Online Selection of Downgoing Starting Low Energy Neutrino Events in IceCube

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Abstract

Most of the background for downgoing neutrino-induced events in the IceCube detector is given by atmospheric muons. The filtering of downgoing starting events reduces this background by three orders of magnitude and enables the selection of signal events from the southern hemisphere. This is done with the arrangement of vetos and cuts with regard to the geometry of the detector. The IceCube experiment is built up in stages year by year since 2005. With the implementation of new strings the detector changes its geometry. Cuts and vetos have to be adjusted to the detector geometry.

The filtered data is sent by satellite and has to be checked for technical and physical accuracy. The performance of the filter in the 2008 season for IceCube in its 40-string configuration shows no deviation between measured data and the simulated background. The filter conditions are violated in a few cases, due to the use of different software versions.

Miscellaneous configurations of vetos for the filter for IceCube in its 59-string configuration are simulated and studied with respect to the data size and the signal passing rate. The performance of the filter is checked with the first measured data from April 2009. There is a higher filter rate observed than expected by the simulation. In later runs until June 2009 the filter rate aligns to the expectation.

The selection of downgoing starting events permits first tests of analysis methods that will be used for DeepCore, the low energy extension of IceCube, and this will enable a view to the southern hemisphere.
Chapter 1

Introduction

The observation of the sky, or more precisely the night sky, fascinated people from many countries and cultures for thousands of years. Those early scientists were limited to their eyes. They could only investigate the visible range of the electro-magnetic spectrum. Fortunately, the Earth’s atmosphere is nearly transparent for visible light. Besides, the atmosphere is also permeable for a wide range of radio wavelengths. The observation was improved by the use of ground-based telescopes, but electromagnetic waves in the gamma, infrared or the x-ray band stayed in secrecy, because these wavelengths are absorbed by the molecules in the atmosphere. The detection has to take place beyond the atmosphere. Satellite and balloon experiments were built and covered the field of x-ray and gamma astronomy.

The observation of light, or in general electromagnetic waves of any wavelength, is based on photons. Cosmic rays consist of photons and other particles such as protons, electrons, neutrinos and so on. With regard to their charge and their interaction probability they can be deflected in magnetic fields or absorbed by matter. As a consequence some cosmic ray particles lose their directional information or they do not reach the Earth at all. Neutrinos are uncharged particles with a low cross section and thus they are not deflected or absorbed as easily as other cosmic ray particles. They carry unaltered information about the position of their sources.

Chapter 2 is concerned with the origin of cosmic rays, why their energy spectrum follows a broken power law and how they are accelerated. Different particles are introduced and the advantages and disadvantages with respect to their charge or their interaction probability is discussed. Due to their small cross section neutrinos serve these investigation purposes well, but it makes the search for them difficult. Neutrinos can be detected in an indirect way. If a neutrino hits a nucleus, the reaction channel of the charged current will lead to a charged lepton. The light emitted by a charged lepton can be received by photomultipiers. Chapter 3 focuses on the underlying mechanism, the Cherenkov effect and the lepton of different flavors that can interact in a Cherenkov detector. The small cross sections of neutrinos implicate a huge detector assuming that statistics have to be collected within a reasonable time scale. Chapter 4 deals with the design of IceCube, a large Cherenkov detector at the South Pole. The energy
CHAPTER 1. INTRODUCTION

threshold is lowered with the implementation of additional DeepCore strings. This enables also to extend the viewing field to the southern hemisphere. The data analyzes are done in working groups in the northern hemisphere. A fast transferring method for the data is the transmission via satellite. Not all of the triggered data can be sent, because the data amount would exceed the available bandwidth. As a consequence of the limited bandwidth the measured data has to be reduced by filters. This is done by the application of several filters. Each filter is aimed at a different physics goal. The online selection in this thesis studies the implementation of the Downgoing Starting Filter. Chapter 5 deals with the simulation of the signal and the background. The measured data of the IceCube run with 40 strings (IC40) in 2008 are compared to the simulated data in chapter 6. Different filter designs for IceCube with 59 string (IC59) are studied with respect to the used bandwidth and the event rate in chapter 7. In chapter 8 the measured data from the IC59 run in 2009 are compared to the simulation. Finally, chapter 9 gives a summary of this study and an outlook on the finished IceCube detector with the DeepCore extension (IC86).
Chapter 2

Neutrino Astrophysics

2.1 Cosmic Rays

Cosmic rays are relativistic particles which consist of protons ($\sim 90\%$), Helium nuclei ($\sim 9\%$), heavier nuclei, gamma photons and electrons [Gai90]. If those particles hit the molecules of the atmosphere they produce a cascade of secondary particles, which they can cover the way through the atmosphere to the ground. These cascades are called air showers.

The sources where cosmic rays originate from are unknown. Particles with energies below $10^{15}$ eV are expected to be produced inside our galaxy and particles beyond $10^{15}$ eV may come from outside our galaxy. There are candidates as Gamma Ray Bursts or Active Galactic Nuclei which can realize an acceleration to the highest energies. The flux of the cosmic rays follows a power law with spectral index $\gamma$

$$F \propto E^{-\gamma}.$$  \hspace{1cm} (2.1)

The flux versus the energy is shown in figure 2.1. The spectral index $\gamma$ is given by the slope that changes its value at the knee ($E \sim 10^{15}$ eV) and at the ankle ($E \sim 10^{19}$ eV). The spectral index can be determined to [Yos03]

$$\gamma = 2.7 \text{ for } E < 10^{15} \text{ eV}$$

$$\gamma = 3.0 \text{ for } 10^{15} \text{ eV} < E < 10^{19} \text{ eV}.$$  

Furthermore there appears to be a cut-off at $E \sim 10^{20}$ eV. This abrupt rupture is a theoretical prediction by Greisen, Zatsepin and Kuzmin. This so-called GZK-effect [Abr07] is a consequence of the interaction between a proton and a photon of the Cosmic Microwave Background (CMB). The proton reacts via a delta resonance $\Delta^+$ to pions:

$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow \pi^0 + p.$$  \hspace{1cm} (2.2)
and
\[ p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow \pi^+ + n. \] (2.3)
This resonance decays to a pion and a nucleon. Hence, a part of the proton energy is carried away by the pion and the nucleons appear with energies below \( E \sim 10^{20} \text{eV} \).

### 2.2 Fermi Acceleration

There are two scenarios, which describe how particles can achieve energies at the order of up to \( 10^{20} \text{eV} \). They can be accelerated from lower energies (bottom-up) or decelerated from even higher energies (top-down). The bottom-up model is the most promising model to explain high energies, though the exact mechanisms of acceleration are still not understood. A theoretical model that tries to explain those mechanisms and the measured power law in figure 2.1 is the Fermi acceleration [Fer49]. Two sub-models are distinguished with regard to the gain procedure and the efficiency.

The second order Fermi acceleration assumes a relativistic particle that moves towards an interstellar magnetic gas cloud, that itself moves with velocity \( v_c \). The particle enters the cloud, scatters several times elastically and the momentum in the rest frame of the cloud stays constant. In the laboratory frame the particle has gained energy proportional to \( \beta^2 \), where \( \beta \) is the velocity of the cloud in units of the velocity of light (\( \beta = \frac{v_c}{c} \)). This mechanism is not efficient enough to allow the high energies of the cosmic rays.

A more efficient mechanism is the first order Fermi acceleration, the so-called diffuse shock acceleration. Particles scatter in magnetized gas clouds on both sides of a shock front. In the laboratory frame the front is moving with \(-v_f\) into a direction called upstream. In the rest frame of the shock front incoming charged particles enter with a velocity \(+v_f\) (perpendicular to the front), reflect by scattering in the shocked material and leave it with \(v'_f\). In this case the velocities to follow \(+v_f > v'_f\). The shocked particles move (relative to the laboratory frame) with \( v_s = -v_f + v'_f \) which implies an increase in their energies. The increase is proportional to \( \beta \), with \( \beta = \frac{v_s}{c} \).

### 2.3 Cosmic Ray Particles and their Sources

#### 2.3.1 Particle Species

Cosmic ray particles carry information about their energy spectrum and their sources, especially about their position. They can be used to study these topics. Each sort of particle has its advantages and disadvantages with a view to the detection methods and their propagation. A draft of the common cosmic ray particles with regard to their mean free path and their deflection is given in figure 2.2. The different species of cosmic ray particle are discussed in the following paragraphs.
Figure 2.1: Cosmic ray energy spectrum. Measured by different experiments. [Cro97]
**Charged particles:** Protons, electrons and other charged particles are deflected by magnetic fields because they carry an electric charge. Thus they lose their directional information. Only at energies above $E \simeq 10^{19} \text{ eV}$ [Tin05] the deflection by the magnetic field can be neglected. However, in this energy range the fluxes are low, therefore large detectors have to be built to get reasonable statistics. Charged particles interact with the atmosphere, so that they can only be measured directly with balloon or satellite experiments. Because of the GZK-cut-off and the magnetic deflection the investigation of those sources is limited to the energy range $10^{19} \text{ eV} < E < 10^{20} \text{ eV}$. 

**Photons:** High energy photons (gamma rays) are electrically neutral and thus are not deflected by magnetic fields. They can be absorbed in the interaction with interstellar matter or the earth atmosphere. These air showers have been measured by Cherenkov telescopes as MAGIC\(^1\) [MAG] or H.E.S.S.\(^2\) [HES]. With satellite experiments as EGRET\(^3\) [Egr] gamma rays have been measured directly. Photons can also annihilate with CMB-photons in the process of pair production:

$$\gamma + \gamma_{\text{CMB}} \rightarrow e^+ + e^-.$$  \hspace{1cm} (2.4)

The mean free path of a TeV-gamma-ray photon is less than 100 Mpc [Cop97].

**Massive electrically neutral particles (except neutrinos):** This sort of particles is not deflected in magnetic fields. The most long-lived electrically neutral particle is the neutron ($\tau \sim 886 \text{ s}$ [Ams08a]). Even at energies about $E = 10^{15} \text{ eV}$ the neutron can travel only a few 10 kpc. If it is detected on Earth it will have its origin in the Galaxy. Electrically neutral particles are not suitable for messengers for extragalactic sources.

