. The telescope is always placed at angles $\varphi = $ azimuth angle $+ 90^\circ$. The impact parameter was set to $r = 120$ m. The hard image cleaning was applied.
Figure 7.85: The mean value of the image parameter SIZE and the \( \gamma \) efficiency as a function of the azimuth angle for 1 TeV \( \gamma \)-rays and ZA between 0\( ^\circ \) and 60\( ^\circ \). The telescope is always placed at angles \( \psi = \text{azimuth angle} + 90^\circ \). The impact parameters were set to \( r = 20 \ldots 200 \text{ m} \). The hard image cleaning was applied.
7.4 Conclusions & Outlook

In summary, the main conclusions of this chapter are:

- **GF effects on the image parameters WIDTH and LENGTH**: On average, the influence of the GF on the image parameters WIDTH and LENGTH is rather small. While γ-ray shower images are elongated perpendicular to the direction of the GF, they appear to be compressed parallel to the direction of the GF. The shape of high-energy γ-ray showers (∼1000 GeV) as well as the one of low-energy γ-ray showers (∼100 GeV) is affected. For γ-ray energies around 100 GeV, the average WIDTH is changed by ∼5%, while for energies around 1 TeV the average WIDTH can be changed by up to ∼15%, depending on the orientation of the EAS. The effect on the image parameter LENGTH is in the order of 5%, for γ-ray energies around 100 GeV as well as 1 TeV. These numbers were derived from the figures in paragraph 7.3.1.1.1.

It remains to be shown how the GF effects on the image parameters WIDTH and LENGTH degrade the γ/hadron separation capability of an analysis.

- **GF effects on the image parameters δ and ALPHA**: The influence of the GF on EAS can significantly alter the pointing of γ-ray shower images and therefore degrades the ALPHA analysis. The disturbance of the pointing can result in a strong broadening of the ALPHA distribution. Some orientations of the primary γ-ray with respect to the direction of the GF result in shower images which are systematically rotated away from the nominal source position in the camera. In general, γ-ray images close to the camera center are more affected, as they are characteristically less elongated. The rotation of shower images away from the camera center can significantly degrade the ALPHA-based γ/hadron separation. The extent of the rotation is directly related to the image parameter δ (the angular distance between the x-axis of the camera coordinate system and the major image axis) and can therefore be partly corrected. The recovery of the γ-ray signal by correcting for the GF effects is expected to increase the sensitivity of the telescope as well as the significance of a detection. However, the correction for the GF effects requires the knowledge of the rotation angle, which depends on various parameters such as the energy of the primary γ-ray, its impact parameter and orientation. The full list of tables containing the rotation angles for the entire set of MC input parameters can be found in [68].

For unfavorable orientations of the primary γ-ray with regard to the influence of the GF (large angle α), shower images occurring at angles

\[ \delta = 2n \cdot 90^\circ \pm \text{azimuth angle}, \quad n \in \mathbb{N}, \]

(7.15)

do not require to be de-rotated. By contrast, the angles

\[ \delta = (2n + 1) \cdot 90^\circ \pm \text{azimuth angle}, \quad n \in \mathbb{N}, \]

(7.16)

correspond to the most unfavorable arrangements, where the pointing of the shower images can be completely disturbed, albeit the average pointing direction δ remains unchanged. The pointing of these events cannot be recovered by de-rotation.

For unfavorable pointing directions, shower images lying inside the quadrants

\[ \delta \neq n \cdot 90^\circ \pm \text{azimuth angle}, \quad n \in \mathbb{N}, \]

(7.17)

The recovery of the γ-ray signal by correcting for the GF effects was successfully demonstrated by the collaboration of the Mark 6 VHE Gamma Ray Telescope [59]. However, new generation IACTs currently in operation or under development have an improved imaging performance and are therefore more sensitive for GF effects. The Mark 6 telescope was a first generation IACT.
of the camera coordinate system can be systematically rotated away from the camera center. It was shown that the de-rotation of the shower images does not help to recover the pointing entirely. Thus, for unfavorable orientations with regard to the influence of the GF, a simple procedure could be to remove those regions in the camera which are expected to be affected strongest, i.e. to keep only events lying inside the intervals

$$\delta = 2n \cdot 90^\circ + \text{azimuth angle} \pm \Delta\delta, \quad n \in \mathbb{N}.$$  \hfill (7.18)

For $\Delta\delta = 60^\circ$, two-thirds of all events are kept, while the events being affected strongest by the influence of the GF are removed from the dataset. This value for $\Delta\delta$ is not optimized and was chosen because the MC simulated datasets were generated in steps of $\phi = 30^\circ$. To remove only those images from a real data sample that are affected strongest by the influence of the GF, the exclusion region $\Delta\delta$ must be considered as impact parameter-, azimuth angle- and ZA-dependent.

It is remarkable that also high-energy $\gamma$-ray shower images are rotated due to the influence of the GF.

- **GF effects on the image parameter SIZE and the $\gamma$-ray efficiency**: It was shown that the GF can significantly affect the image parameter SIZE and the $\gamma$ efficiency. However, both the GF effects on the $\gamma$ efficiency and the one on the SIZE parameter are correlated. In case of low-energy showers and unfavorable orientations with regard to the strength of the GF, the Cherenkov light distribution on ground can be thinned out in a way that most of the events do not survive the trigger level. While the mean SIZE of the events surviving the trigger level and the image cleaning remains unchanged, the efficiency can be significantly altered. Thus, if the effect is not taken into account at low energies, the $\gamma$ efficiency will be overestimated, which in turn affects the effective area calculation and the determination of the flux from a $\gamma$-ray source. For low energies close to the analysis threshold, the $\gamma$ efficiency also depends on the position of the telescope in the Cherenkov light pool (figure 7.21). At higher energies, the $\gamma$ efficiency is affected only at large ZA, where the telescope threshold energy is significantly increased. Depending on the energy of the $\gamma$-ray, the average SIZE can be reduced by up to $\sim 20\%$ (for $\gamma$-rays of $\sim 300$ - $1000$ GeV) compared to the case of favorable directions with regard to the influence of the GF. Thus, if the GF effect is not taken into account, the energy of $\gamma$ candidates will be systematically underestimated, which in turn affects the determination of the flux level. Table 7.6 summarizes the GF effects on both the image parameter SIZE and the $\gamma$ efficiency.

To avoid the effects mentioned beforehand, it is essential to use appropriate MC data covering the same ZA range and azimuth angle range as the dataset being analyzed. By using appropriate MC, the GF effects on the SIZE parameter and the $\gamma$ efficiency are automatically corrected, except for very low energies close to the trigger/analysis threshold where the efficiency depends on the impact point of the $\gamma$-ray with respect to the telescope (figure 7.21).

- **GF effects on the DISP method**: The DISP method allows to estimate the arrival direction of $\gamma$-ray candidates from the source under study (section 6.5). As demonstrated in this chapter, the GF can significantly degrade both the pointing and the shape of $\gamma$-ray shower images. Because the DISP method makes use of the shape of $\gamma$-ray shower images described by the images parameters WIDTH and LENGTH, the influence of the GF is expected to affect the reconstruction of the arrival direction.

The outcome of the DISP analysis is usually depicted on a sky map. The most probable source position is then given by the region in the sky map where most events accumulate.
The influence of the GF on the DISP method is expected to degrade the quality of the sky map in a way that the most frequent arrival direction appears to be blurred. However, the influence of the GF on the DISP method remains to be studied.

- **GF effects on the hadron induced background**: The influence of the GF on the other components of EAS is expected to be much smaller. The scattering angles of nuclear interactions result in a lateral displacement which is typically much larger than that produced by the influence of the GF [67].

  It is impossible to show the rotation effect using shower images from hadron candidates of real data, because they do not point to any source. Therefore, it is difficult to investigate the influence of the GF on the hadron induced background. However, possible GF effects on the hadron induced background presumably do not degrade the background discrimination.

  The result from the MC studies presented in this chapter suggest that the influence of the GF can significantly reduce the γ/hadron separation capability, the imaging performance as well as the energy estimation of an IACT. Altogether, the GF is expected to affect the γ-ray sensitivity of an instrument and the determination of both the differential γ-ray flux and the absolute flux level of a γ-ray source candidate. Furthermore, the MC studies on the GF effect indicate that appropriate MC datasets are not only required for the analysis of low-energy data but also for the reconstruction of VHE γ-rays of at least 1 TeV.

  As the influence of the GF depends on the orientation of the primary γ-ray with respect to the direction of the GF, it is necessary to use appropriate MC data for the data analysis. Therefore, the MAGIC MC library accessible for the standard analysis is certainly incomplete if the GF effects on EAS are taken into consideration. So far, MC data are produced only for 0° and 90° azimuth angle, which is insufficient regarding the strong azimuthal dependence of the GF strength. The findings summarized in this chapter support that the standard MC library has to be extended to account for the GF effects. MC data should be produced with continuous ZA and azimuth angle distribution instead of discrete values.
<table>
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<th>Energy [GeV]</th>
<th>Image Cleaning</th>
<th>ZA [°]</th>
<th>Az [°]</th>
<th>$\Delta \varepsilon_{\gamma}$ [%]</th>
<th>$\Delta$SIZE/SIZE [%]</th>
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<td>$\sim 20$</td>
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Table 7.6: GF effects on the SIZE parameter and the $\gamma$ efficiency for various orientations of the telescope and impact parameters between 20 m and 200 m. The changes of the mean SIZE and the $\gamma$ efficiency are calculated relative to the corresponding values at 0° azimuth angle.
Chapter 8

MAGIC Observations of the Galactic Center Region

This chapter is dedicated to the analysis of a subset of the GC data taken during MAGIC observations. The first part specifies the dataset and the MC sample used for the analysis. The calibration and image cleaning parameters are briefly mentioned, as well as data quality checks are discussed. The results from the application of the RF classifier and RF energy estimation are briefly discussed as well as the agreement between data and MC. In addition, the $\gamma$/hadron separation cuts and quality cuts are elucidated and motivated. Finally, the outcome of the ALPHA analysis and DISP analysis is presented, followed by a discussion of the results.

8.1 The Analysis of the GC Dataset

8.1.1 The GC Dataset

Tabular 8.1 lists the entire GC dataset taken so far with the MAGIC telescope. The dataset used in this work comprises the ON and OFF data from period I and III.

<table>
<thead>
<tr>
<th>Period</th>
<th>Date</th>
<th>Obs. Time [h]</th>
<th>ZA [°]</th>
<th>Az [°]</th>
<th>Events* [10^6]</th>
<th>Obs. Mode</th>
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<td>I</td>
<td>September 2004</td>
<td>2.3</td>
<td>60-68</td>
<td>198-215</td>
<td>1.6 (0.8)</td>
<td>ON</td>
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<td>II</td>
<td>May 2005</td>
<td>10.3</td>
<td>57-62</td>
<td>169-206</td>
<td>4.2 (3.1)</td>
<td>Wobble</td>
</tr>
<tr>
<td>III</td>
<td>May/June/July 2005</td>
<td>18.3/14.7</td>
<td>55-61</td>
<td>160-200</td>
<td>8.2/6.5 (7.3/5.5)</td>
<td>ON/OFF</td>
</tr>
<tr>
<td>IV</td>
<td>August 2005</td>
<td>6.6</td>
<td>57-68</td>
<td>173-215</td>
<td>1.9 (1.7)</td>
<td>ON</td>
</tr>
</tbody>
</table>

Table 8.1: The entire GC dataset taken so far with the MAGIC telescope. *the number of events after calibration as well as after image cleaning and determination of the image parameters is given (in parentheses).

It is noteworthy that for the September dataset, the starguider information is not available. The period IV dataset was taken under presence of moonlight. In appendix C, the whole period I/III datasets are listed in more detail.

It is expected that the sensitivity of the detector is slightly degrading under the presence of moonlight, and the noise level of data is expected to be higher. Thus, moon data has to be treated differently, e.g. the noise level of the MC data used for the analysis of moon data has to be accordingly adjusted to account for the different background conditions.

As the Crab nebula is a standard candle in $\gamma$-ray astronomy, a dataset (appendix C) taken at similar ZA was prepared to verify the analysis at large ZAs. In total, about 6.9 h ON data and about 4.2 h OFF data at ZAs between 52° and 72° have been selected and sub-divided into ZA bins comparable to those of the period I and III datasets.
8.1.2 The MC Dataset

Table 8.2 lists the key parameters of the MC simulated γ-ray showers used for the analysis of the GC data. To obtain enough statistics, the MC sample labeled as Standard MC and High-Energy MC were combined for the analysis of the 2005 GC dataset (period III), whereas the MC sample labeled as LZA MC was prepared for the analysis of the 2004 GC dataset (period I). The differences in the spectral indices were taken into account later on in the flux calculation, i.e. the energy distribution of the MC events was properly re-weighted.

As can be seen from the tables, the azimuth angle at which the LZA MC sample was generated lies within the azimuth angle range covered by the period I dataset. This is apparently not the case for the standard and the HE energy sample, which were generated at 0° and 90° azimuth angle, respectively. Against the background of the results from the MC studies on the GF effects presented in the previous chapter, the analysis of the period III dataset can be affected by the influence of the GF. However, the intensity of the GF at 60° ZA and 180° azimuth angle is comparable to the one at 60° ZA and 90° azimuth angle (figures 7.5 and 7.6 (a)). Therefore, the influence of the GF is taken into account to some extent, since the GF was enabled in the MC.

<table>
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<th>MC Simulation Parameter</th>
<th>Standard MC</th>
<th>High-Energy MC</th>
<th>LZA MC</th>
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<td>γ-ray</td>
<td>γ-ray</td>
<td>γ-ray</td>
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<tr>
<td>energy range</td>
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<td>0 - 700 m</td>
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<td>azimuth angle</td>
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<td>205°</td>
</tr>
<tr>
<td>spectral index ( (E^{-\alpha}) )</td>
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<td>( \alpha = 1.0 )</td>
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<td>simulated showers</td>
<td>∼ 8.6 M</td>
<td>∼ 35 k</td>
<td>∼ 4.6 M</td>
</tr>
<tr>
<td>events after cleaning</td>
<td>∼ 121 k</td>
<td>∼ 27 k</td>
<td>∼ 688 k</td>
</tr>
<tr>
<td>diffuse NSB level (^I)</td>
<td>0.183 Phe/ns</td>
<td>0.183 Phe/ns</td>
<td>0.183 Phe/ns</td>
</tr>
<tr>
<td>optical PSF ((\sigma), each axis )</td>
<td>14 mm</td>
<td>14 mm</td>
<td>14 mm</td>
</tr>
</tbody>
</table>

Table 8.2: The simulation input parameters of the MC datasets. \(^I\) for the flux determination the spectra of the simulated γ showers were re-weighted with the correct source spectral index. \(^II\) NSB level for the inner pixels.

