On the Detection of Low Energy Neutrino Events with Full-Sky Acceptance with the IceCube DeepCore Detector

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Abstract

In the IceCube experiment, the dominant background to the signal of neutrino-induced muons are muons from cosmic ray interactions in the atmosphere. The position of the starting point of a muon track can be used for the discrimination of signal and background. Neutrino-induced muons can produce tracks which are starting inside the detector. Atmospheric muons always start outside. The LLHR-algorithm presented in this thesis allows the identification of starting tracks on a likelihood basis. For a given track, it calculates an estimation of the starting point (the neutrino interaction vertex) and the Log-Likelihood Ratio $LLHR$. The $LLHR$ value is a measure of the probability of the track to be starting. The value does not depend on the energy and the direction of the track.

The algorithm is applied to DeepCore, the low energy optimisation of IceCube. DeepCore will lower IceCube’s energy threshold to about 10 GeV and yield a significantly improved detector performance at low energies. Another objective of DeepCore is to extend IceCube’s field of view at low energies to the southern hemisphere. The immense background of atmospheric muons is rejected by the combination of a specialised veto and cuts on the output of the $LLHR$-algorithm.

Several detector layouts for DeepCore were studied to find the optimum configuration for a full-sky observation. The required background rejection is achieved with all studied geometries. However, the highest signal passing rate is obtained by placing as much instrumentation as possible in the clear ice in the lower part of the IceCube volume. With this optimisation, IceCube may detect several thousand low energy neutrino events per year.
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Chapter 1

Introduction

At any time the Earth is exposed to a bombardment of particles from space. Since their discovery by Victor Hess in 1912, these cosmic rays have been the subject of extensive research that established the field of astroparticle physics. The investigation of the cosmic rays has greatly enhanced our knowledge about the involved particles and shed light on many processes in the universe. In particular the energy spectrum and the composition of the cosmic rays have been studied and are well known today. The energy spectrum stretches out to remarkably high energies. Individual particles with more than $10^{20}$ eV have been detected. This is some orders of magnitude above the energy scale of ground-based particle accelerators. Prior to the era of particle accelerators, the cosmic rays were the main source for the discovery of new particles. Pions and muons, for example, were discovered in cosmic ray induced air showers. The composition of the cosmic rays is dominated by protons and light nuclei. Among the remainder are gamma rays, neutrinos and other particles. However, many questions remain unsolved. Among those are two fundamental problems:

- What are the sources of the cosmic rays of the highest energies?
- Which mechanism provides their enormous energy?

These questions have motivated various experiments. In particular the measurements of the primary component (protons and nuclei) and the gamma rays have proven successful. Another component of the cosmic rays are neutrinos. They are particularly suitable as cosmic messengers, since they are not deflected in galactic magnetic fields. Thus, they point directly to their sources. Furthermore, due to their small interaction cross-section, neutrinos travel through matter nearly unimpeded. They are not absorbed by dust and gas and allow the observation of regions in space not accessible by the other components.

However, the small cross-section also complicates their detection. Only a tiny fraction of all neutrinos passing a detector will actually be observed. Thus, a neutrino telescope has to instrument a huge volume to achieve acceptable event rates. The IceCube detector, which is currently under construction in the clear ice 2000 m below the geographic South Pole, will have an instrumented volume of 1 km$^3$. It detects neutrinos by measuring the Cherenkov light from secondary particles. A neutrino interacting within the earth or the atmosphere can produce a muon. In ice, the muon emits Cherenkov light which is detected by about 5000 individual detection modules. This observation method yields another challenge: background. Muons are not only produced by neutrino interactions, but (far more numerous) in interactions of the cosmic rays with the atmosphere. The IceCube detector is buried deep underground, shielding it to a certain degree from these atmospheric muons. Nevertheless, their trigger rate is some orders of magnitude above the rate of neutrino-induced events. For the suppression of these atmospheric muons, only events which propagate upwards in the detector are selected. Since only neutrinos have the ability to travel through the Earth, these events have to be neutrino-induced.

This thesis presents an approach to identify also downward going neutrino-induced events by searching for muon tracks which start inside the detector. Atmospheric muons are produced far outside the detector.
and should be detected as soon as they enter the instrumented volume. Tracks which start inside the detector are the result of a neutrino interaction. However, the large spacing of the individual detection modules allows atmospheric muons to leak in and stay undetected until they are deep inside the detector. These events have a signature very similar to starting (neutrino-induced) muons.

Chapter 2 of this thesis motivates the use of neutrinos as cosmic messengers and presents possible neutrino sources. Chapter 3 describes the physics behind neutrino detection. After an overview of the IceCube detector (chapters 4 to 6), chapter 7 presents an algorithm for the identification of starting tracks, based on a likelihood approach. The algorithm is tested with Monte Carlo data (chapter 8) and applied to DeepCore, the low energy optimisation of IceCube (chapter 9). The algorithm is used to achieve the required background rejection. The focus of the last part (chapters 10 and 11) is the optimisation of the detector layout of DeepCore with respect to background rejection and signal efficiency.
Chapter 2

Neutrino Astrophysics

2.1 Cosmic Rays

Cosmic rays are highly energetic particles hitting the Earth’s atmosphere from space. About 90% of the cosmic rays are protons and 9% are He nuclei [Gai90]. Among the remainder are gamma ray photons, electrons, heavier nuclei and other particles. When a cosmic ray particle hits an air molecule, the molecule is destroyed and a shower of secondary particles is produced. These particles also interact with air molecules, producing further showers. The result is a cascade of relativistic particles, which can stretch out several kilometres into the atmosphere. This extensive air shower can be observed by detecting the secondary particles on the ground.

Even today, it is not entirely known where the cosmic rays originate from. Only recently the Pierre Auger experiment found an anisotropy in the arrival direction of the cosmic rays of the highest energies. A possible correlation with known Active Galactic Nuclei is currently being discussed [A+07a]. Other prominent source candidates for high energy cosmic rays are Gamma Ray Bursts and Supernova remnants (see chapter 2.4.1). Although the origin of the cosmic rays is not yet completely determined, the energy spectrum and the composition have been measured in detail by many experiments.

The energy spectrum of the cosmic rays stretches out over 12 orders of magnitude in the energy and over 30 orders of magnitude in the flux (see Fig. 2.1). Above \(10^9\) eV it can be described by a power law \(E^{-\gamma}\). Between \(10^9\) eV and \(10^{15}\) eV the spectral index is \(\gamma \approx 2.7\). The cosmic rays in this domain are presumably of galactic origin. Around \(10^{15}\) eV, at the so-called knee, the spectrum steepens to \(\gamma \approx 3.0\). Supposedly, this steepening occurs because particles of this energy have gyroradii large enough to escape our galaxy. Besides, \(10^{15}\) eV is presumably about the maximum energy of particles accelerated by supernovae (see chapter 2.2). Another acceleration mechanism and another source type has to be responsible for the cosmic rays with energies above. At about \(5 \cdot 10^{18}\) eV (the ankle) the spectrum flattens again. The flattening is believed to be a result of the transition to cosmic rays of extragalactic origin. This is however speculative and still under debate.

At energies above \(10^{21}\) eV, the GZK\(^1\)-effect occurs. Cosmic ray protons interact with the Cosmic Microwave Background and produce a \(\Delta\)-resonance, which decays to a pion and a nucleon:

\[
p + \gamma_{\text{CMB}} \rightarrow \Delta^+,
\Delta^+ \rightarrow \pi^0 + p \quad \text{or} \quad \Delta^+ \rightarrow \pi^+ + n.
\]  

(2.1)

Thus, the cosmic ray flux is suppressed at the highest energies. The threshold energy for this reaction is given by

\[
\frac{m_\Delta^2}{2E_\gamma} \approx 10^{20} \text{ eV}
\]

(2.2)

\(^1\)Greisen-Zatsepin-Kuzmin
The mean free path of a cosmic ray particle with an energy above this threshold is of the order of some ten Mpc (see Fig. 2.2). If particles of these high energies are observed, they must have been produced in nearby sources. At the highest energies, the Pierre Auger Observatory has observed a decrease in the flux which is compatible with the hypothesis of the GZK-cutoff [A⁺07a]. A side-effect of the GZK-cutoff is the neutrino flux from the pion decay. However, at such high energies, the flux is less than 1 particle per year and km² so that IceCube may detect only 1 event in 3 years.

2.2 Fermi Acceleration

Not only the origin of the cosmic rays is still unknown. Also the question about the acceleration mechanism that provides their enormously high energies is still not answered satisfactorily. A possible mechanism is the Fermi acceleration. Enrico Fermi developed a theoretical model to explain particle acceleration by scattering at gas clouds confined by strong magnetic fields [Fer49]. A particle with the relativistic velocity \( v \) scatters at the magnetic field of a cloud moving with \( u_c \ll v \). A typical velocity of such a gas cloud is 15 km/s. In the collision the particle gains or looses energy depending on whether the collision is head-on or tail-on (see Fig. 2.3). The particle enters the cloud at the angle \( \theta_1 \). It scatters many times elastically at the magnetic fields and finally leaves the cloud under the angle \( \theta_2 \). In the rest frame of the
cloud, the energy of the particle before the collision is given by [Gai90]

\[ E'_1 = \gamma E_1 (1 - \beta_c \cos \theta_1), \]

with \( \beta_c = u_c/c \) and the Lorentz factor \( \gamma = (1 - \beta_c^2)^{1/2} \). The quantities marked with a prime are measured in the rest frame of the cloud. Due to the elastic scattering within the cloud, in the moving frame the particle energy is not changed: \( E'_2 = E'_1 \). In the lab frame, however, the energy after the scattering is

\[ E_2 = \gamma E'_2 (1 + \beta_c \cos \theta'_2). \]

The energy change is

\[ \frac{\Delta E}{E} = \frac{E_2 - E_1}{E_1} = \gamma^2 (1 - \beta_c \cos \theta_1) (1 + \beta_c \cos \theta'_2). \]

Averaging over all angles \( \theta_1 \) and \( \theta_2 \) in relativistic treatment yields the average energy gain per encounter:

\[ \varepsilon = \left\langle \frac{\Delta E}{E} \right\rangle = \frac{1 + \frac{4}{3} \beta_c^2}{1 - \beta_c^2} - 1 \approx \frac{4}{3} \beta_c^2. \]

Since the energy gain is proportional to \( \beta_c^2 \), this mechanism is called second order Fermi acceleration. The major problem of this concept is that it is by far too slow. With \( \beta_c^2 < 10^{-8} \), this mechanism is too inefficient to accelerate protons to the observed energies within reasonable timescales.

A more plausible scenario is the shock acceleration. A shock front (for example from a supernova explosion) moves with velocity \(-u_1\) (see Fig. 2.4). The typical velocity of a shock front is of the order of \(10^8\) km/s and thus much larger than the typical velocity of a gas cloud. The shocked material moves with \(u_2 < u_1\) away from the shock front. In the lab frame, it moves with \(u_s = -u_1 + u_2\). A particle enters the shocked region with the energy \(E_1\). As in the second order mechanism it gains energy by scattering. In this case, however, the average energy gain is proportional to \(\beta_s = u_s/c\) [Gai90]:

\[ \varepsilon = \frac{\Delta E}{E} \approx \frac{4}{3} \beta_s. \]

This first order mechanism is thus more effective to accelerate particles to high energies.
Figure 2.3: Fermi acceleration by magnetic gas clouds. A particle is accelerated by scattering at the magnetic field of a gas cloud (right). Depending on the relative movement the particle gains or loses energy (left).

A particle will encounter many interactions before it escapes the acceleration site. The mean energy after \( n \) interactions is

\[
E_n = E_0 (1 + \epsilon)^n, \tag{2.8}
\]

where \( E_0 \) is the initial energy. If, in each interaction, \( p \) is the probability of a particle to escape the acceleration process, the probability for undergoing \( n \) interactions is \( (1 - p)^n \). The number of interactions \( n_0 \) required to accelerate a particle from \( E_0 \) to \( E \) is

\[
n_0 = \frac{\ln(E/E_0)}{\ln(1 + \epsilon)}. \tag{2.9}
\]

The fraction of particles \( N(E) \) with an energy larger than \( E \) is given by [Gai90]

\[
N(E) = \left(\frac{1 - p}{p}\right)^{n_0} \propto \frac{1}{p} \left(\frac{E}{E_0}\right)^{-\gamma}, \quad \gamma = \frac{\ln(1/(1 - p))}{\ln(1 + \epsilon)}. \tag{2.10}
\]

The spectral index \( \gamma \) depends on the properties of the shock front. Typical values are \( 2.1 \leq \gamma \leq 2.4 \). However, the observed spectrum has a spectral index \( \gamma \approx 2.7 \). Presumably, this difference is caused by the increased probability to escape from our galaxy for high energy particles.

### 2.3 Cosmic Information Messengers

Observation of the cosmic rays allows to gain knowledge about the particles themselves. Besides, the cosmic rays carry information about their sources. Therefore, they are sometimes referred to as *Cosmic Information Messengers*. For the study of cosmic sources, each component of the cosmic rays and has its specific advantages and disadvantages. Fig. 2.8 shows a synopsis of the different components and their suitability as cosmic messengers.
Figure 2.4: Particle acceleration in a plane shock front.

**Charged Cosmic Rays** The primary component (protons and nuclei) of the cosmic rays has been studied for nearly a century by now. Since these particles interact with the atmosphere (see chapter 2.1), direct measurements are only possible with balloon-borne experiments (BESS$^2$) [S$^{+00}$] or satellites (AMS$^3$) [AMS00]. However, these experiments are limited in size. Due to the steeply falling spectrum, they can collect reasonable statistics only at energies below $10^{14}$ eV, where the charged cosmic rays are fully isotropised due to deflection in magnetic fields. Thus, the observed arrival direction does not point to the production site. Only above $10^{19}$ eV the deflection can be disregarded [TT05]. Cosmic rays of such energies can be observed indirectly by ground based air shower arrays like the Pierre Auger Observatory [A$^{+04a}$], which covers an area of about 3000 km$^2$. However, at the highest energies above $10^{21}$ eV, the flux is suppressed by the GZK-cutoff (Eqs. 2.1 and 2.2). Therefore, the most interesting range for the observation of charged cosmic rays is the relatively small window between $10^{19}$ eV and $10^{21}$ eV.

**Gamma Rays** High energy photons are another component of the cosmic rays. Direct measurements are conducted by satellite-borne experiments like EGRET$^4$ on the CGRO$^5$ satellite [K$^{+88}$]. Like the charged cosmic rays, the photons interact with the atmosphere and induce extensive air showers, which are measured by Cherenkov telescopes like H.E.S.S.$^6$ [A$^{+97}$] or MAGIC$^7$ [B$^{+08}$]. Similar to the GZK-effect, the explorable distance depends on the photon energy. The gamma rays interact with other photons by pair production of electrons:

$$\gamma\gamma \rightarrow e^+ e^- \quad \text{for} \quad 4 \cdot E_{\gamma} \cdot E_{\gamma} > 2 \cdot m_e^2.$$

These interactions can occur with all sorts of photons: The Cosmic Microwave Background, visible or infrared starlight and radio waves. The mean free path for a gamma ray photon with an energy above some TeV is below 100 Mpc [CA97].

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2Balloon-borne Experiment with a Superconducting Spectrometer, [http://bess.kek.jp](http://bess.kek.jp)
3Alpha Magnetic Spectrometer, [http://ams.cern.ch](http://ams.cern.ch)
4Energetic Gamma-Ray Experiment Telescope
Electrically Neutral Cosmic Rays  A third component of the cosmic rays are electrically neutral particles, in particular neutrons. Like gamma rays, they are not deflected in magnetic fields. However, all these particles decay after relatively short times. With a lifetime of 886 s, the neutron is by far the most long-lived among them [Y$^+$06]. A neutron of $10^{15}$ eV can travel at most some ten kpc before it decays. This is roughly the distance from the Earth to the Galactic Centre. Thus, these particles are not suitable as messengers from other galaxies.

Neutrinos  Neutrinos are in some sense the ideal cosmic messengers. They are not deflected in magnetic fields, they do not decay and they do not interact with the Cosmic Microwave Background or with any interstellar matter. The mean free path $\lambda$ of a neutrino is given by

$$\lambda = \frac{1}{n\sigma(E)},$$  \hspace{1cm} (2.12)

where $n$ is the matter density of the universe and $\sigma(E)$ is the neutrino cross-section. For a neutrino with $E = 1$ TeV, the cross-section is approximately $10^{-35}$ cm$^2$ [Gai90]. With $n \approx 6$ nucleons/m$^3$ (critical density of the universe) this yields a mean free path some orders of magnitude larger than the radius of the observable universe. Furthermore, whereas a photon needs some thousand years to diffuse from the centre of a star to the surface, a neutrino can escape instantly. Hence, neutrino observation allows to look into the interior of a source. However, the neutrino’s reluctance to interact is of disadvantage for their detection. The extremely small cross-section causes relatively low event rates. To get at least a handful of events within a reasonable amount of time, detector volumina on the km$^3$-scale are required. More about the neutrino detection can be found in chapter 3. The IceCube experiment is described in detail in chapter 4.

2.4 High Energy Neutrino Sources

Even though neutrinos are ideal cosmic messengers, a huge neutrino telescope like IceCube would be meaningless if there were no cosmic sources. Fortunately, nature let explode a near supernova in the year 1987. Neutrinos from that explosion were detected in the Kamiokande and IMB$^8$ experiments [H$^+$87, B$^+$87]. Solar neutrinos have been detected even since the late 60’s in the Homestake experiment [DHH68]. Neutrinos from these sources have energies far below the IceCube energy threshold, but it is evident that neutrinos are produced in cosmic events. Some classes of high energy neutrino sources shall be presented here.

