# Studying Moon and Sun shadows 

 by using atmospheric muons detected with IceCubeDissertation<br>zur Erlangung des Grades eines<br>Doktors der Naturwissenschaften<br>in der Fakultät für Physik und Astronomie der Ruhr-Universität Bochum

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"Der Frieden ist nicht alles, aber alles ist ohne den Frieden nichts" (Willy Brandt)

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## Chapter 1

## Introduction and cosmic rays

For thousands of years, mankind has been fascinated by the stars in the sky. Early cultures began analyzing star formations. Later, sailors used the stars to navigate during their explorations. Some brighter objects were identified as planets moving around the Sun. It was Johannes Kepler who first described the orbits of the planets in our solar system as ellipses in the $17^{\text {th }}$ century.
Afterwards, Isaac Newton formulated his theory of universal gravitation. It took more than 200 years to extend Newton's theory with Einstein's theory of general relativity. Edwin Hubble discovered that the Universe is expanding according to Hubble's law. All of these discoveries have, in turn prompted more unanswered questions: Dark matter and dark energy have not yet been detected. The origin and extreme accelerators of cosmic rays are still not known. These are only some of the questions left unanswered.

In 2016, the LIGO-experiment discovered gravitational waves from two merging black holes at a distance of $410_{-180}^{+160} \mathrm{Mpc}$ [1], which confirmed Einstein's theory of general relativity. Further, scientists are searching for high energy particles from cosmic accelerators to solve unanswered questions within and beyond the current standard models of cosmology and particle physics. These high energy particles are cosmic rays, gamma rays, and neutrinos.
Viktor Hess was the first scientist to discover radiation from the Universe during balloon flights in the Earth's atmosphere in the early $20^{\text {th }}$ century[2]. Today, many experiments make use of cosmic rays in the search for astrophysical sources.

Before cosmic rays reach the detectors on Earth or in the atmosphere, they propagate through the Universe and are influenced. One important aspect is the deflection in magnetic fields. Cosmic rays from the direction of the Moon and the Sun are blocked and create shadows, which can be seen by cosmic ray and neutrino detectors. Cosmic rays from the direction of the Sun are influenced by the solar magnetic field, which was already seen by other detectors. The goal of this thesis is to study the cosmic ray Moon and Sun shadows of the IceCube Neutrino Observatory. A confirmation of influenced cosmic rays with IceCube can open the possibility of studying the solar magnetic field close to the Sun at various energies. The Moon has already been used to calibrate and verify IceCube's pointing. It is now the first time that the Sun shadow is studied using IceCube data. Such an analysis makes it possible to study the variation of the shadow with the solar cycle and thus the influence of the solar magnetic field on cosmic ray propagation. The analyses are based upon five years of data from 2010 through 2015, detected by the IceCube Neutrino Observatory at the geographic South Pole. This thesis contains the following content:

Chapter 1 gives an overview of cosmic ray particles, their accelerators and candidates for their sources. The energy spectrum of primary cosmic rays and air showers in the Earth's atmosphere are discussed as well.
This thesis is based upon data taken from the IceCube Neutrino Observatory. Chapter 2 introduces cosmic ray and neutrino detectors and IceCube's latest results in the search for high energy neutrinos. Additionally, IceCube's working principle of cosmic ray and neutrino detection is shown. Further, this chapter shows the motivation of this thesis of studying the cosmic ray Moon and Sun shadows with a view of the Sun shadow analysis of the Tibet-As Gamma experiment. Due to the fact that the Sun shadow of the Tibet-As Gamma experiment was influenced by the solar magnetic field close to the surface, two magnetic field models are introduced in Chapter 2.
To understand the atmospheric lepton flux on the surface of the Earth, Chapter 3 deals with a simulation based calculation. To simulate air showers from cosmic rays, the Monte Carlo software CORSIKA is used. For cosmic ray and neutrino detectors, a theoretical estimate of the atmospheric muons and neutrinos is necessary for background studies. Further, a comparison between experimental data and simulations is presented in Chapter 3.
Simulation studies are required to verify a detector such as IceCube. Chapter 4 compares IceCube's experimental data, taken at the South Pole, to simulations. Signal simulations using a CORSIKA sample are presented in Chapter 4.

Two binned analyses in one and two spatial dimensions observe the shadowing effects of the Moon and the Sun, which are presented in Chapter 5. The first analysis represents Moon and Sun in a profile view. It is very important that the shadowing effect of the Moon is constant over time, which can show that the IceCube detector operates correctly. Thus, the angular resolution is calculated. The binned analysis in two dimensions illustrates maps in declination and right ascension.
In Chapter 6, IceCube's Sun shadow results are compared to the solar activity at the same time. A relation between the solar activity and the observed Sun shadow effect can open the possibility to study the solar magnetic field close the Sun's surface.

A more sophisticated method uses a likelihood approach and is presented in Chapter 7. The goal of the unbinned analysis is the investigation of the exact position of Moon and Sun. Moreover, the unbinned analysis is calculated with a GPU method for a higher resolution.

### 1.1 Cosmic rays

The origin and accelerators of cosmic rays are still not known. In the early $20^{\text {th }}$ century, cosmic ray particles were discovered for the first time by Viktor Hess during balloon flights in the Earth's atmosphere [2]. The balloon flights were able to show that the origin of the particles is from outside the Earth as the radiation increased with height. Before accelerator experiments were built, cosmic rays were the only possibility of studying highly energetic particles.

The composition of cosmic ray particles is energy-dependent. However, the largest part is composed of protons and helium nuclei. Further components are anti-protons, electrons, $\gamma$-rays, neutrinos, and heavier nuclei [3].

### 1.1.1 Energy spectrum

Cosmic rays reaching the Earth have various energies. The energy spectrum of primary cosmic ray particles is approximated by a broken power law, see e.g. [4]

$$
\begin{equation*}
\frac{d N_{C R}}{d E_{C R}} \approx E_{C R}^{-\alpha_{C R}} \tag{1.1.1}
\end{equation*}
$$

which is divided into three parts, where the spectral index is approximately given by

$$
\alpha_{C R} \approx\left\{\begin{array}{lll}
2.67 & \text { for } & \log (\mathrm{E} / \mathrm{eV})<15.4,  \tag{1.1.2}\\
3.10 & \text { for } & 15.4<\log (\mathrm{E} / \mathrm{eV})<18.5, \\
2.75 & \text { for } & 18.5<\log (\mathrm{E} / \mathrm{eV}) .
\end{array}\right.
$$

Particles with energies below $E_{C R}<10^{15} \mathrm{eV}$ are assumed to originate from the Milky Way [5]. The main galactic accelerators are supernova remnants. Due to the fact that the particles are influenced by interstellar medium and magnetic fields, it is difficult to reconstruct the origin of the particles. Only indirect measurements have confirmed supernova remnants as candidates for accelerators of cosmic rays in this energy range. These assumptions are derived from phenomenological arguments.
The first break of the spectrum in the region of $E_{C R} \approx 3 \cdot 10^{15} \mathrm{eV}$ is referred to as the knee. The possible reason of the break can only be found in combination with theories. The shape of the kink and the composition can be investigated by experiments, see for example [6], [7].
The second break of the spectral index is called ankle with an energy of $E_{C R} \approx 10^{19} \mathrm{eV}$. Cosmic rays with energies above the ankle are assumed to originate from extragalactic sources and accelerators [8]. Figure 1.1 shows the energy spectrum of primary cosmic rays with an energy range from $10^{8} \mathrm{eV}$ to $10^{21} \mathrm{eV}$ on the $x$-axis. The flux on the $y$-axis is weighted with $E^{2}$. The data are taken from various experiments. For BESS, CREAM, AMS, and PAMELA, only protons are shown. All other experiments show the all-particle spectrum. Approximately $10^{3}$ particles with an energy of 1 GeV pass an area of $1 \mathrm{~m}^{2}$ each second. For ultra high energies with $E_{C R}>10^{19} \mathrm{eV}$, only a single particle goes through an area of $1 \mathrm{~km}^{2}$ each year.

### 1.1.2 The Greisen Zatsepin Kuzmin cutoff

A first particle with an energy above $10^{20} \mathrm{eV}$ was measured by MIT Volcano Ranch station in 1962 [9]. The spectrum cuts off exponentially for energies above several $10^{19}$ eV . High energy protons $(p)$ interact with the cosmic microwave background (CMB, $\left.\gamma_{C M B}\right)[3]:$

$$
p \gamma_{C M B} \rightarrow\left\{\begin{array}{c}
\Delta^{+}  \tag{1.1.3}\\
p e^{+} e^{-}
\end{array}\right.
$$

The energy threshold for a delta baryon $\left(\Delta^{+}\right)$is above $6 \cdot 10^{19} \mathrm{eV}$, which decays further into protons ( $p$ ) and neutral pions ( $\pi^{0}$ ) or neutrons $(n)$ and charged pions $\left(\pi^{+}\right)$[10]

$$
\begin{align*}
& \Delta^{+} \rightarrow p+\pi^{0}  \tag{1.1.4}\\
& \Delta^{+} \rightarrow n+\pi^{+} \tag{1.1.5}
\end{align*}
$$

During these processes, protons lose energy. Due to the fact that the energy loss length is approximately 50 Mpc , sources of very high energy cannot originate from larger distances [3]. This effect was first described by Greisen, Zatsepin, and Kuzmin in 1966 [11], [12]. The exponential cut off is observed experimentally by Auger, shown in Figure 1.1.


Figure 1.1: Primary cosmic ray energy spectrum weighted with $E^{2}$. Data taken from various experiments: BESS (2015) [p] [13], Casa MIA [14], CREAM (2011) [p] [15], HiRes-II Stereo [16], IceTop[17], AMS (2000) [p] [18], PAMELA (2011) [p] [19], Kascade (Sibyll) [20], Auger (2011) [21]. Figure created with [22]

### 1.1.3 Primary cosmic ray models

The primary cosmic ray flux is described by various models. This section deals with various primary cosmic ray models. Two models are used in the analyses of this thesis. Simulations, shown in Chapter 3 and 4, are weighted with the models. The weighting method is described in Chapter 3.
The first model is presented by Gaisser and Honda (GH), where the energy dependent flux $\phi\left(E_{K}\right)$ is described by [23]

$$
\begin{equation*}
\phi\left(E_{K}\right)=K \cdot\left[E_{K}+b \exp \left(-c \sqrt{E_{K}}\right)\right]^{-\alpha} \tag{1.1.6}
\end{equation*}
$$

The parameters $K, b, c$ and $\alpha$ are fit variables for five components, where protons contribute $75 \%$ and helium nuclei $15 \%$. Heavier nuclei, such as CNO, Mg-Si and Fe, contribute $10 \%$ [23]. The parameters are different for each element. The sum over all elements with a mass number $A$ yields the spectrum $\phi_{N}\left(E_{K}\right)=\sum_{A} A \phi_{A}\left(E_{K}\right)$. The GH model is used to simulate the atmospheric lepton in Chapter 4.

The second model is called GaisserH3a and is a standard model in IceCube to weight the results from simulations. Here, the energy dependent flux of the $i$-th element is obtained by [24]:

$$
\begin{equation*}
\phi_{i}(E)=\Sigma_{j=1}^{3} a_{i, j} E^{\gamma_{i, j}} \cdot \exp \left[-\frac{E}{Z_{i} R_{c, j}}\right] \tag{1.1.7}
\end{equation*}
$$

where $j=\{1,2,3\}$ refers to one of three acceleration mechanisms such as supernova remnants, an unknown galactic origin, or an assumed extra-galactic origin [24]. A mixed extragalactic component is assumed in the GaisserH3a model, whereas the GaisserH4a model only uses protons [25].

Equation (1.1.7) yields the primary cosmic ray spectrum seen in Figure 1.2, which shows the energy range of 10 TeV to $10^{8} \mathrm{TeV}$. The sum of all elements $\left(\phi_{N}(E)=\sum_{A} \phi_{i}(E)\right)$ is in good agreement with data from various experiments. Additionally, different nuclei of the primary flux are shown. The flux is weighted with $E^{2.5}$. The knee can be seen at an energy of approximately $5 \cdot 10^{6} \mathrm{GeV}$. Many other models describe the primary cosmic ray flux, see for example Gaisser, Stanev and Tilav (GST) [26] or Hörendel [27]. The models have a similar performance and are used for various energies.


Figure 1.2: Primary cosmic ray flux measured by multiple experiments at different energies compared with the GaisserH3a model. In Chapter 4, the GaisserH3a model is used. The flux is weighted with $E^{2.5}$. Figure taken from [24].

### 1.1.4 Air shower

Cosmic rays propagate and accelerate through the Universe before they hit the Earth's atmosphere. This section deals with the interactions of cosmic rays with air molecules and the resulting air showers of secondary particles.
When cosmic rays interact with the Earth's atmosphere, secondary particles such as pions $(\pi)$ and kaons $(K)$ are produced [28]. Charged pions $\left(\pi^{ \pm}\right)$and the neutral pion $\left(\pi^{0}\right)$ are mesons, consisting of (anti-)up-quarks and (anti-)down-quarks [29]:

$$
\begin{align*}
\left|\pi^{+}\right\rangle & =|u \bar{d}\rangle \\
\left|\pi^{-}\right\rangle & =|d \bar{u}\rangle  \tag{1.1.8}\\
\left|\pi^{0}\right\rangle & =\frac{1}{\sqrt{2}}[|u \bar{u}\rangle-|d \bar{d}\rangle] .
\end{align*}
$$

Charged pions have a mean lifetime of $2.6 \cdot 10^{-8} s$ and a mass of $139.6 \mathrm{MeV} / \mathrm{c}^{2}$ [10]. Kaons are mesons, consisting of one (anti-)up-quark or (anti-)down-quark in combination with one (anti-)strange-quark. Charged Kaons $K^{ \pm}$consist of (anti-)up-quarks and (anti-)down-quarks $\left(K^{+} \rightarrow(u \bar{s}), K^{-} \rightarrow(\bar{u} s)\right)$.
The secondary particles decay and produce further particles. With a probability of $99.99 \%$, charged pions decay into muons and neutrinos, whereas neutral pions decay with a probability of $98.82 \%$ into two gamma rays $\gamma[10]$ :

$$
\begin{align*}
& \pi^{+} \rightarrow \mu^{+}+\nu_{\mu} \\
& \pi^{-} \rightarrow \mu^{-}+\overline{\nu_{\mu}}  \tag{1.1.9}\\
& \pi^{0} \rightarrow 2 \gamma .
\end{align*}
$$

Charged Kaons $\left(K^{ \pm}\right)$mainly decay into muons and neutrinos. Other decays with a smaller branching ratio are also possible.

The dominant branching ratios for $K^{+}$are given by [10]:

$$
K^{+} \rightarrow\left\{\begin{array}{cc}
\mu^{+} \nu_{\mu} & (63.56 \pm 0.11) \%  \tag{1.1.10}\\
\pi^{+} \pi^{0} & (20.67 \pm 0.08) \% \\
\pi^{+} \pi^{+} \pi^{-} & (5.58 \pm 0.02) \% \\
\pi^{0} e^{+} \nu_{e} & (5.07 \pm 0.04) \% \\
\pi^{0} \mu^{+} \nu_{\mu} & (3.35 \pm 0.03) \% \\
\pi^{+} \pi^{0} \pi^{0} & (1.76 \pm 0.02) \%
\end{array}\right.
$$

High energy muons ( $\mu^{ \pm}$) reach the surface of the Earth and can be detected. The muon flux up to an energy of 100 TeV is dominated by muons from kaon and pion decays. Muons are leptons with a mass of $105.7 \mathrm{MeV} / \mathrm{c}^{2}$, which is approximately 200 times the mass of an electron [10]. The mean lifetime of muons ( $\tau_{\mu} \approx 2.2 \cdot 10^{-6}$ ) is two orders of magnitude larger than the mean lifetime of pions [10].
However, muons are expected to decay before they reach the surface of the Earth according to their lifetime. In 1940, Rossi and Hall measured the relativistic lifetime of muons for the first time [30]. Here, the length contraction explains why muons can still be detected on Earth. Muons mainly decay via weak force into electrons/positrons $\left(e^{ \pm}\right)$and (anti-)neutrinos $\left(\nu_{l} / \bar{\nu}_{l}\right)$, where $l$ represents various lepton families such as electrons, muons, and taus [10]:

$$
\begin{align*}
& \mu^{+} \rightarrow e^{+}+\nu_{e}+\overline{\nu_{\mu}}  \tag{1.1.11}\\
& \mu^{-} \rightarrow e^{-}+\overline{\nu_{e}}+\nu_{\mu} . \tag{1.1.12}
\end{align*}
$$

Figure 1.3 illustrates two air showers caused by cosmic rays during interactions with air molecules. A pion decay is shown in Figure 1.3, which was produced in hadronic interactions. The pion decays are described by Equation (1.1.9). Further particles such as charm mesons and unflavored mesons play an important role for higher energies of the cosmic rays. These generated mesons further decay into kaons, pions, and muons.