It was necessary to divide the MC dataset into two statistically independent sub-samples, since one sub-sample is needed for both the training of the RF classifier and the RF energy estimator. The second sub-sample was prepared for the flux determination, i.e. for the determination of the effective γ-ray collection area. Table 8.3 lists the MC sub-samples prepared for the analysis of the period I and period III datasets. The MC sub-samples for the training of the γ/hadron separation RF classifier contain the sub-samples prepared for the RF energy estimator, while the sub-samples for the flux determination are statistically independent from the training samples.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Period/MC Sample</th>
<th>Events (after cleaning)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF γ/hadron separation (training)</td>
<td>I/LZA</td>
<td>∼ 298 k</td>
</tr>
<tr>
<td>RF energy estimation (training)</td>
<td>III/standard &amp; HE</td>
<td>∼ 64 k</td>
</tr>
<tr>
<td>Flux determination</td>
<td>I/LZA</td>
<td>∼ 152 k</td>
</tr>
<tr>
<td></td>
<td>III/standard &amp; HE</td>
<td>∼ 32 k</td>
</tr>
<tr>
<td></td>
<td>I/LZA</td>
<td>∼ 389 k</td>
</tr>
<tr>
<td></td>
<td>III/standard &amp; HE</td>
<td>∼ 84 k</td>
</tr>
</tbody>
</table>

Table 8.3: The arrangement of the MC samples for the training of the γ/hadron separation RF classifier, the RF energy estimator and the flux determination (before re-weighting).

MC simulated hadron data at high ZAs were not available in the MAGIC MC library. In
general, large ZA simulations of hadron data of enough statistics are rather time consuming compared to simulations of $\gamma$-ray data. A dedicated production for the analysis of the GC dataset was therefore omitted. Instead, for the training of the $\gamma$/hadron separation RF classifier, a hadron training sample with comparable statistics to the MC training sample was assembled by taking randomly events from the whole GC OFF sample. This was done for the analysis of the period III dataset. Although ON and OFF data were taken alternately, the OFF data has the same characteristics (weather conditions, telescope sub-system performance, etc.) as the background which is to be discriminated. In case of the period I dataset a hadron training sample was assembled by taking randomly events from the whole ON sample, since neither dedicated OFF data were taken nor comparable OFF data are available. A certain $\gamma$ contamination of the hadron training sample has a negligible impact on the $\gamma$/hadron separation power of the RF (section 6.3), and the GC is known to be a weak source of $\gamma$-rays and a negligible $\gamma$ contamination is expected.

To account for the large ZA range covered by the GC observations of period I, the training samples were divided into two ZA bins ranging from 60° to 64° and 64° to 68°, respectively.

8.1.3 Calibration and Image Cleaning

The GC dataset was calibrated using the standard calibration method of the MARS package\cite{51, 52, 151, 152}. There are several methods to extract the signal from the FADC information implemented into the MARS package. For the calibration of the entire dataset considered in this thesis, a signal extractor making use of the digital filtering method\cite{30, 65, 180} was used.

The Hillas parameters were calculated using relatively high absolute image cleaning levels compared to those used in the standard analysis. The cleaning levels were set to 10 Phe for the core pixels and to 5 Phe for the boundary pixels. The MC generated $\gamma$-ray events were processed with the same image cleaning levels.

There are mainly two reasons in support of using higher cleaning levels: firstly, the starfield around the GC is rather inhomogeneous and bright, i.e. the noise level in the FADC information is expected to be higher than usual. Secondly, it is desired to minimize possible differences between the ON and OFF data sample, as they were taken at different sky regions and therefore under slightly different background conditions.

8.1.4 Data Quality Checks

To ensure the best quality of the dataset considered to extract the $\gamma$ signal of a source some stability checks on the dataset are mandatory. These checks involve the monitoring of the time evolution of some telescope parameters. In the following, the most important data quality checks and its results are elucidated and summarized.

- **Mean FADC pulse position**: To avoid the loss of signal, it is important that the PMT signal lies within the high gain time window. It is sufficient to verify that the signal lies within the high gain time window, because the PMT signal split and fed to the low gain branch is delayed by a fixed time interval with respect to the high gain time window (figure 5.3). Figure 8.1 shows the run-based average FADC pulse position in the high-gain time window versus run number for the period I/III GC dataset.

  The huge variations of the arrival times of a large number of runs of the 2004 dataset are due to very short runs which had been aborted because of problems with the data acquisition (DAQ) system. These runs were excluded from the analysis. Furthermore, calibration runs and interlaced calibration events were excluded.\footnote{The calibration system of the MAGIC telescope allows to take calibration events interlaced with normal data at a rate of 50 Hz [90].}
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![Graph showing FADC pulse position over time with two cameras labeled as Inner Camera and Outer Camera, and run numbers from 36255 to 60783.](image)

**Figure 8.1:** The mean FADC pulse position (run-based) for the whole Sgr A* dataset. Pedestal and calibration runs were excluded as well as interleaved calibration events.

Arrival times can be the response of the external optical signal transmission and readout electronics on internal and external temperature variations. Beside this, the average arrival times lie well within the FADC high gain time window. Large variations of the arrival times have to be considered when setting up the signal extractor. Inappropriate extractor settings may lead to a loss of the PMT signal.

- **Pedestal and Pedestal RMS:** Figure 8.2 shows the run-based pedestal and pedestal RMS for the period I/III GC dataset. Between the observation periods of the 2004 and 2005 dataset, the baseline of the FADC system was re-adjusted from about 10 to about 15 FADC counts. As expected, the pedestal RMS level does not change in between those periods. Large fluctuations of the pedestal RMS level are related to very short runs which had been aborted because of problems with the data acquisition (DAQ) system. These runs were excluded from the analysis.

![Graph showing FADC counts over run numbers with two cameras labeled as Inner Camera and Outer Camera, and run numbers from 36255 to 60783.](image)

**Figure 8.2:** The mean pedestal and pedestal RMS (run-based) for the whole Sgr A* dataset. Calibration runs were excluded as well as interleaved calibration events.
• **Level 2 trigger (L2T) rate**: The L2T rate is useful to monitor the atmospheric conditions, such as the event rate after image cleaning (next item). Data runs whose L2T rate strongly deviates from the average trigger rate of the corresponding night were excluded from the analysis.

• **Stability of the event rate after image cleaning**: It is important to monitor the event rate after the image cleaning since it is related to the atmospheric weather conditions and in addition it can allude to possible malfunctions of some telescope subsystems. Large variations of the event rate may be caused by bad atmospheric conditions, like clouds and dust, i.e. high atmospheric extinction. Apart from variations due to the ZA range covered during observations, it is expected that the event rate after image cleaning stays constant within certain limits. If the event rate significantly drops, the corresponding data are not considered in the analysis.

Figure 8.3 shows the event rate after image cleaning for the period I/III dataset. Compared to the 2005 dataset, the 2004 dataset shows comparatively large rate variations of up to 30%. This can be explained by the large ZA range covered by this dataset (table C.1), but also the relatively high atmospheric extinction coefficient during those nights (table D.1).

![Figure 8.3](image)

**Figure 8.3**: The run-based event rate after image cleaning for the whole GC dataset. To distinguish successive nights, the histogram marker color alternates between red and blue. The nights of June 7th (run 57722 - 57764) and 15th (run 58595 - 58604) were excluded from the analysis, since they show lower rates. Lower rates can be attributed to large atmospheric extinction. Changes in ZA during data taking lead to variations of the event rate.

The gaps in the first part of the plot (2004 dataset) correspond to very short runs which have been aborted by the DAQ system. The two nights of June 7th and 15th 2005 show very low rates, which is, at least in case of June 7th, related to a large atmospheric extinction coefficient. These data were excluded from the analysis. The information on the atmospheric extinction coefficient can be found at the web pages of the Mercator and the Carlsberg Meridian Telescope [20, 21].

• **Stability of the image parameters**: As the image parameters are used to extract the faint $\gamma$ signal, it is important to monitor their time evolution and check their stability. Runs whose image parameter distributions strongly deviate from the average distributions of the corresponding night were rejected from the analysis. In this analysis, the image parameters WIDTH, LENGTH, SIZE and DIST were considered to check the stability of
the datasets.
Abnormal deviations of the image parameters can be due to wrongly determined calibration constants used to convert the FADC information into Phe or due to corrupted runs which are sometimes related to an abnormal termination of the DAQ system.

- **Spark event cut**: So-called spark events appear as circular-shaped events, randomly distributed over the whole dataset. Since spark events are observed also with closed camera while all subsystems are running, they cannot originate from EAS, but only from the detector readout chain itself. Most probably these spark events seem to be caused by some short light-flash emitting PMTs in the camera. The origin of the light-flashes can be electric breakdowns between the PMT anode and shielding aluminum covers installed to protect the PMT anode against external magnetic fields, or due to discharges [160]. The short light-flashes could be reflected by the plexiglass window mounted in front of the camera and thus illuminate neighboring pixels.

To identify the spark events, test runs with closed camera were taken. It was found that the spark events can easily be identified in the $\log_{10}(\text{CONC}) - \log_{10}(\text{SIZE [Phe]})$ plane [160]. In figure 8.4, the $\log_{10}(\text{CONC}) - \log_{10}(\text{SIZE [Phe]})$ distributions for dedicated spark event test runs, MC generated $\gamma$-events and Galactic Center data are shown. The average L2T rate of the spark test runs, taken in November and December 2005, is about 0.79 Hz, and the average event rate after image cleaning (same image cleaning levels as for the analysis of the GC data) is about 0.52 Hz.

![Figure 8.4](image)

**Figure 8.4**: $\log_{10}(\text{CONC}) - \log_{10}(\text{SIZE [Phe]})$ distribution for dedicated spark event test runs, MC generated $\gamma$-events and a sub-sample of GC data. The cut to remove $\sim 90\%$ of the spark events while keeping almost all MC $\gamma$ events is indicated as a red line.

The following condition removes $\sim 90\%$ of the spark events while almost all MC $\gamma$ events are kept:

$$\log_{10}(\text{CONC}) + 0.21 \cdot \log_{10}(\text{SIZE [Phe]}) < 0.32.$$  \hspace{1cm} (8.1)

The SIZE-dependent spark event cut is indicated as a red line in figure 8.4.

- **Camera inhomogeneity**: It is known that differences in the level 1 trigger (L1T) cell synchronization lead to a fixed time spread in the analog pulses recorded by the FADC system [144]. Deviations of the recorded pulse positions from the nominal ones can cause a deficit of reconstructed signal in some parts of the camera. The charge assigned to the corresponding pixels may appear artificially reduced and then later be removed by the image cleaning. Thus, a large camera inhomogeneity diminishes the detection efficiency
and a non negligible fraction of the signal may get lost, which affects the whole analysis afterwards.

![Data (Galactic Center)](image1)

(a) The COG distribution of the shower images for the entire period I dataset.

![MC γ Data](image2)

(b) The COG distribution of the MC generated γ shower images. The ZA range covers the range between 60° and 68°, while the azimuth angle is fixed to 205°.

![Data (Galactic Center)](image3)

(c) The COG distribution of the shower images for the entire period III dataset.

![MC γ Data](image4)

(d) The COG distribution of the MC generated γ shower images. The ZA range covers the range between 57° and 63°. The azimuth angle is fixed to 0° and 90°.

Figure 8.5: The COG distributions for the period I and III datasets as well as for and the MC generated γ-ray showers. The image cleaning levels are always 10 Phe and 5 Phe, respectively.

The COG distributions for the entire period I and period III datasets are shown in figure 8.5 (a) and (c), respectively. Both distributions appear to be largely homogeneous, i.e. the default parameters for the signal extractor used for the calibration and extraction of the photomultiplier signals are chosen such that the camera inhomogeneity, as reported in [160], is largely eliminated. The greatest inhomogeneities lie in the outer part of the camera, at about 0.7° distance from the center. From the COG distributions for the corresponding MC datasets in figure 8.5 (b) and (d) it can be seen that the majority of events differ with regard to the distribution of the events in azimuth and elevation. Hadron induced shower images go to larger DIST values and therefore probe the hexagonal-shaped trigger...
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\[ |\vec{B}| = 37.41 \mu T (La Palma) \]

(a) MC data with enabled GF.

\[ |\vec{B}| = 0 \]

(b) MC data with disabled GF.

Figure 8.6: COG distributions of MC generated $\gamma$ shower images for different magnetic field strengths. The ZA is fixed to $66^\circ$ and the azimuth angle is fixed to $0^\circ$ and $90^\circ$.

\[ \delta \quad 0 \quad 50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \quad 350 \]

Entries

0.04

0.035

0.03

0.025

0.02

0.015

0.01

0.005

0

(a) Angular distributions of the entire period I dataset together with the one for MC generated $\gamma$-ray shower images.

\[ \delta \quad 0 \quad 50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \quad 350 \]

Entries

0.04

0.035

0.03

0.025

0.02

0.015

0.01

0.005

0

(b) Angular distributions of the entire period III dataset together with the one for MC generated $\gamma$-ray shower images.

Figure 8.7: Angular distributions of the shower images for the whole GC dataset (red) and MC generated $\gamma$-ray showers (blue). The image cleaning levels are always 10 Phe and 5 Phe, respectively.

Differences between the distributions in figure 8.5 (a) and 8.5 (c) can be attributed to changes in the response of the readout chain of the telescope, i.e. modifications of the DAQ system.

The corresponding distributions for the MC datasets shown in figure 8.5 (b) and (d) respectively, exhibit differences. While the distribution in figure 8.5 (b) appears to be asymmetric with respect to the camera center, the one in 8.5 (d) is rather symmetric. The asymmetry of the former distribution is presumably an effect of the GF, as the $\gamma$ showers were simulated at a fixed azimuth angle of $205^\circ$, close to $180^\circ$, where the GF is known to have a significant influence on the shower development. At $60^\circ$ ZA and $205^\circ$ azimuth
angle, the influence of the GF is comparable to the one at $60^\circ$ ZA and $90^\circ$ azimuth angle. The COG distribution shown in figure 8.5 (d) was obtained using a mixture of MC data generated at $0^\circ$ and $90^\circ$ azimuth angle, respectively, and the influence of the GF is very small at $60^\circ$ ZA and $0^\circ$ azimuth angle (chapter 7).