2.4.1 Cosmic Sources

To produce neutrinos, a cosmic source requires acceleration of hadrons to very high energies above $10^{20}$ eV. The hadronic beam interacts with a denser target medium like a molecular cloud, a so-called beam dump. This process is illustrated in Fig. 2.8. In proton-proton interactions in the beam dump pions are produced. The pion decay, finally, produces neutrinos:

$$\pi^0 \rightarrow \gamma \gamma,$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu,$$  \hspace{1cm} (2.13)
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu,$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu,$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu.$$
The medium of the beam dump has to be dense enough to for the hadrons to interact, but not too dense, since the pions and muons have to decay rather than re-interact. The above reaction chain produces neutrinos at a flavour ratio of \((v_e : v_\mu : v_\tau) = (1 : 2 : 0)\). Since the distance to the sources is large compared to the oscillation length, the composition is changed by neutrino oscillations. At the Earth, a composition of \((v_e : v_\mu : v_\tau) = (1 : 1 : 1)\) is expected. This is described in detail in [GM03].

This process is believed to be realised in Supernova Remnants, Active Galactic Nuclei and Gamma Ray Bursts. These types of point sources may be detectable with IceCube. The decay of Dark Matter particles is an example for an accelerator-free source.

### Supernovae and Supernova Remnants

The best understood sources of cosmic neutrinos are probably supernovae, the final explosions of high mass stars. During most of its lifetime, a star is in a state of equilibrium between the gravitation and the radiation pressure caused by the nuclear fusion in the core. After all the fuel is spent, the radiation pressure falls off. The gravitation prevails and the star collapses to a neutron star or a black hole. In this process, the inverse beta decay compresses the protons and electrons of the star to neutrons, thereby producing huge amounts of electron neutrinos. More than 99% of the energy of a supernova explosion (\(\sim 10^{56}\) eV) is released in their kinetic energy. Since this enormous energy is distributed over \(\sim 10^{58}\) neutrinos, the energy of each neutrino is only of the order of some ten MeV [Bea99]. On the IceCube energy scale, this is far below the threshold necessary to detect the individual neutrino interaction. However, the number of neutrinos from a nearby supernova would be immense, producing small cascades anywhere in the detector. This would result in a simultaneous increase in the counting rate of all DOMs. IceCube is therefore connected to the Supernova Early Warning System SNEWS\(^9\).

Although the neutrinos produced directly in the supernova explosion have typical energies far below the IceCube energy threshold, the shock front of the explosion can be a source of high energy neutrinos. During the collapse, the outer shell of the star is blown away and starts to propagate through the solar wind of the predecessor star and the interstellar medium. This shock front accelerates particles up to about 100 TeV (see chapter 2.2). The majority of the cosmic rays with lower energies is believed to originate from these so-called shell-type supernova remnants (SNR) [Fun07].

Another class of supernova remnants are Pulsar Wind Nebulae (PWN), also called plerions\(^10\). Like shell-type SNR, plerions are acceleration sites and sources of intensive gamma ray emission [Fun07]. Presumably, the acceleration is powered by the rotation of the pulsar which is found in the centre of the nebula. However, the gamma rays are believed to result from Inverse Compton scattering of electrons and not from hadronic interactions and subsequent pion decay. In such a leptonic acceleration scenario, no neutrinos are expected. The best known example of a PWN is the Crab nebula (Fig. 2.5), the remainder of the supernova of the year 1054.

### Active Galactic Nuclei (AGN)

In the centre of many galaxies, regions of extraordinarily high luminosity are found. These Active Galactic Nuclei are among the most luminous objects in the universe. The emission of AGN is not limited to a certain wavelength band, but covers the whole electromagnetic spectrum from radio waves to gamma rays. It is believed that in the centre of active galaxies a supermassive black hole \((10^6 - 10^9\) solar masses\) accretes matter from the surrounding galaxy. Due to the conservation of angular momentum, an accretion disc perpendicular to the rotation axis of the black hole

\(^9\)http://snews.bnl.gov
\(^10\)from the greek πλήρης, meaning ‘full’. In contrast to shell-type SNR, plerions show a filled and bright central region. The brightness decreases gradually towards the outer regions.
Figure 2.5: The Crab nebula, a pulsar wind nebula [NAS].

is formed. It contains a plasma, whose movement around the centre of the disc induces strong magnetic fields. In the vicinity of the black hole, the magnetic field lines are wound up. As a consequence, matter is ejected along the rotation axis at relativistic velocities, forming so-called jets. They can stretch out up to some Mpc into the surrounding space. The strong magnetic fields, high velocities and mass concentrations make the jets of AGN an ideal candidate for sites of Fermi acceleration. Presumably, the jets are capable of accelerating particles up to the highest energies in the cosmic ray spectrum [Lov76]. In hadronic interactions in the accelerated matter pions are produced. Their decay according to Eq. 2.13 produces neutrinos. Fig. 2.6 shows a schematic view of an AGN.

Figure 2.6: Schematic view of the particle acceleration in the jet of an AGN [Buc98].
2.4 High Energy Neutrino Sources

**Gamma Ray Bursts (GRB)** In contrast to the steady sources described above, Gamma Ray Bursts are only short flashes of high energy photons, randomly distributed over the whole sky. A typical GRB lasts only a couple of seconds. However, they are the most luminous events in the universe since the Big Bang. GRB are expected to accelerate charged particles up to $10^{20}$ eV [Lov76]. Thus, they are another possible source for cosmic rays of the highest energies. The causes of these massive eruptions is still under debate. A likely explanation connects GRB with the gravitational collapse of very massive stars or the collision of two neutron stars or black holes. Similar to the AGN model, strong magnetic fields are present which yield bipolar jets along the rotation axis of the object. Matter is ejected at relativistic velocities along this axis. The jets accelerate charged particles which in turn lose their kinetic energy due to radiation in the gamma ray band [KGH01]. Pions are produced in interactions between the accelerated protons and these gamma ray photons. The pions decay according to Eq. 2.13, producing neutrinos with energies up to $10^{18}$ eV [Wax00].

**Dark Matter** The visible matter accounts for only a small fraction of the mass observed in the visible universe [T+04]. Several astronomical observations (e.g. rotation curves of galaxies or gravitational lensing) suggest the existence of another type of matter, that does neither emit nor reflect electromagnetic radiation. Therefore, it is called Dark Matter. To some extent it consists of normal baryonic matter that simply does not emit enough light to be visible (e.g. planets, faint stars, brown dwarfs, dust) [FFG00]. Neutrinos also account for a small part of the Dark Matter. However, all these contributions can only amount to a small fraction of the Dark Matter. The nature of the remaining part is not known until today. A possible solution to this problem is the hypothetical existence of an additional particle which interacts only through the weak nuclear force and the gravity, the so-called WIMP\textsuperscript{11}. The most promising candidate for the WIMP is the neutralino, the lightest particle predicted by supersymmetric theories [JKG96]. The mass of the neutralino is expected to be between 50 GeV and the lower TeV range, depending on the theoretical assumptions. Due to their large mass, neutralinos are captured in the gravitational potential of massive objects. They accumulate, since they only interact via the weak force and the gravity. With time, the neutralino density increases by many orders of magnitude. However, with increasing density, the probability for neutralino annihilations increases quadratically. The decay of the annihilation products can produce neutrinos. Thus, an increased neutrino flux is expected from nearby massive objects like the Sun or the Earth.

### 2.4.2 Terrestrial Sources

The extensive air showers, which result from cosmic ray interactions in the atmosphere, contain many different particles, among them pions, kaons and charmed mesons. If these particles decay before they can re-interact again, neutrinos are produced. Due to their large number, these atmospheric neutrinos appear as the dominant background to the cosmic neutrinos in the IceCube detector (see chapter 4.6 and Fig. 2.8). The most important contribution to the atmospheric neutrino flux comes from pion and kaon decay. It is described by [Gai90]

$$
\frac{dN_\nu}{dE_\nu} = N_0(E_\nu) \left[ \frac{A_{\pi\nu}}{1 - Z_{NN}} \left( \frac{A_{\pi\nu}}{1 + B_{\pi\nu} \cos \frac{E_\nu}{E_\pi}} + 0.635 \frac{A_{K\nu}}{1 + B_{K\nu} \cos \frac{E_\nu}{E_K}} \right) \right].
$$

\textsuperscript{11}Weakly Interacting Massive Particle
The parameters of this equation are described below:

- The constants \( A_i, B_i, i = (\pi, K) \) take into account the masses and the attenuation length of the involved particles as well as the spectral index of the primary energy spectrum.

- The characteristic energy \( \varepsilon_i, i = (\pi, K) \), reflects the ratio of decay and interaction in the atmosphere. For \( E_\nu < \varepsilon_i \) all particles decay in the atmosphere and the neutrino energy spectrum follows the primary spectrum, i.e. \( \gamma \approx 2.7 \). For higher energies, the mesons start to interact with the atmosphere and the spectrum steepens by approximately one power of \( E \), yielding \( \gamma \approx 3.7 \). The numerical value of this energy for pions and kaons is \( \varepsilon_\pi \approx 115 \text{ GeV} \) and \( \varepsilon_K \approx 850 \text{ GeV} \), respectively [Gai90].

- \( \theta \) is the nadir angle. The atmospheric neutrino flux shows an angular dependency with fewer neutrinos from vertical directions. This is due to the fact that mesons from horizontal showers travel a larger distance through the less dense layers of the upper atmosphere. Thus, their interaction probability is smaller and they have a higher chance to decay and produce neutrinos. Vertical particles tend to interact rather than decay.

- The factor 0.635 in the kaon term describes the branching ratio \( K^+ \rightarrow \mu + \nu_\mu \). For the reaction \( \pi^+ \rightarrow \mu + \nu_\mu \) this factor is approximately 99.99% [Y+06].

The neutrinos produced by the decay of charmed particles are called prompt neutrinos. Their flux can be described in a similar manner with \( \varepsilon_{\text{charm}} = 10^7 \text{ GeV} \). The lifetime of these particles is so short that nearly all of them decay in the atmosphere, even those from vertical directions. Thus, the flux is isotropic and has a spectral index \( \gamma = 2.7 \) also at high energies. Above \( \sim 100\text{TeV} \) prompt neutrinos could dominate the atmospheric neutrino flux. However, this flux has never been measured. Fig. 2.7 shows the fraction of these three contributions to the atmospheric muon neutrino flux as a function of the neutrino energy.

![Figure 2.7: Fraction of the contributions of pion, kaon and charm decays to the flux of atmospheric muon neutrinos [ALL05].](image)

Muons are produced in air showers, too. Due to their long lifetime many of them reach the ground instead of decaying. Therefore, muon decay is not relevant for the neutrino production. However, atmospheric muons appear as the dominant background for neutrino-induced events in a Cherenkov detector like IceCube (see Fig. 2.8).
Figure 2.8: Schematic view of the production, propagation and detection of various cosmic messengers. Protons are accelerated in a cosmic accelerator. They interact with a target medium, producing all sorts of particles. Neutrons decay quickly, photons are absorbed in matter, protons are deflected in magnetic fields. Only neutrinos point to the source. If a neutrino interacts within the Earth or the atmosphere, it produces a muon which can be observed in a Cherenkov detector. However, muons can also be induced by atmospheric neutrinos or result directly from an extensive air shower.
Chapter 3

Neutrino Detection

3.1 Neutrino Interactions

Neutrinos interact with matter in two different channels. In a *neutral current* interaction, the neutrino survives:

\[ \nu_l + N \rightarrow \nu_l + X. \quad (3.1) \]

\(N\) is the target nucleus, \(X\) denotes a hadronic cascade. The other possible interaction channel is the *charged current* interaction. Here, the neutrino produces a charged lepton of the same flavour:

\[ \nu_l + N \rightarrow l + X. \quad (3.2) \]

Since the neutrino interacts only weakly, a direct observation is not possible. Most detectors are sensitive to the reaction products from a charged current interaction. One approach for neutrino detection is the radiochemical method. In a charged current interaction, the nucleus \(N\) is also altered. The number of transmuted nuclei gives the number of neutrino interactions. The GALLEX\(^1\) experiment, for example, searched for Germanium atoms produced in a tank filled with Gallium by the reaction \([\text{H}^+99]\)

\[ \nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^- . \quad (3.3) \]

Naturally, this type of experiment only allows a counting, but no track reconstruction of the events. For a measurement of the neutrino direction the observation of the produced lepton or the cascade is necessary. In a transparent medium, the Cherenkov effect allows a reconstruction of the lepton track.

3.2 Neutrino Detection with the Cherenkov Effect

The *Cherenkov effect* occurs when a charged particle travels through a transparent medium with the refractive index \(n\) at a velocity \(v\), that exceeds the speed of light in that medium:

\[ v \geq c_n = \frac{c}{n}, \quad \text{or} \quad \beta = \frac{v}{c} \geq \frac{1}{n}. \quad (3.4) \]

For muons in ice, this corresponds to an energy threshold of about 160 MeV. The particle polarises and displaces the electrons of the surrounding medium along the track. Like all accelerated charges, the electrons emit electromagnetic radiation, which diffuses with the phase velocity \(c_n\). Constructive interference occurs on the surface of a cone, similar to the Mach cone of supersonic aircraft. This yields

\(^1\)Gallium Experiment, [http://www.mpi-hd.mpg.de/nuastro/galex.html](http://www.mpi-hd.mpg.de/nuastro/galex.html)
a wavefront of light, emitted under the half opening angle of the cone, the Cherenkov angle \( \theta_c \). This is illustrated in Fig. 3.1. The Cherenkov angle \( \theta_c \) is given by [Yö16]

\[
\theta_c = \arccos \frac{1}{n\beta}.
\]  

(3.5)

For highly relativistic muons travelling through ice, \( \beta \approx 1 \) and \( n \approx 1.3 \), the Cherenkov angle is \( \theta_c \approx 41^\circ \). A muon produced by a high energy neutrino has about the same flight direction as the initial neutrino. The angle \( \alpha \) in between can be approximated by [LM00]

\[
\alpha \approx \frac{0.7^\circ}{(E_v/\text{TeV})^{0.7}}.
\]

(3.6)

Since the Cherenkov angle depends only on \( \beta \approx 1 \), it is possible to reconstruct the flight direction of the muon. Because of the small angle \( \alpha \), the reconstructed muon track is a good approximation for the neutrino direction.

The number of photons produced per length and in a certain wavelength range is given by the Frank-Tamm formula [Yö16]:

\[
\frac{d^2 N}{dxd\lambda} = \frac{2\pi \alpha}{\lambda^2} \left( 1 - \frac{1}{n^2\beta^2} \right),
\]

(3.7)

where \( \alpha \) is the Sommerfeld fine-structure constant, \( \alpha^{-1} \approx 137 \). In the wavelength range from 300 nm to 500 nm, a muon in ice produces about 250 photons per cm. The energy loss of the muon due to Cherenkov radiation is

\[
\left. \frac{dE_{\mu}}{dx} \right|_{\text{Cherenkov}} = \frac{dN}{dx} \langle E_\gamma \rangle = \frac{dN}{dx} \frac{hc}{\langle \lambda \rangle} \approx 850 \text{ eV/cm}.
\]

(3.8)

Although the Cherenkov effect occurs with all leptonic flavours, only muons produce long tracks, which allow a good directional reconstruction. There are other signatures for the two remaining flavours (see chapter 3.4). However, this study is only concerned with muon tracks.

This effect is the detection mechanism of IceCube as well as many other experiments. Due to the very small neutrino interaction cross-section and small fluxes, huge volumina have to be instrumented. To find large quantities of a transparent medium is the first problem of neutrino astronomy. Moreover, the
experiment has to be shielded from the reaction products of cosmic rays interactions in the atmosphere. Experiments like Super-Kamiokande\(^2\) or SNO\(^3\) are located deep underground in abandoned caverns of mines. The size of these detectors is of course limited. The most obvious choice of location for an even larger detector is the deep sea or a deep lake. This idea has been realised for example by the now abandoned DUMAND\(^4\) experiment off the coast of Hawaii or the NT-200 telescope in the lake Baikal\(^5\). Currently the ANTARES\(^6\) array is deployed in the Mediterranean sea. IceCube and its predecessor AMANDA\(^7\) rely on the Antarctic ice, which is transparent in depths below 1300 m (see chapter 4.1). The same concept forms the basis of all these detectors: A large volume is instrumented with a regular lattice of photodetectors for the detection of the Cherenkov light of through-going particles.

### 3.3 Other Processes of Muon Energy Loss

Although the Cherenkov effect is the essential interaction mechanism for the muon detection, it is not the dominant process of muon energy loss. Instead, the energy loss is dominated by ionisation of the detector medium, bremsstrahlung, pair production and nuclear reactions with ice molecules. Ionisation yields a continuous energy loss, the other processes occur stochastically along the muon track. In these interactions secondary particles are produced. Due to the high Lorentz boost, their flight direction is closely aligned to that of the primary muon. They also emit Cherenkov photons, far more than the initial muon. It is this secondary Cherenkov emission which makes the detection of the muon possible.