Figure 1.3: Sketch of an air shower resulting from a cosmic ray interacting with a molecule of the Earth's atmosphere. Figure taken from [31]

## Chapter 2

## Cosmic ray and neutrino detectors

This thesis is based upon an analysis of atmospheric muons, which are detected by the IceCube Neutrino Observatory. To detect high energy neutrinos, detectors with large volumes are required. Atmospheric muons often dominate the trigger rate of such detectors. This chapter describes the functional principle of neutrino and muon detectors, Cherenkov radiation, and mainly IceCube and its most important results. Additionally, the motivation of a Moon and Sun shadow analysis with IceCube in comparison with the results of the Tibet AS-Gamma experiment are explained.

### 2.1 Functional principle

Chapter 1 described cosmic ray particles and their interactions with the Earth's atmosphere. Thus, a direct measurement of cosmic ray particles on the Earth's surface is only possible via secondary particles, for example muons. Cosmic ray detectors such as IceTop at the South Pole are typically located at the surface. However, neutrino detectors like IceCube are deployed in ice or deep in the ocean, see [32] for a first proposal of the IceCube Neutrino Observatory and the IceTop array.
Due to the weak interaction of neutrinos, a direct measurement of atmospheric and astrophysical neutrinos is not possible. Neutrinos must interact with a detection medium such as water or ice to produce charged particles [33], which can be detected by optical sensors.

Neutrinos $\nu_{l}$ of the three different flavors $(l=e ; \mu ; \tau)$ interact via the charged current (CC) or the neutral current (NC). The gauge bosons of the charged current are $W^{ \pm}$_

Bosons. For the neutral current a $Z^{0}$-Boson is the gauge Boson. These currents govern the following reactions:

$$
\begin{align*}
& \nu_{l}+N \rightarrow l+X(C C)  \tag{2.1.1}\\
& \nu_{l}+N \rightarrow \nu_{l}+N(N C) \tag{2.1.2}
\end{align*}
$$

where a neutrino $\nu_{l}$ interacts with a nucleon $N$ and produces a lepton $l$ and another particle $X$ in the charged current. When this lepton is a muon $\mu$, a so-called track can be seen in detectors such as IceCube. The muon can be detected via Cherenkov radiation, which is described in the following subsection. An electron $e$ interacts with a nucleon, and a cascade can be seen by the detectors. A tau $\tau$ creates two cascades, which are called double bang.
In the neutral current, the neutrino $\nu_{l}$ transmits parts of its energy to the nucleon $N$, which creates a cascade, as well.

### 2.1.1 Energy losses of charged leptons

Before charged leptons reach a detector, which is not located at the Earth's surface, these particles must propagate through matter. During the propagation, energy losses occur due to various effects. These effects are, for example, Bremsstrahlung, pair production, and ionisation processes. Energy losses of charged particles in matter can be described by [34]

$$
\begin{equation*}
\frac{d E}{d x}=a(E)+b(E) E \tag{2.1.3}
\end{equation*}
$$

with $a=0.259 \mathrm{GeV} /$ mwe (meters water equivalent) and $b=0.363 \cdot 10^{-3} / \mathrm{GeV}$ for a muon propagating through ice. See [34] for a detailed description of the Monte Carlo code, which calculates muon energy losses in different media. In [35], PROPOSAL is used to study energy losses of atmospheric muons while they propagate through ice. This yields a mean maximum range $x_{f}$ of muons in media [34]

$$
\begin{equation*}
x_{f}=\log \left(1+E_{0} \cdot \frac{b}{a}\right) \cdot \frac{1}{b} \tag{2.1.4}
\end{equation*}
$$

with $E_{0}$ as the muon energy. Muons reaching depths between 1500 meters and 2500 meters in ice must therefore have an energy between 0.5 and 1.0 TeV . Electrons usually do not reach depths of this magnitude because Bremsstrahlung is anti-proportional to the squared mass of a charged particle. Due to the fact that the muon mass ( $m_{\mu} \approx 105.6$ $\mathrm{MeV})[36]$ is 210 times greater than the mass of an electron $\left(m_{e} \approx 0.5 \mathrm{MeV}\right)$ [36], more muons reach depths where neutrino detectors are located.
The simulations show that atmospheric muons always reach and trigger neutrino detectors on Earth, as well, and are the major background of these projects. Thus, it is a major challenge to seperate muon and neutrino events. These analyses are presented in the coming sections.

### 2.1.2 Cherenkov radiation

In the special theory of relativity, Albert Einstein assumes that nothing can travel as fast as light [37]. However, this statement is only satisfied for particles that propagate through vacuum. In dielectric media high energy particles such as electrons, muons, and taus reach higher velocities compared to light in the same media.

$$
\begin{equation*}
v>\frac{c}{n} \tag{2.1.5}
\end{equation*}
$$

Here, $v$ is the velocity of a particle, $c$ the speed of light in vacuum, and $n$ is defined by the medium, for example ice $n_{\text {ice }}=1.3$. For charged particles in ice with a velocity $v>0.75 c$, a cone of light results from the superposition of electromagnetic radiation. The opening angle $\Theta$ can be calculated by

$$
\begin{equation*}
\cos (\Theta)=\frac{1}{n \beta}, \tag{2.1.6}
\end{equation*}
$$

with $\beta=v / c$. Cherenkov detectors make use of this effect to measure high energy particles. The Cherenkov photons trigger optical sensors.

### 2.2 IceCube Neutrino Observatory

The IceCube Neutrino Observatory [38] makes use of the Cherenkov light of high energy particles with sensors, which are deployed in the ice at the South Pole at depths between 1500 and 2500 meters. During IceCube's construction, 86 holes where drilled in the glacial ice in Antarctica. In each of these holes, strings with 60 Digital Optical Modules (DOMs) were deployed.
A sketch of a DOM is illustrated in Figure 2.1. To detect Cherenkov light, which is emitted by high energy particles, a DOM includes a Photomultiplier Tube (PMT). Other instruments, which for example calibrate the DOMs such as LEDs, are surrounded by thick glass to protect them against the high pressure of the ice. The DOMs were designed to last approximately 15 years. For a detailed description of IceCube's DOMs, see [38].


Figure 2.1: Sketch of a Digital Optical Module (DOM). In 86 strings, 5160 of these DOMs are deployed in the ice at the South Pole and form IceCube with a detector volume of $1 \mathrm{~km}^{3}$. A Photomultiplier Tube (PMT) detects Cherenkov radiation emitted by charged high energy particles. Figure taken from [38].

IceCube's main goal is the search for high energy neutrinos from astrophysical sources in the Universe. Due to the fact that neutrinos are not influenced by magnetic fields and interact only via weak force, IceCube can be considered a gigantic telescope pointing back to the sources where neutrinos were accelerated. This telescope has the chance to see astrophysical sources without any deflection. The actual detection medium is the glacial ice at the South Pole with a volume of $1 \mathrm{~km}^{3}$, which surrounds the 5160 light sensors. Due to the fact that the glacial ice is very clear, Cherenkov photons can propagate to the DOMs. Before IceCube was completed in December 2010, it operated in smaller detector configurations with fewer strings. Due to the extreme weather conditions at the South Pole, the drilling process was only possible during the antarctic summer. Planes providing the team of the South Pole station can also only land during the antarctic summer.
In 2007, the IceCube detector operated with 22 strings (IC22). Each following year, more strings were deployed and the detector extended. In this thesis, data taken from May 2010 through May 2015 are used. From May 2010 through May 2011, 79 strings (IC79) were in use before IceCube operated in its final detector configuration with 86 strings from May 2011.
A more compact group of DOMs is called DeepCore and is located at the bottom of the IceCube detector, see for example [39]. Its main goal is to detect low energy neutrinos with an energy threshold of 10 GeV . DeepCore can extend IceCube with regard to searches for dark matter and atmospheric neutrino oscillations.
A sketch of the IceCube Neutrino Observatory can be seen in Figure 2.2. Additionally, DeepCore, AMANDA, and IceTop are shown. AMANDA is the predecessor of IceCube. The first 80 strings were deployed in depths between 1500 and 2000 meters in 1995 [40]. IceTop is a cosmic ray surface detector [41], which is described in the upcoming section. The colored dots at the surface demonstrate the 86 strings. Each color represents a detector configuration before IceCube was completed. The IceCube laboratory is located at the surface in the center of the 86 strings. Additionally, the Eiffel Tower demonstrates the actual size of the entire IceCube detector.
So-called online filters, running at the South Pole, select muon events from the sample. In this thesis, data taken from the Moon and Sun filters are used. The Moon and Sun filters are windows around the position of the Moon and Sun. A detailed description of the filter can be seen in Chapter 5 .


Figure 2.2: Sketch showing the IceCube Neutrino Observatory. The IceCube laboratory is located at the surface of Antartica. IceTop consists of 81 water stations at the surface. DeepCore is a low energy extension of IceCube and is a more compact group of DOMs at the bottom near the Bedrock. Figure taken from [42].

### 2.2.1 IceTop

IceTop is a cosmic ray detector array at the surface of Antartica [41]. It consists of 81 stations with two tanks each, which are filled with clear ice and two Digital Optical Modules (DOMs) each, as shown in Figure 2.3. With its 81 stations, IceTop's detection area is $1 \mathrm{~km}^{2}$. The working principle is similar to other experiments, see for example the Haverah Park experiment [43] or the Pierre Auger Observatory [44]. Each of the stations is located close to IceCube's strings, shown in Figure 2.3. Also shown are two DOMs in a tank, which is filled with clear ice.
IceTop's main goal is to detect cosmic ray particles with a lower energy threshold of several hundred TeV . An air shower is measured when at least three stations detect photons from Cherenkov radiation. The bandwidth of the satellite transferring data to the Northern Hemisphere is limited. Thus, filters reduce the amount of data and transfer only selected events.
Cosmic ray particles, which trigger the IceTop array and the IceCube neutrino detector, can be used to investigate the major background of the IceCube Neutrino Observatory. However, compared to IceCube, IceTop's energy threshold is very high. Thus, not all cosmic ray muons which trigger IceCube can be observed with IceTop.
Major analyses with IceTop are studying the anisotropy and composition of cosmic rays, see for example [45], [46], [47], [48], and [49].


Figure 2.3: Each tank (right) of the IceTop array (left) is located close to one of IceCube's strings. Figures taken from [41].

### 2.2.2 Event reconstruction in IceCube

Atmospheric muons and neutrinos, which can be of astrophysical origin or are produced in air showers and decays, can trigger the IceCube neutrino detector. IceCube's DOMs recognize Cherenkov photons, which are emitted by charged particles in the glacial ice as described above. The Cherenkov photons are used to reconstruct the direction of the charged particles. A reconstruction of the direction of an incoming particle is the basis for seeking point-like sources in neutrino analyses and cosmic ray studies.
This thesis discusses two reconstruction algorithms: the Single Photo-Electron (SPE) and the Multiple Photo-Electron (MPE) reconstruction fits. Both fits are based on a provisional fit. The LineFit uses the position $\overrightarrow{r_{i}}$ and time $t_{i}$ of a DOM, which was triggered by a Cherenkov photon and calculates the incoming direction of the particle. The LineFit is a fast and simple reconstruction fit, because it ignores any interactions of the Cherenkov photons with the ice of Antarctica. Using a $\chi^{2}$ minimization, the Line fit is calculated with [50]

$$
\begin{equation*}
\chi^{2}=\sum_{i=1}\left(\overrightarrow{r_{i}}-\vec{r}-\vec{v} t_{i}\right)^{2} \tag{2.2.1}
\end{equation*}
$$

The velocity of the charged particle is given by $v$. Due to the fact that the LinFit assumes vertically emitted photons of the trajectory of the charged particle, the reconstruction is fast and can be used as a first guess for incoming directions [51].
The Single Photon-Electron (SPE) and Multi Photo-Electron (MPE) fits are more sophisticated and need a longer computing time. Both fits are maximum likelihood reconstruction algorithms. To reconstruct the directions of particles, a set of experimentally known values $(x)$ and unknown parameters $(a)$ are used. $\mathcal{L}(x \mid a)$ represents the likelihood that parameters (a) occur under the condition of measured values $(x)$, see for [50] references

$$
\begin{equation*}
\mathcal{L}(x \mid a)=\prod_{i} p\left(x_{i} \mid a\right) . \tag{2.2.2}
\end{equation*}
$$

Here, the parameters $a$ describe the position of an event $\left(r_{0}\right)$, the time $\left(t_{0}\right)$, and the velocity vector in different angular directions. Figure 2.4 shows these parameters and a Cherenkov radiation emitting event.


Figure 2.4: A charged particle (muon) emits Cherenkov photons during its propagation through the IceCube detector. Shown are the variables, which are used to calculate the incoming direction of the muon. Figure taken from [50].

To reduce computing time of the sophisticated reconstruction fits, the sum of the negative logarithmic likelihood function is minimized, see [51] for references

$$
\begin{equation*}
\log \mathcal{L}(x \mid a)=\sum_{i} \log p\left(x_{i} \mid a\right) . \tag{2.2.3}
\end{equation*}
$$

In IceCube the reduced $\log$-likelihood $(r \log l=\log \mathcal{L} /$ ndof) is introduced to calculate the ratio of the logarithm of the likelihood and the numbers of degrees of freedom. In this thesis the reduced log-likelihood is used in the form of a quality cut variable. Quality cuts remove mis-reconstructed events from the data sample. See Chapter 4 for a detailed description of the method. Another quality cut, which is used in this thesis, is the angular uncertainty of each event $\sigma$, which is calculated by a paraboloid around the most likely position

$$
\begin{equation*}
\sigma=\frac{\sqrt{\sigma_{1}^{2}+\sigma_{2}^{2}}}{2}, \tag{2.2.4}
\end{equation*}
$$

where $\sigma_{1}$ and $\sigma_{2}$ are the uncertainties in two spatial dimensions, see for example [52]. In an unbinned analysis in Chapter 7, the angular uncertainty $\sigma$ is used as an input parameter for the signal function.

### 2.2.3 Neutrino detection with IceCube

IceCube is mainly designed to search for high energy neutrinos. This section describes various neutrino analyses. Because muons dominate the trigger rate [53] of the detector, different approaches are required to isolate neutrino events. The first approach is to investigate only upgoing events, which reach the IceCube detector from the Northern Sky. This means that neutrinos can be produced in air showers at the Northern sky and then propagate through the Earth before they reach the IceCube detector [54].
A second approach is to study only events with an energy above 1 PeV , see [55] and [56]. When IceCube first showed evidence for extraterrestrial neutrinos only events starting within the detector were considered [54]. Therefore, so-called veto regions are applied to the detector. These regions are the boundaries of the IceCube detector. Events which do not emit Cherenkov photons within the veto regions are named starting events. This approach excludes $99.999 \%$ of the muon background [54]. Figure 2.5 shows the different veto regions.


Figure 2.5: Sketch of the IceCube veto layers to select starting events inside the detector. The veto layers are in the boundaries. Left shows a top view of IceCube. The right sketch illustrates the veto layer from a side view. An additional layer can be seen in depths between 2085 meters and 2165 meters. Because of a dust concentration, this area is a veto as well. Figure taken from [54].

Within an observation period of four years, IceCube detected 54 High Energy Starting Events (HESE) [57] with energies $E_{\nu}>60 \mathrm{TeV}$, shown in Figure 2.6. A likelihood approach searches for a clustering within the sky. However, a significant clustering is not found. The event with the highest energy so far, is an up-going muon with an energy of $2.6 \pm 0.3 \mathrm{PeV}$, detected in June 2014 [58].


Figure 2.6: Latest High Energy Starting Events (HESE) results observed with IceCube. A clustering of neutrino events can not be shown significantly at this point. Figure taken from [57].

### 2.3 Cosmic ray Moon and Sun shadows

High energy muons can reach detectors on the surface of the Earth, in ice, or below rocks. This section describes how the Moon and the Sun block cosmic rays on their way to Earth creating a shadow. Further, a temporal variation of the cosmic ray Sun shadow measured by the Tibet As-Gamma experiment is shown in this section. To confirm the temporal variation of the Sun's shadow in a different energy range is one of the main motivations of this thesis.
When cosmic rays propagate through the Universe, they can be blocked by celestial bodies such as Moon and Sun. Sinks of cosmic rays from the directions of the Moon and the Sun are observed, for example MACRO [59], L3 [60], MINOS [61], ARGO-YBJ [62], and HAWC [63]. Figure 2.7 illustrates schematically how the Moon blocks particles on their way to Earth.


Figure 2.7: Sketch of cosmic rays propagating from the direction of the Moon to Earth. The Moon blocks particles and creates a sink of the cosmic rays. Figure taken from [31].

Moon shadow analyses are very valuable for many experiments because the position of the Moon is well known and can be calculated easily. Hence, the Moon is often used as a calibrator for cosmic ray detectors.
Before IceCube was completed in December 2010, it operated in smaller detector configurations with 22 strings in 2007/2008 (IC22), 40 strings in 2008/2009 (IC40), 59 strings in 2009/2010 (IC59), and 79 strings in 2010/2011 (IC79). A first measurement of the cosmic ray Moon shadow was performed for the detector configurations with 40 and 59 strings, where the shadowing effect was measured with high statistical significance $(>6 \sigma)$ [64]. Equatorial coordinates, i.e. right ascension and declination, are used to illustrate Moon and Sun shadow analyses in IceCube.

