Simulation Study of the H.E.S.S. Single Telescope Trigger Rate

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Abstract

The H.E.S.S. experiment is a system of imaging Cherenkov telescopes currently under construction. It will be capable to observe cosmic gamma rays with a primary energy between 50 GeV and 50 TeV, in order to explore the non-thermal universe. The performance of the telescope system is limited by background of charged cosmic rays and optical night sky background, dominating the trigger rate of the telescope. This work describes a comprehensive study of the trigger rate of a single H.E.S.S. telescope, using Monte Carlo simulation methods. In order to calculate the night sky background contribution, an efficient simulation algorithm was developed. The simulated trigger rates for a cosmic gamma ray source and all background contributions for several trigger configurations and observation directions are compared. For example, a trigger requiring a coincidence of 4 pixels in a trigger sector with more than 4 photo-electrons in each photo-multiplier of the telescope camera, results in a rate of 0.8 Hz from a Crab-like gamma ray point source at zenith, along with a background of 1130 Hz from hadronic cosmic rays, 1.4 Hz from cosmic electrons/positrons, and 5 Hz from night sky background.

Kurzfassung

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Introduction

Our planet is hit day by day by an incredible number of particles of cosmic origin — cosmic rays. Since their first discovery in 1912 by Victor Hess, many new particles were found by the investigation of these cosmic rays and lead to vast progress in particle physics, helping to understand processes on the microscopic scale. Most of the particles originate from the sun, with energies resulting from thermal processes only. In the last decades, several experiments measured particles with much higher energies up to $10^{20}$ eV. The measured energy spectrum requires a clearly non-thermal origin. Up to the present date, there are only hints what kind of cosmic accelerators are able to produce these energies. Cosmic rays are the best-known example of a non-thermal particle population and have a significant contribution to the energy density of the universe. Thus, the knowledge of cosmic ray production mechanisms and source development could improve the understanding of the universe on a cosmic scale.

The charged component of cosmic rays cannot be tracked back to its source direction, because the particles are deflected by magnetic fields of stars and galaxies and are therefore isotropically distributed. Additionally, a large fraction is produced by interaction of particles with the interstellar medium - they are only secondary products of the primary accelerator. The photon component, especially gamma rays are a more efficient probe, because they carry information about their parent cosmic ray population, do not interact with magnetic fields, and the universe is almost transparent for them. These characteristics of gamma rays lead to the development of new field of research called high energy gamma ray astronomy. The first Chapter gives a short overview on cosmic rays and the associated gamma ray production, describes the detection methods currently in use and introduces the known gamma ray sources.

The task for high energy gamma ray astronomy is the localization and investigation of the non-thermal sources with experimental methods. The Compton Gamma Ray Observatory (1990) with several gamma ray detectors aboard a satellite, brought a breakthrough in the field, providing previously unexcelled data of the complete gamma ray sky with a huge list of point sources at energies up to 10 MeV. Satellite detectors become inefficient at higher energies due to the decreasing flux of particles with rising energy. In the TeV region of gamma ray energy, the imaging atmospheric Cherenkov technique proved to be the most powerful tool, providing spectroscopic measurements together with a good angular resolution using stereoscopic observations. The second Chapter explains the principles of the imaging atmospheric Cherenkov technique, which detects the Cherenkov emission of extensive air showers, produced by the interaction of primary gamma rays with the atmosphere.

The H.E.S.S. experiment (High Energy Stereoscopic System), a system of imaging Cherenkov telescopes, will be described in the third Chapter. It is currently under construction and designed to detect gamma ray air showers with a primary energy above $\sim 50$ GeV. The descrip-
tion will focus on the trigger system of the telescopes, which is of primary interest for this work.

The performance of the system is limited by background of charged cosmic rays and optical night sky background (NSB), dominating the trigger rate of the telescope electronics. For the observations in the near future, estimates of the signal and background trigger rates for the possible trigger configurations have to be obtained, in order to choose an optimum trigger configuration for regular observation. In Chapter 4, the effect of night sky background will be described separately, because it plays a particular role causing random telescope triggers uncorrelated to air showers. The NSB contribution can not be obtained with existing simulation programs and required the development of a completely new simulation algorithm, which calculates the NSB trigger rate for a certain trigger configuration. In the fifth Chapter, the simulated trigger performance of a single H.E.S.S. telescope will be evaluated. The existing air shower and detector simulation programs are explained, which were used to obtain the detector response on a gamma ray point source and the isotropic cosmic ray background. The resulting trigger rates are presented and the consequences for the choice of an optimum trigger configuration are discussed.
Chapter 1

High Energy Cosmic Rays and \(\gamma\)-Ray-Astronomy

This chapter will introduce the energy spectrum and the composition of cosmic rays, give a short overview of the charged components and subsequently focus on high energy gamma rays, how they can be produced and which detection methods are used today, and finally outlines source objects, which could be identified.

1.1 Cosmic Ray Energy Spectrum

The differential energy spectrum of all high energy cosmic ray particles measured by various experiments in the range between \(10^{11}\) eV and \(10^{20}\) eV is shown in figure 1.1. This spectrum represents the flux of particles per energy and follows a power law

\[
\frac{dN}{dE} \propto \left( \frac{E}{1\text{ GeV}} \right)^{-\gamma} \frac{1}{\text{m}^2\text{ sr GeV}},
\]

(1.1)

with \(\gamma\) as the so called spectral index.

Figure 1.1: Measured energy spectrum (multiplied by \(E^{2.7}\)) of all cosmic ray particles above 100 GeV [1].
Between 1 GeV and around 10 PeV the spectrum is well described by $\gamma \approx 2.7$, but at higher energies the spectral index changes to $\gamma \approx 3.0$. The reason for this “knee” is unknown. Measurements indicate a variation in energy of the knee for the various components of cosmic rays. Possible reasons are different acceleration processes [3] or the transition from galactic to extragalactic sources [4].

For energies reaching $10^{20}$ eV, the flux drops to one particle per km$^2$ and century. These energies represent macroscopic energies focused in a single particle and are orders of magnitude higher than any particle accelerators on earth can reach today.

In this range, protons interact with the 2.7K cosmic microwave background radiation via

$$p + \gamma \rightarrow \Delta \rightarrow p + \pi$$

and loose energy. Therefore, after a maximum of 100 Mpc all particles drop below the so called GZK-cutoff at $5 \times 10^{19}$ eV [5, 6]. Thus, higher energy particles could be produced only by “nearby” sources. For instance, recently observed cosmic rays with $3 \times 10^{20}$ eV [11] originate from a maximum distance of 50 Mpc. At this energy and within this range the primary direction of the particle can be measured, because the deflection by magnetic fields can be neglected. Up to now, there is no significant directional correlation of the detected particles.

### 1.2 Composition of Cosmic Rays

Cosmic rays consist of fully ionized nuclei, electrons and positrons, and gamma rays. The charged nuclei are dominated by protons (87%), followed by $\alpha$-particles (12%) and heavier elements up to iron (1%) [2]. Anti-protons have been measured, with a flux suppressed by a factor of $\sim 10^{-4}$ relative to the flux of protons.

The measured differential flux of the individual hadronic components is shown in Figure 1.2. For low energies the interaction with the solar wind, a magnetized plasma, decelerates the cosmic radiation which results in a “cutoff” at these energies. Above 1 GeV the differential spectrum follows the power law (1.1) with slight variations in $\gamma$ for each component.

![Figure 1.2: Major hadronic components of cosmic rays](/1.png)
The leptonic component, mostly electrons (10% positrons below 20 GeV) has a much steeper spectrum with $\gamma \approx 3.3$ above 10 GeV (Fig. 1.3). Under the assumption, that hadrons and electrons are accelerated by a similar mechanism with the same power law, the increased spectral index can be explained by the much higher energy loss of electrons (through processes like synchrotron radiation, bremsstrahlung or inverse Compton scattering) compared to hadrons during the propagation through the cosmic medium.

1.3 Acceleration Mechanisms of Charged Cosmic Rays

The question of the acceleration mechanisms of the cosmic radiation could only be answered for electron accelerators (see Sec. 1.4.3), the origin of the hadronic component remains unknown. A possible explanation for the acceleration of charged particles was introduced by E. Fermi [7]. A particle gains energy by the reflection on a moving magnetized plasma cloud. This was called second-order Fermi acceleration, because the energy gain is proportional to the squared ratio of the velocity of the cloud and the speed of light $c$, i.e. $\beta^2$. Later, this idea was applied to shock fronts of plasma, where multiple reflections in this shock were considered, leading to a more effective acceleration with

$$\frac{\Delta E}{E} \propto \beta.$$ 

Therefore it is called first-order Fermi acceleration [8, 9].

In order to prove this mechanism directly, the particles have to be observed in direction of the source object, but the magnetic interaction of these particles does not allow to trace them back to its origin. The gyroradius $r_L$ of a charged particle with momentum $p$ and charge $Q$ in a magnetic field $B$ [10], with angle $\theta$ between the particle direction and the field lines, is given by

$$r_L = \frac{pc}{Q} \sin \theta \frac{\sin \theta}{cB}.$$ 

Our galaxy ($\approx 20$ kpc diameter) is penetrated by a magnetic field of $\approx 10^{-11}$ T, thus a proton with energy below $10^{17}$ eV will loose information about its primary source direction within 1 kpc. Another probe is needed in order to trace the sources of cosmic rays.

1.4 High Energy Gamma Rays

High energy gamma rays allow to identify the sources of cosmic rays. This section will illustrate the production mechanisms of gamma rays and which absorption processes limit the propagation through space. The experimental techniques used for detection of gamma rays on and around the earth are introduced, and some relevant results are discussed. Many sources of high energy
CHAPTER 1. HIGH ENERGY COSMIC RAYS AND \γ-RAY-ASTRONOMY

gamma rays have been found, and could be identified with astronomical objects. Finally, an overview of these objects and the possible gamma ray production mechanisms is given.

In gamma ray astronomy, the photon energy is divided into several subranges, according to the particular experimental method used to detect the gamma rays [12]:

\[
\begin{array}{ll}
\text{energy} & \text{classification} \\
30 \text{MeV} - 30 \text{GeV} & \text{HE (high)} \\
30 \text{GeV} - 30 \text{TeV} & \text{VHE (very high)} \\
30 \text{TeV} - 30 \text{PeV} & \text{UHE (ultrahigh)} \\
> 30 \text{PeV} & \text{EHE (extremely high)}
\end{array}
\]

1.4.1 Production and Absorption

Production Processes

In general, the processes that produce high energy gamma rays are directly connected to high energy charged particle populations. The most important mechanisms and the implications for the gamma ray spectra, according to [13], will be listed here:

- **Electrons**

In principle, high energy electrons can lose energy by radiation processes within electromagnetic fields. If relativistic electrons interact with electric fields of, e.g. interstellar matter, they radiate **bremsstrahlung**. The spectral index of the resulting continuous gamma ray emission is identical to the parent electron spectrum \(\gamma_e\).

\[
dN/dE_\gamma \propto E_\gamma^{-\frac{1}{2}(\gamma_e+1)}.
\]

(1.2)

In very strong magnetic fields (for example around pulsars, see Section 1.4.3) the electrons are effectively bound to the field lines. In general, these lines are curved, so that the electrons emit **curvature radiation** with the energy

\[
E_\gamma \approx \frac{3 \hbar c \Gamma^3}{2 r_B},
\]

(1.3)

with \(\Gamma\) as Lorentz factor and \(r_B\) the local curvature radius of the magnetic field lines. For example, the photon energy produced by an electron with \(10^{13}\) eV moving along a pulsar magnetic field line (see Sec. 1.4.3) with a curvature of \(10^8\) cm, is about 2.5 GeV.

The most important effect, producing high energy photons is **inverse Compton scattering**, where relativistic electrons boost up low energy photons. The resulting spectrum of gamma rays is similar to the synchrotron radiation spectrum (1.2), but depends on the energy of the primary electron. Thus, e.g. TeV gamma rays can be produced by some 10 TeV electrons interacting with photons of the cosmic microwave background.
1.4. HIGH ENERGY GAMMA RAYS

Protons

The $\pi^0$ decay is induced by the interaction of charged cosmic ray nuclei with nuclei of the interstellar matter, mostly protons, i.e.

$$p_{\text{CR}} + p_{\text{ISM}} \rightarrow \pi^\pm + \pi^0 + X.$$  

The cross section of this inelastic collision process slightly increases and the particle flux decreases with energy, therefore only 1–10 GeV cosmic ray protons contribute. The $\pi^0$ then decays into two photons and in consideration of the kinematic limit of the pion production of approximately 280 MeV a photon bump around 100 MeV is observed.