**Ionisation** The energy required to ionise an ice molecule is of the order of some eV. Continuous ionisation is the dominant process of muon energy loss below \(E_\mu \approx 600\text{GeV}\). It is described by the Bethe-Bloch formula \([Y^+06]\):

\[
\frac{dE_\mu}{dx}_{\text{ionisation}} \approx \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \left( \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} \right) - \beta^2 - \frac{\delta}{2} \right]. \tag{3.9}
\]

The parameters are described below:

- \(Z\) and \(A\) are the proton and the nucleon number of the target nucleus.
- \(m_e c^2 = 511\text{keV}\) is the electron rest energy.
- \(\beta = \frac{v}{c}\) and \(\gamma = \frac{1}{\sqrt{1-\beta^2}}\).
- \(T_{\text{max}} = \frac{2m_e \beta^2}{m_\mu + m_e + 2m_e E_\mu / c^2}\) is the maximum transfer of kinetic energy in a muon-electron collision.
- \(I\) is the mean ionisation energy of the target material.
- \(\delta\) is a density correction term.

---

\(^2\)http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html  
\(^3\)Sudbury Neutrino Observatory, http://www.sno.phy.queensu.ca  
\(^5\)http://baikalweb.jinr.ru  
\(^7\)Antarctic Muon And Neutrino Detector Array, http://amanda.uci.edu/
Bremsstrahlung If the muon is deflected in the electromagnetic field of a nucleus, it emits bremsstrahlung. The average energy loss is proportional to the muon energy $E_\mu$ [Gru00]:

$$\frac{dE_\mu}{dx}_{\text{bremsstrahlung}} \propto \frac{Z^2}{A} \ln \left( \frac{183}{Z^{1/3}} \right) E_\mu. \quad (3.10)$$

Pair Production The muon can produce virtual photons. If their energy is sufficient, these can in turn produce particle-antiparticle pairs. The energy threshold is the sum of the rest masses of the particles to be produced. Thus, for $e^+e^-$ pairs it amounts to 1 MeV. For $\mu^+\mu^-$ pairs it adds up to about 210 MeV. The average muon energy loss due to pair production is also proportional to $E_\mu$ [Gai90].

Nuclear Reactions If a nucleus in the ice is hit by a muon directly, it can be destroyed. This process has a very low probability, though. Again, the average energy loss due to nuclear reactions is proportional to $E_\mu$.

The total energy loss of a muon in ice can be summarised [Y+06, CR08]:

$$\frac{dE_\mu}{dx}_{\text{total}} = a + b \cdot E_\mu, \quad a \approx 2.4 \text{ MeV cm}^{-1}, \quad b \approx 4 \cdot 10^{-6} \text{ cm}^{-1}. \quad (3.11)$$

The contribution by ionisation is described by $a$, whereas $b$ combines the contributions of the stochastic processes. Figure 3.2 shows the energy loss as a function of the muon energy. Below $\sim 600\text{GeV}$, the energy loss is dominated by continuous ionisation and almost independent of the muon energy. Muons in this energy range are thus referred to as minimum ionising. At energies above $\sim 600\text{GeV}$, the stochastic contributions prevail. Here, the energy loss increases approximately linear with $E_\mu$. This relation allows to estimate the energy deposited within the detector from the amount of measured Cherenkov light.

![Figure 3.2: Total muon energy loss according to 3.11](image)

#### 3.4 Signatures for Neutrinos of Other Flavours

Only muons produce long tracks, which are necessary for a good directional reconstruction. Nevertheless, there are signatures for the other flavours, too.
**Electron Neutrinos** create local cascades when they hit a nucleus in the ice. The particles produced in such a shower emit Cherenkov light, but travel in all directions. The signature is thus a spherical wavefront of diffusing Cherenkov light (see Fig. 3.3), with larger intensity in forward direction. This anisotropy permits a directional reconstruction also for cascades, although it is more complicated than a track reconstruction.

![Figure 3.3: An electron produces a local cascade, which yields a spherical wavefront of Cherenkov light.](image)

**Tau Neutrinos** produce a local cascade and a tau lepton. Like a muon, the tau lepton generates a track. However, it decays very quickly, creating a second cascade. For energies below 1 PeV, the length of the track in between is less than 50 m. Thus, only at the highest energies the second cascade can be separated from the first. Due to its characteristic signature, this type of event is called a *double-bang*.

![Figure 3.4: A tau neutrino hits a nucleus, producing a cascade and a tau lepton. The decay of the tau lepton results in another cascade.](image)
Chapter 4

The IceCube Neutrino Detector

The IceCube experiment is the largest neutrino detector on Earth. It is currently under construction near the Amundsen-Scott Station at the Geographic South Pole. IceCube is a Cherenkov detector using the Antarctic ice as detector medium. In its baseline design, IceCube consists of 4800 light detection modules, distributed over 80 so-called strings. A string is basically a long cable holding 60 detection modules (or DOMs\(^1\)) which is deployed in a hot-water-drilled hole in the ice. The strings are arranged in a hexagonal structure with a spacing of 125 m between two strings. The lowest DOM is at a depth of 2450 m, the highest at 1450 m, resulting in a vertical spacing of about 17 m. The instrumented volume adds up to 1 km\(^3\). These dimensions correspond to an energy threshold of about 100 GeV and a maximum sensitivity around 10 TeV. Embedded in IceCube is the older AMANDA detector, the predecessor of IceCube. It consists of 677 Optical Modules (OMs) on 19 strings which are irregularly distributed on three concentric circles. It has a denser instrumentation with a string spacing of about 40 m and an OM spacing of about 10 m. Consequently, it has a lower energy threshold of about 50 GeV. Most of the Optical Modules are located in depths between 1500 m and 2000 m. Currently, AMANDA serves as a low energy optimisation of IceCube (see chapter 5.4). Fig. 4.1 shows a map of the IceCube baseline layout. Also shown is the IceCube Counting House in the middle of the array. Here, the cables from all strings are united and the information sent by the DOMs is acquired.

In parallel to IceCube the IceTop array is installed on the surface above [Gai07]. It consists of two Cherenkov tanks on top of each string, similar to the water Cherenkov tanks of the Pierre Auger Observatory [A\(^+\)04a]. In contrast to the Auger tanks, the IceTop tanks are filled with clear ice and equipped with two standard IceCube DOMs. IceTop allows to measure cosmic ray induced air showers. Additionally, it serves as a calibration array for IceCube.

4.1 The Ice at the South Pole

IceCube uses its natural environment as its Cherenkov material. The ice is an integral part of the detector. The Antarctic ice sheet is the largest connected ice mass of the Earth. It covers nearly the complete Antarctic continent. As every glacier, it has grown (and still grows) in an annual cycle by accumulation and compression of the snowfall. At the South Pole the ice reaches down to a depth of about 3000 m. The EPICA\(^2\) drilling project has brought up an ice core from a depth of 3200 m. The ice of that core is estimated to be about 800000 years old [A\(^+\)04d]. The atmospheric conditions at the production time have a direct impact on the properties of the ice. Over the last hundreds of thousands of years, these conditions have varied considerably. Therefore, the IceCube experiment has to work with an inhomogeneous detector material.

\(^1\)Digital Optical Module

\(^2\)European Project for Ice Coring in Antarctica, \url{http://www.esf.org/index.php?id=855}
Figure 4.1: Baseline geometry of IceCube. Left: Top view, including the predecessor experiment AMANDA and the IceCube Counting House [Sch]. Right: Side view.

For the IceCube experiment two properties of the ice are most important: The abundance of enclosed air bubbles and the amount of volcanic dust. These quantities strongly influence the scattering and absorption of light. Therefore, their abundance has been measured in detail. Fig. 4.2 shows profiles for scattering and absorption of light as a function of the depth and the wavelength, measured in the South Pole ice. At lower depths, scattering is dominantly caused by air bubbles. Under the higher pressure at greater depths, these bubbles decrease in size. Below 1300 m, the bubbles are no longer relevant for scattering. Here, scattering and absorption are caused by μm-sized dust grains. The deposit of dust has fluctuated over the millennia. Consequently, a fluctuating structure in the scattering and absorption profiles is visible. At depths between 2000 m and 2100 m, a particularly pronounced dust layer is present. In the following, this is referred to as the Dust Layer. Below this Dust Layer, the ice is exceptionally clear. More information about the ice structure can be found in [A+06b].

Fig. 4.2 draws the effective scattering coefficient $b_e$ and the absorptivity $a$. These quantities are defined as the reciprocals of the effective scattering length $\lambda_e$ and the absorption length $\lambda_a$, respectively. The effective scattering length is given by [A+06b]

$$\lambda_e = \lambda_s \sum_{i=0}^{n} \langle \cos \theta \rangle^i,$$

(4.1)

where $n$ is the number of photon scatters, $\theta$ the angle and $\lambda_s$ the mean distance between two scatters. For large $n$, this can be written as

$$\lambda_e = \frac{\lambda_s}{1 - \langle \cos \theta \rangle}.$$

(4.2)

The absorption length $\lambda_a$ is defined as the length where the survival probability of the photon drops to $1/e$. Below 1300 m, where the contribution of air bubbles wears off, typical values for the scattering and absorption length are [A+06b]

$$\lambda_e = 15 \text{ m} - 25 \text{ m} \quad \text{and} \quad \lambda_a = 90 \text{ m} - 110 \text{ m}.$$

(4.3)
4.2 The IceCube DOM

The Digital Optical Modules (DOMs) are the ‘eyes’ of IceCube. Each DOM consists of a glass pressure sphere containing a variety of instrumentation. Fig. 4.3 shows a schematic view of an IceCube DOM. Its essential part is a hemispherical 25 cm-photomultiplier (PMT) built by Hamamatsu [A⁺06a]. The coupling to the glass sphere is ensured by the use of an optical gel in between. A high voltage unit supplies the PMT. Moreover, the DOM contains a data acquisition main board and a flasher board with 12 LEDs. By flashing the LEDs in one DOM and measuring the arrival time of the light in the neighbouring DOMs, it is possible to calibrate the positioning and the timing of the DOMs. Besides, the LEDs were used for measuring the ice properties described in chapter 4.1. More information on the calibration using LED flashers can be found in [K⁺07]. Although all PMTs are looking downwards, the IceCube DOMs have an omnidirectional acceptance. The sensitivity depends on the zenith direction of the incoming photon. It is minimal for photons from directly above the DOM and maximal for photons from directly below the DOM.

4.3 The Process of Event Detection

IceCube detects charged, relativistic particles by the Cherenkov light which they emit. The detection process is done in the following steps:

1. Photon Detection
2. Digitisation
3. Feature Extraction
4. Local Coincidences
5. Trigger
Photon Detection  The *PMTs* detect light by the photoelectric effect. When a photon strikes the photocathode, electrons are generated. They are accelerated towards the anode and generate an analogue signal.

Digitisation  If a *DOM* records a signal, it is called a *hit DOM* or simply a *hit*. Typically, the analogue signal of a *PMT* comprises a first main pulse and several afterpulses. This pulse shape is digitised in situ by the main board of the *DOM*. The digitised signal is called *waveform*. Sending the signal in digital form to the surface avoids several problems encountered with the AMANDA detector. In the AMANDA experiment, as little electronics as possible was deployed in the ice. Thus, the digitisation of the AMANDA signals is done on the surface. The first deployed AMANDA cables are either coaxial cables with strong attenuation and dispersion, or twisted-pair cables. The twisted-pair cables show a lower attenuation, but introduce the problem of cross-talk between parallel cables. The last deployed AMANDA *strings* use optical transmission, which also solves these problems.

Feature Extraction  The digitised waveform contains information about the number of photons hitting a *PMT* and their arrival times. The process of calculating these numbers from the waveform is called *feature extraction*. For most of the pulses, only the amplitude and the timing information are stored, thus reducing the data volume.

Local Coincidences  As every *PMT*, the IceCube *PMTs* have a certain *noise rate*. In the IceCube detector, the noise is mostly caused by the decay of radioactive isotopes in the glass sphere of the *DOM*. 
Thermal noise is significantly reduced by the low temperatures. Hence, the IceCube DOMs have quite a low noise rate of less than 650 Hz. Nonetheless, hits caused by noise and not associated with the physical event are a difficulty for each reconstruction algorithm and introduce additional uncertainties. Therefore, a method to reduce the number of noise hits is required. This hit-cleaning is accomplished by Hard Local Coincidences (HLC). The probability that two neighbouring DOMs have a noise hit at the same time is very small. Thus, a DOM reports a hit to the surface only if one of its neighbours on the same string has also been hit within a time window of 800 ns \([\text{A}^+06\alpha]\). If this is not the case, the hit is called isolated, treated as noise and not transmitted to the surface. However, because virtually each physical event causes also a certain number of isolated hits, there is a high chance that information is lost. Fig. 4.4 illustrates the principle.

![Figure 4.4: Hit-cleaning by Hard Local Coincidences. Hits in DOMs, where the neighbouring DOMs in the same string have no hit, are called isolated hits. These are treated as noise and removed from the event.](image)

The loss of information is a problem in particular for low energy analyses. It complicates an accurate track reconstruction and compromises the veto capability (see chapter 9.2.1). Therefore, it is planned to replace HLC by Soft Local Coincidences (SLC). In this approach, all hits are preserved. Isolated hits (which would be removed completely by HLC) are not stored with full information, though, since the DAQ could not handle the data volume. Instead of the complete waveform, only a timestamp and the peak amplitude of the first pulse are recorded.

**Trigger** It is not possible to continuously save all hits in IceCube. Only small time windows with potentially interesting physical events are stored. These packages are called event. To be recognised as such an event, the momentary condition of IceCube has to fulfil one of several trigger conditions. The most straightforward trigger is the Simple Majority Trigger: A certain number of DOMs have to be hit within a certain time window. The thresholds can be adjusted to control the data volume. In the 2008
data taking season, the required number of DOMs is eight\textsuperscript{3} and the time window has a length of 5 µs. Another example is the String Trigger, which requires (in the 2008 season) at least five DOMs out of a series of seven on one string being hit. This trigger is in particular efficient for nearly vertical and low energy events. Additionally, there are separate trigger conditions for IceTop and AMANDA. If these experiments are triggered, also the status of IceCube is stored, even if no IceCube trigger condition was fulfilled.

4.4 Reconstructing Events

A stored event contains only information about the amount and the arrival time of the Cherenkov light measured by the individual DOMs. The position and direction (the track) of the emitting particle as well as the energy and eventually the particle type have to be reconstructed from this information. The IceCube software contains many different algorithms for that purpose. Only the two algorithms which have been used in this study shall be presented here.

4.4.1 line-fit

The line-fit is a fast, lightweight algorithm which is primarily used for a first guess of the particle track [A\textsuperscript{+}04c]. Its main power is its speed. Therefore, it is performed on all events directly at the South Pole. The existence of the Cherenkov cone is ignored, as are optical properties of the ice. The algorithm yields a fit only on the basis of the hit times $t_i$. It assumes light travelling through a 1-dimensional projection of the detector (from one hit DOM to the next) with a velocity $v$. The positions of the hit DOMs are $r_i$. In the $r$-$t$-plane the propagation of the light can be described approximately by a straight line:

$$r_i \approx r + v \cdot t_i.$$  \hspace{1cm} (4.4)

Then a simple linear fit is performed by minimisation of the $\chi^2$

$$\chi^2 = \sum_{i=1}^{N_{hit}} (r_i - r - v \cdot t_i)^2.$$  \hspace{1cm} (4.5)

The minimisation can be done analytically by calculating the fit parameters $r$ and $v$:

$$r = \langle r_i \rangle - v \cdot \langle t_i \rangle \quad \text{and} \quad v = \frac{\langle r_i \cdot t_i \rangle - \langle r_i \rangle \cdot \langle t_i \rangle}{\langle t_i^2 \rangle - \langle t_i \rangle^2}.$$  \hspace{1cm} (4.6)

The direction of the track is given by $e = v/|v|$. The position $r$ is an approximation for the starting point of the track.

4.4.2 muon-llh

The muon-llh algorithm is a more sophisticated track reconstruction tool based on a maximum likelihood approach. The algorithm needs a first guess for the track, obtained with another reconstruction algorithm (for example line-fit). It changes the reconstructed track gradually and calculates the value of a likelihood function for each variation of the track. The maximum of the likelihood distribution denotes the best fitting track hypothesis. The likelihood function $L$ is based on the timing information of the hits, but it can be extended to incorporate information about the topology of the hits and their amplitude [A\textsuperscript{+}04c]. The algorithm searches for the minimum of $-\log L$, thus maximising the likelihood.

\textsuperscript{3}HLC has to be taken into account. This means that eight isolated hits do not fulfil the trigger condition, but four pairs of hits do, a pair and two groups of three hits do, and so on.
4.5 Classification of Muon-Induced Events

This study explores only muons and muon neutrinos, although IceCube is sensitive also to the other flavours (see chapter 3.4). Thus, the following terms for the classification of events apply only to muon tracks.

The first classification parameter is related to the direction of the track:

- Events, which enter the detector at the top and travel downwards are called **down-going**.
- Events propagating from the bottom to the top are called **up-going**.

The largest fraction of down-going events is caused by muons from cosmic ray induced air showers. These atmospheric muons are by far the most abundant type of events in the IceCube detector. The rate of atmospheric muon events is $\sim 10^6$ times higher than the rate of neutrino-induced events. Below the horizon, the rate of atmospheric muons decreases rapidly, as the amount of matter in the line of sight increases. In the matter of the Earth, the mean free path of muons is of the order of some km. Only neutrinos have the ability to travel through the whole planet. Thus, up-going muons originate always from neutrino interactions in the ice or the rock below the detector.

Another classification is done according to the positions of the starting and stopping points of the track:

- A **starting track** is a track that starts inside the IceCube volume.
- If the muon ranges out inside the IceCube volume, the track is called a **stopping track**.
- A track with both the starting and the stopping point inside the IceCube volume is called a **contained track**.
- If the starting and the stopping point are both outside the IceCube volume, the track is called an **infinite track**.