The Tibet AS-Gamma experiment observed a temporal variation of the cosmic ray Sun shadow. In [65], a seasonal variation of the shadowing effect of the Sun was seen at a mean energy of 10 TeV for an observation period of 14 years, from 1996 though 2009.

During the same observation period, the shadowing effect of the Moon remained stable in [65]. Figure 2.8 shows maps in two spatial dimensions for each observation period. The $x$-axis represents the East-West direction, the $y$-axis the North-South direction. The size of the Sun is illustrated by a black circle located in the center of each map. The seasonal variations of the cosmic ray Sun shadow of the Tibet As-Gamma experiment are clearly visible. See [65] for a detailed description of the method.


Figure 2.8: Seasonal variations at a mean energy of 10 Tev of the Sun's shadow of the Tibet AS-Gamma experiment. In 2006, no results are presented due to a detector shut down. Figure taken from [65].

During the same observation period, the cosmic ray shadow of the Moon remained stable with the expected fluctuations as presented in [65]. Thus, an influence of the solar magnetic field close to the surface of the Sun is expected. Following [65] further, two source surface models are assumed to propagate particles near the surface of the Sun. The potential field source surface (PFSS), described in [66] and [67], and the current sheet source surface (CSSS), described in [68], are these two models of the solar magnetic field close the Sun. The upcoming section gives a short overview of the models. Figure 2.9, taken from [65], compares the number of sunspots and the relative deficit of Sun and Moon shadows. In Figure 2.9 (a) the solar cycle is observed by [69]. A variation of the number of sunspots over time is clearly visible.
Figure 2.9 (b) shows the deficit of cosmic rays observed around the Sun, illustrated by white squares. The Sun shadow was not observed constantly during the 14 -year observation period. Further, simulation studies, which propagate cosmic ray particles through the source surface models, show expected values for the shadowing effect of the Sun. These results are presented as colored data points in Figure 2.9 (b) with the result that the CSSS model with a source surface at $10 R_{\odot}$ fits best with Tibet's experimental data.

In [65], a $\chi^{2}$ test quantifies the relation between experimental data and simulations as $\chi^{2} / \mathrm{DOF}=8.3(10.3) / 14$, which yields a probability of $0.87(0.74)$. The dashed line represents the Sun shadow without any influence of the solar magnetic field. In the last plot, Figure 2.9 (c), the relative deficit of the Moon shadow is shown to be almost constant over time. Only slight differences within the statistical uncertainty can be seen [65].
Additionally, the ARGO collaboration was able to see a seasonal variation of the cosmic ray Sun shadow at an energy of 5 TeV from 2008 through 2012, see [70].


Figure 2.9: Seasonal variations at a mean energy of 10 TeV of the Sun's shadow of the Tibet AS-Gamma experiment. The shadowing effect of the Sun varied during the 14 year observation period, while the Moon shadow remained almost stable. Expectations were calculated for different models of the solar magnetic field close the surface of the Sun. Figure taken from [65].

### 2.3.1 Motivation to study the Sun's cosmic ray shadow with IceCube

The Tibet AS-Gamma experiment showed that studying the cosmic ray shadows of the Moon and the Sun can provide information about the solar magnetic field close the Sun's surface. Thus, one goal of this thesis is to look for evidence of a temporal variation of the cosmic ray Sun shadow with the IceCube detector at higher energies compared to Tibet's analysis with a mean energy of 10 TeV . Such a result would verify previous results by Tibet for the previous solar cycle and thus provide the opportunity to compare data for two solar cycles. IceCube's Moon and Sun shadow analyses with a median energy of 40 TeV of primary cosmic ray particles can open the door to a new possibility of studying the solar magnetic field close to the Sun's surface at such high energies, while Tibet results a media energy of 10 TeV [65].

Another goal of this work is to confirm the shadowing effect of the Moon as a verification tool for a correctly working detector. Therefore, the angular resolution can be calculated with a binned analysis in one dimension in Chapter 5. A stable angular resolution over time can show that a detector such as IceCube works correctly, which is very important for seeking high energy neutrinos from astrophysical sources. However, a calculation of the pointing accuracy is only possible with a more sophisticated method. Therefore, an unbinned analysis is presented in Chapter 7. This work is based upon five years of IceCube's experimental data, taken from May 2010 through May 2015.

### 2.4 Solar magnetic field models

The Sun has a strong magnetic field with an eleven-year cycle. During the eleven-year cycle, the sunspot number, which is regularly updated in [71], varies significantly. Due to the fact that the sun rotates, the interplanetary magnetic field (IMF) is described by the Parker Spiral; see [72] for a detailed description of the Parker Spiral. In [72], Eugene Parker also predicted the solar wind. The Parker spiral is a large-scale distance description of the interplanetary magnetic field.
However, closer to the Sun's surface, the solar magnetic field becomes more complex and is described by different models. Chapter 5 already pointed to different models describing the magnetic field close to the surface of the Sun. The potential field source surface (PFSS) model [66], [67] and the current sheet source surface (CSSS) model [68] describe the Sun's magnetic field between the Sun's surface and $2.5 R_{\odot}$. The PFSS assumes that the corona is current-free. Beyond $2.5 R_{\odot}$ from the Sun's surface, the magnetic field is assumed to be radial. This area is called the source surface.

Figure 2.10 simulates magnetic field lines of the PFSS model during low solar activity. The inner sphere illustrates the magnetogram of the photosphere with a range of $\pm 15$ Gauss. However, very active regions can reach up to 500 Gauss; see [73] for a detailed analysis of the magnetogram. The outer sphere shows the source surface with a magnetic field strength of $\pm 0.15$ Gauss. Due to the low activity of the Sun at the time of the simulation, most of the magnetic field lines are closed. A simulation of the PFSS of the Sun in a more active state would show open magnetic field lines.


Figure 2.10: The potential field source surface (PFSS) model describes the magnetic field structure of the solar magnetic field from the Sun's surface to the source surface at $2.5 R_{\odot}$. The magnetogram at the photosphere shows a magnetic field strength with a range of $\pm 15$ Gauss. At the source surface, the magnetic field strength has a range of $\pm 0.15$ Gauss. Figure taken from [73].

## Chapter 3

## Atmospheric lepton flux with CORSIKA

This chapter describes the simulation of the atmospheric lepton flux in comparison to experimental data from various experiments. When cosmic ray particles hit the Earth's atmosphere, secondary particles are produced. The secondary particles decay and further secondary particles propagate towards the Earth's surface. At ground level, detectors like IceTop or IceCube, which is deployed in the glacial ice at the South Pole, can measure the flux of the secondary particles.
Primary cosmic ray particles can only be measured directly by detectors on balloons or satellites. However, these detectors have a limited energy. To calculate the flux of higher energies cosmic ray particles and to understand the propagation of secondary particles, a Monte Carlo based simulation program, called CORSIKA [74] was developed for the KASCADE experiment located in Karlsruhe [75].
Nowadays, CORSIKA is a standard simulation program for detectors like IceCube, where cosmic ray secondaries are the major background of the trigger rate [53]. In the IceCube analysis in this thesis, CORSIKA is also used: An expectation of the Moon and Sun shadow analyses are based on simulations with CORSIKA in Chapter 4.

This chapter describes the simulation and measurement of the muon and neutrino fluxes at ground level at an energy range between $1-100 \mathrm{GeV}$. A detailed analysis of the fluxes is very valuable for the IceCube detector to estimate the atmospheric background to search for high energy neutrinos from astrophysical sources. Also important is the ratio between negative charged muons $\mu^{-}$and positive charged muons $\mu^{+}$, which can be measured by experiments.

The flux of the atmospheric neutrinos $\nu$ and anti-neutrinos $\bar{\nu}$ can be compared to experimental data as well. These analyses were mainly performed by Sebastian Schöneberg [76].

### 3.1 CORSIKA software

CORSIKA (COsmic Ray SImulations for KAscade) is a Monte Carlo-based simulation program, which calculates extensive air showers in the Earth's atmosphere using a test-particle approach [74]. The simulation tool takes protons and nuclei as primary particles with an energy range between $10^{12} \mathrm{eV}$ and greater than $10^{20} \mathrm{eV}$. To calculate the hadronic interactions, different models are provided. QGSJET [77], DPMJET [78], SIBYLL [79], SIBYLL2.3 [80] and EPOS [81] are high energy models. At lower energies below 80-100 GeV FLUKA [82] or UrQMD [83] are used. Only interactions with a branching ratio bigger than $1 \%$ are taken into account. This work is based upon simulations with FLUKA and a combination with UrQMD for lower energies and EPOS with energies above $80-100 \mathrm{GeV}$. FLUKA is also a low energy model with a threshold of $80-100 \mathrm{GeV}$. However, for higher energies the DPMJET model is included in FLUKA. FLUKA calculates inelastic cross-sections of hadrons at lower energies [82]. Elastic and inelastic interactions below 80 GeV are computed with UrQMD [83]. A previous work simulated lepton fluxes and muon charge ratios for energies of leptons above 80 GeV with Sibyll 2.1, QGSJET-01 and QGSJET-II-03, see [84].
With the CORSIKA software, the type and energy of the primary energy can be defined manually. During the interactions, more than 50 elements can be simulated. First, primary particles such as protons and heavier nuclei produce baryons, their anti-particles, and their resonances. Further, mesons such as pions and kaons decay into leptons such as $e^{ \pm}, \mu^{ \pm}, \nu_{e}$ and $\mu_{\nu}$ [74].
The composition of the Earth's atmosphere is defined as a fraction of $N_{2}, O_{2}$, and Ar . The density of the atmosphere is divided in 5 parts with a maximum height of 112 km above the Earth's surface, see [74].
When charged particles propagate through the atmosphere of the Earth, energy losses occur. Charged particles interact with electrons of the molecules of the air above Earth. These molecules then are ionized by charged secondary particles. CORSIKA uses the Bethe-Bloch formula to describe energy losses in air showers. The Bethe-Bloch formula shows that energy losses increase for highly relativistic charged particles with $\beta \approx 1$.

Particles propagating to the surface of the Earth are influenced by different interactions. Muons usually decay or are influenced by Bremsstrahlung and pair production. Due to the weak interactions of neutrinos, CORSIKA does not simulate neutrino cross-sections or neutrino oscillations, see [74] for a detailed description of the CORSIKA simulation tool.
CORSIKA also simulates the influence of the geomagnetic field to charged particles. Therefore, it is important to know the location of the detector to chose correct magnetic field parameters.
This work is based upon a modified version of CORSIKA. The high energy limit of FLUKA is chosen to be 100 TeV for the first data set. A second dat set uses UrQMD for energies below 50 GeV and EPOS above 50 GeV . Additionally, histogram with the energy of secondary particles are used to simulate the lepton fluxes.

### 3.2 Primary cosmic rays

The composition of cosmic ray particles that hit the Earth's atmosphere include a range of elements from protons up to iron nuclei. Integrated over the entire energy range, primary cosmic rays are dominated by protons and helium nuclei. However, at higher energies the fraction of other nuclei becomes more significant. Therefore, not only protons can be used as primary cosmic ray particles to calculate the flux of muons and neutrinos at ground level.
In [76], a comparison between nuclei and a superposition method of protons and neutrons is shown. At lower energies the differences between the superposition method and other nuclei are a few percent points. At higher energies the differences increase up to $10 \%$. However, due to other uncertainties this error seems acceptable for this approach. The advantage of a proton and neutron-only simulation is the shorter computing time of air showers.

### 3.3 Muon flux and charge ratio

Detectors on the surface of the Earth do not measure comic rays directly. This section deals with the atmospheric muon flux and the muon charge ratio simulated with CORSIKA.
CORSIKA provides histograms with the energy of the secondary particles, named yields. The yields are weighted with a model, which describes the primary cosmic ray flux. The model is called GH, see Chapter 1. In [76], a comparison between the

GH model and the GST model [26] shows a higher accuracy for the GH model.
Figure 3.1 presents the simulated muon flux at ground level for energies between 1 GeV and $10^{3} \mathrm{GeV}$. The red line illustrates the muon flux calculated with FLUKA and the blue line the muon flux computed with EPOS and UrQMD.
Additionally, the simulations are compared to experimental data, taken from Bess [85], L3+C [86], and Caprice [87]. The FLUKA simulation matches the experimental data well, while the EPOS simulations are calculated below the observed muon flux for energies above 40 GeV .


Figure 3.1: Simulated muon fluxes with various models (FLUKA and EPOS/UrQMD) compared to experimental data from Bess [85], L3+C [86] and Caprice [87]. FLUKA shows good agreement with the experimental data from various experiments. Figure taken from [76].

The muon charge ratio is the fraction of negative charged muons $\mu^{-}$and positive charged muons $\mu^{+}$. Due to the fact that the hadronic cosmic rays are charged positively, the charge ratio is above 1.0. A comparison between the muon charge ratio of experimental data taken from Bess [85], L3+C [86], and MINOS [88] is shown in Figure 3.2. Both FLUKA and EPOS/UrQMD simulations match experimental data above energies of 20 GeV .
Further, the muon charge ratio with Sibyll 2.1 and QGSJET-II are compared as well. In [84], the charge ratio was either simulated above or below the charge ratio measured by various experiments. The charge ratio increases with higher energy, which shows the larger contribution of kaons.


Figure 3.2: Comparing the muon charge ratio of Bess [85], L3+C [86], MINOS [88], and simulation studies. Sibyll 2.1 and QGSJET-II were calculated in [84]. FLUKA and EPOS match for energies above 20 GeV with experimental data. Figure taken from [76].

### 3.4 Neutrino oscillations with SQuIDS and NuSQuIDS

To investigate neutrino oscillations SQuIDS, see [89], and NuSQuIDS, see [90], are used. This section describes the implementation of neutrino oscillations to the CORSIKA software.
The solar neutrino flux has been measured by the Homestake solar neutrino experiment since 1970 [91]. The goal of the Homestake solar neutrino experiment was to detect the neutrino flux above 0.814 MeV . Solar electron neutrinos $v_{e}$ interact with ${ }^{37} \mathrm{Cl}$ atoms and produce ${ }^{37} \mathrm{Ar}$ atoms and an electron $e^{-}$

$$
\begin{equation*}
{ }^{37} \mathrm{Cl}+v_{e} \rightarrow{ }^{37} \mathrm{Ar}+e^{-} . \tag{3.4.1}
\end{equation*}
$$

The Homestake neutrino detector, which is located in a mine in South Dekota (USA), makes use of this neutrino capture process to calculate the solar neutrino flux. Following [91] further, the measured and predicted neutrino fluxes are different. This could be explained by neutrino oscillations. Other experiments showed statistical evidence for neutrino oscillations, see for example [92]. This evidence of oscillations of the flavors also shows that neutrinos, which are predicted as massless in the Standard Model, have a mass [93].
NuSQUDIS uses SQUIDS to solve the Schrödinger equation numerically and provides tables with the probability of the three different neutrino flavors $\nu_{e}, \nu_{\mu}$ and $\nu_{\tau}$. NuSQUIDS provides probability values for different energies, heights, and media. Thus, neutrino oscillations can be calculated for in-air shower produced neutrinos above ground level. Further, the software can calculate oscillations for neutrinos, which propagate through the Earth. Figure 3.3 shows the probability for a muon neutrino $\nu_{\mu}$ with a propagation length of 100 km and an energy of 1.5 GeV . For this particle an oscillation to an electron neutrino $\nu_{e}$ is very unlikely. The muon neutrino can only oscillate to a tau neutrino $\nu_{\tau}$.


Figure 3.3: The oscillation probabilities for a muon neutrino $\nu_{\mu}$ to a tau neutrino $\nu_{\tau}$ or electron neutrino $\nu_{e}$. The energy of the muon neutrino $\nu_{\mu}$ is 1.5 GeV .

### 3.5 Neutrino flux and oscillations

The observation of atmospheric neutrinos requires detectors with a large volume, such as IceCube [38], AMANDA [40], Frejus [94], and ANTARES [95]. Figure 3.4 compares neutrinos fluxes for muon-neutrinos $\nu_{\mu}$ and electron neutrinos $\nu_{e}$ from various experiments to simulation studies with FLUKA and EPOS/UrQMD. The energy range is from 1 GeV to $10^{4} \mathrm{GeV}$. Both simulations describe the experimental data equally well within the statistical uncertainties. However, IceCube's and AMANDA's experimental data lies systematically above the simulations.


Figure 3.4: Atmospheric neutrino fluxes for muon-neutrinos $\nu_{\mu}$ and electron neutrinos $\nu_{e}$. Simulations with FLUKA and EPOS are compared to experimental data taken from Freijus [94], AMANDA [96], ANTARES [95], and IceCube[97] for energies between 1 GeV to $10^{4} \mathrm{GeV}$. Figure taken from [76].

Neutrino oscillations are not implemented in CORSIKA's code. NuSQuIDS [90] can thus be used to include oscillation probabilities in the simulation studies. Figure 3.5 shows the atmospheric neutrino flux detected by Super Kamiokande [98]. Additionally, FLUKA simulations with neutrino oscillations and without neutrino oscillations are shown.
For energies above 100 GeV , neutrino oscillations influence neither experimental data nor simulations. Comparing Super Kamiokande's experimental neutrino flux to the down-going simulations without oscillation probabilities, differences can be seen at lower energies. This fact shows that Super Kamiokande's neutrino fluxes are influenced by neutrino oscillations. The average of down-going simulations and up-going simulations, which include oscillations probabilities, match the experimental data well.