The correlation between the GF strength and the asymmetry of the angular distribution is illustrated in figure 8.6, were the COG distributions for MC generated $\gamma$ shower images are shown for enabled as well as disabled GF. The distribution in figure 8.6 (a) exhibits the same feature as the one in figure 8.5 (b). Instead, the distribution in figure 8.6 (b), where the GF was disabled in the MC simulation, appears to be rather symmetric with respect to the camera center. In figure 8.7, the angular distributions of the shower images for the period I and III datasets are compared to the ones from the corresponding MC datasets. The distribution for data appears to be rather flat, whereas the one for MC data is rather dominated by fluctuations, which is due to limited statistics. The impact of the Earth’s magnetic field on the shower development is not apparent in this representation.

- **Pointing correction**: Due to the alt-azimuth mount of the telescope, the starfield rotates in the camera, as well does the point in the sky where the telescope is supposed to point to. As some of the most powerful image parameters for the background discrimination are calculated with respect to the source position (which is, in absence of a misalignment of the telescope axis, supposed to be located in the center of the camera), it is mandatory to know the true source position. An optical starguiding system equipped with a very sensitive $4.6^\circ \times 4.6^\circ$ FOV CCD camera monitoring the starfield in the FOV around the pointing position, provides the offset of the telescope pointing position with respect to the true source position. The pointing offset can be used in the offline analysis to determine the true source position. The starguiding system estimates the pointing offset by comparing the monitored starfield with an expected one, based on a regularly updated telescope pointing model.

Although the starguiding system was not calibrated at the period were the GC data were taken, its information can be used for a relative pointing correction. The GC dataset collected in 2005 is affected by the so-called culmination problem. The culmination problem occurred whenever the telescope tracked a source during its culmination. After having passed the culmination, a kind of hysteresis effect of the telescope structure due to alternation of load may introduce a certain pointing offset, which usually lasts for several minutes. To exemplify this effect, the starguider information for the ON dataset of June 29th 2005 is shown in figure 8.8. While the deviation in the azimuth angle stays constant within a certain level (upper right plot), the ZA shows noticeable deviations from the nominal ZA (upper left plot). After having reached the pointing position, the tracking system of the telescope needs some minutes to stabilize, as indicated by the transient decrease of the ZA deviation at the beginning of the observation. The passage of the culmination at around $180^\circ$ azimuth angle gives rise to a big ZA deviation. Although the ZA deviation decreases fast after some minutes, a constant offset with respect to the deviation before culmination remains. The residual deviation in ZA before culmination is indicated by the blue line (upper left plot). It is obtained from a fit to the data points which were collected before the culmination was reached and after the tracking system was stabilized.

To correct for the mis-pointing introduced by the culmination problem, it is necessary to calibrate the starguiding system. Under the assumption that the mis-pointing is negligible after the tracking system has stabilized, a relative calibration can be made with respect to the residual offset. It is noteworthy that this assumption requires the active mirror control (AMC) to operate properly during data taking.

The correction for mis-pointing due to the culmination problem involves several steps:
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Figure 8.8: Starguider information for the ON dataset of June 29th 2005.

- determination of the residual offset for each night.
- determination of the true source position in the camera reference frame after correction for the residual offset. The true source position is obtained by a linear interpolation of neighboring starguider reports after their synchronization to the time stamp of the data.
- re-calculation of the source-dependent image parameters for each event.

Figure 8.9 shows the reconstructed source position in the camera reference frame for the entire period III dataset. To distinguish successive nights, the histogram marker color changes every night. The mis-pointing in $y$-direction extends up to about $0.2^\circ$ which corresponds to two inner pixels, while the mis-pointing in $x$-direction is confined to the size of an inner pixel. Table E.1 lists the residual offsets in azimuth angle and ZA used for the relative calibration of the starguider.

Since the starguiding system was not operable in September 2004, there is no starguider information available for the period I dataset which could be used to monitor and to correct for a possible mis-pointing. But, as the data were not taken during culmination, they are not affected by the culmination problem but rather by a small residual mis-pointing.
**Figure 8.9:** The reconstructed source position in the camera reference frame after correction for the residual offset. To distinguish successive nights, the histogram marker color changes every night. The true source position is determined on an event-by-event basis. Neighboring starguider reports are linearly interpolated and assigned to the corresponding event.
8.1.5 The Hillas Parameter Distributions after Quality Cuts

Figure 8.10 shows the distributions of the most important image parameters for ON and OFF data from the entire period III dataset.

Figure 8.10: ON-OFF comparison of the image parameters SIZE, LENGTH, DIST, WIDTH, CONC and ALPHA for the entire 2005 Sgr A* ON/OFF dataset.
Only quality cuts as mentioned in the previous section were applied. Furthermore, some corrupted runs were excluded from the analysis. The agreement between ON and OFF data is very good, which is important because the dedicated OFF dataset is afterwards used to estimate the hadron induced background. Although the ON and OFF distributions of the image parameter ALPHA agree well, their means are not centered at zero. This may be attributed to the remaining camera inhomogeneity, as mentioned in the previous section (figure 8.5).

8.1.6 $\gamma$/hadron Separation using Random Forest

As already mentioned in section 6.3, the RF method was used for the $\gamma$/hadron separation.

![Figure 8.11](image1.png)

(a) RF training with source-dependent image parameters for zenith angles between 60° and 64°.

(b) RF training with source-dependent image parameters for zenith angles between 64° and 68°.

**Figure 8.11:** The relative importance of the RF-input parameters in terms of the mean Gini decrease (section 6.3), for the period I dataset. 6 image parameters were used as input parameters for the training of the RF.

![Figure 8.12](image2.png)

(a) RF training with source-dependent image parameters.

(b) RF training without source-dependent image parameters DIST and M3LONG.

**Figure 8.12:** The relative importance of the RF input parameters in terms of the mean Gini decrease for the period III dataset. The left figure was obtained using 6 RF input parameters, while the right one shows the relative importance in case of only 4 (source-independent) RF input parameters.

The hadron training sample prepared for the analysis of the period I dataset and the dedicated MC dataset were divided into two zenith angle bins ranging from 60° to 64° and 64° to 68°, respectively. For both sub-samples, the RF cuts were generated using the MC $\gamma$ and hadron
training samples listed in table 8.3, after sub-division into ZAs. Figure 8.11 shows the relative importance of the RF input parameters in terms of the mean Gini decrease. The Gini-index is a statistical measure for the inequality of a distribution, i.e. 0 corresponds to perfect equality, 1 to perfect inequality (section 6.3). The difference between the distributions of the Gini-indices in 8.11 (a) and 8.11 (b) can be attributed to the different ZA ranges of the training samples. Different statistics in each ZA bin does also contribute to the deviant deviation of the Gini-indices. Both classifiers were applied to the entire period I dataset.

In case of the period III dataset, two RF classifiers were generated, one with 6 input parameters, another one with only 4 source-independent input parameters. The former RF classifier (6 input parameters) was intended to be used for the ALPHA analysis and determination of the differential flux, while the latter one (4 input parameters) was intended to be used in the determination of the \( \gamma \)-ray sky map, by means of the DISP method, as described in section 6.5. In the remaining part of this work, the RF classifier based on 6 input parameters is referred to as the RF standard classifier. Both RF classifiers were generated using MC \( \gamma \) and hadron training samples as listed in table 8.3 and were then applied to the period III dataset.

Figure 8.12 shows the relative importance of the RF input parameters in terms of the mean Gini decrease. Figure 8.12 (a) was obtained using 6 input parameters for the RF training, while figure (b) shows the relative importance in case of only 4 source-independent image parameters. Both cases involve the same amount of MC generated \( \gamma \) and hadron showers. In all cases, the SIZE parameter was used as an input parameter for the training of the RF classifiers, as the image parameters depend on this parameter. In order to avoid an overbalance of the SIZE

Figure 8.13: HADRONNESS distributions for different SIZE bins, as obtained after application of the RF standard classifier to the MC \( \gamma \) flux and the entire period III dataset.
parameter in the classification of the events, the SIZE distributions of hadron and γ training sample were made overlap. Furthermore it was assured that the statistics of the MC γ and the hadron training sample are comparable in every SIZE bin.

Figure 8.13 shows the distributions of the HADRONNESS parameter for different bins in the image parameter SIZE, as it is obtained after application of the RF standard classifier to the entire period III dataset and the corresponding MC flux dataset (table 8.3). The upper left plot, which corresponds to the lowest values of the parameter SIZE, i.e. low energies, indicates a rather poor γ/hadron separation power.

![Figure 8.13](image)

**Figure 8.13:** The integral γ and hadron acceptance as a function of the HADRONNESS parameter for different SIZE bins, as obtained after application of the RF standard classifier to the entire period III dataset.

At these values of the SIZE parameter close to the energy threshold of the telescope, a poor selection of γ-like showers from the dataset is to be expected. For SIZE ≲ 320 Phe (upper right figure), the γ/hadron separation power is expected to be significantly better than in the previous case. For higher SIZE values, the ability for efficient γ/hadron separation improves (lower left and right figure, respectively).

Figure 8.14 shows the integral acceptance for γ and hadron showers as a function of the parameter HADRONNESS for different SIZE bins. As the HADRONNESS distributions, the integral acceptances were calculated after application of the RF standard classifier to the entire period III dataset and the corresponding MC flux sample. As can be seen from the run of the curves, the separation of the γ and hadron acceptances becomes better for higher SIZE bins, i.e. the signal to background ratio will be enhanced at larger SIZE values. For SIZE ≳ 320 Phe (upper left figure), an integral γ acceptance of 50% is reached at a relatively large...
HADRONNESS value of around 0.3, whereas for SIZE $\gtrsim 320 \text{ Phe}$ such an integral $\gamma$ acceptance is already reached at HADRONNESS $\lesssim 0.1$. The $\gamma$/hadron separation for low-energy EAS is worsened because the Cherenkov light yield on ground is considerably smaller and subject to great intrinsic fluctuations. The differences between $\gamma$-ray and hadron induced EAS start to clear out and the shower images in the camera become worn away. There again, in case of large ZA observations, the distance from ground to the maximum of the EAS is greater than for low ZAs. The greater distance to the shower maximum in turn shifts the accessible energy range towards higher energies (section 4.3.1), as the Cherenkov light yield on ground is decreased. Thus, close to the threshold energy, the $\gamma$/hadron separation is expected to be worsened.

Figure 8.15: The quality factor as a function of the HADRONNESS parameter for different logarithmic SIZE bins, as obtained after application of the RF standard classifier to the MC $\gamma$ flux and the entire period III dataset.

Figure 8.15 shows the integral quality factor $Q$ as a function of the HADRONNESS parameter for different logarithmic SIZE bins, as obtained after application of the RF standard classifier to the MC $\gamma$ and the entire period III dataset. The integral quality factor is defined as $Q = \frac{\varepsilon_{\gamma}}{\sqrt{\varepsilon_h}}$, where $\varepsilon_{\gamma}$ denotes the $\gamma$ and $\varepsilon_h$ the hadron selection efficiency, respectively (section 6.8). It is crucial to find a reasonable compromise between a high $\gamma$ acceptance and low hadron acceptance, respectively. A high quality factor is not necessarily associated with a high integral $\gamma$ acceptance, as one can see from the comparison of figure 8.14 and 8.15. The choice of a high quality factor is rather related to a small acceptance for both signal and background events which may result in a sample with high $\gamma$ purity but reduced statistics. Furthermore, it is important to keep in mind that the RF-based $\gamma$/hadron separation entirely relies on the agreement between MC generated showers and real data. Although the MC chain used to simulate development and evolution
of EAS and their subsequent detection by the IACT is tuned in a way that it describes the detection of real EAS as good as possible, some discrepancies may still remain. For instance, a tight cut on the HADRONNESS parameter naturally selects rather MC-like \( \gamma \)-ray showers than real \( \gamma \)-ray induced showers. To minimize a possible bias introduced by MC-data discrepancies, it is better to keep the \( \gamma \)/hadron separation cuts as loose as possible.

### 8.1.7 \( \gamma \)-Ray Selection Cuts

In order to keep possible systematics introduced by MC-data discrepancies as small as possible and to obtain enough statistics, loose cuts were applied. While the cuts on the HADRONNESS and ALPHA parameters are the most efficient ones, all other cuts essentially represent quality cuts. The filter cuts on the trigger rate as well as the spark cut (section 8.1.4) are not included in the following list, but they were applied at an early stage of the analysis.

![Graphical representation of the most important \( \gamma \)-ray selection cuts for the period III dataset.](image)

**Figure 8.16:** The graphical representation of the most important \( \gamma \)-ray selection cuts for the period III dataset. The dark red-shaded area indicates the image parameter space which is rejected from the analysis. The light red-shaded area indicates the range of variation of the HADRONNESS cut. The integral acceptance is plotted for shower images fulfilling the condition \( \text{SIZE} > 150 \text{ Phe} \).

The cuts on the ALPHA and HADRONNESS parameter listed below were optimized beforehand on the selected large ZA Crab datasets. Although the Crab dataset was taken in different observation periods and therefore under different observation conditions, it serves as a reference sample to verify the analysis at large ZA. Some important telescope hardware parameters, like the PSF, are subject to temporal changes. As these changes may significantly affect the analysis,
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e.g. due to their impact on the image parameters involved in the \( \gamma \)/hadron separation, the cuts obtained from the large ZA Crab analysis may not just be the best ones, but provide an idea on how to treat a large ZA dataset in either case.

The following \( \gamma \)-ray selection cuts were applied to the Crab nebula, the period I and the period III datasets:

- **SIZE**: A lower cut on the SIZE parameter restricts the analysis to the region where the \( \gamma \)/hadron separation works. Thus, all events fulfilling the condition

  \[
  \text{SIZE} > 150 \text{ Phe} \tag{8.2}
  \]

  were kept.

- **LEAKAGE**: To remove shower images that are not fully contained in the camera, an upper cut on the LEAKAGE parameter was applied. Events surviving the condition

  \[
  \text{LEAKAGE} > 0.1 \tag{8.3}
  \]

  were rejected from the analysis.