![Figure 4.5: Classification of muon tracks according to the starting and stopping point.](image)

Tracks with their starting point inside the IceCube volume (i.e. starting and contained tracks) can only be neutrino-induced. Here applies the same argument as for up-going tracks. In these cases, the starting point is the neutrino interaction vertex. Atmospheric muons always create stopping or infinite tracks, since the starting point has to be somewhere in the atmosphere. It should be noted that starting tracks can result not only from cosmic, but also from atmospheric neutrinos.
4.6 Background for Neutrino-Induced Muon Tracks

As described above, only one out of $10^5$ events is neutrino-induced. This yields several background classes for neutrino-induced muons.

**Atmospheric Muons**  This class is the largest background source. In most analyses, all events reconstructed as down-going are rejected by a zenith cut. A approach to find neutrino-induced events among the atmospheric muons is to search for starting tracks.

**Coincident Muons**  Cosmic ray induced air showers may produce several nearly collinear muons at the same time. This can confuse the reconstruction.

**Uncorrelated Coincident Muons**  Coincident muons can also result from two uncorrelated air showers occurring at the same time in the atmosphere. A first muon may generate hits in the lower part of the detector. If shortly afterwards a second muon is detected in the upper region of the detector, the resulting signature can easily be misreconstructed as an up-going and thus neutrino-induced event.

**Cascades**  The stochastic energy losses (see chapter 3.3) of high energy muons can produce cascade-like events around the initial muon track. These cascades can be misinterpreted as up-going tracks.

**Scattering by Dust Layers**  If a muon crosses a dust layer, scattering can distort the Cherenkov cone. This also complicates the reconstruction.

4.7 Future Upgrades of the IceCube Detector

4.7.1 New Techniques

Due to the low fluxes at energies above 100 PeV, the instrumented volume of IceCube is too small to detect a sufficiently large number of particles. An efficient detector for energies in the EeV region requires an instrumented volume of about 100 km$^3$. However, it is impossible to instrument a much larger volume with the same technique as in IceCube. When IceCube will be finished in 2011, the deployment of all strings will have taken more than six years. One IceCube string costs about one million dollars. To deploy a future extension of IceCube within a reasonable time scale and at acceptable costs, a different approach is required. At the moment, two new methods of neutrino detection are under investigation:

- The **radio method** uses the Askaryan (or radio Cherenkov) effect, first predicted by G. A. Askaryan [Ask62]. Similar to the Cherenkov cone in the visible wavelength band, the Askaryan effect describes a cone of coherent radio emission.

- Also from G. A. Askaryan stems the idea behind the **acoustic method** [A$^+79$]. Charged particles deposit ionisation energy in the ice. The ice expands thermally, thus creating a sound wave.

More about these efforts can be found in [LRV07] for the radio method and in [B$^+07$] for the acoustic method.
4.7 Future Upgrades of the IceCube Detector

4.7.2 Optimisations for Higher and Lower Energies

For the near future, optimisations of the IceCube baseline design for higher and lower energies are planned.

As mentioned above, for the detection of high energy neutrinos a larger volume is needed. The current planning for a High Energy Optimisation is to move up to 11 of the not yet deployed strings further outside to the southwestern side of IceCube. Among them are strings 79 and 80 in the northeast corner of IceCube, which originally should have been deployed in one of the first construction seasons. The strings of the High Energy Optimisation will be arranged on a larger grid with a string spacing of about 300 m. A map of the possible locations is shown in Fig. 5.6.

For the low energy optimisation, additional strings with a smaller spacing will be deployed in the centre of IceCube. This low energy optimisation, called DeepCore, is the main topic of this study and is therefore discussed in detail in the next chapter.
Chapter 5
The Low Energy Optimisation DeepCore

5.1 Physics Case for a Low Energy Optimisation

The IceCube baseline design is optimised for neutrino energies above 10 TeV. However, there are several processes that might produce neutrinos with energies below that threshold. To study these processes, an increased sensitivity for lower energies is necessary. Four prominent examples shall be presented here.

Dark Matter As described in 2.4.1, the neutralino mass is expected to be between 50 GeV and the lower TeV range. Since the energy of neutrinos from neutralino annihilations cannot exceed the neutralino mass, a search for Dark Matter would profit substantially from a low energy optimisation [Rot07].

Galactic Neutrino Sources Shell-type SNR and plerions (assuming hadronic acceleration) are among the most prominent candidates for neutrino emission from within our Galaxy. One benchmark source of this type is the Crab nebula, a plerion (Fig. 2.5). Older measurements from experiments like HEGRA\(^1\) indicated a gamma ray energy spectrum with an spectral index \(\gamma \approx 2.6\) up to an energy of about 80 TeV [A\(^+\)04b]. However, recent results from the H.E.S.S. experiment show a steepening at higher energies. The spectrum can be described by a power law with spectral index \(\gamma = 2.39 \pm 0.03\text{ stat} \pm 0.09\text{ sys}\) and an additional exponential cut-off at the energy \(E_c = (14.3 \pm 2.1\text{ stat} \pm 2.8\text{ sys})\text{ TeV}\) [A\(^+\)06c]. A similar behaviour is found for other sources as well, for example in the shell-type SNR RX J1713.7-3946 [A\(^+\)07b].

The left plot in Fig. 5.1 shows the energy spectra of photons and neutrinos produced in proton-proton interactions. The mean energy of the gamma rays is about half an order of magnitude above the mean energy of the neutrinos. Thus, the measured gamma ray spectrum allows to estimate the neutrino spectrum. The measured gamma ray spectrum and the expected neutrino spectrum of the Crab nebula are shown in the right plot of Fig. 5.1, together with the expected IceCube sensitivity. In the baseline configuration, IceCube has none or only little sensitivity to these sources. A study of them requires a detector optimised for energies of about 1 TeV.

Atmospheric Neutrinos As described in chapter 2.4.2, cosmic ray induced air showers produce neutrinos. Atmospheric muon neutrinos have been studied by several experiments in the energy range below 10 GeV [Gai05]. Above, the flux and the spectrum are only poorly known. Measurements in this range have been conducted by Fréjus [D\(^+\)95] and AMANDA [Gee03], but with large uncertainties. IceCube will collect unprecedented statistics of atmospheric neutrinos and thus improve the measurements in the energy region above 1 TeV. For a similar improvement in the lower energy range and to achieve an overlap with other experiments, a low energy optimisation for IceCube is necessary. Also the electron neutrino spectrum has never been measured above 100 GeV. Moreover, the transition from pion decay

\(^1\)High Energy Gamma Ray Astronomy, http://www-hegra.desy.de
to kaon decay as the dominant source of atmospheric neutrinos takes place in the energy region around 30 GeV [ALL05] (see chapter 2.4.2 and Fig. 2.7). A low energy optimisation would allow to study this transition in detail.

**Neutrino Oscillation** Many experiments have shown evidence for neutrino oscillation. For example, the GALLEX experiment has found a deficit in the electron neutrino flux from the sun [H+99]. Super-Kamiokande has found a deficit also in the flux of atmospheric muon neutrinos [F+98]. Fig. 5.3 shows the survival probability (the probability not to oscillate) for vertically up-going atmospheric muon neutrinos. From this, a disappearance between 15 GeV and 100 GeV is expected. Neutrino oscillation measurements have only been done for energies below 10 GeV. With an energy threshold low enough, an optimisation for IceCube could also close this gap.

### 5.2 Physics Case for a Detector with Full-Sky Acceptance

Due to the massive background of atmospheric muons (see chapter 4.6), IceCube analyses normally exclude the southern hemisphere. However, many interesting regions in space are located there, for example the Galactic Centre and many gamma ray sources detected by the H.E.S.S. experiment. At present, they cannot be studied with IceCube simply because they are above the horizon. Among them are the most promising candidates for galactic neutrino sources. A map of H.E.S.S. sources is shown in Fig. 5.4. An optimisation which extended IceCube’s field of view would significantly increase the discovery potential. Besides, it would establish an overlap with experiments in the northern hemisphere (e.g. ANTARES).

### 5.3 Veto against Atmospheric Muons

Because of the background of atmospheric muons, a search for down-going neutrino-induced events has to rely on the identification of starting tracks. As described in chapter 4.5, these tracks are neutrino-induced. The most straightforward approach is to discard all events with hits in the outer layers of the detector. An atmospheric muon has to travel through the ice above the detector. Therefore, it emits Cherenkov light before entering the instrumented volume and should generate hits in the first DOMs it passes. A muon produced by a neutrino interaction inside the instrumented volume, in contrast, creates the first hits in DOMs somewhere in the interior of the IceCube volume. Thus, a track with no hits in the outer layers of IceCube should be neutrino-induced. This is the basic idea of a veto against atmospheric muons: Every event with hits in the outer layers is treated as atmospheric background and rejected. Admittedly, the veto rejects many through-going neutrino-induced events as well. Fig. 5.5 illustrates the principle. Due to the large string spacing, a muon has a certain probability to pass a layer undetected. Consequently, the veto region comprises several layers to optimise the background rejection. Up-going tracks are always neutrino-induced. Thus, no veto from below is needed.

### 5.4 AMANDA as a Low Energy Core

The first idea for a low energy optimisation is to use the AMANDA detector. Because of its denser spacing, lower energies are accessible. This idea has already been realised. AMANDA is fully integrated into IceCube and improves the performance for low energy events considerably [G+07]. However, this concept suffers from three major problems. At first, AMANDA is an inhomogeneous detector, composed
Figure 5.1: Left: Energy spectra of decay products from proton-proton interactions in units of the initial proton energy. [KAB06]. Right: Gamma ray flux of the Crab nebula, measured by H.E.S.S. The measurements are fitted by a power law with spectral index $\gamma = 2.39$ and an exponential cut-off at $E_c = 14.3$ TeV. Also shown is the expected neutrino flux and the IceCube sensitivity [Gab07].

Figure 5.2: Atmospheric neutrino flux, measured by Fréjus and AMANDA [Gee03].
of various types of hardware. This is an additional effort for every physics analysis. Secondly, the AMANDA counting house, as every building on the ice surface, is gradually buried by snow. It needs to be elevated, if AMANDA is to be operated for more than a couple of years from now. But most important, AMANDA’s location within IceCube is not optimal for a low energy optimisation: AMANDA is located in the upper half and shifted from the centre of IceCube (see Fig. 4.1). Because of the better shielding from the atmospheric background, the optimal place for a low energy detector is always as far from the surface as possible. Also the superior ice properties at great depths favour a deeper location. Finally, the horizontal displacement from the centre of IceCube makes an evenly shaped veto for AMANDA impossible.

### 5.5 IceCube DeepCore

Because of the drawbacks described in the previous chapter, the concept of a new low energy optimisation has been developed. This concept suggests to deploy additional strings forming a low energy core within IceCube. Consequently, the project has been entitled IceCube DeepCore or, in short, IC/DC. At least six new strings will be deployed in the centre and the lower part of IceCube. This location yields an efficient veto against atmospheric muons and thus enlarges the field of view of IceCube to the southern hemisphere. Fig. 5.6 shows the location of these six standard DeepCore strings as well as possible locations for four additional DeepCore strings. The new strings will have 60 DOMs as the standard IceCube strings, but with a denser spacing. Fig. 5.7 shows the final DeepCore string configuration compared to a standard IceCube string. The grey bar indicates the location of the Dust Layer. By placing most DOMs below, DeepCore can profit from the clear ice down there. The Dust Layer itself is not instrumented, because DOMs in this region are almost useless due to the high absorption and scattering. The DOMs above the Dust Layer are used to improve the veto capabilities. The DeepCore DOMs will be equipped with a new PMT with higher quantum efficiency, to collect as much light as possible from low energetic and therefore not so bright events. Presumably, the first string will be deployed in the austral summer of 2008/09.

The comparison of different possible detector layouts has been an important part of this thesis and is described in detail in chapters 9 to 11. The results presented there had a significant impact on the decision about the DeepCore geometry.
Figure 5.3: Survival probability (probability not to oscillate) for vertically upward going muon neutrinos. The flux around 30 GeV is suppressed due to neutrino oscillations [DeY07].

Figure 5.4: Gamma ray sources detected by H.E.S.S. in the southern sky. Most of them are in the Galactic plane and not observable from the South Pole for a detector with $2\pi$ sr field of view.
Figure 5.5: Veto against atmospheric muons. Events with hits in the veto region (shaded) are treated as atmospheric background and rejected.

Figure 5.6: Possible scenario for the final IceCube layout, top view (left) [Sch] and side view (right). The locations for the six to ten DeepCore strings are shown in green. The maximal 11 strings of the High Energy Optimisation are shown in red. The IceCube strings which would be relocated for that purpose are shown in grey.
Figure 5.7: DOM locations and spacing of the final DeepCore string configuration compared to a standard IceCube string. The scale on the right shows the depth from the surface. The left scale denotes detector coordinates. The grey bar indicates the Dust Layer, the red curve maps the dust concentration [Sch].
Chapter 6
Simulation

An important aspect of the IceCube experiment (as well as virtually any particle physics experiment) is the Monte Carlo simulation of the detector. By simulating a particle with known direction and energy and its interactions in the detector, a simulated event is generated. The simulated data mimics the structure of experimentally gathered data. However, the properties of the initial particles are known, whereas measured data contains information only about the detector response. The simulated data can be reconstructed and analysed in the same way as measured data. By comparing the results of the reconstruction with the generated data, it is possible to test and improve the reconstruction algorithms. The accuracy of the reconstruction is a crucial aspect for the IceCube experiment. Furthermore, different detector geometries can be simulated. Thus, it is possible to determine the best detector layout. Finally, many physics results are found by comparing the measured data with expectations from simulated data.

Naturally, the quality of the simulation depends on the accuracy of the input parameters. An accurate simulation requires detailed knowledge not only about the particle physics behind neutrino and muon interactions. The detector response and the optical properties of the ice have a major impact on the simulation and have to be well understood.

In the IceCube experiment, the simulation is done in four steps:

1. Generation
2. Muon Propagation
3. Photon Propagation
4. Hardware Simulation

6.1 Generation

In the first step of the simulation, primary particles are generated. These are either cosmic ray particles or neutrinos. The interactions of these particles with the atmosphere and the ice are simulated. At some point, muons are produced which potentially could trigger the detector.

**Signal** The neutrino signal is simulated with the program *NeutrinoGenerator (NuGen)*. It is capable of simulating muon neutrinos as well as electron neutrinos. The neutrinos are generated on the surface of a cylinder around the IceCube volume. Due to their small cross-section, only a tiny fraction of these neutrinos would produce a muon, which could be detected by IceCube. To avoid this problem, all neutrinos are forced to interact and produce a muon inside the generation cylinder. The program then calculates the probability for that particular interaction to occur. According to that probability, a weight is assigned to the resulting event. Many parameters can be chosen freely according to the intended use.
of the simulated dataset. Among them are the flavour of the primary neutrinos, the spectral index of the generated energy spectrum, the minimum and maximum energy, the range in zenith and azimuth angle and the size of the injection cylinder. Most datasets are generated with an isotropic angular distribution and an $E^{-1}$ spectrum. This ensures that bins of equal size in $\log E$ hold the same number of events. Thus, sufficient statistics is provided also for the highest energies. For dedicated low energy studies, most datasets are generated with an $E^{-2}$ spectrum, which yields better statistics at low energies. However, the atmospheric neutrino spectrum has a spectral index $\gamma \approx 3.7$ and the interaction probability depends on the zenith angle (see chapter 2.4.2). Thus, for studies of atmospheric neutrinos, the events have to be reweighted accordingly. All datasets used throughout this study (with one exception, see chapter 8.1) have been reweighted to the atmospheric spectrum.

**Background** The program **CORSIKA**$^1$[H+98] is used for the simulation of the background of atmospheric muons from cosmic ray induced air showers. It was originally designed for use with the KASCADE$^2$ experiment. The simulation starts with primary cosmic ray particles. The energy spectrum and the composition are based on measurements. A particle is propagated through the atmosphere until it interacts with an air molecule or decays. An interaction results in an extensive air shower of secondary particles, which are again tracked with their interactions and decays until they reach the ground level. Among other particles, the interactions produce muons.

### 6.2 Muon Propagation

In the second step, the program **MMC** [CR08] simulates the propagation of the muons (generated by NuGen or CORSIKA) through the ice. The simulation includes the continuous energy loss by ionisation as well as stochastic energy losses. If a stochastic energy loss occurs, the type of the interaction and the amount of lost energy are reported. The simulation continues until the muon has lost all of its energy.

### 6.3 Photon Propagation

**MMC** provides information about the position and direction of the muon, its continuous energy loss and the positions of stochastic energy losses. Photons are produced by the muon itself and by the secondary particles from the stochastic events. These secondaries produce small showers, which are treated as point-like photon sources. For the simulation of the photon propagation the **Photonics** software package [L+07] is used. Instead of tracking each single photon, it is based on pre-defined tables. Different tables exist for the photons from continuous energy loss and for those from the point-source-like showers along the muon track. These tables provide information about the expected number of photo electrons and their arrival times in any DOM, depending on the distance to the source and the detection angle. Furthermore, the depth-dependent ice properties are fully included. In the simulation process, the number of photo electrons in a certain DOM is obtained as follows: First the expected average number of photo electrons from the **Photonics** tables is taken as the mean of a Poisson distribution. A random number from that distribution gives the number of photo electrons stored with the simulated event.