Protons will, like electrons, also undergo synchrotron radiation and bremsstrahlung, but these processes are much less efficient, due to the higher proton mass $m_p \gg m_e$.

In principle, there are many more production processes possible, for example radioactivity and matter-antimatter annihilations, but they are either low energetic or very rare and do not contribute to the high energy spectrum.

Thermal origin of high energy gamma rays is excluded. Using Wien’s law, it is easy to show that black body emission with a maximum photon energy of 1 MeV corresponds to temperatures of more than $10^{10}$ K, which require gigantic explosions. Additionally, far away sources become red-shifted, because of the expansion of the universe.

Energy Loss Mechanisms

High energy gamma rays, propagating through space, can be absorbed by interstellar matter similar to cosmic ray absorption. The relevant interaction process with matter depends on the energy. Between 100 keV and 10 MeV photon energy, the Compton effect is dominant. Above 10 MeV the photons produce electron positron pairs in Coulomb fields of nuclei in the interstellar medium.

Most restrictive for the mean free path of gamma rays is the photon-photon interaction producing pairs of particles, mostly $e^+e^-$. Figure 1.4 shows the mean free path of gamma rays, depending on their energy. Thus, extragalactical TeV photons are affected by the infrared background of stars and galaxies. The cosmic microwave background absorbs mostly PeV photons, limiting the gamma ray propagation to a few kpc, which excludes observations of even most of our galaxy. Beyond $10^{16}$ eV the universe regains its transparency for gamma rays.
1.4.2 Detection

The energy and direction of gamma rays are measured via two different methods. They can be directly detected with detectors aboard satellites or balloons around the earth, or traced back by their interaction with the atmosphere, which results in an extensive air shower of secondary particles. The applied method depends on the energy of the incoming photon. A detailed overview can be found in [12].

The HE range can only be explored in space, because the air shower produced by these energies is rather small and (up to now) inaccessible from ground. The detector usually absorbs the photon by the pair-production process. The direction is reconstructed by a tracking system and the energy is determined by a calorimeter. The latest and most successful experiment was EGRET [14] on board of the Compton Gamma Ray Observatory launched in 1991 (Sec. 1.4.3).

The photon flux decreases rapidly with increasing energy. The limit for significant detection with satellites is reached at 10 GeV due to the restricted detection area. Extensive air showers (details in Section 2.1) cover a large area on ground, and allow detectors with high sensitivity in the energy range above 100 GeV. The disadvantage of this method is a huge background of charged cosmic ray air showers.

Air showers of VHE photons can be detected by the Imaging Atmospheric Cherenkov Technique (see Chapter 2), which is the most efficient and progressing method in ground based γ-ray astronomy today. The Cherenkov light, emitted by the shower particles, is focused with an optical telescope, creating an image of the development of the shower in a camera, which usually consists of an array of photo-multiplier tubes. The detection of visible photons introduces optical background, in addition to the isotropic cosmic ray background.

Furthermore, in the EHE range, detector arrays can be used which directly detect a part of the shower particles on ground using many particle detectors covering a large area. Air fluorescence detectors capture the fluorescence light resulting from nitrogen excitation by shower particles from UHE gamma rays. Both methods are more efficient for cosmic ray detection and have problems to distinguish between charged primaries and photons. Besides, the angular and energy resolution, compared to satellites or Cherenkov telescopes, are hardly acceptable for the identification of a source.

1.4.3 Measurements and Sources

Figure 1.5 shows an image of the all-sky gamma ray emission above 100 MeV as measured by the EGRET instrument. It shows a non-isotropic gamma ray emission. An extended band of diffuse emission is observed and originates from the galactic disk. Removing the point sources from the “γ-ray sky”, it corresponds to the mass distribution in our galaxy and results from the interaction of charged cosmic rays with matter. Diffuse emission is also observed from the Large Magellanic Cloud (LMC) and other galaxies, which points out the extra-galactic origin of cosmic rays.

In addition to the diffuse background, EGRET located 271 point sources [16] above 100 MeV from which 170 do not have any known counterpart in other wavelengths of the electromagnetic spectrum and remain unidentified. A few identified sources were confirmed by ground based experiments at the TeV level.
1.4. HIGH ENERGY GAMMA RAYS

These photons have to be produced by high energy particles, accelerated by the source object. An overview of the identified source objects is given, along with the most accepted explanation of the origin of gamma ray emission [12]:

**Supernova Remnants**

Exploding stars — *supernovae* — produce fast expanding plasma shock waves, which interact with the surrounding matter and form a nebula. Particles can gain energy within these shockwaves. The observations of gamma rays are consistent with a model of high energetic electrons. Inside the plasma they radiate photons (bremsstrahlung) and boost them to high energies via inverse Compton scattering.

**Pulsars**

Pulsars are rotating neutron stars, remaining from a supernova explosion. They emit electromagnetic radiation in the direction of the poles of their strong magnetic fields. Pulsed emission of gamma rays is observed by satellites. The production mechanism is still unknown and its determination requires measurements of gamma rays between 10 and 100 GeV, in order to verify existing models of the pulsed gamma ray emission.

A class of a pulsar nebula, a so-called *plerion*, creates a strong electron/positron wind which terminates in a shock front inside the supernova remnant. The electrons and positrons get accelerated in the shock and undergo inverse Compton scattering with their own synchrotron radiation in the magnetic field of the neutron star (synchrotron self-Compton (SSC) model [17]).
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The most stable intense source of TeV gamma ray emission is the Crab nebula, a supernova remnant of the plerion type. The measured energy spectrum (Fig. 1.6, Crab Nebula) clearly shows a synchrotron emission peak below 100 MeV and another one, with less intensity, from the inverse Compton scattering (see Sec. 1.4.1).

Active Galaxies

Highly variable TeV emission was measured on the ground from objects called blazars. A model [18] was introduced, which unifies various types of galaxies to have an active galactic nuclei (AGN) under different observation angles. A super-massive black hole in the center accretes surrounding matter in a disk and forms huge relativistic jets. A blazar is an AGN, where the jet is directly emitted in direction of the observer. The obtained spectra are consistent with electrons, accelerated by shocks in the jet and producing inverse Compton (IC) gamma rays (Fig. 1.6, MKN 501).

![Figure 1.6](image)

Figure 1.6: Measured energy spectrum of the Crab nebula and the active galaxy MKN 501 at different time periods [12]. The lines represent the expectations from the SSC-model [17].

X-ray Binaries

These binary star systems consist of a neutron star accreting matter from an orbiting main sequence star. This can result in “hotspots” on the neutron star with strong x-ray emission or even relativistic jets similar to AGNs.

There are many more gamma ray sources believed to exist which could not yet be observed, including primordial black holes and astroparticle phenomena, like annihilation lines of dark matter or particle decay along cosmic strings.
Chapter 2

Imaging Atmospheric Cherenkov Technique

In this chapter the imaging atmospheric Cherenkov technique is introduced, which allows to detect extensive air showers, especially from cosmic gamma rays in the VHE range. It is an advanced technique to reconstruct shower type, direction and energy, by imaging the Cherenkov light emission of these showers. The first section describes the characteristics of the air showers and their Cherenkov emission. The second section will outline the functionality of Cherenkov telescope systems in general and the principles of the shower reconstruction.

2.1 Extensive Air Showers

Whenever a high energy (primary) particle enters the atmosphere it interacts with air molecules, producing a cascade of secondary particles. A photon or electron/positron induced shower is dominated by electromagnetic interactions, thus called an electromagnetic shower. Hadronic particles additionally undergo strong and weak interactions with electromagnetic sub-cascades, which allow the distinction between both shower types on the basis of the differences in the Cherenkov emission as explained in Section 2.2.4.

2.1.1 Shower Development

Electromagnetic Showers

Electromagnetic cascades are produced by high energy gamma rays or electrons. The dominant interaction processes for production and absorption of secondary particles within the atmosphere are

- photon $e^+e^-$ pair production and
- electron bremsstrahlung within electric fields of air constituents,
- ionization of air molecules,

which are described in general in [19]. These processes determine the longitudinal development of the shower. The lateral distribution is dominated by multi-scattering of the shower particles in the air.

Bremsstrahlung and pair production processes during the particle propagation in air increase
the number of particles in the shower, while the average energy per particle $\langle E \rangle$ decreases exponentially:

$$\langle E \rangle = E_0 e^{-\frac{X}{X_r}}, \quad (2.1)$$

with $E_0$ as initial energy and $X$ the atmospheric depth (see (2.2)). $X_r$ is a characteristic length, after which the energy is reduced by the factor $1/e$. There exists a relation between the radiation length $X_b$ of bremsstrahlung and the conversion length $X_p$ from pair production, given by $X_p = \frac{3}{2}X_b$ [20]. The atmospheric depth is given in units of g/cm$^2$, which corresponds to an atmospheric height $h$ in km according to

$$X(h) = X_0 e^{-\frac{h}{h_0}}, \quad (2.2)$$

with $X_0 = 1013$ g/cm$^2$ and $h_0 = 8$ km.

With decreasing energy, the ionization of air molecules becomes important resulting in the absorption of shower particles. A critical energy $E_c$ is defined, where the absorption dominates the production processes and the shower runs out of particles. For air, this critical energy is $E_c \approx 81$ MeV.

A simple model [21] illustrates the characteristic longitudinal shower development of a photon. This model (Fig. 2.1) assumes a cascade, starting with the pair production of an electron and positron, which radiate bremsstrahlung in the second step, and so forth. Therefore, the number of particles in the shower is doubled after one radiation length

$$X_r := X_b \approx X_p.$$  

The number of particles in the shower is

$$N = 2^n, \quad (2.3)$$

after $n$ radiation lengths. In each of these steps, the energy $E_0$ is equally distributed between all particles, leading to an energy

$$E_n = E_0 2^{-n}, \quad (2.4)$$

d of the shower particles in step $n$. After $n_{\text{max}}$ radiation lengths, the shower particles reach the critical energy $E_{n_{\text{max}}} \approx E_c$, and with (2.4) it is

$$n_{\text{max}} = \frac{1}{\ln 2} \ln \frac{E_0}{E_c}, \quad (2.5)$$

This corresponds to the maximum number of particles, derived from (2.3, 2.5):

$$N_{\text{max}} \approx \frac{E_0}{E_c},$$
and the position of this shower maximum is located at the atmospheric depth

\[ X_{\text{max}} = n_{\text{max}} X_r = \frac{X_r}{\ln 2} \ln \frac{E_0}{E_c} \]

A more detailed analytic model of the longitudinal development can be found in [22, 23], which includes an approximation of the lateral shower development. The deviation from the primary photon direction is dominated by elastic collisions with air molecules – multi-scattering. It is characterized by the Molière-radius

\[ X_M \approx 9.6 \text{ g/cm}^2 \]

The shower describes a cone around the shower axis, which has a radius of approximately 80 m at sea level and includes 90% of the energy of shower particles.

The lateral contribution from bremsstrahlung and pair production is given by the average opening angle \( \theta \) between the momentum of the produced particle and the shower axis, which depends on the energy \( E \) of the shower particle according to

\[ \langle \theta \rangle = \frac{m_e c^2}{E}. \]

The energy of these particles, which is relevant for the further development of the shower is above the ionisation threshold of 80 MeV. At this energy, the resulting directional divergence of the produced particles from the shower axis can be neglected. The time period of the development of an air shower, starting with the first interaction and ending with the absorption of the particles by ionisation, is approximately 50 \( \mu \)s [25].

Recapitulating, the main characteristics of an electromagnetic shower obtained by simplified models are:

- The number of particles increases exponentially with a maximum proportional to the energy of the primary particle \( E_0 \).
- The depth of the shower maximum increases logarithmically with \( E_0 \).
- The lateral size of the shower is approximately constant in units of atmospheric depth.

For the purpose of shower energy reconstruction and background estimations, more detailed Monte Carlo simulations of air showers are essential (see Sec. 5.1.1).

**Hadronic Showers**

If a cosmic ray nucleus hits the atmosphere, the first interaction is dominated by strong interaction (inelastic scattering) with air nuclei. The cross section and thus the hadronic interaction length\(^1\) \( X_h \) depends on the mass of the target nucleus and is for a proton at 1 TeV approximately 80 g/cm\(^2\) [24]. The shower has a larger longitudinal size compared to the electromagnetic shower, because the radiation length is doubled.

\[^1\text{defined by the loss of intensity } I \text{ starting with intensity } I_0 \text{ after a length } X: \]

\[ I(X) = I_0 e^{-\frac{X}{X_h}} \]
The collision results in a fragmentation of the target nucleus into a jet-like cascade of excited nuclei and additional mesons, mainly pions. For the excited nuclei, this process is recurrent. Figure 2.2 shows a schematic view of a generic first interaction. The pions have significant transverse momenta, resulting in a larger lateral development of the hadronic shower compared to the electromagnetic shower. They decay into photons ($\pi^0$-decay), inducing an electromagnetic subcascade, or muons and neutrinos ($\pi^\pm$-decay) which reach the ground level.