Figure 3.5: Comparing neutrino fluxes with oscillation probabilities and experimental data from Super Kamiokande [98] for energies between $10^{-1}$ GeV to $10^{4} \mathrm{GeV}$. The oscillation probabilities are calculated with NuSQuIDS [90]. Figure taken from [76].

## Chapter 4

## Simulation studies with CORSIKA in IceCube

Simulation studies are required to verify and improve experimental data detected by IceCube. This chapter compares experimental data to simulations. Further, an expectation for the binned analysis in Chapter 5 is calculated using a Toy Monte Carlo method.
To simulate particles and extensive air showers in the Earth's atmosphere, CORSIKA, a Monte Carlo based code [74], is used in these simulation studies. When a cosmic ray particle interacts with the atmosphere of the Earth, secondary particles such as high energy muons are produced and propagate to the surface of Antarctica, where the IceCube Neutrino Observatory is located.
Additional inice simulations are applied after the particles hit the surface of Antarctica in order to simulate ice conditions and propagation of particles through ice. When charged secondary particles travel through the ice, energy losses occur. In [64], cosmic ray particles are described, which trigger the Moon filter and produce muons with a mean energy of 2 TeV on the surface of Antartica. The muons that reach the DOMs of the IceCube detector have a mean energy of 200 GeV of detection [64].
These particles are then treated as experimental data. Reconstruction algorithms, such as the MPE and SPE fits described above (see also [99] and [52]), compute the directions of the simulated particles. A major advantage is that the primary directions of the simulated particles are known and can be compared to the reconstructed direction of the same simulated cosmic ray particle.
The difference between the true direction of a particle and the reconstructed direction is called the opening angle and provides a hint for the angular resolution of the IceCube
detector. The goal of the simulation studies is to verify IceCube's experimental data by comparing different distributions to simulated air showers.
In this context, a Toy Monte Carlo method is used to compare simulated Moon and Sun shadows to experimental data from the IceCube detector. An expected shadowing effect of the Moon and Sun can be used to verify the IceCube detector. A Toy Monte Carlo method uses generated events instead of a full Monte Carlo simulation.

### 4.1 Simulation data sample

This section describes the simulation data set, which is used to compare various distributions at various declinations above the horizon.
This work makes use of simulation datasets with an energy range of primary cosmic ray particles between 600 GeV and $10^{11} \mathrm{GeV}$ with a median energy of 40 TeV , with $68 \%$ of events in an energy range between 11 TeV and 200 TeV , and $90 \%$ between 5 TeV and 500 TeV , which satisfy the Moon and Sun filters of the IC79 and IC86 configurations. Figure 4.1 shows the energy distribution of primary cosmic rays of the simulated datasets. The energy ranges are in good agreement with the simulation data sample used in the IC40 and IC59 configurations.
Table 4.1 shows simulation datasets for various declinations above the horizon at the geographic South Pole simulated with CORSIKA and Sibyll 2.1 as the hadronic interaction model. The lifetime of each simulation set is approximately 18 minutes. As a primary simulated spectrum an $E^{-2.6}$ spectrum with five components is used. The five components and the primary cosmic ray model GaisserH3a are described in Chapter 1.

| Declination $\left[^{\circ}\right]$ | 23 | 20 | 18 | 15 |
| :---: | :---: | :---: | :---: | :---: |
| $E_{C R}[G e V]$ | $600-10^{11}$ | $600-10^{11}$ | $600-10^{11}$ | $600-10^{11}$ |
| Sim. Spectrum | $E^{-2.6}$ | $E^{-2.6}$ | $E^{-2.6}$ | $E^{-2.6}$ |
| Weighted Spectrum | H3a | H3a | H3a | H3a |
| Composition | 5 -Component | 5-Component | 5 -Component | 5-Component |
| Events [\#] | 272119 | 179677 | 138517 | 85033 |
| Lifetime [s] | 1130 | 1154 | 1178 | 1216 |

Table 4.1: Simulation datasets at various declinations above the horizon calculated with CORSIKA and Sibyll 2.1 as the hadronic interaction model. The 5 components are proton, helium, CNO, Mg-Si, and Fe nuclei. The energy range of the primary cosmic ray particles is $\left(600-10^{11}\right)$ GeV .

Chapter 1 showed that the cosmic ray spectrum has two breaks: "knee" and "ankle". Thus, a primary cosmic ray model, such as GaisserH3a, is required to weight the primary simulated spectrum of $E^{-2.6}$. The weights $w$ are the ratio of the flux of the model $\phi_{\text {Model }}$ and the simulated flux $\phi_{\text {sim }}$

$$
\begin{equation*}
w=\frac{\phi_{\text {Model }}}{\phi_{\text {sim }}} \tag{4.1.1}
\end{equation*}
$$

## Primary Cosmic Ray Energy



Figure 4.1: Energy distribution of primary cosmic ray particles, which satisfy the Moon and Sun filters of the IC79 and IC86 configurations with a median energy of 40 TeV . In energy ranges of $11 \mathrm{TeV}-200 \mathrm{TeV}$ and 5 $\mathrm{TeV}-500 \mathrm{TeV}, 68 \%$ and $90 \%$ of the events are located, respectively.

### 4.2 Distributions

One goal of the simulation studies is to verify IceCube's experimental data. Thus, various simulated distributions are compared to experimental data in this section. These distributions are two spatial distributions, zenith and azimuth, of the Moon and Sun filters. Further, the NChannel distribution, which is an energy estimator, is verified. The reduced logarithmic likelihood is a quality value of the reconstruction fits. The different simulation distributions created with CORSIKA are compared with experimental data from IceCube's Moon and Sun filters. The crosscheck is done for four different elevations $\left(23^{\circ}, 20^{\circ}, 18^{\circ}\right.$, and $\left.15^{\circ}\right)$ of the celestial bodies. Further, these distributions are used to calculate a Toy Monte Carlo Moon and Sun shadow analysis to compare its results with the experimental data analyses.

### 4.2.1 Zenith distribution

In Zenith, the Moon and Sun filters have a range of $\pm 10^{\circ}$ around the expected position of each celestial body. In Figure 4.2, experimental data and simulations are compared for the zenith distribution at a Moon and Sun elevation of $23^{\circ}$ above the horizon $\left(\approx 67^{\circ}\right.$ in zenith and $\approx 0.39$ in $\cos (\theta))$.
Due to the range of the filters, an edge is expected at $13^{\circ}$ elevation $(\approx 0.22$ in $\cos (\theta)$ )and $33^{\circ}$ elevation $(\approx 0.54$ in $\cos (\theta))$, which can be seen in Figure 4.2. Simulations and experimental data match well in the region around the celestial body. Figure 4.3 shows the ratio of experimental data and simulations in a region of $\pm 5^{\circ}$ around the Moon. The analyses in this thesis only use data of this region. CORSIKA can not simulate edges of a filter, thus simulations and experimental data do not match beyond the boundaries. The error bars represent the statistical uncertainty.
Additionally, when comparing zenith distributions, when Moon and Sun are at an elevation of $20^{\circ}, 18^{\circ}$, and $15^{\circ}$ also match and can be seen in the attachment, Figures A.1, A.2, and A.3.

Zenith, Elevation 23


Figure 4.2: Experimental data (red) and simulated data (blue) of the zenith distribution of the Moon and Sun filters are compared for a Moon/Sun elevation of $23^{\circ}$. The simulations are weighted with the GaisserH3a model. Simulations and experimental data match and can be used for further studies.


Figure 4.3: Comparison of experimental data and simulations calculated with CORSIKA. In a region of $\pm 5^{\circ}$ around the position of the celestial body experimental data and simulations match well.

### 4.2.2 RLogL distribution

The reduced $\log$-likelihood ( $\mathrm{R} \log \mathrm{L}$ ), which is the logarithm of the best track divided by the number of degrees of freedom, is used as a cut variable, which will be calculated in the next section. Figure 4.4 and Figures A.4, A.5, A. 6 in the appendix show that simulations and experimental data match for the RlogL distributions for different Moon and Sun elevations.


Figure 4.4: Experimental data (red) and simulated data (blue) of the RlogL distribution of the Moon and Sun filters are compared for a Moon/Sun elevation of $23^{\circ}$. Simulations and experimental data match and can be used as a cut variable.

### 4.2.3 NChannel distribution

When a Cherenkov photon is detected by IceCube's DOMs, the number of hit DOMs, called NChannel, is an estimator for the energy of the particle that triggers the detector. Figure 4.5 compares the NChannel distribution for simulations and IceCube's experimental data. The error bars illustrate the statistical uncertainties. The NChannel distribution is expected to be correlated to the muon energy deposited in ice, which
is sensitive to the primary cosmic ray model. This could cause the deviations between simulations and experimental data occur, seen at values around NChannel $=25$ in Figure 4.5. However, these deviations are still in an acceptable range. In the appendix, Figures A.7, A.8, and A. 9 compare these distributions for different Moon and Sun elevations. In combination with other variables, the variable NChannel can be used to estimate the muon energy and to measure the Moon and Sun shadow at different energies. A future projekct is to observe the shadowing effects of Moon and Sun at various energies.

NChannel, Elevation $23{ }^{\circ}$


Figure 4.5: Experimental data (red) and simulated data (blue) of the RlogL distribution of the Moon and Sun filters are compared for a Moon/Sun elevation of $23^{\circ}$. Simulations and experimental data match. In further studies, NChannel can be used to calculate the Moon and Sun shadow analysis for different energies.

### 4.2.4 Azimuth distribution

In the IC79 configuration, the Moon and Sun filters are limited in azimuth, while the IC86 configuration takes the entire azimuth band. The advantage of an entire band is a higher statistic for a background estimation. Figure 4.6 shows that experimental data and simulations match and can be used for further simulation studies. Simulations and experimental data match within the statistical uncertainties, which are represented by the error bars. The comparison for different elevations can be seen in the appendix, Figures A.10, A.11, and A. 10 .


Figure 4.6: Experimental data (red) and simulated data (blue) of the azimuth distribution of the Moon and Sun filters are compared for a Moon/Sun elevation of $23^{\circ}$. Simulations and experimental data match. The distribution can be used for further simulation studies.

### 4.3 Quality cuts determined with CORSIKA

Quality cuts improve the statistical significance of the Moon and Sun shadow analyses. Their goal is to exclude misconstructed events from the muon sample. This section deals with the determination of quality cuts, which are used in the binned analysis in Chapter 5.
Two independent cut variables are used in this analysis: The reduced log-likelihood ( $\mathrm{R} \operatorname{logL}$ ) and the angular uncertainty $\sigma_{i}$, which are described in Chapter 2. A similar method is used in [64] for the IC40 and IC59 detector configurations, as well as in the Moon and Sun shadow analysis for the IC79, IC86 I, and IC86 II configurations, see [100]. In a search of point sources of astrophysical high energy neutrinos [101] and for a diffuse flux [102], the reduced log-likelihood (RlogL) and the angular uncertainty $\sigma_{i}$ are used as standard cut variables.
Following [64] and [100], Poisson statistics are assumed and yield a proportionality of events passing the quality cuts RlogL and $\sigma_{i}(\eta)$, and the median angular resolution of the track reconstruction ( $\Psi_{\text {med }}$ ):

$$
\begin{equation*}
S \propto \frac{\sqrt{\eta}}{\Psi_{m e d}} . \tag{4.3.1}
\end{equation*}
$$

Using equation (4.3.1) the cut variable RlogL and $\sigma_{i}$ yield Figure 4.7 and Figure 4.8, which show optimisations for both variables. The highest significance is achieved for RlogL $<8.1$ and $\sigma_{i}<0.71^{\circ}$. Table 4.3 shows cuts for IC40, IC59, IC79, and IC86.

| Year | RlogL | $\sigma_{i}$ |
| :---: | :---: | :---: |
| IC40 | $<9$ | $<1.01^{\circ}$ |
| IC59 | $<8.8$ | $<1.04^{\circ}$ |
| IC79 | $<8.1$ | $<0.71^{\circ}$ |
| IC86 | $<8.1$ | $<0.71^{\circ}$ |

Table 4.2: The cut variables RlogL and $\sigma_{i}$ for four different detector configurations. Data taken from [64] and [100].

Due to a greater detector volume, the angular uncertainty for the best significance becomes smaller. This shows that the IceCube detector operates with higher accuracy in IC79 and IC86, because only events with a good track reconstruction are used in this analysis.


Figure 4.7: Maximizing equation (4.3.1) for the best significance of the Moon and Sun shadow analysis yields events with $\mathrm{R} \log \mathrm{L}<8.1$.


Figure 4.8: Maximizing equation (4.3.1) for the best significance yields events with $\sigma_{i}<0.71$.

### 4.4 Pull corrections for the MPE fit

Energy losses of the muon track are not implemented in the MPE reconstruction fit, which can influence the angular uncertainty $\sigma$. There is evidence that the angular uncertainty is underestimated by the MPE reconstruction fit at higher energies, due to stochastic energy losses, which are not implemented in the MPE fit [64]. Thus a so-called pull is used to estimate an improved angular resolution. The pull is defined as the ratio between the real and reconstructed angular uncertainty [52]:

$$
\begin{align*}
p u l l & =\frac{\text { true }_{\text {err }}}{\sigma_{\epsilon}} & & , \text { with }  \tag{4.4.1}\\
\sigma_{\epsilon} & =0.57\left(\epsilon+\frac{1}{\epsilon}\right) \cdot \sigma_{a} & & , \text { and } \\
\epsilon & =\frac{\sigma_{1}}{\sigma_{2}} & & \text { and } \\
\sigma_{a} & =\sqrt{\sigma_{1} \cdot \sigma_{2}} & &
\end{align*}
$$

Here, $\sigma_{1}$ and $\sigma_{2}$ illustrate the uncertainty in two directions. In [64], the average pull is calculated as 1.00 for the SPE reconstruction fit, while simulation studies show that the average pull of the MPE reconstruction fit is 1.55 . However, the effect of the underestimation of the angular uncertainty $\sigma$ is energy dependent and must be corrected in this dependence.
As the number of hit DOMs (NChannel) is correlated to the energies of the detected leptons, this variable can be used for pull corrections analysis. By scaling the average pull of each bin (NChannel) with equation (4.4.2), the pull of the MPE reconstruction fit can be corrected:

$$
\begin{equation*}
F(\mathrm{NCh})=\alpha+\beta \cdot \mathrm{NCh}+\gamma \cdot \mathrm{NCh}^{2}+\delta \cdot \mathrm{NCh}^{3}+\epsilon \cdot \mathrm{NCh}^{4}+\zeta \cdot \mathrm{NCh}^{5} . \tag{4.4.2}
\end{equation*}
$$

Here, $\alpha$ to $\zeta$ are the fit parameters and NCh represents the number of hit DOMs (NChannel). Figure 4.9 shows the mean pull for each NChannel before (red line) and after (blue line) pull corrections. The expected mean pull is $10^{0}$, which is achieved after pull corrections. Figures 4.10 and 4.11 show the pull for each NChannel in a map with two dimensions and confirm the effect of pull corrections.

| Parameter | Value |
| :---: | :---: |
| $\alpha$ | $0.18 \pm 0.05$ |
| $\beta$ | $-(2.2 \pm 4.0) \cdot 10^{-3}$ |
| $\gamma$ | $(2.3 \pm 1.0) \cdot 10^{-5}$ |
| $\delta$ | $(1.0 \pm 1.2) \cdot 10^{-7}$ |
| $\epsilon$ | $-(2.4 \pm 2.0) \cdot 10^{-9}$ |
| $\zeta$ | $(7.0 \pm 10.2) \cdot 10^{-12}$ |

Table 4.3: Parameters resulting from equation (4.4.2) to scale the pull for each NChannel.


Figure 4.9: Mean pull of each NChannel before (red line) and after (blue line) corrections. The expected mean value of each NChannel is $10^{\circ}$ after pull corrections.


Figure 4.10: Mean pull before pull corrections


Figure 4.11: Mean pull after pull corrections

### 4.5 Toy Monte Carlo Moon and Sun shadow analysis

To analyse the shadowing effects of Moon and Sun, a binned analysis in one and two dimensions is used. A detailed description is provided in Chapter 5. The goal of a Toy Monte Carlo Moon and Sun shadow analysis is to determine expected values for the angular resolution and the amplitude of a fitted Gaussian, which illustrates the relative deficit of the cosmic ray flux from the direction of Moon and Sun. This Toy Monte Carlo method uses generated events weighted with simulated distributions instead of a full Monte Carlo sample. These expected Moon and Sun shadow results can then be compared to IceCube's experimental data.
The Moon and Sun filters have characteristic zenith and azimuth distributions, which are shown in Figures 4.2 and 4.6 , as well as in the appendix. Weighted with the given zenith and azimuth distributions, random numbers are generated. A detailed description of the Toy Monte Carlo method can be found in [10]. Then, taking the Point-Spread-Function (PSF) of the IceCube detector, each random number experiences a push in zenith and azimuth.