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$^1$Cosmic Ray Simulations for Kascade

$^2$Karlsruhe Shower Core and Array Detector, [http://www-ik.fzk.de/KASCADE](http://www-ik.fzk.de/KASCADE)
6.4 Hardware Simulation

Finally, the detector response is simulated. The program ROMEO\(^3\) simulates the charge measured by the PMT and the resulting voltage pulse. Furthermore, this step includes the digitisation and feature extraction by the DOM main board and the simulation of the Local Coincidences and the trigger logic as described in chapter 4.3.

\(^3\)Root-based Optical Module Emulator
Chapter 7

Reconstruction of Finite Muon Tracks

7.1 General Idea

As explained in chapter 4.5, the identification of starting muon tracks offers a possibility to separate the signal of neutrino-induced events from the background of atmospheric muon events. Apart from the veto described in chapter 5.3, this chapter presents another approach to identify starting tracks. It is based on the idea to check non-hit DOMs in the close proximity of the reconstructed infinite track. In particular, close DOMs up-stream of the first hit are a good indicator for a starting track. This approach is illustrated in Fig. 7.1. It allows to recognise a set of most likely starting tracks. The method is implemented in an algorithm developed by Jan-Patrick Hülß as part of the finiteReco project of the IceCube software [Hü]. In this thesis, the algorithm is referred to as LLHR-algorithm.

![Diagram illustrating the general idea of the LLHR-algorithm. Non-hit DOMs up-stream of the first hit are an indicator for a starting track.](image)

**Figure 7.1:** General idea of the LLHR-algorithm. Non-hit DOMs up-stream of the first hit are an indicator for a starting track.

7.2 The Algorithm

The LLHR-algorithm requires for each event the measured pattern of hit DOMs as well as a the direction and position of a reconstructed track. In this study, the initial track reconstruction has always been performed by the muon-llh algorithm which was seeded by a line-fit (see chapter 4.4). The LLHR-algorithm estimates the neutrino interaction vertex and calculates the so-called Log-Likelihood Ratio LLHR. This ratio is used as degree of believe of that track being starting. The algorithm separates into four parts, which are described in detail in the following sections:
1. Projection of the position of Cherenkov light emission on the assumed track and determination of the neutrino interaction vertex
2. Calculation of the hit probabilities for non-hit DOMs up-stream of the interaction vertex
3. Combination of the individual hit probabilities to a likelihood for the observed hit pattern
4. Calculation of the Log-Likelihood Ratio $LLHR$

### 7.2.1 Calculation of the Position of Cherenkov Light Emission and Determination of the Neutrino Interaction Vertex

Due to the fixed Cherenkov angle of 41°, each DOM has a corresponding position on the reconstructed track (see Fig. 7.2). This projection is calculated for all DOMs within a cylindrical volume around the track\(^1\). The DOMs are then ordered according to this position. The projection of the first hit DOM in up-stream direction defines the neutrino interaction vertex (the reconstructed vertex). A reconstructed vertex inside IceCube is a sign for a potentially starting (neutrino-induced) track.

![Diagram of DOMs and reconstructed vertex](image)

**Figure 7.2:** The algorithm calculates for each DOM the corresponding position of the Cherenkov light emission on the assumed track. The first position is taken as the reconstructed vertex. $\theta_c$ is the Cherenkov angle of 41°.

### 7.2.2 Calculation of Hit Probabilities

All non-hit DOMs with a projection on the assumed track up-stream of the first hit DOM are selected. All these DOMs could have been hit by an infinite track (see Fig. 7.3). For each of these DOMs the probability to have no hit is calculated. Two track hypotheses are evaluated: An infinite track and a track starting at the reconstructed vertex. Under the assumption of an infinite track $p(\text{noHit}|\text{Track})$ is calculated. In this case, the hit probability depends on track parameters, ice properties and the detector.

\(^1\)This is done for the saving of computing time. The hit probability for a DOM far away is close to zero anyway. The radius of the cylinder can be given as a parameter.
status. The used track parameters are the energy of the light emitting particle and the position and direction of the track, determining the distance between the track and the DOM. Non-operating DOMs, as defined by the detector status, are excluded from the analysis. In the second case, the hit probability under the assumption of a starting track $P(\text{noHit}|\text{noTrack})$ is calculated. This is equal to the probability of a noise hit.

Figure 7.3: Calculation of the hit probabilities for all DOMs in the shaded region (all DOMs with a projection on the assumed track up-stream of the first hit DOM). Left: Assuming an infinite track, $P(\text{noHit}|\text{Track})$ is calculated. Right: The assumption of a track starting at the reconstructed vertex leads to the calculation of $P(\text{noHit}|\text{noTrack})$.

Three different methods are used to calculate the hit probabilities:

- The first approach is a simple parametrisation: The probability for a hit in a certain DOM depends only on the perpendicular distance between the track and the DOM and decreases exponentially with growing distance:

$$P(\text{Hit}) \propto e^{-d}, \quad P(\text{noHit}) = 1 - P(\text{Hit}).$$

This approach uses parameters obtained with Monte Carlo simulations for the AMANDA experiment, which were used in the AMANDA reconstruction techniques [A+04c]. It does not take into account any detector effects (i.e. only AMANDA related effects), nor the changing of the ice properties with the depth, nor the angular response of the DOMs. Scattering effects are introduced only via the fitted AMANDA parameters. This method also ignores the energy of the track. On the one hand, this is obviously not correct. However, it means that the energy does not need to be known. Since energy reconstruction is a challenging task, this can be of some advantage. Nevertheless, this method is not used in this study.

- The second method is based on a table created from a set of about 200000 simulated IceCube events. For each event, the distances between the position of Cherenkov light emission and all hit and non-hit DOMs are calculated. Two distributions are determined: The number of hit DOMs and the number of all DOMs with respect to the distance. For a chosen distance, the probability for a hit is the ratio of these distributions.

$$P(\text{Hit}) = \frac{\# \text{ hit DOMs}}{\# \text{ all DOMs}}, \quad P(\text{noHit}) = 1 - P(\text{Hit}).$$

This implementation again does not consider the variable ice properties, the DOM orientation or the energy of the track. On the other hand, it includes the full detector response (as far as the
Monte Carlo does), is easy to handle and requires only minimal computation resources. Again, the calculation is independent of the energy of the light emitting particle. This method is used in the first part of this study (chapter 8).

- A third implementation uses the Photorec tables of the Photonics project [L⁺07]. As mentioned in chapter 6.3, for each DOM and a given track, the expected number of photo electrons can be extracted directly from these tables. In this method, the number of photo electrons depends on the energy of the light emitting particle. If it is unknown, an energy of 1 GeV is assumed. The probability for a hit in a certain DOM is calculated from the number of photo electrons, assuming Poisson statistics. The probability for no hit is given by:

\[
p_\lambda(\text{noHit}) = p_\lambda(0) = \frac{\lambda^0}{0!} e^{-\lambda} = e^{-\lambda}.
\]  
(7.3)

\(\lambda\) is the expected number of photo electrons from the Photorec tables.

This method was implemented in the course of this study. It was tested, found to be superior to the Monte Carlo method and used afterwards. All LLHR values concerning DeepCore (chapters 9 to 11) have been calculated with this method.

### 7.2.3 Construction of the Likelihoods

In the next step the likelihood for the full, observed pattern of hit DOMs is constructed. In principle, this is done by multiplication of the individual hit probabilities. As described in chapter 4.3, IceCube is currently operated in Hard Local Coincidence (HLC) mode. Isolated hits are removed from the event. Consequently, the probability that a certain DOM reports a hit depends on whether one of the neighbouring DOMs are also hit or not. Thus, with HLC the simple product of the individual probabilities cannot be used as the likelihood for the observed hit pattern. Alternatively, HLC are replaced by Soft Local Coincidences (SLC), where each hit is preserved (see chapter 4.3). In this case, the likelihoods are actually given by the product of the individual hit probabilities:

\[
P(\text{noHit}|\text{Track}) = \prod_i p_i(\text{noHit}|\text{Track}),
\]

\[
P(\text{noHit}|\text{noTrack}) = \prod_i p_i(\text{noHit}|\text{noTrack}),
\]  
(7.4)

with the index \(i\) running over all selected DOMs.

For HLC, the combined hit probabilities for all DOMs of one string, \(S(\text{hitPattern}|\text{Track})\) and \(S(\text{hitPattern}|\text{noTrack})\), have to be calculated first. These calculations are done by the class StringLLH within the finiteReco project. A detailed explanation can be found at [Hü]. In this case, the likelihoods are given by the product of the likelihoods for the individual strings:

\[
P(\text{noHit}|\text{Track}) = \prod_j S_j(\text{hitPattern}|\text{Track}),
\]

\[
P(\text{noHit}|\text{noTrack}) = \prod_j S_j(\text{hitPattern}|\text{noTrack}),
\]  
(7.5)

with the index \(j\) running over all strings.
7.2.4 Calculation of the Log-Likelihood Ratio $LLHR$

Finally, a track is classified as starting according to the probability given by the Log-Likelihood Ratio $LLHR$. To obtain this parameter, the logarithm of the ratio of $P(\text{noHit}|\text{Track})$ and $P(\text{noHit}|\text{noTrack})$ is taken:

$$LLHR = \log \frac{P(\text{noHit}|\text{Track})}{P(\text{noHit}|\text{noTrack})}.$$  \hfill (7.6)

For a clearly starting track, $P(\text{noHit}|\text{Track})$ is small, whereas $P(\text{noHit}|\text{noTrack})$ is close to 1. The resulting Log-Likelihood Ratio $LLHR$ is therefore negative with a large absolute value. For less evidently starting tracks, the two probabilities are in the same order of magnitude. The Log-Likelihood Ratio $LLHR$ in this case is close to 1. In other words, the algorithm delivers $LLHR$-values between 0 and any negative number. For tracks with a $LLHR$ of about 0, it is uncertain if they are starting or not. The larger the absolute value of the Log-Likelihood Ratio $LLHR$ is, the higher is the track’s probability to be starting. Thus, the Log-Likelihood Ratio $LLHR$ is used for each track as degree of believe of being starting. With a cut on the $LLHR$, it is possible to select events with a high probability to be neutrino-induced.

Besides the Log-Likelihood Ratio $LLHR$, the algorithm also returns the coordinates of the reconstructed vertex.

7.2.5 Stopping Muon Tracks

A similar calculation can be done to identify stopping tracks. Here, the projection of the last hit DOM on the assumed track defines the stopping vertex. The likelihoods are then calculated for the DOMs down-stream of the last hit. The corresponding $LLHR$ is a degree of believe of being stopping. Since this study is only concerned with starting tracks, this information is not used.
Chapter 8

Identification of Starting Tracks with the *LLHR*-Algorithm

The first task of this thesis was to test the *LLHR*-algorithm, to explore its behaviour and to evaluate its capability to reject atmospheric muon events. This analysis was done with datasets from the official IceCube simulation production, no specialised Monte Carlo data was created. All datasets contain only muon neutrinos and are for the full IceCube detector with 80 *strings*.

8.1 First Tests

Three quantities play a fundamental role throughout this study: The energy, the zenith angle and the *LLHR*. Energy and zenith angle are important track parameters. It has to be studied, if the algorithm works equally well for all energies and directions. The algorithm returns the *LLHR* value, which is supposed to be the main parameter for the discrimination between signal and background events. The spectra of these three quantities have a characteristic shape, which shall be presented in this introductory section.

Fig. 8.1 shows exemplary spectra of the three quantities for dataset 78, a neutrino signal dataset generated with *NuGen*. The plots show the spectra of the neutrino-induced muons which triggered the IceCube detector. The neutrino properties have to be deduced from these spectra. The dataset was generated with an $E^{-1}$ spectrum. In contrast to all other neutrino datasets used throughout this study, the histogram entries are reweighted to an $E^{-2}$ spectrum. Since each event has got an interaction weight assigned by *NuGen* (see chapter 6.1), the number of events in arbitrary units is shown on the y-axis. Table 8.1 displays the parameters of dataset 78.

<table>
<thead>
<tr>
<th>dataset 78</th>
</tr>
</thead>
<tbody>
<tr>
<td># events</td>
</tr>
<tr>
<td>20674</td>
</tr>
</tbody>
</table>

*Table 8.1*: Parameters of dataset 78: The number of events in the dataset, the energy and zenith ranges and the spectral index $\gamma$

**Energy Spectrum** The muon energy spectrum peaks at 10 TeV. This is the energy IceCube is optimised for (see chapter 4). The decrease at higher energies corresponds to the falling neutrino spectrum. The decrease at lower energies represents the detector efficiency to detect low energy events. As expected (chapter 4), the energy threshold is around 100 GeV.
**Angular Spectrum**  This dataset contains only up-going events. The zenith angle $\theta$ is plotted as $\cos(180^\circ - \theta)$, which is 0 for horizontal events and 1 for vertically up-going events. The spectrum shows the expected excess from horizontal directions (see chapter 2.4.2). It extends to directions slightly beyond the horizon, caused by the difference between neutrino and muon direction. Up-going neutrinos from nearly horizontal directions can produce muons which are slightly down-going.

**LLHR Spectrum**  The $LLHR$ spectrum is shown between -6 and 0. It was calculated with the second method presented in chapter 7.2.2. Tracks with highly negative $LLHR$ value (in the left part of the spectrum) have a high probability to be starting. At $LLHR \approx 0$ the algorithm cannot decide whether the track is starting or not. This is the case for most of the tracks. At $LLHR \approx -2$, the spectrum bends upwards. This could indicate a transition from infinite to starting tracks as illustrated in Fig. 8.2. An important aspect of the following section is to verify this assumption.

**Figure 8.2:** Hypothetical composition of the $LLHR$ spectrum of dataset 78. The bend in the spectrum could indicate the transition from infinite to starting tracks.

### 8.2 Identification of Starting Tracks

To test the capability of the algorithm to identify starting tracks, it is applied to tracks known to be starting. A new dataset of better statistics is used, which has a low energy threshold of only 1 GeV and covers the whole sky including the southern hemisphere. Table 8.2 lists the parameters of that dataset.
### 8.2 Identification of Starting Tracks

#### 8.2.1 Definition of a Starting Track

The location of the neutrino interaction vertex is provided within the simulated data. Thus, a definition of starting tracks from the Monte Carlo data is possible. However, IceCube has no well-defined border. Events which emit light beyond the outermost layer of DOMs can still be detected. Hence, there is also no natural definition of a starting track. Therefore, the definitions given in chapter 4.5 were modified for this study. The detector boundary was set to the position of the outermost DOMs. Tracks with a neutrino interaction vertex more than 50 m inside are called starting tracks. If the vertex is more than 50 m to the outside, the track is called an infinite track. Tracks which start in between are called 'null' tracks. Fig. 8.3 illustrates these definitions. No information about the stopping point of the tracks is used. Thus, contained tracks as defined in chapter 4.5 are included in the new class of starting tracks. Likewise, stopping tracks according to the old definition are included in the class of infinite tracks.

![Schematic explanation of the definition of starting, infinite and 'null' tracks.](image)

**Figure 8.3:** Schematic explanation of the definition of starting, infinite and 'null' tracks.

Table 8.3 shows the number of events of each track type for dataset 557. About 54% of all tracks are starting tracks according to the above definition. Less than 10% of all tracks are lost in the 'null' region around the detector boundary.

#### Table 8.2: Parameters of dataset 557.

<table>
<thead>
<tr>
<th># events</th>
<th>$E_{\text{min}}$ (GeV)</th>
<th>$E_{\text{max}}$ (GeV)</th>
<th>$\theta_{\text{min}}$ (°)</th>
<th>$\theta_{\text{max}}$ (°)</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>281725</td>
<td>1</td>
<td>10^7</td>
<td>0</td>
<td>180</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 8.2: Parameters of dataset 557.
### Table 8.3: Event numbers in dataset 557, broken down to the different track types.

<table>
<thead>
<tr>
<th>Track type</th>
<th># events</th>
<th>percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>starting (red)</td>
<td>152101</td>
<td>53.99</td>
</tr>
<tr>
<td>infinite (green)</td>
<td>105026</td>
<td>37.28</td>
</tr>
<tr>
<td>'null' (blue)</td>
<td>24598</td>
<td>8.73</td>
</tr>
</tbody>
</table>

#### 8.2.2 Discrimination of Starting and Infinite Tracks

If the algorithm works as expected, the resulting LLHR spectra should be different for starting and infinite tracks. Fig. 8.4 shows the energy, zenith and LLHR spectra of dataset 557 for the different track types.

**Figure 8.4:** Energy, zenith and LLHR spectra of the NuGen dataset 557, broken down to starting, infinite and 'null' tracks according to the definitions in section 8.2.1. Top left: Energy spectrum (normalised). Top right: Zenith spectrum. Bottom left: LLHR spectrum. Bottom right: LLHR spectrum in another representation. The plot shows for a given LLHR value the fractions of starting, infinite and 'null' events.

The two bottom plots show the LLHR spectrum. On the left, it is shown similarly to the presentation of Fig. 8.1. The algorithm assigns highly negative LLHR values mostly to starting tracks. Around 0, the spectrum is dominated by infinite tracks. The composition follows the assumption of section 8.1. The 'null' tracks behave similar to infinite tracks. With decreasing LLHR, the spectrum of infinite tracks falls steeply, whereas the spectrum of starting tracks decreases only slightly. At \( LLHR \approx -6 \), the difference between the two components is about two orders of magnitude. A cut on the LLHR value allows the
separation of signal and background events.