In summary, the hadronic shower has a wider longitudinal and especially lateral distribution compared to an electromagnetic cascade. Figure 2.3 gives an example of the simulated longitudinal development of a 300 GeV photon and a 1 TeV proton.

Figure 2.2: Particle types produced by the first interaction of a hadronic particle with an atmospheric nucleus. The hadronic sub-cascade is induced by nuclei fragments [24].

Figure 2.3: Comparison of vertical photon and proton shower particle tracks (2-D projection) [25].
2.1. EXTENSIVE AIR SHOWERS

2.1.2 Cherenkov Emission

The secondary particles in an extensive air shower have relativistic energies due to the high energy of the primary particle. Therefore, their velocity exceeds the speed of light in the medium air and the charged particles emit Cherenkov light. The Cherenkov emission leads to a characteristic “image” of an extensive air shower on the ground.

Cherenkov Effect

The Cherenkov effect can be understood as the electromagnetic counterpart of the supersonic cone in air and was explained on the level of quantum mechanics by Ginzburg [26].

A charged particle with a velocity \( v \) exceeding the speed of light \( c \) in air, polarizes the surrounding medium and induces constructive interference of electromagnetic waves. This creates a cone of light emission (Fig. 2.4) with a characteristic angle between the direction of the radiation and the particle track:

\[
\cos \theta = \frac{c_n}{v} = \frac{c}{nv} = \frac{1}{n \beta}
\]

with \( n \) as the refraction index of air, by neglecting dispersion. \( \beta \) has to exceed a certain threshold \( \beta_{\text{min}} = \frac{1}{n} \), in order to satisfy (2.6). This corresponds to a threshold energy \( E_{\text{min}} \) of the radiating particle:

\[
E = \gamma m_0 c^2 \\
\Rightarrow E_{\text{min}} = \sqrt{\frac{1}{1 - \beta_{\text{min}}^2}} m_0 c^2 \\
= \sqrt{\frac{1}{1 - \frac{1}{n^2}}} m_0 c^2. \quad (2.7)
\]

Cherenkov Emission of Air Showers

The threshold energy \( E_{\text{min}} \) (2.7) indicates that light particles dominate the Cherenkov emission, preferably electrons and positrons. Because the refraction index \( n \) is not constant within the atmosphere

\[
n = n(h),
\]

the threshold energy and the emission angle depend on the atmospheric altitude \( h \). \( \theta \) varies between 0.5 and 1.4 ° within 15 km altitude above sea level (asl.). In this range, \( E_{\text{min}} \) of electrons is always below the critical ionisation energy and all electrons and positrons emit Cherenkov light. The energy loss due to Cherenkov radiation is negligible compared to ionisation losses.
The Cherenkov emission of a single shower electron at the altitude $h$ results in a ring of light on the ground (observation level $H$). The average radius $R$ of the ring (see Fig. 2.5) is given by

$$\tan \theta = \frac{h - H}{R}.$$ 

The maximum amount of Cherenkov photons is emitted at the shower maximum, which is between 7 and 10 km altitude for a primary photon energy range of 100 GeV to 10 TeV [12]. For electromagnetic showers, the superimposed light of all contributing particles results in a light front ($\sim 2 - 3$ ns “thick”), producing an almost symmetric ring of light on the ground. The emission of hadronic showers is dominated by their electromagnetic sub-cascades and features an heterogeneous, asymmetric image (see Fig. 2.6).
2.1. EXTENSIVE AIR SHOWERS

Figure 2.7 shows the lateral Cherenkov photon density on the ground. It is nearly constant within the Cherenkov ring of approximately 120 m distance from the shower axis (R). With Cherenkov telescopes inside this “light pool” it is possible to measure the energy of the primary particle $E_0$, because the total amount of light measured is proportional to $E_0$.

**Extinction of Cherenkov Light**

Since the atmosphere is an open calorimeter, variations lead to differences in the propagation of Cherenkov light in air. Photons are partially scattered or absorbed and do not contribute to the measurable Cherenkov emission of a shower, leading to systematic limitations of the measurement. In general, the light extinction can be described (more details in [28]) by the extinction coefficient $\alpha$, corresponding to the loss of intensity

$$I(x) = I_0 e^{-\alpha x}.$$  

The coefficient $\alpha$ strongly depends on the wavelength $\lambda$. For Cherenkov light of air showers the distribution of $\lambda$ [26] peaks at $\sim 400$ nm corresponding to blue light and covers the spectral range from UV to IR. In particular, the scattering of photons is described by

- **Rayleigh scattering**, for target molecules which are significantly larger than $\lambda$, e.g. oxygen and nitrogen. The extinction $\alpha_{\text{Rayleigh}}$ depends on the density $\rho$ of targets and the cross section $\sigma$:

$$\alpha_{\text{Rayleigh}} = \rho \sigma \propto \lambda^{-4}.$$  

- **Mie scattering**, for targets with dimensions similar to $\lambda$, e.g. small dust-like particles (aerosols). The cross section is more complicated and can only be approximated numerically:

$$\alpha_{\text{Mie}} \propto \lambda^{-c},$$

with $c \in [1, 1.5]$.

Another critical effect is the absorption of Cherenkov light from ozone and aerosols. Light in the spectral range below $\sim 300$ nm is nearly totally absorbed by ozone, whereas large aerosols are less efficient, but affect the whole spectrum. Fig. 2.8 shows the contributions of scattering and absorption to $\alpha$ as a function of the altitude at certain wavelengths. The total extinction is a superposition of all effects:

$$\alpha = \alpha_{\text{Rayleigh}} + \alpha_{\text{Mie}} + \alpha_{\text{ozon}}.$$
2.2 Imaging Atmospheric Cherenkov Telescopes

Imaging Atmospheric Cherenkov Telescopes (CT) allow to measure the direction and the energy of a primary gamma ray. The Cherenkov light from the shower is mapped with a photosensitive camera of an optical telescope.

2.2.1 Telescope Design

In order to provide accurate measurements of the air shower Cherenkov emission, Cherenkov telescopes have to fulfill several requirements:

- **accurate source pointing and tracking**
  The limited field of view of an optical telescope requires a turnable mechanical mounting system. Additionally, sources have to be tracked along the sky.

- **large reflector area**
  In order to discriminate the Cherenkov light against isotropic optical background, as much Cherenkov light as possible has to be collected. Single spherical mirrors are expensive and have a large aberration, while parabolic mirrors are unaffordable. Thus, many small spherical mirrors are arranged in the reflector dish. This Davis-Cotton-design [30] reduces the aberration and, among other advantages, allows a more simple alignment.

- **good light sensitivity and image resolution**
  The camera, consisting of an array of photo-detectors (diodes, photo-multipliers etc.) should be able to detect single photons and have an acceptable imaging resolution, which allows to distinguish between gamma and hadron induced showers on the basis of image characteristics.

- **fast camera trigger and readout electronics**
  The Cherenkov light flash of the shower maximum has a duration in the order of $\sim 10\text{ns}$. The camera trigger is usually requiring a number of detected photons in coincidence in several camera channels within a few nanoseconds, requiring a reasonable time resolution. An accurate energy estimate of the shower from the integrated light in the camera is only possible if the signal integration time is not much longer than the duration of the flash, otherwise the optical background dominates the signal. Additionally, air showers of hadronic origin in the field of view of the camera cannot be rejected by the telescope trigger (up to now) and produce a very high trigger rate. The camera electronics has to process the signal of a single shower without too much dead time (in which other triggered showers can not be detected). Modern experiments use therefore fast analog-digital converters (Flash-ADCs) with sampling rates up to $1\text{GHz}$, in order to reach a high data readout rate.

Fig. 2.9 shows a design example of a Cherenkov telescope, as used in the H.E.S.S. project. It is described in detail in Section 3.1.
2.2. Shower Imaging

Figure 2.10 shows the principle of shower imaging of a single telescope. The telescope points to a source of gamma rays. Cherenkov light, emitted from the shower axis, is reflected by a mirror and focused on the camera plane (focal plane). Different emission angles from the shower correspond to different positions in the camera. Therefore the angular distribution of longitudinal and lateral emission of the shower determine the image shape. It represents the projection of the shower maximum onto the camera plane ($x, y$-plane). Because an electromagnetic shower has a much larger longitudinal than lateral extent, images from gamma rays have an elliptical shape.

![Diagram of Cherenkov imaging](image)

Figure 2.10: Principle of the optical imaging of Cherenkov emission from air showers. The camera plane is magnified and rotated, in order to show the image shape.
2.2.3 Image Parametrisation

The parametrisation of the shower profile as an ellipse was initially proposed by Hillas [29]. It can be used to classify the characteristics of the recorded shower images (events), in order to determine the shower direction, energy and type. For a single event, all of these so called Hillas parameters (see Fig. 2.11) are calculated from the amount of light detected in each camera channel (or pixel).

The **length** and **width** characterize the longitudinal and lateral shower development dependent on the inclination between shower and telescope axis. E.g., in the special case of a vertically approaching shower front, with the shower axis matching the telescope axis, only the lateral distribution is projected, resulting in a circular image. With increasing distance between both axes, the image forms more elliptical with an orientation towards the impact point of the shower axis in the camera plane. As a consequence, the ellipse center moves away from the camera center, corresponding to the parameter **distance**. Increasing the inclination of the shower axis, the orientation of the ellipse changes and the **miss** and **alpha** parameter grow. They are proportional to the inclination, but cannot be used for the 3-dimensional direction of the shower (see 2.2.5). The total amount of detected light in all camera pixels, **size**, corresponds to the shower energy. By selecting the two brightest pixels in the image and dividing through the **size**, the **concentration** is obtained and represents the compactness of the shower.

In principle, with all of these parameters the essential discrimination of gamma ray showers from the hadronic background can be achieved by applying cuts on the image parameters.

2.2.4 Signal and Background

The significant detection of gamma rays with Cherenkov telescopes strongly depends on the discrimination against various types of background. The individual contributions of these different types, together with possible reduction methods are:

- **hadronic cosmic rays**
  
  As discussed above, hadronic cosmic rays produce air showers with only slightly different Cherenkov emission, resulting in typical trigger rates of factor 1000 larger than the trigger rate due to gamma ray sources. The spectral index of cosmic ray protons (Sec. 1.1) is similar to many gamma ray sources, thus this background covers the whole detectable energy range. Therefore, hadronic events have to be rejected by data anal-

![Figure 2.11: Hillas parameters of the elliptical shower image.](image)

![Figure 2.12: Distributions of the (scaled) width parameter of a MKN 501 data sample (from the HEGRA experiment) for signal+background and background only [20].](image)
2.2. IMAGING ATMOSPHERIC CHERENKOV TELESCOPES

ysis techniques. The lateral extent of hadronic showers is much larger than that of electromagnetic showers. Typically 98% of hadronic shower events can be rejected by applying a cut on a scaled width parameter (see Fig. 2.12) while retaining 50% of electromagnetic shower events.

- **cosmic electrons**
  Electron showers are indistinguishable from photon showers. Still, their energy spectrum is much steeper and the absolute flux is lower compared to hadrons, therefore they significantly contribute only for energies below 100 GeV. Additionally, electron showers are not correlated in direction.

- **optical background**
  This night sky background (NSB) constitutes of isotropically distributed photons, which can cause uncorrelated triggers of the telescope camera due to the high photon sensitivity. Details on the origin of NSB and the implications for an efficient camera trigger are described in Chapter 4. If NSB triggers the camera, the resulting events are easy to reject, because they lack the elliptic shape of the image, but they cause dead time of the camera electronics.

- **atmospheric muons**
  The muon background originates from hadronic air showers, where muons are produced as products of the charged pion decay and they reach, mostly unabsorbed, the ground level. If they directly hit a telescope within the field of view, their Cherenkov emission triggers the camera. Similar to NSB, the camera image (a small light ring) can be easily identified and removed in the analysis, but such events increase the dead time of the readout electronics.

The isotropic character of background in general, implies that it is distributed uniformly within the alpha parameter space, while the photon showers are clearly correlated in direction. Usually, when observing gamma ray point sources, the significance of a signal is determined, calculating the excess of “clean” events above the background within the alpha distribution (Fig. 2.13).

2.2.5 Stereoscopic Systems

A system consisting of two or more CTs has several advantages compared to a single telescope. The first point is the increased mirror area and therefore an enhanced sensitivity to air showers. The Cherenkov light distribution is examined at several points on the ground with independent measurements and allows a more accurate energy estimation of the primary particle.

