Searching for an Ultra High-Energy Diffuse Flux of Extraterrestrial Neutrinos with IceCube 40

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Abstract

Neutrino astronomy has the potential to greatly improve our understanding of the high-energy universe. An unresolved, diffuse, flux of neutrinos is sensitive to the properties of the population of cosmic accelerators in the universe. Data from 2008 and 2009 collected with the IceCube in-ice detector in a 40-string configuration were searched for an all-flavor ultra high-energy diffuse flux of astrophysical neutrinos. Data were divided into three streams based on signal and background event topology. Robustness was prioritized and a good agreement between real and simulated background data was observed. The search was optimized to give a high sensitivity to a neutrino flux with energy spectrum $E^{-2}$ and energy greater than 1 PeV. The data sample used in the search for signal had a live time of 345.7 days and the estimated background was $1.2 \pm 0.5$ events. Taking systematic and statistical uncertainties into account, the sensitivity $\Phi_S$ was estimated at $E^2\Phi_S = 1.15 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ assuming a 1 : 1 : 1 ratio between neutrino flavors at Earth.

The full data sample was unblinded once the analysis procedure was fixed and approved by the IceCube collaboration. Three events survived the final filter level. The surviving events look like reasonable neutrino candidate events. Assuming a background only hypothesis, the probability of seeing three or more events is 10%. The resulting 90% confidence level upper limit $\Phi_{UL}$ is the most strict to date with $E^2\Phi_{UL} = 2.32 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. The central 90% signal energy interval is 282 TeV to 214 PeV, and signal acceptance is distributed as 32% muon neutrinos, 39% electron neutrinos and 29% tau neutrinos.

The upper bound on a diffuse extragalactic neutrino flux calculated by Waxman and Bahcall [1] is excluded at a 3 standard deviation confidence level.
Till mina föräldrar, Inger och Roine
Contents

Abstract ................................................................. iii
About this thesis ............................................................ viii
Acknowledgements ......................................................... x

Part I: Neutrino production and detection
1 Introduction ................................................................... 3
2 High-energy neutrino astrophysics ..................................... 7
   2.1 Cosmic rays .......................................................... 7
   2.2 Astrophysical neutrino production ............................. 10
   2.3 Astrophysical neutrino sources ................................. 12
3 Atmospheric muons and neutrinos .................................... 17
   3.1 Extensive air showers .............................................. 17
   3.2 Atmospheric muons ................................................ 17
   3.3 Atmospheric neutrinos ............................................. 20
4 Neutrino detection .......................................................... 23
   4.1 Neutrino interactions .............................................. 23
   4.2 Cherenkov radiation ............................................... 24
   4.3 Lepton energy loss ............................................... 25
   4.4 Electromagnetic cascades ....................................... 28
   4.5 Hadronic cascades ................................................. 29
   4.6 The Antarctic ice .................................................. 30
5 The IceCube detector ..................................................... 33
   5.1 Hole ice .............................................................. 35
   5.2 Digital optical module ........................................... 36
   5.3 Data acquisition system ......................................... 39
   5.4 Triggering and online filtering ................................... 39

Part II: Simulation and reconstruction methods
6 Simulation ...................................................................... 43
   6.1 Event generation ................................................... 43
   6.2 Propagation .......................................................... 46
   6.3 Detector simulation ............................................... 46
   6.4 Simulation production ............................................ 47
   6.5 Simulated data sample ........................................... 47
7 Event reconstruction ..................................................... 53
   7.1 Waveform calibration and feature extraction ................ 53
7.2 First guess algorithms ............................................. 54
7.3 Likelihood description ............................................. 56
7.4 Track reconstructions .............................................. 58
7.5 Cascade reconstructions ........................................... 60

**Part III: Searching for an Ultra-High Energy Diffuse Flux of Extraterrestrial Neutrinos with IceCube 40**

8 Analysis overview ................................................. 63
  8.1 Signal ............................................................ 63
  8.2 Background ..................................................... 63
  8.3 Structure ....................................................... 63
  8.4 Blindness ....................................................... 63
  8.5 Experimental data sample ....................................... 64
  8.6 The IceCube frame of reference ............................... 64

9 Filter level 1 .......................................................... 65
  9.1 Muon filter ....................................................... 65
  9.2 Cascade filter ................................................... 66
  9.3 EHE filter ........................................................ 66

10 Filter level 2 ........................................................ 67
  10.1 fADC information ............................................. 67
  10.2 Pre-cut .......................................................... 72
  10.3 Reprocessing ................................................... 74

11 Filter level 3 ........................................................ 77
  11.1 Event topology .................................................. 77
  11.2 Cut variables ................................................... 82
  11.3 Structure ........................................................ 84
  11.4 Passing rates ................................................... 108

12 Final cut ............................................................. 111
  12.1 Unbiased optimization ....................................... 111
  12.2 Passing rates ................................................... 112
  12.3 Sensitivity and effective area ............................... 114

13 Non-signal events .................................................. 117
  13.1 Tagging of flasher-type events ............................... 117
  13.2 IceTop coincidences .......................................... 120

14 Systematic uncertainties ....................................... 121
  14.1 DOM efficiency ................................................ 122
  14.2 Ice model ....................................................... 123
  14.3 Absolute energy scale ....................................... 123
  14.4 Neutrino-nucleon interaction cross sections ............... 124
  14.5 Atmospheric neutrino flux normalization .................... 126
  14.6 Cosmic ray flux normalization ............................... 128
  14.7 Cosmic ray composition ..................................... 129
  14.8 Seasonal variation ............................................. 129
  14.9 Neutrino coincidences ....................................... 130
About this thesis

This thesis is divided into three parts. Part I describes neutrino production and detection. Chapter 2 covers astrophysical neutrino production. Atmospheric neutrino and muon production is described in chapter 3. Chapter 4 deals with the principles behind neutrino detection and chapter 5 gives an overview of the IceCube detector.

Part II describes methods used in simulation and event reconstruction. Chapter 6 gives an overview of the simulation chain and details the particular simulation samples used in this work. Reconstruction algorithms applied in this work are described in chapter 7.

Part III describes a search for a diffuse flux of astrophysical ultra high-energy neutrinos. A general overview of the analysis is given in chapter 8. Chapters 9 and 10 cover the first two filter levels of the analysis. The main filter level is described in chapter 11 and the optimization of a final cut in chapter 12. Chapter 13 deals with a tagging of non-signal events. Systematic uncertainties are investigated in chapter 14. The results of the analysis are detailed in chapter 15, and an outlook is given in chapter 16.

Appendix A shows the details involved in evaluating multivariate classifiers.

Author’s contribution

I have developed a search for a diffuse flux of astrophysical ultra high-energy neutrinos using data from 2008 and 2009 acquired with the IceCube detector in a 40-string configuration. This work is presented in this thesis. It is based on previous knowledge and efforts within the IceCube collaboration and has been carried out within the diffuse analysis working group.

Work not included in this thesis where I have contributed during my time as a PhD student at Stockholm University include:

- Geometry and timing calibration of newly deployed detector strings, and visualization of detector performance for the purpose of verification and monitoring, at the South Pole, February 2008.
- Developing a weighting scheme for biased coincident CORSIKA event simulation.
- Developing a method for calibration of photon detection efficiency [2], within the calibration working group.
- Developing observables describing detector performance and methods for quantifying and visualizing performance, within the verification and monitoring working groups.
- Developing the high-energy event reconstruction algorithm Hyperreco [2], in collaboration with the extremely high-energy working group in Chiba, Japan.
• Characterizing signal-like detector artefact events in AMANDA-II [2].
• Developing an interface facilitating general use of IceCube’s software framework IceTray on SweGrid [3]. This includes management of files on SweGrid storage elements.
• Installing and maintaining IceTray specific runtime environments on SweGrid.
• Responsibility for production of standardized simulated data on SweGrid. This includes developing a plugin interfacing IceCube’s central job management system IceProd with SweGrid, maintaining a local job management server, and continuous cooperation with IceProd developers to improve job management.
• Configuring, generating and verifying simulated data sets for use in high-energy analyses and in evaluation of systematic uncertainties. Data sets include ultra high-energy neutrino simulation, high-energy biased coincident atmospheric muon simulation, neutrino simulation using state-of-the-art neutrino-nucleon cross sections [4], and neutrino simulation using different ice models (see section 14.2).
• Configuring the processing of atmospheric muon simulation with a non-standard cosmic ray composition model, the so-called 2-component model (see section 6.1.1). A comparative study between the 2-component and the standard composition model was performed, identifying essential differences and focusing on agreement with real data. Some of the conclusions are discussed in section 11.3.4.
• A study of fADC digitizer (see section 5.2) information and how well simulation agrees with real data, for the purpose of determining if it is reasonable to use in analysis. Part of this study is described in section 10.1.

I have participated in collaboration wide work on IceCube research, publications and talks. I represented the IceCube collaboration at the Lake Louise Winter Institute 2011, presenting the results of the analysis described in this thesis. I have given technical talks at nine collaboration meetings. I have represented IceCube and the Stockholm group by giving overview talks at Partikeldagarna 2007 and AlbaNova open house 2007. I have represented IceCube and the Stockholm group at Fysik i Kungsträdgården 2009 and with a poster for Fysikumdagen 2006.
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I most feel like a physicist in relaxed, exploratory conversation with colleagues, and I would particularly like to thank Chad Finley and Seon-Hee Seo for enlightening and inspiring discussions.

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Part I:
Neutrino production and detection
Observations of photons from the universe have shed light on mysteries of the night sky for centuries, and continue to do so. Traditionally in the form of visible light, now photons are observed in a range from low frequency radio waves to very high-energy gamma rays. Photons are good carriers of information in the sense that they are stable, emitted in large numbers, easy to detect and point back to the source. Furthermore, the photon spectrum contains detailed information about the chemical and physical properties of the source.

Photons are, however, attenuated by interstellar dust and gas and cosmic background radiation. Gamma ray astronomy has made remarkable discoveries of sources with extreme physical conditions, but the range for further exploration is limited by the attenuation due to pair production in interactions with the cosmic background radiation. Above 100 TeV gamma rays are not expected to survive from extragalactic distances, as shown in figure 1.1.

Due to the optical thickness of astrophysical sources, photons reveal information about the surface of objects. Charged cosmic rays provide information about the inner processes which lead to their acceleration but directional information is degraded in galactic magnetic fields. For the highest energy cosmic rays the magnetic deflection is expected to be small and there are indications of possible correlations with nearby extragalactic matter distributions [6–8].

Neutrinos are uncharged, interact weakly and travel unimpeded over vast distances. Neutrinos escape unaffected from the inner regions of the most energetic objects seen in the universe and therefore carry crucial information about the nature of the energy-release processes. Observations of gamma rays are often equally well described by electromagnetic and hadronic acceleration models, which makes the correlation between gamma rays and cosmic rays unclear. High-energy neutrinos provide a direct link between gamma rays and cosmic rays. Observations of all messengers are necessary to deepen our understanding of the processes driving non-thermal astrophysical sources, illustrated in figure 1.2.

What makes neutrinos excellent messengers also makes them difficult to detect. Since interactions are rare, a very large detection volume is required to observe high-energy neutrinos. The IceCube Neutrino Observatory was recently completed, resulting in a detector volume of one cubic kilometer deep in the Antarctic ice.

Neutrino astronomy is a young field, so far the only confirmed sources of extraterrestrial neutrinos are the sun and supernova SN 1987a. The detection
of sources of high-energy neutrinos is the main goal of the IceCube Neutrino Observatory. This work describes a search for ultra high-energy extraterrestrial neutrinos from unresolved sources, using data from 2008 and 2009 when the detector was roughly half the size of its now final configuration. Such a diffuse flux of neutrinos is sensitive to the properties of the population of cosmic accelerators in the universe.
Figure 1.2: The role of neutrinos as messengers in high-energy astrophysics. Cosmic rays are charged and therefore lose directional information in galactic and intergalactic magnetic fields. Gamma rays are attenuated by cosmic background radiation and interstellar dust clouds. Neutrinos are uncharged and interact weakly, making them ideal messengers for the high-energy universe. Image credit: Wolfgang Rhode.
Neutrino astronomy is a young field with the potential to greatly improve our understanding of the high-energy universe. There is a close link between the production of high-energy astrophysical neutrinos and the acceleration of high-energy cosmic rays. Neutrino observations can elucidate the mystery of the origin of the highest energy cosmic rays. Neutrinos escape virtually unimpeded from the inner regions of extreme astrophysical objects such as active galactic nuclei (AGNs) and gamma ray bursts (GRBs) and therefore probe the underlying energy-release processes. Astrophysical neutrinos provide a direct link between gamma rays and cosmic rays.

2.1 Cosmic rays

Cosmic rays are stable charged particles and nuclei traversing the universe at nearly the speed of light. When such a particle reaches the Earth’s atmosphere, interactions with air nuclei produce a shower of particles propagating through the atmosphere. For high-energy cosmic rays this cascade can reach the surface of the Earth. Observations of cosmic rays can be made directly or indirectly, with detectors carried by satellites or balloons or at the surface of the Earth. The composition of cosmic rays range from protons and electrons to the heaviest nuclei produced in stellar and supernova nucleosynthesis. About 79% of primary cosmic rays are protons and about 70% of the rest are helium nuclei [9].

Figure 2.1 shows the observed energy spectrum of cosmic rays. The spectrum follows a power law over many orders of magnitude which indicates a non-thermal acceleration mechanism capable of focusing the energy outflow from a source onto a relatively small number of particles. A mechanism widely held as responsible is diffusive shock acceleration, based on Fermi acceleration. Shocks are driven for example by supernovae exploding into the debris of stellar winds from the progenitor stars. Charged particles gain energy by repeated scattering on magnetic inhomogeneities as they cross back and forth across the shock front. For non-relativistic shock fronts the particle spectrum becomes

\[
\frac{dN}{dE} \propto E^{-2}
\]  

(2.1)
In the case of relativistic shocks the particle spectrum steepens. The shock acceleration scenario has been developed continuously and is based on well-understood theory [11].

Hillas established a relation for the maximum attainable particle energy $E_{\text{max}}$ based on the magnetic field strength $B$ and size $R$ of the accelerating region [12]

$$E_{\text{max}} = \beta Z e \left( \frac{B}{1 \mu G} \right) \left( \frac{R}{1 \text{kpc}} \right) \text{EeV} \quad (2.2)$$

where $\beta$ is the velocity of the shock front in terms of the speed of light and $Ze$ is the charge of the particle.

The observed cosmic ray energy spectrum is steeper than the injection spectrum of $E^{-2}$ owing to energy dependent escape probability from the galaxy and energy loss during propagation. A general energy loss process is the redshift due to the expansion of the Universe. At high energies cosmic rays lose energy through interactions with the cosmic background photons. At around
1 EeV, $e^+e^-$ pair production becomes relevant for protons and is the dominant energy loss process up to around 70 EeV where pion production takes over. Heavier nuclei also lose energy through photo-disintegration [13].

The low cosmic ray flux at energies above around 100 TeV makes measurements with small detectors carried by satellites or balloons difficult. Ground based air shower detectors operated for a long time are well-suited for studying higher energy cosmic rays. There are three main types of air shower detectors [9]: arrays of detectors that study the shower size and the lateral distribution, Cherenkov detectors that detect the Cherenkov radiation emitted by the charged shower particles, and fluorescence detectors that study the nitrogen fluorescence excited by the charged shower particles. Cross-calibrations between different types of detectors and detailed simulations are required to determine the primary cosmic ray energy spectrum from air shower experiments. Figure 2.2 shows the all-particle cosmic ray energy spectrum measured by air shower experiments.

The change in spectral slope at around 3 PeV is commonly called the “knee”. Shock acceleration in galactic supernova remnants (SNRs) can explain observations up to PeV energies [10]. It is suspected that the
steepening of the spectrum at the knee has to do with the upper reach in energy of galactic sources. Acceleration and propagation both depend on magnetic fields and therefore on magnetic rigidity. A rigidity dependent cutoff around the knee has been suggested [14], as first lighter and then heavier nuclei reach an upper limit on energy per particle. Figure 2.2 shows that measurements in the knee region differ by as much as a factor of two, which indicates experimental systematic uncertainties.

To reach higher energies, larger acceleration sites and stronger magnetic fields are necessary. It is generally believed that the flattening of the spectral slope at around 5 EeV, commonly called the “ankle”, is caused by the onset of an extragalactic component. Natural extragalactic source candidates include AGNs and GRBs. The power required to generate the observed spectrum of cosmic rays above the ankle seems consistent with the observed output in electromagnetic energy of these sources [15].

Composition measurements at the highest energies differ. HiRes data is consistent with a composition of mainly protons and light nuclei [16], while Auger sees a more mixed composition intermediate between proton and iron [17].

There is a suppression in the cosmic ray energy spectrum above around 50 EeV [18, 19]. At these energies cosmic ray protons are above the energy threshold for pion production through the $\Delta^+$ resonance in interaction with the cosmic microwave background radiation, the so-called Greisen-Zatsepin-Kuzmin (GZK) mechanism. Protons lose most of their energy over a propagation length of less than around 50 Mpc. In the case of heavier nuclei a suppression because of photo-disintegration would have a similar effect [13, 20, 21].

2.2 Astrophysical neutrino production

Cosmic ray acceleration sites are surrounded by matter and radiation fields of varying density. Neutrinos are produced through pion decay in cosmic ray interactions with radiation or matter. The main pion production channels are

\[
p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}
\]  

\[
n + \gamma \rightarrow \Delta^0 \rightarrow \begin{cases} n + \pi^0 \\ p + \pi^- \end{cases}
\]  

\[
p + p \rightarrow \begin{cases} p + p + \pi^0 \\ p + n + \pi^+ \end{cases}
\]
Neutrinos are produced through decay of charged pions. Neutral pion decay gives rise to gamma rays

\[ p + n \rightarrow \begin{cases} 
  p + n + \pi^0 \\
  p + p + \pi^- 
\end{cases} \quad (2.6) \]

Neutrinos can also be produced similarly through decay of kaons produced in cosmic ray interactions, which may contribute significantly at very high energies [22].