The right plot shows the abundance of the different track types at a given $LLHR$ value. This allows to evaluate the purity of a sample of signal events obtained by a cut on the $LLHR$ value. At $LLHR \approx -1.5$ the sample consists to about 50% of starting tracks and to 50% of infinite tracks. At $LLHR \approx -6$, the sample consists to more than 99% of starting tracks. Hence, a cut $LLHR < -6$ yields a sample of starting tracks at a purity level of better than 99%.

### 8.2.3 Energy and Zenith Distribution

**Starting and Infinite Tracks** Starting tracks have lower average energies than infinite tracks. This is caused by the muon range, which rises with energy. Therefore, the probability of a track to be infinite (in terms of the definition in section 8.2.1) increases as well. The zenith spectrum of starting tracks is relatively flat. The excess from horizontal directions (see chapter 2.4.2), is caused by infinite tracks.

**'Null' Tracks** The energy spectrum of the ‘null’ tracks follows the spectrum of the starting tracks and so does the zenith spectrum. However, the fact that the $LLHR$ spectrum of ‘null’ tracks is similar to that of the infinite tracks justifies the ‘null’ region around the detector border. These are tracks which are starting inside or close to the detector. However, they are hard to identify, since no non-hit DOMs up-stream of the reconstructed vertex can be found.

### 8.3 Properties of Events Passing a Cut on the $LLHR$

The results of the last section show that the $LLHR$-algorithm allows the identification of starting tracks. However, the questions, which events actually pass a cut on the $LLHR$ value and what the properties of these events are, are not yet answered. To investigate this matter, three distances were defined for each track. Fig. 8.5 illustrates the definitions.

- **The Distance To Border (D2B)** is the distance between the neutrino vertex and the detector boundary. The distance is measured along the direction of the track. If the distance is negative, the vertex is down-stream of the intersection with the detector boundary and the track is starting inside. If the distance is positive, the vertex is up-stream of the intersection point. In this case the muon has entered the detector volume from outside and the track is not a starting track. This is the most important distance, since it allows the decision whether a track is starting or not.

- **The Distance Through Detector (DTD)** is the length of that part of the track which is inside the detector volume, assuming an infinite track. It is basically the length between the two intersections of the track (or its imaginary extension) with the detector boundaries. Tracks with large DTD are more clearly identifiable as starting, since they pass more DOMs, which simplifies the task of the $LLHR$-algorithm. Tracks with a small DTD pass only through a corner of the detector and are sometimes referred to as Corner Clippers.

- **The Impact Parameter (IP)** is the perpendicular distance between the track and the detector centre. Tracks with a small IP travel a longer distance through the detector and have thus a higher probability to start inside the detector. Since this definition is related to the definition of the distance DTD, a correlation between DTD and IP is expected. Tracks with a large IP are Corner Clippers.
Fig. 8.6 shows the passing rate depending on the Distance To Border (D2B) for various cuts on the \textit{LLHR} value. The detector boundary is at D2B = 0 (see Fig. 8.5), the shaded region marks the inside of the detector. The passing rates fall off towards the detector border. Beyond, they are constant. Events in this region are starting outside the detector and the \textit{LLHR} does not depend on how far outside an event starts. Even for a weak cut \textit{LLHR} < −1 (the red coloured area in Fig. 8.6), the passing rate of tracks starting deep inside the detector is about a factor 10 higher than the passing rate of tracks with D2B > 0. Tightening the cut increases the difference between the passing rates of events starting inside and outside. At a cut \textit{LLHR} < −5 (the blue area), the ratio is about three orders of magnitude.

More information about the events which are kept by a cut on the \textit{LLHR} value is shown in Fig. 8.7. The passing rate is plotted against each pair of the three distances. Five plots for different cuts on the \textit{LLHR} value are shown. The left two plots of each section show the Distance To Border (D2B) on the x-axis. As observed above, even the first cut removes most of the tracks with D2B > 0. Of particular interest is the bottom right plot in each section. If no cut is applied (all tracks), it shows two populations of tracks:

- Tracks with an Impact Parameter (IP) below 500 m. These tracks show the expected correlation between IP and DTD. With decreasing IP the DTD increases.
- Tracks with an IP around 700 m and a DTD of about 0. These are obviously Corner Clippers.

\textbf{Figure 8.5:} Definition of the three distances: Distance To Border (D2B), Distance Through Detector (DTD) and Impact Parameter (IP).
The second category of events is also rejected with the first cut. Tightening the cut leads to a selection of events with negative D2B, large DTD and small IP. These are central, clearly starting tracks. The neutrino travels a long distance through the detector before it interacts. The muon starts deep inside the IceCube volume. Moreover, these events are no Corner Clippers, but pass close to the centre of the detector.

### 8.4 Energy and Zenith Dependence of the LLHR

#### 8.4.1 Signal: Neutrino-Induced Muons

The LLHR is tested for dependence on the energy and the zenith angle. For that purpose, the dataset is divided into different energy and zenith bins. For each of these bins, the LLHR spectrum is calculated separately. Again, another dataset is used for these tests. Table 8.4 lists the parameters of that dataset. Fig. 8.8 shows the resulting LLHR spectra.

**Zenith Dependence** The zenith range is divided into four bins of equal size in \( \cos(\theta) \). Hence, each bin covers the same amount of sky surface. No correlation between LLHR and zenith angle is visible,
### Table 8.4: Parameters of dataset 462.

<table>
<thead>
<tr>
<th># events</th>
<th>$E_{\text{min}}$ (GeV)</th>
<th>$E_{\text{max}}$ (GeV)</th>
<th>$\theta_{\text{min}}$ ($^\circ$)</th>
<th>$\theta_{\text{max}}$ ($^\circ$)</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>224161</td>
<td>10</td>
<td>$10^7$</td>
<td>0</td>
<td>180</td>
<td>2</td>
</tr>
</tbody>
</table>

i.e. the algorithm has no preferred direction.

**Energy Dependence** The energy range is divided into four bins of roughly equal size in $\log(E)$. In contrast to the zenith case, the LLHR depends clearly on the energy. Low LLHR values are mainly assigned to low energy events. This behaviour can be explained by the energy spectra shown in Fig. 8.4. Starting tracks have a lower average energy than infinite tracks.

### 8.4.2 Background: Atmospheric Muons

In the previous sections the algorithm has shown its capability to identify a sample of very likely starting tracks from a neutrino dataset. These results are cross-checked with a muon background dataset. All background events are starting in the atmosphere and not within the detector. Thus, the LLHR distribution for these events should follow the one for infinite tracks in Fig. 8.4.

For these tests, the CORSIKA dataset 72 with a statistics of 102075 events is used. Again, the energy and zenith ranges are divided into bins of equal size. Fig. 8.9 shows the resulting LLHR spectra. The y-axis shows the true number of events, since the CORSIKA datasets are not reweighted.

As expected, the algorithm calculates mostly large LLHR values. The spectra stretch out to LLHR values below -6, even if the graphs in Fig. 8.9 show only the part above. However, they lack the characteristic bend seen with the neutrino datasets, that indicates a component of starting tracks. Instead, they follow the expected distribution of infinite tracks. The offset between the different energy and zenith bins is caused by the energy and zenith distribution of the atmospheric muons.

**Zenith Dependence** In contrast to the neutrino spectrum, most atmospheric muons are vertically down-going. The number of events decreases with increasing zenith angle (approaching the horizon). Vertical muons travel the shortest distance through the atmosphere and have therefore a higher probability to reach the detector. With increasing zenith angle, the amount of matter in the line of sight increases, thus suppressing the muon flux from horizontal directions.

**Energy Dependence** The dataset contains about the same number of events below 1 TeV and between 1 TeV and 10 TeV. Above 10 TeV, the number of events is lower by some orders of magnitude. This reflects the steeply falling energy spectrum of the atmospheric muons with a spectral index of $\gamma \approx 3.7$. However, the slope is the same in all bins. This verifies that the performance of the algorithm does not depend on the energy. The energy dependence of the LLHR seen with the NuGen dataset (Fig. 8.8) is a result of the different average energy of starting and infinite tracks.
8.4 Energy and Zenith Dependence of the \textit{LLHR}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure87.png}
\caption{Neutrino passing rate depending on the distances D2B, IP and DTD for different cuts on the \textit{LLHR}}
\end{figure}
Figure 8.8: LLHR spectra of the NuGen dataset 462 for different zenith (left) and energy (right) bins. All histograms are normalised.

Figure 8.9: LLHR spectra of the CORSIKA dataset 72 for different zenith (left) and energy (right) bins.
Chapter 9

Application of the LLHR-Algorithm to IceCube DeepCore

A motivation for IceCube DeepCore is the prospect of a detector with full-sky acceptance. However, the massive background of atmospheric muons considerably complicates the observation of down-going neutrino-induced events. Their identification can be accomplished by searching for starting tracks. The LLHR-algorithm provides a tool for that purpose. Therefore, the idea emerged to use the algorithm in the context of DeepCore.

When this study was done, the final geometry described in chapter 5.5 was not yet established. Instead a preliminary geometry was being discussed, which includes twelve DeepCore strings arranged between the central IceCube strings. Each string is instrumented with 40 DOMs at a spacing of 10 m, covering a volume between depths of 2050 m and 2450 m. This geometry is referred to as DeepCore-12. Fig. 9.1 shows the locations of the 12 strings in the centre of IceCube. The results obtained here hold also for the later geometries, even though they differ significantly from this configuration.

Figure 9.1: Top view of the central section of IceCube (black) with the 12 strings of the DeepCore-12 geometry (red).
9.1 Additional Events with DeepCore

Four individual datasets are used for this part of the study: A signal and a background dataset were simulated for both the baseline IceCube geometry with 80 strings (IC-80) and for the combined IceCube + DeepCore-12 geometry (IC/DC). The signal datasets were generated with NuGen and contain up-going and down-going muon neutrinos. The datasets were generated with an $E^{-2}$ spectrum and then reweighted to the atmospheric neutrino spectrum. The background datasets were simulated with CORSIKA and contain only down-going atmospheric muons. All signal and background datasets were simulated with the same settings, the only difference is the geometry of the detector. However, the IC/DC signal dataset contains about 20% more events than the IC-80 signal dataset. This can be explained by a higher trigger rate due to the denser instrumentation of IC/DC. The properties of these additional events are the main topic of this section.

9.1.1 Position of the Reconstructed Vertex

Figs. 9.2 to 9.4 show the spatial distribution of the reconstructed vertex returned by the LLHR-algorithm. The reconstructed vertex is the point, where the Cherenkov light was emitted that hit the first DOM (see chapter 7.2). Thus, the reconstructed vertex will be inside or close to the IceCube volume, even for tracks starting far outside.

Figure 9.2: Positions of the reconstructed vertices of the neutrino signal events for IC-80. The events are weighted to the atmospheric spectrum. The data contains down-going and up-going events. Left: Top view. Right: Side view.

Fig. 9.2 shows the distribution for the IC-80 signal dataset. In the top view the pattern of the individual IceCube strings is clearly visible. This is caused by hit probability decreasing exponentially with the distance between the track and the DOM\(^1\). If a DOM is hit, the track is in most cases less than 50 m away. Hence, the reconstructed vertex tends to be located closer to a DOM. Besides, other features are visible in the side view: The concentration of vertices at the lower and upper edge of the detector volume is caused by muons entering the detector from outside. The reconstructed vertex of these events is close to the first layer of DOMs which they pass. Moreover, the layered structure of the ice can be noticed. In particular the Dust Layer directly above the DeepCore volume stands out. Furthermore, even in the case of IC-80, a concentration of vertices in the clear ice below the Dust Layer is noticeable.

\(^1\)This relation is used for example in the parametrisation of the hit probability (see chapter 7.2.2)
Figure 9.3: Positions of the reconstructed vertices of the neutrino signal events for IC/DC. The events are weighted to the atmospheric spectrum. The data contains down-going and up-going events. Left: Top view. Right: Side view.

The corresponding plot for IC/DC is shown in Fig. 9.3. A comparison to the plot for IC-80 shows a massive increase of the vertex density in the DeepCore region. The density in the other parts of the detector remains unchanged. This implies that nearly all of the additional tracks have their first hit close to the DeepCore volume. Thus, they are good candidates for being starting and therefore neutrino-induced tracks.

Fig. 9.4 shows the distribution of the reconstructed vertex in the case of the IC/DC background dataset. Here, the reconstructed vertices are concentrated at the top of IceCube. This is the expected signature for atmospheric muons, which enter the detector from the top. Again, the string pattern and the Dust Layer are visible. The corresponding plot for IC-80 shows no significant differences and is therefore not shown here.

Figure 9.4: Positions of the reconstructed vertices of the background of down-going atmospheric muons for IC/DC. Left: Top view. Right: Side view.

The differences of these distributions motivate to use the position of the reconstructed vertex as a cut parameter to distinguish the neutrino signal from the background of atmospheric muons.
9.1.2 Length of the Additional Tracks

Most of the events which are triggered additionally by the IC/DC configuration have a short length. This is evident from Fig. 9.5. The left plot shows the simulated length of the events triggered by IC-80 (black) and IC/DC (red). The configuration with DeepCore shows an excess of tracks with a length less than 200 m. Since the track length is correlated with the energy (see chapter 3.3), these are events of lower energy.

The right plot illustrates the accuracy of the vertex reconstruction for IC-80 and IC/DC. It shows the difference between the simulated track length and the distance between the reconstructed vertex and the stopping point delivered by the LLHR-algorithm (see chapter 7.2.5). The length is more often underestimated than overestimated. This can be understood as follows: The reconstructed vertex marks the position, where the light was emitted that hit the first DOM. Virtually all particles will emit light before that point. Therefore, the true starting point of an event will always be up-stream of the reconstructed vertex. A similar argument applies to the stopping point: Particles will still emit light, after they have hit the last DOM. However, for IC/DC the distribution has a smaller width. Due to the denser DOM spacing, the reconstructed vertex and the stopping point can be determined more precisely by the algorithm. Hence, the uncertainties in the length in between are smaller.

Figure 9.5: Left: Track length for IC-80 (black) and IC/DC (red). The graph for IC-80 is normalised to 1, the graph for IC/DC shows the excess caused by the additional instrumentation. Right: Difference between true and reconstructed length for IC-80 (black) and IC/DC (red). The reconstructed length here is not calculated by a track reconstruction algorithm, but simply the length between the reconstructed vertex and the stopping point as returned by the LLHR-algorithm. Both graphs are normalised to 1.
9.2 The L1 Veto

The identification of starting and thus neutrino-induced events requires a rejection power of about six orders of magnitude (see chapter 4.6. It soon became apparent that a simple veto as described in chapter 5.3 is not able to achieve this requirement. The LLHR-algorithm can be used in a similar way to identify a sample of starting tracks, but it also fails to achieve the necessary rejection power. Thus, the idea of a combined approach was developed. In a first step a modified conventional veto rejects events with hits in the outer layers of IceCube. From the remaining events, the LLHR-algorithm selects the most likely starting tracks. Due to the preselection of starting events by the level 1 (L1) veto, its task is simplified considerably.

The L1 veto was developed by the IceCube group at the Max Planck Institute for Nuclear Physics in Heidelberg, in particular by Dr. Andreas Groß and Dr. Elisa Resconi [R08]. The procedure comprises two steps: First, a hit-cleaning is applied to the data to get rid of noise hits. Afterwards the actual veto is performed.

9.2.1 Hit-Cleaning

When the first DeepCore simulations were studied, it became apparent, that the background events in these simulations have many isolated hits, which are not noise, but clearly associated with the physical event. Most of these isolated hits are found in the veto volume in the upper part of the detector. In the fiducial volume, the clearer ice and the denser instrumentation increase the probability for a second hit in a neighbouring DOM. The removal of the isolated hits by the HLC (see chapter 4.3), however, affects the veto efficiency. Therefore, in the simulation HLC was replaced by SLC and a more sophisticated method of hit-cleaning was applied. The new hit-cleaning is accomplished in two steps:

1. First an RT cut is applied. RT stands for radius and time: Only hits with a second hit within a certain radius and time are kept. This is a less rigorous form of the principle of local coincidences. The radius is set to 150 m, the time to 1 µs.

2. In a second step a Time-Window cleaning is applied. Only hits within the time-window of 5 µs which contains most hits are kept. The other hits are treated as not associated with the physical event and are removed.

9.2.2 Geometrically Penalised Veto

Based on this hit-cleaning the conventional veto as discussed in chapter 5.3 is also enhanced to a geometrically penalised veto. A veto weight is assigned to all hits depending on their geometrical position. Hits close to the fiducial volume are more likely associated with a starting event and get a small weight. Hits far away from the fiducial volume are more likely caused by atmospheric muon events and get a larger weight.

The detector volume is divided into a veto volume and a fiducial volume. The fiducial volume is located in the lower centre of the detector and around the DeepCore volume. The remaining part of the detector, around and on top of the fiducial volume, constitutes the veto volume. It is composed of two regions, where the weight is calculated differently. The veto is illustrated in Fig. 9.6. The first

---

2This explains, why the isolated hits in the upper part of the detector are so important for the veto: They are far away from the fiducial volume and get a large weight.
region contains the complete upper part of the detector down to the 37th layer of DOMs. Here, the veto parameter \( W \) is given by

\[
W = 1000 \cdot \exp \left( -\sqrt{W_{\text{ring}}^2 + W_Z^2} \right).
\]  

(9.1)

\( W_{\text{ring}} \) is the number of the veto ring, counted from the outermost ring, and \( W_Z = (N_{\text{DOM}} - 1)/10 \) is the contribution of the top layers. \( N_{\text{DOM}} \) denotes the number of the DOM layer, counted from the top. In the lower part of the detector, the four outermost rings of strings contribute to the veto volume. Here, the distance to the fiducial volume does not depend on the depth of the hit. Therefore, the weight depends only on the number of the ring. Hits on the outermost ring get \( W = 15 \), on the second \( W = 10 \), on the third \( W = 5 \) and on the fourth \( W = 1 \). Hits in the fiducial volume are not included in the weight. The total veto parameter \( W_{\text{tot}} \) for an event is the sum of the individual weight parameters \( W_i \):

\[
W_{\text{tot}} = \sum_{\text{hits}} W_i.
\]  

(9.2)

**Figure 9.6:** The geometrically penalised veto. Middle: Definitions of the fiducial volume and the two veto regions. Left: \( W_{\text{ring}} \) in veto region I, the upper part of the detector. Right: \( W_{\text{ring}} \) in veto region II, the lower part of the detector.