Secondly, the coincidences of more than one telescope can suppress local background. Especially, an atmospheric muon, triggering a single telescope only, will not result in a trigger of the whole system. Local NSB coincidences in a single camera can also be rejected. Both effects
reduce the system trigger rate and therefore the dead time of the system significantly.

Additionally, stereoscopic observation allows a 3-dimensional reconstruction of the inclination and the impact point of an air shower. Assuming a vertical gamma ray shower, observed by a system of two telescopes, the impact point (shower core) corresponds to the point of intersection of the straight lines on the observation level \((x, y)\), defined by the major axes of the two ellipses in each camera (Fig. 2.14 A). For non-vertical showers, in the calculation of the shower core position it has to be taken into account that the camera planes do not lie in the same plane. The direction of the initial particle can be obtained by the superposition of the two camera images of both telescopes in a single camera plane coordinate system. In this system, the distance between the center and any point \((x, y)\) of the camera plane can be expressed as an inclination \((\theta_x, \theta_y)\) relative to the optical axis

\[
\theta = \frac{180^\circ}{\pi} \cdot \frac{d}{f},
\]

with \(f\) as the focal length of the telescope. The intersection point of the major axes corresponds to the shower direction \((\theta_x, \theta_y)\) (Fig. 2.14 B).

![Diagram](image.png)

**Figure 2.14:** A, Reconstruction of the shower core position for a vertical shower, using the intersection of the major axes from the shower image in an arbitrary coordinate system on the observation level. B, Reconstruction of the shower direction using the superimposed camera images.

With more than two telescopes, the impact position and inclination is overdetermined and can be fitted, in order to reduce the systematic error. Therefore, stereoscopic systems have the advantage of a much better angular resolution than a single telescope, which also improves the gamma/hadron separation. A detailed description of the shower reconstruction can be found in [31].
Chapter 3

The H.E.S.S. Experiment

The High Energy Stereoscopic System is a system of four Cherenkov telescopes in the Khomas Highlands of Namibia which is currently under construction. The four telescope system will be ready in the beginning of 2003. At the moment, the construction of the first telescope is nearly completed and “first light” is expected at the end of this year. The H.E.S.S. site in Namibia is located at 23° 16’ 18” southern longitude, 16° 30’ 00” eastern latitude, and lies 1800 m above sea level. This area, near the Gamsberg, is known for its excellent optical quality for astronomical purposes [34]. Figure 3.1 shows a possible view of the four telescopes at the site. H.E.S.S. is intended to observe gamma rays in the energy range between 100 GeV and several TeV with a sensitivity of a few mCrab (one thousands of the Crab Nebula intensity). The system will provide an angular resolution of 0.1 degree and an energy resolution of about 20%. With this experimental setup it will be possible to improve the existing measurements on identified TeV gamma ray sources and localize the emission regions of extended objects. More information about the physical goals can be found in [32] and the official representation of the experiment at [33].

This chapter will give an overview of the array configuration and the telescope components, with focus on the design of the trigger system. The simulation of the performance of the camera trigger is the central part of this work.

Figure 3.1: Photo-montage of the H.E.S.S. telescopes on the Namibia site [33].
CHAPTER 3. THE H.E.S.S. EXPERIMENT

3.1 The Telescope System

3.1.1 Array and Telescope Structure

The four identical telescopes will be placed on the corners of a square with edges of 120 m length (Fig. 3.2). In order to point a telescope at a particular position on the sky, it has an altitude-azimuth mount. The base-frame is assembled on a circular rail and can be turned horizontally. It holds the reflector dish, which can be moved in vertical direction, requiring two separate drive systems for source tracking using computer controlled step motors. Each telescope has a mass of 52 t. The 381 round, spherical mirrors are arranged on a spherical surface (Davis-Cotton-Design, Sec. 2.2.1) with 15 m focal length. The mirrors have a diameter of 60 cm, an average reflectivity of 80% and are mounted on a special motorized support unit for alignment. In total, they provide a telescope reflector area of 108 m$^2$.

3.1.2 Camera

The camera is a cylindrical box of 1.4 m diameter and 1 m depth containing 960 photo-multiplier tubes (PMT or pixel) and the whole trigger and readout electronics.

Photo-multiplier

Each pixel has a size of 0.16° resulting in a total field of view of 5°. In order to avoid photon losses, Winston cones are used, which close the gaps between the neighboring pixels and deflect the light directly onto the glass window of each photo-multiplier. The incoming photons are detected with a quantum efficiency of about 25%, creating a characteristic voltage pulse. This signal is amplified and split up and fed into the trigger and readout system (channel) simultaneously.

Readout System

If the telescope array is triggered (see Sec. 3.2), the amplified analog signal of several photo-electron pulses in a PMT is digitized by 1 GHz Flash-ADCs in 1 ns steps. The joined data of all camera pixels forms an event and is delivered via network to the central data acquisition (DAQ) system. The readout process has a duration of ~ 500 μs, where no further data can be taken (dead time) [37]. Figure 3.3 shows an event display with an simulated image of a 1 TeV gamma ray shower and reconstructed Hillas ellipses of all four telescopes.
3.1.3 Central Data Acquisition

The telescope event data is sent through optical fiber cables to a computer farm. The data is distributed by a gigabit-switch to 16 farm PCs, gets preprocessed and stored locally or on a RAID-system for later archiving. The software package, which manages the DAQ, is object oriented and follows the inter-process communication standard CORBA. The data storage and analysis software uses ROOT [38], a data analysis framework. A complete overview on the H.E.S.S. central DAQ system can be found in [39].

3.1.4 Calibration and Monitoring

There are several devices used for telescope calibration and monitoring:

▷ There are two CCD cameras installed. One allows accurate pointing and monitoring of the telescope tracking by observing the position of bright stars. The second is used for mirror alignment [40].

▷ A LED system in the camera lid is used for calibration and testing of the PMTs.

▷ A LIDAR system fires laser pulses into the atmosphere and measures the backscattered light to determine the atmospheric extinction.

▷ A weather station with cloud monitoring.

3.2 Trigger

The H.E.S.S. trigger system divides the camera into 38 overlapping trigger sectors (Fig. B.1). Whether or not the camera triggers depends on the PMT trigger threshold, and how many PMTs in the camera simultaneously trigger. Furthermore, the triggered PMTs must be in the same trigger sector. Since the sectors overlap, the trigger information of a particular pixel can be used up to four times in the trigger channel.

A telescope trigger configuration is defined by the two thresholds, \((p, q)\), where

▷ \(q\) is the PMT threshold in photo-electron equivalents

▷ \(p\) is the number of PMTs in coincidence.

The \((p, q)\) configuration is also often referred to as “\(p\) pixels at \(q\) p.e.”.

This section describes the aspects of the trigger electronics that are needed for the simulation studies in the following chapters (more details can be found in [41, 44]).

3.2.1 The Photo-multiplier

If a photon is detected by the PMT, it produces a characteristic voltage pulse in each channel (trigger and readout). The pulse shape of both channels (Fig. 3.4) can be described by the parameterization

\[
f(t) = C t^\alpha e^{-\alpha_1 t}.
\]
**PMT Pulse**

For the trigger channel, the parameters,

\[
a_0 = 2.37, \\
a_1 = 1.32 \text{ ns}^{-1},
\]

have been measured in [41] and \( C \) is chosen so that the maximum of the function is one photo-electron (\( f_{\text{max}}(t) = 1 \text{ p.e.} \)). The distribution of the single photo-electron pulse amplitude has been measured in [42]. Additionally, afterpulses have also been observed, which result from gas ions hitting the photo-cathode inside the phototube. The afterpulses have the same pulse shape, but increased amplitude and occur with the rate

\[
R_{\text{AP}}(q) \propto e^{-bq}, \quad (3.2)
\]

at the threshold \( q \) [42]. This does not affect the trigger system behavior for air showers, because afterpulses occur with a delay of several hundred ns, but they increase the trigger rate due to night sky background. Figure 3.5 shows the amplitude distribution of the photo-electron pulses and its afterpulses. The high probability for thresholds less than 1 p.e. results from photo-electron hits that missed the first dynode and get less amplified. The distribution peaks at 1.2 p.e., while the mean is 1 p.e., and the tail represents the afterpulses.

This tail can be described by two parameters: \( P_{\text{AP}} \approx 3 \cdot 10^{-5} \) as the afterpulse probability at \( q = 4 \text{ p.e.} \) and \( b \approx 0.28 \) as the afterpulse exponent.

**PMT Comparator**

The superimposed voltage signal of all photo-electron pulses in a PMT is routed to the PMT comparator, which creates the trigger pulse. If the signal exceeds the PMT threshold \( q \), the comparator accumulates charge. The average time this charge is collected is \( \tau_c = 1.7 \text{ ns} \) [44].

After a specific rise time, the comparator provides a trigger signal with a nearly constant amplitude. When the input drops below threshold again, the same amount of charge must be discharged. The trigger signal has a width equal to the time over threshold (\( \tau_{\text{over}} \)), with a minimum time \( \tau_{\text{min}} \) of 1.8 ns [44] (see Fig. 3.6).
3.2. TRIGGER

![Diagram of PMT response and comparator pulses]

Figure 3.6: Typical PMT response of 50 ns and the corresponding comparator pulses.

3.2.2 Trigger Sector

Each sector has 64, 56, 48, or 32 pixels and has a sector comparator similar to the PMT comparator. In the sector comparator, the logical PMT comparator signals are superimposed and checked for if the signal is above a threshold value. This threshold corresponds to the discrete number $p$ of pixels in coincidence. The sector comparator generates a sector trigger if the signal remains the minimum width of $\tau_c$ (see Sec. 3.2.1) above this threshold, e.g. 4 pixels ($p = 4$). The camera triggers if at least one sector has triggered.

3.2.3 Array Trigger

Any local camera trigger signal starts the readout and simultaneously sends a message to the central system trigger electronics. The central system checks for coincidences of several telescope triggers within a certain time window and initiates the readout of the whole array or stops the readout of the triggered telescopes. An advantage of an array of CTs, is the rejection of background triggers due to muons and night sky background.
Chapter 4

Night Sky Background Simulation

Night Sky Background (NSB) is defined as any light which is not Cherenkov light from atmospheric showers. NSB causes uncorrelated photo-electron hits in each PMT of the telescope camera, which can result in random camera triggers depending on the trigger conditions. The trigger configuration, used for a telescope camera is determined by the contribution of background. Therefore, the camera trigger rate due to NSB has to be estimated.

This chapter gives an overview of the NSB origin and discusses the effect on the H.E.S.S. camera. An efficient simulation algorithm for the calculation of the trigger rate for any trigger configuration of the H.E.S.S. camera is introduced and finally the results are discussed.

4.1 NSB Origin and Implications

4.1.1 Known Sources

The astronomical darkness begins, if the sun sinks 18° below the horizon and does not contribute anymore to the light of the night sky. In the presence of the moon, observations of gamma rays with Cherenkov telescopes are nearly impossible, therefore the measurements can only be performed during moonless nights. The following list shows the remaining sources of light, along with a short explanation [45]:

- **Anthropogenous light**
  This, so called “light pollution” from the ground, is composed of the emission lines from artificial light sources, such as lamps.

- **Atmospheric nightglow**
  The nightglow is created by chemical and physical processes in the upper atmosphere (100 km height) and has an increased intensity on higher zenith angles. It results from the ionization of atmospheric components, mainly through sunlight or particles, travelling along the magnetic field lines.

- **Zodiacal light**
  Interplanetary dust formations within the solar ecliptic scatter sunlight towards our atmosphere. This component is the major contribution to NSB.

- **Starlight**
  The light of stars depends on the star density across the sky, therefore it is much stronger within the galactic plane, where the star density is a factor 10 higher than outside.
Diffuse galactic light
The optical emission of stars in our galaxy is additionally scattered on galactic dust formations, increasing the galactic component by $\sim 30\%$.

Extragalactic light
Light from outside of our galaxy has only a small contribution, but is not known very precisely. It is believed to result mainly from red-shifted galaxies. It can be estimated by measuring the intergalactical absorption of gamma ray emission from active galaxies. Furthermore, the light intensity depends on the exact location and varies in time, because the extinction of the atmosphere is not constant (see Sec. 2.1.2).

NSB measurements on the Namibia site were necessary and had been performed by [45]. Using a test device, the rate of photo-electron pulses in a photomultiplier was determined. The pulses are clearly uncorrelated and occur with a rate of approximately 100 MHz at 0° zenith angle remaining nearly constant down to zenith angles of 60°. For observations within the galactic plane this rate increases to 200–300 MHz.