On average, the fraction of energy going to the pion in \( p\gamma \) interactions is \( \sim 0.2 \) [15]. Assuming the four leptons resulting from the charged pion decay carry an equal amount of energy, the energy transferred from the proton to the neutrino becomes \( E_\nu \sim E_p / 20 \). Sophisticated approximations based on simulations give a similar value, for both \( p\gamma \) [23] and \( pp \) interactions [24].

The decay channels (2.7) and (2.8) show that neutrinos are produced in a flavor ratio of

\[ \nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0 \quad (2.10) \]

Experiments have provided compelling evidence for the existence of neutrino oscillations between flavors during propagation, caused by nonzero neutrino masses and neutrino mixing [25]. For astrophysical neutrinos, this implies an expected flavor ratio at Earth of [26]

\[ \nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1 \quad (2.11) \]

which is assumed in the work presented in this thesis.

A differing neutrino production flavor ratio at the source, for example due to muon energy loss in strong magnetic fields, may result in different flavor ratios at Earth [27,28]. Effects of quantum decoherence would alter the flavor ratio towards 1 : 1 : 1 regardless of initial flavor content [29].
Channel 2.9 shows the decay of neutral pions to gamma rays, which implies that gamma production occurs in astrophysical neutrino sources. The photons are produced at $>\ TeV$ energies, which means that optically thin sources emit TeV gamma rays in coincidence with neutrinos. If the source is optically thick, the photons will avalanche to lower energies until they can escape the source region.

The opposite is not true, observations of gamma rays do not necessarily imply neutrino production. Gamma rays can be produced through electromagnetic acceleration of electrons that lose energy through synchrotron radiation. The accelerated electrons can further boost photons from the synchrotron field or external photon fields through inverse Compton scattering. Gamma ray production models based on electromagnetic or hadronic acceleration can be difficult to distinguish. Neutrino production implies hadronic acceleration and therefore provides a direct link between gamma rays and cosmic rays.

2.3 Astrophysical neutrino sources

The particle physics responsible for neutrino production is well established. However, the astrophysics underlying hadronic acceleration of cosmic rays is not as well known. There is a large range of models predicting neutrinos from different astrophysical source classes. Common for these models is to normalize the neutrino flux based on correlations to observations of photons or cosmic rays. A good review of astrophysical neutrino source models is given in Ref. [30].

The power required to generate the observed spectrum of extragalactic cosmic rays seems consistent with the observed output in electromagnetic energy of AGNs and GRBs, which is why they have emerged as natural candidate sources of ultra high-energy cosmic rays [15].

The analysis presented in this thesis is a search for an unresolved (“diffuse”) flux of ultra high-energy neutrinos. A diffuse flux of neutrinos is sensitive to the properties of the population of cosmic accelerators in the universe. The models considered in the analysis are shown in figure 2.3. They describe the diffuse flux from extragalactic source classes and are described further in this section.

2.3.1 Neutrinos from active galactic nuclei

AGNs are the most luminous persistent sources of electromagnetic radiation in the universe. An AGN radiates more power than our entire galaxy from a region smaller than the size of our planetary system. Roughly 1% of all bright galaxies are believed to have an active nucleus. The only known mechanism that could sustain this luminosity is the gravitational energy release associated with accreting supermassive black holes [37]. Assuming hadronic acceleration
for different classes of AGNs, the electromagnetic emission should be associated with a neutrino signal.

In the model by Mücke et al. [32], sources of TeV photons are interpreted as optically thin to neutron-photon interactions. In this scenario charged cosmic rays are produced close to the source through the decay of escaping neutrons. The resulting neutrino flux is assumed to be proportional to the observed extragalactic flux of cosmic rays. In this model the neutrino flux from high frequency peaked BL Lacs was calculated using the connection between neutrinos and cosmic rays.

In the case of optically thick sources, gamma rays produced in the decay of neutral pions would avalanche to lower energies before escaping. The diffuse extragalactic background measured by EGRET (Energetic Gamma Ray Experiment Telescope) and COMPTEL (COMpton TELeScope) can then be interpreted as an avalanched TeV signal from blazars, which can be used to calculate the normalization of the neutrino flux. In the model by Mannheim [34] protons interact with photons in the AGN and with protons in the host galaxy. The model by Stecker [31] uses the COMPTEL diffuse background to normalize the neutrino flux.
In the model by Becker, Biermann and Rhode [33], the diffuse neutrino flux from radio galaxies of class FR-II was calculated. It was assumed that the neutrino flux is proportional to the total power of the jet, which can be related to disk luminosity, which in turn can be related to the radio output. The prediction is highly sensitive to the energy spectrum resulting from the acceleration mechanism. The neutrino spectrum was assumed to follow the proton spectrum. Effects on the neutrino spectrum from multi-pion production were considered small in comparison to other uncertainties. For the model considered here the assumed spectrum is $E^{-2}$. Changing the spectral index to -2.6 would reduce the total flux by two orders of magnitude.

### 2.3.2 Neutrinos from gamma-ray bursts

GRBs are the most luminous outbursts of gamma radiation known, where one GRB can outshine an entire galaxy by a hundred times. On average around one GRB per day is detected. They appear isotropically over the sky and observations suggest that they lie at cosmological distances.

The appearance of observed GRBs is diverse, with durations from a few ms to several minutes. A distinction is commonly made between short and long GRBs, where short GRBs last on average around 0.3 s and long around 30 s [38]. Long GRBs are often accompanied by massive stellar explosions [39] while a viable model for short GRBs is the merger of compact binary systems [40].

There are three phases of non-thermal emission connected with GRBs: the less bright precursor phase 10–100 s before the bright gamma ray burst, the bright prompt phase, and an afterglow phase. A precursor model was developed by Razzaque and Meszaros in Ref. [35], based on a general class of massive stellar collapses. Neutrino spectra were calculated from shock accelerated protons in jets just below the outer stellar envelope, before their emergence. The precursor in this model is thus not observable in photons. The observation of neutrinos provides the possibility to alert photon experiments before the GRB prompt phase occurs.

A model for average neutrino emission in the prompt phase, normalized to the observation of ultra high-energy cosmic rays, was developed by Waxman and Bahcall in Ref. [1]. In the region where electrons are accelerated, protons are also expected to be accelerated, and neutrinos are produced in interactions with the gamma ray burst photons. In this model, the neutrino spectrum is determined by the observed gamma ray spectrum.

### 2.3.3 The Waxman-Bahcall upper bound

The upper bound calculated by Waxman and Bahcall [1] refers to a diffuse extragalactic flux of neutrinos and is valid for optically thin sources. The bound
is often used as a measuring rod in high-energy neutrino searches and is therefore described here in somewhat more detail.

It is assumed that protons are accelerated in the source region and the dominating interaction process is with photons, producing charged and neutral pions along with neutrons and protons. Neutrinos are produced through the decay of charged pions, and neutrons decay producing protons.

Assuming a cosmic ray generation spectrum of $E^{-2}$ and taking into account energy loss during propagation, the energy production rate for protons was calculated based on the observed cosmic ray energy spectrum above $\sim 10^{19}$ eV, giving

$$E_{CR}^2 \frac{dN_{CR}}{dE_{CR}} \approx 10^{44} \text{ erg Mpc}^{-3} \text{yr}^{-1}$$  \hspace{1cm} (2.12)

It is assumed that the energy going to pions is roughly equal to the energy ending up in protons. Neutral pions, which do not contribute to neutrino production, are produced with approximately the same probability as charged pions, and in the decay of charged pions, muon neutrinos carry approximately half the charged pion energy. Over Hubble time $t_H \approx 10^{10}$ yr, the present day muon neutrino energy density then becomes

$$E_{\nu}^2 \frac{dN_{\nu}}{dE_{\nu}} \approx 0.25 \times t_H E_{CR}^2 \frac{dN_{CR}}{dE_{CR}}$$  \hspace{1cm} (2.13)

The upper bound on the muon neutrino flux $\Phi_{\nu}^{\text{max}}$ can then be calculated through the relation flux = velocity $\times$ density, which results in

$$E_{\nu}^2 \Phi_{\nu}^{\text{max}} = \frac{c}{4\pi} E_{\nu}^2 \frac{dN_{\nu}}{dE_{\nu}} \approx 1.5 \times 10^{-8} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$  \hspace{1cm} (2.14)

Taking into account neutrino energy loss due to redshift, and evolution of cosmic ray sources with redshift, the upper bound becomes $3 \times \Phi_{\nu}^{\text{max}}$. Considering neutrino oscillations the muon neutrino flux at Earth becomes $E_{\nu}^2 \Phi_{\nu}^{\text{WB}} = 2.25 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$.

Note that even if protons are trapped by magnetic fields in the source region, escaping neutrons decay into observable cosmic ray protons. The calculation is referred to as an upper bound in part because in reality more energy is transferred to the neutron than to the charged pion in the source. Halzen shows [15] that the bound should rather be interpreted as a flux estimate based on the relation between neutrinos and cosmic rays.

### 2.3.4 Cosmogenic neutrinos

Ultra high-energy cosmic ray protons above around 50 EeV can interact with the cosmic microwave background radiation via the $\Delta^+$ resonance. Protons lose most of their energy over a propagation length of 50 Mpc causing the so-called GZK suppression of cosmic rays. Neutrinos are produced through
the decay of the $\Delta^+$ resonance via production of charged pions. The resulting diffuse neutrino flux is commonly referred to as cosmogenic or GZK neutrinos.

The model by Engel, Seckel and Stanev [36] is normalized to the observed spectrum of ultra high-energy cosmic rays. The model assumes an extragalactic cosmic ray energy spectrum of $E^{-2}$ with a maximum energy of $10^{21}$ eV. Cosmological evolution of sources is taken into account.

The predictions from cosmogenic neutrino models are sensitive to the fraction of ultra high-energy cosmic rays composed of heavy nuclei, which is uncertain. Heavy nuclei lose energy via photo-disintegration which results in far less efficient neutrino production [41].

The primary source candidates are AGNs and GRBs but it is not clear to what extent each source class contributes. GRBs follow a stronger cosmological evolution than AGNs, which affects the resulting neutrino flux [42].

2.3.5 Other sources

Other sources of astrophysical neutrinos have not been considered in this work. They are for example neutrinos resulting from annihilation of neutralino dark matter and top-down scenarios such as decay of superheavy particles.
3. Atmospheric muons and neutrinos

Muons and neutrinos created in the atmosphere in cosmic ray induced air showers constitute the main background in searches for astrophysical neutrinos.

3.1 Extensive air showers

An air shower is created by a single cosmic ray colliding with Earth’s atmosphere. Interactions with air nuclei create a chain of secondary particle production and decay, resulting in a cascade of particles. Extensive air showers are induced by high energy cosmic rays and produce particles that reach the Earth’s surface. Air showers typically have a hadronic core which acts as a collimated source of electromagnetic subshowers, mainly through decay of neutral mesons [9]. Figure 3.1 shows a schematic view of particle production in an air shower.

Figure 3.2 shows the vertical flux of air shower particles with energy greater than 1 GeV as a function of atmospheric depth. At the surface of the Earth muons and neutrinos are most abundant, and they are the only particles to reach depths relevant for the IceCube in-ice detector.

3.2 Atmospheric muons

Muons are produced in the air shower through decay of charged pions and kaons and charmed hadrons. The muon flux resulting from decay of charged pions and kaons is called the conventional component and dominates at energies up to around 10 TeV. The decay of pions (see section 2.2) dominates up to TeV energies, where the contribution from kaons becomes significant [44]. The critical energy, which is defined as the energy where decay length and interaction length are equal, is 115 GeV for pions and 855 GeV for kaons. This means that for energies above 115 GeV pions are more likely to interact with air than to decay. This causes an energy dependent reduction in muon production and for energies greater than 1 TeV the muon energy spectrum approaches one power steeper than the primary spectrum [9]. At zenith angles closer to horizontal the effect is smaller, because pions will travel further through the low density upper atmosphere where the probability to decay is enhanced in relation to interaction.
Figure 3.1: Schematic view of an air shower, showing the production of conventional atmospheric muons and neutrinos. Figure taken from Ref. [43].
The semi-leptonic decay of charmed hadrons, mainly D-mesons and $\Lambda_c^+$-hyperons, gives rise to muons through the decay modes

\[
D \rightarrow K + \mu + \nu \quad (3.1)
\]
\[
\Lambda_c \rightarrow \Lambda_0 + \mu + \nu \quad (3.2)
\]

Charmed hadrons are very short-lived and decay before they have a chance to interact, which means that the resulting muon energy spectrum is flatter than for the conventional component. The muon flux resulting from decay of charmed hadrons is called the prompt component. The energy threshold for charmed hadron production is higher than for pions and kaons, and the crossover between the conventional and prompt component may occur between 10 TeV to 1 PeV [45].
3.3 Atmospheric neutrinos

Neutrinos are also produced in the decay of charged pions and kaons (see section 2.2). Muon decays contribute substantially to the neutrino flux only up to a few GeVs, which means that a very small fraction will decay at the energies relevant for this work. The conventional atmospheric neutrino component will therefore be dominated by muon neutrinos. Following the same line of argument as for muons, the energy spectrum for the conventional component is close to one power steeper than the primary spectrum for energies greater than 1 TeV.

Since cosmic ray primaries are positively charged, more positive than negative pions and kaons will be produced in the air shower [44]. This results in an asymmetry between neutrinos and anti-neutrinos [46].

The model used in this work to describe the conventional atmospheric neutrino component is derived by Honda et al [47].

Charmed hadrons decay equally likely into muons or electrons which results in equal flux of muon and electron neutrinos for the prompt component. The flux of tau neutrinos is much smaller than for the other flavors, more than an order of magnitude [48] since only the $D_s$ meson decays into $\nu_\tau$. For this reason the atmospheric tau neutrino flux was not considered in this work.

The cross-over between the conventional and prompt component may be around 300 TeV for muon neutrinos. Because of the small electron neutrino flux in the conventional component, the cross-over for electron neutrinos may be already at around 10 TeV [48].

The model used in this work to describe the prompt component is due to Enberg et al [48].

Figure 3.3 shows the Honda and Enberg models for the conventional and prompt atmospheric neutrino flux along with the astrophysical models considered in this work.

Oscillation effects for baselines equal to the diameter of the Earth are not present for neutrino energies greater than 50 GeV, and are therefore not important for this work.
Figure 3.3: Conventional and prompt atmospheric neutrino flux models are shown in blue. Atmospheric neutrinos show a steeper energy spectrum than predictions from astrophysical models. The astrophysical models are described in section 2.3.
4. Neutrino detection

What makes neutrinos excellent cosmic messengers also makes them difficult to detect. Because of the low interaction cross sections, the detection of high-energy neutrinos requires very large detector volumes. The IceCube Neutrino Observatory detects neutrinos via Cherenkov light resulting from neutrino-nucleon interactions in the Antarctic ice. IceCube is sensitive to neutrinos in an energy range from 10 GeV to above 100 EeV.

For energies above $\sim 100$ PeV, other detection techniques are possible. Cherenkov radiation also has a strong effect in radio, the so-called Askaryan effect [49], which is utilized by the RICE (Radio Ice Cherenkov Experiment) [50] and ANITA (ANtarctic Impulsive Transient Antenna) [51, 52] experiments. SPATS (South Pole Acoustic Test Setup) [53] utilizes the fact that an acoustic signal can be produced by neutrino-induced cascades with high energy density. Air showers induced in the outer mantle of the Earth by Earth-skimming neutrinos have been studied by the Pierre Auger Observatory [54–56].

4.1 Neutrino interactions

At energies relevant for ultra high-energy astrophysical neutrino searches, neutrino-nucleon interactions are in the deep inelastic scattering regime. Neutrinos interact weakly, through charged-current (CC) via the exchange of a $W$ boson or through neutral-current (NC) via the exchange of a $Z$ boson

$$\nu_l(\nu_l) + N \rightarrow l^- (\bar{l}^+) + X \quad \text{(CC)} \quad (4.1)$$
$$\nu_l(\nu_l) + N \rightarrow \nu_l(\bar{\nu}_l) + X \quad \text{(NC)} \quad (4.2)$$

where $l$ denotes lepton flavor, $e$, $\mu$ or $\tau$, $N$ a nucleon, and $X$ the hadronic product of the interaction. The neutrino transfers enough energy to a parton to dissociate the parent nucleon which results in a hadronic shower. Feynman diagrams depicting the interactions are shown in figure 4.1.

For $\bar{\nu}_e$ neutrinos, resonant $W^-$ production is possible through

$$\bar{\nu}_e + e^- \rightarrow W^- \quad (4.3)$$

the so-called Glashow resonance [58]. It occurs at neutrino energy around 6.3 PeV where the center of mass energy is close to the rest mass of the $W$
4.2 Cherenkov radiation

A charged particle traversing a dielectric medium polarizes the medium. Radiation is emitted when the medium depolarizes. Contributions from different points along the particle trajectory interfere destructively and the far field vanishes, unless the particle travels with a speed that exceeds the phase speed of light in the medium. In this case a shock front is formed in the form of a cone, so-called Cherenkov radiation, depicted in figure 4.3. The shock front forms at a characteristic angle $\theta_c$ which depends on the index of refraction $n$ of the medium

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

(4.4)

where $\beta = v/c$ is the velocity of the particle. The index of refraction for ice is around 1.32, which gives $\theta_c \approx 41^\circ$ for $\beta \approx 1$. 

boson, $M_W = 80$ GeV. The $W$ boson decays into hadrons or leptons. Other neutrino-electron cross sections are negligibly small at energies relevant for this work [59].

The neutrino-nucleon interaction cross sections differ slightly for neutrinos and anti-neutrinos and depend on energy, as shown in figure 4.2. The cross sections used for neutrino simulation in this work are based on HERA data and were calculated by Cooper-Sarkar and Sarkar (CSS) [4]. The CSS cross sections are included in a recent comparative study of high-energy neutrino cross sections in Ref. [60].
Figure 4.2: Neutrino and anti-neutrino cross sections for CC and NC interactions. An isoscalar target is assumed. The Glasow resonance is shown at 6.3 PeV. Note that the cross sections shown here are based on CTEQ5 PDFs \[61\]. At high energies large cross section uncertainties are illustrated by showing two different models. Figure taken from Ref. \[59\].