An event is kept if it has more than 10 hits in the fiducial volume and a veto parameter \( W_{\text{tot}} < 60 \). In the conventional veto only the number of hits within the veto volume decides if the event is rejected. In contrast to this, the veto weight \( W \) depends strongly on the position of the hits. Hence, the geometrically penalised veto allows to keep events with a certain number of hits in the veto volume, if these hits are close to the fiducial volume. Events with the same number of hits far away from the fiducial volume, are rejected.

### 9.2.3 Properties of the Events Surviving the L1 Veto

In the application of the LLHR-algorithm to the DeepCore-12 datasets, the construction of the likelihoods is done without \( \text{StringLLH} \) (see chapter 7.2.3), since \( \text{HLC} \) are not used.

Of initially 20 million simulated background events only 9259 survive the L1 veto. This is a rejection factor of about \( 5 \cdot 10^{-4} \). The signal passing rate of down-going neutrino events is about 13%: Of initially 200267 events 25264 survive the veto. Figs. 9.7 and 9.8 show the positions of the reconstructed vertex of all signal and background events which survive the L1 veto. The reconstructed vertices of the signal events are concentrated at the lower central part of IceCube, thus around the DeepCore volume. This is the expected signature, since events with distant hits are rejected. The plot for the background events
reveals a more surprising structure. The reconstructed vertices are located predominantly at a medium depth inside the IceCube volume. Most of the vertices are found on the outer ring of strings. However, there is another component of more central events, with a reconstructed vertex some hundred metres above the first population.

Figure 9.7: Positions of the reconstructed vertices of the neutrino signal events after the L1 veto with atmospheric weighting. The data contains up-going and down-going events. Left: Top view. Right: Side view. The black lines mark the outline of IceCube.

Figure 9.8: Positions of the reconstructed vertices of the atmospheric muon background events after the L1 veto. Left: Top view. Right: Side view. The black lines mark the outline of IceCube.

This ‘sombrero-hat’ structure can be understood with the help of the zenith distribution of the surviving events, shown in Fig. 9.9. The distribution shows two maxima. One is located at \( \cos(180^\circ - \theta) = -1 \), corresponding to vertically down-going events. The second maximum has a broader peak at about \( \theta \approx 50^\circ \). Background events from these two zenith directions have a higher probability to pass the L1 veto. The vertical component can be explained by the large spacing of the IceCube strings. The hit probability of a DOM decreases exponentially with the distance. Therefore, vertical events in the middle between neighbouring strings may travel undetected through the veto volume. The first hit is produced when they enter the denser instrumented DeepCore volume. The reconstructed vertex of these events is thus located central above the fiducial volume. These events form the cap of the sombrero. The other class of surviving events is caused by the Dust Layer (see chapter 4.1). Due to the high absorption, events have a low detection probability in that region. Events with a zenith angle of about 50°, which enter the IceCube volume in a medium depth, can stay undetected until they leave the Dust Layer and reach the
clear ice below. Thus, they also produce their first hit inside the fiducial volume. The reconstructed vertex of these events is found in the depth of the Dust Layer around the fiducial volume. These events form the rim of the sombrero. It should be noted, that the lower veto efficiency in the region of the Dust Layer does not mean that DOMs there are useless. They are crucial for the veto. For the rejection of events entering through the Dust Layer every single DOM can be essential. The Dust Layer is however not a suitable place for the fiducial volume. Fig. 9.10 illustrates the two event classes with a higher probability to pass the veto.

![Zenith spectrum](image)

**Figure 9.9:** Zenith distribution of the background events which survive the L1 veto.

### 9.3 The L2 Cuts Based on the Output of the LLHR Algorithm

The L1 veto achieves a background rejection of about four orders of magnitude. Thus, about two or three orders of magnitude have still to be rejected until the background rate of atmospheric muons falls below the rate of muons from down-going atmospheric neutrinos. This rejection is achieved by cuts based on the output of the LLHR-algorithm. The cut parameters are the LLHR value and the position of the reconstructed vertex. The event is required to have a high probability to be starting, i.e. a highly negative LLHR value. The position of the reconstructed vertex \( r_{\text{vertex}} \) is required to be below a certain depth \( z \) and within a certain radius around the centre of DeepCore. This radius is defined as

\[
r_{\text{vertex}} = \sqrt{(x_{\text{vertex}} - 100\,\text{m})^2 + y_{\text{vertex}}^2}.
\] (9.3)

\( x_{\text{vertex}} \) and \( y_{\text{vertex}} \) are the \( x \) and \( y \) component of the position of the reconstructed vertex. The origin of the coordinate system is the centre of IceCube. The centre of DeepCore is shifted about 100 m in \( x \)-direction. Two sets of cuts were developed to reduce the number of surviving background events to 10 and 1, respectively:

- **L2 cut1**: \( r_{\text{vertex}} < 230\,\text{m} \), \( z_{\text{vertex}} < -130\,\text{m} \) and \( LLHR < -4.5 \).
- **L2 cut2**: \( r_{\text{vertex}} < 220\,\text{m} \), \( z_{\text{vertex}} < -150\,\text{m} \) and \( LLHR < -6 \).

The cuts were developed manually by gradually varying the cut values until the desired number of surviving background events was reached. At the same time the number of passing signal events was maximised. Figs. 9.11 and 9.12 show the distribution of the cut parameters and the final cuts. The cuts...
Figure 9.10: The two event classes which predominantly survive the L1 veto. Nearly vertical events in the middle between the IceCube strings can produce their first hits in the fiducial volume. The same argument applies to events which enter the fiducial volume through the Dust Layer.

on the position of the reconstructed vertex are most effective. In a first step, their approximate positions were determined. For the fine-tuning of the signal passing rate, the cut on the LLHR value was varied. If necessary, the other two cuts were adjusted. This procedure was repeated until the highest signal passing rate was found. Finally, it was checked if another, very different setting of the cuts would yield an even better signal passing rate.

<table>
<thead>
<tr>
<th></th>
<th>before L1 veto</th>
<th>after L1 veto</th>
<th>after L2 cut1</th>
<th>after L2 cut2</th>
</tr>
</thead>
<tbody>
<tr>
<td># background events</td>
<td>~ 20 million</td>
<td>9259</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td># signal events</td>
<td>200267</td>
<td>25264</td>
<td>5383</td>
<td>3984</td>
</tr>
</tbody>
</table>

Table 9.1: Numbers of background events and down-going signal events after L1 veto and L2 cuts.

Table 9.1 shows the event numbers for signal and background after the cuts. The cuts achieve another four orders of magnitude in background rejection. Thus, the combined veto has a background rejection power of about eight orders of magnitude. The total signal passing rate is only about 2.5%. However, it should be noted, that the 200267 signal events in the initial dataset are mostly through-going events. Only about 87000 events have a neutrino interaction vertex inside the DeepCore volume. Of these events
about 6% are kept by the L2 cuts.

Fig. 9.13 shows the expected event rates for signal and background depending on the cut level. After the L2 cuts, the rate of neutrino-induced events exceeds the background rate and accounts to $2 \cdot 10^{-4}$ Hz. That adds up to about 6300 events per year. Hence, the combined veto allows IceCube to observe events from above the horizon and extends its field of view to the southern sky.

Fig. 9.14 shows the energy and zenith spectra of the neutrino events surviving the L1 veto and the L2 cuts. The energy and zenith composition is not changed by the L2 cuts.
9.3 The L2 Cuts Based on the Output of the LLHR Algorithm

Figure 9.12: Distribution of the cut parameter LLHR for signal (left) and background (right). The darker lines show the distribution after the L1 veto, the brighter graphs after the cuts on $r_{\text{vertex}}$ and $z_{\text{vertex}}$. The black lines designate the L2 cuts. The solid line marks the L2 cut1, the dashed line L2 cut2.

Figure 9.13: Event rates depending on the cut level. Level 1 represents the veto, level 2 the cuts based on the output of the LLHR-algorithm.

Figure 9.14: Neutrino energy (left) and zenith (right) spectra of the signal events surviving the L1 veto (black) and the L2 cut1 (red) and L2 cut2 (green).
Chapter 10
Design Study for DeepCore - Part I

The first discussed DeepCore geometry (DeepCore-12) consisted of 12 new strings with 40 DOMs each. This concept was not feasible for various reasons. Besides the financial challenge to get the funding for 12 strings, drilling issues might constrain the number of deployable strings. The region where the new holes should have been drilled is densely occupied by the cables running from the strings to the Counting House. Furthermore, the deployment schedule might restrict the number of additional strings. The number of drilling seasons was planned for the deployment of the 80 strings of the IceCube baseline design. This number is not likely to be increased. Although there is some buffer time in the last drilling season in the austral summer of 2010/11, the deployment of 12 additional strings appears to be unrealistic. Thus, it was studied if the objectives of DeepCore could be accomplished by less strings, but with a denser instrumentation.

Two new string configurations with 60 DOMs each, shown in Fig. 10.1, were developed for these studies. Configuration I is similar to the DeepCore-12 string configuration, but features an even smaller DOM spacing of only 6.67 m. Configuration II retains the larger spacing of 10 m. In an attempt to improve the veto capabilities, in particular against vertically down-going events, the additional 20 DOMs are placed above the Dust Layer, at depths between 1650 m and 1850 m.

Section 10.1 investigates, how much efficiency is lost, if fewer strings are deployed. Section 10.2 is dedicated to the question, how much is gained by a smaller DOM spacing. Section 10.3 finally explores the effect of the 20 dedicated veto DOMs of configuration II. All studies are done after the L1 veto.

10.1 Signal Loss by Fewer Strings

A comparison is done between configuration I with 6 strings and with 10 strings. Fig. 10.2 shows the neutrino energy spectra after the L1 veto for these two geometries. The 10 string geometry shows significantly more triggered events below 100 GeV. The ratio of the event numbers of the two geometries is about 1.6. This indicates that the number of triggered events depends roughly linearly on the amount of instrumentation: The ratio of the number of strings is also 1.6.

10.2 Signal Gain by a Denser Instrumentation

A second comparison probes the advantages of a smaller DOM spacing. Configuration II is compared to configuration I. Both studied geometries have 6 strings. Fig. 10.3 shows the resulting neutrino energy spectra after the L1 veto. The small DOM spacing shows a higher event rate at low energies. At 10 GeV and below an improvement by a factor of 5 is noticeable. Thus, a denser instrumentation can (at least partly) recover the efficiency lost by the reduced number of strings. This result supports a smaller DOM spacing.
Figure 10.1: The preliminary DeepCore string configurations I and II, compared to a standard IceCube string. The scale on the right shows the depth from the surface. The left scale denotes detector coordinates. The grey bar indicates the Dust Layer, the red curve maps the dust concentration [Sch].

10.3 The Effect of Dedicated Veto DOMs

Apart from the larger DOM spacing, configuration II is used to study the effect of the 20 dedicated veto DOMs above the Dust Layer. Fig. 10.4 shows the distribution of the reconstructed vertices for the background dataset after the L1 veto. The vertically down-going tracks, which constituted the cap of the ‘sombrero’ in Fig. 9.8 have almost completely disappeared. Only the rim remains, which is formed by events entering diagonally through the Dust Layer.

The nearly complete suppression of vertical events is a strong argument for specialised veto DOMs within DeepCore. Due to the high efficiency of the rejection, it is reasonable to assume that less than 20 layers of DOMs are equally sufficient. Thus, a part of these DOMs can be placed in the fiducial volume to benefit from a smaller DOM spacing. The spacing can be further reduced by constraining the fiducial volume strictly to the region below the Dust Layer. As shown in Fig. 10.1, both preliminary configurations I and II reach up into the Dust Layer. Because of the high absorption and scattering in that region, these DOMs might be more useful somewhere else.
10.3 The Effect of Dedicated Veto DOMs

Figure 10.2: Left: Neutrino energy spectra after the L1 veto for a DeepCore geometry with 6.67 m DOM spacing and 6 strings (red) and 10 strings (blue), respectively. Right: Signal gain by 10 strings.

Figure 10.3: Left: Neutrino energy spectra after the L1 veto for a DeepCore geometry with 6 strings and 10 m DOM spacing (red) and 6.67 m DOM spacing (green), respectively. The geometry with the 10 m spacing places the 20 additional DOMs as veto DOMs above the Dust Layer. Right: Signal gain by the smaller 6.67 m DOM spacing.

Figure 10.4: Positions of the reconstructed vertices of background events for configuration II with 6 strings after the L1 veto. Left: Top view. Right: Side view. These plots were generated with considerably lower statistics than the plots shown in chapter 9.
Chapter 11
Design Study for DeepCore - Part II

For the determination of the final geometry of DeepCore, it was decided to simulate and study three further geometries, optimised in the light of the information provided by the study of the preliminary geometries. The resulting configurations A, B and C are sketched in Fig. 11.1.

- **Configuration A** minimises the energy threshold and gains as much as possible from the exceptionally clear ice below the Dust Layer. 50 DOMs with a vertical spacing of 7.5 m are placed below a depth of 2075 m. To improve the veto, 10 DOMs are placed above the Dust Layer. They have a vertical spacing of 10 m.

- Configurations B and C maximise the detector volume. The drawback is the larger DOM spacing of 10 m. In **configuration B**, 30 DOMs are placed below the Dust Layer and 30 DOMs directly above. This geometry has no dedicated veto DOMs. The veto can be chosen for every analysis individually from the top 30 DOMs.

- **Configuration C** places 10 veto DOMs at the top of the detector, at depths between 1450 m and 1550 m. Since DOMs far away from the fiducial volume have a larger weight in the L1 veto, this improves the rejection capabilities. In addition, the fiducial volume could potentially be extended up to the bottom edge of the veto DOMs. The depth in which the veto DOMs are deployed, is irrelevant for atmospheric muons from vertical directions. However, the gap beneath the veto DOMs may enable inclined atmospheric muons to leak in.

The most realistic installation scenario constrains the number of deployable DeepCore strings to six. The improvement by deploying additional strings can be estimated (see chapter 10.1). Thus, for each geometry only six strings are simulated. Moreover, strings 79 and 80 in the northeast corner of IceCube have been removed from the simulation. If they are ever deployed, they will contribute to the planned High Energy Optimisation (see chapter 4.7.2 and Fig. 5.6). Since these two strings are a part of the outermost veto ring, their absence may have an impact on the efficiency of the veto. The same argument applies to the relocation of the nine other strings of the High Energy Optimisation. All these strings are part of the outermost veto ring. Besides, the veto was modified and two different veto configurations were studied. For reasons of time the High Energy Optimisation was simulated with only one veto configuration. In total, three signal and background datasets were simulated for each of the three string configurations.

### 11.1 The New L1 Veto

For the new geometries, the L1 veto was refined by Olaf Schulz of the Heidelberg group. The same hit-cleaning as before is applied to the data (see chapter 9.2.1). In the actual veto process, the definitions
Figure 11.1: The preliminary DeepCore string configurations A, B and C, compared to a standard IceCube string. The scale on the right shows the depth from the surface. The left scale denotes detector coordinates. The grey bar indicates the Dust Layer, the red curve maps the dust concentration [Sch].

of veto volume and fiducial volume are modified. In horizontal direction, the perimeter of the fiducial volume is given by the locations of the six DeepCore strings. In vertical direction, two different alternatives were studied. The first is referred to as Veto0. Here, the veto volume is the same for all string configurations. It reaches down into the Dust Layer and includes all DOMs above a depth of 2075 m. In the second configuration, called Veto1, the lower bound of the veto volume is adjusted to the string configuration.

- For configuration A, the veto volume includes all DOMs above a depth of 1845 m. The 10 DOMs above the Dust Layer are added to the fiducial volume, i.e. no DeepCore DOMs contribute to the veto.

- For configuration B, all but the 10 topmost DOMs on DeepCore strings are added to the fiducial volume. The lower boundary of the veto volume is set to a depth of 1755 m.

- For Configuration C, the veto volume reaches down to a depth of 1740 m, shortly above the 20 remaining DOMs above the Dust Layer.

The most significant modification is related to the calculation of the veto weight. In the new version, the weight of the hits depends no longer on the numbers of the DOM layer and the ring of strings, but
directly on the distance $d$ to the surface of the fiducial volume. The veto weight $W$ is defined as

$$W = \exp\left(\frac{d}{75\text{ m}}\right) .$$

(11.1)

The length of 75 m corresponds roughly to the photon absorption length in ice. Summation of the individual hit weights yields the total veto weight $W_{\text{tot}}$. As before (chapter 9.2.2), an event is required to have more than 10 hits in the fiducial volume and a veto weight $W_{\text{tot}} < 60$ to pass the veto.