- **Number of core pixels**: A lower cut on the number of core pixels (section 6.1) was applied to avoid pixelization effects. To ensure that the shower image parameters (section 6.2) are well defined, only shower images that include a minimum number of core pixels were kept:

  \[
  \text{NUMCOREPIXELS} > 4. \tag{8.4}
  \]

- **Number of islands**: Although the image cleaning removes most of the noise, the remaining distribution of the reconstructed Cherenkov light may not be suited for the image parameter calculation, as it may contain isolated clusters referred to as islands. Especially in case of hadron induced EAS islands accumulate. A cut on the number of islands is expected to remove a certain amount of background. Only events with one cluster were considered in the analysis:

  \[
  \text{NUMISLANDS} < 2. \tag{8.5}
  \]

- **HADRONNESS**: An energy dependent cut on the HADRONNESS parameter was applied in a way that at least 60% of the MC generated \( \gamma \)-rays remain after cuts. For the high-energy part of the data, the HADRONNESS cut was relaxed in order to keep the maximum amount of the events:

  \[
  \text{HADRONNESS} < 0.1, \ldots 0.25. \tag{8.6}
  \]

- **Lower DIST cut**: Since the ALPHA parameter is not well defined for events with too small values of the DIST parameter, the cut

  \[
  \text{DIST} > 0.3^\circ \tag{8.7}
  \]

  was applied.
• **Upper DIST cut:** An upper cut on the DIST parameter was applied. All events surviving the cut

\[
\text{DIST} < 0.22^\circ + 0.25^\circ \cdot \log_{10}(\text{SIZE [Phe]}) \quad (8.8)
\]

were kept. The upper DIST cut ensures that only events are kept where the telescope is located somewhere in the Cherenkov light pool (section 4.2.4).

• **ALPHA:** The best cut for the significance determination was obtained from the analysis of the corresponding large ZA Crab datasets (appendix F). For estimated energies above 1 TeV, the best signal-to-background ratio was obtained for

\[
|\text{ALPHA}| \leq 6.5^\circ. \quad (8.9)
\]

For the determination of the $\gamma$-ray flux, the cut on the parameter ALPHA was kept constant. In case of the differential $\gamma$-ray energy spectrum, all events lying within $|\text{ALPHA}| \leq 7.5^\circ$ were kept. However, for the determination of the integrated $\gamma$-ray flux, the upper cut on the absolute value of the parameter ALPHA was relaxed to 10$^\circ$ (to preserve the limited statistics).

• **Consideration of the GF effects:** The findings of the previous chapter (section 7.4) suggest that the datasets considered in this work are affected by the influence of the GF. Using the definitions $\delta_{\pm} = \Delta\delta_{\pm} + \text{Az}$, the condition defined by equation 7.18 can be converted to

\[
\begin{align*}
\{ \text{sgn} & (\cos(\delta_-) y > - \tan(\delta_-) \text{sgn}(\cos(\delta_-)) x) \ \wedge \ \{ \text{sgn} (\cos(\delta_+) y < \tan(\delta_+) \text{sgn}(\cos(\delta_+)) x) \} \} \\
\vee \\
\{ \text{sgn} & (\cos(\delta_-) y < - \tan(\delta_-) \text{sgn}(\cos(\delta_-)) x) \ \wedge \ \{ \text{sgn} (\cos(\delta_+) y > \tan(\delta_+) \text{sgn}(\cos(\delta_+)) x) \} \},
\end{align*}
\]

\[
\text{Az denotes the azimuth angle and } \delta \text{ the angle between the major axis of a shower image and the } x\text{-axis of the camera coordinate system (figure 6.2). } x \text{ and } y \text{ denote the coordinates of the centroid of a shower image and } \text{sgn}(x) \text{ the sign function being defined as}
\]

\[
\text{sgn}(x) = \begin{cases} 
+1, & x \geq 0 \\
-1, & x < 0.
\end{cases}
\]

The pointing of events surviving the condition 8.10 are affected least by the influence of the GF. Instead, events surviving the condition

\[
\begin{align*}
\{ \text{sgn} & (\cos(\delta'_-) y < - \tan(\delta'_-) \text{sgn}(\cos(\delta'_-)) x) \ \wedge \ \{ \text{sgn} (\cos(\delta'_+ y < \tan(\delta'_+) \text{sgn}(\cos(\delta'_+)) x) \} \} \\
\vee \\
\{ \text{sgn} & (\cos(\delta'_-) y > - \tan(\delta'_-) \text{sgn}(\cos(\delta'_-)) x) \ \wedge \ \{ \text{sgn} (\cos(\delta'_+ y > \tan(\delta'_+) \text{sgn}(\cos(\delta'_+)) x) \} \},
\end{align*}
\]

are expected to be affected strongest by the influence of the GF, where $\delta'_\pm = \Delta\delta'_\pm + \text{Az}$ and $\Delta\delta' = 90^\circ - \Delta\delta$. For $\Delta\delta = 30^\circ$ one third of all events is kept.
Figure 8.16 illustrates the most important cuts mentioned beforehand. The image parameter space rejected from the analysis is indicated as a light red and dark red-shaded area. For the determination of the differential $\gamma$-ray energy spectrum, the cut on the HADRONNESS parameter was relaxed with increasing energy, which is indicated by the dark red-shaded area (upper right plot). In order to get an estimate on the systematic error in the flux determination, the cut on the HADRONNESS parameter was varied within the limits mentioned above.

8.1.8 Energy Estimation using Random Forest

The energy estimation was done by means of the RF method, as elucidated in section 6.6. The MC training samples listed in table 8.3 served for the training of the RF energy estimator. Only events surviving the quality cuts listed in section 8.1.7 were considered for the training. Figure 8.17 (a) shows a comparison of the estimated and the true energy for the MC generated $\gamma$ showers of the period III data sample, i.e. ZA between $57^\circ$ and $63^\circ$.

![Figure 8.17: Results of the RF energy estimation for the period III MC test sample before $\gamma$/hadron separation cuts.](image)

It can be seen that both estimated energy and true energy are strongly correlated, whereas in the low-energy range, i.e. below some $\log_{10} (E_{\text{True}} [\text{GeV}]) \approx 3$, the energy of $\gamma$ showers will be systematically overestimated. This systematical bias can be, to some extent, attributed to the detector trigger. Close to the threshold energy of the telescope, the possibility to accept those EAS that statistically produce more Cherenkov light is higher. Furthermore, especially low-energy shower images are subject to larger fluctuations and are thus expected to be more affected by the overestimation. As the energy distribution of the MC $\gamma$-ray showers follows a power law, high energies are represented less frequent. This is what eventually restricts the analysis to a certain energy window.

Figure 8.17 (b) shows the true energy and RF estimated energy as a function of the image parameter SIZE of the MC generated $\gamma$ shower images. It can be seen that both estimated energy and true energy are strongly correlated, whereas in the low-energy range, i.e. below some $\log_{10} (E_{\text{True}} [\text{GeV}]) \approx 3$, the energy of $\gamma$ showers will be systematically overestimated. This systematical bias can be, to some extent, attributed to the detector trigger. Close to the threshold energy of the telescope, the possibility to accept those EAS that statistically produce more Cherenkov light is higher. Furthermore, especially low-energy shower images are subject to larger fluctuations and are thus expected to be more affected by the overestimation. As the energy distribution of the MC $\gamma$-ray showers follows a power law, high energies are represented less frequent. This is what eventually restricts the analysis to a certain energy window.
as a function of the true energy, is shown in figure 8.18 (a). After logarithmic binning in $E_{\text{True}}$, the quantity $(E_{\text{Est.}} - E_{\text{True}}) / E_{\text{True}}$ is calculated for each event and then averaged. Down to energies of around 1 TeV, the bias is very small. This can be seen also in figure 8.18 (b) where the estimated and the true energies are plotted as a function of the parameter SIZE. The bias is taken into account by the unfolding of the differential $\gamma$-ray energy spectrum (section 6.7). Figure 8.18 (b) shows the energy resolution as a function of the true energy for the MC generated $\gamma$-ray events. The energy resolution is defined as the standard deviation from a Gauss fit to the distribution of the quantity $(E_{\text{Est.}} - E_{\text{True}}) / E_{\text{True}}$. The energy resolution stays mostly around 25% and increases to about 15% at true energies beyond 10 TeV.

![Figure 8.18](image)

(a) The bias versus true energy of the MC generated $\gamma$ showers.

(b) The energy resolution versus true energy of the MC generated $\gamma$ showers.

**Figure 8.18:** The bias and the energy resolution after application of the RF energy estimator on the period III MC test sample before $\gamma$/hadron separation cuts.

### 8.1.9 Monte Carlo Data Comparisons

As the $\gamma$/hadron separation and determination of the differential $\gamma$-ray flux rely on MC simulations, it is important to compare the Hillas parameters of MC generated $\gamma$ showers to the one of $\gamma$-like candidates from real data. Although the application of filter cuts and cuts on the HADRONNESS and ALPHA parameter allow for the separation of $\gamma$-like events, the remaining sample will still be contaminated with hadron showers, especially in case of weak $\gamma$-ray sources. For a detailed study on the agreement between MC and data, an extremely strong $\gamma$-ray source would be required. Nevertheless, the comparison of the most important image parameters is important so as to find out about the proper simulation of the telescope’s response. In particular, the image parameter WIDTH is sensitive to the PSF of the telescope. The PSF is an input parameter to the MC simulation programs (section 5.2.6.2).

The MC data comparisons were done in logarithmic bins of the SIZE parameter. In order to keep only $\gamma$-like events from the data, only events for which the condition HADRONNESS $< 0.1$ and $|\text{ALPHA}| < 10^\circ$ was fulfilled were kept.

To reject all images where the image parameters are not well defined (section 6.2), only events with more than 4 core pixels were kept. A quality cut on the LEAKAGE parameter assures
that only images fully contained in the camera are taken into account. All events for which the condition LEAKAGE < 0.1 was fulfilled were kept. Additionally, a static cut on the DIST parameter was applied, i.e. 0.3° < DIST < 1.0°. The latter cut was not applied in case of the MC data comparison of the DIST parameter. Figure 8.19 shows the MC data comparison of the image parameters LENGTH, WIDTH, DIST and CONC for events whose SIZE parameter lies within the window 2.0 < log_{10}(SIZE [Phe]) < 2.5. This SIZE window corresponds to γ-ray energies between about 500 GeV and 1 TeV (figure 8.17 (b)). Given the admixture of hadronic events, the agreement between the distributions of the image parameters LENGTH and WIDTH within statistical errors is good. The distributions of the image parameters DIST and CONC exhibit a reasonable agreement, too. Figure 8.20 shows the MC data comparison for energies between about 1 TeV and 3.5 TeV. While the agreement between the image parameters LENGTH, WIDTH and CONC remains reasonable, the one of the parameter DIST degrades. It is noteworthy that both distributions of the parameter DIST disagree at about 1°, close to the edge of the trigger region of the camera. However, hadron induced showers are preferentially rather uniformly distributed over the entire trigger area of the camera, which is not the case for (MC generated) γ-ray showers (figures 8.5 (a) - (d)).

The MC data comparison for primary energies between about 3.5 TeV and some 10 TeV is shown in figure 8.21. Within errors, the agreement between MC and data is reasonable. However, because of the limited statistics at these high energies, a precise interpretation is not possible.

The agreement in the lowest bin of the parameter SIZE is fairly good, whereas it seems to
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\[ 2.5 < \log_{10}(\text{SIZE [Phe]}) < 3.0 \]

Figure 8.20: Post-cut comparison of various image parameters of GC data (period III) and MC generated \( \gamma \)-ray showers for \( 2.5 < \log_{10}(\text{SIZE [Phe]}) < 3.0 \).

degraded with increasing SIZE, i.e. increasing energy. At low energies (small SIZE) \( \gamma \)-ray and hadron induced shower images are more similar than at high energies. Since the data have a significant admixture of hadrons, these hadrons separate from the \( \gamma \)-rays especially at higher energies leading to larger discrepancies between MC and data.

There are several possibilities that can lead to a disagreement between the image parameter distributions of MC simulations and data: The PSF, currently approximated by a single Gaussian for both dimensions in the camera plane, might not be properly simulated. Furthermore, the PSF of the telescope is subject to temporal variability, which was not taken into account in the MC data comparisons presented above. The PSF of the telescope can be inferred from muon images [157], which is done on a daily basis [149]. Moreover, aberration effects of the telescope optics may not be taken into account precisely enough. Another possible reason for the disagreement between the image parameters of MC and data could originate from the influence of the GF. However, given the limited statistics and the fact that the considered \( \gamma \)-ray source is weak, the agreement between MC and data is satisfactory. The agreement between the image parameters of MC and data indicates that the MC input value for the PSF reasonably describes the true PSF of the telescope. In this regard it is worth mentioning that, because of the improved AMC, the PSF of the telescope is stable and well under control [42].
Figure 8.21: Post-cut comparison of various image parameters of GC data (period III) and MC generated $\gamma$-ray showers for $3.0 < \log_{10} (\text{SIZE [Phe]}) < 4.0$. 
8.1.10 Results from the ALPHA Analysis

8.1.10.1 The Effective Observation Time

The knowledge about the effective observation time is crucial for the determination of the differential $\gamma$-ray flux.

Figure 8.22: The distribution of event time differences for the period I dataset after data quality checks. The effective observation time amounts to about 2.3 h. To be well above the dead time, which is about 40 $\mu$s, the lower limit for the fit was set to 0.001 s.

(a) The effective observation time for the ON observations of the GC period III dataset.

(b) The effective observation time for the OFF observations of the GC period III dataset.

Figure 8.23: The distribution of event time differences for ON (a) and OFF data (b) for the remaining period III dataset after data quality checks. The effective observation time amounts to about 16.6 h for the ON dataset and to about 11.7 h for the OFF dataset. In order to be well above the dead time of the DAQ, which is about 40 $\mu$s, the lower limit for the fit was set to 0.001 s.

The effective observation time was determined by means of an exponential fit to the distribution of event time differences (section 6.7.1). The distribution of event time differences for the entire period I dataset is shown in figure 8.22. From this distribution, the effective observation time is determined to be about 2.3 h.
Figure 8.23 shows the distribution of event time differences for the entire ON and OFF datasets of period III that remain after data quality cuts. In case of the ON observations, the effective observation time amounts to about 16.5 h, while for the OFF dataset it is only 11.7 h. This results in a normalization scale factor of \( \alpha = 1.42 \). If the observation times dedicated to ON- and OFF-source observations differ, the OFF data have to be scaled to the ON data to get an estimate of the background.