The number of Cherenkov photons emitted per unit track length and wavelength is given by the Frank-Tamm formula \[62, 63\]

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

(4.5)

where \( \alpha \sim 1/137 \) is the fine structure constant. Because of the \( 1/\lambda^2 \) dependence, Cherenkov emission is dominated by short wavelengths. The optical sensors in IceCube set the short wavelength sensitivity cutoff at about 350 nm \[64\].

Cherenkov radiation is described in detail in Ref. \[65\].

4.3 Lepton energy loss

The leptons produced in neutrino interactions lose energy as they propagate through the medium. Cherenkov radiation is a very small fraction of that energy loss. Muons lose energy continuously through ionization of the medium, and stochastically through radiative processes: bremsstrahlung, pair production and photonuclear interactions. Figure 4.4 shows the energy dependence
Figure 4.3: Cherenkov cone geometry formed by a relativistic charged particle with speed $\beta$ traversing a dielectric medium with refractive index $n$. Figure taken from Ref. [57].

of the different energy loss processes for muons in ice. Stochastic energy loss dominates at high energies.

The average rate of energy loss for a muon can conveniently be written as [63]

$$-\frac{dE}{dx} = a(E) + b(E)E,$$  \hspace{1cm} (4.6)

where $a(E)$ is the ionization energy loss and $b(E)$ is the sum of the contributions from the stochastic processes. These functions can be approximated as constant. Typical values for ice are [66]

$$a = 0.259 \text{ GeV mwe}^{-1}$$
$$b = 3.63 \times 10^{-4} \text{ mwe}^{-1}$$

Integrating equation 4.6 gives the mean range $x_0$ for a muon with initial energy $E_0$

$$x_0 \approx \frac{1}{b} \ln \left( 1 + \frac{E_0}{E_{\text{crit}}} \right)$$  \hspace{1cm} (4.7)

where $E_{\text{crit}}$ is the critical energy where continuous and stochastic energy loss is equal. For ice, $E_{\text{crit}} \approx 710$ GeV. This gives a mean range for a 1 TeV muon of 2.4 km, significantly larger than the size of the IceCube in-ice detector.

For electrons, the dominating energy loss process is bremsstrahlung. As a consequence, electrons initiate electromagnetic cascades and, as opposed to muons, do not travel far.
For tau leptons, the life time is seven orders of magnitude shorter than for muons, resulting in a typical decay length of $\sim 50 \times (E_\nu/\text{PeV})$ m [67]. The main tau decay modes are [68]

\[
\begin{align*}
\tau^- \rightarrow \text{hadrons} + \nu_\tau & \quad 65\% & (4.8) \\
\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau & \quad 17.85\% & (4.9) \\
\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau & \quad 17.36\% & (4.10)
\end{align*}
\]

The dominating energy loss processes for tau leptons are pair production and photonuclear interactions.
4.4 Electromagnetic cascades

The secondaries produced as a charged particle loses energy through bremsstrahlung or pair production also suffer radiative energy loss and generate new secondaries. This results in an electromagnetic cascade.

To get an idea of how the main features of an electromagnetic cascade scale, a simplistic model can be considered [69]. An initial electron with energy $E_0$ loses $1/2$ of its energy to a bremsstrahlung photon in one radiation length $X_0$. The photon produces an electron-positron pair in the next radiation length, each with energy $E_0/4$. During this radiation length another bremsstrahlung photon is radiated from the original electron, with energy $E_0/4$. This process is repeated until the energy of the electrons fall below the critical energy $E_c$, where energy loss through ionization becomes dominant and the development of the cascade ceases.

After $t$ radiation lengths, each particle has energy $E(t) = E_0/2^t$. The maximum number of particles is reached when each particle is down to the critical energy, after $t_{\text{max}}$ radiation lengths

$$E_c = \frac{E_0}{2^{t_{\text{max}}}} \implies t_{\text{max}} = \frac{1}{\ln 2} \ln \left( \frac{E_0}{E_c} \right) \quad (4.11)$$

$$N_{\text{max}} = 2^{t_{\text{max}}} = e^{t_{\text{max}} \ln 2} = \frac{E_0}{E_c} \quad (4.12)$$

The depth of shower maximum, reached after $t_{\text{max}}$ radiation lengths, scales with the logarithm of $E_0$, while the number of particles scales linearly with $E_0$.

The total track length for all charged particles is then given by

$$L = \left( \frac{2}{3} \right) X_0 \int_0^{t_{\text{max}}} 2^t dt \sim \left( \frac{2X_0}{3 \ln 2} \frac{E_0}{E_c} \right) \quad (4.13)$$

where the factor of $2/3$ roughly accounts for the fraction of charged particles in this simplified model. The total track length is proportional to the initial energy $E_0$. The amount of Cherenkov photons emitted is roughly proportional to the total track length, and this relation is used in simulation to estimate the total light output from cascades.

Detailed simulations have been performed where the behavior of cascades was parameterized [70]. An effective track length was defined to take into account that the number of emitted Cherenkov photons depends on the velocity of the particle. For an electromagnetic cascade it was parameterized as

$$L_{\text{eff}} = 0.894 \times \frac{E_0}{1 \text{ GeV}} \times 4.889 \text{ m} \quad (4.14)$$
where the first factor accounts for the velocity dependence. The amount of Cherenkov photons emitted is then calculated as

\[ N_C = L_{\text{eff}}(E_0)n_C \]  

(4.15)

where \( n_C \) is given by integrating the Frank-Tamm formula, equation 4.5, taking the sensitivity profile of the optical sensor into account.

The longitudinal extension of an electromagnetic cascade is typically contained within \( \sim 10 \) m. The lateral spread is small, typically less than \( \sim 1 \) m. Because of the angular distribution of the direction of cascade particles, the shape of the Cherenkov cone from a cascade becomes slightly smeared.

At energies above \( \sim 100 \) PeV energy loss through bremsstrahlung and pair production is suppressed by the so-called Landau-Pomeranchuk-Migdal (LPM) effect [71–73]. This can result in elongated electromagnetic cascades on the order of 100 m [74].

### 4.5 Hadronic cascades

Hadronic interactions such as neutrino-nucleon interactions, photonuclear interactions, and hadronic decay of the tau lepton, result in secondary hadrons which in turn interact with nucleons producing new secondaries, yielding a hadronic cascade. Hadronic cascades have a slightly lower Cherenkov photon yield than electromagnetic cascades. This has several reasons. Part of the cascade energy goes into neutrons, which do not produce Cherenkov radiation. Energy is lost in hadronic processes because of the large nuclear binding energies involved. Furthermore, charged hadrons have a higher Cherenkov photon emission threshold than electrons.

Hadronic cascades have an electromagnetic component, mainly from decay of neutral pions. This component becomes larger with energy and therefore the difference in light yield between hadronic and electromagnetic cascades becomes smaller with energy. The electromagnetic component does not further contribute to the development of the hadronic cascade. Muons can be produced in the decay of charged pions or other hadrons. The muons escape the cascade and do not contribute further either. If these processes occur early it affects the development strongly. The behavior of hadronic cascades therefore fluctuates more than for electromagnetic cascades.

For a hadronic cascade the effective track length was parameterized through detailed simulations as [70]

\[ L_{\text{eff}} = 0.860 \times \frac{E_0}{1 \text{ GeV}} \times 4.076 \text{ m} \]  

(4.16)
4.6 The Antarctic ice

For the faint Cherenkov light to be detectable, the medium must be highly transparent and the surroundings as dark as possible. IceCube uses the Antarctic glacial ice at the South Pole as a detector medium. The IceCube optical sensors are sensitive to photons with wavelengths in a range from 350 nm to 650 nm [64], with a peak sensitivity around 400 nm. The Antarctic glacial ice is the most transparent solid known for wavelengths between 200 nm and 400 nm [75].

The glacial ice at the South Pole was created over a period of 165,000 years [76] and has a thickness of 2820 m [75]. The ice has a structure of roughly horizontal ice sheets with varying concentrations of dust impurities that can be correlated to climatological changes. The IceCube in-ice detector is situated at depths between 1450 m and 2450 m.

The propagation of photons is governed by the scattering and absorption properties of the medium. The absorption length $\lambda_a$ is defined as the distance of travel at which the photon survival probability drops to $1/e$. The scattering length $\lambda_s$ is the average distance a photon travels before scattering. The average scattering angle is described by $\langle \cos \theta \rangle$ which is strongly forward peaked with a value of 0.94 typical for South Pole ice conditions. An effective scattering length can be defined as the average distance after which the photon direction is randomized [75]

$$\lambda_e = \frac{\lambda_s}{1 - \langle \cos \theta \rangle} \quad (4.17)$$

At depths down to $\sim 1350$ m scattering is dominated by residual air bubbles in the ice. Below 1400 m air bubbles have gone through a phase transition into solid nonscattering air hydrates [77]. Scattering and absorption below 1400 m is therefore determined by the concentration of dust impurities.

The effective scattering length and the absorption length were parameterized in a six parameter model based on Mie scattering [75]. The effective scattering coefficient $b_e$ and absorption coefficient $a$ are defined as

$$b_e = \frac{1}{\lambda_e} \quad (4.18)$$

$$a = \frac{1}{\lambda_a} \quad (4.19)$$

The model fits $b_e$ and $a$ at a wavelength of 400 nm, close to where the photon detection sensitivity is maximum, taking the optical sensor sensitivity and wavelength dependence of Cherenkov radiation into account. The model depends on the temperature of the ice $\Delta T$ and the six parameters $\alpha, \kappa, A, B, D$ and $E$. 

30
\[
b_e(\lambda) = b_e(400) \left( \frac{\lambda}{400 \text{ nm}} \right)^{-\alpha} \]  
(4.20)

\[
a(\lambda) = C_{\text{dust}} \left( \frac{\lambda}{\text{nm}} \right)^{-\kappa} + A e^{-B(\frac{\lambda}{\text{nm}})^{-1}} \left( 1 + 0.01 \frac{\Delta T}{K} \right) \]  
(4.21)

\[
C_{\text{dust}} = b_e(400)D + E
\]

where \( \alpha \) describes the wavelength dependence of the effective scattering coefficient. The wavelength dependence of the absorption coefficient is described by the sum of two components. The first component is a power law due to absorption by dust with a normalization proportional to the depth dependent dust concentration. The second component is a rising exponential due to intrinsic ice absorption which dominates at wavelengths greater than \( \sim 500 \text{ nm} \). \( \Delta T \) is the difference in temperature from the temperature at a depth of 1730 m.

The ice properties were measured using *in situ* light sources, resulting in the Millenium ice model. The effective scattering coefficient and absorption coefficient as a function of depth and wavelength are shown in figures 4.5 and 4.6. The average effective scattering length is around 25 m, with depth dependent variations of around a factor of 3. The average absorption length is long, around 110 m. In contrast, water typically has longer effective scattering length but shorter absorption length. The neutrino experiment ANTARES is situated in the Mediterranean Sea and measures an effective scattering length of more than 250 m and an absorption length around 60 m at a wavelength of around 470 nm [78]. Less scattering implies better conditions for directional reconstruction of muons, while less absorption implies better conditions for event energy estimations (see chapter 7).

Later studies of systematic errors showed the presence of a systematic smearing of the dust layer structure in the ice model. The optical properties were measured by fitting timing distributions from Monte Carlo simulation to data. The smearing was caused by assuming homogeneous ice in simulation. A new ice model was therefore developed where the smearing was corrected for, called the AHA model.

Furthermore, the Millenium ice model was developed for depths relevant for the AMANDA detector, IceCube’s predecessor. Ice properties below the largest dust peak at a depth of 2050 m were therefore not directly measured. The AHA model was extrapolated to the region of very clean ice below the largest dust layer using ice core measurements from the Vostok Station and Dome Fuji in Antarctica. The effective scattering and absorption coefficients were estimated based on an age versus depth relation [76]. It was later concluded that this region is even cleaner than described by the AHA model.

The AHA ice model is used as a baseline in this work. The work to measure ice properties using *in situ* light sources over the full detector depth range is ongoing.
**Figure 4.5:** Effective scattering coefficient in the Millenium ice model, as a function of depth and wavelength. The dashed line at 2300 m shows the wavelength dependence: a power law due to dust. Figure taken from Ref. [75].

**Figure 4.6:** Absorption coefficient in the Millenium ice model, as a function of depth and wavelength. The dashed line at 2300 m shows the wavelength dependence: the sum of a power law due to dust and an exponential due to pure ice. Figure taken from Ref. [75].
5. The IceCube detector

As neutrinos interact with nucleons in the Antarctic ice, secondary particles are produced which in turn emit Cherenkov radiation. The detection of this Cherenkov radiation is the principle behind indirect detection of neutrinos with the IceCube Neutrino Observatory. By drilling holes deep in the glacial ice at the South Pole, optical sensors installed on strings are embedded into the ice.

The last phase of construction of the IceCube Neutrino Observatory was recently completed, resulting in a detector volume of one cubic kilometer. IceCube comprises 86 strings in total, with 60 digital optical modules (DOMs) installed on each string at a depth of 1450 m to 2450 m. A schematic view of the detector is shown in figure 5.1.

Figure 5.1: The IceCube Neutrino Observatory.

The IceCube Neutrino Observatory is versatile and offers a wealth of science. IceCube is sensitive to neutrinos in an energy range from 10 GeV to
above 100 EeV. By studying overall counting rate, the reach of IceCube extends to supernovae neutrinos at tens of MeV. IceCube’s main science goal is to discover new sources of high-energy neutrinos. The science goals include revealing sources of the highest energy cosmic rays, providing information about the nature of the energy release processes behind extreme objects such as AGNs and GRBs, determining the properties of the population of cosmic accelerators in the universe, exploring the nature of dark matter, and constraining neutrino oscillation parameters.

IceCube’s predecessor AMANDA was decommissioned at the end of the data taking season of 2008 to 2009, after 13 years of successful operation. Between the years 2005 and 2009 data were collected using both IceCube and AMANDA strings. The size and dense instrumentation of AMANDA made it well-suited for detection of lower energy neutrinos.

The IceCube Neutrino Observatory includes IceTop, an air shower array at the glacier surface above the in-ice detector. There is one IceTop station above 81 out of 86 IceCube strings. IceTop stations are composed of two tanks of ice, with two DOMs frozen into the ice in each tank. IceTop detects atmospheric muons through the Cherenkov radiation emitted as they pass through the ice as well as electromagnetic cascades induced by the electromagnetic part of the air shower. Correlating events between IceTop and the in-ice detector expands the range of possible exploration of astroparticle physics.

The in-ice detector includes Deep Core, a low energy extension of IceCube. A large fraction of the Deep Core DOMs are extra photo-sensitive. The Deep Core DOMs are installed on 8 strings in regions of clean ice at the center of the in-ice detector. The dense instrumentation of Deep Core renders it optimal for lower energy neutrino detection.

Figure 5.2: The IC40 configuration of the in-ice detector during the data taking season of 2008 – 2009.
In this work, data acquired with the in-ice detector from April 2008 to May 2009 are analyzed in the search for a diffuse flux of ultra high-energy neutrinos. During this data taking season, the detector was in a configuration with 40 strings, shown in figure 5.2.

5.1 Hole ice

The holes in the ice, typically around 60 cm in diameter and 2500 m deep, are drilled using a hot water drill. A hole is first drilled through the firm, which is about 50 m of compacted snow on top of the ice, using a firn drill that melts the snow. Water is pressurized and heated to around 88 °C using high pressure pumps and a heating plant with generators capable of generating 5 MW. The hot water is pumped through a hose into the hole, melting the ice. The hose is slowly lowered using a hose reel capable of storing more than 2.9 km of hose. Water is continuously pumped back using a submersible pump, and is reheated and recycled into the system. The drill and drilling process has been continuously improved upon, making it possible to drill a 2500 m deep hole in less than 30 hours.

Typically it takes around two weeks for a hole to freeze in. The upper part of the hole freezes first. Also after freeze-in there is a temperature gradient from around −30 °C at the uppermost DOM to around −10 °C at the bottom of the string because of the temperature difference between the atmosphere and the bedrock. The freeze-in is monitored by studying noise rates. During freeze-in, noise rates can increase by more than a factor of 40 owing to tribo-luminescence.

The hole ice is the refrozen column of ice in which the DOMs are embedded. It is believed that the hole ice contains residual air bubbles. The air bubbles increase scattering near the DOMs, which has the effect of isotropizing the angular sensitivity of the DOMs, in the sense that downgoing photons that would otherwise pass by have a larger probability of scattering into the DOM. In simulation this effect is taken into account by modifying the angular DOM sensitivity measured in the lab. Early measurements indicated a geometrical scattering length of around 0.5 m in the hole ice.

During the last season of deployment two video cameras housed in glass spheres were installed at the bottom of one of the detector strings. Observations of the freeze-in process indicate that bubbles might be restricted to a narrow column at the center of the hole, while the rest of hole ice appears very clear.
5.2 Digital optical module

The fundamental element for both optical detection and data acquisition is the digital optical module (DOM). It contains a 25 cm diameter photomultiplier tube (PMT), a high voltage (HV) generator for the PMT, a DOM mainboard (MB) with analog and digital signal processing electronics and an LED flasher board. The components are housed in a 13 mm thick glass pressure sphere capable of withstanding pressures up to 70 Mpa. The PMT is supported and optically coupled to the glass sphere by a flexible, room temperature vulcanizing, optical gel. A schematic overview of the DOM components is shown in figure 5.3.

![Figure 5.3: Schematic overview of a DOM. The 25 cm PMT is supported and optically coupled to the glass housing by a flexible optical gel. A mu-metal grid shields against the terrestrial magnetic field. PMT high voltage is provided by the high voltage generator. Most of the electronics reside on the DOM mainboard, where analog and digital signal processing is handled as well as external communication. The delay board provides enough time for downstream electronics to receive a trigger from the PMT discriminator. LED flashers are used for calibration of timing and geometry and measuring ice properties as well as higher level diagnostics. The penetrator allows wires to pass through the glass sphere.](image)

The glass housing is filled with dry nitrogen at around 1/2 of atmospheric pressure, maintaining a strong compressive force on the sphere before and during deployment. After freeze-in the DOMs are inaccessible, and they have therefore been designed to operate reliably in a cold, high-pressure environment for a period of at least 15 years [79].