**Neutrinos:** Neutrinos are not deflected in magnetic fields, they do not decay and they only interact rarely with interstellar matter or background photons. Because of their low cross section (e.g. $\sigma(E = 1 \text{ TeV}) = 10^{-35} \text{ cm}^2$) and with the density of the universe ($n \sim 6 \text{ nucleons m}^{-3}$) their mean free path is larger than radius of the observable universe [Ga90].

### 2.3.2 Neutrino sources

Cosmic sources accelerate hadrons to energies as up to $10^{20} \text{ eV}$. The hadrons interact with a target (beam dump). This target can be, for example, a cloud that consists of a denser medium. The majority of the hadrons are protons and the beam dump is dominated by proton-proton-reactions. The material has to be dense enough to allow these reactions, but it has to be thin enough for the

\(^1\)Major Atmospheric Gamma-ray Imaging Cherenkov Telescope
\(^2\)High Energy Stereoscopic System
\(^3\)Energetic Gamma Ray Experiment Telescope
Figure 2.2: Cosmic ray particles on their way from the source to the Earth. Protons are accelerated and shot into a target. Different particles are produced. They decay or interact with interstellar medium [Eul08].
produced particles to escape. Instead of their decay, several kinds of particles
like photons, neutrons, neutrinos or pions are produced. The pions can be
electrically charged or neutral. In the second case they decay into photons:
\[ \pi^0 \rightarrow \gamma \gamma \]  
(2.5)

and in the first case they decay into muons and neutrinos:
\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]  
(2.6)
\[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \]  
(2.7)

which then themselves decay into neutrinos and electrons:
\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]  
(2.8)
\[ \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu. \]  
(2.9)

The produced neutrinos can have one of the three lepton-flavors. The ratio of
those flavored neutrinos, based on the decay chain above, is about:
\[ (\nu_e : \nu_\mu : \nu_\tau) = (1 : 2 : 0). \]  
(2.10)

After considering neutrino oscillations on their way from the source to the Earth
a ratio of
\[ (\nu_e : \nu_\mu : \nu_\tau) = (1 : 1 : 1) \]  
(2.11)
is expected [Gou03].
Candidates for those sources are Supernovae (SN), Supernova Remnants (SNR),
Active Galactic Nuclei (AGN) and Gamma Ray Bursts (GRB). Furthermore,
neutrinos can be produced in the decay of dark matter.

**Supernovae and their Remnants:** A Supernova is a scenario that occurs
at the end of the lifetime of a massive star. The nuclear fusion reaction in stars
is accompanied by the balance of thermal pressure and gravitational pressure.
After the fuel is used up the star collapses due to a deficit on thermal pressure.
The object becomes a neutron star or a black hole. Neutrons are produced by
the compression of protons and electrons. The protons capture electrons by the
inverse beta decay. This explosion causes the appearance of electron neutrinos.
Nearly the complete energy of a supernova explosion (\( \sim 10^{55} \) eV) is deposited in
the kinetic energy of the neutrinos, but the huge number of produced neutrinos
(\( \sim 10^{58} \)), there is the consequence that a single neutrino can carry only a few
MeV [Bea99]. This is an energy below the IceCube threshold.
However, the outer shell of the star is blown away and has the possibility to
speed up charged particles by shock acceleration (chapter 2.2). This shell is
initiated by the invasion of matter into the compact remnant of the Supernova
explosion (SNR). It accelerates particles from the solar wind and the interstellar
medium up to 100 TeV [Fun07]. Those breakouts can occur hundreds of years
after star’s explosion.
2.3. COSMIC RAY PARTICLES AND THEIR SOURCES

Active Galactic Nuclei: Some galaxies have an enormous luminosity in their center, where the emitted photons have wavelengths from the radio band to the gamma band. They can be classified into Seyfert galaxies (spiral galaxies distinguished by their emission lines), radio galaxies (elliptic), quasars and blazars. A more precise investigation shows that the observed wavelength depends on the viewing angle (figure 2.3). In the center of the AGN is a super massive black hole that accretes matter with a high rate. The black hole is surrounded by an accretion disk and a dense dust torus. The accretion disk includes plasma and due to its rotation strong magnetic fields are induced. Perpendicular to this disk jets of relativistic plasma are emitted. Charged particles are accelerated in shocks up to highest energies by Fermi acceleration [Lov76].

Gamma Ray Bursts: Gamma ray bursts are short flashes of high energy photons (gamma rays) mostly located outside the Galaxy. Since they are very luminous they are also candidates for high energy particle sources ($E \sim 10^{20}$ eV) [Lov76]. The typical duration amounts a few seconds. Short bursts can last some milliseconds [Hur05] and long bursts can last up to almost one hour [Blo06]. The GRB is followed by an afterglow, which lasts longer and emits photons of lower energies. The causes of such a burst are thought to be the collision of two neutron stars or black holes. Similar to AGNs rotating plasma induces strong magnetic fields and relativistic particles are accelerated in bipolar jets along the rotation axis. Charged particles are deflected by the magnetic field and emit photons in the gamma range [Sar99]. These emitted photons
interact with the protons and produce pions which decay into neutrinos.

**Dark Matter:** Rotation curves and the effect of gravitational lensing have shown that the visible matter is only a small part (~17% [Ams08b]) of the matter in the universe. The other component is called dark matter because it doesn’t emit light and is therefore not visible with electromagnetic-based detection methods. Neutrinos are in principle dark matter, but their mass and their number is too low. They only account for a small fraction of Dark Matter. Hypothetical particles that only interact weakly and gravitationally are supposed to make up the rest of the Dark Matter mass. These particles are called WIMPs\(^4\). One candidate is the neutralino with a mass of 50 GeV [Jun96]. These particles are captured by the gravitational interaction with massive objects, where their number increases in time until they annihilate to neutrinos.

**Earth Atmosphere:** When cosmic ray particles hit the atmosphere mesons are produced. If these mesons don’t re-interact during their life time they will decay into neutrinos. Pions and kaons make the largest contribution to this atmospheric neutrino flux. Due to a short lifetime, charmed mesons almost decay before re-interacting. The produced neutrinos are called prompt neutrinos. The spectral index is \(\gamma = 3.7\) and the flux is isotropic. At energies > \(10^{14}\) eV the atmospheric neutrino flux is dominated by prompt neutrinos. [Gai90] [Sta04]

\(^4\)Weakly Interacting Massive Particles
Chapter 3

Neutrino Detection

3.1 Interaction Channels

There are two interaction channels for neutrinos. One channel is characterized by a neutral current

\[ \nu_l + N \rightarrow \nu_l + X \]  

(3.1)

where the neutrino hits a nucleus \( N \) and initiates a hadronic cascade \( X \). The neutrino persists without change. The other channel is characterized by a charged current

\[ \nu_l + N \rightarrow l + X. \]  

(3.2)

The neutrino also hits a nucleus and initiates a cascade. The neutrino converts into a charged lepton. The charged lepton has the same flavor as the neutrino. Most of the neutrino momentum is transferred to the charged lepton. For large Lorentz boosts both neutrino and charged lepton tracks are collinear. The deflection, or more precisely the angular difference \( \Delta \epsilon \) between their tracks, is approximately [Lea00]

\[ \Delta \epsilon = 0.7^\circ \cdot \left( \frac{E_\nu}{\text{TeV}} \right)^{-0.7}. \]  

(3.3)

The neutrino only interacts weakly with matter. Thus it can’t be observed directly (in the neutral current channel). An indirect observation uses the interaction by the charged current channel.

Besides the radiochemical method, which is based on the counting of neutrino-induced reaction products, the Cherenkov detection method gives the possibility to determine the lepton direction.

3.2 The Cherenkov Effect

Cherenkov radiation is emitted when a charged particle moves with a high velocity through a medium. This velocity \( v \) has to be higher than the speed of
light $c_n$ of the medium:

$$v \geq c_n = \frac{c}{n}$$

and

$$\beta = \frac{v}{c} \geq \frac{1}{n}$$

For ice, with a refractive index of $n \approx 1.3$, this means that the particle speed has to be larger than 77% of the light velocity. Charged particles with this velocity have an energy of more than $E = 160$ MeV.

Due to the polarization of the medium the atoms send out electromagnetic waves. The so-called Cherenkov photons are emitted under an angle $\theta_c$ that depends on the refraction index and the velocity of the through passing particle [Amsd]

$$\cos \theta_c = \frac{1}{n\beta}$$

As presented in figure 3.1, the particle is surrounded by a cone. A similar effect can be seen in acoustics. When a supersonic aircraft breaks through the sound barrier it is encircled by a Mach cone.

The photons can be detected with PMT$^1$. From the measured time and the well-known position of these PMTs it is possible to reconstruct the particle track.

![Figure 3.1: Signature of a muon traveling through the ice [Eul08]. Cherenkov light is emitted under the angle $\theta_c \approx 41^\circ$.](image)

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$^1$Photomultiplier Tube
3.3 Signatures

Electrons When high energetic electrons hit the detector material photon cascades are initiated by bremsstrahlung and pair production. These photons move in all directions. Thus a nearly spherical figure is observed with a slight deformation and larger intensity in the electrons direction (figure 3.2). A directional reconstruction is possible but difficult.

![Figure 3.2: Signature of the electron [Eul08].](image)

Muons During their life-time (\(\sim 2.2 \, \mu s\)) they can travel, depending on their energy, a long way through the detector until they decay. A distinct Cherenkov cone is visible and a more precise reconstruction of the direction is possible.