### 4.5.1 Description of the method

Moon and Sun have an angular size of $0.5^{\circ}$ and remove events from the muon sample from these directions. Thus, a decrease in cosmic rays is detected. A further description of the Moon and Sun shadow analyses can be found in Chapter 5. In conclusion, one can say that the profile view of the Moon and Sun is described by a Gaussian function, see e.g. [64] or [100].

$$
\begin{equation*}
f(\Psi)=-\frac{\Phi \pi R_{M / S}^{2}}{\sigma^{2}} e^{-\Psi^{2} / 2 \sigma^{2}} \tag{4.5.1}
\end{equation*}
$$

Here, $\sigma$ illustrates the angular resolution of the Toy Monte Carlo sample and $R_{M / S}$ the angular size of Moon and $\operatorname{Sun}\left(\approx 0.26^{\circ}\right) . \Phi$ is the cosmic ray flux at the position of Moon and Sun. Figures 4.2 and 4.6 show good agreement of simulated and IceCube experimental data. Thus, these distributions can be used to generate random numbers for the Toy Monte Carlo sample. It is important to generate the same amount of random numbers as IceCube's Moon and Sun shadow analysis, in order to be able to calculate expected values for the profile view analysis. The binned analysis takes into account events that are in a radius of $5^{\circ}$. To avoid boundary effects, a larger window
was used to generate random numbers. Because Moon and Sun filter trigger rates are correlated to the elevation of the celestial bodies (see Figure 4.2), the maximum elevation of the celestial bodies above the horizon at the geographic South Pole in each year is determined using the description of [103]. The results of this investigation can be found in Chapter 5. Due to the fact that the Sun's maximum elevation remains stable, the amount of muon events is also similar in each year. However, the Moon's maximum elevation decreases from IC79 through IC84 IV. Thus, fewer events are detected after 2010, when IceCube operated in its configuration with 79 strings.

In the next step, events in the radius of $0.26^{\circ}$ are removed from the Toy Monte Carlo sample to simulate the shadowing effects of Moon and Sun. At this point, the sample shows a perfectly operating detector without any angular uncertainty. Thus, each event experiences a push by the PSF of the detector in a random direction. This yields a simulation data set similar to IceCube's experimental data.

### 4.5.2 PSF described by a Gaussian

In [64] and [100], the Point-Spread-Function is represented by a Gaussian function in two dimensions. Figure 4.12 shows a Toy Monte Carlo Moon shadow analysis. The $y$-axis represents the relative deficit in each bin, the $x$-axis the radial distance to Moon and Sun. Instead of taking IceCube's PSF, a Gaussian with a width of $0.55^{\circ}$ is used to push each event of the simulation data set in a random direction. The red function is a Gaussian, which is fitted to the simulation data set with a width of $(0.55 \pm 0.01)^{\circ}$ and an amplitude of $10 \%$. A $\chi^{2}$-test $\left(\chi^{2} /\right.$ ndof $\left.=1.0\right)$ shows that a Gaussian is an appropriate function to test the Toy Monte Carlo method.
Thus, this Toy Monte Carlo method can be tested by Gaussians with different widths. If the widths of the PSFs and the fitted Gaussians match, the Toy Monte Carlo method can be used to calculate expected values for the angular resolution and amplitude of the fitted Gaussian, which represents the relative deficit of the Moon and Sun shadowing effects.
Figure 4.13 shows the relation of the input width $\left(\sigma_{i n}\right)$ and the reconstructed width ( $\sigma_{\text {reco }}$ ) of the fitted Gaussian. Due to the fact that the input and reconstructed width match within their statistical uncertainties, the Toy Monte Carlo method can be used.


Figure 4.12: Profile view of a Toy Monte Carlo Moon and shadow analysis with a Gaussian function as an input parameter to push each event of the simulation data set in a random direction. A $\chi^{2}$-test ( $\chi^{2} /$ ndof $=1.0)$ shows a good approximation for the Gaussian function. The amplitude of the Gaussian is fitted to $10 \%$, the angular resolution to $(0.55 \pm 0.01)^{\circ}$.

### 4.5.3 Expected Sun and Moon shadows

The goal of section 4.5.2 was to verify the Toy Monte Carlo method. However, the PSF of the IceCube detector is only approximated by a Gaussian. In this section the PSF is used for the push of the generated events in the Toy Monte Carlo sample.
The PSF for a Moon and Sun elevation of $23^{\circ}$ is shown in Figure 4.14. Further PSFs of elevations at $20^{\circ}, 18^{\circ}$ and $15^{\circ}$ can be seen in the appendix (A.13, A.14, and A.15). By using these Point Spread Functions, expected values for the angular resolution and amplitude of the fitted Gaussian can be estimated. Figure 4.15 shows the Toy Monte Carlo profile view of Moon and Sun. The $y$-axis represents the relative deficit in each bin, the $x$-axis the angular distance of the bins from the expected position of Moon and Sun. A more detailed description of the profile view method can be seen in Chapter 5, where IceCube's experimental data is used to observe the shadowing effects of Moon and Sun. Because Moon and Sun have approximately the same angular size (diameter $D_{M / S} \approx 0.5^{\circ}$ ), the same Toy Monte Carlo sample can be used to compute expected angular resolution and amplitude for both celestial bodies. However, the Sun has a solar magnetic field which could influence charged particles on their way to Earth and the IceCube detector at the South Pole.
Thus, a more sophisticated method, taking into account the solar magnetic field, is needed to simulate an expected Sun shadow effect.
The expected angular resolution is determined to be $\sigma=0.5^{\circ}$, the amplitude of the fitted Gaussian is $12 \%$. The fact that the gaussian is a good approximation for a fit to the profile view method is shown by a $\chi^{2}$-test with $\chi^{2} /$ ndof $=1.2$. The shadowing effect is also calculated with very high statistical significance with a probability value of $10^{-270}$. In Chapter 5, these expected values are compared with IceCube's experimental data to verify the quality of the detector.


Figure 4.13: Comparison of a Gaussian as the Point Spread Function (PSF) ( $\sigma_{i n}$ ) with the reconstructed angular resolution $\sigma_{\text {reco }}$ of the Toy Monte Carlo sample.


Figure 4.14: Point Spread Function (PSF) at an elevation of $23^{\circ}$ of Moon and Sun


Figure 4.15: Profile view of the Toy Monte Carlo Moon and Sun shadow analysis. The expected angular resolution is calculated to $\sigma=0.5^{\circ}$, the amplitude to $12 \%$. A $\chi^{2}$-test $\left(\chi^{2} /\right.$ ndof $\left.=1.2\right)$ shows that a Gaussian function is a good approximation for the profile method of Moon and Sun. The expected values can be used to verify IceCube's experimental data. Due to the solar magnetic field, a more sophisticated simulation study is necessary to calculate expected Sun shadows.

## Chapter 5

## Binned analysis of the Moon and Sun shadows

This chapter describes two binned analyses in one- and two spatial dimensions to observe the shadowing effects of Moon and Sun with the IceCube Neutrino Observatory. The main goal of this chapter is to confirm Tibet's observation of a temporal variation of the cosmic ray Sun shadow at higher cosmic ray energies. Tibet's median energy is 10 TeV [65], whereas IceCube's median energy is 40 TeV for primary cosmic ray particles that trigger Moon and Sun filters. Another goal of this chapter is to verify the angular resolution of the IceCube detector using the muon sample from the Moon and Sun filters during the five year observation period from 2010 through 2015.

Cosmic rays from the direction of Moon and Sun are blocked, preventing them from reaching the Earth and the IceCube detector. Although IceCube is a neutrino detector, its trigger rate is dominated by muons with a rate of $3000 \mathrm{~s}^{-1}$ [53].

The binned analysis in one dimension represents a profile view of Moon and Sun. A Gaussian is fitted to IceCube's experimental data. The width of the Gaussian represents the angular resolution of the IceCube detector. The second approach is a binned analysis in two spatial dimensions. The shadowing effects of Moon and Sun are visible in maps in right ascension and declination.
In Chapter 6, the results of the binned analysis in one dimension are compared to the solar activity during the five year observation period.

### 5.1 Data sample

The analysis of the Moon and Sun shadows as observed with IceCube presented in this thesis is using five year experimental data taken from different detector configurations with 79 and 86 strings, respectively. The trigger rate is dominated by down-going muons with a rate of $3000 \mathrm{~s}^{-1}$ [53]. These muon events are then transferred from the South Pole to IceCube's headquarters the the University of Wisconsin (USA).
Because the satellite used to transfer IceCube's experimental data has a limited bandwidth, only 100 GB data can be used each day. Online filters running at the South Pole are used to reduce the amount of data to a first level (Level1). This work is based upon muon events that satisfy the Moon and Sun filters, which are windows around the calculated position of Moon and Sun. A muon event enables the filters if it is within the spatial boundaries of the windows and if at least 12 DOMs in three different strings recognize Cherenkov photons. To avoid mis-reconstructed events with high angular uncertainty, Moon and Sun must reach a threshold of $15^{\circ}$ above the horizon, or else neither filter is enabled and neither transfers data to the Northern Hemisphere.
During the five year observation period, Moon and Sun reached different maximum elevations. The Sun reached a constant maximum elevation of $\approx 24^{\circ}$ each year. However, the Moon's maximum elevation fluctuated during the observation period between $\approx$ $18^{\circ}$ and $\approx 24^{\circ}$. Elevations of Moon and Sun are calculated according to the projected motion of the celestial bodies on the sky using the tool provided in [103]. Thus, the Moon filter is enabled for approximately 7 days each month, while the Sun reaches the $15^{\circ}$ threshold for roughly 90 consecutive days each year.
The filters transfer an enormous amount of data. In windows with a size of $[72 \times 16]^{\circ}$ around Moon and Sun, up to 200 million muon events reach the databases in Madison each season. Each of these events passed the criteria of the Moon or Sun filter. For neutrino analyses, this high number of background events is a major obstacle for IceCube's scientists seeking high energy neutrinos. However, analyses such as the Moon and Sun shadow analyses benefit from the muon background and this background is the basis for exact results. Only detectors with a high muon trigger rate are able to illustrate Moon and Sun shadows. Further, an atmospheric neutrino Moon and Sun shadow is possible to measure with IceCube. Each year, 100,000 neutrinos produced in cosmic ray interactions with the Earth's atmosphere trigger the IceCube detector. While neutrinos are not abundant enough in order to detect the shadows with statistical significance, muons are detected with a rate approximately $10^{6}$ higher than neutrinos and can therefore be used to study the cosmic ray shadows of Moon and Sun.

### 5.2 Data processing

Data analyses with the IceCube Neutrino Observatory are based upon a large number of events, especially if the major muon background is used. Thus, various steps are required to process the data from the Moon and Sun filters. In the last step a first quality cut $(0<\operatorname{rlog} l<25)$ and a window with a size of $[72 \times 16]^{\circ}$ around the positions of Moon and Sun select events from the experimental data sample. Other variables such as the number of hit DOMs (NChannel), Modified Julian Day (MJD), the reduced $\log$-likelihood ( $\mathrm{R} \log \mathrm{L}$ ), and the angular uncertainty $(\sigma)$ are defined as well.

### 5.3 Simulations and quality cuts

In Chapter 4, quality cuts are calculated for both detector configurations as $\mathrm{RlogL}<8.1$ and $\sigma<0.71^{\circ}$. These quality cuts are necessary to improve the statistical significance of the shadowing effects of Moon and Sun, because mis-reconstructed events are excluded from the data sample. Each year, approximately $30 \%$ of all muon events pass the quality cuts and are used to study the cosmic ray Moon and Sun shadows. The Moon shadow analysis is based upon 15-24 million events each year in a window with a size of $[72 \times 16]^{\circ}$ around the Moon. A window with the same size around the Sun collects 40-48 million muon events each year.

Atmospheric muons from a vertical direction must pass 100 kilometers of the atmosphere and 1.5 kilometers of Antarctic ice before they reach the DOMs. Other muons with an incoming angle must pass a longer distance through the Earth's atmosphere and a longer distance through the ice at the South Pole. Thus, as the Sun remains at a higher elevation for more days, more muons can reach the IceCube detector. Further, simulation studies are used to compare IceCube's experimental data. Details can be seen in Chapter 4.

### 5.4 MPE vs. SPE reconstruction fit

IceCube uses different fits to reconstruct the direction of neutrino and muon events. In a previous work, the SPE and MPE reconstruction fits are compared, see [104] for references.

Due to the large computing time of the MPE and SPE reconstruction fits, in addition to the large amount of muon events, only one of these fits can be used to study the shadowing effects of Moon and Sun for a large number of years. In the previous work
[104], the angular resolution of the muon sample of IceCube's detector configuration with 79 strings is investigated for the MPE and SPE reconstruction fits. With an angular resolution of $(0.52 \pm 0.05)^{\circ}$, the MPE fit performs better than the SPE fit with an angular resolution of $(0.62 \pm 0.08)^{\circ}$. These results of the angular resolution cannot be compared to this work, because only the reduced $\log$-likelihood was applied to the data sample of the previous work. This work also uses a quality cut, which is provided by the paraboloid package that comes with the MPE reconstruction fit. The unbinned likelihood approach in Chapter 7 also makes use of data calculated in the previous work, see [104] for a data sample.

### 5.5 1-Dimensional approach

The goal of the binned analysis in one dimension is to produce a profile view of the Moon and Sun shadows. Further, the angular resolution of the muon event reconstruction of the data sample can be calculated with this method. Additionally, the depth of the shadows is observed and compared to the solar activity. A similar analysis was already performed in [64] for the detector configurations with 40 and 59 strings.

### 5.5.1 Description of the method

To observe the profile view of the Moon and Sun shadows, the binned analysis in one dimension compares on-source and off-source regions. Both regions are windows with a size of $\pm 5^{\circ}$. The on-source region is located at the position of each celestial body, while the off-source regions have an offset of $\pm 5^{\circ}, \pm 10^{\circ}, \pm 15^{\circ}$, and $\pm 20^{\circ}$ in right ascension. It is important that the offset is only in right ascension, because more muon events are detected at higher elevations.
Each bin of the on-source region is compared to the mean value of events of the offsource regions. The relative deficit in each i-th bin is then calculated to

$$
\begin{equation*}
\frac{\Delta N_{i}}{\langle N\rangle_{i}}=\frac{N_{i}^{\text {on }}-\left\langle N_{i}^{\text {off }}\right\rangle}{\left\langle N_{i}^{\text {off }}\right\rangle}, \tag{5.5.1}
\end{equation*}
$$

with $N^{\text {on/off }}$ as all events in on-source/off-source regions. The statistical uncertainty of each bin is given by

$$
\begin{equation*}
\sigma_{\Delta N_{i} /\langle N\rangle_{i}}=\frac{N_{i}^{\text {on }}}{\left\langle N_{i}^{\text {off }}\right\rangle} \sqrt{\frac{1}{N_{i}^{\text {on }}}+\frac{1}{s \cdot\left\langle N_{i}^{\text {off }}\right\rangle}} . \tag{5.5.2}
\end{equation*}
$$

Here, the number for the off-source regions is represented as $s=8$, see [64] and [100] for references.

Both celestial bodies have an angular size of $0.5^{\circ}$. However, in [64] and [100] it is assumed that the Moon is a point-like sink, which reduces $\Phi \pi R_{M / S}^{2}$ events from the muon sample. Here, $R_{M / S}$ describes the angular radius of Moon and Sun with a size of $\approx 0.26^{\circ}$. It is estimated that the angular resolution of the muon sample is better than $1^{\circ}$. The MINOS collaboration investigated the one-dimensional approach with an angular size of the Moon. In [105], it is assumed that the deficit in the muon sample $\Delta N_{\mu} / \Delta_{\Omega}$ is described by a radial two-dimensional Gaussian (r, $\phi$ ) and a Gaussian at each point within the region of the Moon $\left(r^{\prime}, \phi\right)$

$$
\begin{equation*}
\frac{\Delta N_{\mu}}{\Delta_{\Omega}}=\lambda\left(1-\frac{1}{2 \pi \sigma^{2}} \int_{0}^{R_{m}} r^{\prime} d r^{\prime} \int_{0}^{2 \pi} d \phi e^{-\left(r^{2}+r^{\prime 2}-2 r r^{\prime} \cos \phi\right) / 2 \sigma^{2}}\right) . \tag{5.5.3}
\end{equation*}
$$

A sketch of equation (5.5.3) can be seen in [106]. Here, $\sigma$ is the angular resolution of the detector. With a Taylor expansion and $\Theta=r$ this yields [105]

$$
\begin{equation*}
\frac{\Delta N_{\mu}}{\Delta_{\Omega}}=\lambda\left[1-\frac{R_{M}^{2}}{2 \sigma^{2}} e^{-\Theta^{2} / 2 \sigma^{2}}\left(1+\frac{\left(\Theta^{2}-2 \sigma^{2}\right) R_{M}^{2}}{8 \sigma^{4}}+\frac{\left(\Theta^{4}-8 \Theta^{2} \sigma^{2}+8 \sigma^{4}\right) R_{M}^{4}}{192 \sigma^{8}}\right)\right] . \tag{5.5.4}
\end{equation*}
$$

The terms of higher order can be neglected. For an angular resolution $\sigma$ smaller than $1^{\circ}$, the error in the first bin $(\Theta=0)$ varies between $1 \%$ and $5 \%$. An additional test with IceCube's experimental data showed that the effect is within a few percentage points and can be neglected in the Moon and Sun shadow analysis. Thus, it is justified to treat Moon and Sun as point-like objects.
Further, the point spread function (PSF) of the IceCube detector smears the deficit. A perfectly operating detector would show an almost flat background with no relative deficit and a completely shadowed Moon area with the actual angular size of the celestial body. Due to the angular uncertainty, muon events can be reconstructed in front of Moon or Sun although they are background events.