4.1.2 Effect on the Camera
Coincidences of several NSB photo-electrons or afterpulses in a single PMT above the threshold result in a rate of random PMT triggers. If the number of simultaneously triggering PMTs in a sector exceeds the trigger condition of $p$ pixels, the camera sends a telescope trigger signal to the central trigger and is blocked, until the trigger is rejected. There are cases of an array coincidence, but the rates are negligible for any trigger configurations used for observations. Thus, the limiting effect of NSB is the dead time of a single camera.

4.2 Simulation Methods
Each level of the trigger channel was simulated using a combination of analytical and Monte Carlo techniques. A straightforward Monte Carlo simulation (shown in Sec. 4.2.1) is very time consuming, especially for high PMT thresholds. A second approach substitutes the simple simulation by a flexible semi-analytical method in a two step procedure (shown in Sec. 4.2.2, 4.2.3).

4.2.1 PMT Simulation
PMT response
Single photo-electron pulses in the PMT were simulated in time bins of 0.1 ns according to Poisson statistics. In each time bin, the simulation

- created a NSB pulse according to a Poisson distribution. An amplitude $A_0$, was chosen randomly according the amplitude distribution (Sec. 3.2.1).

- computed the amplitude at this specific time for each pulse according to $A(t) = A_0 f(t)$, where $f(t)$ is the normalized pulse shape (3.1).

- summed up all pulse amplitudes and determined the status of the comparator trigger signal (off/on) with respect to $\tau_c$ and $\tau_{\text{min}}$ by neglecting the signal rise time.

An event was counted each time the comparator status switches from off to on.
This simple algorithm will be called further straightforward simulation. Figure 4.1 shows the simulated PMT trigger rate for several bin sizes. The bin size of 0.1 ns was sufficiently small, while larger bins introduced unacceptable systematic biases.

PMT Trigger Rate

Figure 4.2 shows the trigger rates of a single PMT as a function of the PMT threshold, as obtained from the straightforward simulation. The rate is saturated for lower thresholds, where single comparator pulses merge together because of the high frequency at which they occur. At higher thresholds, a flat exponential tail results from the afterpulses.

Comparison with HEGRA PMT Trigger Rate

In order to confront the simulation with measurements [46], the method was also adapted to simulate the HEGRA discriminators. These discriminators provide a trigger signal with constant width (15 ns) after the threshold is reached. Figure 4.3 displays the measured counting rates for four different H.E.S.S. PMTs that are illuminated by photo diodes (at rates of 100 MHz and 1 MHz photo-electrons) using the HEGRA trigger electronics.

For the 100 MHz photo-electron rate, the measured trigger rate for low thresholds is smaller than the rate obtained from the simulation. This results from counter saturation (electronics) and does not appear at 1 MHz photo-electron rate. Overall though, the simulation demonstrates a reasonable agreement, especially if the variability between different PMTs is taken into account.

Figure 4.1: Effect of the time bin size on the simulated PMT trigger rate.

Figure 4.2: Simulated PMT trigger rate vs. PMT threshold for 100 MHz (full triangles) and 200 MHz (open triangles) photo-electron rate.
CHAPTER 4. NIGHT SKY BACKGROUND SIMULATION

Figure 4.3: **Comparison of PMT simulation with the measured trigger rate of H.E.S.S. PMTs using the HEGRA trigger cards and photo-electron pulses with 1 MHz and 100 MHz.**

**Performance**

The CPU time consumed by this simple simulation increased exponentially with the PMT threshold. It was almost impossible within a reasonable time to simulate the camera with coincidences of more than 2 PMTs ($p > 2$) using the described straightforward algorithm for each PMT in the camera. These problems appeared, because the majority of photo-electron pulses that were simulated did not contribute to triggered events.
4.2 SIMULATION METHODS

4.2.2 PMT Comparator Database

In order to avoid the simulation of each PMT in the camera repeatedly without any trigger signal, the simulation can, instead, directly use the probability of a PMT trigger and its comparator output.

The idea of this method is to apply the straightforward PMT simulation algorithm to a generic time slice of width $T = 15\,\text{ns}$ (the length of a single photo-electron pulse) and to create a database of the comparator outputs each time a trigger occurs. Additionally, only those cases were simulated where, by definition, at least one photo-electron pulse occurred. All other cases cannot produce a trigger.

The zero suppression method (App. A.1) simulated a single PMT in the extended time interval $[-2T, T]$ (in order to take into account preceding pulses), and required that a photo-electron pulse was within the interval $[-T, T]$.

If a trigger occurs within $[0, T]$, the comparator status (off/on) is added as an entry (150 bits per interval) to the database (sample in Fig. 4.4). This is done until sufficient statistics are accumulated ($10^5$ entries per simulated PMT threshold).

The probability of a trigger in $[0, T]$ is calculated as

$$P_{\text{PMT}}(q) = (1 - e^{-2\nu_{\text{NSB}}}) \frac{N_{\text{DB}}(q)}{N_T(q)},$$

(4.1)

where $\nu_{\text{NSB}}$ is the rate of NSB photo-electron pulses, $N_{\text{DB}}(q)$ is the number of database entries (number of intervals $[0, T]$ with at least one trigger), and $N_T(q)$ is the total number of simulated intervals for a certain threshold $q$. This probability is later used to calculate probabilities of trigger coincidences for a single sector and for the whole camera.

4.2.3 Camera Simulation

In the next step, the whole camera is simulated within the generic time interval $[0, T]$.

The camera trigger rate can be efficiently calculated if only those configurations are computed which will have a chance to result in a camera trigger. Thus, only the configurations with at least $p$ triggering PMTs in one sector are generated and weighted according to their probability.
In order to simulate $N$ time intervals $[0, T]$, the following steps are performed:

- A number of triggered PMTs $H_i \ (i = 1 \ldots N)$ is generated, which is greater or equal to the threshold $p$, anywhere in the whole camera. This situation, where $H_i$ PMTs have triggered within $[0, T]$, each with the probability $P_{\text{PMT}} (4.1)$, introduces the weight $(1 - F)$ (see App. A.2), where $F$ is the probability for less than $H_i$ triggered PMTs. The position of these PMTs remains unknown, together with their affiliation to a trigger sector.

- The probability $P_i$ is computed, for at least $p$ out of these $H_i$ triggering PMTs to lie in one sector. The list of triggered PMTs is generated (see A.3), and although at least one sector will exceed the threshold $p$ within $[0, T]$, it will not necessarily produce a sector trigger. The sector trigger must be verified by the sector comparators.

- The sector comparators are simulated to determine the number of camera triggers $n_i$ (events) using the random PMT comparator database entries. Each of these events is given a weight $w_i$ equivalent to its probability $P_i$.

The final camera trigger rate is then

$$R(q, p) = (1 - F) \frac{1}{TN} \sum_{i=1}^{N} w_i n_i.$$  \hspace{1cm} (4.2)

### 4.2.4 Camera Trigger Rate

**Direct vs. Geometry Simulation**

With the straightforward simulation it is possible to calculate the camera trigger rate for trigger configurations requiring two or less PMTs ($p \leq 2$). It is compared in Figure 4.5 with the Geometry Simulation (Sec. 4.2.3) and a perfect agreement is found between both methods.

Note that the directly simulated points in this graph for two PMTs required two weeks of CPU time (450 MHz PIII) for a 10% statistical error. In comparison, the creation of the Trigger Database needed only one night and the Geometry Simulation lasted only 10 minutes, resulting in a statistical error of less than 1%. For more complicated trigger configurations, the direct simulation becomes totally impractical while the Geometry Simulation is practically unrestricted.
Final Camera Trigger Rates

With the existence of the PMT Trigger Database and the geometry weights, the simulation has been run

- for each pair \((p, q)\) with \(p = 2, \ldots, 6\) and \(q = 2.75, 3.0, 3.25, \ldots, 12.0\) p.e.
- with \(\nu_{\text{NSB}} = 100, 200\) MHz.

Figure 4.6 shows the camera trigger rates over 20 orders of magnitude. For the rates above \(10^6\) Hz, all results were checked against the direct simulation and were found to be in perfect agreement.

![Camera Trigger Rate](image)

Figure 4.6: Camera trigger rate calculated by the Geometry Simulation.
Systematic Uncertainties

There were two parameters of a single PMT (Sec. 3.2.1) which introduced sizable systematic uncertainties in NSB trigger rate:

- the photo-electron pulse shape
- the afterpulse probability of the amplitude distribution.

The pulse shape \(1\) used in the simulation was only measured with a pulse generator (not with a PMT) \([47]\) and remained indetermined. In order to check the resulting variability of the camera trigger rate, the simulation has been run with another pulse shape (Fig. 4.7), with the parameters

\[
\begin{align*}
a_0 &= 4.573, \\
a_1 &= 1.254 \text{ ns}^{-1}
\end{align*}
\]

used in a H.E.S.S. detector simulation program (see Sec. 5.1.2) \([43]\).

The afterpulse probability \(P_{\text{AP}}(q = 4)\) and the exponent \(b\) (see Sec. 3.2.1) also varies from PMT to PMT. The H.E.S.S. PMT database \([42]\) showed that

\[
P_{\text{AP}} \approx 6 \cdot 10^{-5}, \\
b \approx 0.18
\]

could be used as values for extremely high afterpulse probability (only 2 PMTs exceed \(P_{\text{AP}} = 6 \cdot 10^{-5}\)), leading to an exaggerated afterpulse contribution (Fig. 4.8).

Figure 4.9 shows the resulting camera trigger rate for 4 pixels as a function of PMT threshold due to the variation of both parameters, the pulse shape and the amplitude distribution. The longer pulse results in a drastic shift of the whole curve, increasing the trigger rate by orders of magnitudes. The variation of the afterpulse probability raises only the afterpulse tail, while the smaller exponent \(b\) results in a smaller slope.
Chapter 5

Simulation of the Air Shower Trigger Performance

The systematic study of trigger configurations for the H.E.S.S. telescopes requires, in addition to the contribution of random NSB triggers, estimates of the signals of air showers from a typical gamma ray source and the total air shower background trigger rate.

Detailed Monte Carlo simulations of extensive air showers and the complete H.E.S.S. detector have to be used for this investigation. The first section describes these simulation programs. Subsequently, the concepts of data analysis of MC data, used for the calculation of the trigger rate are explained, and finally the results are discussed.

5.1 Simulation Programs

5.1.1 Air Shower Simulation

For the simulation of extensive air showers several independent program packages exist. In this work, the simulation package CORSIKA was used, which was initially developed by members of the KASKADE collaboration [48].

Interaction Models

CORSIKA simulates the interaction of various types of primary particles with the atmosphere, employing various interaction models. The simulation of electromagnetic interactions are based on QED calculations. Major uncertainties exist in the description of hadronic interactions, since the processes in air showers feature only low momentum transfers, which cannot be described by perturbative QCD. CORSIKA uses some phenomenological models depending on the energy of the interactions [48].

Simulation Parameters

In CORSIKA several parameters can be set. Some of them are related to the environment, like atmospheric composition and absorption, geomagnetic field strength, observation level and detector arrangement. They were adapted for the H.E.S.S. site and did not change.
The following list contains those parameters, which were modified in order to simulate showers of gamma rays and the different background types (see Fig. 5.1):

- the primary particle type,
- the energy range $\delta E$ of the particles for the simulated data sample,
- the primary direction, described by $\theta$ (zenith angle) and $\phi$ (azimuth angle),
- a view cone with an opening angle of $2\beta$ in which the primary direction can vary (useful for extended sources or isotropic background in the field of view of a Cherenkov telescope),
- a circle with radius $R_{\text{max}}$ on the observation level around the detector, in which the impact position of the shower is randomized.

**Simulated Cherenkov Emission**

The Cherenkov emission of the shower particles is simulated in the wavelength range between 200 and 700 nm by creating groups of photons (bunches), for which the direction, position, wavelength and emission time is monitored. The photon loss, caused by extinction in the atmosphere on the way from the emission point to the observation level is taken into account. The photon bunches, which hit a virtual sphere around the detector (see Fig. 5.2), are stored and can be used by any Cherenkov detector simulation program.

**5.1.2 H.E.S.S. Telescope Array Simulation**

The Cherenkov photon data is processed by a detector simulation program. There are three programs available for the H.E.S.S. array. For this work, sim_hessarray from K. Bernloehr [43] was used, which reads in CORSIKA files and simulates a H.E.S.S. telescope in very high level of detail [50]. The influence of NSB is included in the simulation by a NSB photo-electron pulse probability for each PMT. This leads to an increased trigger probability of a simulated air shower. But it does not allow to calculate random NSB coincidence rates (see Chap. 4).
5.2. TRIGGER RATE AND COLLECTION AREA

The parameters of the H.E.S.S. trigger hardware, implemented within the program, were not modified. Especially, the photo-electron pulse shape parametrisation used in sim_hessarray (shown in figure 4.7), differs from the H.E.S.S. MC standard pulse shape, introduced in section 3.2.1. The shape in sim_hessarray leads to increased air shower trigger rates [53].