Tauons Tau neutrinos produce a hadronic cascade and a tauon (figure 3.3). Tauons generate tracks such as muons and electrons. Even at high energies up to the PeV-range this track can be short, because the tauon decays after \(\sim 0.3 \, \text{ps} \) [Ams08c]. At the end of the track, the tauon initiates cascades again. With large PMT spacings, these cascades can only be distinguished, if the track between those cascades is long enough. This requires high particle energies.
Figure 3.3: Signature of the tauon \cite{Eul08}.
Chapter 4

IceCube Detector

4.1 IceCube

The IceCube detector is a Cherenkov detector that uses ice as the detection medium. The experiment is located at the South Pole, because Antarctica disposes of a natural huge amount of ice. Therefore it is possible to build a large instrument. IceCube does not consist of a tank filled with a medium like water (for example experiments like Kamiokande\textsuperscript{1} or SuperKamiokande). Instead, the detector is built into the medium. At the moment the detector is under construction. Detection modules, which consist mainly of a PMT (the so-called DOMs\textsuperscript{2}) are placed in a lattice-like structure into the ice. For the deployment several holes are drilled with hot water and the strings are inserted into the water-filled holes. Then the water hole refreezes. In its originally proposed design, IceCube consists of 80 strings. Each string contains 60 optical modules placed in equidistant positions. The instrumented length of a string is 1000 m what results in a DOM spacing of 17 m. The strings are placed horizontally in a hexagonal structure with 125 m distance. The topmost DOM is located at a depth of 1450 m and the lowest DOM at 2450 m. The final volume is 1 km$^3$. A schematic view is given in figure 4.1. In total there will be 4800 DOMs deployed. These dimensions confine the detectable particle energy to $E > 100$ GeV. IceCube is optimized for $E \approx 10$ TeV [Pdd].

The ice and snow has accumulated for hundreds of thousands of years. During that time the atmospheric conditions have changed. In the deeper region (between $\sim 2000$ m and $\sim 3000$ m) of the detector the ice features a certain purity. Above this a dust layer can be found. This is a slightly soiled region that causes scattering and photon absorption in the ice. Volcanic ashes and air bubbles also appear in Antarctica. As a consequence of the pressure the bubbles are compressed to a negligible size below 1300 m [Ack06] [Aug04].

In the year 2008 there were 40 strings deployed. The detector is nick-named IC40. This year there are 58 IceCube strings and one DeepCore string deployed. Hence the name of the 2009 detector is IC59.

\textsuperscript{1}Kamioka Nucleon Decay Experiment
\textsuperscript{2}Digital Optical Modules
4.2 DeepCore Extension

The DeepCore extension (figure 4.2) is conceptualized to lower the energy threshold and to enlarge the physics scope of IceCube. The essential function is the potential of DeepCore in rejection a large amount of the atmospheric muon background. Therefore the Icecube detector is used as a veto region around DeepCore. By selecting signal events that have the interaction vertex in the DeepCore volume the search for neutrinos from the full sky becomes possible. The southern hemisphere was not visible for IceCube so far (for energies below the PeV range).

The IceCube energy threshold is lowered from $\sim 100$ GeV to $\sim 10$ GeV. Thus the sensitivity for signal such as WIMPs will be improved. For this purpose 6 additional strings are placed around a central IceCube string. These strings are equipped with 60 DOMs in a smaller spacing. Each DOM contains a high quantum efficiency PMT. 50 DOMs are placed in a 7 m-spacing beneath the dust layer in a region of clearest ice and 10 DOMs are placed in a 10 m-spacing above the dust layer at a depth of 1760 m 1850 m. These DOMs have the task to identify atmospheric muons.
Figure 4.2: Top and side view of the DeepCore extension in IceCube [Sch].
4.3 Detection Method

The Cherenkov light is detected with DOMs. These are glass bowls that enclose a PMT and a DAQ³ platform, which records and stores signals of the PMT. If requested, the data will be sent to the surface DAQ system [Pdd]. When photons activate the PMT, the DOM digitalizes the PMT pulses to a waveform.

The noise rate of a DOM is \(~ 650\) Hz [Ice06]. To remove those noise hits, it is required that each hit has a hit in a neighboring DOM. This is called HLC⁴. Isolated hits are cut out of the data.

In case that a certain number of DOMs are hit the event is triggered by the SMT⁵. The SMT8, for example, triggers when there are at least eight DOMs hit in a certain time window, for example 6000 ns.

After the event is triggered directional information for example is calculated by reconstruction algorithms.

4.4 Classification of Events

Muon events can be classified by the position of their starting and stopping points. The starting point is the vertex where the muon is produced. The stopping point is that point where the muon gets invisible for the Cherenkov detector, because it does not any longer emit light. This is caused by the energy loss and the muon moves to slow through the medium. In figure 4.3 there are four different kinds of events.

- **Throughgoing tracks** (or infinite tracks) have their starting and stopping points outside IceCube. They are going through the full detector.

- **Contained tracks** have their starting and stopping points inside IceCube.

- **Stopping tracks** have their starting point outside and their stopping point inside IceCube.

- **Starting tracks** have their stopping point outside and their starting point inside IceCube.

---

³Data Aquisition
⁴Hard Local Coincidence
⁵Simple Multiplicity Trigger
Another classification can be done in the traveling direction relative to the zenith angle

- Events that have zenith angle of $\theta < 90^\circ$ move downwards. These events come from the southern hemisphere.
- Events that have zenith angle of $90^\circ < \theta < 180^\circ$ move upwards. These events come from the northern hemisphere.

### 4.5 Background

The largest background contribution for this experiment is given by atmospheric muons. These muon events move downwards in the detector. An event is identified as downwards going or downgoing when the zenith angle is smaller than $90^\circ$. Otherwise the event is named upgoing. Muons produced by air showers in the atmosphere can reach, due to their lifetime, the Earth’s surface. The identification of upgoing events can reject this background because the Earth absorbs atmospheric muons. This restrains the observable region to the northern hemisphere. It is a challenge to look at the southern hemisphere, because the events from this direction are background dominated. The rate of downgoing events in IceCube is $f = o(\text{kHz})$ with a ratio of atmospheric muons to neutrino-induced muons of $10^6$.

Atmospheric muons reach the detector and cause stopping or throughgoing tracks. But they don’t initiate starting tracks. The identification of downgoing starting events is a suggestive method to reject background on the one hand and to select events from the southern hemisphere on the other hand.
4.6 Data Transfer

A small fraction of the data is transferred via satellite. The data handling at the South Pole is done with SPADE\(^6\) [SPA]. The satellite bandwidth is limited. The satellite transfer system is regularly upgraded. In the 2009 season there are 70 GB\(^{\text{GB/day}}\) available for the IceCube collaboration [Bla]. The two satellites TDRS\(^7\)-1 and GOES\(^8\)-3 are used for the data transfer [SCCF]. Each satellite is visible for six to nine hours a day. Additionally, some data is transferred with the Iridium communication system. (It was planned to consist of 77 satellites, and the name was given referring to the atomic number of iridium. Currently, there are 72 satellites working for this system.) Besides, there are further experiments running in Antarctica, as the South Pole Telescope [SPT] that also uses a part of the satellite bandwidth. The trigger rate of IceCube is \(\sim 1800\) Hz. If each triggered event would be sent by satellite it would need a bandwidth of 450 GB\(^{\text{GB/day}}\). Therefore the data amount has to be reduced. Several filters with different purposes are applied and share the available bandwidth. All filters have to be tested in terms of bandwidth usage and data rate for estimating the required bandwidth. It must be assured that the filter aims to the intended physics goal. This is the motivation of this work.

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\(^6\)South Pole Archival and Data Exchange  
\(^7\)Tracking and Data Relay Satellite  
\(^8\)Geostationary Operational Environmental Satellite
Chapter 5

Simulation

The Monte Carlo Study is done with a simulation of the signal and a simulation of the background.

5.1 Generation

The signal events are generated with the neutrino generator NuGen[NuG]. This program is able to simulate neutrinos of each flavor. In this study the simulation of muon neutrinos is used. The neutrinos are generated in a few kilometer distance around IceCube. The low cross section would let the neutrinos produce too little muons, so every neutrino produces a muon and is weighted with the interaction probability. The spectral index $\gamma$ can be set.

The background events are generated with CORSIKA\textsuperscript{1}. This program simulates extensive air showers caused by high energetic cosmic ray particles [Fzk]. Primary particles (such as protons, alpha particles, heavier nuclei or photons) hit the atmosphere and interact with air molecules or decay in to secondary particles. Atmospheric muons are one of the decay components. They are the largest background contribution for the IceCube experiment (chapter 4.5).

5.2 Propagation

The propagation of the generated muons through the ice is simulated with MMC\textsuperscript{2} [Chi08]. The program considers the stochastic energy loss and the energy loss by ionization. In case of a stochastic energy loss the interaction type and the deposited energy is determined.

Photons are produced by Cherenkov radiation from the muon and by secondary particles that produce cascades. The propagation of the photons is done with the Photonics [Lun07] software. This software is based on tables, which contain the expected number of photons and the arrival time at the DOM. Besides, the ice properties are considered. The HitMaker module [Hit] generates Monte Carlo hits using Photonics.

\textsuperscript{1}Cosmic Ray Simulation for Kascade
\textsuperscript{2}Muon Monte Carlo
5.3 Hardware and Detector

The photon propagation inside the DOM and the PMT response is simulated with ROMEO\textsuperscript{3} [Rom]. It includes tables of photon acceptance in dependence on the incidence angle and the timing fluctuation of radio active noise. It consists of the DOMPMTPhotoCathode module that simulates the fluctuation of the collecting efficiency, the DOMPMTChargeResponse module that simulates the charge response of the DOMs and the DOMPMTWaveForm module that simulates the wave form function with a Gaussian model. DOMSimulator [DOMSim] takes the PMT signal as its input and simulates the DOM mainboard response. This module also considers local coincidence. The simulation of the trigger is done with trigger-sim [TrigSim]. This module rejects events that do not fulfill the trigger.

\textsuperscript{3}Root-based Optical Module EmulatOr
Chapter 6

Downgoing Starting Filter For IC40

In this chapter the filter performance is evaluated by comparing the simulated data with the measured data. The measured data is Run00110998. This run has a duration of about 8 hours and contains $2.9 \cdot 10^7$ events. As background the Corsika data set 1313 with $2.1 \cdot 10^6$ events is taken. NuGen data set 1548 with a spectrum $\sim E^{-2}$ and $1.6 \cdot 10^6$ events is used. The real flux of the signal is unknown. Therefore an arbitrary normalized reference flux is used.