In [64] and [100], this PSF is described by a Gaussian function in two dimensions. It is assumed that this Gaussian is symmetric in azimuth, which only depends upon the radial distance $\Psi$. This Gaussian is described as [64]

$$
\begin{equation*}
f(\Psi)=-\frac{\Phi \pi R_{M / S}^{2}}{\sigma^{2}} \cdot e^{-\Psi^{2} / 2 \sigma^{2}} \tag{5.5.5}
\end{equation*}
$$

The relative deficit in $i$-th bin is then given by [64]

$$
\begin{equation*}
\Delta N_{i}\left(\Psi_{i}\right)=-\frac{R_{M / S}^{2}}{2 \sigma^{2}} e^{-\Psi_{i}^{2} / 2 \sigma^{2}} \tag{5.5.6}
\end{equation*}
$$

The amplitude of equation (5.5.6) is equal to the first order term equation (5.5.4) and can be fitted to IceCube's experimental data. A constant line, which illustrates no shadowing effect, is also fitted to the experimental data. The $\chi_{\text {constant }}^{2}$ of a constant value can be compared to the Gaussian's $\chi_{\text {gaussian }}^{2}$

$$
\begin{equation*}
\frac{\Delta \chi^{2}}{\Delta \text { dof }}=\frac{\chi_{\text {gaussian }}^{2}-\chi_{\text {constant }}^{2}}{\text { dof }} \tag{5.5.7}
\end{equation*}
$$

The difference in the degrees of freedom ( $\Delta$ dof) is automatically 1 . Additionally the probability value ( p -value) can be used to calculate the statistical significance of the shadowing effects by Moon and Sun

$$
\begin{equation*}
S=\sqrt{2} \cdot \operatorname{erf}^{-1}(1-p) \tag{5.5.8}
\end{equation*}
$$

with the inverse error function ( $\mathrm{erf}^{-1}$ ). The results of the statistical test can be compared to IceCube's previous Moon shadow analyses and other cosmic ray detectors.

### 5.5.2 Results

## Moon shadow

The shadowing effect of the Moon is observed with high statistical significance ( $>12 \sigma$ ) in each year. Further, the angular resolution of the muon sample is calculated with values between $(0.43 \pm 0.05)^{\circ}$ and $(0.49 \pm 0.05)^{\circ}$. These results show that the IceCube neutrino observatory operates constantly because the calculated angular resolution of the Moon shadow analysis varies only in its statistical uncertainty. Also, the amplitude shows a constant behavior with values between $0.11 \pm 0.02$ and $0.13 \pm 0.02$, which is illustrated by Figure 5.2.
In [64], when IceCube operated in its IC40 and IC59 configuration, the angular resolution $\sigma$ was calculated with $(0.71 \pm 0.07)^{\circ}$ and $(0.63 \pm 0.04)^{\circ}$ in $2009 / 2010$. This work shows a better angular resolution with a mean value of $(0.46 \pm 0.05)^{\circ}$, which can be explained by the fact that IceCube was completed in 2010. The larger detector results in an improved track reconstruction and thus a better average PSF. To choose between the MPE and SPE reconstruction fit, the angular resolution with $(0.52 \pm 0.05)^{\circ}$ was calculated in the previous work to this thesis, see [104]. However, the data sample in the previous work did not include the sigma $\sigma$ cut of the paraboloid package of the MPE reconstruction fit. Table 5.1 shows the results of the profile view analysis of the Moon.

|  | Year | $\sigma_{\text {gauss }}\left[^{\circ}\right]$ | $\Delta\left(\sigma_{\text {gauss }}\right)\left[^{\circ}\right]$ | $A$ | $\Delta(A)$ | $\mathrm{S}[\sigma]$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Moon | IC79 | 0.43 | 0.05 | 0.12 | 0.02 | $>12 \sigma$ |
|  | IC86-I | 0.45 | 0.05 | 0.13 | 0.02 | $>13 \sigma$ |
|  | IC86-II | 0.49 | 0.05 | 0.11 | 0.02 | $>12 \sigma$ |
|  | IC86-III | 0.47 | 0.05 | 0.12 | 0.02 | $>12 \sigma$ |
|  | IC86-IV | 0.47 | 0.06 | 0.13 | 0.02 | $>12 \sigma$ |

Table 5.1: Results of the 1-Dimensional analysis, with $A$ as the amplitude and $\sigma$ as the width of the Gaussian. The statistical significance is illustrated by $S$. The amplitude and width of the fitted Gaussian remain stable during the five-year observation period.

Figure 5.1 shows the results of the binned analysis in one dimension of the Moon. The Gaussian is illustrated by the red function, the constant line by the blue dashed line. The $y$-axis represents the relative deficit in each bin, the $x$-axis the radial distance of the muon events to the position of the Moon. A $\chi^{2}$-test shows that a Gaussian is an appropriate function to fit the Moon shadow effect with values of $0.9<\chi^{2} 1.1$.



Moon, IC86-II



Figure 5.1: Profile view of the cosmic ray Moon shadow analysis of the IceCube Neutrino Observatory. The $y$-axis shows the relative deficit in the number of events in on-source and off-source regions as a function of the radial distance $\Psi$ to the Moon. During the five-year observation period, the amplitude $A$ and the angular resolution $\sigma$ of the muon sample remain stable.


Figure 5.2: The amplitude of the Moon shadow (blue data points) varies slightly between $(11 \pm 2) \%$ and $(13 \pm 2) \%$. In a Toy Monte Carlo simulation, an expected Moon shadow was calculated to $12 \%$. Experimental data and simulations are in good agreement. This shows that the IceCube neutrino observatory operates constantly over time. A constant angular resolution is the basis for seeking high energy neutrinos from astrophysical sources.

## Sun shadow

The Sun cannot be used as a calibrator for the IceCube Neutrino Observatory, because the solar magnetic field influences particles near the source surface. This effect has already been observed in [65] from 1996 through 2009 by the Tibet group and in [70] from 2008 through 2012 by the ARGO experiment. Table 5.2 shows the results of IceCube's cosmic ray Sun shadow analysis in one dimension. The angular resolution remains stable with a mean value of $(0.54 \pm 0.07)^{\circ}$, which is similar to the Moon shadow analysis. However, the amplitude of the fitted Gaussian varies during the fiveyear observation period significantly. In Chapter 4, an expectation of $12 \%$ is calculated for the shadowing effect of the Sun. These simulations do not include solar magnetic field effects. The differences between the expected and measured Sun shadow can be quantified with $\chi^{2} /$ ndof $=124.0 / 5=24.8$. This statistical evidence hints that the solar magnetic field could influence cosmic ray particles in the energy range of 40 TeV . Moreover, the statistical uncertainty of the Sun shadow analysis is lower than for the Moon shadow analysis. Due to the fact that the Sun shadow is based on twice as many events than the Moon shadow analysis, the statistical uncertainty decreases. This effect can also be seen in the statistical significance of the shadows, which is higher in the first year (IC79), when the amplitude is not significantly different from the Moon shadow analysis. In the first year (IC79), the shadowing effect can be compared with the Moon shadow analysis. The weakest shadowing effect is seen in IC86-III with an amplitude of $(5 \pm 1) \%$. A comparison of these results and the solar activity, expressed by the number of sun spots, during the five-year observation period can be seen in Chapter 6. Figure 5.4 shows the temporal variation of the Sun shadow during the five-year observation period, represented by the red data points in comparison to the expectation illustrated by the black line.

|  | Year | $\sigma_{\text {gauss }}\left[^{\circ}\right]$ | $\Delta\left(\sigma_{\text {gauss }}\right)\left[^{\circ}\right]$ | A | $\Delta(\mathrm{A})$ | $\mathrm{S}[\sigma]$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Sun | IC79 | 0.53 | 0.05 | 0.11 | 0.01 | $>16 \sigma$ |
|  | IC86-I | 0.49 | 0.06 | 0.08 | 0.01 | $>13 \sigma$ |
|  | 0.57 | 0.05 | 0.09 | 0.01 | $>16 \sigma$ |  |
|  | IC86-III | 0.58 | 0.07 | 0.05 | 0.01 | $>10 \sigma$ |
|  | IC86-IV | 0.57 | 0.07 | 0.06 | 0.01 | $>10 \sigma$ |

Table 5.2: Results of the 1-dimensional analysis, with A as the amplitude and $\sigma$ as the width of the Gaussian. The statistical significance is illustrated by $S$. The amplitude of the fitted Gaussian varies significantly during the five-year observation period.


Sun, IC86-I


Sun, IC86-II



Figure 5.3: Profile view of the cosmic ray Sun shadow analysis of the IceCube Neutrino Observatory. The $y$-axis shows the relative deficit in the number of events in on-source and off-source regions as a function of the radial distance $\Psi$ to the Sun. During the five-year observation period, the amplitude A of the fitted Gaussian varies significantly.


Figure 5.4: During the five-year observation period, the amplitude of the Gaussian that is fitted to IceCube's Sun shadow analysis varies between $(11 \pm 1) \%$ and $(5 \pm 1) \%$. The amplitude is represented by the red data points. An expectation is calculated with $12 \%$ with a Toy Monte Carlo method, which does not include any solar magnetic field effects. The differences between the expectation and IceCube's observed amplitude can be quantified to $\chi^{2} /$ ndof $=124.0 / 5=24.8$.

### 5.5.3 Smaller time binning

A temporal variation of the cosmic ray Sun shadow with the IceCube detector is seen in the binned analysis in one dimension. The Sun reaches a declination of $15^{\circ}$ above the horizon at the South Pole from November through February each season, while each month the Moon rises above this threshold, where the Moon and Sun filters are enabled. To achieve a smaller time binning, each month of the Sun shadow analysis can be calculated separately. However, the Sun shadow of each February cannot be observed due to low statistics. The season of the Moon shadow analysis of each year is divided into three parts. Because of lower statistics in the Moon shadow analysis, the statistical uncertainty is higher. Table 5.3 shows the amplitude of the fitted Gaussian of the Moon and Sun shadow analysis.

| Month | $A_{\text {Sun }}[\%]$ | $\Delta A_{\text {Sun }}[\%]$ | $A_{\text {Moon }}[\%]$ | $\Delta A_{\text {Moon }}[\%]$ |
| :---: | :---: | :---: | :---: | :---: |
| November 2010 | 13.3 | 3.2 | 11.0 | 2.4 |
| December 2010 | 9.2 | 1.4 | 11.6 | 2.7 |
| January 2011 | 15.1 | 2.5 | 13.3 | 3.1 |
| November 2011 | 8.3 | 2.3 | 13.1 | 2.9 |
| December 2011 | 9.1 | 1.6 | 12.3 | 2.7 |
| January 2012 | 6.5 | 1.7 | 11.6 | 2.5 |
| November 2012 | 9.3 | 2.1 | 12.7 | 2.4 |
| December 2012 | 7.1 | 1.1 | 10.4 | 2.5 |
| January 2013 | 9.0 | 1.7 | 11.6 | 2.9 |
| November 2013 | 6.1 | 1.8 | 13.4 | 3.1 |
| December 2013 | 5.8 | 1.3 | 11.3 | 2.5 |
| January 2014 | 5.1 | 1.3 | 13.0 | 3.1 |
| November 2014 | 6.1 | 1.7 | 13.3 | 2.8 |
| December 2014 | 4.9 | 1.2 | 14.0 | 3.1 |
| January 2015 | 6.0 | 1.5 | 12.6 | 2.6 |

Table 5.3: Results of the 1-dimensional analysis for a smaller time binning shown by the amplitude $A$ of the Gaussian. However, the amplitude of the Moon shadow is not only taken during a specific month. The entire year is divided in three parts.

A deficit ratio between the expected shadowing amplitude and the observed depth of the shadows can be seen in Figure 5.5. The expected deficit is shown by the black line at 1.0. The depth of the Moon shadow analysis remains stable. All observed amplitudes vary around the expectation of $12 \%$.

The temporal variation of the Sun shadow is also observed for a smaller time binning. In IC79, the amplitude of the Sun shadow can be compared to the Moon shadow. In IC86 I and II, first variations from the expectation of $12 \%$ are visible. A statistical significant difference is calculated for IC86 III and IV. Chapter 6 compares these results to the number of sunspots during the observation period.


Figure 5.5: Smaller time binning of the Moon and Sun shadow analysis. The amplitude of the Moon shadow analysis remains stable, while significant variations of the Sun shadow are observed. The expectation was calculated to $12 \%$.

### 5.6 2-Dimensional approach

Another approach to study the cosmic ray Moon and Sun shadows is the binned analysis in two spatial dimension. This work presents IceCube's first Moon and Sun shadow analysis in two dimensions, which makes use of a smoothing rebinning radius to illustrate the shadowing effects of Moon and Sun. Similar maps were already used to investigate the anisotropy of cosmic rays in the southern sky by the IceCube collaboration through the use of the IceCube detector and the IceTop array, see for example [45], [46], [47], and [48]. The goal is to draw maps in two dimensions as in [65] and in [70], where Moon and Sun are located in the center of the maps.
The binned analysis in two dimensions is very valuable for the IceCube detector because of the enormous amount of data, which can be calculated with acceptable computation time. This method is also a good estimator for the pointing capabilities of the IceCube detector. However, a more sophisticated unbinned likelihood method is presented in Chapter 7, which studies the actual position of Moon and Sun.

### 5.6.1 Description of the method

The binned analysis in two spatial dimensions compares on-source and off-source regions. These regions are similar to the regions that are used in the binned analysis in one dimension. Due to computational reasons, only two off-source regions with an offset of $\pm 18^{\circ}$ are used in this analysis. The offset must be in right ascension. More events from a higher declination reach the IceCube detector. In each bin of a map, the number of events is compared to the average number of events in the two off-source regions.

A map with relative declination on the $x$-axis and relative right ascension on the $y$-axis computes the deficit in the muon flux in each bin. Both celestial bodies are located in the center of these maps. Further, maps showing the statistical significance are used to illustrate the shadowing effects of Moon and Sun. The statistical significance is calculated by Li and Ma, see [107] for references

$$
\begin{equation*}
N_{S}=N_{\mathrm{on}}-\alpha N_{\mathrm{off}} . \tag{5.6.1}
\end{equation*}
$$

The ratio of on-source and off-source regions is defined by $\alpha=0.5$.

Li and $\mathrm{Ma}[107]$ thus calculate the statistical significance as

$$
\begin{equation*}
S=\sqrt{2\left\{N_{\mathrm{on}} \cdot \ln \left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\mathrm{on}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right]+N_{\mathrm{off}} \cdot \ln \left[(1+\alpha)\left(\frac{N_{\mathrm{off}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right]\right\}} . \tag{5.6.2}
\end{equation*}
$$

Using the relative deficit and equation (5.6.2) lead to maps in two spatial dimensions. A smoothing method takes the average of all events in a certain radius. A smoothing method was already used by the IceCube collaboration to illustrate the anisotropy of cosmic rays. The optimal rebinning radius will be discussed in the upcoming section.

### 5.6.2 Optimal bin radius

This section describes the method to optimize the rebinning radius of the binned analysis in two dimensions. In Chapter 4, the quality cuts are optimized for the best significance of the shadowing effects of Moon and Sun. The rebinning radius is thus optimized for the highest statistical significance.
Figure 5.6 shows significance maps for various rebinning radii from $0.25^{\circ}$ to $1.00^{\circ}$. The best average significance in an area of the size of Moon and Sun is achieved for a rebinning radius of $0.80^{\circ}$. However, this radius is greater than the estimated PSF of the IceCube detector and the sources Moon and Sun. The relative deficit maps are thus presented with two different rebinning radii of $0.35^{\circ}$ and $0.80^{\circ}$. The smaller rebinning radius represents a good agreement between high statistical significance and the size radius of Moon and $\operatorname{Sun}\left(R_{M / S} \approx 0.26^{\circ}\right)$.
The maps showing the statistical significance are rebinned with a smoothing radius of $0.80^{\circ}$. The angular resolution of the IceCube detector was calculated with approximately $0.5^{\circ}$. In [108], the optimal bin radius is described by

$$
\begin{equation*}
r_{\text {opt }}=\left(1.58+0.7 e^{-0.88 N^{0.36}}\right) \cdot \sigma . \tag{5.6.3}
\end{equation*}
$$

Here, N describes the number of background events and $\sigma$ the angular uncertainty. For an enormous amount of muon events, such as in IceCube's Moon and Sun shadow analyses, the optimal bin radius is $r_{\text {opt }}=1.58 \cdot \sigma$, which is $r_{\text {opt }}=0.8^{\circ}$ for the Moon and Sun shadow analysis.


Figure 5.6: Sun shadow maps for various rebinning radii between $0.25^{\circ}$ and $1.00^{\circ}$. The best significance is achieved for a rebinning radius of $0.80^{\circ}$ with an average significance of $11.9 \sigma$ in the region of the Sun. Data are taken when IceCube operated in its IC79 configuration.