In order to study the trigger performance of a telescope, the viewing direction \((\theta_{CT}, \phi_{CT})\) and the trigger configuration \((p, q)\) have to be set up. By running the program and processing the data from a particular CORSIKA data sample, the following information of each simulated shower was obtained from the program:

- the energy \(E\) of the primary particle,
- the primary direction \((\theta_s, \phi_s)\) of each shower,
- the impact (core) position in the observation plane \((x_{core}, y_{core})\), with \(R = \sqrt{x_{core}^2 + y_{core}^2}\), and
- the trigger decision (yes or no).

The telescope pointing direction is set to the initial shower direction in the simulation settings, i.e. \(\theta_{CT} := \theta_s\) and \(\phi_{CT} := \phi_s\) in each MC data sample.

### 5.2 Trigger Rate and Collection Area

#### Definitions

The integral rate \(\Gamma\) of events, induced by a single type of primary particle is given [20] by:

\[
\Gamma(E, \theta) = \int_{\delta E} \frac{dN}{dE} S_{eff}(E, \theta) \ dE. \tag{5.1}
\]

It depends on the energy spectrum \(dN/dE\) of the source within the energy range \(\delta E\). The effective area (or collection area) \(S_{eff}(E, \theta)\) is the area, in which the core position of a shower with particular type and energy has to be located, in order to trigger the telescope (array). An extended source requires an integration over the solid angle

\[
d\Omega = 2\pi \sin \beta d\beta,
\]

in which the showers occur. \(\beta\) is the opening angle of the viewcone around the shower axis (Fig. 5.1.1). The effective area is then defined by

\[
S_{eff}(E, \theta) = 2\pi \int_{\Omega} \int_{0}^{\infty} P(E, \theta, \Omega, R) R \ d\Omega \ dR. \tag{5.2}
\]

\(P(E, \theta, \Omega, R)\) is the probability of a system trigger for a particular shower as function of energy, direction \(\theta\) and distance \(R\) from the detector to the shower core. The dependence on \(\Omega\) results from a varying detector response and differences in the detected Cherenkov emission of air showers of extended sources within the field of view of the telescope. For point sources, the integration over the solid angle does not contribute and the trigger rate (5.1) can be rewritten as

\[
\Gamma(E, \theta) = 2\pi \int_{\delta E} \frac{dN}{dE} \int_{0}^{\infty} P(E, \theta, R) R \ dE \ dR. \tag{5.3}
\]

Furthermore, the integrand of (5.3) is defined as differential trigger rate:
\[ \frac{d\mathcal{T}}{dE} = 2\pi dN \int_0^\infty P(E, \theta, R) R \, dR. \]

**Simplifications**

In each Monte Carlo data sample, obtained from the telescope simulation, the parameters $\theta$, $\phi$, $\beta$, $R_{\text{max}}$ (see Fig. 5.1) and $\delta E$ were fixed. The trigger probability $P$, in an energy interval $\Delta E$, is then defined by the ratio

\[ P(\Delta E) = \frac{n(\Delta E)}{N(\Delta E)}. \]

$n$ is the number of simulated showers with a positive trigger decision and $N$ the total number of showers. In particular, $P$ is approximately zero, if the shower core is far away from the telescopes, beyond a distance $R_0$. Likewise, $P$ vanishes if the difference between the shower direction and the pointing axis of the telescope is greater than an angle $\beta_0$, so that the shower is not within the field of view of the camera. Thus, the parameters $\beta$ and $R_{\text{max}}$ in CORSIKA had to be set to $\beta_0$, $R_0$ respectively, in order to avoid information loss due to showers which could be triggered but were not simulated. Both values had to be obtained empirically from the simulation, by verifying the trigger probability in dependency of the core distance (Fig. 5.3) and of the shower direction (Fig. 5.4). Additionally, these limits varied with particle type, energy range, and telescope pointing direction.

![Figure 5.3: Shower core positions of triggered events. The MC sample contains $10^6$ gamma ray showers. There is no significant number of events with a distance > 400 m.](image)
5.3. SINGLE TELESCOPE TRIGGER

Consequently, with $R_0$, $\beta_0$ known, (5.2) can be integrated:

$$S_{\text{eff}}(\Delta E) = 2\pi \int_{0}^{R_0} \int_{0}^{\beta_0} P(\Delta E) R dR \frac{1}{\sin \beta} d\beta$$

$$= 2\pi R_0^2 (1 - \cos \beta_0) \frac{n(\Delta E)}{N(\Delta E)}. \quad (5.4)$$

Finally, the trigger rate can be calculated by substituting the differential energy spectrum $dN/dE$ of the source with the ratio $\Delta N/\Delta E$, the number of primary particles in the energy range $\Delta E$:

$$\Gamma(\Delta E) = \frac{\Delta N}{\Delta E} S_{\text{eff}}(\Delta E). \quad (5.5)$$

5.3 Single Telescope Trigger

In this section, MC data samples of a specific gamma ray source and the contributing background (cf. Sec. 2.2.4) from the simulation of a single telescope will be explained and analyzed, in order to obtain estimates of the expected trigger rates and the signal-to-noise ratio.

5.3.1 Gamma Rays from a Point Source

Crab Nebula

The Crab Nebula is the standard candle of $\gamma$-ray astronomy and the energy spectrum is the best known. Thus, the Crab spectrum has been used, in order to simulate a gamma ray point source. The following approach will serve as an example for the calculation of the trigger rate (5.5).

The measured flux of gamma rays from the Crab between 0.5 and 20 TeV (HEGRA experiment) [51] can be fitted by the power law

$$\frac{dN_{\gamma}}{dE} = 2.79 \cdot 10^{-7} \left( \frac{E}{1 \text{ TeV}} \right)^{-2.59} \frac{1}{\text{m}^2 \text{s} \text{TeV}}.$$  

The expectations from a SSC model (cf. Sec. 1.4.3) would prefer a flattening of the spectrum at energies below 500 GeV [17].
The H.E.S.S. array will have a much lower energy threshold than HEGRA. Hence the flattening was taken into account by a logarithmic steepening of the power law [51]

\[
\frac{dN_{\gamma}}{dE} = 2.67 \times 10^{-7} \left( \frac{E}{1\text{ TeV}} \right)^{-2.47-0.11\lg E} \text{ m}^2\text{s TeV}^{-1},
\]

which is consistent with the HEGRA measurements. This flux was converted into a histogram (Fig. 5.5), in order to be used for the calculation of the trigger rate (5.5).

**Effective Area**

The effective area \( S_{\text{eff}}(\Delta E) \) was calculated, using a Monte Carlo sample of \( 10^6 \) vertical (\( \theta = 0^\circ \)) gamma rays in the energy range \( \delta E = [10\text{ GeV}, 10\text{ TeV}] \), distributed in a circle with radius \( R_{\text{max}} = 500\text{ m} \) around the vertical pointing telescope. This shower sample was processed by the telescope simulation with trigger configurations of \( p = 4 \) pixels and \( q = 4.0 \) p.e..

For each configuration the number of triggered events in an energy bin \( \Delta \lg E \) was filled into a histogram and divided by the distribution of the total number of simulated showers in each bin, obtaining the trigger probability. A logarithmic scale was chosen, in order to have the same statistical weight in each bin. This avoids statistical fluctuations in the low energy range, resulting from the exponential energy distribution from the simulated showers. Using (5.3) and (5.4), the effective area (see Fig. 5.6) is given by

\[
S_{\text{eff}}(\Delta \lg E) = \pi R_{\text{max}}^2 \frac{n(\Delta \lg E)}{N(\Delta \lg E)}.
\]

Below 100 GeV \( S_{\text{eff}} \) rises rapidly showing a threshold behavior of the detector. The Cherenkov light density resulting from these showers is insufficiently low, in order to trigger the telescope. The turning point around 100 GeV is defined as energy threshold \( E_t \). Beyond the threshold, \( S_{\text{eff}} \) increases slightly, reflecting the extending shower size and Cherenkov emission. Further, it shows a saturation at the highest energies, which results from the limited distance \( R_{\text{max}} \) of the shower core position. The maximum is reached at \( \pi R_{\text{max}}^2 \). The distribution is approximated by the empirical function [52]:

\[
S_{\text{eff}}(E) = a E^b \left( 1 + (E/c)^d \right)^{-1},
\]

used for comparison.

Figure 5.6: Effective area of the gamma ray sample for a trigger configuration of \((4 \text{ pixel}, 4 \text{ p.e.})\).
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Trigger Rate

The differential trigger rate was finally obtained by multiplying the effective area and Crab flux histograms (Fig. 5.7). The maximum of the differential trigger rate is the energy threshold of a single telescope. It was determined by a Gaussian fit of the maximum with an error of < 20\% for all data samples. The rate falls off rapidly towards lower energies and reflects the source energy spectrum at higher energies. The integral trigger rate of the “simulated” Crab Nebula for the 4 pixel/4 p.e. trigger configuration is of the order of 1 Hz.

![Differential Trigger Rate](image.png)

Figure 5.7: Differential trigger rate resulting from the gamma sample.

Trigger Variation

The procedure described above, was applied to several trigger configurations in order to explore the variation of the integral trigger rate as a function of the PMT threshold and pixel coincidences (i.e. the \((p,q)\)-space). Figure 5.8 shows the integral trigger rates for \(p = 2, \ldots, 6\) pixels and \(q = 2.5, 3.0, \ldots, 15.0\) p.e. and the estimated energy threshold (\(< 20\%\) uncertainty) for each simulated data point. The trigger rate decreases with increasing \(p\) and \(q\) and the energy threshold is raised. For configurations with fixed \(p\), the trigger rate follows a power law above a certain value of \(q\). For \(p = 4\) the rates can be fitted by

\[
\Gamma(q)_{\geq3\text{p.e.}} \propto q^{-1.49 \pm 0.02}
\]

and are dominated by the influence of NSB below \(q = 3\text{p.e.}\), resulting in an abrupt rise of the rate.
For a fixed integral trigger rate, the energy threshold is proportional to the number of pixel coincidences \( p \). Showers with low energy have a smaller image size leading to a rejection for high pixel coincidences \( p \), while passing coincidences with low \( p \)-values.

Figure 5.8: *Integral trigger rates as a function of PMT threshold \( q \) for different pixel coincidences \( p \). The numbers next to the data points represent the energy thresholds.*

Zenith Angle Variation

Observations of a source will be performed with different pointing directions. The Crab Nebula will be visible on the H.E.S.S. site at a minimum zenith angle of 20°. The larger distance between the shower maximum and the telescope increases the lateral shower size and decreases the density of the Cherenkov photons inside the light pool. The gamma ray shower MC samples were simulated for \( \theta = 0, 20, 40, 60° \). In order to take the modified effective area into account,
5.3. **SINGLE TELESCOPE TRIGGER**

with $R_{\text{max}} = 500, 700, 900, 1200 \text{ m}$ respectively. Simulations with $\theta > 60^\circ$ were not performed in this analysis, because the NSB contribution increases rapidly at higher elevations $\theta$.

In Figure 5.9, the differential trigger rate for $\theta = 0, 20, 40, 60^\circ$ is shown for an exemplary trigger configuration of 4 pixels at 3 p.e.. It can be seen, that the energy threshold $E_t$ is reduced for rising zenith angles. Furthermore, the differential rate beyond the energy threshold for a particular $\theta$ is higher than the differential rate for a lower $\theta$. Hence, the effective area becomes smaller at energies below $E_t$ and increases at energies higher than $E_t$ with rising zenith angle.

![Differential Rate at Different Elevations](image_url)

**Figure 5.9:** Differential trigger rates for the simulated elevations and the corresponding energy thresholds, obtained by a Gaussian fit.

The integral trigger rates for each elevation $\theta$ were calculated as a function of PMT threshold $q$ for different pixel coincidences $p$ and the results are shown in Appendix C.1. Figure 5.10 shows, that the observed reduction of the trigger rate compared to vertical showers is approximately proportional to $\cos \theta$. There, the integral trigger rates of the gamma ray showers for all trigger configurations were normalized to vertical showers and plotted as a function of the zenith angle $\theta$.