6.1 Signal Definition

The purpose of this filter is to collect events from the southern hemisphere. Events from the southern hemisphere move downwards (see chapter 4.4) in the detector. NuGen events are considered as signal, when they start downwards in the inner core of the detector. The starting point is defined by the true position of the interaction vertex where the neutrino-induced muon starts. This inner core (figure 6.1) is subject to the following conditions:

$$-170m < x < 415m$$

$$120m < y < 350m$$

$$0m < z < 500m$$

With the true Monte Carlo information about the position $x, y$ and $z$ in detector coordinates. This inner core comprises the lower half of the detector (side view in figure 6.1) and the inner strings (top view in figure 6.1).
CHAPTER 6. DOWNGOING STARTING FILTER FOR IC40

6.2 Filter Configuration

The reconstruction is done with the likelihood algorithm PoleTrackLlhFit/ipdfGConvolute. In 2008 the filter ran with SMT8 triggered data in a 6000 ns window and $N_{\text{chan}} \geq 10$. $N_{\text{chan}}$ is the number of hit DOMs in an event. The angular cuts relate to reconstructed values of the zenith and the azimuth direction. In detail the configuration of the filter is:

- **Top veto**: This veto provides the selection of starting tracks and reduces the rate of downgoing muon events. Each event with at least one hit in the upper 30 DOMs of the detector is rejected. Downgoing muons have a high chance to deposit light in the upper 30 DOMs.

- **First hit string veto**: This veto has the function to select starting events entering from the side. Events which have their first hit on an outer string (figure 6.2) are cut out from the data.

- **Azimuth cut**: Due to the longish shape of the IceCube-40 detector, events that come from an azimuth direction of $\phi = 30^\circ$ to $\phi = 135^\circ$ or $\phi = 225^\circ$ to $\phi = 300^\circ$ are rejected. This is chosen because the detector is thicker in the kept directions. In the kept azimuth directions there are two strings involved in the outer layer. Otherwise, one string joins the outer layer.
6.3. ** DEFINITION OF THE STRING SLICES **

- **Zenith cut:** The zenith selection comprehends to the range from $\theta = 50^\circ$ to $\theta = 180^\circ$. This rejects most of the atmospheric muon background from the southern hemisphere.

Figure 6.2: Top view of IC40 with the azimuth cut. The cut regions are $225^\circ - 300^\circ$ and $30^\circ - 135^\circ$. The inner strings are represented by the red points and the outer strings by the blue points.

6.3 Definition of the String Slices

As shown in figure 6.3 the strings in IC40 can be classified in 10 slices. For example the strings number 60, 68 and 75 form string slice number one and the strings number 21, 30, 40 and 50 form string slice number 10. This is done for the side view representation of the hit strings in chapter 6.4.4 and 6.4.7. The digits before the decimal point give information about the string position with respect to the long side of the detector (east to west) and the digit after the decimal point gives information about the short side of the detector (north to south). In the following the name of the string slice is called $\text{StringPos}$.

6.4 Performance

The Downgoing Starting Filter 08 for IC40 worked from April 2008 to May 2009. Figure 6.4 shows the time evolution of the filter rate from April to December 2008. Figure 6.5 shows the same development for the period from January to May 2009. A few runs have a different configuration from the other runs. This causes deviant values for the event rate. Hence, these runs are disregarded in the following chapters. On 20th and 21st of April 2009 the Downgoing Starting Filter 08 is turned off for test runs of the Downgoing Starting Filter 09 (the successor for the next season). This causes the fall-off in the event rate. Generally, the curve represents a seasonal variation, which is caused by the changing
density of the atmosphere. For example, in the coldest months (July/August), the atmosphere is denser in comparison to the warmer months. This has the consequence that pions and kaons interact in the atmosphere instead of decaying into muons. Thus, the rate of the atmospheric muon background is lower. The muon rate is higher for a thinner atmosphere. This effect has also an influence on the SMT trigger rate.

Figure 6.6 and figure 6.7 show the time evolution of the trigger rate in IceCube. There are two jump discontinuities in the trigger rate, which are caused by the switch-on of strings. The first jump is caused by the changeover from IC22 to IC40 in April 2008. The trigger rate changed from $\sim 600$ Hz to $\sim 1000$ Hz. The second jump is caused by the changeover in May 2009 when another 19 strings were engaged. The first spike in figure 6.7 is caused by the switch-on of strings in the test run. The second spike is caused by configuration tests, which led to a higher trigger rate. The trigger rate changed from $\sim 1000$ Hz to $\sim 1800$ Hz. Table 6.1 shows the rate of selected events, the trigger rate and the data size in a four week interval. The relative error of these rates is $< 1\%$. The filter rate stays approximately constant at $\sim 0.18\%$ and the data size does not exceed $450 \text{ MB/day}$. The filter rate at the beginning of October 2008 is slightly higher ($\sim 0.19\%$). This value agrees with the expectation. The Corsika data set used here is simulated for an atmosphere density that was determined on 1st October 1997 at the South Pole. The measured data size is a little lower than the expected data size. This is caused by a lower average $N_{\text{chan}}$ than expected from simulation. A lower number of hit DOMs requires less disk space. 37.2 $\%$ of the defined signal pass the filter.

On the following pages it is tested if the filter selects events as intended.
6.4. PERFORMANCE

Figure 6.4: Event rate versus time for the *Downgoing Starting Filter 08* in 2008 [Mon].

Figure 6.5: Event rate versus time for the *Downgoing Starting Filter 08* in 2009 [Mon].
Figure 6.6: IceCube trigger rate in 2008 [Mon]. Note: Time range is different from figure 6.4.

Figure 6.7: IceCube trigger rate in 2009 [Mon]. Note: Time range is different from figure 6.5.
## 6.4 Performance

<table>
<thead>
<tr>
<th>Date</th>
<th>Rate of events selected with the filter [Hz]</th>
<th>Trigger rate [Hz]</th>
<th>Passing Rate [%]</th>
<th>Data Size [MB/day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>17 Apr 2008</td>
<td>1.885 ± 0.008</td>
<td>1036.13 ± 0.19</td>
<td>0.1819 ± 0.0008</td>
<td>408.5 ± 1.8</td>
</tr>
<tr>
<td>15 May 2008</td>
<td>1.844 ± 0.009</td>
<td>1002.50 ± 0.22</td>
<td>0.1840 ± 0.0009</td>
<td>399.7 ± 2.1</td>
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<tr>
<td>12 Jun 2008</td>
<td>1.759 ± 0.008</td>
<td>976.89 ± 0.19</td>
<td>0.1800 ± 0.0008</td>
<td>381.1 ± 1.7</td>
</tr>
<tr>
<td>10 Jul 2008</td>
<td>1.739 ± 0.008</td>
<td>958.80 ± 0.19</td>
<td>0.1814 ± 0.0008</td>
<td>376.9 ± 1.7</td>
</tr>
<tr>
<td>7 Aug 2008</td>
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<td>960.28 ± 0.19</td>
<td>0.1836 ± 0.0008</td>
<td>382.1 ± 1.7</td>
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<tr>
<td>4 Sep 2008</td>
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<td>0.1829 ± 0.0008</td>
<td>382.1 ± 1.7</td>
</tr>
<tr>
<td>2 Oct 2008</td>
<td>1.820 ± 0.008</td>
<td>962.74 ± 0.19</td>
<td>0.1891 ± 0.0008</td>
<td>394.5 ± 1.8</td>
</tr>
<tr>
<td>31 Oct 2008</td>
<td>1.932 ± 0.008</td>
<td>1051.52 ± 0.20</td>
<td>0.1837 ± 0.0008</td>
<td>418.7 ± 1.8</td>
</tr>
<tr>
<td>27 Nov 2008</td>
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<td>432.3 ± 1.8</td>
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<tr>
<td>25 Dec 2008</td>
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<td>1113.68 ± 0.20</td>
<td>0.1821 ± 0.0008</td>
<td>439.5 ± 1.9</td>
</tr>
<tr>
<td>22 Jan 2009</td>
<td>2.042 ± 0.009</td>
<td>1128.18 ± 0.20</td>
<td>0.1810 ± 0.0008</td>
<td>442.5 ± 1.9</td>
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<tr>
<td>19 Feb 2009</td>
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<td>0.1815 ± 0.0008</td>
<td>436.1 ± 1.8</td>
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<td>430.6 ± 1.8</td>
</tr>
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<td>406.5 ± 1.8</td>
</tr>
<tr>
<td>14 May 2009</td>
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<td>1003.92 ± 0.19</td>
<td>0.1815 ± 0.0008</td>
<td>394.9 ± 1.8</td>
</tr>
</tbody>
</table>

Table 6.1: Event rates and data sizes in IC40
6.4.1 Azimuth and Zenith Distribution

Figure 6.8 shows the (reconstructed) azimuth distribution of the measured data and the expected background. On trigger level these distributions are almost flat with the exception of small deviations caused by the geometry of the detector. Peaks occur in those directions where the detector has more strings (seen from the center). The filtered background and measured data both show an increase near the edges of the cuts (see figure 6.2) until the distribution abruptly decreases at the edges. The reason for the increase is that there is just one outer string in the cut region. More background is passing the first hit string veto in the cut azimuth regions. There are two outer strings in the kept region and less background is passing. The decrease is just a binning problem. For a clear representation a 10-degree-binning is used. Since the cuts are done at angles that are not divisible by 10 the bins at the edges are partially filled. The same decrease can be seen at the filtered signal data.