The PMT is optically well coupled to the ice through the optical gel and glass. The PMT is sensitive to wavelengths from 300 nm to 650 nm, with a
peak sensitivity at around 400 nm [64]. The optical gel and glass set the lower sensitivity cutoff at 350 nm.

The nominal gain for the in-ice PMTs was chosen at $10^7$ to give single photoelectron (SPE) pulses around 8 mV, well above electronics noise [64]. The PMT response is linear to within 10% for currents up to 31 photoelectrons/ns (PE/ns), and saturates completely at 93 PE/ns. Simulations show that at a 60 m distance, a 600 TeV cascade would cause a peak intensity of 30 PE/ns. Above $\sim$10 PeV many nearby PMTs would saturate and energy reconstructions would have to rely more on information from DOMs further away.

The Hamamatsu R7081-02 PMT was chosen based on low dark noise and good time and charge resolution for single photons [64]. At temperatures relevant to the detector environment, between $-40^\circ$C and $-10^\circ$C, a dark noise rate of around 300 Hz was measured. The low temperature noise rate is believed to be dominated by radioactive decay in the PMT glass. A similar dark noise contribution comes from decays in the glass housing, resulting in a total dark noise rate of around 650 Hz. Typically, a high-energy muon neutrino event has a duration of less than 3 $\mu$s, with most information contained within a time window of 300 ns for each DOM. This implies that only 1% of muons would have a relevant noise count among the 100 DOMs closest to the track. The degradation of reconstructions due to dark noise is expected to be small.

The charge resolution for SPEs was measured to be approximately 30% [64]. Including on-board digitization delay, the time resolution was measured to be 2.7 ns. Because of the strong photon scattering in the ice the timing resolution is not the limiting factor for reconstruction of event properties.

The mainboard contains the analog front-end and two digitizer systems. A trigger is issued when the PMT signal exceeds a programmable discriminator threshold, set to 0.25 PE for in-ice DOMs in IC40. In order for the digitizers to capture the entire waveform, the PMT signal is delayed by 75 ns using an 11.2 m long strip line on a dedicated delay board [79]. The MB also contains a 20 MHz quartz oscillator, which is doubled to 40 MHz and controls local timing [80]. The local clock is regularly calibrated relative to a master clock at the surface. The trigger is given a time stamp by the local clock.

The first digitizer is an application specific integrated circuit, the Analog Transient Waveform Digitizer (ATWD) [80]. The ATWD has four channels, where three are used for waveform capture. The three channels amplify the input signal by $16\times$, $2\times$ and $0.25\times$. This way the full dynamic range of the PMT is well resolved. 128 samples of 10-bit data are collected per channel at a sampling frequency of 300 mega-samples per second (MSPS). The sampling frequency is variable, the current setting results in a bin width of 3.3 ns and a total waveform length of 422 ns. The fourth channel measures signals from sources on the DOM MB and is used for calibration and monitoring. The ATWD takes 29 $\mu$s to digitize a waveform after capture. To minimize dead
time, each DOM has two ATWDs which allows one to be available for signal capture while the other is processing input signals.

For very high-energy events the PMT signal can be longer than the ATWD capture window. The second digitizer is a fast ADC (fADC) which continuously samples the PMT signal at 40 MSPS [80]. The fADC collects 256 samples of 10-bit data, resulting in a waveform with a sample spacing of 25 ns and a length of 6.4 µs. The waveform length more than covers the maximum time interval over which the most energetic events are expected to yield detectable light to any one DOM. The fADC is operated at relative low gain to give a reasonable dynamic range. An SPE pulse produces approximately a 13-count value above the baseline.

Communication between a DOM and surface electronics occurs over a copper-wire twisted-pair, including power distribution, data transmission and timing calibration signals. Signal and communications processing, data transport, system testing and monitoring is performed by a field programmable gate array (FPGA) containing a 32-bit ARM CPU, 8 MB flash storage and 32 MB RAM [80]. The FPGA code, ARM software and DOM operating parameters are remotely configurable.

To reduce noise, DOMs can operate in different local coincidence (LC) modes. Each DOM is connected to its nearest neighbor via copper-wire twisted-pairs. When a DOM triggers it sends an LC signal to its nearest neighbours. DOMs receiving an LC signal can send it along to the next neighboring DOM, depending on the LC mode. Upon triggering, or upon receiving an LC signal, the DOM opens a time window that is typically at most 1 µs long. The LC condition is met if a trigger occurs and an LC signal is received within the time window, indicating that at least one of its neighbors also triggered. Noise hits are uncorrelated and typically isolated which makes LC unlikely.

During data taking with IC40, all DOMs were required to fulfill the LC condition to contribute event information, referred to as hard local coincidence (HLC) operating mode. The HLC condition reduces the single DOM noise trigger rate to less than 1 Hz. During more recent data taking, the detector has been operated in soft local coincidence (SLC) mode. In this mode, DOMs with isolated triggers that do not fulfill the LC condition contribute limited information. A coarse charge stamp is created from the fADC waveform, based on the highest sample within 400 ns. By including isolated triggers, more fine-grained event information is provided. However, a large fraction of isolated triggers are caused by noise, and a sophisticated cleaning procedure is performed at a later stage to reduce the noise contribution.

The flasher board contains 12 gallium nitride LED flashers, directed radially outwards [79]. 6 flashers point horizontally and 6 upwards at a 48° angle. The LEDs are capable of emitting $10^7$ to $10^{10}$ photons per pulse at a flashing rate up to 610 Hz. The peak wavelength is in the range 400 nm to 420 nm. The flashers are used for calibration of timing, geometry and PMT response.
linearity, measurement of optical properties of the ice, calibration of cascade event reconstructions, etc.

A number of DOMs are equipped with multi-wavelength flashers, so-called color DOMs (CDOMs). Each CDOM has LEDs of 4 different wavelengths: 340 nm, 370 nm, 450 nm, and 505 nm. The multi-wavelength flashers will be used to measure ice properties and the wavelength range was chosen to match the Cherenkov light seen by the DOMs.

5.3 Data acquisition system

The general purpose of the data acquisition (DAQ) system is to capture and timestamp all detected optical signals [80]. The digitization is performed inside the DOMs. The digital output record sent from a DOM is often referred to as a DOM launch (in Ref. [80] it is referred to as a Hit, which is not used here because of a different connotation from the perspective of physics analysis). A DOM launch contains a timestamp generated locally within the DOM, a coarse charge stamp, and in the case of a fulfilled LC condition, several waveforms from the digitizers.

The data are collected in the counting house in the IceCube laboratory (ICL) on the surface of the ice [80]. Each string is connected to a DOMHub, which is a computer in the ICL that communicates with all DOMs on the string. Each DOMHub contains eight DOM readout (DOR) cards, each of which is capable of communicating with eight DOMs. The DOR cards control the power, boot-up, software, firmware, calibration and data transfer of the DOMs. There is a master clock which distributes time calibration signals to the DOMHubs. The master clock is based on timing from a GPS receiver and is accurate to within ±10 ns averaged over 24 h. A software element called the StringHub converts the DOM launch timestamp from local DOM time to ICL clock time and time-orders the stream of launches from a string.

5.4 Triggering and online filtering

Events are transferred to the northern hemisphere via a satellite link with limited bandwidth. The DAQ data rate, around 1.5 kHz for IC40, is far above the available bandwidth, which was 35 GB/day for IC40. The DAQ data are required to pass one or more higher level triggers. The relevant trigger for this work is called simple majority trigger 8 (SMT8), which requires 8 triggered DOMs within 5 µs.

Events which fulfill the higher level trigger condition are passed on to the processing and filtering (PnF) system. The PnF runs on a cluster of computers in the ICL. A number of online filters are developed by different working groups searching for different types of signal events. The PnF runs fast event
reconstruction algorithms (see chapter 7) which are utilized by the online filters.

Events that pass one or more online filters are scheduled for transmission to the northern hemisphere via satellite through the South Pole Archival and Data Exchange (SPADE) system.
Part II:
Simulation and reconstruction methods
6. Simulation

Reliable Monte Carlo (MC) simulation is essential in order to make meaningful statements about an unknown signal flux. With a good description of background components the claim to understand the detector is substantiated and there can be confidence in the predicted expression of signal components.

Simulation in IceCube takes place within the software framework *IceSim*. The simulation starts with generation of particles with physical properties like energy, direction, distance from the detector and type. Particles are then propagated through matter, taking energy loss and secondary particle production into account. This includes the propagation of photons in the Antarctic ice. Finally, the detector response is simulated. The simulation chain is summarized in figure 6.1.

6.1 Event generation

6.1.1 Atmospheric muons

The largest background component for most IceCube analyses is downward muons produced in extensive air showers initiated by high-energy cosmic rays. Extensive air showers are simulated using the Monte Carlo event generator CORSIKA (COsmic Ray SImulations for KAascade) [81]. Nuclei in the range from protons to iron can be treated as cosmic ray primaries. Particles are tracked through the atmosphere until they interact with air nuclei or decay. High-energy hadronic interactions are described by the SIBYLL model [82]. The CORSIKA simulation used in this analysis assumes atmospheric conditions typical for the South Pole in October.

The poly-gonato model by Hörandel [14] is used in the default IceCube simulation to describe the primary cosmic ray spectrum. In this model, the cosmic ray flux is a superposition of individual primary fluxes from protons to uranium nuclei. Here, the “knee” in the cosmic ray energy spectrum is the result of a rigidity-dependent cutoff in the individual primary spectra.

For technical reasons, only primaries up to iron can be simulated with CORSIKA. Furthermore, the poly-gonato model does not describe the observed cosmic ray flux at ultra high energies, where it omits what is generally assumed to be an extragalactic contribution. In this analysis, the cosmic ray spectrum at ultra high energies is approximated by extending the iron component with a power law with index -3, following that of the observed overall
cosmic ray spectrum. This implicitly assumes that the cosmic ray spectrum continues indefinitely as $E^{-3}$ and that the ultra high-energy cosmic ray flux consists mainly of heavy nuclei. This approximation does not mitigate the limited statistics at the highest energies due to the inherent rigidity-dependent cutoffs in generation spectra.

The live time for simulated data should ideally be substantially larger than for experimental data to minimize the impact of statistical uncertainties. The cosmic ray energy spectrum falls steeply with energy and this analysis is optimized for ultra high energies. If simulated data were generated according to a physical spectrum, an unfeasibly large amount of data would be required to get satisfying statistics in the relevant energy range. Instead, simulation is biased to oversample events at high energies and can then be weighted to a physical spectrum. For poly-gonato CORSIKA, events are generated according to an energy spectrum one power flatter than the model spectrum.

There is a significant probability of two or more atmospheric muon events triggering the detector within the DAQ readout window. Double and triple coincident events are simulated separately from single events. Previously it was not possible to oversample coincident events at high energies, which severely limited statistics at high energies. The work on simulation within the context of this analysis included implementing a weighting scheme for coincident events, which allowed the use of high-energy biased simulation. Coincident events were generated according to an energy spectrum one half power flatter than the model spectrum.
A second composition model was used as well in this analysis. The 2-component model assumes that the cosmic ray flux is composed of protons and iron nuclei only. The energy spectra of the two components were fitted to data taken with the KASCADE array [83]. The components are generated according to an $E^{-2}$ spectrum, which gives good statistics at the highest energies.

Figure 6.2 shows the energy spectra for the two composition models at filter level 3 of the analysis, described in chapter 11. The difference at lower energies is caused by a larger proton component in the 2-component model.

6.1.2 Neutrinos

The generation of neutrinos of all flavors is handled by the software package neutrino-generator, which is based on the event generator ANIS (All Neutrino Interaction Simulation) [59]. Neutrinos are injected at random positions on the Earth’s surface. ANIS handles the propagation of primary neutrinos through the Earth, including energy loss due to neutral-current interactions and absorption in the Earth due to charged-current interactions. The Earth is modeled according to PREM (Preliminary Reference Earth Model) [84].

Neutrinos that reach the IceCube detector are forced to interact in nearby Antarctic ice or bedrock in such a way that secondary particles would have a non-negligible probability of triggering the detector. Each event is assigned a weight describing the probability of the particular interaction. The target
medium is assumed to be isoscalar, which is a valid assumption for rock, but not for ice, which has more protons than neutrons. In the low energy deep inelastic scattering regime the error due to non-isoscalarity is on the order of 4% [85]. At higher energies the error is smaller, and at energies relevant for this work the error is expected to be negligible.

For simulation used in this analysis neutrinos are generated according to an $E^{-1}$ spectrum. A number of atmospheric and astrophysical neutrino flux models are available within IceSim and can be used to weight the neutrino simulation accordingly.

Assumptions of atmospheric conditions are included in the atmospheric neutrino flux models. The baseline model for the conventional flux component in this analysis is derived by Honda et al [47] and assumes an atmosphere that is a climatological average (the U.S. Standard Atmosphere 1976). The model used to describe the prompt flux component is due to Enberg et al [48] and assumes an isothermal atmosphere where the density decreases exponentially with height.

### 6.2 Propagation

Atmospheric muons and neutrino induced leptons are propagated through ice and rock using the software package MMC (Muon Monte Carlo) [66]. MMC takes continuous and stochastic energy losses into account and handles propagation of secondary leptons.

The propagation of Cherenkov photons is handled separately. Real-time photon propagation is computationally intensive. Given a model for the propagation medium, the software package Photonics [86] determines photon flux and time distributions throughout a volume containing a light source through Monte Carlo simulation. Photons are propagated and time distributions are recorded throughout a cellular grid constituting the simulation volume. Tables are generated with the photon distribution results for light sources with varying properties. In the simulation chain, predicted light distributions are drawn from the tables. This is a computationally efficient approach which also allows usage of the full ice model information in event reconstructions, described in chapter 7.

### 6.3 Detector simulation

The detector simulation starts with hit construction. Based on lepton propagation information the expected number of photoelectrons produced in a particular DOM is drawn from the Photonics tables, along with the expected photon arrival time distribution. The expected number of photoelectrons is affected by the DOM efficiency, which is a collective term describing the local hole
ice, the transmittance of the glass housing and optical gel, and the quantum efficiency of the PMT. These effects are taken into account in the Photonics tables. However, new PMTs with higher quantum efficiency have been deployed in the Deep Core array. The increased sensitivity is taken into account by a factor that scales the DOM efficiency appropriately. Further individual variations in DOM efficiency is currently not taken into account.

The PMT simulation describes the PMT response to a photoelectron. The DOM electronics simulation describes the response of the DOM mainboard and electronics to the output pulse from the PMT. It includes the PMT base transformer, the mainboard input discriminator and waveform digitization by the ATWD and fADC. Trigger simulation finally applies trigger logic to build an IceCube event and rejects events that do not pass a trigger condition.

6.4 Simulation production

Simulation production in IceCube takes place within the comprehensive job management framework IceProd. Managing jobs on specific clusters or grids is possible via local servers utilizing plugins developed for every site. A plugin was developed for the national computational resource SweGrid [3] and simulation production has been maintained on SweGrid for several years. SweGrid has contributed significantly to IceCube simulation production.

Simulation of ultra high-energy events is memory intensive and can only be done at sites where individual nodes have access to large amounts of memory. Specific ultra high-energy data sets were produced for this analysis on SweGrid. Furthermore, the investigation of systematic uncertainties described in chapter 14 required production of benchmark data sets with various parameters varied within a reasonable range. This was feasible thanks to efficient simulation production on SweGrid.

The 2-component CORSIKA had undergone generation and propagation but not detector simulation or further processing. In cooperation with University of Maryland the last stages of simulation along with further processing was performed, which made this data set available to all IC40 analyses.

6.5 Simulated data sample

For simulation generated according to physical parameter values, the live time is simply the total number of generated events divided by the physical event rate. For simulation biased to oversample events at high energies, an energy dependent effective live time can be defined as the total number of generated events divided by the physical event rate, per energy interval.

It is important to have satisfying statistics in an energy region relevant to the particular analysis. This analysis is optimized for neutrino energies greater
than 1 PeV. The live time of the experimental data sample used in the search for signal is 345.7 days.

6.5.1 Atmospheric muons

A total of $1.75 \times 10^5$ files of high-energy biased poly-gonato CORSIKA was used in the analysis. Each file corresponds to $4 \times 10^5$ generated air showers. For double coincident poly-gonato CORSIKA, two simulated samples were used. The first sample was used during development of the analysis, $1.1 \times 10^4$ files were produced with $2 \times 10^6$ air showers generated per file. The second sample was more strongly high-energy biased, referred to as a UHE sample, and was used to verify the final level prediction. For the UHE sample, $3 \times 10^3$ files were produced with $4 \times 10^5$ air showers generated per file. The effective live time for single and double coincident poly-gonato simulation is shown in figures 6.3, 6.4 and 6.5. Triple coincident events are rare and unlikely to impact the analysis. All available triple coincident simulation was removed from the analysis upon reaching higher levels.

For 2-component CORSIKA, 600 files per component were produced, with $2 \times 10^6$ air showers generated per file. The weight applied for each event is shown as a function of energy in figures 6.6 and 6.7. A weight lower than 1 indicates that the energy interval is oversampled with respect to the live time of the experimental data. At the final level of the analysis, described in chapter 12, 2-component simulation is oversampled, which can be seen in figure 6.8.
Figure 6.4: Effective live time for high-energy biased double coincident poly-gonato CORSIKA, for $E_{\text{primary}}^1 = E_{\text{primary}}^2$. $-\Delta$ indicates the change in generation spectral index with regards to the poly-gonato model spectrum. Files used in training of multivariate classifiers are excluded.

Figure 6.5: Effective live time for high-energy biased double coincident poly-gonato CORSIKA, for $E_{\text{primary}}^1 = 10^5$ GeV. $-\Delta$ indicates the change in generation spectral index with regards to the poly-gonato model spectrum. Files used in training of multivariate classifiers are excluded.
Figure 6.6: Weight as a function of energy for the proton component and a live time corresponding to the experimental data sample. A weight less than 1 indicates that the energy interval is oversampled.