### 5.6.3 Results

## Moon

Figure 5.7 shows maps with the relative deficit in each bin of the Moon shadow analysis in two spatial dimensions. Each map represents one year of the five-year observation period. The black circle in the center of the maps illustrates the angular size of the Moon. The Moon's shadow remains stable during the entire observation period with a deficit of $\approx 12 \%$ in each bin at the position of the Moon. The background is almost flat. However, fluctuations occur in the background. Figure 5.8 presents the same maps with a rebinning radius of $0.80^{\circ}$. Also these maps show that the shadowing effect remains stable. The fluctuations of the background are smoothed due to the greater rebinning radius.
By counting all muon events in the center of the on-source region with a radius of $0.26^{\circ}$ and all events in the center of the two off-source regions, the relative deficit is calculated for the binned analysis in two spatial dimensions. In Table 5.4, the relative deficit is shown for each season.

| Year | on-source region [\#] | off-source region [\#] | rel. deficit [\%] |
| :---: | :---: | :---: | :---: |
| IC79 | $3737 \pm 61$ | $4186 \pm 64$ | $10.7 \pm 1.7$ |
| IC86-I | $3011 \pm 54$ | $3513 \pm 59$ | $14.2 \pm 1.8$ |
| IC86-II | $3160 \pm 56$ | $3542 \pm 60$ | $10.8 \pm 1.8$ |
| IC86-III | $2274 \pm 47$ | $2564 \pm 51$ | $11.3 \pm 2.0$ |
| IC86-IV | $1664 \pm 40$ | $1938 \pm 44$ | $14.1 \pm 2.3$ |

Table 5.4: The results of the 2-dimensional analysis confirm that the relative deficit of the Moon shadow remains stable during the five-year observation time. The relative deficit is calculated by a comparison of the muon events in the center of the on-source region and the number of events in the center of two off-source regions.

These results confirm the stable relative deficit over time of the Moon shadow analysis. Slight uncertainties are observed during the five-year observation time within the statistical fluctuations. The decreasing number of events in the on-source and off-source regions from IC79 through IC84 IV can be explained by the maximum elevation of the Moon, which decreases from $23^{\circ}$ in IC79 to $18^{\circ}$ in IC86 IV.


Figure 5.7: Maps of the binned analysis of the Moon shadow in two dimensions. The expected position of the Moon is located in the middle of the [ $6^{\circ} \times 6^{\circ}$ ] plot. The black circle shows the actual size of the Moon. A smoothing radius has a size of $0.35^{\circ}$. Each map shows the cosmic ray Moon shadow for a season from 2010 through 2015. The contour represents the relative deficit of events in each bin. The shadowing effect remains stable for the entire observation period, which is expected for a correctly operating detector.


Figure 5.8: Results for the binned analysis of the Moon shadow analysis in two dimensions with a rebinning radius of $0.80^{\circ}$. The shadowing effect remains stable, fluctuations in the background are smoothed due to the greater rebinning radius.

Maps representing the statistical significance of the shadowing effect of the Moon are presented in Figure 5.10. The reconstructed position of the Moon is shown by the black circle in the center of the maps, which shows a good pointing of the IceCube detector. It is required to test the background of the significance maps. Otherwise, the significance could be overestimated by the method itself. The calculated significance values of the background are thus filled in a histogram, see Figure 5.9.
A normal distribution fits to the histogram with a width of $\sigma_{f i t}=1.07 \pm 0.06$ and a mean value of $\bar{x}_{f i t}=0.02 \pm 0.01$. The median value of significances of the background is $\bar{x}_{\sigma}=0.02 \sigma$, with $68 \%$ between $-0.99 \sigma$ and $1.01 \sigma$, and $95 \%$ between $-2.00 \sigma$ and $2.04 \sigma$. This shows that the background is normally distributed and the significances are not overestimated. The Gaussian is illustrated by the red line and the significance values of the background are represented by the blue line.


Figure 5.9: The significance values (blue line) of the background on the $x$-axis follow a normal distribution (red function).

In a radius of $0.26^{\circ}$ in the center of maps, the average significance is $(8.9 \pm 0.1) \sigma$. During the entire observation period, the seasonal significance remains in the statistical uncertainty.


Figure 5.10: Maps showing the statistical significance of the shadowing effect of the Moon. The rebinning radius is optimized to be $0.80^{\circ}$. The significances of the background follow a normal distribution. During the five-year observation period the significance maps remain stable.

## Sun

A temporal variation of the cosmic ray Sun shadow is seen in the profile view analysis. The goal of the binned analysis in two spatial dimensions is to confirm this trend. Figures 5.11 and 5.12 show maps for various rebinning radii with the relative deficit in each bin of the Sun shadow analysis in two dimensions. In the first season of the five-year observation period, the shadowing effect of the Sun is similar to the Moon. The second year already shows differences to the Moon shadow analysis. In the fourth and fifth year, the shadowing effect is still visible but weaker than the Moon shadow. These results confirm the binned analysis in one dimension, which also sees a variation over time. Table 5.5 illustrates the number of muon events in a radius of $0.5^{\circ}$ at the expected position of the Sun.
In IC79 and IC86 II, the relative deficit between the on-source and off-source regions can be compared to the Moon shadow analysis. However, significant deviations are seen for IC86 III and IV, which confirm the results of the binned analysis in one dimension. The number of events in the off-source regions is constant from IC86 I through IC86 IV, which shows the stability of the IceCube detector. In IC79, the detector operated with a smaller detector volume. Fewer events are thus detected.

| Year | on-source region [\#] | off-source region [\#] | rel. deficit [\%] |
| :---: | :---: | :---: | :---: |
| IC79 | $5326 \pm 73$ | $5958 \pm 77$ | $10.6 \pm 1.2$ |
| IC86-I | $7747 \pm 88$ | $8425 \pm 92$ | $8.0 \pm 1.1$ |
| IC86-II | $7593 \pm 87$ | $8467 \pm 92$ | $10.3 \pm 1.1$ |
| IC86-III | $8099 \pm 90$ | $8563 \pm 93$ | $5.4 \pm 1.1$ |
| IC86-IV | $7956 \pm 89$ | $8493 \pm 92$ | $6.3 \pm 1.1$ |

Table 5.5: The results of the 2-dimensional analysis confirm the temporal variation of the cosmic ray Sun shadow during the five-year observation period. With values between $(10.6 \pm 1.2) \%$ and $(5.4 \pm 1.1) \%$ the relative deficit varies significantly.


Figure 5.11: Maps of the binned analysis of the Sun shadow in two dimensions. The expected position of the Sun is located in the middle of the [ $6^{\circ} \times 6^{\circ}$ ] plot. The black circle shows the actual size of the Sun. A smoothing radius has a size of $0.35^{\circ}$. Each map shows the cosmic ray Moon shadow for a season from 2010 through 2015. The contour represents the relative deficit of events in each bin. The shadowing effect varies during the five-year observation period.


Figure 5.12: For a rebinning radius of $0.80^{\circ}$, the shadowing effect of the Sun varies as well. The background is smoothed due to the larger rebinning radius. These result confirm the trend of binned analysis in one dimension.

The statistical significance of the shadowing effect of the Sun is shown in Figure 5.14 with a rebinning radius of $0.80^{\circ}$. The reconstructed position of the Sun is in the center of the maps. However, in IC86 IV a slight deviation from the center of the map is visible. Further studies with an unbinned analysis are required to investigate the shift at this point.
Similar to the Moon shadow analysis, the background must be investigated. Figure 5.13 illustrates the fact that the significance values of the background follow a normal distribution. The Gaussian is fitted with a mean value of $\bar{x}_{f i t}=0.04 \pm 0.01$ and a width of $\sigma_{f i t}=1.05 \pm 0.04$. The median of the histogram is $\bar{x}_{\sigma}=0.05 \sigma$, with $68 \%$ between $-1.15 \sigma$ and $1.04 \sigma$, and $95 \%$ between $-2.03 \sigma$ and $2.08 \sigma$. This shows that the significance of the shadowing effect is not overestimated.


Figure 5.13: The significance values (blue line) of the background on the $x$-axis follow a normal distribution (red function).

The temporal variation is also investigated in the significance maps. The average significances in a radius of $0.26^{\circ}$ in the center of the maps are: IC79 (11.7 $\left.\pm 0.1\right) \sigma$, IC86 I $(9.5 \pm 0.1) \sigma$, IC86 II $(11.4 \pm 0.1) \sigma$, IC86 III $(7.5 \pm 0.1) \sigma$, and IC86 IV $(8.0 \pm 0.1) \sigma$.


Figure 5.14: The significance maps show the shadowing effect of the Sun with high statistical significance. The rebinning radius is optimized to $0.80^{\circ}$. A temporal variation of the Sun shadow is also observed.

### 5.7 Conclusion

The goal of the binned analysis is to investigate the cosmic ray Moon and Sun shadows of the IceCube Neutrino Observatory. In the binned analysis in one dimension, the main goal is to measure the angular resolution and the depth of the shadows. The binned analysis in two dimensions makes the shadows visible and is a good estimator for the pointing accuracy of the detector. Both, Moon and Sun are observed with high statistical significance $(>10 \sigma)$. The angular resolution is calculated between $(0.43 \pm 0.05)^{\circ}$ and $(0.49 \pm 0.05)^{\circ}$ in the Moon shadow analysis. Additionally, the amplitude of the Gaussian remains stable between $(11 \pm 2) \%$ and $(13 \pm 2) \%$. A smaller time binning shows similar results. Further, the binned analysis in two spatial dimensions confirms that the Moon shadow remains constant during the five-year observation period from 2010 through 2015.

A seasonal change of the Sun shadow for energies of 5 TeV and 10 TeV was observed by [65] and [70]. IceCube also sees a statistical significant temporal variation of the cosmic ray Sun shadow with a median energy of 40 TeV of primary cosmic ray particles. Both the binned analyses in one and two dimensions confirm the significant variation over time. The amplitude of the Gaussian in the one-dimensional analysis is measured between $(11 \pm 1) \%$ and $(5 \pm 1) \%$, which yields a deviation of $\chi^{2} /$ ndof $=124.0 / 5=24.8$ from the uninfluenced depth of $12 \%$. Chapter 6 compares these results to the solar activity using the number of sun spots. x

## Chapter 6

## Solar physics and IceCube's Sun shadow results

In Chapter 2, the temporal variation of the Sun shadow of the Tibet-As Gamma experiment was shown from 1996 through 2013. Further, the Tibet collaboration investigated the influence of cosmic rays of various solar magnetic field models [65]. In Chapter 5 a statistical influence of the Sun shadow was observed with the IceCube Neutrino Observatory. This Chapter compares the solar activity to the results of the binned analysis in one dimension.

### 6.1 IceCube's Sun shadow results

In Chapter 5, the shadowing effect of the Sun was observed with two binned analyses in one and two dimensions. A significant change over time was observed during the fiveyear period. The statistical differences between the results of the one-dimensional analysis and a Toy Monte Carlo expected deficit is calculated to $\chi^{2} /$ ndof $=124.0 / 5=24.8$, which hints that comic ray particles are influenced by the solar magnetic field. In [65], a significant influence was observed at lower energies. This section compares the results of the Sun shadow analysis to the solar activity.
IceCube's Sun shadow analysis is based upon data taken between November and February of each season. Thus, the results can be compared with the solar activity at the same time, which is represented by the number of sunspots. This monthly average number of sunspots is measured by [71]. In December 2010, a minimum of $24.5 \pm 3.6$ and a maximum of $146.1 \pm 10.7$ sunspots in February 2014 were seen by [71].

Figure 6.1 shows the monthly average number of sun spots from 1995 through 2016, observed by [71]. The red bands illustrate the five observation periods, where the Sun is above the $15^{\circ}$ horizon at the South Pole. If the Sun reaches this threshold, the Sun filter is enabled and muon events from the direction of the Sun are detected by IceCube. During each observation period, the number of sunspots vary significantly. Tibet's 14 -year observation period of the Sun is illustrated by the green band from 1995 through 2009. Comparing the solar cycle from 1996 through 2007 to the current solar cycle, one can see that the current cycle is much weaker. Additionally, the Tibet AS-Gamma experiment measures cosmic rays from the direction of the Sun during the entire year, while IceCube's observation period is limited from November through February each season.
IceCube's Sun filter was implemented in 2010 for the first time. An extension of the observation period to previous detector configurations is therefore not possible. During the upcoming years 2017 and 2018, the number of sunspots is expected to decrease.


Figure 6.1: Almost two solar cycles are observed from 1995 through 2016, illustrated by the monthly average number of sun spots on the $y$-axis. The green band shows the 14 -year observation period of the Tibet As Gamma experiment from 1995 through 2009. IceCube's Sun filter is enabled from November through February each season, represented by the red bands. The current cycle is much weaker than the cycle when the Tibet As Gamma experiment studied the cosmic ray Sun shadow. Data taken from [71].

Figure 6.2 compares the number of sunspots and the amplitude of the Sun shadow analysis in one dimension. The $x$-axis shows the monthly average number of sunspots, observed by [71], the $y$-axis the amplitude of the Gaussian fitted to IceCube's Sun shadow analysis. Fitting a line to this comparison leads to

$$
\begin{equation*}
f(x)=-(0.064 \pm 0.021) \cdot x+(13.29 \pm 1.51) \tag{6.1.1}
\end{equation*}
$$

Here, $x$ represents the monthly average number of sunspots. A Spearman's rank correlation coefficient [109] of -0.89 shows that a correlation is likely with $96.3 \%$. However, further observation periods are necessary to prove this correlation. The expected Sun shadow, which is calculated in Chapter 4 with a Toy Monte Carlo method, is illustrated by the blue line. The fitted function reaches an amplitude of ( $13.3 \pm 1.5$ ) \% for zero sunspots, which is in good agreement with the simulated amplitude of $12 \%$. The deviations are within the statistical uncertainty.
Equation (6.1.1) can be used to calculate a prediction for the season from November 2015 through February 2016, where $58.4 \pm 9.3$ sunspots were observed. Thus, the amplitude of the Gaussian of the binned analysis in one dimension is predicted to $A=(9.6 \pm 2.3) \%$.
A smaller time binning, which is investigated in Chapter 5, is compared to the monthly number of sunspots in Figure 6.3. Due to fewer muon events in a smaller time binning, the statistical uncertainty of the amplitude increases. A fit through the small time binned data is thus overestimated.

Figure 6.4 shows three different plots. In a.) each blue data point represents the monthly average number of sunspots. The red band illustrates the average of sunspots for November and February of each season. The second plot b.) shows the amplitude of the Gaussian that was fitted to IceCube's one-dimensional analysis. The variation over time shows a significant difference to the Toy Monte Carlo analysis, which is quantified to $\chi^{2} /$ ndof $=124.0 / 5=24.8$. Plot c.) shows that the IceCube detector operates in a stable manner over time. Here, the amplitude of the Gaussian, which is fitted to IceCube's Moon shadow analysis, is illustrated by blue data points matches the expected amplitude of $12 \%$ (red line).


Figure 6.2: Comparing the monthly average number of sunspots with IceCube's Sun shadow analysis. A rank correlation test shows that a correlation is likely at this point. Sunspot data was taken from [71]


Figure 6.3: Comparing the monthly average number of sunspots with IceCube's Sun shadow analysis for a smaller time binning. Sunspot data was taken from [71]


Figure 6.4: Comparing solar activity to IceCube's cosmic ray Moon and Sun shadow analyses. a.) Monthly mean number of Sun Spots in November, December, January, and February of each year. The red line shows the weighted number of Sun Spots. b.) Amplitude of the fitted Gaussian in the 1-dimensional analysis for the Sun shadow. The blue line shows the expected shadowing effect. c.) Amplitude of the fitted Gaussian in the 1-dimensional analysis for the Moon shadow. The red line shows the expected shadowing effect. Sunspot data was taken from [71]

## Chapter 7

## Unbinned analysis of the Moon and Sun shadows

This chapter describes the likelihood approach of the Moon and Sun shadow analysis of the IceCube Neutrino Observatory. An unbinned likelihood approach is a standard method in point-like searches for high-energy neutrinos in IceCube [110]. The pointing capabilities of the IceCube neutrino detector and the exact reconstruction of the positions of Moon and Sun are the goals of this analysis, which makes use of the most likely position of Moon and Sun. Normally CPUs are used to calculate the likelihood functions. However, this chapter compares results of a graphics processing units (GPU) code, as well. These GPUs are designed to compute images for a display output.

### 7.1 Description of the method

The main goal of the IceCube Neutrino Observatory is to search for high-energy neutrinos and their point-like sources in the sky. In IceCube's neutrino analyses, a common likelihood method is used [110]. This unbinned approach can also be used to study the shadowing effects of Moon and Sun. For the detector configurations with 40 (IC40) and 59 (IC59) strings, this method was implemented for the first time; see [64], [111] and [112] for references. The main goal of this approach is to search for the most likely position of Moon and Sun and the number of shadowed events. Such as the binned analysis in two spatial dimensions, the unbinned likelihood analysis compares on-source and off-source regions.