The zenith distribution in figure 6.9 shows an increase of the data rate with rising $\cos(\theta)$. This is caused by atmospheric muons which move downwards in the detector. The background simulation and the measured data agree for small zenith angles (corresponding to a higher $\cos(\theta)$). The selected data shows the same behavior up to the cut angle of $50^\circ$. The last bin before the non-kept region appears to be less filled. This is also a binning effect, because $\cos(50^\circ) \approx 0.643$. The signal (filtered as well as triggered) is approximately flat for $\cos(\theta) > 0$ and for $\cos(\theta) < 0.3$, but these two sections have a different rate. These angular distributions show the same signal loss for different azimuth or zenith directions. The most background is in the signal region.
6.4. PERFORMANCE

Figure 6.8: Reconstructed azimuth distribution of triggered (empty markers/dotted line) and filtered (full markers/full line) events. Black points: measured data. Blue squares: Background. Green triangles: Signal (arbitrary normalization).

Figure 6.9: Reconstructed zenith distribution of triggered (empty markers/dotted line) and filtered (full markers/full line) events. Black points: measured data. Blue squares: Background. Green triangles: Signal (arbitrary normalization).
6.4.2 All Hit DOMs

Figure 6.10 shows all hit DOMs in the events on trigger and filter level in the measured and the simulated data. The trigger distribution is nearly flat with the exception of the area between optical module 30 and 40. This is the region of the dust layer. The ice is less clear in this region, the absorption is higher and the DOMs detect less light. On filter level the signal and the background distributions begin, due to the top veto, at DOM number 31. The measured data distribution has on filter level a few hits in the top veto region. This is discussed in chapter 6.4.8. All three filtered distributions decrease near the border of the top veto region, because events have to start downwards. These events induce more likely hits in the lower part. Additionally, this region suffers from the dust layer. The signal follows about the same distribution as the background and the measured data. On trigger level there is also a decrease because the signal is defined as downgoing events with a vertex in the inner core. The bump between DOM layer 30 and 35 again is caused by the dust layer. Between layer 24 and 30 there are also hit DOMs outside of the inner core. The light from those events is scattered into the veto region. The hits in the upper region are noise hits.

6.4.3 First and Highest Hit DOMs

In the left diagrams in figure 6.11 the frequency of the number of the highest hit DOM of an event is plotted. Measured data and background on trigger level have their highest hit preferably in the upper part of the detector. The distribution decreases on the way downwards. The bumps are caused by the changing ice properties. The distribution stops abruptly at layer 57. Events that go downwards and start below layer 57 seldom activate the trigger. The signal shows a behavior like the all hit DOM distribution (figure 6.10) with the scattered hits above the veto border and the noise hits in the upper region. The decrease at the lowest part is also observed. The filtered signal is nearly flat in the range from DOM number 37 to number 52. The distributions of the first hit DOMs in the right diagrams in figure 6.11 have the same characteristics as the highest hit DOM distributions. They differ in the cut-off. The first hit DOM in an event can be on the lowest DOM, but the light probably scatters to higher DOM layer. A highest hit DOM on one of the lowest layer is possible but unlikely. That concerns nearly horizontal tracks that activate exclusively DOMs from the lowest layer.
Figure 6.10: Distribution of all hit DOMs (filter (full) and trigger (dotted)). Top (black): Measured data. Center (blue): Background. Bottom (green): Signal.
Figure 6.11: Left: The highest hit DOM in an event. Right: The first hit DOM in an event. Top: Measured data. Center: Background. Bottom: Signal. Trigger level (dotted) and filter level (full).
6.4.4 First Hit Strings

Figure 6.12 shows the first hit strings of each event. The trigger distribution for the background and the measured data are flat. Only the signal distribution decreases towards the border of the detector. This is caused by the signal definition. Signal events start in the inner core and move downwards. Thus, all events hit inner strings first and then outer strings afterwards. The same structure is observed for the signal on filter level, but less distinctive. There are also first hit string veto violations in the measured data that will be discussed in chapter 6.4.8.

The sample is divided into two sub-sets for the azimuth region $135^\circ < \phi < 225^\circ$ and $300^\circ < \phi < 30^\circ$. That corresponds with events that travel across the long side of the detector. The first hit strings from those events are shown in figure 6.13. Filtered measured events and filtered background events have more often first hits on strings near the entering border.
CHAPTER 6. DOWNGOING STARTING FILTER FOR IC40

Figure 6.13: First hit strings on filter level depending on the entering direction of the events. Top left: Measured data (entering from the west). Center left: Background (entering from the west). Bottom left: Signal (entering from the west). Top right: Measured data (entering from the east). Center right: Background (entering from the east). Bottom right: Signal (entering from the east). Red: Inner strings. Black: Outer strings
6.4.5 Vertices

Figure 6.14 shows the reconstructed position of the interaction vertex in the measured data. The top view of IceCube is identifiable in the left diagram. The string positions appear as hot spots. This is caused by the reconstruction method, which determines the vertex near the string positions. In the right diagram the rectangular shape of the side view of the detector is observed. The vertices appear more probable in the upper region. This is caused by the frequent incidence of atmospheric muons.

On filter level the range where the interaction occurs is reduced. The colored area in the left diagram in figure 6.15 represents mainly the area enclosed by the inner strings. In the right diagram in figure 6.15 the vertices are situated in the lower part of the detector. The distribution of the reconstructed vertices show that the selected events start in the lower central region of the detector. This area resembles the inner core, where the signal is expected to start.

Figure 6.14: Position of the likelihood-reconstructed vertices of the measured data on trigger level. Left: Top view. Right: Side view.

Figure 6.15: Position of the likelihood-reconstructed vertices of the measured data on filter level. Left: Top view. Right: Side view.
6.4.6 $N_{\text{chan}}$ distribution

Figure 6.16 shows the distribution of the number of hit DOMs in an event ($N_{\text{chan}}$). The measured data agrees with the simulated background for lower $N_{\text{chan}}$. For higher $N_{\text{chan}}$ the measured and the simulated data diverge from each other. The rejection of the data amount by three orders of magnitude is visible, while the signal is cut less than one order of magnitude. Due to the condition $N_{\text{chan}} \geq 10$ the distribution shows no entries at $N_{\text{chan}} < 10$. All distributions have a maximum for lowest $N_{\text{chan}}$. Due to a binning issue the bin with $N_{\text{chan}} = 10$ is not fully filled. The signal distribution does not fall as steep as the background distribution for rising $N_{\text{chan}}$. Signal events are expected to have higher $N_{\text{chan}}$ than the background.

Figure 6.16: $N_{\text{chan}}$ distribution of triggered (empty markers/dotted line) and filtered (full markers/full line) events. Black points: measured data. Blue squares: Background. Green triangles: Signal (arbitrary normalization).
6.4.7 All Hit Strings

Figure 6.17 shows all hit strings in the events on trigger and filter level in the measured and the simulated data.

The distributions of the measured data and the background are nearly flat on trigger level. The filtered data has a maximum of hit strings in the middle of the detector and decreases towards the border of the detector. This is due to the first hit string veto. Events entering the instrumented volume close to the outer strings most probably cause an early hit in an outer string and get removed. This is observed for the long direction as well as for the short.

A comparison of the measured and the simulated data shows an agreement of the background and the measured data. The signal distribution for trigger and filter level shows a maximum in the center and decreases to the border of the detector. This behavior is again caused by the signal definition as it is explained in chapter 6.4.4.

The distributions of filtered measured and background data also show now the decrease towards the detector border similar to the signal. This is characteristic for the filtering as it is explained above. The measured and the background data is reduced by about two orders of magnitude.

6.4.8 Violations of the Filter Conditions

As seen in chapter 6.4.2 and chapter 6.4.4 some events survive violating one or both of the veto conditions

**First Hit String Veto Violations**  The first hit string veto is violated, if the first hit of an event lies on an outer string. This violation happens with 0.05% of the filtered events.

**Top Veto Violations**  The top veto is violated if there is at least one hit in the top veto region. This concerns 0.02% of all filtered events.

**Top Veto and First Hit String Veto Violations**  Both the top veto and the first hit string veto is violated for 0.03% of all filtered events.

The veto violations is an effect that is caused by the offline reprocessing with other code versions. Figure 6.18 shows the $N_{\text{chan}}$ distribution, the zenith distribution and the azimuth distribution of events that violate at least one of the veto conditions. These distributions show within the bounds of the statistics a random occurrence of the violations. A scatter plot of these events is given in figure 6.19. It can be seen that the violations occur almost uniformly throughout the detector. No peculiarity is visible.
Figure 6.18: Events that violate one or both of the filter conditions. Top: $N_{\text{chan}}$ distribution. Center: Zenith distribution. Bottom: Azimuth distribution.
6.4. PERFORMANCE

6.4.9 Summary of the IC40 Filter Performance

The investigation of the angular distribution, the hit strings and the hit DOMs showed that the Downgoing Starting Filter for IC40 works as expected. The measured data has the predicted behavior before and after the cuts. There are violations of the veto in a few events that are caused by the reprocessing with different software. The dominant cut is the azimuth cut that rejects 50% of the data. The filter rate is stable ($\sim 1.8\%$) and the data is transferred with $\sim 0.4$ GB day by satellite.
Chapter 7

IC59 Filter Design

19 new strings are deployed in the 2009 season. IceCube consists of 58 IceCube strings and one DeepCore string and is briefly called IC59. In comparison to the 2008 season the detector has changed its geometry. Due to this change the filter conditions are adjusted. This chapter describes the configuration of the angular selection and the veto. A new veto based on a velocity cut is developed and tested for its signal and background passing rate and the used satellite bandwidth. This new veto is compared to the top veto as it was used in IC40. The optimum found in this study is applied to the filter.

As background the Corsika data set 1628 with $3.0 \cdot 10^6$ events is taken. NuGen data set 1542 with a spectrum $\sim E^{-2}$ and $7.4 \cdot 10^5$ events is used. The real flux of the signal is unknown. Therefore an arbitrary normalized reference flux is used.

7.1 Signal Definition

An energy spectrum $\sim E^{-2}$ is used for the simulation of signal events which start downwards in the inner core. The inner core is a cylinder shaped volume positioned in the bottom center of IceCube. It has a radius of 300 m around the center and a height of 370 m from the bottom. Thus, the complete volume is below the dust layer. The starting point is defined by the true position of the interaction vertex where the neutrino-induced muon starts. Figure 7.1 shows the inner core in relation to IceCube and the future DeepCore.