### 8.1.10.2 The \( \gamma \)-Ray Signal from the GC

The ALPHA distributions shown below were obtained after data quality checks and \( \gamma \)/hadron separation cuts. The cut on the HADRONNESS parameter was set to 0.1 and the estimated energy was required to be greater than 1 TeV.

Figure 8.24 (a) shows the \( \gamma \)-ray signal for the period I dataset in terms of the distribution of the absolute value of the image parameter ALPHA. The ALPHA distribution was fitted by a polynomial of second order as well as by a polynomial of second order plus a Gauss function. The number of excess events was estimated using the extrapolation of the second order polynomial into the signal region.

The significance was calculated for \(|\text{ALPHA}| \lesssim 6.5^\circ\). The number of excess events is \(27 \pm 13\), resulting in a significance of about 2 standard deviations. The significance was calculated using equation 6.1 (section 6.4) [143]. Beforehand, the analysis at large ZAs between 59° and 69° was verified using a subset of the Crab nebula dataset (appendix C). In total, about 4.5 h ON Crab data and about 2.2 h OFF Crab data were used. The results from the analysis are shown in appendix F.

![Figure 8.24: The distributions of the absolute value of the image parameter ALPHA for the period I and period III datasets. The estimated energy was required to be greater than 1 TeV.](image)

Figure 8.24 (b) shows the \( \gamma \)-ray signal of the period III dataset. The ALPHA distribution for ON data is shown in blue, whereas the one for OFF data in light gray. The OFF data were scaled to the ON data in order to get an estimate for the background in the region of small ALPHA values. Within statistical errors, the agreement between ON and OFF ALPHA distributions is satisfactory. It is noteworthy that the datasets were obtained from different NSB integration regions.
(a) ALPHA plot for events oriented at favorable directions with regard to the influence of the GF. The interval for the angle \( \delta \) was set to \( \Delta \delta = 30^\circ \).

(b) The ALPHA plot for events oriented at the most unfavorable directions with regard to the influence of the GF. The interval for the angle \( \delta \) was set to \( \Delta \delta = 30^\circ \).

(c) The ALPHA plot for events oriented at favorable directions with regard to the influence of the GF. The period I dataset (\( \Delta \delta = 30^\circ \)).

(d) The COG distribution of selected shower images for the period I dataset (\( \Delta \delta = 30^\circ \)).

Figure 8.25: The distributions of the absolute value of the image parameter ALPHA for the period I dataset, considering the influence of the GF. The estimated energy was required to be greater than 1 TeV.

The normalization scale factor from the ON-OFF normalization, derived from the region \( 20^\circ \leq |\text{ALPHA}| \leq 90^\circ \), amounts to \( \alpha = 1.52 \pm 0.21 \).

In the ideal case, the scale factor derived from the ON-OFF normalization should be equal to the one obtained from the ratio of the effective observation times (preceding section). The moderate agreement between the normalization factors can be partially attributed to variations of the trigger rate that was assumed to be constant. Another reason for the discrepancy may be that the ON and OFF datasets were obtained at slightly different ZA intervals. Furthermore,
8.1. THE ANALYSIS OF THE GC DATASET

(a) ALPHA plot for events oriented at favorable directions with regard to the influence of the GF. The interval for the angle $\delta$ was set to $\Delta \delta = 30^\circ$.

(b) The ALPHA plot for events oriented at the most unfavorable directions with regard to the influence of the GF. The interval for the angle $\delta$ was set to $\Delta \delta = 30^\circ$.

(c) The ALPHA plot for events oriented at favorable directions with regard to the influence of the GF. The interval for the angle $\delta$ was enlarged to $\Delta \delta = 60^\circ$.

(d) The COG distribution of selected shower images for the period III dataset ($\Delta \delta = 30^\circ$).

Figure 8.26: The distributions of the absolute value of the image parameter ALPHA for the period III dataset, considering the influence of the GF. The estimated energy was required to be greater than 1 TeV.

there could be some contribution from $\gamma$-rays to the region $|\text{ALPHA}| > 20^\circ$ in the ON dataset leading to the increase of the normalization factor obtained from the ON-OFF normalization.

Apart from different exposure times dedicated to the ON and OFF observations, the scaling of the ON and OFF datasets is required to account for different observation conditions, like differences in the sky brightness or changing weather conditions. However, the impact of these environmental conditions is minimized by the application of quality cuts.

To extract the number of excess events, the OFF distribution was fitted by a polynomial of
second order and the ON distribution was fitted by a polynomial of second order plus a Gauss function. The number of excess events was estimated using the extrapolation of the second order polynomial to the signal region. As in case of the period I dataset, the significance, after cut optimization on the corresponding large ZA Crab dataset, was calculated for $|\text{ALPHA}| \lesssim 6.5^\circ$. The excess amounts to $358 \pm 34$ events. The significance of the $\gamma$-ray signal was calculated using equation 6.1. It amounts to about 11 standard deviations.

As for the period I dataset, the analysis was verified beforehand using a subset of the large ZA Crab nebula dataset (appendix F).

To investigate the influence of the GF on the GC datasets, both the most unfavorable and favorable regions with regard to the influence of the GF were considered separately. Figure 8.25 shows the ALPHA distributions for the period I dataset, considering the influence of the GF. As expected, the ALPHA distribution for events surviving condition 8.10 (figure 8.25 (a)) yields a better signal-to-background ratio than the one obtained by application of condition 8.11 (figure 8.25 (b)). In both cases, the interval $\Delta \delta$ was set to $30^\circ$. The events corresponding to favorable and unfavorable arrangements are drawn as green-colored and red-colored histograms into the camera display (figure 8.25 (d)). Figure 8.25 (c) shows the ALPHA distribution for events surviving the condition 8.10, but with the interval $\Delta \delta$ set to $60^\circ$. The ALPHA distribution appears to be slightly enhanced compared to the one obtained for the entire camera (figure 8.24 (a)).

Figure 8.26 shows the corresponding distributions for the period III dataset. As for the period I dataset, the GF effects are clearly visible. The GF disturbs the pointing of shower images oriented at the most unfavorable directions with regard to the influence of the GF and the corresponding ALPHA distribution (figure 8.26 (b)) appears to be broadened. The ALPHA distribution obtained for the favorable regions in the camera is rather narrow and stronger peaked at small ALPHA values. Furthermore, for a fixed cut on the ALPHA parameter the number of excess events can significantly alter depending on the region in the camera. In case of the period III dataset, the number of excess events lying within $|\text{ALPHA}| < 6.5^\circ$ varies by $\sim 30\%$.

The large ZA Crab nebula dataset exhibits the same feature like the GC datasets. Depending on the orientation of the $\gamma$-ray candidates with respect to the pointing direction of the telescope, the pointing of the shower image is disturbed by the influence of the GF. As for the GC datasets, the ALPHA distribution obtained for the favorable regions in the camera is rather narrow and stronger peaked at small ALPHA values (figure F.2 (a)).

In conclusion it can be stated that the predictions of the MC studies presented in the preceding chapter apply to real data acquired with the MAGIC telescope. The influence of the GF is clearly visible even at $\gamma$-ray energies above 1 TeV. The Crab nebula dataset as well as the period I and the period III GC datasets are affected by the influence of the GF. The latter is expected, as the absolute value of the vertical component of the GF strength is comparable for Crab nebula and GC observations carried out at $\gtrsim 60^\circ$ ZA (figure 7.6). For GC observations carried out at $\sim 60^\circ$ ZA, the GF strength is about $37 \mu T$ and for Crab observations carried out at similar ZA the GF strength amounts to about $35 \mu T$.

The recovery of the $\gamma$ signal which is lost due to the influence of the GF is possible to some extent but would require dedicated MC datasets. In the preceding chapter it was shown that the rotation angle of shower images depends on the azimuth angle and the impact parameter. Thus, to be able to partially recover the pointing of shower images it would be necessary to estimate the impact parameter of the $\gamma$-ray candidates, which is possible on the 20\% level [135]. However, the $\gamma$-ray signal may be partly recovered by relaxing the cut on the ALPHA parameter. The relaxation of the ALPHA cut may help to reduce systematics introduced by GF effects, especially in case of the determination of the differential $\gamma$-ray spectrum. Another approach would be to scale the excess obtained for the unfavorable regions in the camera to the one obtained for the favorable regions.
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As mentioned in section 8.1.7, for the determination of the differential \( \gamma \)-ray energy spectrum the cut on the ALPHA parameter was relaxed to 10\(^{\circ} \).

8.1.10.3 The Differential \( \gamma \)-Ray Energy Spectrum

The differential \( \gamma \)-ray flux before application of the unfolding procedure is shown in figure 8.27.

![Figure 8.27: The differential \( \gamma \)-ray energy spectrum for the period III dataset before application of the unfolding procedure. The solid black line shows the result of the power-law fit to the spectrum. The gray-shaded area indicates the range within which the data points are shifted for varying \( \gamma \)/hadron separation cuts.](image)

The spectrum is consistent with a power law and the result from the correlated fit to the data is

\[
\frac{dF_\gamma}{dE} = (0.29 \pm 0.07 \text{stat.} \pm 0.12 \text{sys.}) \cdot 10^{-12} \left( \frac{E}{3.0 \text{ TeV}} \right)^{-2.08 \pm 0.19 \text{stat.} \pm 0.2 \text{sys.}} \text{ph cm}^2 \text{s TeV} \]

(8.13)

In the ideal case, the flux level as well as the spectral slope of the energy spectrum should be independent of the \( \gamma \)/hadron separation cuts. In order to investigate the systematics, the cut on the HADRONNESS parameter for each energy bin was changed in a way that the \( \gamma \) efficiency varied by up to 20\%. Altogether, the HADRONNESS cuts were modified 100 times. The gray-shaded area around the data points in figure 8.27 indicates the range by which the data points are shifted for different cuts on the HADRONNESS parameters. The systematic change of the spectral index obtained from a power-law fit is in the order of 5\%, and the flux level changes by up to 15\%.

The quantities required for the determination of the differential \( \gamma \)-ray flux before unfolding are listed in table 8.4. As can be seen from the table, the most dominant error is the one on the number of excess events, whereas all other quantities involved in the spectrum calculation exhibit rather small errors.
Table 8.4: The relevant quantities for the determination of the differential γ-ray flux from the period III dataset before unfolding. Only statistical errors (1 standard deviation) are given. \( \langle E \rangle \) denotes the mean energy of a certain energy bin, \( \Delta E \) the corresponding bin width, \( N_{\text{Excess}} \) the number of excess events in the signal region, \( \varepsilon \) the γ efficiency, incorporating all cuts, and \( A_{\text{Eff.}} \) the post-cut effective collection area.

<table>
<thead>
<tr>
<th>( \langle E \rangle ) [GeV]</th>
<th>( \Delta E ) [GeV]</th>
<th>( N_{\text{Excess}} )</th>
<th>( \varepsilon )</th>
<th>( A_{\text{Eff.}} ) [10^5 cm^2]</th>
<th>( \frac{dF_\gamma}{dE} ) ( \times 10^{-12} ) ph TeV^{-1} cm^{-2} s^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>397.37 ± 113.5</td>
<td>396.85</td>
<td>69.49 ± 56.67</td>
<td>0.206</td>
<td>0.44 ± 0.02</td>
<td>6.710 ± 5.372</td>
</tr>
<tr>
<td>1191.60 ± 224.8</td>
<td>791.61</td>
<td>217.03 ± 56.63</td>
<td>0.426</td>
<td>1.61 ± 0.04</td>
<td>2.871 ± 0.895</td>
</tr>
<tr>
<td>2376.92 ± 422.4</td>
<td>1579.1</td>
<td>112.94 ± 39.27</td>
<td>0.514</td>
<td>2.26 ± 0.06</td>
<td>0.534 ± 0.186</td>
</tr>
<tr>
<td>4741.34 ± 805.6</td>
<td>3149.8</td>
<td>48.15 ± 22.29</td>
<td>0.541</td>
<td>2.56 ± 0.07</td>
<td>0.101 ± 0.047</td>
</tr>
<tr>
<td>9457.72 ± 1482.7</td>
<td>6283.0</td>
<td>26.14 ± 11.19</td>
<td>0.595</td>
<td>2.78 ± 0.07</td>
<td>0.025 ± 0.011</td>
</tr>
<tr>
<td>18865.7 ± 2829.0</td>
<td>12532.9</td>
<td>17.0 ± 4.12</td>
<td>0.670</td>
<td>2.86 ± 0.07</td>
<td>0.008 ± 0.002</td>
</tr>
</tbody>
</table>

Figure 8.28: The total cut efficiency and the effective collection area for the period III dataset. Both quantities were determined from the corresponding MC dataset after quality and γ/hadron separation cuts. The gray-shaded regions indicate the range within which the data points are shifted for different cuts on the HADRONNESS parameter. The cut efficiency of the second lowest energy bin varies by up to 20%. For the determination of the differential γ-ray energy spectrum, only data points with a total cut efficiency above 20% were kept.

The γ efficiency after cuts is shown in figure 8.28 (a). For γ-ray energies above of about 1 TeV, the efficiency is greater than 40%. The post-cut effective collection area for γ-rays is shown in figure 8.28 (b).

The migration matrix, an important input to the unfolding procedure of the differential γ-ray energy spectrum, is shown in figure 8.29.

The unfolded differential γ-ray energy spectrum for the period III dataset is shown in figure 8.30. The spectrum is consistent with a power law and the result from the correlated fit to the data is

\[
\frac{dF_\gamma}{dE} = (0.23 \pm 0.04_{\text{stat.}} \pm 0.09_{\text{sys.}}) \times 10^{-12} \left( \frac{E}{3.0 \text{ TeV}} \right)^{-2.19\pm0.19_{\text{stat.}}\pm0.2_{\text{sys.}}} \text{ ph cm}^{-2} \text{ s TeV}^{-1}. \quad (8.14)
\]

The solid black line shows the result from the power-law fit to the energy spectrum. Within statistical errors, the result is consistent with measurements from the H.E.S.S. experiment [4].
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Figure 8.29: The migration matrix for the period III dataset. The migration matrix shows how the estimated MC \( \gamma \) energies are distributed along the true energy, which is required for the unfolding procedure of the differential \( \gamma \)-ray energy spectrum. The lowest bin in \( E_{\text{True}} \) was excluded, as the acceptance for this bin is very low (\( \lesssim 3 \% \), figure 8.28). The highest bin in \( E_{\text{True}} \) was excluded because the MC statistics for this bin is limited. The entire range of estimated energies \( E_{\text{Est}} \) was taken into account for the unfolding.