Figure 6.7: Weight as a function of energy for the iron component and a live time corresponding to the experimental data sample. A weight less than 1 indicates that the energy interval is oversampled.
6.5.2 Neutrinos

At a late stage of the analysis it was decided to change baseline neutrino simulation, from simulation using neutrino cross sections based on outdated CTEQ5 PDFs [61] to simulation using state-of-the-art cross sections [4]. For each neutrino flavor 1000 files were produced on SweGrid, where 5000 neutrinos with an energy spectrum of $E^{-1}$ were generated per file. To make sure that there was sufficient statistics at the low end of energies at final analysis level, all available old neutrino simulation generated with an $E^{-2}$ energy spectrum was compared to the new simulation. The new neutrino simulation showed better statistics for the full final energy range.
7. Event reconstruction

The main purpose of reconstruction is to estimate physical quantities of an event, such as type, direction, location and energy. Depending on the context, event type can refer to lepton or neutrino flavor, or interaction type, and is commonly characterized as track-like or cascade-like (see section 11.1). Estimates of physical quantities of events are essential since signal and background typically differ in for example direction and energy. The estimation is based on the waveforms registered by the two types of digitizers in the DOMs, the ATWD and fADC (see section 5.2). The reconstruction algorithms applied in this analysis are based on pulses extracted from the waveforms.

7.1 Waveform calibration and feature extraction

The software module DOMcalibrator calibrates the waveforms digitized by the ATWD and fADC. Between the PMT and the high voltage board there is a transformer that causes tails of waveforms to “droop”. In DOMcalibrator, baseline subtraction is performed, individual gain is accounted for and a transformer droop correction is applied. The ATWD has three channels with different gain which results in three different waveforms. DOMcalibrator combines the three waveforms to maximize the dynamic range. The digitizer clock speed is determined and PMT transit time and relative start time offsets are corrected for.

Feature extraction is the method by which pulses are extracted from waveforms. A pulse is characterized by a leading edge time, an amplitude and a width. The amplitude of a pulse is measured in photoelectrons (PEs), the typical charge a single photoelectron (SPE) pulse would yield. Feature extraction is performed by the software module FeatureExtractor [87].

Feature extraction is done differently for ATWD and fADC waveforms. An fADC waveform is composed of 256 bins with a bin width of 25 ns. For fADC waveforms, a threshold charge value is defined and the first bin with charge above the threshold is located. Advancing through the waveform, the pair of bins between which the rate of ascent is locally at maximum is found. A line is fitted to the charge values in these two bins. The point of intersection between the fitted line and the baseline is taken as the leading edge of the found pulse, as illustrated in figure 7.1. The end of the pulse is defined as the lower bin edge of the succeeding bin closest to the first bin, that has charge below the threshold. The sum of the charge for bins belonging to the pulse is used as
the pulse charge. The number of constituent bins times bin width is defined as the pulse width. Starting at the end of the found pulse, the procedure is repeated until the end of the waveform is reached. There are further methods implemented to deal with saturated waveforms.

Waveforms from the ATWD are composed of 128 bins with a bin width of 3.3 ns. The feature extraction is based on the typical shape of a single photoelectron pulse. FeatureExtractor uses an iterative Bayesian unfolding method [88, 89] to deconvolve the ATWD waveform into pulses with an SPE pulse shape. The amplitude of the pulse corresponds to the number of photons producing photoelectrons at the corresponding leading edge time. The pulse width carries no further information in this case.

7.2 First guess algorithms

More sophisticated likelihood based reconstructions perform a minimization procedure to find the most likely event hypothesis. An initial event hypothesis, a seed, is required to start the minimization. An initial hypothesis reasonably close to true parameter values reduces the risk for mis-reconstructions. The seeds are provided by fast first guess methods that do not require initial event hypotheses. Quickly calculable variables based on first guess methods are also important in low level filters where computational efficiency is essential.

7.2.1 LineFit

LineFit is an analytical first guess track reconstruction algorithm. The algorithm ignores the geometry of the Cherenkov cone and the optical properties
of the ice, and assumes that photons are travelling along a 1-dimensional line with a certain velocity $\vec{v}_{LF}$. A vertex point $\vec{r}$ and the velocity $\vec{v}_{LF}$ is attained by minimizing

$$\chi^2 = \sum_{i=1}^{N_{\text{pulse}}} (\vec{r}_i - \vec{r} - \vec{v}_{LF} t_i)^2$$

(7.1)

where $\vec{r}_i$ is the position of a DOM, $t_i$ is the leading edge time of a pulse detected in the corresponding DOM, and the sum goes over all pulses in an event. The minimization has an analytic solution

$$\vec{r} = \langle \vec{r}_i \rangle - \vec{v}_{LF} \langle t_i \rangle$$

(7.2)

$$\vec{v}_{LF} = \frac{\langle \vec{r}_i t_i \rangle - \langle \vec{r}_i \rangle \langle t_i \rangle}{\langle t_i^2 \rangle - \langle t_i \rangle^2}$$

(7.3)

where $\langle x \rangle$ denotes the mean of parameter $x$ with respect to all pulses. The direction is given by $\vec{v}_{LF}/|\vec{v}_{LF}|$.

For track-like events $\vec{v}_{LF}$ is typically close to the speed of light, whereas for cascade-like events where there is little commonality to the direction of photons $\vec{v}_{LF}$ is typically small, approaching 0.

### 7.2.2 Tensor of inertia

The tensor of inertia algorithm assigns a virtual mass $(a_i)^w$ to a DOM at position $\vec{r}_i$. The virtual mass corresponds to the number of detected photoelectrons in the DOM and $w$ is a weight chosen according to how one wants to weigh photoelectrons. For applications in this work, $w$ is set to 1. The origin of the tensor of inertia is the center of gravity (COG) of the mass distribution

$$\vec{r}_{\text{COG}} = \frac{\sum_{i=1}^{N_{\text{ch}}} (a_i)^w \vec{r}_i}{\sum_{i=1}^{N_{\text{ch}}} (a_i)^w}$$

(7.4)

where $N_{\text{ch}}$ denotes the number of DOMs with non-zero virtual mass. The tensor of inertia $\vec{I}$ for the virtual mass distribution is

$$I^{k,l} = \sum_{i=1}^{N_{\text{ch}}} (a_i)^w [\delta^{k,l} (\vec{r}_i)^2 - \vec{r}_i^k \vec{r}_i^l]$$

(7.5)

$\vec{I}$ has three eigenvalues corresponding to three main axes, with the smallest eigenvalue corresponding to the longest axis. For track-like events, the direction of the longest axis can be used as a first guess seed. Cascade-like events are typically fairly spherical which means that the main axes will be similar in magnitude. The ratio between the smallest eigenvalue and the sum of all eigenvalues is called the eval ratio and is an indicator of the sphericity of an event. The COG can be used as a first guess for the interaction vertex position in cascade reconstructions.
7.2.3 CFirst

CFirst is a cascade first guess algorithm that uses the COG as estimated vertex position.

For the purpose of estimating a vertex time, the \textit{geometrical time} is defined as the time when unscattered Cherenkov photons reach a DOM. The \textit{shifted residual time} is defined as the first registered pulse time in a DOM minus the geometrical time from the COG to the DOM. This is calculated for all DOMs within a radius of 1000 m around the COG. For each DOM, with corresponding shifted residual time \( t_{\text{shift}} \), the number of DOMs with shifted residual time within 200 ns following \( t_{\text{shift}} \) is counted. The earliest \( t_{\text{shift}} \) for which there are at least 3 such DOMs is used as the vertex time [90].

7.3 Likelihood description

The general problem is estimating a set of unknown parameters \( \vec{a} \) given a set of measured values \( \vec{x} \). The parameters \( \vec{a} \) are determined by maximizing the likelihood function \( L(\vec{a}|\vec{x}) \) which for independent measured values \( x_i \) becomes

\[
L(\vec{a}|\vec{x}) = \prod_{i} p(x_i|\vec{a})
\]

where \( p(x_i|\vec{a}) \) is the probability density function (PDF) of observing the measured value \( x_i \) given the parameter values \( \vec{a} \). The reconstruction is performed by minimizing \( -\log(L) \) with respect to \( \vec{a} \). An event is generally described by the parameters

\[
\vec{a} = (\vec{r}_0, t_0, \hat{p}, E_0)
\]

where \( \vec{r}_0 \) in the case of a track hypothesis is an arbitrary point along the track, and in the case of a cascade hypothesis is the interaction vertex position, \( t_0 \) is the time of the event at \( \vec{r}_0 \), \( \hat{p} \) is the direction of the event and \( E_0 \) the energy of the event at \( \vec{r}_0 \). For cascades there are seven degrees of freedom, the vertex time and position, and the direction and energy of the event. For tracks there are six degrees of freedom, since the point along the track can be chosen arbitrarily. All parameters can be reconstructed simultaneously or the geometrical parameters and the energy can be reconstructed separately. The measured values \( \vec{x} \) correspond to the feature extracted pulses.

If the observed number of photoelectrons and the expected number of photoelectrons are binned in time into \( K \) bins, the probability of observing \( n_i \) photoelectrons in the \( i \)th bin given an expectation of \( \mu_i \), is given by Poissonian statistics. The likelihood for a single DOM is given by

\[
L(\vec{a}|\vec{x}) = \prod_{i=1}^{K} \frac{e^{-\mu_i}}{n_i!} (\mu_i)^{n_i}
\]
The full log-likelihood is then given by the sum of \(\log(L)\) for all DOMs, which is maximized with respect to the parameters describing the event hypothesis. 

\(\mu_i\) is given by a PDF which describes the photon arrival time distribution given a certain event hypothesis. A commonly used PDF is the Pandel function, which parameterizes the arrival time distribution of Cherenkov photons as a gamma distribution. It assumes bulk ice without dust layers and is motivated by an analysis of laser light signals in the BAIKAL experiment [91,92]. The Pandel function is normalized, can be integrated over time analytically and is computationally efficient.

The main drawback with the Pandel function is that it assumes bulk ice, with scattering and absorption coefficients constant over depth. The properties of the Antarctic ice have been measured using in situ light sources, resulting in a model of the depth dependence of scattering and absorption. The software package Photonics [86] (see section 6.2) simulates photon propagation taking the ice model into account and stores the result in tables. An interface for the purpose of reconstruction called Photorec provides a numerical PDF describing the arrival time of Cherenkov photons based on the full ice description.

Both PDFs depend on whether the light source hypothesis is an electromagnetic cascade or a muon track. The shape of the PDF is mainly determined by the scattering of photons in the ice. The final PDF is modified to also account for PMT jitter and dark noise.

As mentioned previously, all event parameters can be reconstructed simultaneously, or the geometrical parameters and the energy can be reconstructed separately. Looking at the components separately simplifies the likelihood expression. When reconstructing location and direction, the arrival times of the photoelectrons carry the most crucial information and the total charge information can be ignored. Given a geometrical hypothesis, the energy can be reconstructed by modeling the expected total charge as a function of event energy. In the simplest case, where total charge scales linearly with energy, the problem has an analytical solution. For electromagnetic cascades the dependence of the amount of Cherenkov light on the cascade energy can be modeled as linear [93].

The minimization procedure can sometimes find local instead of global minima of \(-\log(L)\). A way of dealing with this undesired behavior is to repeat the reconstruction for several seeds, which is here referred to as performing iterations of the reconstruction. One seed is provided to the reconstruction and the other seeds are chosen with directions according to a pseudo-random uniform distribution on the unit sphere. Ultimately the event hypothesis with the best likelihood is used.
7.4 Track reconstructions

For the track reconstructions used in this analysis the geometry of the track is reconstructed separately from the energy. The geometry reconstructions are based on the Pandel PDF describing photon arrival times.

7.4.1 SPE track reconstruction

The single photoelectron (SPE) PDF describes photon arrival times at a specific location. Only information about the first photoelectron detected by a DOM contributes to the likelihood function in the SPE track reconstruction. This has been seen to give a more robust reconstruction than when using information from all detected photoelectrons. The SPE track reconstruction is seeded by LineFit, and the result is used as a seed for a 32-iteration SPE reconstruction (SPE-32).

7.4.2 MPE track reconstruction

The multi-photoelectron (MPE) PDF describes the arrival time of the first of \( N \) photons, where \( N \) corresponds to the detected number of photoelectrons per DOM. The result of the SPE-32 reconstruction is used as a seed for the MPE reconstruction. The MPE PDF works very well for high energy muon tracks. The first of many photons is likely to have suffered little scattering and therefore carry most information about the geometry of the track. In the case of many photons the PDF becomes narrow. In the likelihood calculation emphasis is therefore placed on the information from DOMs that detect a large amount of light. The MPE reconstruction is relatively sensitive to local minima, compared to SPE, and a good seed is required.

7.4.3 Bayesian track reconstruction

The likelihood function can be extended to incorporate prior information about the atmospheric muon flux. Bayes’ theorem for an event with parameters \( \vec{a} \) and measured values \( \vec{x} \) states

\[
P(\vec{a}|\vec{x}) = \frac{P(\vec{x}|\vec{a})P(\vec{a})}{P(\vec{x})}. 
\]  

(7.9)

\( P(\vec{a}) \) is the prior probability distribution for the event hypothesis. The atmospheric muon flux has a well characterized zenith dependence, shown in figure 7.2, which serves as a prior in the likelihood function of the Bayesian track reconstruction. Close to the horizon, the atmospheric muon flux becomes zero, which enforces downgoing track hypotheses. \( P(\vec{x}) \) does not depend on the event parameters and is therefore constant and can be ignored. The Bayesian track reconstruction is based on the SPE PDF, is seeded by the SPE-32 track.
reconstruction, and performs 32 iterations with seeds distributed over down-going directions.

### 7.4.4 Two-track reconstructions

There is a significant probability of having one or more atmospheric muon events occurring in coincidence with another event within the DAQ readout window. Coincident events easily confuse reconstructions that assume a single event hypothesis. This is dealt with by dividing DOMs or pulses into two groups and performing separate track reconstructions based on information from each group. The separation is done in two ways based on timing and geometry. The first algorithm separates pulses into two groups based on the mean time of all pulses. Pulses in the first group have times before the mean time and pulses in the second group after the mean time. The second algorithm is seeded by the SPE-32 single track hypothesis. A plane that divides DOMs into two groups is defined perpendicular to the track and through the COG. Both SPE and Bayesian track reconstructions are performed on the subsets, seeded by LineFit and performing 16 iterations.

### 7.4.5 Paraboloid sigma

The paraboloid sigma is a likelihood based track-by-track measure of the error in reconstructed direction, based on Ref. [95]. A region in zenith and azimuth around a given seed is explored on a grid. For a track with fixed direction
at one of the grid points, the vertex position is reoptimized to give a new likelihood. An error ellipse is defined as the curve in parameter space on which \(-\log(L)\) is 0.5 times higher than \(-\log(L_{\text{best}})\), where \(-\log(L_{\text{best}})\) is the best likelihood in the explored region. The paraboloid sigma is formed as

\[
\sigma = \sqrt{\frac{\sigma_1^2 + \sigma_2^2}{2}},
\]  

(7.10)

where \(\sigma_1\) and \(\sigma_2\) are the minor and major axes of the error ellipse.

The paraboloid sigma is evaluated for the SPE-32 and MPE track reconstructions.

### 7.4.6 MuE energy reconstruction

The muon track energy reconstruction used in this analysis is called MuE. MuE assumes bulk ice but nevertheless performs as well as an alternative energy reconstruction utilizing Photorec PDFs. Based on observed signal efficiency, MuE was chosen as the main track energy reconstruction for this analysis. The MPE track hypothesis is used as a seed and MuE performs a likelihood based reconstruction of energy only. The energy is reconstructed based on an estimation of the number of emitted photons per unit track length.

### 7.5 Cascade reconstructions

#### 7.5.1 CLLH vertex reconstruction

The CLLH vertex reconstruction uses the Pandel PDF for describing photon arrival times. It is seeded by the CFirst first guess method.

#### 7.5.2 ACER energy reconstruction

The ACER (Atmospheric Cascade Energy Reconstruction) energy reconstruction models the expected total charge detected by a DOM as linearly dependent on cascade energy. The problem can therefore be solved analytically which results in a fast reconstruction. The expected total charge is given by the Photorec PDF which takes the full ice description into account. For this analysis ACER uses the vertex position from CLLH.

#### 7.5.3 Credo vertex and energy reconstruction

Credo reconstructs all event parameters simultaneously and uses the Photorec PDF to describe photon arrival times and total expected charge. It is seeded by the CLLH vertex, the direction of the longest main axis from tensor of inertia, and the energy from ACER.
Part III:
Searching for an Ultra-High Energy Diffuse Flux of Extraterrestrial Neutrinos with IceCube 40
8. Analysis overview

8.1 Signal
Signal for this analysis is defined as an all-flavor, extraterrestrial, diffuse flux of neutrinos with an energy spectrum of $E^{-2}$. The upper bound calculated by Waxman and Bahcall, described in section 2.3.3, is used as a test signal flux. The analysis is optimized for neutrinos with energy greater than 1 PeV.

8.2 Background
The largest background component is muons produced in cosmic ray induced extensive air showers, described in section 3.2.

The second largest background component is neutrinos produced in the same air showers, described in section 3.3. This component is smaller by about five orders of magnitude but constitutes an irreducible background.

8.3 Structure
The analysis consists of three filter levels followed by a final cut that defines a final level.

In general, level is correlated to the signal to background ratio at a certain point in the analysis. When different points in the analysis are compared, “higher level” implies a higher signal to background ratio. Higher level also implies more signal-like events where underlying physical quantities are more easily discernible.

8.4 Blindness
In a blind analysis some aspect of the data or the result is kept hidden to prevent experimenter’s bias [96]. Experimenter’s bias can be defined as the unintended influence on a measurement in a particular direction, typically towards prior results or theoretical predictions. Minimizing experimenter’s bias is especially important in the search for a small signal, where one event can impact the statistical significance of an excess or strictness of an upper limit.
Here, blindness is achieved by using a sub-sample of experimental data during the development of the analysis, a so-called “burn sample”. The burn sample is used to verify that simulated data describe the experiment well. Since the signal region for this analysis is not well known or localized, the final background estimate cannot be based on experimental data and is instead based on the prediction from simulation. The burn sample is also used to search for detector artefacts or any previously unforeseen problems. It is not used in the search for a signal, instead it is discarded (“burned”).