7.2 Cuts

The reconstruction is done with the likelihood algorithm $PoleMuonLlhFit / ipdfGConvolute$. In 2009 the filter runs with SMT8 triggered data to a 6000 ns window. A part of the background is excluded by a zenith dependent cut on the number of hit DOMs ($N_{chan}$). The zenith is estimated by a first guess ($linefit$, a quick reconstruction algorithm). If $\theta_{linefit} \geq 70^\circ$ events with $N_{chan} \geq 8$ are taken. Otherwise the event must have $N_{chan} \geq 10$. This reduces the background of atmospheric muon background, because it has primarily a lower
$N_{\text{chan}}$. The angular cuts relate to reconstructed values of the zenith and the azimuth direction. In detail the configuration of the filter is:

- **First hit string veto**: This veto has the purpose to select starting events entering from the side. Events which have their first hit on an outer string (figure 7.2) are removed. In the kept directions there are two strings involved in the outer layer.

- **Azimuth cut**: Due to missing outer strings in the azimuth region of $\phi = 150^\circ$ to $\phi = 280^\circ$ events from that direction are rejected.

- **Zenith cut 1**: The zenith selection is reduced to the range from $\theta = 0^\circ$ and $\theta = 110^\circ$. This is dedicated to downgoing tracks.

- **Zenith cut 2**: Most of the background enters with low zenith angles. If the bandwidth gets tight a cut can be applied to tune the background passing rate. The default value is $0^\circ$ and can be varied up to $50^\circ$.

To reject events entering the detector from above a top veto is applied. The number of DOMs and the number of allowed hits in the veto region can be adjusted. In section 7.3.1 this is compared to a velocity veto that is investigated in section 7.3.2.
7.3 Veto Selection

In the following two different types of vetos are compared: The velocity veto and the top veto. The velocity veto was designed to be used with DeepCore. This veto is based on the velocity (VC) of the particle and it is combined with an upper layer veto (ULV). The top veto, as it was applied to IC40, involves the upper 37 DOM layer. The tests for the top veto are optionally done with allowing an HLC pair in the veto region. In each case the data size $R$ is calculated by:

$$R = T[H\text{z}] \cdot 0.01 \cdot f[\%] \cdot (1 + (1.1 \cdot \frac{< N_{\text{chan}} >}{14})) \cdot 165\text{MB day}^{-1}.$$  

(7.1)

This is an empiric formula from the Trigger Filter Transmission Board. The data size has a summand that is independent from the average value of $N_{\text{chan}}$. Each event has a header and reconstruction information that is stored. The other summand increases linear with $< N_{\text{chan}} >$. This is due to the amplitude and time information that the hit DOMs provide. The data size is linear with the trigger rate $T \simeq 1800$ Hz and the background passing rate $f$. The signal passing rate is based on the signal definition as mentioned above.

7.3.1 Top Veto

The top veto uses the upper 37 DOM layers of IceCube as a veto region. With the zenith selection of downward going events the top veto guarantees a selection of downward going starting events. There are two variations. One rejects each event with at least one hit in the veto area. The other allows two hits in the
veto region (from the hard local coincidence (HLC) pair (chapter 4.3)). The data and passing rates for the background and the signal depending on the HLC pairs are listed in table 7.1. Though the data size and data rate in the no-HLC case is slightly smaller the signal efficiency is at 12.0%. In the HLC case this efficiency is increased by a factor $\sim 1.3$ to 15.0%. Thus, it will be used as a veto in the filter configuration in IC59 and it is further discussed in chapter 7.4.

<table>
<thead>
<tr>
<th>Number of allowed HLC pairs</th>
<th>Corsika Passing Rate[%]</th>
<th>Corsika Data Rate[Hz]</th>
<th>Average $N_{chan}$</th>
<th>Corsika Data Size [MB/day]</th>
<th>Signal Passing Rate [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.12</td>
<td>2.1</td>
<td>14.6</td>
<td>744</td>
<td>12.0</td>
</tr>
<tr>
<td>1</td>
<td>0.22</td>
<td>4.0</td>
<td>14.5</td>
<td>1403</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Table 7.1: Passing rates and data rates with HLC pair compared to no HLC pair allowed

### 7.3.2 Velocity Veto

Different to the top veto events are not discarded due to the number of hits in the veto volume. Instead a test is applied to determine whether a hit in the veto volume is related to the no-veto hits. Therefore the hit velocity is calculated by:

$$v_j = -\frac{|\vec{x}_j - < \vec{x}>|}{(t_j - < t >)} \quad (7.2)$$

where $\vec{x}_j$ and $t_j$ are the position and time of the hit in an veto volume DOM. $< t >$ is the mean time of the hits in the inner volume.

The mean value $< \vec{x}>$ is calculated by:

$$< \vec{x}> = \frac{1}{\sum_i A_i} \sum_i A_i \cdot \vec{x}_i. \quad (7.3)$$

All inner core hits with one standard deviation around the mean time $< t >$ are included in the weighted center of gravity $< \vec{x}>$ (COG). $A_i$ is the amplitude of the hit in the inner core.

This veto considers the causality of the hits in the veto region. Hits with a velocity $v = c$ have a causal coherence with the COG. Deviant hits should be noise hits. A cut on the velocity can exclude a huge amount of background and noise hits. A closer look at equation 7.2 reveals that veto hits of downgoing events have a positive value of the velocity. In other words these hits are located before the inner core. A causal coherence is given for hits with $v = -c$. Cuts have to be done on greater values.

Figure 7.3 shows the distribution of the minimum and the maximum velocity. There are two peaks both at $+c$ and $-c$. The peak at $+c$ appears before the entrance into the inner core and the other at $-c$ appears after the event has left the inner core. Due to misreconstruction the distribution gets diffuse. With the condition $v_j < 0$ stopping or throughgoing events can be rejected. The
background has two peaks for the expected velocities and the signal has only one peak at \(-c\).

The tests are done with a cut on velocities greater than \(v = -0.1 \text{ m/ns}\), \(v = +0.0 \text{ m/ns}\) and \(v = +0.1 \text{ m/ns}\) with an upper layer veto of 37 DOMs (regard that \(|v| = 0.1 = c/3\)). Additional, the velocity cut \(v = +0.0\) is done with an upper layer veto of 30 and 45 DOMs. This has the purpose to reduce the inner volume. This has an influence on the calculation of the COG. The data and passing rates of the background and the signal are registered in table 7.2. With a constant upper layer veto of 37 DOMs and varying velocity cut it can be seen that the background appearance can be reduced from 0.15\% to 0.13\%. The signal passing rate is lowered by 0.8 percentage points and the data size is lowered by \(\sim 200 \text{ MB/day}\). Although the background rejection is notable the signal passing rate is low in comparison to the signal efficiency of the top veto in chapter 7.3.1. The velocity veto at \(v = +0.0 \text{ m/ns}\) with an upper layer veto of 37 DOMs as a default value, the extension of the upper layer veto rejects the background nearly four orders of magnitude and reduces the data size to approximately 300 \(\text{MB/day}\). This configuration is beyond all question because the signal passing rate is reduced to 5.6\%. In case of downsizing the upper layer veto to 30 DOMs the increase of the signal efficiency from 11.0\% to 11.6\% is insufficient at increasing the background passing rate to a factor \(\sim 1.5\).

![Figure 7.3: Distribution of the the minimum velocity (left) and the maximum velocity (right) for the signal (black) and for the background (grey)](image)

### 7.4 Final Configuration

As it was mentioned in chapter 7.3.1 and 7.2 the top veto of 37 DOMs with one HLC pair are combined with the angular selection and the first hit string veto. The velocity veto is not taken because it introduces systematic uncertainties due to the calculation of the velocity from the hit time and the DOM position. The top veto as it was used in IC40 is well-understood.

In case of a shortage in the satellite bandwidth the filter has to be fit with a tunable parameter. This tunable parameter is the lower zenith limit \(\theta_{\text{min}}\). Table 7.3 shows the data size, data rate and the signal passing rates for different values of \(\theta_{\text{min}}\). It appears that the data amount both the rates and the sizes decrease...
Table 7.2: Data and passing rates for the background and the signal for different combinations of the velocity cut (VC) and the upper layer veto (ULV)

<table>
<thead>
<tr>
<th>VC [m/s]</th>
<th>ULV</th>
<th>Corsika Passing Rate [%]</th>
<th>Corsika Data Rate [Hz]</th>
<th>Average $N_{chan}$</th>
<th>Corsika Data Size [MB/day]</th>
<th>Signal Passing Rate [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>30</td>
<td>0.22</td>
<td>4.0</td>
<td>15.4</td>
<td>1460</td>
<td>11.6</td>
</tr>
<tr>
<td>0.0</td>
<td>37</td>
<td>0.15</td>
<td>2.6</td>
<td>15.6</td>
<td>950</td>
<td>11.0</td>
</tr>
<tr>
<td>0.0</td>
<td>45</td>
<td>0.04</td>
<td>0.8</td>
<td>15.9</td>
<td>288</td>
<td>5.6</td>
</tr>
<tr>
<td>-0.1</td>
<td>37</td>
<td>0.13</td>
<td>2.3</td>
<td>15.1</td>
<td>820</td>
<td>10.3</td>
</tr>
<tr>
<td>+0.1</td>
<td>37</td>
<td>0.15</td>
<td>2.7</td>
<td>15.5</td>
<td>1006</td>
<td>11.1</td>
</tr>
</tbody>
</table>