### 11.1.1 Background Passing Rates

Table 11.1 displays the number of surviving atmospheric muon events for all studied geometries. With Veto0, configuration A triggers about 25% more background events than configurations B and C. This is obviously due to the smaller DOM spacing. With Veto1, the number of passing events increases strongly. For configuration A, the increase is not as pronounced as in the case of configurations B and C, since the difference in veto volume between Veto0 and Veto1 is smaller. Although configurations B and C are very similar, configuration C shows a slightly lower passing rate. This is caused by the veto DOMs being placed further away from the fiducial volume and thus yielding larger veto weights.

Also the High Energy Optimisation leads to an increased background passing rate. The effect is not as strong as in the case of Veto1, but still amounts to a factor of about 3.

<table>
<thead>
<tr>
<th># background events after L1 veto</th>
<th>Config A</th>
<th>Config B</th>
<th>Config C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Veto0</td>
<td>3710</td>
<td>26472</td>
<td>2717</td>
</tr>
<tr>
<td>Veto1</td>
<td>9644</td>
<td>7723</td>
<td>8023</td>
</tr>
<tr>
<td>no HE Extension</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 strings HE Ext.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 11.1: Background events after L1 veto for the DeepCore string configurations A, B and C.

### 11.1.2 Properties of the Events Surviving the L1 Veto

Fig. 11.2 shows the neutrino energy spectra for the three studied configurations and the two versions of the L1 veto. In chapter 10.2 it was shown that a smaller DOM spacing yields a significantly enhanced rate of low energy events. With Veto0, configuration A verifies this observation, as it has a smaller DOM spacing than the other two configurations. The energy threshold can be lowered from around 100 GeV (see chapters 4 and 8.1) to below 10 GeV. Configurations B and C, which are very similar to each other, show no significant differences. With Veto0, their larger DOM spacing in the same fiducial volume yields a lower trigger rate, in particular at the lowest energies. The advantage of configuration A is lost with Veto1. Here, configurations B and C possess a significantly larger volume and detect roughly the same number of events as configuration A, in spite of the larger DOM spacing (for the number of signal events after the L1 veto see Table 11.3).

The distribution of the reconstructed vertices allows a first estimation of the veto characteristics of a certain configuration. The reconstructed vertices of the signal events are concentrated around the DeepCore volume in all geometries. Fig. 11.3 shows the position of the reconstructed vertices for configuration A with Veto0 and without High Energy Optimisation. The distributions for the other configurations show no significant differences and are found in the appendix.
Figure 11.2: Neutrino energy spectra of the signal events surviving the L1 veto for configurations A (black), B (red) and C (green). No High Energy Optimisation, Veto0 (left) and Veto1 (right).

Figure 11.3: Positions of the reconstructed vertices of signal events for configuration A without High Energy Optimisation after Veto0. Left: Top view. Right: Side view.

Fig. 11.4 shows the distribution of the reconstructed vertices for the background dataset of configuration A with Veto0 and without High Energy Optimisation. The structure resembles the distribution of the preliminary configuration II (Fig. 9.8) with better statistics. Since only 10 dedicated veto DOMs are placed above the Dust Layer, the rejection of central events is not as complete as in the case of configuration II. Configurations B and C, which have (with Veto0) 30 DOMs in the veto volume, show an almost complete rejection of vertical tracks. Fig. 11.5 shows the corresponding distribution for configuration B. Nevertheless, also in configuration A, most events have a reconstructed vertex on the outer ring, caused by events entering through the Dust Layer. A striking feature is the massive accumulation of events from the direction of the missing strings 79 and 80. One veto layer less increases the background by a factor 10 from that direction. About 25% of all background events surviving the L1 veto arrive from the direction of the two missing strings.

The effect of missing strings in the outermost veto ring becomes even more apparent in the case of a geometry with High Energy Optimisation. Fig. 11.6 shows the distribution for configuration A with Veto0 and with High Energy Optimisation. All areas with an enlarged background rate correspond to directions of strings relocated from the outer veto ring (see Fig. 5.6).

The effect of the second veto configuration (Veto1) is shown in Fig. 11.7. Due to the reduced veto volume, considerably more events pass the veto. The accumulation of events from the direction of strings...
79 and 80 is again visible, but no longer the main contribution. In the side view, the vertical elongation of this feature is visible. In the top view the pattern of the IceCube string positions appears, because events passing close to a DOM are easily rejected. The region between strings is densely populated with not rejected events. However, these events might receive a high LLHR value and thus be rejected in the L2 cuts. The corresponding distributions for configurations B and C show similar features and are found in the appendix.

For all configurations, the reduced veto volume of Veto1 results in a massive increase of passing background events. Due to the enlarged fiducial volume the number of measured signal events will increase as well. This holds especially for configurations B and C, where the increase in fiducial volume is larger. If the LLHR-algorithm is capable of rejecting the additional background events without rejecting the signal events as well, this veto configuration could be of advantage. Thus, the essential number is the amount of signal events remaining after the L2 cuts.

11.2 The L2 Cuts

As described in chapter 9.3, cuts on the LLHR value and on the position of the reconstructed vertex are applied to the events surviving the L1 veto. For all geometries, the cuts are set to a level which keeps
only one background event. This background rejection is achieved with all geometries. All background datasets were generated with the same statistics. The number of passing signal events is thus a measurement for the efficiency of the veto. The signal passing rates are discussed in section 11.3. Table 11.2 displays the cut values for all studied geometries.

The cut values are adjusted in an iterative procedure as described in section 9.3. The cut values for Veto0 without the High Energy Optimisation are taken as benchmark values for all other configurations. Configuration A shows a remarkable stability for Veto1. In contrast, the cuts for configurations B and C have to be tightened considerably. The better stability of configuration A can be explained by the smaller difference in the veto volume between Veto0 and Veto1. The tight cuts on $z_{\text{vertex}}$ for configuration B and C indicate that the advantage of the increased fiducial volume is lost in the L2 cuts. Also the High Energy Optimisation has a larger impact on configurations B and C. The relocation of the outer strings causes in particular inclined events in shallower depths to leak in. Since configurations B and C possess more instrumentation in that region, they are more strongly affected.
### 11.3 Signal Passing Rates

As mentioned above, the signal passing rate after the L2 cuts is a measurement for the efficiency of the veto. Table 11.3 shows the number of surviving down-going signal events after the L1 veto and the L2 cuts.

<table>
<thead>
<tr>
<th>Config A</th>
<th>Config B</th>
<th>Config C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Veto0</td>
<td>Veto1</td>
<td>Veto0</td>
</tr>
<tr>
<td>$r_{\text{vertex}}$</td>
<td>$z_{\text{vertex}}$</td>
<td>LLHR</td>
</tr>
<tr>
<td>no HE Extension</td>
<td>260</td>
<td>-100</td>
</tr>
<tr>
<td>11 strings HE Ext.</td>
<td>230</td>
<td>-115</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Configuration B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Veto0</td>
</tr>
<tr>
<td>$r_{\text{vertex}}$</td>
</tr>
<tr>
<td>no HE Extension</td>
</tr>
<tr>
<td>11 strings HE Ext.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Configuration C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Veto0</td>
</tr>
<tr>
<td>$r_{\text{vertex}}$</td>
</tr>
<tr>
<td>no HE Extension</td>
</tr>
<tr>
<td>11 strings HE Extension</td>
</tr>
</tbody>
</table>

Table 11.2: L2 cut values for the DeepCore string configurations A, B and C with and without High Energy Optimisation and for Veto0 and Veto1.

<table>
<thead>
<tr>
<th># signal events after L1 veto / L2 cuts</th>
<th>Config A</th>
<th>Config B</th>
<th>Config C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Veto0</td>
<td>Veto1</td>
<td>Veto0</td>
<td>Veto1</td>
</tr>
<tr>
<td>no High Energy Extension</td>
<td>after L1</td>
<td>562</td>
<td>769</td>
</tr>
<tr>
<td></td>
<td>after L2</td>
<td>142</td>
<td>145</td>
</tr>
<tr>
<td>11 strings HE Extension</td>
<td>after L1</td>
<td>845</td>
<td>603</td>
</tr>
<tr>
<td></td>
<td>after L2</td>
<td>118</td>
<td>95</td>
</tr>
</tbody>
</table>

Table 11.3: Number of signal events after L1 veto and L2 cuts for the DeepCore string configurations A, B and C.

Configuration A shows the highest event rates. Before the L2 cuts, Veto1 yields a higher rate than Veto0, since the fiducial volume is larger and more events trigger the detector. However, this advantage is lost in the process of the L2 cuts, which result in nearly the same number of surviving events. The High Energy Optimisation also causes an increase in the signal event rate before L2. In contrast to the case of Veto1, the L2 cuts have to be tightened. Hence, the number of signal events after the L2 cuts is about 20% lower than in the case without a High Energy Optimisation.

Due to their similar geometries, configurations B and C show nearly identical results, in particular after the L2 cuts. With Veto0, the signal passing rates after L2 for configurations B and C are about 40% lower than for configuration A. With Veto1, the signal passing rate is further reduced by about 20%. Here, the rate is only about 50% of the rate for configuration A, in spite of a significantly larger fiducial volume. The explanation for this low rate is that the Veto1 allows significantly more background events to leak in. To reject these events, the L2 cuts have to be tightened strongly. In contrast to configuration A, the numbers with and without the High Energy Optimisation after L2 are roughly the same. However, they
are still 20% lower than for configuration A.

Two general conclusions can be drawn from these results:

1. A high L1 background passing rate results usually in a low L2 signal passing rate. This supports the approach of a rather strict L1 veto. A weak L1 veto causes too much background to leak in, forcing the L2 cuts to be very tight.

2. The fiducial volume cannot be extended far above the Dust Layer. A small veto volume also causes a massive increase in the number of background events, which cannot be rejected efficiently with the L2 cuts.

These results strongly support configuration A as the most promising DeepCore geometry for the identification of starting down-going events. Based on these studies [E⁺08b, E⁺08a] and the results of a similar study [Gra08a, Gra08b], the low energy working group has proposed configuration A to the IceCube collaboration as the baseline configuration for the construction of the DeepCore detector. The only modification in the finally agreed string configuration is the reduced DOM spacing of 7 m to stay clear of the Dust Layer. Based on the number of 6300 events per year for the DeepCore-12 geometry (chapter 9.3) and the findings presented in chapter 10, an event rate of several thousand events per year can be expected for the final DeepCore detector configuration.
Chapter 12

Summary and Outlook

IceCube detects neutrinos by means of the Cherenkov light emitted by secondary muons. However, muons are produced far more numerous in cosmic ray induced air showers. These atmospheric muons appear as background to the signal of down-going neutrino-induced muons. Therefore, neutrino telescopes usually search for up-going tracks as a signature for neutrino-induced muons.

Within this thesis a new approach is presented, which attempts to search also for down-going neutrinos by selecting muons which start inside the IceCube detector. Atmospheric muons always enter the detector volume from the outside and should generate hits in the outer layers of IceCube. Starting tracks, in contrast, can only result from a neutrino interaction.

This thesis has presented the LLHR-algorithm which allows the identification of starting muon tracks. It is based on the survey of the hit probabilities for non-hit DOMs up-stream of the first hit. For a given track, the algorithm returns an estimation of the starting point (the neutrino interaction vertex) and calculates the likelihood ratio $LLHR$ as the ratio of the probability of a starting track with respect to the probability of a track passing undetected through the detector up-stream of the first hit. The $LLHR$ value is used as degree of believe of that track to be starting. The algorithm was tested with simulated data. The $LLHR$ value does not depend on the energy and the direction of the track. A sample of starting tracks can be obtained by a cut on the $LLHR$ value. Tightening the cut leads to the selection of tracks which are starting central and deep inside the IceCube volume. Hence, the algorithm is used for the discrimination between the signal of neutrino-induced muons and the background of atmospheric muons.

In a next step, the $LLHR$-algorithm was applied to DeepCore, the low energy optimisation of IceCube. DeepCore will greatly enhance IceCube’s capabilities in the energy range below 100 GeV, lower its energy threshold to about 10 GeV and significantly improve the sensitivity, for example, to Dark Matter effects and neutrino oscillations. Moreover, it will enable IceCube to look above the horizon and achieve a $4\pi$ sr field of view. The necessary background rejection of 6 orders of magnitude is achieved by a combination of the $LLHR$-algorithm with a geometrically penalised veto. In a first step, the veto rejects events based on the geometry of their hit pattern. Afterwards, cuts are applied to the position of the reconstructed vertex and the $LLHR$ value.

During the development of DeepCore, several detector geometries were examined. The first studied geometry included 12 new strings with 40 DOMs each. Since the number of additional DeepCore strings is presently restricted to 6, it was investigated if a similar performance could be achieved by a denser instrumentation of only 6 strings. The positive result of this survey led to the decision to instrument the new strings with 60 DOMs. The DOMs will be equipped with a new high quantum efficiency PMT.

For the final decision about the vertical distribution of the DOMs, three different configurations (A, B and C) have been studied in detail (see Fig. 11.1). The background rejection power and the signal passing rate have been analysed for these configurations. The necessary background rejection can be achieved with all studied geometries. However, the signal passing rates differ significantly. Configurations B and C place half of the DOMs above the Dust Layer, thus maximising the fiducial volume. The resulting small
veto volume causes a massive amount of background events to leak in, forcing strict tightening of the cuts. This, in turn, yields a low signal passing rate. A more efficient approach is realised in configuration A, which places nearly all DOMs below the Dust Layer and minimises the vertical DOM spacing. This corresponds to a significantly larger veto volume and thus a better background rejection. Consequently, there is no need to tighten the cuts as strict as in the case of configurations B and C. Therefore, a higher signal passing rate is achieved. Another advantage of the smaller spacing is a lower energy threshold of about 10 GeV and a significantly enhanced event rate at the lowest energies.

Together with results from other studies, these findings have led to the choice of configuration A as the baseline design for the DeepCore strings. The final configuration has been modified only slightly (see Fig. 5.7). The vertical DOM spacing has been further reduced to stay clear of the Dust Layer. Presumably, the first string will be deployed in the austral summer 2008/09. The completion of DeepCore is scheduled for 2010, one year before the completion of the full IceCube detector. With this optimisation, IceCube may detect several thousand low energy neutrino events per year. The scientific value of DeepCore has been acknowledged also by the IceCube Science Advisory Committee, a board of external advisors, which “sees a large increase in the scientific potential of IceCube due to this modification.”
Appendix A

Distribution of the Reconstructed Vertex - Signal

Figure A.1: Positions of the reconstructed vertices of signal events for configuration A without High Energy Optimisation after Veto0. Left: Top view. Right: Side view.

Figure A.2: Positions of the reconstructed vertices of signal events for configuration A with High Energy Optimisation after Veto0. Left: Top view. Right: Side view. An increase of events from the direction of the High Energy Optimisation is noticeable.
Appendix A Distribution of the Reconstructed Vertex - Signal

Figure A.3: Positions of the reconstructed vertices of signal events for configuration A without High Energy Optimisation after Veto1. Left: Top view. Right: Side view.

Figure A.4: Positions of the reconstructed vertices of signal events for configuration B without High Energy Optimisation after Veto0. Left: Top view. Right: Side view.

Figure A.5: Positions of the reconstructed vertices of signal events for configuration B with High Energy Optimisation after Veto0. Left: Top view. Right: Side view. An increase of events from the direction of the High Energy Optimisation is noticeable.
Figure A.6: Positions of the reconstructed vertices of signal events for configuration B without High Energy Optimisation after Veto1. Left: Top view. Right: Side view.

Figure A.7: Positions of the reconstructed vertices of signal events for configuration C without High Energy Optimisation after Veto0. Left: Top view. Right: Side view.

Figure A.8: Positions of the reconstructed vertices of signal events for configuration C with High Energy Optimisation after Veto0. Left: Top view. Right: Side view. An increase of events from the direction of the High Energy Optimisation is noticeable.
Figure A.9: Positions of the reconstructed vertices of signal events for configuration C without High Energy Optimisation after Veto1. Left: Top view. Right: Side view.
Appendix B

Distribution of the Reconstructed Vertex - Background

Figure B.1: Positions of the reconstructed vertices of background events for configuration A without High Energy Optimisation after Veto0. Left: Top view. Right: Side view.

Figure B.2: Positions of the reconstructed vertices of background events for configuration A with High Energy Optimisation after Veto0. Left: Top view. Right: Side view.
Figure B.3: Positions of the reconstructed vertices of background events for configuration A without High Energy Optimisation after Veto1. Left: Top view. Right: Side view.

Figure B.4: Positions of the reconstructed vertices of background events for configuration B without High Energy Optimisation after Veto0. Left: Top view. Right: Side view.

Figure B.5: Positions of the reconstructed vertices of background events for configuration B with High Energy Optimisation after Veto0. Left: Top view. Right: Side view.
Figure B.6: Positions of the reconstructed vertices of background events for configuration B without High Energy Optimisation after Veto1. Left: Top view. Right: Side view.

Figure B.7: Positions of the reconstructed vertices of background events for configuration C without High Energy Optimisation after Veto0. Left: Top view. Right: Side view.

Figure B.8: Positions of the reconstructed vertices of background events for configuration C with High Energy Optimisation after Veto0. Left: Top view. Right: Side view.
Figure B.9: Positions of the reconstructed vertices of background events for configuration C without High Energy Optimisation after Veto1. Left: Top view. Right: Side view.
Appendix C

Logo of IceCube DeepCore

Figure C.1: The logo of IC/DC.
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Erklärung

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

Aachen, 15. Juni 2008
Bibliography


[Gab07] S. Gabici, private communication, taken from: Sources we can miss without a low energy extension of IceCube, talk by E. Resconi at the Low Energy Workshop, Aachen, 2007.


[Sch] O. Schulz, private communication.