![Scaled Integral Trigger Rates](image_url)

**Figure 5.10:** Scaled integral trigger rates of gamma ray showers as a function of the zenith angle $\theta$. The reduction is proportional to $\cos \theta$ (dashed line).
5.3.2 Hadronic Background

The isotropic hadronic background was simulated using two independent MC samples of protons and alpha particles. The simulation parameters are listed in the table. Both types represent the hadronic cosmic ray component with the highest flux. The heavier nuclei have been taken into account (see 5.3.6), by doubling the trigger rate of the alpha particles [1].

The flux of primary hadrons [2] follows the power law

\[
\frac{dN_h}{dE} = N_0 \left( \frac{E}{1\text{ TeV}} \right)^{-\gamma} \frac{1}{\text{m}^2\text{sr}\text{s}\\text{TeV}},
\]

\[
N_0^{(\text{proton})} = 10.9 \cdot 10^{-2}, \quad \gamma^{(\text{proton})} = 2.75
\]

\[
N_0^{(\text{alpha})} = 6.6 \cdot 10^{-2}, \quad \gamma^{(\text{alpha})} = 2.62.
\]

The effective area and differential trigger rate was calculated using (5.4) and (5.5). In Figure 5.11 an example of the differential trigger rate is given. The distribution in energy misses the clear threshold behavior as seen for the gamma ray showers. For the 4 pixel, 4 p.e. trigger the integral rate of vertical protons is \(~700\text{Hz}\) and for vertical alpha particles \(~200\text{Hz}\), resulting in a total hadronic contribution in the order of 1 kHz, which is a factor of \(10^3\) higher compared to the Crab-like gamma ray rate. A complete overview of the simulated integral trigger rates of the hadronic background can be found in Appendix C.2.

\[
\theta = 0^\circ \quad R_{\text{max}} = 600\text{ m} \quad 700\text{ m} \\
\delta E = 0.05–10\text{ TeV} \quad 0.05–10\text{ TeV} \\
\beta = 4^\circ \quad 5^\circ
\]

\[
\theta = 20^\circ \quad R_{\text{max}} = 700\text{ m} \quad 800\text{ m} \\
\delta E = 0.05–10\text{ TeV} \quad 0.05–10\text{ TeV} \\
\beta = 5^\circ \quad 5^\circ
\]

\[
\theta = 40^\circ \quad R_{\text{max}} = 800\text{ m} \quad 900\text{ m} \\
\delta E = 0.05–20\text{ TeV} \quad 0.1–20\text{ TeV} \\
\beta = 5^\circ \quad 5^\circ
\]

\[
\theta = 60^\circ \quad R_{\text{max}} = 1000\text{ m} \quad 1200\text{ m} \\
\delta E = 0.05–20\text{ TeV} \quad 0.1–20\text{ TeV} \\
\beta = 5^\circ \quad 5^\circ
\]
5.3. SINGLE TELESCOPE TRIGGER

5.3.3 Muon Background

In principle, atmospheric muons produced by hadronic showers are simulated within CORSIKA. An additional amount of muons is produced by hadronic showers with energies below the energy range used in the simulation, i.e. less than 50 GeV. Simulating low energy protons consumes an unacceptable amount of CPU time due to the extremely low trigger efficiency of the telescope. The muons can be simulated separately instead. Muons with energies below 4 GeV do not emit Cherenkov light. Above this threshold energy they are produced by pions beyond 10 GeV resulting from primary cosmic rays above 30 GeV. The cosmic ray energy range between 30 and 50 GeV produces muons with approximately up to 10 GeV. In order to consider this muon contribution, MC samples for \( \theta = 0, 20, 40, 60^\circ \) containing \( 10^6 \) muons each, scattered within \( R_{\text{max}} = 100 \text{m} \), isotropically distributed within a viewcone of \( \beta = 6^\circ \), and in the energy range from 4 to 10 GeV were simulated. The starting height in the atmosphere was set to \( 200 \text{g/cm}^2 \), roughly the height of the hadronic shower maximum. The possible decay of muons, producing electron showers in short distance to the telescopes turned out to be negligible.

The flux of atmospheric muons (see Fig. 5.12) at sea level [1],

\[
\frac{dN_\mu}{dE} = 285 \left( \frac{E}{1 \text{GeV}} \right)^{-2.3} e^{-2.3 \text{ GeV}/E} \left( 1 - e^{-50 \text{ GeV}/E} \right) \times \cos^2 \theta \frac{1}{\text{m}^2 \text{s} \text{sr} \text{GeV}},
\]

depends on the zenith angle \( \theta \). The resulting integral trigger rates are shown Figure 5.13 for \( p = 4 \) pixels as an example. The rate at \( q = 4 \) p.e. with vertical pointing is of the order of 100 Hz. The dependency on the zenith angle is dominated by the reduced flux, i.e. proportional to \( \cos^2 \theta \) and at 4 p.e. with vertical pointing in the order of 100 Hz. This number demonstrates the non-negligible contribution of low energy muons to the trigger rate of a single telescope.

![Figure 5.12: Energy spectrum of atmospheric muons for \( \theta = 0, 70^\circ \) [1].](image)

![Figure 5.13: Integral muon trigger rates as a function of PMT threshold \( q \) with pixel coincidences of 4 pixel.](image)
5.3.4 Electron Background

The MC samples of cosmic electrons were simulated using parameters similar to the gamma ray simulations. Exceptions were the isotropic distribution with $\beta = 4^\circ$ and the particle type. Using the particle flux from [2]

$$\frac{dN_e}{dE} = 0.95 \cdot 10^{-4} \left( \frac{E}{1\text{ TeV}} \right)^{-3.26} \cdot \frac{1}{\text{m}^2 \text{ sr s TeV}},$$

the trigger rates were calculated (see Fig. 5.14). The example of the 4 pixels at 4 p.e. trigger configuration leads to an integral rate of the order of 1 Hz. The rate rises much faster with decreasing threshold than the Crab gamma rates, because low PMT thresholds enhance the contribution of low energy showers, which have a much higher flux due to the steep energy spectrum of cosmic electrons.

5.3.5 Night Sky Background

In Chapter 4, the random trigger rates due to NSB were calculated. In order to compare the shower trigger rates and the NSB contribution, the simulation parameters regarding the camera electronics should match. Especially the PMT pulse shape, which turned out to be a critical parameter, has to be similar (cf. Sec. 5.1.2). For this reason, the NSB simulation was run with the pulse shape, used by the telescope simulation program $\text{sim} \_\text{hessarray}$. The result is given in Figure 5.15, showing a significant rise of the rate compared to the standard pulse (cf. Fig. 4.6).

![Electron Background Trigger Rates](image1)

![Adapted NSB Trigger Rate](image2)

**Figure 5.14:** Integral electron trigger rates as a function of PMT threshold $q$ for different pixel coincidences $p$.

**Figure 5.15:** Trigger rate of NSB, simulated with the PMT pulse shape of the detector simulation.
5.3. SINGLE TELESCOPE TRIGGER

5.3.6 Results

All individual contributions to the telescope trigger rate have been calculated, yielding the total event rate:

\[
\Gamma_{\text{tot}} = \Gamma_p + 2\Gamma_\alpha + \Gamma_e + \Gamma_\mu + \Gamma_{\text{NSB}} + \Gamma_\gamma,
\]

with the trigger rate of gamma ray showers \( \Gamma_\gamma \) and the sum of the individual background contributions \( \Gamma_{\text{bg}} \) (protons, alphas, electrons, muons, NSB). Figure 5.16 shows the total and air shower (w/o NSB) background trigger rates for the \( p = 4 \) pixels trigger and all simulated elevations \( \theta \) compared to the Crab-like gamma signal. The rates for \( p = 2, 3, 5, 6 \) pixels are shown in Appendix C.3. For low thresholds, the NSB dominates and sets a sharp PMT threshold limit for each value of trigger pixel coincidences \( p \), independent of the pointing direction. Beyond this limit, the air shower background, especially of hadronic origin, rules the trigger rate as expected.

Figure 5.16: Trigger rates of the Crab signal and background for coincidences of \( p = 4 \) pixels and for all simulated zenith angles \( \theta \) as a function of PMT threshold \( q \).
The performance of the telescope is limited by the total event rate $\Gamma_{\text{tot}}$, which leads to a specific dead time. In Table 5.1, the trigger configurations with a minimum PMT threshold $q$ are listed, dependent on $\Gamma_{\text{tot}}$. Additionally to the trigger configuration $(p, q)$, the energy threshold $E_t$ and the trigger rate $\Gamma_\gamma$ for the simulated Crab-like signal are given, in order to estimate the performance of the certain trigger configuration. The statistical error for the listed trigger rates is less than 5%. The determination of the energy threshold was done with a systematic uncertainty of less than 20% (cf. Fig. 5.9).

At 200 Hz total event rate, the required PMT thresholds were outside the simulated range. At the time, where the range was specified, the expectations of the camera dead time were more optimistic, thus this (very low) event rate for 10% dead time was not foreseen. The existing numbers result from extrapolations.

Obviously, the $p = 2$ pixels trigger has the worst performance, because of the low gamma event rate and high energy threshold. Additionally, the NSB contribution is rather critical and any variation in the NSB photo-electron rate will increase the trigger rate dramatically by after-pulse events (see Fig. 4.6). The $p = 6$ pixels configuration will be outperformed, because it has the highest energy threshold. A rise in energy threshold proportional to the number of pixel coincidences $p$ is visible at fixed detection rates.
### Table 5.1: Trigger configurations with a minimum PMT threshold \( q \) dependent on different camera event rates \( \Gamma_{\text{tot}} \), along with the energy threshold and the event rate of a Crab-like point source.

<table>
<thead>
<tr>
<th>Trigger rate</th>
<th>Dead time</th>
<th>Zenith Angle</th>
<th>PMT threshold / Energy threshold / Gamma trigger rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma_{\text{tot}} )</td>
<td>( \theta )</td>
<td>2 pixel / ( q / E_t / \Gamma_{\gamma} )</td>
<td>3 pixel / ( q / E_t / \Gamma_{\gamma} )</td>
</tr>
<tr>
<td>1 kHz</td>
<td>50%</td>
<td>0°</td>
<td>9.6/150/0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20°</td>
<td>9.6/180/0.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40°</td>
<td>9.3/310/0.42</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60°</td>
<td>8.5/1000/0.30</td>
</tr>
<tr>
<td>500 Hz</td>
<td>25%</td>
<td>0°</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20°</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40°</td>
<td>11.8/400/0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60°</td>
<td>10.3/1250/0.22</td>
</tr>
<tr>
<td>200 Hz</td>
<td>10%</td>
<td>0°</td>
<td>–</td>
</tr>
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<td></td>
<td></td>
<td>20°</td>
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<tr>
<td></td>
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<td>40°</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60°</td>
<td>–</td>
</tr>
</tbody>
</table>
Summary

The H.E.S.S. experiment is a system of imaging Cherenkov telescopes for the observation of cosmic gamma rays with an energy between 50 GeV and 50 TeV, currently under construction.

In this work, a comprehensive simulation study of the expected trigger rate of a single H.E.S.S. Cherenkov telescope with a camera of 960 photo-multipliers was performed. The trigger rates for a representative gamma ray source, the Crab nebula, and the various background contributions were simulated within the parameter space of trigger configurations.

The gamma-induced and background-induced extensive air showers were calculated with existing simulation programs. The simulated background includes cosmic ray protons, alpha particles, electrons, additional secondary muons and night sky background. The background of hadronic origin dominates the trigger rate, while the electron rates are comparable to the estimated rate of the Crab nebula. Observations under a large zenith angle will require low PMT thresholds in order to compensate the low Cherenkov light density, increasing the sensitivity to NSB triggers. Additionally, the rate of triggered gamma ray showers is more strongly reduced than the hadronic event rate.

For the estimation of the night sky background, a novel simulation algorithm was developed, which allowed to compute the trigger rates over more than 20 orders of magnitude within a reasonable time. This algorithm can further be applied to an arbitrary trigger scheme of coincidences in any PMT array. It was shown, that the photo-electron pulse shape of the PMT response is a critical parameter, leading to large variations of the trigger rate. The NSB defines an absolute minimum PMT threshold. The effect of PMT afterpulses can be neglected for trigger configurations with coincidences of at least 4 pixels in a trigger sector. Furthermore, for observations in the galactic plane with an increased NSB of more than 200 MHz photo-electron rate the trigger rate increases drastically.

The limited knowledge of the photo-electron pulse shape introduces a large systematic uncertainty in the trigger rate and makes a recommendation of an optimum trigger configuration difficult. Direct measurements of this parameter are urgently required but make high demands on the experimental setup. Eventually, the observations with the first H.E.S.S. telescope will allow an adjustment of the simulation results to real data.
Appendix A

Algorithms

A.1 Zero Suppression

In the first step, the trigger time-structure for individual PMT channels is simulated for a time interval \([-\tau_c, T]\). The comparator output and trigger probability is stored in a database.