Table 7.3: Passing rates and data rates with top veto and one HLC pair allowed

<table>
<thead>
<tr>
<th>$\theta_{min}[^\circ]$</th>
<th>Corsika Passing Rate [%]</th>
<th>Corsika Data Rate [Hz]</th>
<th>Average $N_{chan}$</th>
<th>Corsika Data Size [MB/day]</th>
<th>Signal Passing Rate [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.22</td>
<td>4.0</td>
<td>14.5</td>
<td>1403</td>
<td>15.0</td>
</tr>
<tr>
<td>5</td>
<td>0.22</td>
<td>3.9</td>
<td>14.5</td>
<td>1376</td>
<td>14.9</td>
</tr>
<tr>
<td>10</td>
<td>0.20</td>
<td>3.7</td>
<td>14.6</td>
<td>1293</td>
<td>14.8</td>
</tr>
<tr>
<td>15</td>
<td>0.19</td>
<td>3.4</td>
<td>14.6</td>
<td>1194</td>
<td>14.8</td>
</tr>
<tr>
<td>20</td>
<td>0.17</td>
<td>3.1</td>
<td>14.7</td>
<td>1103</td>
<td>14.7</td>
</tr>
<tr>
<td>25</td>
<td>0.16</td>
<td>2.9</td>
<td>14.8</td>
<td>1019</td>
<td>14.5</td>
</tr>
<tr>
<td>30</td>
<td>0.14</td>
<td>2.8</td>
<td>14.8</td>
<td>925</td>
<td>14.3</td>
</tr>
<tr>
<td>35</td>
<td>0.13</td>
<td>2.3</td>
<td>15.1</td>
<td>840</td>
<td>13.9</td>
</tr>
<tr>
<td>40</td>
<td>0.12</td>
<td>2.1</td>
<td>15.2</td>
<td>750</td>
<td>13.5</td>
</tr>
<tr>
<td>45</td>
<td>0.10</td>
<td>1.8</td>
<td>15.3</td>
<td>653</td>
<td>12.9</td>
</tr>
<tr>
<td>50</td>
<td>0.08</td>
<td>1.5</td>
<td>15.5</td>
<td>531</td>
<td>12.3</td>
</tr>
</tbody>
</table>

with rising low-zenith-cut. The rate of 4.0 Hz and the data size of $\sim 1400 \text{ MB day}^{-1}$ can be reduced to 1.5 Hz and $\sim 530 \text{ MB day}^{-1}$ due to the particular exclusion of atmospheric muons. The average value of $N_{chan}$ increases from 14.5 to 15.5. This is caused by the fact that atmospheric muons have a lower average $N_{chan}$. Moreover, the signal passing rate is reduced from 15.0% to 12.3%. Figure 7.4 shows the energy distribution for the chosen configuration. The efficiency is stable in the energy range from $E = 100 \text{ GeV}$ to $E = 10 \text{ TeV}$.
Figure 7.4: Energy distribution of the signal (one HLC in the top veto allowed) in arbitrary units. The energy spectrum is $\sim E^{-2}$. 
Chapter 8

Downgoing Starting Filter For IC59

In this chapter the filter performance is evaluated by comparing the simulated data to the measured data. The measured data that is used is the Run00113587, which has a duration of about 8 hours and contains $5.6 \cdot 10^7$ events. For the background study the Corsika data set 1628 with $3.0 \cdot 10^6$ events is taken. NuGen data set 1542 with a weighted spectrum $\sim E^{-2}$ and $7.4 \cdot 10^5$ events is used. Before the implementation of the new filters was done, a test run has been made.

8.1 Test Run

The event rate of the Downgoing Starting Filter 08 is $\sim 4.6$ Hz with a data amount of $\sim 1.8 \text{ GB/day}$. The proposed rates are $\sim 4.0$ Hz and $\sim 1.4 \text{ GB/day}$. The trigger rate is about 1800 Hz. About 0.26% of the triggered atmospheric muon induced events pass the filter. A detailed inspection of the increase of the data rate leads to the assumption that there is a difference between the simulation and real data. The data size is $\sim 400 \text{ MB/day}$ larger than the assumed one. This is about 1% of the available bandwidth and therefore this increase is acceptable. There are no problems with regard to the data transfer because there is enough bandwidth for the transmission. Hence, the configuration of the filter is not changed. The performance of the test data is investigated.

Figure 8.1 shows the angular distribution of the events in the measured data. There are no entries in the zenith distribution with a value lower than $-0.34$ which corresponds an angle of more than $\theta = 110^\circ$. The azimuth distribution is almost flat with the exception of small deviations which are caused by the geometry of the detector. Most events come from the southern hemisphere. This can be seen in the maximum at $\cos \theta = 1$ in the zenith distribution.

The left diagram in figure 8.2 shows the string which was first hit by an event. The first hit must be located on one of the inner strings (figure 7.1). Therefore, it is preferably positioned at the edge of the inner core. The two most hit strings with the first hit are those which are situated in the center of the kept azimuth region. In the right diagram of figure 8.2 the distribution of all hit DOMs is
Figure 8.1: Angular distribution (reconstructed) of the measured data in the test run. Left: Zenith. Right: Azimuth.

Figure 8.2: First hit strings (left) and all hit optical modules (right) in the test run.

shown. Most of the hits are in the lower 23 layers of the detector. There are a few hits in the veto region due to allowing an HLC pair in the veto region (see chapter 7.3.1). The number of hits in the DOMs near the veto region are lower than the other DOMs, because events with hits in the veto-near region are likely to have hits in the veto region as well and are therefore discarded. Furthermore the lowest DOMs of the detector are hit less frequently, because events which start downwards at the lower edge of the detector do not produce enough hits to pass the SMT8 trigger.
8.2 Performance

Figure 8.3 shows the time evolution of the filter rate from April to July 2009. As explained in chapter 6.4, a few runs with too low statistics or a different configuration are left out. On 20\textsuperscript{th} and 21\textsuperscript{st} of April 2009 the filter is switched on for a test run and since 20\textsuperscript{th} May the filter has been running. This curve shows also the seasonal variation due to the density of the atmosphere. Table 8.1 shows the rate of selected events, the trigger rate and the data sizes for ten day intervals. The relative error of these rates is < 1\%. The filter rate is nearly stable at \(\sim 0.26\%\) and the data size is \(\sim 1800\,\text{MB day}^{-1}\). The bandwidth and the data rate are estimated by Monte Carlo simulations. The measured filter rate does not agree with the expectation (\(\sim 0.22\%)\) as mentioned in chapter 8.1. 15.0\% of the defined signal pass the filter. In this section the performance of the filter with regard to the angular distribution, the hit strings and the hit optical modules is analyzed. It is tested whether the filter selects events as intended.

![Figure 8.3: Event rate versus time for the Downgoing Starting Filter 09 in 2009 [Mon].](image-url)
<table>
<thead>
<tr>
<th>Date</th>
<th>Rate of events selected with the filter [Hz]</th>
<th>Trigger rate [Hz]</th>
<th>Passing Rate [%]</th>
<th>Data Size [MB/day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 May 2009</td>
<td>4.335 ± 0.014</td>
<td>1649.31 ± 0.27</td>
<td>0.2629 ± 0.0008</td>
<td>1811.4 ± 5.8</td>
</tr>
<tr>
<td>31 May 2009</td>
<td>4.262 ± 0.012</td>
<td>1622.50 ± 0.24</td>
<td>0.2627 ± 0.0008</td>
<td>1780.7 ± 5.2</td>
</tr>
<tr>
<td>10 Jun 2009</td>
<td>4.228 ± 0.012</td>
<td>1611.91 ± 0.24</td>
<td>0.2623 ± 0.0008</td>
<td>1766.6 ± 5.2</td>
</tr>
<tr>
<td>20 Jun 2009</td>
<td>4.206 ± 0.012</td>
<td>1590.58 ± 0.24</td>
<td>0.2644 ± 0.0008</td>
<td>1757.2 ± 5.1</td>
</tr>
<tr>
<td>30 Jun 2009</td>
<td>4.182 ± 0.012</td>
<td>1582.49 ± 0.24</td>
<td>0.2643 ± 0.0008</td>
<td>1747.2 ± 5.1</td>
</tr>
<tr>
<td>10 Jul 2009</td>
<td>4.247 ± 0.012</td>
<td>1553.74 ± 0.24</td>
<td>0.2734 ± 0.0008</td>
<td>1774.6 ± 5.2</td>
</tr>
<tr>
<td>20 Jul 2009</td>
<td>4.149 ± 0.012</td>
<td>1577.36 ± 0.24</td>
<td>0.2630 ± 0.0008</td>
<td>1733.5 ± 5.1</td>
</tr>
<tr>
<td>30 Jul 2009</td>
<td>4.124 ± 0.012</td>
<td>1578.87 ± 0.24</td>
<td>0.2612 ± 0.0008</td>
<td>1723.0 ± 5.1</td>
</tr>
</tbody>
</table>

Table 8.1: Event rates in IC59
8.2. PERFORMANCE

8.2.1 Azimuth and Zenith Distribution

Figure 8.4 shows the azimuth distribution of measured data, background and signal for trigger and filter level. The distribution of the measured data and the background look similar. On trigger level the distributions are nearly flat with the exception of small deviations caused by the geometry of the detector. In some azimuth directions the detector is a little thicker. The signal has also the same structure caused by the shape of the inner core. On filter level the signal follows the same distribution for the uncut region. The filter rate per bin is close to the trigger bin rate because the signal is hardly cut (signal efficiency 35.4%). The distributions of the measured data and the simulated background are also nearly flat on filter level. Figure 8.5 shows the zenith distribution of measured data, background and signal for trigger and filter level. There is an accordance between the background and the measured data. The background simulation shows a higher rate for upgoing events on trigger level as the real data show. The upgoing events are mostly cut in the filter data. Therefore the higher event rate is not visible on filter level. The filter keeps downward going events in an azimuth range from 150° to 280°.
CHAPTER 8. DOWNGOING STARTING FILTER FOR IC59

Figure 8.4: Reconstructed azimuth distribution of triggered (empty markers/dotted line) and filtered (full markers/full line) events. Black points: measured data. Blue squares: Background. Green triangles: Signal (arbitrary normalization).