Figure 8.30: The differential \( \gamma \)-ray energy spectrum as obtained for the period III dataset together with the measurements of the H.E.S.S. (solid dark green line) and the CANGAROO experiment (solid light blue line). The solid black line shows the result of the power-law fit to the spectrum. The gray-shaded area indicates the range within which the data points are shifted for varying \( \gamma \)/hadron separation cuts. For sake of comparison, the Crab nebula spectrum from MAGIC observations [207] is shown as a blue dotted line.

The measured flux in direction of the GC amounts to about 10\% of the flux from the Crab nebula at energies beyond \( \sim 1 \text{ TeV} \). For comparison, the energy spectrum of the Crab nebula is indicated as a dotted blue line [207].
Apart from GF effects, the overall systematic error in the determination of the flux level is estimated to be in the order of 40\%, and the one of the differential spectral index is estimated to be about 0.2 [160, 203]. There are several sources that may contribute to the overall systematic error:

- **Detector performance**: some telescope subsystems may introduce systematic errors in the determination of the flux level from a VHE $\gamma$-ray emitter. The calibration of the energy scale depends on the performance of the calibration system. Fluctuations of the light output of the calibration system may introduce systematic uncertainties in the energy scale. The excess noise factor method (section 5.2.5) may introduce systematic uncertainties, as it is based on the signal-to-noise ratio of the individual photomultipliers, which is afflicted with a certain error. In addition, uncertainties of the QE of the photomultipliers contribute to the systematic error of the calibration. The conversion factors for the calibration of the FADC information into Phe is estimated to be 10\% [148, 160]. Light losses due to deteriorating mirror reflectivity are taken into account in the MC simulation chain. At the time where the period III dataset was taken, the average specular reflectivity of the mirror was about 77\%. It was lastly measured in 2005 [71]. Furthermore, the deposition of dust on the plexiglass window in front of the photomultiplier camera may cause light losses. The camera inefficiency (section 8.1.4) may artificially attenuate the reconstructed signal in some parts of the camera, which in turn introduces a systematic error. The error is estimated to be in the order of 10\% [160]. The optical PSF of the telescope, an input parameter to the MC simulations, is subject to temporal fluctuations. In case of the period I and period III dataset, it was determined to be about 14 mm [157].

- **MC simulations**: MC simulations of EAS are based on certain models describing the relevant properties of the atmosphere. In case of IACTs, the Cherenkov light originating from charged particles in EAS is collected at all altitudes. The longitudinal development of EAS depends on the atmospheric density profile, and the amount of emitted Cherenkov light depends on the refractive index of air. Thus, the precise knowledge of the density profile as well as the refractive index is important for the proper MC simulation of EAS. The atmospheric transmission is also part of the atmospheric models used in the MC simulations. Altogether, seasonal variations of the characteristics of the atmosphere as well as inappropriate atmospheric models may change the Cherenkov light density on ground by some 15\% [38].

- **GF effects**: In the previous chapter it was shown that the influence of the GF can thin out the Cherenkov light distribution on ground. For $\gamma$-ray energies around 1 TeV, 60\° ZA and 180\° azimuth angle, the effect on the image parameter SIZE is in the order of 10\%. Therefore, if the GF effect is not properly taken into account by using appropriate MC data, the energy of $\gamma$-ray candidates detected under unfavorable conditions with regard to the influence of the GF is expected to be underestimated by 5 - 10\%. It remains to be shown to what extent the GF effects on the parameters WIDTH and LENGTH degrade the $\gamma$/hadron separation capability and therefore the determination of the differential $\gamma$-ray flux. However, the GF on the image parameters WIDTH, LENGTH and ALPHA are partially taken into account as parts of the MC dataset used for the analysis of the GC, and the Crab nebula datasets were simulated under appropriate conditions with respect to the GF effects.

- **Analysis method**: As mentioned beforehand, the variation of the cut on the HADRONNESS parameter can systematically change the outcome of the flux calculation. The change of the spectral index obtained from a power-law fit is about 5\%, and the flux level
8.1. **THE ANALYSIS OF THE GC DATASET**

can be changed by up to 15\%, which is in the order of the statistical errors obtained from the fit. So far, an extensive study of the systematics introduced by different analysis methods is missing. Since the systematic change of the flux parameters is in the same order of magnitude as the statistical error, they do not represent the dominant contribution to the overall systematic error.

The main contributions to the overall systematic uncertainty are due to the atmospheric model used in the MC simulations (15\%), the influence of the GF (5\%), the camera inefficiency (10\%) and the calibration (10\%).

### 8.1.10.4 The Time Variability of the VHE $\gamma$-Ray Emission

The investigation of the time variability of the VHE $\gamma$-ray emission from a VHE $\gamma$-ray emitter can be done by means of the so-called light curve. To obtain the light curve, the entire dataset was divided into sub-samples, and the integrated $\gamma$-ray flux was determined for each time bin.

<table>
<thead>
<tr>
<th>MJD</th>
<th>$N_{\text{Excess}}$</th>
<th>$\alpha$</th>
<th>$t_{\text{Eff.}}$ [s]</th>
<th>$A_{\text{Eff.}}$ [10^{9} \text{ cm}^2]</th>
<th>$F_{\gamma,E &gt; 1 \text{ TeV}}$ [$10^{-12}$ \text{ ph cm}^{-2} \text{s}^{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>53557.0</td>
<td>42.2 ± 19.2</td>
<td>-</td>
<td>8149.88 ± 22.44</td>
<td>1.78 ± 0.01</td>
<td>2.91 ± 1.32</td>
</tr>
<tr>
<td>53620.5</td>
<td>10.8 ± 7.1</td>
<td>0.040 ± 0.003</td>
<td>1419.07 ± 10.83</td>
<td>2.23 ± 2.56</td>
<td>3.41 ± 2.25</td>
</tr>
<tr>
<td>53521.4</td>
<td>11.4 ± 8.4</td>
<td>0.059 ± 0.004</td>
<td>2186.69 ± 13.00</td>
<td>2.13 ± 3.18</td>
<td>2.45 ± 1.81</td>
</tr>
<tr>
<td>53524.4</td>
<td>37.1 ± 12.2</td>
<td>0.109 ± 0.005</td>
<td>4181.62 ± 18.42</td>
<td>2.21 ± 2.26</td>
<td>4.02 ± 1.33</td>
</tr>
<tr>
<td>53526.3</td>
<td>34.9 ± 12.4</td>
<td>0.116 ± 0.005</td>
<td>4100.50 ± 18.12</td>
<td>2.19 ± 2.23</td>
<td>3.88 ± 1.38</td>
</tr>
<tr>
<td>53530.2</td>
<td>17.2 ± 11.6</td>
<td>0.114 ± 0.005</td>
<td>3910.26 ± 17.81</td>
<td>2.13 ± 3.18</td>
<td>2.03 ± 1.38</td>
</tr>
<tr>
<td>53532.2</td>
<td>49.6 ± 14.4</td>
<td>0.150 ± 0.006</td>
<td>3588.06 ± 21.29</td>
<td>2.19 ± 2.23</td>
<td>4.05 ± 1.18</td>
</tr>
<tr>
<td>53534.2</td>
<td>0.16 ± 13.7</td>
<td>0.122 ± 0.006</td>
<td>5271.76 ± 20.69</td>
<td>2.19 ± 2.77</td>
<td>3.34 ± 1.19</td>
</tr>
<tr>
<td>53547.8</td>
<td>40.8 ± 11.2</td>
<td>0.082 ± 0.004</td>
<td>3441.86 ± 17.87</td>
<td>2.25 ± 1.97</td>
<td>5.26 ± 1.44</td>
</tr>
<tr>
<td>53549.8</td>
<td>5.9 ± 11.3</td>
<td>0.118 ± 0.005</td>
<td>4357.66 ± 19.04</td>
<td>2.13 ± 3.18</td>
<td>0.65 ± 1.22</td>
</tr>
<tr>
<td>53551.8</td>
<td>42.1 ± 14.3</td>
<td>0.156 ± 0.006</td>
<td>5958.47 ± 22.50</td>
<td>2.19 ± 2.77</td>
<td>3.23 ± 1.09</td>
</tr>
<tr>
<td>53553.7</td>
<td>25.3 ± 12.4</td>
<td>0.123 ± 0.006</td>
<td>4946.33 ± 20.44</td>
<td>2.19 ± 2.23</td>
<td>2.34 ± 1.14</td>
</tr>
<tr>
<td>53555.7</td>
<td>35.0 ± 13.4</td>
<td>0.138 ± 0.006</td>
<td>5167.17 ± 21.19</td>
<td>2.19 ± 2.23</td>
<td>3.10 ± 1.18</td>
</tr>
<tr>
<td>53557.6</td>
<td>42.7 ± 13.1</td>
<td>0.134 ± 0.006</td>
<td>3832.76 ± 20.52</td>
<td>2.19 ± 2.77</td>
<td>3.09 ± 1.23</td>
</tr>
<tr>
<td>53559.6</td>
<td>20.4 ± 8.8</td>
<td>0.057 ± 0.004</td>
<td>2547.58 ± 14.65</td>
<td>2.06 ± 4.48</td>
<td>3.87 ± 1.68</td>
</tr>
<tr>
<td>53561.5</td>
<td>17.3 ± 7.0</td>
<td>0.032 ± 0.003</td>
<td>1456.60 ± 11.24</td>
<td>2.06 ± 4.48</td>
<td>5.78 ± 2.34</td>
</tr>
</tbody>
</table>

**Table 8.5:** The relevant quantities for the determination of the light curve. Only statistical errors (1 standard deviation) are given. The number of excess events $N_{\text{Excess}}$, the ON-OFF normalization factor $\alpha$, the effective observation time $t_{\text{Eff.}}$, the post-cut effective collection area $A_{\text{Eff.}}$, as well as the integral flux of $\gamma$-ray candidates were determined for each MJD.

In order to obtain enough statistics for the determination of the integrated $\gamma$-ray flux, all three days of the period I dataset were combined. In case of the period III dataset, the integrated flux was determined on a day-to-day basis yielding 15 sub-samples. The period III OFF dataset was combined for each time bin, resulting in some correlation between the individual bins. Figure 8.31 shows the reconstructed $\gamma$-ray flux for estimated energies above 1 TeV as a function of the time. There is no indication for a variability of the VHE $\gamma$-ray flux within the observation periods I and III. Within statistical errors, the VHE $\gamma$-ray flux derived from the MAGIC GC observations considered in this work is compatible with a steady emission.

A one-parameter fit to the integrated $\gamma$-ray flux above 1 TeV yields

$$F_{\gamma,E > 1 \text{ TeV}} = (3.33 \pm 0.37_{\text{stat.}} \pm 1.33_{\text{sys.}}) \cdot 10^{-12} \text{ ph cm}^{-2} \text{s}^{-1}. \quad (8.15)$$

The relevant quantities for the determination of the integral $\gamma$-ray flux are listed in table 8.5. As can be seen from the table, the error on the integrated flux of $\gamma$-ray candidates is dominated by the error on the number of excess events obtained for each time bin. As for the differential $\gamma$-ray energy spectrum, the systematic error for integrated flux is estimated to be about 40\%.
8.1.11 Results from the DISP Analysis

This section summarizes the results from the DISP analysis of the period III dataset. The DISP method (section 6.5) allows to reconstruct the arrival direction of $\gamma$-ray candidates in sky coordinates. In order to perform an unbiased DISP analysis, only source-independent image parameters were taken into account in the training of the RF $\gamma$/hadron separation classifier (section 8.1.6).

After mis-pointing correction, the DISP parameter was determined for each event of the ON and OFF dataset. The de-rotation was done on an event-by-event basis, and the new coordinates for each event were transformed into equatorial coordinates and then filled into a two dimensional histogram referred to as the sky map. The rotation of the FOV inside the camera of the MAGIC telescope has to be taken into account to get a meaningful sky map of arrival directions.

Figure 8.32 shows the background-subtracted angular distribution of $\gamma$-ray candidates in the direction of the GC for estimated energies greater than 1 TeV. The ON-OFF normalization factor was obtained from the region in the ON and OFF sky map where no signal is expected. All events within the circular disk defined by $0.6^\circ \leq r \leq 0.9^\circ$ were taken into account for the ON-OFF normalization. Therein $r$ denotes the distance measured from the center of the map. The lower cut on the parameter HADRONNESS was set to 0.1. To preserve the limited statistics, i.e. to minimize the impact of background fluctuations, the upper cut on the DIST parameter was taken away.

The sky map is folded with a two-dimensional Gaussian of standard deviation $0.1^\circ$ roughly corresponding to the telescope PSF, i.e. the $\gamma$-ray angular resolution of the telescope (section 4.3.1.3). The smoothing of the sky map helps to reduce the impact of statistical fluctuations. The maximum excess is located at (RA, Dec) = (17h 45m 35.05 s, $-28^\circ 59' 47.58''$) (J2000 coordinates). For comparison, the BH candidate Sgr A* is located at (RA, Dec) = (17h 45m 40.00 s, $-29^\circ 00' 30.00''$). The excess exhibits a certain elongation under a small angle with respect to the galactic plane. It was discussed elsewhere that the extension of the emission along the galactic plane can be attributed to CR interactions with giant molecular clouds in the vicinity of the GC [6]. The galactic plane ($b = 0^\circ$) is indicated as a gray dotted line.

For the sake of comparison, the DISP analysis was performed for the corresponding Crab
nebula dataset. The result of Crab nebula observations at ZA between 57° and 63° is shown in figure F.3 (a). The excess in direction of the Crab nebula, known to be a point-like emitter of VHE $\gamma$-rays, appears to be roundish. This is the case even for very large ZA of up to 69°. Figure F.3 (b) shows the result from the DISP analysis for a Crab nebula dataset covering ZAs between 59° and 69°. Thus, a systematic error introduced by the DISP method is rather unlikely. Apart from the elongation of the excess in the GC sky map, the sky map obtained from the analysis of the corresponding Crab nebula dataset, and the GC sky map are rather comparable.