The on-source region is a window with a size of $[8 \times 8]^{\circ}$ around the expected position of Moon and Sun. The analysis makes use of the relative distance between the muon event in right ascension $(\Delta \alpha)$ and declination $(\Delta \delta)$ :

$$
\begin{align*}
& |\Delta \delta|=\left|\delta_{\mu}-\delta_{\mathrm{sun}}\right| \leq 8^{\circ}  \tag{7.1.1}\\
& |\Delta \alpha|=\left|\alpha_{\mu}-\alpha_{\mathrm{sun}}\right| \leq 8^{\circ} \tag{7.1.2}
\end{align*}
$$



Figure 7.1: Figures show data from an on-source region of the IceCube detector operating with 79 strings between May 2010 and May 2011. The onsource region is a window with a size of $[8 \times 8]^{\circ}$ around the position of Moon and Sun. Figures taken from [104]

Figure 7.1 shows an example Run ( 8 hours of data) used as an on-source region region. In a.) events in relative right ascension ( $\Delta \alpha$ ) are illustrated, in b.) events in declination $(\Delta \delta)$. The celestial body is located at $0^{\circ}$. Data and figures are taken from [104], when IceCube operated in its IC79 string configuration. As a reconstruction fit, the SPE fit was chosen.

The off-source regions are windows with an offset in right ascension. These regions thus represent a location in the sky with no shadowing effect of Moon and Sun. With an offset of $\pm 18^{\circ}$, these regions are defined as

$$
\begin{align*}
& |\Delta \delta|=\left|\delta_{\mu}-\delta_{\text {Moon/Sun }}\right| \leq 8^{\circ}  \tag{7.1.3}\\
& |\Delta \alpha|=\left|\alpha_{\mu}-\alpha_{\text {Moon/Sun }}+\alpha_{\text {off }}\right| \leq 8^{\circ} \tag{7.1.4}
\end{align*}
$$

Figure 7.2 represents the off-source regions with an offset in right ascension to the expected position of Moon and Sun. The relative right ascension can be seen in a.), the relative declination in b.).

The log-likelihood function is a combination of signal $S$ and background $B$, which yields [64]

$$
\begin{equation*}
\log L\left(n_{s}, \overrightarrow{x_{s}}\right)=\sum_{i=1}^{N} \log \left[\frac{n_{s}}{N} S\left(\overrightarrow{x_{i}}, \sigma_{i} ; \overrightarrow{x_{s}}\right)+\left(1-\frac{n_{s}}{N}\right) B\left(\overrightarrow{x_{i}}\right)\right] \tag{7.1.5}
\end{equation*}
$$

The likelihood function $L$ depends upon the ratio of shadowed events $n_{S}$ and the total number of events used in the unbinned analysis $N$. The signal function depends on the position of Moon and Sun $\left(x_{s}\right)$, the reconstructed direction of each event $\left(x_{i}\right)$, and the reconstruction uncertainty of each muon event $\left(\sigma_{i}\right)$. The uncertainty of the reconstructed event is provided by the "Paraboloid" package of the MPE fit. Therefore, only Level3 can be used for this analysis. The signal function is defined as a Gaussian, see [64] for references

$$
\begin{equation*}
S\left(\overrightarrow{x_{i}}, \sigma_{i} ; \overrightarrow{x_{s}}\right)=\frac{1}{2 \pi \sigma_{i}^{2}} \cdot \exp \left[-\frac{\left|\overrightarrow{x_{i}}-\overrightarrow{x_{s}}\right|^{2}}{2 \sigma_{i}^{2}}\right] \tag{7.1.6}
\end{equation*}
$$



Figure 7.2: Figures show off-source regions with an offset in right ascension. Data is taken from IceCube's IC79 configuration. This data can be compared with the on-source region. Figures taken from [104].

Using CPU units, the log-likelihood function is calculated for a grid with 1089 points around the expected position of Moon and Sun. Taking the most likely number of shadowed events, which is the minimum of the negative log-likelihood function, will yields the shadowing effects of Moon and Sun. Each function is computed on a single CPU for approximately one hour. The grid is defined by

$$
\begin{align*}
& x_{i}=-4^{\circ}+i \cdot 0.1^{\circ}  \tag{7.1.7}\\
& y_{j}=-4^{\circ}+j \cdot 0.1^{\circ} . \tag{7.1.8}
\end{align*}
$$

The variables $i$ and $j$ define the length and the width of the grid. However, one single GPU is able to calculate 16384 functions at the same time. Figure 7.3 shows the grid for a CPU.


Figure 7.3: Grid points around the expected position of the Sun, which is represented by the black square with point $[16,16], \overrightarrow{x_{S}}=(0,0)$. Figure taken from [64].

Both the CPU and the GPU code minimize the negative log-likelihood function. The CPU algorithm computes the negative log-likelihood function for different $n_{s}$ in steps of $50 n_{s}$ between $-10000 n_{s}$ and $4000 n_{s}$. Figure 7.4 shows the negative log-likelihood function for the grid point, which is located in the center of the map.

IC79, SPEFit, Gridpoint [16:16]


Figure 7.4: Calculated negative log likelihood function for different number of shadowed events $n_{s}$. The minimum illustrates the most likely number of shadowed events in the center of the grid. Figure shows data taken from IceCube's IC79 string configuration and the SPE reconstruction fit. Figure taken from [104].

### 7.1.1 Previous results

When IceCube operated in its IC40 and IC59 configuration from May 2008 through May 2010, the unnbinned approach was used for the first time to study the cosmic ray Moon shadow. Figure 7.5 shows the results of the unbinned analysis of the IC40 (left) and IC59 (right) configurations. Due to the fact that IceCube operated during 2008 with a smaller detector volume with 40 strings, the shadowing effect of the Moon was measured weaker than in 2009 with $5320 \pm 520$ compared to $8700 \pm 550$ shadowed events, see [64] for references.
A further goal of the unbinned analysis is to study the pointing accuracy of the IceCube detector. Figure 7.6 thus shows a map with a higher resolution around the expected position of the Moon. The white circle illustrates the exact position of the Moon. This position is shifted in right ascension, because a deflection by the geomagnetic field is expected. The black dot shows the most likely position of the Moon. For the IC59 configuration, the expected and most likely position match.



Figure 7.5: Unbinned analyses of the IC40 (left) and IC59(right) configurations. Due to the smaller detector volume in IC40, the number of shadowed events is smaller than in IC59. Figure taken from [64]


Figure 7.6: The exact position of the Moon shadow is important to verify the pointing accuracy of the IceCube detector. The white circle illustrates the expected position of the Moon. A deflection in right ascension is caused by the geomagnetic field. In IC59, the expected and most likely position of the Moon matches. Figure taken from [64]

A first unbinned analysis on the cosmic ray Sun shadow was performed in a previous work to this thesis, see [104]. The Sun was never used as a calibrator of the IceCube detector before. However, it is expected that the solar magnetic field influences cosmic ray particles near the Sun's surface. Because of a solar minimum in 2010, the Sun shadow analysis can still be compared to the Moon shadow analysis in [64].
Figure 7.7 shows the unbinned analysis of the cosmic ray Sun shadow when IceCube operated with 79 strings. To reconstruct the muon events, the SPE fit was used. The expected position of the Sun is located in the center of the two-dimensional map. The $x$-axis illustrates the relative right ascension, the $y$-axis the relative declination. Additionally, on both axes, the grid points are shown. Grid point $[16,16]$ is the most likely position of the Sun with $6181 \pm 262$ shadowed events. The expected deficit is calculated to $7028 \pm 84$ [104]. The differences between the observed and expected deficit are comparable to the results in the IC40 and IC59 analysis, see [64].
Comparing the resolution of the unbinned analysis, one can see that in IC40 and IC59, more grid points are calculated than in the IC79 analysis. This effect is due to a smoothing method, which is included in the plotting program Root [113].
Figure 7.8 presents the exact position of the Sun shadow analysis. Therefore, a map with a smaller scale around the Sun is necessary. The expected position of the Sun, which is illustrated by the white circle, is equal to the position of the Moon in the IC40 and IC59 analysis. The solar magnetic field near the Sun's surface is not included in the simulations. The most likely position of the Sun, shown by the black circle, and the simulated position are within the one sigma environment. Due to the fact that cosmic rays are deflected by the geomagnetic field, a shift of the central position of the Sun shadow is expected in right ascension. A deflection in declination is not expected; see [64] for a detailed description.

## IC79, SPEFit Likelihood Analysis



Figure 7.7: The unbinned likelihood approach shows the cosmic ray Sun shadow with the SPE reconstruction fit. The $x$-axis shows the relative right ascension and the $y$-axis represents the relative declination. The negative log-likelihood function is minimized for each of the 1089 grid points.

The expected position of the Sun and the most likely position match, which is calculated to $6181 \pm 262$ shadowed events. Figure taken from [104]


Figure 7.8: Another goal of the unbinned likelihood method is to calculate the exact position of the Sun. Thus, a smaller scale around the expected position of the Sun is chosen for $-0.4^{\circ}$ to $0.4^{\circ}$ in right ascension and declination. Due to deflection effects of the geomagnetic field, the expected position is shifted in right ascension. The expected position of the Sun is illustrated by a white circle. The black circle shows the most likely position of the Sun in a smaller scale. The expected and most likely position match within the one sigma environment.

### 7.2 Graphic Processing Units (GPU)

Graphic Processing Units (GPUs) can be used instead of CPUs to minimize the negative log likelihood function. GPUs were originally designed to process pixels for computer displays and video games [114]. However, NVIDIA implemented a programming language (CUDA) to use GPUs as processing units for parallel programming. An unbinned analysis takes 1000 CPU hours of computing time. Here, the advantage of the GPUs is clearly visible. Only one GPU hour of computing time is required to calculate a grid with $128 \times 128$ grid points.

### 7.3 Results

The results of the unbinned analysis of the cosmic ray Moon shadow are presented in Figure 7.9. The maps are identical known from the binned analysis in Chapter 5. However, the $z$-axis shows the number of shadowed events $n_{s}$. Maps presenting the significance of the shadows can be found in the appendix A.16.
It is obvious that the background in the number of shadowed event is underestimated, which could be an effect of the MPE reconstruction fit. Due to the overestimation of the sigma $\sigma$ of the paraboloid package, pull corrections are necessary. Further studies of these effects are required to present a stable Moon shadow analysis with the likelihood approach.
On the other hand, the advantage of the GPU method is clearly visible. Comparing Figure 7.7 and Figure 7.9 makes obvious the difference in the resolution.


Figure 7.9: Results of the unbinned analysis of the Moon shadows with the likelihood approach. The black circle illustrates the size and the position of the Moon. These maps are similar to the binned analysis in Chapter 5 with the number of shadowed events on the $z$-axis.

## Chapter 8

## Conclusion and Outlook

The goal of this thesis is to investigate the cosmic ray Moon and Sun shadows with the IceCube Neutrino Observatory and to confirm a variation of the Sun shadow over time at a median energy of 40 TeV primary cosmic ray energy during a five year observation period form 2010 through 2015. Further, the Moon shadow analysis is used to verify and calibrate the IceCube detector.

### 8.1 Conclusion

In Chapter 1 an overview of this thesis, an introduction of cosmic rays, the energy spectrum of cosmic rays, and air showers is given.
The working principle of neutrino and cosmic ray detectors is described in Chapter 2. Moreover, an introduction to Moon and Sun shadow analyses and the temporal variation of the Tibet As-Gamma experiment is described.
The atmospheric lepton flux is calculated with a modified version of CORSIKA in an energy range of 1 and 1000 GeV lepton energy in Chapter 3. Simulations and data taken from various experiments match within the statistical uncertainties.

The Moon and Sun shadow analyses are based upon five years of the IceCube Neutrino Observatory from 2010 through 2015. Simulation studies are required to verify IceCube. In Chapter 4 simulation studies are used to compare various distributions to experimental data from the IceCube detector. Further, quality cuts, which exclude mis-reconstructed from the analyses, are calculated with simulations ( $\sigma<0.71^{\circ}$, Rlogl $<8.1$ ). A Toy Monte Carlo method is used to compute a prediction for the shadowing
effects of the Moon and Sun with $12 \%$ for the binned analysis in one dimension. The prediction is calculated without deflection of the solar magnetic field.

Two binned analyses are used to compute the shadowing effects of Moon and Sun in Chapter 5. The first analysis, a binned in one dimension, shows Moon and Sun in a profile view. The Moon shadow remains stable during the five year observation period, which is seen by the amplitude and the angular resolution, where the amplitude fluctuates between $(11 \pm 2) \%$ and $(13 \pm 2) \%$ and the angular resolution between $(0.43 \pm 0.05)^{\circ}$ and $(0.49 \pm 0.05)^{\circ}$ within the statistical uncertainties.
The width of the Gaussian in the Sun shadow analysis also remains with the statistical uncertainties between $(0.49 \pm 0.06)^{\circ}$ and $(0.58 \pm 0.07)^{\circ}$. However, the amplitude the Gaussian fluctuates significantly between $(11 \pm 1) \%$ and $(5 \pm 1) \%$. The deviation from the uninfluenced expectation of $12 \%$ is calculated significantly to $\chi^{2} /$ ndof $=124.0 / 5=$ 24.8. Maps, showing the relative deficit and the statistical significance, are presented in Chapter 5. A binned analysis in two spatial dimensions shows a stable Moon shadow and fluctuations of the Sun shadow during the five year observation period.
Thus, a temporal variation of the cosmic ray Sun shadow at a median energy of 40 TeV and a confirmation of the Sun shadow, measured by the Tibet As-Gamma experiment, is observed with two binned analyses for the IceCube Neutrino Observatory.

In Chapter 6, the sunspot number during the five year observation period is compared to IceCube's cosmic ray Sun shadow, observed with a binned analysis in one dimension. A Spearman's rank correlation test shows that a correlation between the sunspot number and the amplitude of the Gaussian is likely with $96.3 \%$. Further observation periods are necessary to quantify this correlation with higher statistics. Moreover, a prediction of the amplitude of the Gaussian is calculated to ( $9.8 \pm 2.34$ ) \% for the observation period from November 2015 through February 2016.
A likelihood approach, in Chapter 7, is used to investigate the pointing of the IceCube detector. Due to the fact that the MPE reconstruction fit underestimates the angular resolution of the IceCube detector, a correction is required. However, after these corrections, the background of the resulting maps is underestimated. Additionally, a GPU code is used to calculate the unbinned analysis with higher resolution.

Summarizing, in this doctoral thesis a temporal variation of the cosmic ray Sun shadow is presented significantly. This opens the window for studies of the solar magnetic field close the the Sun's surface with the IceCube Neutrino Observatory.

### 8.2 Outlook

In this thesis a five year observation period from 2010 through 2015 is used to investigate the Moon and Sun shadows. In a future work, further observations will be able to quantify a correlation between the sunspot number and the Gaussian of the binned analysis in one dimension with high statistical significance.

Simulation studies of cosmic ray particles through the solar magnetic field close to the Sun's surface can be investigated and help in the understanding of cosmic ray propagation. Additionally, the shadowing effects of the Moon and the Sun can be measured for different energies with IceCube, which can provide valuable informations about the solar magnetic field.

Further, analyses that investigate the shapes of the Moon and the Sun shadows can be used to study the solar magnetic field.

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## Appendix A

## Appendix

## A. 1 Simulation Studies with CORSIKA in IceCube

## A.1.1 Zenith Distributions



Figure A.1: Zenith distribution of the Moon/Sun filters at an elevation of $20^{\circ}$.


Figure A.2: Zenith distribution of the Moon/Sun filters at an elevation of $18^{\circ}$.


Figure A.3: Zenith distribution of the Moon/Sun filters at an elevation of $15^{\circ}$.

## A.1.2 RLogL Distributions



Figure A.4: RlogL distribution of the Moon/Sun filters at an elevation of $20^{\circ}$.


Figure A.5: RlogL distribution of the Moon/Sun filters at an elevation of $18^{\circ}$.


Figure A.6: RlogL distribution of the Moon/Sun filters at an elevation of $15^{\circ}$.

## A.1.3 NChannel Distributions



Figure A.7: NChannel distribution of the Moon/Sun filters at an elevation of $20^{\circ}$.


Figure A.8: NChannel distribution of the Moon/Sun filters at an elevation of $18^{\circ}$.


Figure A.9: NChannel distribution of the Moon/Sun filters at an elevation of $15^{\circ}$.

## A.1.4 Azimuth Distributions



Figure A.10: Azimuth distribution of the Moon/Sun filters at an elevation of $20^{\circ}$.

Azimuth, Elevation 18


Figure A.11: Azimuth distribution of the Moon/Sun filters at an elevation of $18^{\circ}$.

Azimuth, Elevation 15


Figure A.12: Azimuth distribution of the Moon/Sun filters at an elevation of $15^{\circ}$.

## A.1.5 Point Spread Functions



Figure A.13: Point Spread Function of the Moon/Sun filters at an elevation of $20^{\circ}$.


Figure A.14: Point Spread Function of the Moon/Sun filters at an elevation of $18^{\circ}$.


Figure A.15: Point Spread Function of the Moon/Sun filters at an elevation of $15^{\circ}$.


Figure A.16: Unbinned analysis showing the statistical significance of the Moon shadows in four seasons.