The full experimental data sample is kept hidden until the analysis method, selection cuts and background estimate is fixed. Once the analysis has passed the scrutiny of the working group and internal referees, the full data sample is unblinded and an observation is made or an upper limit is set.

8.5 Experimental data sample

With the detector in the 40-string configuration, experimental data were acquired from April 6 2008 to May 20 2009. Detector uptime was \( \sim 92\% \), resulting in a total live time of 375.5 days. The burn sample was chosen as data from the month of August 2008, giving a live time of 29.8 days. This choice was made by the analysis working group, to allow the development of analyses to start before the end of the data taking season.

8.6 The IceCube frame of reference

The coordinate system used by IceCube has the same orientation as the global coordinate system used by the South Pole surveyors. The y axis is Grid North, aligned with the Prime Meridian, pointing towards Greenwich, UK. The x axis is Grid East, pointing 90 degrees clock-wise from Grid North. The z axis is normal to the Earth’s surface, pointing up, completing a right-handed coordinate system. The y axis unit is called Northings (N) and the x axis unit Eastings (E).

The origin of the IceCube coordinate system is defined in the global coordinate system and is located close to the center of the full IceCube in-ice detector. The precise location of the origin is 46500 ft E, 52200 ft N, at an elevation of 2900 ft.

The official meaning of “depth” in IceCube is the vertical distance from the floor of the tower used for deployment of string 21, the first IceCube string, at an elevation of 9291.31 ft.

Zenith and azimuth angles refer to the direction which is opposite to the particle’s direction, that is they refer to the direction the particle came from.
This analysis searches for an ultra high-energy all-flavor neutrino flux. Neutrinos of different flavors show different characteristic event topologies in the detector. Two main topologies are track-like and cascade-like, described further in section 11.1. Filter level 1 is defined by selecting which online filters events are required to pass. Because signal includes all neutrino flavors, several online filters are included in the analysis. Filter level 1 requires that events pass one or more of the muon filter, cascade filter or EHE filter. These online filters are described in the following sections. The muon and cascade filter have the highest passing rate of all online filters.

9.1 Muon filter

The muon filter aims at rejecting down-going atmospheric muons and retaining neutrino induced muons from near or below the horizon. The filter consists of two branches, summarized in table 9.1.

The branches are complementary to one another, with branch 2 aiming at events with higher energy. The variables are described below:

- **Number of channels**, \( N_{\text{ch}} \): The number of DOMs that detected photons per event. *Channel* is commonly used to indicate a DOM. The number of channels can serve as a crude energy estimator.
- **Number of photoelectrons**, \( N_{\text{pe}} \): The total number of photoelectrons detected per event. It can be calculated by summing the charge of all pulses per event. The number of photoelectrons can serve as a crude energy estimator.
- **Zenith angle of the SPE reconstruction**, \( \theta_{\text{SPE-X}} \): \( X \) signifies how the SPE reconstruction was seeded. \( I \) indicates that the first guess reconstruction

<table>
<thead>
<tr>
<th>Branch</th>
<th>Selection criteria</th>
</tr>
</thead>
</table>
| 1      | \((\theta_{\text{SPE-I}} \text{ AND } \theta_{\text{SPE-II}} \geq 80^\circ \text{ AND } N_{\text{ch}} \geq 10) \text{ OR}\)  
\((\theta_{\text{SPE-I}} \text{ AND } \theta_{\text{SPE-II}} \geq 70^\circ \text{ AND } N_{\text{ch}} \geq 16)\) |
| 2      | \(N_{\text{pe}}/N_{\text{ch}} \geq 5 \text{ AND } ((\theta_{\text{SPE-I}} \text{ OR } \theta_{\text{SPE-II}} \geq 50^\circ \text{ AND } N_{\text{ch}} \geq 20) \text{ OR}\)  
\((\theta_{\text{SPE-I}} \text{ OR } \theta_{\text{SPE-II}} \geq 70^\circ \text{ AND } N_{\text{ch}} \geq 10))\) |
LineFit was used as a seed. II indicates that both the LineFit direction and its reciprocal were used as seeds. The SPE reconstruction that gives the best likelihood would then be used. This is a technique used to reduce misreconstructions.

9.2 Cascade filter

The cascade filter aims at selecting cascade-like events while rejecting track-like events. Cascade-like events are characterized by a roughly spherical light emission. The selection criterion is \( v_{LF} < 0.13 \) AND \( R_{\text{eval}} > 0.12 \). The variables are described below:

- **LineFit velocity**, \( v_{LF} \): The LineFit first guess algorithm is described in section 7.2. For track-like events, the LineFit velocity is usually close to the speed of light, \( \sim 0.3 \) m/ns, the speed with which a muon traverses the detector. For cascade-like events, where the expansion of light typically does not have a common directionality, the velocity is usually small, approaching 0. For coincident events, the velocity can be significantly larger than the speed of light.

- **Eval ratio**, \( R_{\text{eval}} \): The eval ratio is based on the calculation of the tensor of inertia for an event, using the total number of detected photoelectrons per DOM as the mass at the corresponding DOM position. The eval ratio is defined as the ratio between the smallest eigenvalue of the tensor of inertia and the sum of all three eigenvalues. For events that are highly spherical the eval ratio is close to 1/3 and for track-like events the eval ratio approaches 0.

9.3 EHE filter

The EHE filter is optimized to keep signal events with in-ice energies above 1 PeV. The selection criterion, \( \log_{10}(N_{\text{pe}}) > 3 \), selects very bright events.
10. Filter level 2

There is a common offline filter level 2 intended to serve as a base for general types of analyses performed with IceCube. Different reconstructions are performed depending on which online filter the event passes. Since three online filters are included in this analysis, real and simulated data at the common level 2 are not homogeneous. In order to get a homogeneous data set, a reprocessing of data was required. For the reprocessing to be feasible, a data reduction was necessary. This was achieved by a pre-cut. Filter level 2 for this analysis is defined by a pre-cut and a reprocessing.

10.1 fADC information

In each DOM there are two types of waveform digitizers, the fADC and the ATWD, described in section 5.2. In previous analyses fADC information was not used, because it was considered inadequately described by simulation. For very bright events one would expect a broad distribution of photon arrival times. This is especially true for very bright uncontained events. The ability to characterize uncontained events implies that the effective volume of the detector can be increased. The fADC capture window is 6.4 μs while the ATWD capture window is 422 ns. Thus it would be advantageous to be able to use fADC information. The agreement between experimental and simulated data is investigated in the following sections, with the purpose of determining if fADC information can be used in this analysis.

10.1.1 fADC pulses

An fADC pulse is composed of consecutive waveform bins with charge above a certain threshold value. Feature extraction from one waveform can result in many pulses. The pulse charge is the integrated charge over the waveform bins that make up the pulse. An fADC pulse is characterized by a leading edge time, a charge and a width. Feature extraction is described further in section 7.1.

A disagreement between real and simulated data was noticed for fADC pulses that arrive later than 400 ns after the first pulse, see figure 10.1. Since the ATWD provides waveform data with higher resolution and larger dynamic range up to 422 ns, fADC information mainly contributes at later times. In the
following study, all fADC pulses have arrival times later than 400 ns. Also note that distributions are normalized to the same number of events.

### 10.1.2 Afterpulses

A distinction was made between *small* and *large* pulses. Small pulses are defined as having charge less than 3 photoelectrons (PEs), and large pulses as having charge greater than or equal to 3 PE. The arrival time distribution for all pulses and large pulses is shown in figure 10.2, for real data.

The distribution for all fADC pulses looks roughly like a normal photon arrival time distribution, with some smaller substructures. For large fADC pulses there is a clear broad bump that peaks at around 2 \( \mu \)s. For even larger pulses this structure broadens and the peak moves to slightly earlier times.
These structures agree fairly well with observations of afterpulses in the lab, see figure 10.3.

Afterpulses are a common feature of PMTs, and are attributed to ionization of residual gases by electrons accelerated in the space between dynodes [64]. Ions created this way can be accelerated back to the photocathode and cause ejection of photoelectrons which are amplified like the original photoelectrons. The differing mass of ions causes differing flight times in the accelerating field which yields typical arrival times for the corresponding afterpulses. Because some ions eject multiple photoelectrons there is a typical charge distribution associated with different arrival times. Multiple ions may be created as well. Note that afterpulses would be most common in very bright events, which is what this analysis is optimized for.

Quantitative differences between PMTs have been seen, due to differing mixes and amounts of residual gases. The observed pulse time structure in figure 10.2 is averaged between all DOMs present in an event. Individual PMT high voltage settings will also affect afterpulse arrival times.

In simulation, pulses smaller than around 7 PE show no discernable afterpulse structure. For larger pulses there is a clear peak at around 660 ns and possibly a peak at around 540 ns, shown in figure 10.4. These prominent afterpulse peaks are part of simulation, with a large typical charge. Other common afterpulses are simulated, although seemingly with a charge distribution that
does not agree with observations from real data. The disagreement between real and simulated data is seen clearly in figure 10.5.

The largest structure caused by afterpulses is the bump with a peak at around 2 µs seen in figure 10.2. To gauge the effect of afterpulses, the area of this bump is calculated above a baseline that estimates the “afterpulse-free” photon arrival time distribution. The baseline is estimated with a straight line fitted between the lowest point between 500 ns to 2000 ns, and the point at 3500 ns. The fraction of pulses belonging to this bump is shown as a function of pulse charge in figure 10.6. The fraction of afterpulses becomes significant somewhere between 2 and 4 PE. The figure 10.7 shows a comparison between real and simulated data, after the fraction of afterpulses has been subtracted from real data. The nice agreement suggests that inadequately simulated afterpulses is the main cause of the initially observed disagreement.
Figure 10.6: Fraction of likely afterpulses as a function of pulse charge, for real data.

Figure 10.7: fADC pulse charge distribution, for real and simulated data. For real data the original distribution is shown with the thin line, and with likely afterpulses subtracted with the thick line. Note that the subtraction of likely afterpulses is only performed up to a pulse charge of 10 PE.
10.1.3 Conclusion

The fADC pulse charge disagreement seen between real and simulated data seems to stem from inadequately simulated afterpulses. It mainly affects pulses with charge greater than around 3 PE. The majority of pulses, 94%, have charge less than 3 PE. To reduce sensitivity to the disagreement while still utilizing fADC information it was decided to consider small fADC pulses for use in the pre-cut, that is pulses with charge less than 3 PE. The pre-cut is described in the next section.

Higher level observations

At higher levels of the analysis, variables are constructed based on event-averaged properties of fADC pulses. These variables do not show worse agreement when using all fADC pulses than when using small pulses only. It seems likely that afterpulses do not have a large effect on average properties.

In general, at higher levels, the agreement for variables based on ATWD information is better than for variables based on fADC information. Note that there are many factors other than PMT characteristics which affect fADC information. The largest factor may well be uncertainties on the properties of the ice, since scattering and absorption of photons directly affects photon arrival times. To remain as insensitive as possible to disagreements between real and simulated data it was decided to only use ATWD information at higher levels.

Note that the separation power between signal and background is in general greater for variables based on fADC information. A new software module devoted to simulation of afterpulses is in the process of being included in the standard simulation chain, and reducing systematic uncertainties is an ongoing effort. Future analyses will hopefully be able to rely on both ATWD and fADC information.

10.2 Pre-cut

To make the reprocessing feasible it was estimated that data had to be reduced to around 10% by the pre-cut.

10.2.1 Selection of variables

Since this analysis is optimized for a UHE signal and background is largest at lower energies, the most signal efficient variables are related to energy. The pre-cut must be evaluated for all events, so to reduce the time required for evaluation the variables must be calculated quickly. This rules out variables based on sophisticated reconstructions. The variables are required to show a fairly good agreement between real and simulated data. Each variable was calculated twice, once based on small fADC pulses and once based on ATWD pulses. The considered variables are summarized below:
Figure 10.8: Number of small fADC pulses, for real and simulated data. Note that the Waxman-Bahcall test signal $\nu_\mu$ flux has been scaled by $5 \times 10^4$.

- **Number of pulses**, $N_{\text{pulse}}$: The total number of feature extracted pulses per event.
- **Maximum current**, $I_{\text{max}}$: The maximum current is defined as $\text{max}(Q/T)$ for an event, where $Q$ is the total registered charge during time $T$, and $T$ is a time window of $1\ \mu s$ sliding through the event. Note that charge is measured in units that correspond to the expected charge from one photo-electron.
- **Fraction of DOMs with one hit only**, $F_{\text{1h}}$: A hit corresponds to a pulse in this case.
- **Fraction of total charge registered by DOM with most charge**, $Q_{\text{max}}/Q_{\text{tot}}$.
- **Event duration**: The last pulse time plus the last pulse width minus the first pulse time.

10.2.2 Evaluation of cut

Because these variables are related to energy they are highly correlated. Using more than one variable does not improve the signal efficiency by much, so for simplicity only one variable is used. Based on signal efficiency and agreement between real and simulated data, the total number of small fADC pulses is chosen, shown in figure 10.8. The pre-cut is described in table 10.1.

Table 10.1: Summary of the pre-cut. $N_{\text{pulse}}$ refers to small fADC pulses. Signal efficiency is given for a Waxman-Bahcall neutrino flux with energy greater than 1 PeV.

<table>
<thead>
<tr>
<th>Selection criterion</th>
<th>Data efficiency</th>
<th>Signal efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{pulse}} &gt; 56$</td>
<td>10%</td>
<td>82%</td>
</tr>
</tbody>
</table>

73
Figure 10.9: The ratio between simulated and real data rate is shown on the left axis and efficiency is shown on the right axis, as a function of cut on the number of small fADC pulses.

Table 10.2: Passing rates before and after the pre-cut, for real and simulated data. The last column shows pre-cut efficiency.

<table>
<thead>
<tr>
<th>Online filter</th>
<th>Before: exp/sim</th>
<th>After: exp/sim</th>
<th>Eff: exp/sim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>34.8 Hz / 33.9 Hz</td>
<td>3.36 Hz / 2.74 Hz</td>
<td>9.7% / 8.1%</td>
</tr>
<tr>
<td>Muon</td>
<td>19.9 Hz / 22.0 Hz</td>
<td>1.81 Hz / 1.65 Hz</td>
<td>9.1% / 7.5%</td>
</tr>
<tr>
<td>Cascade</td>
<td>16.2 Hz / 13.1 Hz</td>
<td>0.91 Hz / 0.54 Hz</td>
<td>5.6% / 4.1%</td>
</tr>
<tr>
<td>EHE</td>
<td>1.12 Hz / 0.90 Hz</td>
<td>1.05 Hz / 0.87 Hz</td>
<td>93% / 96%</td>
</tr>
</tbody>
</table>

10.2.3 Effect of cut

The effect of the pre-cut follows expectation, events far from the detector and low energy events are removed. The agreement between real and simulated data is adequate in a region around the pre-cut, as shown in figure 10.9. The pre-cut reduces data by one order of magnitude only and is not likely to have a large impact on the final level of the analysis. The passing rates before and after the pre-cut is shown in table 10.2.

The signal efficiency of the precut for different classes of events is shown in table 10.3. Rejected events are rather evenly distributed between classes.

10.3 Reprocessing

The common filter level 2 processing includes almost all of the most sophisticated track and cascade reconstructions available within the IceCube software framework. The reprocessing performed for the analysis discussed here closely follows the common filter level 2 processing, with the addition of two
Table 10.3: Signal efficiency of the pre-cut for different classes of events. Signal efficiency is given for a Waxman-Bahcall neutrino flux with energy greater than 1 PeV. The left column lists online filters. For the muon filter the direction of the neutrino is listed. Down is defined as having a zenith angle less than 80 degrees, up as greater than or equal to 100 degrees and horizontal in between. The value in parenthesis next to the signal efficiency is the event class fraction of total signal rate, before the pre-cut.

<table>
<thead>
<tr>
<th>Event class</th>
<th>Eff: $E^{-2}\nu_\mu$</th>
<th>Eff: $E^{-2}\nu_e$</th>
<th>Eff: $E^{-2}\nu_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon down</td>
<td>89% (16%)</td>
<td>88% (12%)</td>
<td>88% (8%)</td>
</tr>
<tr>
<td>Muon horiz</td>
<td>77% (24%)</td>
<td>88% (3%)</td>
<td>81% (8%)</td>
</tr>
<tr>
<td>Muon up</td>
<td>75% (10%)</td>
<td>85% (1%)</td>
<td>77% (7%)</td>
</tr>
<tr>
<td>Cascade</td>
<td>85% (20%)</td>
<td>91% (16%)</td>
<td>89% (16%)</td>
</tr>
<tr>
<td>EHE</td>
<td>100% (32%)</td>
<td>100% (12%)</td>
<td>100% (15%)</td>
</tr>
</tbody>
</table>

newer cascade reconstructions. Furthermore, a module was included that calculates useful and otherwise omitted variables, based on pulse information.

At the time of the reprocessing several bugs had been found in the common filter level 2 processing. By updating software and module settings all known bugs could be fixed in the reprocessing.

A pre-requisite for the reprocessing to be considered was access to the national computing resource SweGrid [3]. Much work has been devoted to facilitating processing within the IceCube software framework on SweGrid, which now can be done swiftly.
Filter level 3 is the main filter level. Variables from the most sophisticated reconstructions are available for all events, owing to the reprocessing. Emphasis is placed on developing a robust analysis, well described by simulation. For this reason, agreement between real and simulated data is often prioritized before signal efficiency when selecting cut variables.

11.1 Event topology

Different types of events have different topology in the detector. The main event signatures are listed below:

- **Track-like**: A track topology is simple and fairly insensitive to many systematic uncertainties, for example ice properties.
- **Cascade-like**: Roughly spherical light emission. The sphericity of an event describes the three-dimensional shape of the photon distribution and is highly sensitive to for example ice properties.
- **Composite**: A combination of track-like and cascade-like.