The effect of the mis-pointing correction is illustrated in figure 8.33 (a) and (b), respectively. The excess in the uncorrected sky map 8.33 (a) appears to be slightly broadened. However, one can hardly see the influence of the mis-pointing correction. The excess of the uncorrected sky map is offset in declination by only $\Delta$Dec = $-00^\circ 00'49.68''$. Thus, the mis-pointing correction has a rather small impact on the source location but slightly reduces the fluctuations around the signal region. The systematic pointing uncertainty during the acquisition of the period III dataset is estimated to be $O(1')$ [52].

The asymmetric VHE $\gamma$-ray emission could be due to a residual mis-pointing or a point-like source with a weak elongation in direction of the galactic plane. Moreover, the large ZA Crab nebula dataset, included in the DISP analysis, covers a large observation period, including the one of the GC dataset. Even though there is no overlap between the observation periods, the Crab nebula dataset provides a kind of long-run check for the pointing performance of the telescope. The elongation of the excess in the GC sky map cannot be due to the influence of the Earth’s magnetic field on the shower development. For MAGIC observations of the Crab nebula carried out at $\sim 60^\circ$ ZA, the influence of the Earth’s magnetic field on the shower development is comparable to the one expected for MAGIC observations of the GC (figure 7.6). At $\sim 60^\circ$ ZA, the absolute value of the GF strength is comparable for both sources. The sky maps obtained from the DISP analysis of the Crab nebula datasets do not exhibit any feature like the one in the GC sky map.

The results from GC observations carried out by the H.E.S.S. experiment do not exclude the presence of non-azimuthally symmetric tails in the VHE $\gamma$-ray emission [4, 186]. Furthermore,
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Figure 8.33: The background-subtracted sky maps for γ-ray candidates in the direction of the GC region for estimated energies greater than 1 TeV, before and after correction for the mis-pointing. The maximum excess, indicated as a black cross, coincides with the position of the maximum excess reported by the H.E.S.S. experiment.

GC observations carried out at the H.E.S.S. observatory site are expected to be affected least by the influence of the GF (figure 7.7). Thus, the Earth’s magnetic field can be excluded as the source for the elongation of the γ-ray excess in the GC sky map.

8.2 Conclusions & Outlook

The MAGIC observations of the GC confirm that the GC region is a source of VHE γ-rays. The reconstructed spectrum with spectral index $\alpha = 2.19 \pm 0.19_{\text{stat.}}$ is rather hard, and the γ-ray flux at energies above 1 TeV is about 10% of the Crab nebula flux. While the results from the MAGIC observation obtained in this work as well as in [11, 160] confirm the results from the H.E.S.S. experiment [4], they exhibit substantial differences compared to the results reported by the CANGAROO [204] and Whipple [133] collaborations. The flux level derived from the MAGIC dataset considered in this work as well as the shape of the differential γ-ray energy spectrum are compatible within errors with the H.E.S.S. measurement.

Even though MAGIC can access only energies above some 700 GeV for observations of the GC region, i.e. there is only limited overlap between the energy ranges covered by the H.E.S.S., CANGAROO and MAGIC experiments, the results obtained from the MAGIC observations carried out in 2004 and 2005 allow to draw some important conclusions.

As the absolute calibration of the energy scale of an IACT represents a difficult task, the measurement of the VHE γ-ray emission with MAGIC and the comparison to previous measurements provides an important crosscheck. It is worth mentioning that the results from the MAGIC observations carried out at large ZA agree well with the H.E.S.S. measurements, which were performed at rather low ZA. Nevertheless, investigating a possible time variability of the VHE γ-ray emission in direction of the GC provided a strong case for extended MAGIC observations in 2005.

MAGIC observations indicate that there is no significant time variability on time scales of
The flux level derived from the small dataset acquired in September 2004 and the one obtained for the bigger 2005 dataset are consistent within errors. Furthermore, there is no significant time variability between the measurements of the H.E.S.S. experiment and the results obtained from the MAGIC dataset. Thus, MAGIC observations rather affirm that the GC is a steady emitter of VHE $\gamma$-rays, although the presence of sub-hour flares in VHE $\gamma$-rays cannot be excluded. To further resolve the question of time variability, long-term monitoring of the VHE $\gamma$-ray emission from the GC region is necessary. Simultaneous observations of present IACTs would be advantageous to compare independent measurements, which is particularly important in respect of the discrepancies between the MAGIC/H.E.S.S. and the CANGAROO measurements.

The observed excess in direction of the GC is point-like, although there are indications for a faint elongation in direction of the galactic plane, which is also reported in [4, 6, 160, 186]. It was shown elsewhere that the extension of the emission along the galactic plane can be attributed to CR interactions with giant molecular clouds in the vicinity of the GC [6]. The position of the excess coincides with the one of the compact radio source Sgr A*. However, given the limited angular resolution of present IACTs ($\mathcal{O}(0.1^{\circ})$) source confusion is possible, and the VHE $\gamma$-ray emission cannot yet be non-ambiguously assigned to any of the source in the GC region. Thus, a number of different sources could contribute to the VHE $\gamma$-ray signal. Within the angular resolution of MAGIC, the location of the VHE $\gamma$-ray excess is spatially consistent with the SNR Sgr A East as well as the BH candidate Sgr A*. Stereoscopic observations of both the MAGIC and the MAGIC II telescope [26] carried out in the near future may help to shed light on the origin of these VHE $\gamma$-rays. The detection of EAS from different views allows for their geometrical reconstruction which in turn increases the precision of the estimated arrival direction of individual $\gamma$-rays.

It was demonstrated that the GF can affect the reconstruction of the $\gamma$-ray signal. Depending on the camera region considered for the extraction of the $\gamma$-ray signal, the shape of the ALPHA distribution is noticeably altered. For unfavorable directions of the $\gamma$-ray candidate with regard to the influence of the GF, the distribution of the parameter ALPHA is significantly broadened. This effect was demonstrated by means of the large ZA Crab nebula dataset as well as in the GC datasets. Further studies using dedicated MC samples are required to investigate the influence of the GF on the determination of the $\gamma$-ray energy spectrum in greater detail. Nevertheless, the GF can be excluded as the origin for the faint elongation in direction of the galactic plane. The results from the analysis of a Crab nebula dataset acquired at similar ZA as well as similar conditions with regard to the intensity of the GF indicate that the feature of the GC sky map is presumably not due to the influence of the GF on the development of EAS.

The $\gamma$-ray signal is very likely not dominated by SUSY DM annihilation. MAGIC and H.E.S.S. observations [4, 7, 184] show that the $\gamma$-ray energy spectrum extends to at least 10 TeV, thus shifting a possible cutoff to a range well beyond the one expected for SUSY DM annihilation. If the observed $\gamma$-ray signal is interpreted to be due to SUSY DM particle annihilation, the best particle candidate is provided by the neutralino or the KK photon ($B^{(1)}$) in case the KK scenario is realized by nature. A high cutoff energy of some 10 TeV would imply a DM particle mass beyond some 10 TeV, which is very close to the unitarity limit [104]. Such a scenario is disfavored by particle physics arguments, where a sub TeV-scale neutralino/KK photon is favored [79, 176]. Furthermore, the spectrum appears to follow a simple power-law, which is not expected for $\gamma$-rays that are due to annihilation of DM particles [219]. Instead, the main part of the observed $\gamma$-rays is presumably of astrophysical origin. However, a small DM contribution to the observed $\gamma$-ray signal cannot be entirely excluded [184]. The fluxes expected from DM annihilation are rather low and strongly depend on the innermost density profile of the DM halos [36, 107, 161, 162, 163, 168, 197] and the $\gamma$-ray flux measured from the GC is far above theoretical expectations [80, 154, 219].

To gain information on the nature of the TeV $\gamma$-ray source, simultaneous observations with
present IACTs and satellite experiments will help. Chandra [60] and XMM-Newton [218] in X-rays as well as INTEGRAL [118] in the optical, X-ray and sub-GeV range and the future GLAST experiment [96] in the MeV - GeV-energy range will provide important information to find out about the nature of the source and the emission mechanism taking place at the GC. In case of variable emission, the multi-wavelength coverage of future GC observations is important, because correlations between different energy windows allows to figure out the origin of the VHE \(\gamma\)-rays. For instance, an indication for the hadronic origin of the VHE \(\gamma\)-ray emission would be the presence of sub-hour TeV flares that are accompanied by X-ray flares, as the Synchrotron radiation from \(e^+e^-\) pairs from secondary \(\pi\) meson decays is expected to be extended into the hard X-rays [5]. The detection of TeV neutrino flares would provide strong evidence for the hadronic origin of the \(\gamma\)-rays. The KM3NeT project, a future deep-sea research infrastructure hosting a neutrino telescope with a volume of at least one cubic kilometer to be constructed in the Mediterranean Sea [130], may be best suited for simultaneous observations of the GC region, together with \(\gamma\)-ray telescopes. The absence of TeV neutrinos would provide an argument against the hadronic origin, but may strengthen the hypothesis of the leptonic origin of the VHE \(\gamma\)-rays. However, correlated TeV \(\gamma\)-ray and X-ray flares are also possible in SSC models.

In conclusion it can be stated that the VHE \(\gamma\)-ray source at the center of our Galaxy is confirmed, even though its localization is not yet known precisely enough to be assigned to any of the objects at the GC, and its origin is not yet clear. Future observations in the next years will hopefully reveal the mechanism taking place at the GC and provide more interesting physics.
Appendix A

Definition of Moments and Spreads

A.1 The Moments of the Shower Images

The moments of the light distribution in the camera are defined as follows:

\[
\langle x \rangle = \sum \frac{s_i x_i}{s_i}, \quad \langle y \rangle = \sum \frac{s_i y_i}{s_i},
\]

\[
\langle x^2 \rangle = \sum \frac{s_i x_i^2}{s_i}, \quad \langle y^2 \rangle = \sum \frac{s_i y_i^2}{s_i},
\]

\[
\langle x^3 \rangle = \sum \frac{s_i x_i^3}{s_i}, \quad \langle y^3 \rangle = \sum \frac{s_i y_i^3}{s_i},
\]

\[
\langle xy \rangle = \sum \frac{s_i x_i y_i}{s_i},
\]

\[
\langle x^2 y \rangle = \sum \frac{s_i x_i^2 y_i}{s_i}, \quad \langle x y^2 \rangle = \sum \frac{s_i x_i y_i^2}{s_i},
\]

\[
\langle x y \rangle = \sum \frac{s_i x_i y_i}{s_i}.
\]

The coordinates \(x_i\) and \(y_i\), measured in degrees, correspond to the position the \(i\)th pixel in the camera reference frame. The number \(s_i\) is given by the ADC information of the \(i\)th pixel after gain normalization, pedestal subtraction and image cleaning. The sum runs over all pixels of the camera.

A.2 The Spreads of the Shower Images

Spreads of shower images in different directions are defined in terms of the moments, described beforehand:

\[
\sigma_{x^2} = \langle x^2 \rangle - \langle x \rangle^2, \quad \sigma_{y^2} = \langle y^2 \rangle - \langle y \rangle^2, \quad \sigma_{xy} = \langle xy \rangle - \langle x \rangle \langle y \rangle,
\]

\[
\sigma_{x^3} = \langle x^3 \rangle - 3 \langle x^2 \rangle \langle x \rangle + 2 \langle x \rangle^3, \quad \sigma_{y^3} = \langle y^3 \rangle - 3 \langle y^2 \rangle \langle y \rangle + 2 \langle y \rangle^3,
\]

\[
\sigma_{x^2 y} = \langle x^2 y \rangle - \langle x^2 \rangle \langle y \rangle - 2 \langle xy \rangle \langle x \rangle + 2 \langle x \rangle^2 \langle y \rangle, \quad \sigma_{xy^2} = \langle xy^2 \rangle - \langle x \rangle \langle y^2 \rangle - 2 \langle xy \rangle \langle y \rangle + 2 \langle x \rangle \langle y \rangle^2.
\]
A.3 Hillas Parameters

The definition of the source-independent SIZE, WIDTH, LENGTH and CONC, as well as the one of the source-dependent image parameters DIST, ALPHA, ASYM and M3LONG is given below.

The orientation of a shower image in the camera can be expressed by a linear equation:

\[ y = a \cdot x + b, \]

where the coordinates \( x \) and \( y \) are measured in the camera reference system. The slope \( a \) and the offset \( b \) are given by

\[
\begin{align*}
a &\equiv \tan \delta = \frac{d + \sqrt{d^2 + 4\sigma_{xy}^2}}{2\sigma_{xy}}, \\
b &\equiv \langle y \rangle - a \cdot \langle x \rangle.
\end{align*}
\]

The quantity \( d \) is defined as \( d \equiv \sigma_{y^2} - \sigma_{x^2} \). The Hillas parameters are then calculated according to

\[
\begin{align*}
\text{SIZE} &\equiv \sum_i s_i, \\
\text{WIDTH} &\equiv \sqrt{\frac{\sigma_{y^2} + a^2 \sigma_{x^2} - 2a \sigma_{xy}}{1 + a^2}}, \\
\text{LENGTH} &\equiv \sqrt{\frac{a^2 \sigma_{y^2} + \sigma_{x^2} + 2a \sigma_{xy}}{1 + a^2}}, \\
\text{CONC} &\equiv \frac{s_{\text{max}} + s_{\text{max, 2nd}}}{\sum_i s_i}, \\
\text{DIST} &\equiv \sqrt{\langle x \rangle^2 + \langle y \rangle^2}, \\
\text{ALPHA} &\equiv \arcsin \left( \frac{|b|}{\text{DIST} \cdot \sqrt{1 + a^2}} \right), \\
\text{ASYM} &\equiv \left( \langle x \rangle - x_{\text{max}} \right) \cos \delta + \left( \langle y \rangle - y_{\text{max}} \right) \sin \delta, \\
\text{M3LONG} &\equiv \frac{3}{\sum_i s_i} \left[ \left( x_i - \langle x \rangle \right) \cos \delta + \left( y_i - \langle y \rangle \right) \sin \delta \right]^3.
\end{align*}
\]

Therein \( s_i \) denotes the signal of the \( i \)th pixel after gain normalization, pedestal subtraction and image cleaning, \( s_{\text{max}} \) the maximum and \( s_{\text{max, 2nd}} \) the 2nd largest signal of all pixels in the shower image and \( x_{\text{max}} \) respectively \( y_{\text{max}} \) the coordinates of the pixel with the maximum signal. The coordinates \( x_i \) and \( y_i \), measured in degrees, correspond to the position the \( i \)th pixel in the camera reference frame. The sum in the expressions given beforehand runs over all pixels of the camera.