In order to take into account any influence of preceding photo-electron pulses, the time interval \([-2T, 0]\) is additionally simulated, because pulses which arrive in \([-T, 0]\) can directly result in a trigger in \([0, T]\), while pulses from \([-2T, -T]\) in principle can affect the comparator switch probability in \([-\tau_c, 0]\) (see Fig. A.1).

![Diagram showing pulse distribution and trigger signal](image)

Figure A.1: Typical pulse distribution in the simulation time interval \([-2T, T]\). The second pulse starting in \([-T, 0]\) has direct influence on the width of the trigger signal in \([0, T]\).

The number of pulses \(n\) in \([-2T, T]\) is Poisson-distributed,

\[
P_P(n, 3T) = \frac{(3T\nu_{\text{NSB}})^n}{n!} e^{-3T\nu_{\text{NSB}}},
\]

At least one pulse in \([-T, T]\) is required so that the interval \([0, T]\) is always non-empty. The
suppression of zeros is achieved by applying a truncated Poisson distribution for pulse generation in \([-T, T]\),

\[
P_0(n, 2T) = \begin{cases} 
0 & , \quad n = 0 \\
\frac{1}{1 - e^{-2T\nu_{NSB}}} \frac{(2T\nu_{NSB})^n}{n!} e^{-2T\nu_{NSB}}, & , \quad n > 0 
\end{cases}
\]

The probability for empty time intervals is taken into account analytically by an appropriate weighting factor. For the preceding time interval \([-2T, -T]\), pulses are generated according to the undistorted Poisson distribution \(P_P(n, T)\). Furthermore, the starting time of the pulses thus generated is chosen randomly. The comparator signal is determined and the number of trigger pulses \(n_i\) in \([0, T]\) is counted. Eventually, the trigger probability and rate for \(N\) simulated time intervals can be calculated as

\[
P_{\text{PMT}}(q, T) = (1 - e^{-2T\nu_{NSB}}) \frac{1}{N} \sum_{i=1}^{N} \text{sgn}(n_i),
\]

\[
R_{\text{PMT}}(q) = (1 - e^{-2T\nu_{NSB}}) \frac{1}{TN} \sum_{i=1}^{N} n_i.
\]

### A.2 Hit Numbers

Next, the number \(H\) of triggered pixels (hits) in the whole camera within any time interval \([0, T]\) from NSB photo-electron pulses is computed.

A single PMT trigger occurs with the probability \(P_{\text{PMT}}(q, T)\) (4.1). The probability of \(k\) hits is given by the binomial distribution

\[
P_B(k) = \binom{K}{k} (P_{\text{PMT}})^k (1 - P_{\text{PMT}})^{K-k}
\]

with \(K = 960\). \(P_B\) is modified for coincidences of at least \(p\) hits; that means all \(k < p\) are excluded, which occurs with the probability

\[
F = \sum_{l=0}^{p-1} \binom{K}{l} (P_{\text{PMT}})^l (1 - P_{\text{PMT}})^{K-l}.
\]

The resulting distribution is

\[
P_C(k) = \begin{cases} 
0 & , \quad k < p \\
\frac{1}{1 - F} \binom{K}{k} (P_{\text{PMT}})^k (1 - P_{\text{PMT}})^{K-k}, & , \quad k \geq p 
\end{cases}
\]

from which \(H\) is generated. Analogously to A.1, the probability \(F\) is taken into account analytically by an appropriate weighting factor of the trigger rate (4.2).

### A.3 Geometry Simulation

The probability \(P(H, p)\) of a configuration in which at least \(p\) pixels trigger in a single sector, if \(H\) trigger in the camera, is computed using a semi-analytical approach, and is stored. In the simulation, lists of triggering pixels can be generated (event generation) according to these probabilities.
A.3. GEOMETRY SIMULATION

Definitions

(1) **Camera**: \( C = \{P_1, \ldots, P_K\}, \ P_i = \text{pixel}, \ K = \#\text{pixels} = 960 \)

(2) **Sectors**: \( S_1, \ldots, S_{r=38} \subset C \), \( \bigcup_{i=1}^r S_i = C \), \( n_i = \|S_i\| = \#\text{pixels in } S_i \)

Note: The index which is assigned to each sector is arbitrary, but it has to be defined.

(3) **Leading Sector**: \( S_l \) is called leading, if

a) The number of triggered pixels (= hits) in \( S_l \) is not exceeded by another sector

b) No \( S_k \) with \( k < l \) has the same number of hits as \( S_l \).

Obviously, the leading sector is uniquely defined by these conditions.

(4) **Configuration**: The triplet \((l, H, h)\) with

\[
\begin{align*}
l & = \text{index of the leading sector} \\
H & = \text{number of hits in } C \\
h & = \text{number of hits in } S_l
\end{align*}
\]

is called a configuration.

(5) **Configuration probability** \( G(l, H, h) \):

This is the probability for a situation, where \( S_l \) is the leading sector with \( h \) hits, while \( C \) has \( H \geq h \) hits.

Because the sectors are overlapping (see App. B.1), the calculation of \( G(l, H, h) \) for every possible configuration \((l, H, h)\) is not trivial.

Configuration Probability

The factorization

\[
G(l, H, h) = g(l, H, h) \cdot w(l, H, h),
\]

is used, with \( g(l, H, h) \) as the probability, that out of \( H \) hits in \( C \), exactly \( h \) lie in \( S_l \) and \( (H-h) \) in \( C \setminus S_l \). The factor \( w(l, H, h) \leq 1 \) represents the probability for \( S_l \) being the leading sector in such situations.

a) \( g(l, H, h) \) can be calculated analytically. Using

\[
\begin{align*}
\binom{n_l}{h} & = \text{number of possibilities to choose } h \text{ hits in } S_l \\
\binom{K}{h} & = \text{number of possibilities to choose } h \text{ hits in } C \\
\binom{K - n_l}{H - h} & = \text{number of possibilities to choose the remaining } (H-h) \text{ hits in } C \setminus S_l \\
\binom{K - h}{H - h} & = \text{number of possibilities to choose the remaining } (H-h) \text{ hits from the remaining } (K-h) \text{ pixels of } C \\
\binom{H}{h} & = \text{number of permutations of hit-numbering},
\end{align*}
\]
APPENDIX A. ALGORITHMS

one finds

$$g(l, H, h) = \frac{n_l}{h} \cdot \frac{(K - n_l)}{(H - h)} \cdot \frac{(H)}{h} \cdot \frac{(K - h)}{(H - h)} \cdot \frac{(H)}{h}$$

$$= \left( \frac{h - 1}{K - l} \right) \cdot \left( \prod_{i=0}^{h-1} \frac{K - n_l - j}{K - h - j} \right) \cdot \left( \prod_{k=0}^{h-1} \frac{H - k}{h - k} \right)$$

b) $w(l, H, h)$ is acquired from a Monte Carlo Simulation:

For each configuration $(l, H, h)$, $N$ events are generated with $h$ hits in $S_l$ and $(H-h)$ in $C \setminus S_l$. Counting the number of cases $n$, where the sector $S_l$ is leading, finally one obtains

$$w(l, H, h) = \frac{n}{N}.$$

Sufficient statistics are generated, so that statistical errors are negligible.

Event Generation

Using these preparations, it is now possible to generate trigger configurations according to pre-defined trigger configurations $(p, q)$ and to compute the appropriate weighting factors for an event.

First, the ordered accumulated configuration probabilities

$$P(l, H, h) \in \{P(r, H, H), \ldots, P(1, H, p)\} \quad (A.1)$$

are calculated, which represent the probability for $H$ hits in $C$, when at least $h$ hits lie in $S_l$. They can be derived from the recursion relation

$$P(r, H, H) = G(r, H, H)$$

$$P(l-1, H, H) = P(l, H, H) + G(l-1, H, H) : 2 \leq l \leq r$$

$$P(l, H, h-1) = P(l, H, h) + G(l, H, h-1) : 2 \leq h \leq H.$$ 

The total probability of all trigger configurations $P(H, p) := P(1, H, p)$, has to be applied as a weighting factor. In order to choose a random configuration, a random number

$$\eta \in [0, P(H, p)]$$

is generated, and the first configuration $(l, H, h)$ with

$$P(l, H, h) \geq \eta$$

is selected from the ordered set (A.1). The final list of hits for this configuration is obtained by generating (possibly repeatedly) $h$ hits in $S_l$ and $H-h$ hits in $C \setminus S_l$, until $S_l$ is found to be the leading sector.

Thus, an event with a weight $P(H, p)$ and a list of triggering pixels is constructed, which is then passed to the camera trigger simulation in the time interval $[0, T]$.

Note that the probabilities $P(l, H, p)$ have to be calculated only once, because they only depend on the camera geometry. Only the list of hits has to be generated event by event.
Appendix B

Trigger Sectors

Figure B.1: The trigger sectors of a single camera. For the purpose of clarity, the complete map of all sectors was split up into four images.
Appendix C

Trigger Rates

C.1 Crab-like Gamma Ray Point Source

The following graphs display all calculated integral trigger rates of the Crab-like gamma ray source for all zenith angles as a function of PMT threshold. Each graph contains the rates for a certain pixel coincidence number $p$.

Figure C.1: Trigger rates of a Crab-like gamma ray source at coincidences of $p = 2$ pixels and zenith angles $\theta = 0^\circ, 20^\circ, 40^\circ, 60^\circ$ as a function of PMT threshold $q$. 
C.1. CRAB-LIKE GAMMA RAY POINT SOURCE

Figure C.2: Trigger rates of a Crab-like gamma ray source at coincidences of $p = 3$ pixels and zenith angles $\theta = 0^\circ, 20^\circ, 40^\circ, 60^\circ$ as a function of PMT threshold $q$.

Figure C.3: Trigger rates of a Crab-like gamma ray source at coincidences of $p = 4$ pixels and zenith angles $\theta = 0^\circ, 20^\circ, 40^\circ, 60^\circ$ as a function of PMT threshold $q$. 
APPENDIX C. TRIGGER RATES

Figure C.4: Trigger rates of a Crab-like gamma ray source at coincidences of $p = 5$ pixels and zenith angles $\theta = 0^\circ, 20^\circ, 40^\circ, 60^\circ$ as a function of PMT threshold $q$.

Figure C.5: Trigger rates of a Crab-like gamma ray source at coincidences of $p = 6$ pixels and zenith angles $\theta = 0^\circ, 20^\circ, 40^\circ, 60^\circ$ as a function of PMT threshold $q$. 

5 Pixel Trigger

6 Pixel Trigger
C.2 Hadronic Background

Figure C.6: Trigger rates of proton background for all pixel coincidences and zenith angles as a function of PMT threshold $q$. Isotropic protons with energies between 50 GeV and 20 TeV and single telescope configurations are considered. The graph shows trigger rates for different numbers of pixel coincidences (2 to 6) and varying PMT thresholds.
Figure C.7: Trigger rates of alpha particle shower background for coincidences of \( p = 4 \) pixels and all simulated zenith angles as a function of PMT threshold. 

<table>
<thead>
<tr>
<th>PMT Threshold [p.e.]</th>
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</table>

Alpha Background Trigger Rates

- Single Telescope
- \( 50 \) GeV - \( 20 \) TeV isotropic alpha particles
- \( 4 \) pixel trigger
C.3 Total Background

Figure C.8: Trigger rates of air shower background, NSB and total background for coincidences of $p = 2$ pixels and zenith angles $\theta = 0^\circ, 20^\circ, 40^\circ, 60^\circ$ as a function of PMT threshold $q$. 
Figure C.9: Trigger rates of air shower background, NSB and total background for coincidences of $p = 3$ pixels and zenith angles $\theta = 0^\circ, 20^\circ, 40^\circ, 60^\circ$ as a function of PMT threshold $q$. 
Figure C.10: Trigger rates of air shower background, NSB and total background for coincidences of $p = 4$ pixels and zenith angles $\theta = 0^\circ, 20^\circ, 40^\circ, 60^\circ$ as a function of PMT threshold $q$. 
Figure C.11: Trigger rates of air shower background, NSB and total background for coincidences of $p = 5$ pixels and zenith angles $\theta = 0^\circ, 20^\circ, 40^\circ, 60^\circ$ as a function of PMT threshold $q$. 
Figure C.12: Trigger rates of air shower background, NSB and total background for coincidences of $p = 6$ pixels and zenith angles $\theta = 0^\circ, 20^\circ, 40^\circ, 60^\circ$ as a function of PMT threshold $q$. 
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Erklärung


Stefan Schlenker