11.1.1 Neutrinos

Neutrino-nucleon interactions result in a hadronic shower. Neutral-current interactions therefore yield cascade-like events. The remainder of this section discusses charged-current interactions.

$\nu_\mu$

Muons traversing the detector produce track-like signatures. In IceCube, analyses searching for muon neutrinos are the most mature. The atmospheric muon neutrino energy spectrum has been measured [97] and point source analyses are possible owing to the good pointing resolution.

Muon neutrinos interacting inside the detector volume produce “starting track” events. The combination of the hadronic shower at the interaction point and the outgoing muon constitutes a composite event.

$\nu_e$

Electromagnetic showers are produced in electron neutrino charged-current interactions resulting in cascade-like events. The atmospheric electron neu-
Figure 11.1: An upgoing neutrino induced muon track from the IC40 burn sample. Colors indicate the time of detected photoelectrons, where red indicates early times. The size of spheres indicate the number of detected photoelectrons per DOM.

The neutrino flux is about five orders of magnitude lower than for atmospheric muon neutrinos and an atmospheric signal has not yet been established [98].

$\nu_\tau$

Tau neutrino charged-current interactions can produce a variety of signatures. The $\tau$ lepton produced has a typical decay length of $\sim 50 \times (E_\nu/{\rm PeV}) \text{ m}$ [67].

Figure 11.2: A contained cascade candidate event from the IC40 burn sample. The color scale is modified because of an early noise hit.
The largest decay branching fractions produce a hadronic or electromagnetic shower, depending on decay branch. For tau neutrinos with energy less than around 100 TeV such decays will produce cascade-like event signatures.

At energies greater than about 20 PeV the decay length typically exceeds 1 km and a track-like signature can be produced. Note that the light yield from $\tau$ leptons is lower than from muons owing to different dominating energy loss processes.

At energies between 1 and 20 PeV it is possible for the interaction and decay induced showers to be contained within the detector volume, while still being separable, producing so-called “double bang” events [99].

If only one shower is contained within the detector volume so-called “lol-lipop” events [100] are produced, which are similar or identical to starting track events.

The $\tau$ lepton can also decay producing a muon, which would yield a track-like signature. If the decay vertex is contained within the detector, it is possible that the increase in light yield from the muon could be discernable [67].

**Directionality**

For energies greater than around 1 PeV the charged-current neutrino-nucleon interaction cross section becomes large enough that the Earth becomes opaque to muon and electron neutrinos. This limits the direction of muon and electron neutrinos to the horizontal and downgoing region. Because of limited overburden the probability of interaction in the ice is largest for horizontal directions. High energy muons traverse kilometers of ice, which means that muon neutrinos can be detected even if the interaction point is far from the detector.
The most likely direction for high energy muon neutrinos is therefore close to horizontal.

A charged-current electron neutrino interaction produces an electromagnetic cascade, which has a typical extension of less than 10 m. Proximity of the interaction point to the detector is required for detection. This reduces the directional dependence of the sensitivity to electron neutrinos in the horizontal and downgoing region.

Tau neutrinos go through the process of regeneration [101] when traversing the Earth. The $\tau$ lepton produced in the charged-current interaction decays back into a tau neutrino before losing significant energy, which in effect makes the Earth less opaque to high energy tau neutrinos. Figure 11.4 shows the zenith distribution for simulated signal neutrinos of all flavors.

### 11.1.2 Atmospheric muons

Muons produced in the atmosphere in cosmic ray induced air showers is the largest background component, about 5 orders of magnitude larger than atmospheric neutrinos.

**Directionality**

Atmospheric muons are absorbed in the Earth. They are therefore restricted to downgoing directions in the detector, as shown in figure 11.5. A common analysis technique is to look at upgoing events only, which reduces the atmospheric muon background to mis-reconstructed events.

**Muon multiplicity**

Muon multiplicity in air showers typically increases with primary cosmic ray energy and mass. Higher multiplicity implies lower individual muon energy.
Lower energy muons mainly lose energy continuously, higher energy muons stochastically. Bundles of muons can survive to detector depth. A high multiplicity bundle typically emits light smoothly, while few high energy muons will yield stochastic cascades along the track.

Large muon bundles are very bright due to the muon multiplicity. Because of the lateral extension of a bundle the photon arrival time distribution at a certain distance from the track will look slightly different than from a similarly bright single muon. For very bright events it has been seen that the reduced log-likelihood from the MPE track reconstruction can separate between the two cases.

High energy cosmic ray primaries with low mass, typically protons, are likely to give rise to few, or single, high energy muons in the detector. Stochastic energy losses are cascade-like. If the muon track is not detected, for example if the muon passes outside the detector or sneaks between strings, the event could appear cascade-like. This is the type of events that constitutes the main background in searches for neutrino induced cascades.

**Coincident events**

It is not unlikely to have an atmospheric muon event occurring in coincidence with another event. Given one event, the probability that an atmospheric muon event gives rise to a second event with at least one hit DOM within a DAQ readout window of 20 µs is about 7%.

A coincident event is likely dominated by one of the constituent events. Most variables will then describe the dominating event well and a special treatment is not necessary.

For coincident events where more than one of the constituent events contribute significantly, special care must be taken. Both directional and energy reconstructions are easily confused by this type of events.
11.2 Cut variables

Reconstruction algorithms are described in chapter 7. The variables used in filter level 3 are summarized below:

- **Zenith from MPE track reconstruction**, $\theta_{\text{MPE}}$: Powerful observable since atmospheric muons, atmospheric neutrinos and predicted signal neutrinos have differing zenith distributions.
- **Total number of photoelectrons**, $N_{\text{pe}}$: Can serve as a crude energy estimator. Especially powerful in conjunction with an energy reconstruction, to reject mis-reconstructed events.
- **Energy from MuE track reconstruction**, $E_{\text{MuE}}$: Sophisticated energy estimator based on a track hypothesis and observed average energy loss.
- **Reduced log-likelihood from MPE and SPE-32 track reconstructions**, $\rho_{\text{MPE}}$ and $\rho_{\text{SPE32}}$: A low value indicates a well reconstructed track.
- **Sigma from paraboloid based on MPE and SPE-32 track reconstructions**, $\sigma_{\text{MPE}}$ and $\sigma_{\text{SPE32}}$: An indication of the error on the reconstructed track direction.
- **Direct length based on MPE track reconstruction**, $L_{\text{DirC}}$: The geometrical time is defined as the time when unscattered Cherenkov photons reach a DOM. Direct pulses are defined and categorized depending on the pulse time in relation to the geometrical time. Pulse times between $-15$ ns and $+75$ ns around the geometrical time fall in category $C$. The positions of DOMs with direct pulses can be projected onto the track. The maximum distance between projected DOM positions is called the direct length.
- **Smoothness based on MPE track reconstruction**, $S_{\text{MPE}}$: Smoothness is a measure of how uniformly the detected photons are distributed along the track. The value of smoothness lies in a range between -1 and 1. Positive values indicate that photons cluster at the beginning of the track and the opposite is true for negative values. A value close to 0 indicates uniformly distributed photons.
- **The Bayesian likelihood ratio**, $\log(\ell_{\text{SPE32}}) - \log(\ell_{\text{Bayes}})$: The Bayesian reconstruction uses the observed atmospheric muon zenith distribution as a prior. The Bayesian likelihood ratio thus compares the hypothesis of a downgoing track to that given by SPE-32. For the upgoing track stream this is a powerful observable to reject mis-reconstructed atmospheric muons. It has also been found to be useful for the downgoing track stream, likely because the zenith distribution for atmospheric muons and neutrinos differ. Low values of the likelihood ratio support the hypothesis of a downgoing track, high values support the track hypothesis from SPE-32.
- **LineFit velocity**, $v_{\text{LF}}$: See section 9.2.
- **Minimum zenith angle of a time split two-track reconstruction**, $\theta_{\text{min}}$: Two tracks are reconstructed using information from two non-overlapping subsets of pulses. The subsets are formed using pulse time information. $\theta_{\text{min}}$ is the zenith angle for the track with the smallest zenith angle.
For the upgoing track stream this is a powerful observable to reject mis-reconstructed coincident events.

- **The time split Bayesian likelihood ratio**, \( \log(\ell_{\text{SPE32}}) - (\log(\ell_{\text{BayesT1}}) + \log(\ell_{\text{BayesT2}})) \): The time split Bayesian likelihood ratio compares the hypothesis of a single track with the hypothesis of two downgoing tracks. The two-track reconstruction is performed using information from two non-overlapping subsets of pulses formed based on timing information. Note that the likelihood for the two-track hypothesis depends on how well the splitting algorithm works. For the upgoing track stream this is a powerful observable to reject mis-reconstructed coincident events.

- **The geometry split likelihood ratio**, \( \log(\ell_{\text{SPE32}}) - (\log(\ell_{G1}) + \log(\ell_{G2})) \): The geometry split Bayesian likelihood ratio compares the hypothesis of a single track with the hypothesis of two tracks. The two-track reconstruction is performed using information from two non-overlapping subsets of DOMs formed based on geometry information. Note that the likelihood for the two-track hypothesis depends on how well the splitting algorithm works. For the downgoing track stream this is a useful observable to reject coincident events.

- **Average pulse charge**, \( Q_{\text{avg}} \): The average pulse charge per event is a good indicator of dim events, which are either low energy or far away from the detector.

- **Fraction of DOMs with one hit only**, \( F_{1h} \): One hit corresponds to one pulse in this case. \( F_{1h} \) is a good indicator of dim events. Signal typically has lower values than background events.

- **Fill ratio**, \( R_{\text{fill}} \): The algorithm looks at the distribution of distances from a given cascade vertex hypothesis to the hits in the event. A sphere is defined based on a radius proportional to the RMS of the distance distribution. The fill ratio is calculated as the ratio between the number of hit DOMs and active DOMs within the sphere. Cascade-like events are typically highly spherical and would therefore get a large fill ratio, approaching 1. Track-like events on the other hand typically has a small fill ratio, approaching 0. Coincident events also cluster close to 0.

- **Reduced log-likelihood from CLLH cascade vertex reconstruction**, \( \rho_{\text{cllh}} \): Low values indicates a well reconstructed cascade.

- **Fraction of total charge registered by the DOM with most charge**, \( Q_{\text{max}}/Q_{\text{tot}} \): Events where one DOM detects the majority of photons are called “balloon events”. It has been shown that they are caused by stochastic energy loss in immediate proximity of a DOM. Balloon events can confuse energy reconstructions. \( Q_{\text{max}}/Q_{\text{tot}} \) is a good indicator of balloon events.

- **Energy from ACER cascade reconstruction**, \( E_{\text{acer}} \): Sophisticated analytical cascade energy reconstruction.

- **Maximum current**, \( I_{\text{max}} \): See section 10.2.1.
11.3 Structure

Signal neutrino events show two main topologies, track-like and cascade-like. Composite events displaying a combination of these signatures constitute another level of complexity and is the subject of dedicated analyses in IceCube. Furthermore, it is likely that composite signal event signatures show likeness to one of the two main topologies.

Background mainly consists of track-like events. Downgoing background is dominated by atmospheric muons, while upgoing background is dominated by mis-reconstructed atmospheric muons and, at higher levels, atmospheric neutrinos. A large fraction of the atmospheric muons mis-reconstructed as upgoing are coincident events.

Cascade-like background mainly arises from large stochastic energy losses from atmospheric muons passing outside or just at the edge of the detector, in a way such that the event is dominated by the stochastic energy loss.

Filter level 3 is divided into three data streams based on signal and background topology: a downgoing track stream, an upgoing track stream, and a cascade stream. The structure is shown in figure 11.6 and the streams are summarized in table 11.1. The streams are partly overlapping, an event can pass through one or two of the streams.

11.3.1 Plots and labels

Plots are often shown without legends because of limited space. Table 11.2 lists how different data components typically are displayed.
Table 11.1: Summary of level 3 data streams.

<table>
<thead>
<tr>
<th>Data stream</th>
<th>Selection criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downgoing track</td>
<td>(Muon OR EHE filter) AND $\theta_{MPE} &lt; 90^\circ$</td>
</tr>
<tr>
<td>Upgoing track</td>
<td>(Muon OR EHE filter) AND $\theta_{MPE} \geq 90^\circ$</td>
</tr>
<tr>
<td>Cascade</td>
<td>(Cascade OR EHE filter)</td>
</tr>
</tbody>
</table>

Table 11.2: Display style for different data components. Exp is short for experimental (real) data. CORSIKA is atmospheric muon simulation, poly-gonato and 2-component signify different cosmic ray composition models, and coinc indicates coincident event simulation. Atmospheric muon neutrino simulation is shown on plots where this component clearly stands out. Signal neutrino simulation is usually shown.

<table>
<thead>
<tr>
<th>Data component</th>
<th>Line style</th>
<th>Line color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp</td>
<td>Solid (filled area)</td>
<td>Black (gray)</td>
</tr>
<tr>
<td>Poly-gonato CORSIKA</td>
<td>Solid</td>
<td>Red</td>
</tr>
<tr>
<td>2-comp CORSIKA</td>
<td>Solid</td>
<td>Magenta</td>
</tr>
<tr>
<td>Coinc poly-gonato CORSIKA</td>
<td>Dashed</td>
<td>Red</td>
</tr>
<tr>
<td>Atm $\nu_\mu$</td>
<td>Dashed-dotted</td>
<td>Green</td>
</tr>
<tr>
<td>Signal $\nu$</td>
<td>Long dashed</td>
<td>Blue</td>
</tr>
</tbody>
</table>

11.3.2 Downgoing track stream

This stream has by far the largest background rate from atmospheric muons. In particular, background reaches very high energies, which means a hard cut on energy is required to select the signal region. Also among the most powerful observables is direction, where signal typically has close to horizontal directions. Track quality is another important property, although in this very high energy signal region less important than energy and direction.

This stream is optimized for UHE track-like neutrino events with an $E^{-2}$ energy spectrum. To ensure that simulated signal is track-like, the error on the reconstructed direction is required to be smaller than 5 degrees. For all figures in this section, signal is shown for muon neutrinos with energy greater than 1 PeV and reconstructed directional error less than 5 degrees. Signal efficiencies are also quoted for this type of signal. Note that the Waxman-Bahcall test signal flux is scaled by a factor $5 \times 10^4$ to make plots easier to read.

The downgoing track stream consists of a “coincidence cut” and the evaluation of a multivariate classifier, a boosted decision tree (BDT).

Coincidence cut

The purpose of the coincidence cut is to remove coincident events. This type of events can confuse reconstructions that assume a single event hypothesis.
For the downgoing track stream this cut can be viewed as a cleaning cut, where tails that are dominated by coincident events are removed. The coincidence cut is described in table 11.3 and variable distributions are shown in figure 11.7. Note that data components and display styles in the figures are explained in table 11.2.

**Evaluation of BDT**

To efficiently separate signal from background, a multivariate classifier was used. Based on previous experience the boosted decision tree classifier implemented in the toolkit TMVA [102] within the data analysis framework ROOT [103] was chosen.

The variables used to characterize signal and background are shown in figure 11.8. The variables describe the energy, direction and track quality of an event. Note that these distributions are shown with the coincidence cut applied. Three variables used in the coincidence cut are also included in the BDT: the geometry split likelihood ratio, the Bayesian likelihood ratio and LineFit velocity.

Atmospheric muon simulation was used as background when training the BDT. UHE track-like muon neutrino simulation with an $E^{-2}$ energy spectrum was used as signal. A further restriction was imposed on signal, a direct length greater than 300 m was required. This improved background rejection without loss of signal efficiency. The BDT score is shown in figure 11.9. See appendix A for detailed information about the BDT evaluation.
(a) The geometry split likelihood ratio ("logl" indicates negative log-likelihood).

(b) The Bayesian likelihood ratio ("logl" indicates negative log-likelihood).

(c) LineFit velocity.
Smoothness based on MPE track reconstruction.

Figure 11.7: Distributions for variables used in the downgoing track stream coincidence cut.

Table 11.3: The downgoing track stream coincidence cut, which is a composite cut comprising several individual cuts. Individual cuts are combined with a logical AND, from the top of the table going down. Efficiencies are given in relation to the beginning of level 3. Values in parenthesis show the efficiency for a cut by itself.

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>Signal eff</th>
<th>Exp eff</th>
<th>Coinc eff</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\log(\ell_{SPE32}) - (\log(\ell_{G1}) + \log(\ell_{G2}))) &lt; 53$</td>
<td>100%</td>
<td>99.9%</td>
<td>99.1%</td>
</tr>
<tr>
<td>$5 &lt; (\log(\ell_{SPE32}) - \log(\ell_{Bayes})) &lt; 65$</td>
<td>100%</td>
<td>99.7% (99.8%)</td>
<td>98.3% (99.2%)</td>
</tr>
<tr>
<td>$0.03 &lt; v_{LF} &lt; 0.37$</td>
<td>99.4% (99.4%)</td>
<td>99.6% (99.9%)</td>
<td>97.6% (99.3%)</td>
</tr>
<tr>
<td>$-0.6 &lt; S_{MPE} &lt; 0.6$</td>
<td>99.1% (99.7%)</td>
<td>99.5% (99.9%)</td>
<td>97.0% (99.4%)</td>
</tr>
</tbody>
</table>
(a) Zenith from MPE track reconstruction.

(b) Energy from MuE track reconstruction. A large fraction of high energy events are mis-reconstructed coincident events.

(c) Total number of photoelectrons.
(d) Reduced log-likelihood from MPE track reconstruction.

(e) Sigma from paraboloid based on MPE track reconstruction.

(f) Sigma from paraboloid based on SPE-32 track reconstruction.

Figure 11.8: Distributions for variables included in the downgoing track stream BDT.
Figure 11.9: BDT score for the downgoing track stream. High values indicate signal-like events.
11.3.3 Upgoing track stream

At lower levels the upgoing track stream background is dominated by mis-reconstructed atmospheric muons, the majority of which are coincident events. At higher levels the main background is atmospheric neutrinos. Background does not reach as high energies as for the downgoing track stream. Atmospheric neutrinos arrive from all directions while signal is most likely close to the horizon.