To make the image parameter M3LONG signed it is multiplied by \( \cos \delta_{\text{ALPHA}} / |\cos \delta_{\text{ALPHA}}| \), where \( \delta_{\text{ALPHA}} \) is the angle between the vector from the source position to the COG of the shower image and a vector along the major axis of the Hillas ellipse, whose \( x \)-coordinate is always positive.
Appendix B

Flux Sensitivity

Measurements with IACTs are generally performed in a domain where the $\gamma$-ray flux is dominated by background due to CR events. The energy spectrum of CRs obeys a power law which can be parameterized as

$$\Phi_{\text{CR}}(E) \sim E^{-\alpha_{\text{CR}}},$$  \hfill (B.1)

where $\alpha_{\text{CR}} \approx 1.7$ in the energy range that is covered by today’s IACTs. The spectral index $\alpha_{\gamma}$ of the energy distribution of a $\gamma$-ray source

$$\Phi_{\gamma}(E) \sim E^{-\alpha_{\gamma}},$$  \hfill (B.2)

typically ranges from 1 to 3. The number $N_{\gamma}$ of $\gamma$-rays detected from a source in a certain time interval $t$ can be obtained from

$$N_{\gamma} = \text{LDE} \, \Phi_{\gamma}(E) A_{\gamma}(Z,A,E) t,$$  \hfill (B.3)

where LDE denotes the light detection efficiency for Cherenkov light and $A_{\gamma}(Z,A,E)$ the effective collection area for $\gamma$-rays. Correspondingly, the number $N_{\text{CR}}$ of detected background events in the same time interval $t$ is given by

$$N_{\text{CR}} = \text{LDE} \, \Phi_{\text{CR}}(E) A_{\text{CR}}(Z,A,E) t.$$  \hfill (B.4)

The flux sensitivity, i.e. the minimum detectable flux can be estimated as

$$S(Z,A,E,t) \approx \frac{N_{\gamma}}{\sqrt{N_{\text{CR}}}} \sim \sqrt{\frac{\alpha_{\text{CR}}}{\alpha_{\gamma}}} A_{\gamma}(Z,A,E) \sqrt{\text{LDE} \sqrt{t}} \sim \sqrt{t}. $$  \hfill (B.5)

As the effective collection area for $\gamma$-rays and CRs and also the spectral indices of the observed spectra scale with the ZA, the sensitivity of an instrument depends on the ZA.
### Appendix C

## Dataset

<table>
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**Table C.1:** The Sgr A* ON dataset.
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**Table C.3:** The Crab nebula ON dataset.

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**Table C.4:** The Crab nebula OFF dataset.
Appendix D

Atmospheric Extinction

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Table D.1: Atmospheric extinction data as determined by the Carlsberg Meridian Telescope (CMT) on the Canary Island of La Palma. The nightly values are derived from CCD frames in the SDSS r’ band. Each frame contains an average of 30-40 photometric standard stars [21].
Appendix E

Starguider Calibration

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<td>0.0246 ± 0.0007</td>
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Table E.1: Residual offsets for the calibration of the starguider. The requirement for the starguider information to be taken into account for the offset calculation is that at least 10 stars were recognized in the FOV.
Appendix F

Crab Nebula Observations at large Zenith Angle

F.1 The Crab Nebula $\gamma$-Ray Signal at large Zenith Angle

Figure F.1: The distributions of the absolute value of the image parameter ALPHA for the selected subsets of the LZA Crab nebula dataset. The estimated energies were required to be greater than 1 TeV.
F.1. THE CRAB NEBULA $\gamma$-RAY SIGNAL AT LARGE ZENITH ANGLE

(a) The ALPHA plot for events oriented at favorable directions with regard to the influence of the GF. The unfavorable directions with regard to the influence of the interval for the angle $\delta$ was set to $\Delta \delta = 30^\circ$.

(b) The ALPHA plot for events oriented at the most unfavorable directions with regard to the influence of the GF. The interval for the angle $\delta$ was set to $\Delta \delta = 30^\circ$.

(c) The ALPHA plot for events oriented at favorable directions with regard to the influence of the GF. The unfavorable directions with regard to the influence of the interval for the angle $\delta$ was enlarged to $\Delta \delta = 60^\circ$.

(d) The COG distribution of selected shower images for Crab nebula observations at ZA between $57^\circ$ and $63^\circ$ ($\Delta \delta = 30^\circ$).

Figure F.2: The distributions of the absolute value of the image parameter ALPHA for LZA Crab nebula observations at ZA between $57^\circ$ and $63^\circ$, considering the influence of the GF. The estimated energy was required to be greater than 1 TeV.
F.2 Results from the DISP Analysis

(a) The events incoming direction map for Crab nebula observations at ZA between 57° and 63°. The maximum excess is located at (RA, Dec) = (5 h 34 m 34 s, 22° 01' 54.09") (J2000 coordinates).

(b) The events incoming direction map for Crab nebula observations at ZA between 59° and 69°. The maximum excess is located at (RA, Dec) = (5 h 34 m 34.68 s, 21° 57' 20.86") (J2000 coordinates).

Figure F.3: The background-subtracted sky maps for γ-ray candidates in the direction of the Crab nebula for estimated energies greater than 1 TeV, for observations at ZA between 57° and 63° as well as for observations between 59° and 69°. The distributions are folded with a two-dimensional Gaussian with standard deviation 0.1° (γ-ray angular resolution).
Appendix G

GC Data Analysis - Supplementary Material

Figure G.1: The ALPHA plots for the determination of the differential γ-ray energy spectrum. For each energy bin, the ALPHA distribution for OFF data was scaled to the one for ON data. The number of excess events was then obtained by subtracting the ALPHA distribution for OFF data from the one for ON data. Both the ON and OFF distributions were not fitted. The ALPHA distribution for the ON data cannot be properly approximated by a simple polynomial plus a Gauss function, and the one for OFF data does not follow a simple polynomial function. After ON-OFF normalization, both distributions agree reasonably well for $|\text{ALPHA}| \gtrsim 15^\circ$. 

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Appendix H

List of Acronyms and Abbreviations

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<th>Explanation</th>
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<td>Alternating Current</td>
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<td>Air Cherenkov Telescope</td>
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<td>AGASA</td>
<td>Akeno Giant Air Shower Array</td>
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<td>AGILE</td>
<td>Astro-rivelatore Gamma a Immagini LEggero</td>
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<td>Active Galactic Nucleus</td>
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<td>AMC</td>
<td>Active Mirror Control</td>
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<td>BATSE</td>
<td>Burst and Transient Source Experiment</td>
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<td>BH</td>
<td>Black Hole</td>
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<td>CCD</td>
<td>Charged Coupled Device</td>
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<td>CMB</td>
<td>Cosmic Microwave Background</td>
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<td>COG</td>
<td>Center Of Gravity</td>
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<td>CR</td>
<td>Cosmic Ray</td>
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<td>DC</td>
<td>Direct Current</td>
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<td>Extended Air Showers</td>
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<td>EBL</td>
<td>Extragalactic Background Light</td>
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<td>EGRET</td>
<td>Energetic Gamma-Ray Experiment Telescope</td>
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<td>FADC</td>
<td>Flash Analog-to-Digital-Converter</td>
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<tr>
<td>FOV</td>
<td>Field Of View</td>
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<td>FWHM</td>
<td>Full Width at Half Maximum</td>
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<td>GF</td>
<td>Geomagnetic Field</td>
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<td>Gamma Ray Large Area Space Telescope</td>
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<td>Gamma-Ray Burst</td>
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<td>High Energy</td>
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<td>High Energy Stereoscopic System</td>
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<td>Imaging Air Cherenkov Telescope</td>
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<td>Inverse Compton</td>
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<td>Light Emitting Diode</td>
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<td>Large Zenith Angle</td>
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<td>MAGIC</td>
<td>Major Atmospheric Gamma-ray Imaging Cherenkov</td>
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<td>MARS</td>
<td>MAGIC Analysis and Reconstruction Software</td>
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<td>MC</td>
<td>Monte Carlo (simulation)</td>
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<td>MJD</td>
<td>Modified Julian Day</td>
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<td>NRAO</td>
<td>National Radio Astronomy Observatory</td>
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Appendix I

Definitions and Conversion Units

This chapter summarizes some physical and astrophysical constants used in this thesis as well as terms and definitions which are common in astronomy and astro-particle physics [176].

Energy Range Definitions Table I.1 lists the energy range definitions commonly used in astro-particle physics. The unit \( 1\text{ eV} = 1.6022 \cdot 10^{-19} \text{ J} \) is the energy increase of an electron that underwent a potential difference of 1 Volt.

<table>
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<th>Synonym</th>
<th>Energy Range</th>
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<tr>
<td>Low Energy (LE)</td>
<td>1 eV - 100 MeV</td>
<td>1 - 10^8 eV</td>
</tr>
<tr>
<td>High Energy (HE)</td>
<td>100 MeV - 100 GeV</td>
<td>10^8 - 10^{11} eV</td>
</tr>
<tr>
<td>Very High Energy (VHE)</td>
<td>100 GeV - 100 TeV</td>
<td>10^{11} - 10^{14} eV</td>
</tr>
<tr>
<td>Ultra High Energy (UHE)</td>
<td>100 TeV - 1 EeV</td>
<td>10^{14} - 10^{18} eV</td>
</tr>
<tr>
<td>Extreme High Energy (EHE)</td>
<td>beyond 1 EeV</td>
<td>&gt; 10^{18} eV</td>
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</tbody>
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Table I.1: Common energy range definitions. The definitions are used throughout this thesis.

Speed of light in vacuum \( c = 2.998 \cdot 10^8 \text{ m/s} \)

Jansky In radio astronomy the non-SI unit jansky, \( 1\text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1} \), is commonly used for the electromagnetic flux.

Light year 1 light year = 1 ly = 0.946 \cdot 10^{16} \text{ m} is defined as the distance light travels in one year.

Parsec 1 parsec = 1 pc = 3.086 \cdot 10^{16} \text{ m} = 3.262 ly, a unit of length in astronomy and astrophysics, is defined as the distance from the Earth to a star of 1 arcsecond parallax. The parallax of star is defined by half of the angular distance of the apparent movement of a star against the celestial sphere due to the Earth’s orbit around the sun.

MJD Modified Julian Day (MJD) The Modified Julian Day denotes the number of days that have elapsed since midnight at the beginning of Wednesday November 17, 1858. It can be defined in terms of the Julian Day (JD): \( \text{MJD} = \text{JD} - 2,400,000.5 \). The JD is the integer number of days that have elapsed since Monday, January 1, 4713 BC.

Hour Angle In astronomy, the hour angle (HA) of an object, measured in hours, is defined as the difference between the current local sidereal time (LST) and the right ascension (RA) of the object. In other words, it denotes how much sidereal time has elapsed since the object has crossed the local meridian.
Equatorial Coordinates The equatorial coordinate system, whose coordinates are Declination \( \delta \) and Right Ascension \( \alpha \) is widely used in astronomy. The RA, fixed to stars, is measured eastwards from the vernal equinox point along the celestial equator, which is the projection of the Earth’s equator onto the celestial sphere. The declination, measured in degrees, denotes the latitudinal angle of an object above or below the celestial equator. The declination varies from \(-90^\circ\) to \(+90^\circ\). The RA is usually measured in hours. The hour angle is related to the LST and the RA by \( HA = LST - RA \). The precession and nutation of the Earth’s axis require to specify the epoch of an observation, e.g. J2000, or B1950 for earlier observations. Due to the Earth’s precession and nutation, the position of the vernal equinox will change, thus the equatorial coordinates of stars are time dependent.

Galactic Coordinates The galactic coordinate system, a spherical coordinate system, is used to mark distant objects far beyond our solar system. Its coordinates are the galactic latitude \( b \) and the galactic longitude \( l \), respectively, both of which are measured in degrees. The latitude \( b \) varies from \(+90^\circ\) (perpendicular above the galactic plane) to \(-90^\circ\), whereas the longitude \( l \) counts from the direction to the GC \( (l = 0^\circ) \) via the galactic anti-center \( (l = 180^\circ) \), away from the sun) back to the galactic center. The galactic coordinates define a spherical coordinate system with the sun at the center and a plane parallel to the orientation of the Milky Way galaxy’s central plane, defining the galactic equator. The longitudinal origin is defined by the center of our galaxy. It was calibrated to 17h 45m 37.224s, \(-28^\circ\ 56'\ 10.23''\) (J2000). The GC, located at 17h 45m 40.04s, \(-29^\circ\ 00'\ 28.1''\) (J2000), is offset from the longitudinal origin because the plane of the galactic equator lies above the plane through the center of the galaxy.

A useful tool to convert equatorial into galactic coordinates can be found in [66].
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Curriculum Vitæ

Sebastian Caspar Commichau
Physicist, University of Aachen (TH)

PERSONAL INFORMATION:

Date and place of birth: 5th of November 1976, Aachen (Germany)

Place of origin: Roetgen, Kreis Aachen (Germany)

Nationality: German

EDUCATION & BACKGROUND:

1983 - 1985 Primary school in Roetgen, Germany.

1985 - 1996 Secondary school and high school (Freie Waldorfschule Aachen) in Aachen, Germany.

1996 - 1997 Civil service: supervision of severely handicapped children and adolescents in Neumark, Germany.

1997 - 2002 Study at the faculty of Mathematics and Physics at the University of Aachen (TH). Diploma work on Prototyp einer Ausleseelektronik für einen Synchrotron-Strahlungs-Detektor im Weltraum, performed under the supervision of Prof. Dr. Günter Flügge and Prof. Dr. Joachim Mnich of the Third Institute for Physics (Chair B).

2003 - 2007 PhD thesis in astroparticle physics (this work) performed at the Swiss Federal Institute of Technology (ETH) Zurich within the group of the Institute for Particle Physics, under the supervision of Prof. Dr. Felicitas Pauss, Prof. Dr. Jan Stenflo and Dr. Adrian Biland.