Figure 8.5: Reconstructed zenith distribution of triggered (empty markers/dotted line) and filtered (full markers/full line) events. Black points: measured data. Blue squares: Background. Green triangles: Signal (arbitrary normalization).
8.2.2 All Hit DOMs

In figure 8.6 the distribution of the hit DOMs of the signal, background and measured data are plotted on trigger and filter level. Both triggered and filtered measured data agree with the simulated background data. The trigger distribution is nearly flat. The bumpiness including the dip between the DOM layer 30 and 40 is caused by the ice properties (Light is more likely absorbed and the optical modules do not registers pulses). On filter level the measured data and the background distribution have less entries on optical module layers with a number lower than 37. This is caused by the top veto. The existing entries are caused by the HLC pair (two hots in the top veto region). These distributions increase from layer 37 to 40 and decrease slightly in the lowest two layers. The signal on trigger level has less hits in the veto region. The height of the signal definition volume is 370 m. This is 3 m below optical module layer 37. The true vertex (starting position) is located inside of that signal volume. Some DOMs in the top veto region can be hit by scattered light from a signal event. The hits in the veto region are not ascribed to violations of the filter conditions. The hits in the DOMs in the kept events are admissible.

8.2.3 First and Highest Hit DOMs

The left diagrams in figure 8.7 show the number of the highest hit DOM in an event on trigger and filter level. The DOMs in the upper layers are more often hit than DOMs of lower layers for all distributions on trigger level for the simulation and the measured data. This frequency decreases with rising DOM number. The bumpiness that is visible for all hit DOMs (see chapter 8.2.2) is caused by ice properties. The distribution abruptly stops at layer 57, as downgoing starting events below layer 57 do not activate the trigger. After filtering the measured data and the simulated background, distributions are flattened for lower DOM numbers. This is caused by the HLC pairs in the upper regions which are equally distributed. The right diagrams in figure 8.7 show the number of the first hit DOM in an event on trigger and filter level. These distributions show characteristics similar to the highest hit DOM distributions. There is no cut-off at lower layers. The first DOM can be located on the lowest layer, but the scattered light can hit enough DOMs for the triggering. The signal distributions of the first hit and the highest hit DOMs show mostly hits in DOMs with a number higher than 37 (beneath the dust layer). Thus, a veto with 37 layers fits. Only some noise hits or hits by light scattering occur in the upper region. There is no DOM layer where the signal is extremely cut.
Figure 8.6: Distribution of all hit DOMs (filter (full) and trigger (dotted)). Top (black): Measured data. Center (blue): Background. Bottom (green): Signal.
Figure 8.7: Left: The highest hit DOM in an event. Right: The first hit DOM in an event. Top: Measured data. Center: Background. Bottom: Signal. Trigger level (dotted) and filter level (full).
8.2.4 First Hit Strings

The first hit string of each event is shown in figure 8.8. The measured data and the background simulation look alike on trigger and on filter level. Both distributions are flat on trigger level. Only the DeepCore string is less often the first hit string on trigger level. The filtered distribution of the measured and the simulated background is nearly flat, but it shows a slightly higher rate on strings at the border of the inner string layer. Filtered events have more likely their first hit on the first string at the entrance in the inner string layer. The signal distribution on trigger level shows that the strings of the outer layer (compare with figure 7.1) are less often the first hit string. Signal events start in a volume that is a bit smaller than the inner core. Thus, their first hit is most likely on an inner string. Hits on the outer strings are most likely caused by signal events leaving the detector at one side. The measured data agrees with the expectation.
8.2.5 Vertices

Figure 8.9 shows the position of the interaction vertex after a likelihood reconstruction in the measured data. The left diagram is a top view of IceCube, where the string positions appear as hot spots. This is caused by the reconstruction method, which favors vertices close to the string positions. In the right diagram the rectangular shape of the detector is observed. The vertices appear more probable in the upper region. This is caused by the high rate of atmospheric muons. On filter level the range where the interaction occurs is reduced. The displayed region in the left diagram in figure 8.10 mainly represents the area enclosed by the inner strings. More clear than in the top view of the reconstructed vertices in IC40 (figure 6.15 (left)) the inner strings emerge. The likelihood algorithm reconstructs the vertices preferably on the position of inner strings. In the right diagram in figure 6.15 the vertices are situated in the lower part of the detector. The distribution of the reconstructed vertices show that the selected events start in the lower centered region of the detector. This area resembles the inner core, where the signal is expected to start. A combination of the side and the top view on filter level makes sure that events that start in the inner core are kept.

Figure 8.9: Position of the likelihood-reconstructed vertices of the measured data on trigger level. Left: Top view. Right: Side view.

Figure 8.10: Position of the likelihood-reconstructed vertices of the measured data on filter level. Left: Top view. Right: Side view.
8.2. PERFORMANCE

8.2.6 $N_{\text{chan}}$ distribution

Figure 8.11 shows the distribution of $N_{\text{chan}}$ for the simulated and the measured data on trigger level and on filter level. The data amount depends on the average value of $N_{\text{chan}}$. Therefore the run of the $N_{\text{chan}}$ curve has to be inspected. For low $N_{\text{chan}}$ the background simulation agrees with the measured data. These distributions diverge for higher values $N_{\text{chan}} > 40$ especially for the filtered data. The minimum of all this distributions in figure 8.11 is due to the trigger conditions $N_{\text{chan}} = 8$ and they decrease with rising number of hit DOMs per event. Events with 8 hits are kept if the zenith (reconstructed with the linefit) has a value of $\theta_{\text{linefit}} \geq 70^\circ$. This explains the small value in the first bin. The signal distribution does not fall as steep as the background distribution for rising $N_{\text{chan}}$. Signal events are expected to have higher number of hit DOMs than background events. This is the motivation for the trigger condition as mentioned in 7.2.

![Figure 8.11: $N_{\text{chan}}$ distribution of triggered (empty markers/dotted line) and filtered (full markers/full line) events. Black points: measured data. Blue squares: Background. Green triangles: Signal (arbitrary normalization).](image-url)
8.2.7 All Hit Strings

Figure 8.12 shows all hit strings on trigger and filter level in the measured and simulated data. The distribution on trigger level is nearly flat with the exception of the DeepCore string (string number 83). This is caused by the high quantum efficiency of the DeepCore DOMs. The filtered data has a higher rate hit strings in the inner core. This is caused by the first hit string veto. Events with first hits on outer stings are cut out of the data. Events that make their first hit in the inner core can later produce hit on outer strings.
8.2. PERFORMANCE

Measured and simulated background data look alike. The inner strings are more frequently hit for the triggered signal. Per definition the signal starts downwards in the inner core. The outer strings on filter level are for all three distribution less frequently hit, what is characteristic for the filtering.

8.2.8 Summary of the IC59 Filter Performance

The analysis of the angular distribution, the hit strings and the hit DOMs show that the Downgoing Starting Filter approximately agrees with the expectation. There are deviation in the simulated background and the measured data concerning the filter rate. Compared to the simulation, the rate of the measured data has increased from 4.0 Hz to 4.6 Hz. This is an issue of the Monte Carlo simulations and cannot be resolved within this study. The hit DOMs show the expected behavior depending on the depth of the ice. The azimuth cut is dominant, because it rejects approximately 36% of the measured data or the simulated background. The data is filtered with a nearly stable rate of $\sim 0.26\%$ and is transferred per satellite with 1.8 GB day$^{-1}$. 
Chapter 9  
Summary and Outlook

IceCube is a neutrino detector at the South Pole that detects the emitted Cherenkov light from muons. The search for neutrino sources was directed to the northern hemisphere so far. Upgoing tracks are caused by neutrino-induced muons and they are identified as signal events. Searching for neutrinos from the southern hemisphere downgoing events have to be analyzed. Muons are produced by cosmic rays in air shower in the atmosphere. These atmospheric muons are background for downgoing neutrino-induced muons. The zenith cut ensured the selection of downgoing events. For excluding the atmospheric muons starting tracks have to be identified in the detector. This is realized by a top veto and a first hit string veto. Due to the shape of the detector and the scarce outer layer strings in a certain direction the azimuth cut is applied.

This thesis is about the Downgoing Starting Filter. Simulated data are compared to measured data. This is done for IceCube with 40 strings and for IceCube with 59 strings. The Downgoing Starting Filter almost works at the pole as expected in the simulation. It increases the viewing field of IceCube to the southern hemisphere. A data set with potential neutrino-induced events is kept. This test data are used for DeepCore studies. In the IC40 study there are no deviation in the real and the simulation data. With a stable rate of 1.8 Hz (0.18% of the triggered data) the filtered data is transferred to the North with a bandwidth of 0.45 GB day. The hit DOMs and the hits strings are understood. The filter condition are violated for a few events. This is caused by the use of different software and it happens randomly.

A new veto method, the velocity veto, is tested in the simulation for IC59 and is compared to the common top veto as it was used in IC40. The top veto of 37 DOM layers with one HLC pair turn out to be the most efficient configuration for the filter. The signal passing rate is 35.4% and the signal efficiency is stable in the energy range from 100 GeV to 100 TeV.

The Monte Carlo simulation of IC59 assumes a rate of 4.3 Hz (0.24% of the triggered data) and a bandwidth of 1.5 GB day. But the measured data is filtered with 4.6 Hz (with a stable rate of 0.26%) and 1.8 GB day. As the measured data in IC40 the hit DOMs and the angular distributions are approximately in agreement with the simulated data.
When IceCube and DeepCore are finished the Downgoing Starting Filter is replaced by a DeepCore filter. The DeepCore extension plays the role of the inner core and IceCube represents the veto for DeepCore. Both, the top veto region and the outer string layer are constituted by IceCube DOMs. An azimuth cut is due to the approximate rotation symmetry not needed. The energy threshold is lowered to 10 GeV and the sensitivity for WIMPs and neutrino oscillations will be improved. DeepCore will be able to look at the northern hemisphere as ell as the southern hemisphere. Therefore, 6 strings will be placed round the center of IceCube. Each string consists of 60 DOMs with high quantum efficiency PMT, whereas 50 of them will be placed below the dust layer and 10 DOMs will be placed above the dust layer. The DOMs above the dust layer will improve the veto efficiency. This will reject the background by 6 orders of magnitude. The first DeepCore string is deployed in the 2009 season and one year later the DeepCore extension is completed. In 2011 all strings of the IceCube detector will be deployed.
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Erklärung

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet habe.

Aachen, 11. August 2009
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