This stream is also optimized for UHE track-like muon neutrino events with an $E^{-2}$ energy spectrum. Again, to ensure that simulated signal is track-like, the error on the reconstructed direction is required to be smaller than 5 degrees. For all figures in this section, signal is shown for muon neutrinos with energy greater than 1 PeV and reconstructed directional error less than 5 degrees. Signal efficiencies are quoted for this type of signal. Note that the Waxman-Bahcall test signal flux is scaled by a factor $5 \times 10^4$ to make plots easier to read.

The upgoing track stream also consists of a coincidence cut and the evaluation of a BDT.

Table 11.4: The upgoing track stream coincidence cut, which is a composite cut comprising several individual cuts. Individual cuts are combined with a logical AND, from the top of the table going down. Efficiencies are given in relation to the beginning of level 3. Values in parenthesis show the efficiency for a cut by itself.

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>Signal eff</th>
<th>Exp eff</th>
<th>Coinc eff</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\log(\ell_{\text{SPE32}}) - (\log(\ell_{\text{BayesT1}}) + \log(\ell_{\text{BayesT2}}))) &gt; 0$</td>
<td>100%</td>
<td>62.8%</td>
<td>59.1%</td>
</tr>
<tr>
<td>$(\log(\ell_{\text{SPE32}}) - \log(\ell_{\text{Bayes}})) &gt; 0$</td>
<td>100%</td>
<td>62.5% (98.9%)</td>
<td>58.9% (99.0%)</td>
</tr>
<tr>
<td>$\nu_{\text{LF}} &lt; 0.35$</td>
<td>100%</td>
<td>61.9% (99.3%)</td>
<td>57.7% (98.8%)</td>
</tr>
</tbody>
</table>

**Coincidence cut**

The coincidence cut is described in table 11.4. The variable distributions are shown in figure 11.10. Note that data components and display styles in the figures are explained in table 11.2.

**Evaluation of BDT**

To efficiently separate signal from background, a BDT was evaluated. The variables used to characterize signal and background are shown in figure 11.11. They describe the energy, direction and track quality of an event. Note that the distributions are shown with the coincidence cut applied.

Atmospheric muon simulation was used as background when training the BDT. UHE track-like muon neutrino simulation with an $E^{-2}$ energy spectrum
(a) The time split Bayesian likelihood ratio is particularly powerful for rejecting coincident events (“logl” indicates negative log-likelihood).

(b) The Bayesian likelihood ratio (“logl” indicates negative log-likelihood).

(c) LineFit velocity.

*Figure 11.10:* Distributions for variables used in the upgoing track stream coincidence cut.
(a) Zenith from MPE track reconstruction.

(b) Energy from MuE track reconstruction. A large fraction of high energy events are mis-reconstructed coincident events.

(c) Total number of photoelectrons.
(d) Reduced log-likelihood from MPE track reconstruction.

(e) Reduced log-likelihood from SPE-32 track reconstruction.

(f) Sigma from paraboloid based on SPE-32 track reconstruction.
Direct length based on MPE track reconstruction.

Minimum zenith angle of a time split two-track reconstruction.

Figure 11.11: Distributions for variables included in the upgoing track stream BDT.

was used for signal. The BDT score is shown in figure 11.12. The transition from atmospheric muons to atmospheric neutrinos can be seen clearly in real data. There is a rate discrepancy between real and simulated data at low BDT scores. This was not investigated further. At low levels data are dominated by mis-reconstructed events, which reasonably may be more difficult to describe well. At higher levels, which effectively means higher BDT scores, the underlying physical properties of an event is more clearly reflected in the observables and agreement is therefore more important. See appendix A for detailed information about the BDT evaluation.
Figure 11.12: BDT score for the upgoing track stream. High values indicate signal-like events. The transition from atmospheric muons to atmospheric neutrinos can be seen at around 0.2.
11.3.4 Cascade stream

The major background for the cascade stream is atmospheric muon events that are dominated by stochastic energy loss. The track part of the events goes mostly undetected, which implies that the events are most likely uncontained, close to the the edge of the detector. Directional resolution for cascade-like events is in general poor, especially so for uncontained events. The variables most powerful at separating signal from background are based on energy and cascade quality.

The signal optimized for is electron neutrinos with energy greater than 1 PeV. This is the type of signal shown in the figures in this section and for which signal efficiency is quoted. The Waxman-Bachall test signal flux has been scaled by a factor $5 \times 10^4$ to make plots easier to read.

Disagreements between real and simulated data

Cascade analyses are not as mature as muon neutrino analyses in IceCube. A neutrino induced cascade baseline has not yet been established, which limits the possible studies of systematic uncertainties. Disagreements between real and simulated data for cascade-like background has been a long-standing issue.

The following general observations were made for the cascade stream:

- The rate is higher in real than simulated data.
- At higher levels of the analysis, a disagreement persists in the cascade stream but not in the track streams.
- The disagreement is largest for low energy and uncontained events, that is dim events.
- The disagreement is largest for events with small reconstructed zenith angles.

In the following paragraphs, hypotheses are formulated in an attempt to form a coherent, simplified picture of why and where simulation does not describe the real data well.

General rate disagreement

A higher rate in real data implies that events are lost in simulation. This indicates that events are brighter and/or more cascade-like in real data.

Hypothesis The disagreement is mainly caused by uncertainties on ice properties or photon propagation, and cosmic ray composition.

The main indications of this is that the disagreements are depth dependent, and that the 2-component CORSIKA simulation seems to describe real data better than poly-gonato CORSIKA. Both indications can be seen in figure 11.13, which shows the z-coordinate of the reconstructed cascade vertex position.
Persistent disagreement for cascade-like events

**Hypothesis I** Cascade-like events are more sensitive to ice properties than track-like events.

Cascade-like events have a more localized energy deposit than track-like events and will therefore probe local ice only. Because track-like events typically cross several ice layers, observables will reflect averaged ice properties.

Furthermore, a three dimensional cascade topology is presumably more sensitive to ice features than a one dimensional track topology. A track retains its properties even if the ice is not described perfectly. Ice features impact observables describing cascade quality. In particular the variable eval ratio, which describes the sphericity of an event, seems sensitive to ice features. Eval ratio is used in the cascade online filter and might partly cause the disagreement.

**Hypothesis II** Cascade-like events are more sensitive to cosmic ray composition than track-like events.

Lighter cosmic ray primaries produce fewer and therefore higher energy muons, which implies more stochastic behavior and more cascade-like events. This was observed in the comparison between 2-component and poly-gonato CORSIKA. The proton component is higher in 2-component CORSIKA, which results in a higher rate for the cascade stream, as well as better agreement with real data. For the track streams, the two composition models do not differ by much.

*Figure 11.13:* The z-coordinate of the reconstructed vertex position from the cascade reconstruction Credo. Data components and display styles are explained in table 11.2.
Disagreement largest for dim events

Dim events would be the first to be lost if the ice is less clean in simulation. Furthermore, it seems reasonable that the topology of dim events would be more sensitive to ice features than the topology of bright events. For dim events, there might be many DOMs for which a change in ice properties would change the typical number of detected photons from 1 to 0, while for bright events the same change would be from many photons to fewer.

Disagreement largest at small zenith angles

This observation was made looking at the zenith angle from the MPE track reconstruction. There may be at least two effects in play. First, it seems likely that the zenith angle is an indication of the direction of the major axis of the energy deposit for an event. Roughly speaking, vertical events deposit energy across ice layers, horizontal events in the same ice layer. This hypothesis is supported by figure 11.14, which shows the z-coordinate of the center of gravity for detected photoelectrons, for events reconstructed as horizontal and events reconstructed as vertical. For horizontal events the ice properties are reflected more sharply. This implies that the majority of horizontal events will be in clean ice, while the majority of vertical events will see a changing and on average less clean ice. Less clean ice implies dimmer events, and as previously mentioned, dimmer cascades should be more sensitive to ice features. Note that the same is not necessarily true for tracks because of the extended one dimensional track topology, which as mentioned should retain its properties even if the ice is not described perfectly.

Second, from simulated data one can see that the energy of the largest cascade per event typically is larger for horizontal events. The reason might be that a brighter cascade would naturally yield a more horizontally reconstructed
Table 11.5: Summary of Quality cut I, which is a composite cut comprising several individual cuts. Individual cuts are combined with a logical AND, from the top of the table going down. Efficiencies are given in relation to the beginning of level 3. Values in parenthesis show the efficiency for a cut by itself.

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>Sig eff</th>
<th>Exp eff</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\theta_{\text{MPE}} &lt; 60 \text{ AND } Q_{\text{avg}} &gt; 2.0)$ OR $(\theta_{\text{MPE}} \geq 60 \text{ AND } Q_{\text{avg}} &gt; 1.1)$</td>
<td>56.5%</td>
<td>8.4%</td>
</tr>
<tr>
<td>$F_{1h} &lt; 0.45$</td>
<td>55.7%</td>
<td>(75.2%)</td>
</tr>
</tbody>
</table>

As mentioned before, the topology of brighter cascades should be less sensitive to ice features.

**Quality cut I**

The strategy for dealing with the observed disagreement is based on achieving a robust analysis. The idea is to cut away the region of phase space that is badly described by simulation while remaining signal efficient. Since the disagreement is largest for dim events this seems possible. The cut, labeled “Quality cut I”, should be applied as early on in the analysis as possible.

The average pulse charge per event, $Q_{\text{avg}}$, and the fraction of DOMs with one hit only, $F_{1h}$, are good indicators of dim events. Quality cut I is summarized in table 11.5 and the variables are shown in figure 11.15.

It should be emphasized that the disagreement has been studied in many variables and at many different levels of the analysis. The cut was not based on the expression of the variables at the level shown in figure 11.15. During the development of the analysis, several high level selections of cascade-like events were made. At such high levels, where events are more cascade-like, the region of disagreement is fairly consistently more localized to the relevant parts for the cut. An example is given in figure 11.16, where distributions are shown at “Quality cut A”, defined in table 11.6.

The cut on average pulse charge removes lower energy events. To further illustrate what Quality cut I does, the true interaction vertex position for signal events is shown in figure 11.17. One can see that uncontained events are also removed.
Figure 11.15: Distributions for variables used in Quality cut I.

(a) Average pulse charge for events reconstructed as downgoing.

(b) Average pulse charge for events reconstructed as horizontal and upgoing.

(c) Fraction of DOMs with one hit only.
Figure 11.16: Distributions for variables used in Quality cut I, shown after Quality cut A. Statistical errors are shown for real data and background simulation.
(a) $y_{\text{true}}$ versus $x_{\text{true}}$ for events passing Quality cut I.

(b) $y_{\text{true}}$ versus $x_{\text{true}}$ for events removed by Quality cut I.

Figure 11.17: Interaction vertex position for signal electron neutrinos. Quality cut I removes uncontained and low energy events.
Table 11.6: **Summary of Quality cut II**, which is a composite cut comprising several individual cuts. Individual cuts are combined with a logical AND, from the top of the table going down. Efficiencies are given in relation to the beginning of level 3. Values in parenthesis show the efficiency for a cut by itself. The last column indicates which cuts are included in “Quality cut A”.

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>Sig eff</th>
<th>Exp eff</th>
<th>Quality cut A</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{fill}} &gt; 0.2$</td>
<td>54.7% (96.7%)</td>
<td>$6.3 \times 10^{-3} (33.3%)$</td>
<td>x</td>
</tr>
<tr>
<td>$\nu_{\text{LF}} &lt; 0.15$</td>
<td>54.2% (98.4%)</td>
<td>$4.7 \times 10^{-3} (44.9%)$</td>
<td>x</td>
</tr>
<tr>
<td>$\rho_{\text{cllh}} &lt; 8.5$</td>
<td>53.8% (89.9%)</td>
<td>$3.3 \times 10^{-3} (25.2%)$</td>
<td>x</td>
</tr>
<tr>
<td>$Q_{\text{max}}/Q_{\text{tot}} &lt; 0.6$</td>
<td>53.5% (99.7%)</td>
<td>$3.0 \times 10^{-3} (97.5%)$</td>
<td></td>
</tr>
<tr>
<td>$\log_{10}(E_{\text{acer}}) &gt; 1.0$</td>
<td>53.0% (71.0%)</td>
<td>$1.3 \times 10^{-3} (22.9%)$</td>
<td>x</td>
</tr>
<tr>
<td>$\log_{10}(I_{\text{max}}) &gt; 0.0$</td>
<td>52.5% (58.6%)</td>
<td>$5.9 \times 10^{-4} (2.5%)$</td>
<td></td>
</tr>
<tr>
<td>$z_{\text{credo}} &lt; 450$</td>
<td>48.3% (92.6%)</td>
<td>$3.6 \times 10^{-4} (94.4%)$</td>
<td>x</td>
</tr>
</tbody>
</table>

**Quality cut II**

Because of the observed disagreement between real and simulated data, it was decided to use straight cuts to select a higher quality sample of events before evaluating a multivariate classifier. Straight cuts are transparent and easy to handle. “Quality cut II” selects events based on cascade quality and energy, and removes specific types of background: balloon events and atmospheric muon events at the top of the detector. Quality cut II is summarized in table 11.6. Distributions for the variables included in Quality cut II are shown in figure 11.18. The distribution of the reduced log-likelihood from the cascade reconstruction CLLH indicates that 2-component CORSIKA simulation describes cascade-like data better than poly-gonato CORSIKA.

**Evaluation of BDT**

Because of the quality cuts, the evaluation of a BDT takes place at a higher level, which means a higher signal to background ratio, than for the track streams. Atmospheric muon and atmospheric muon neutrino simulation was used as background in the training of the BDT. Electron neutrinos with energy greater than 1 PeV and an $E^{-2}$ energy spectrum were used as signal. The variables used in the quality cuts are well described by simulation and still retain much separation power at this level. The variables used to characterize signal and background in the BDT are fill ratio, linefit velocity, reduced log-likelihood from CLLH, energy from ACER, maximum current and the fraction of DOMs with one hit only. The BDT score is shown in figure 11.19. See appendix A for detailed information about the BDT evaluation.
(a) Fill ratio.

(b) LineFit velocity.

(c) Reduced log-likelihood from the cascade reconstruction CLLH.
(d) Fraction of charge detected by DOM with most charge.

(e) Energy from cascade reconstruction ACER.

(f) Maximum current.
Containment

There is sensitivity to UHE cascades located well outside the detector. Only in the context of discovery might a containment cut be required, depending on the degree of confidence in simulation. Uncontained events are more difficult to conclusively characterize as neutrino induced or not. In the case of a less than significant excess, an upper limit is set and characterizing surviving events is not strictly required. This seems like a possible scenario based on results from previous IceCube high energy diffuse cascade analyses [98].

A containment cut would significantly reduce the UHE signal efficiency. Selecting the region immediately above the last burn sample data event when cutting on the cascade stream BDT score, 47% of signal is inside the detector and 90% is inside $1.5 \times$ the detector size.

After thorough investigation of the cascade stream and after devising quality cuts, the degree of confidence in the simulation was deemed adequate.

In light of this a containment cut was not included.

11.4 Passing rates

Passing rates at different cut levels are shown in table 11.7. The cut levels are described in table 11.8, and were chosen for the purpose of evaluating passing rates at different points in the analysis. They were not chosen arbitrarily but could have been. Level 3-II was chosen to remove almost pure background and keep most signal. Level 3-III defines the region where the final cut was developed.
Figure 11.19: BDT score for the cascade stream. High values indicate signal-like events. Note that Quality cut II has been applied. Statistical errors are shown both for real data and background simulation. Two cosmic ray composition models are shown for CORSIKA simulation, poly-gonato (pg) and 2-component (2c) (see chapter 6).
Table 11.7: Passing rates at different cut levels.

<table>
<thead>
<tr>
<th>Cut level</th>
<th>Exp</th>
<th>Tot bg (poly-gonato)</th>
<th>Tot bg (2-comp)</th>
<th>Coinc</th>
<th>Atm $\nu_\mu$</th>
<th>Atm $\nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 3</td>
<td>3.37 Hz</td>
<td>2.80 Hz</td>
<td>3.16 Hz</td>
<td>0.67 Hz</td>
<td>119.75 $\mu$Hz</td>
<td>6.41 $\mu$Hz</td>
</tr>
<tr>
<td>Level 3-I</td>
<td>2.68 Hz</td>
<td>2.32 Hz</td>
<td>2.58 Hz</td>
<td>0.47 Hz</td>
<td>112.97 $\mu$Hz</td>
<td>5.73 $\mu$Hz</td>
</tr>
<tr>
<td>Level 3-II</td>
<td>895 mHz</td>
<td>813 mHz</td>
<td>890 mHz</td>
<td>117 mHz</td>
<td>99.35 $\mu$Hz</td>
<td>4.21 $\mu$Hz</td>
</tr>
<tr>
<td>Level 3-III</td>
<td>1.03 mHz</td>
<td>0.74 mHz</td>
<td>1.17 mHz</td>
<td>0.19 mHz</td>
<td>54.05 $\mu$Hz</td>
<td>0.49 $\mu$Hz</td>
</tr>
</tbody>
</table>

Table 11.8: Description of cut levels. Each cut level is defined as an OR between cuts for each stream. Each cut level builds on the previous level.

<table>
<thead>
<tr>
<th>Cut level</th>
<th>Track down</th>
<th>Track up</th>
<th>Cascade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 3</td>
<td></td>
<td>Start of Level 3</td>
<td></td>
</tr>
<tr>
<td>Level 3-I</td>
<td>Coinc cut</td>
<td>Coinc cut</td>
<td>Quality cut I</td>
</tr>
<tr>
<td>Level 3-II</td>
<td>$BDT_{\text{trackdown}} &gt; -0.25$</td>
<td>$BDT_{\text{trackup}} &gt; -0.25$</td>
<td>Quality cut II AND $BDT_{\text{cascade}} &gt; -0.15$</td>
</tr>
<tr>
<td>Level 3-III</td>
<td>$BDT_{\text{trackdown}} &gt; 0.152$</td>
<td>$BDT_{\text{trackup}} &gt; -0.008$</td>
<td>$BDT_{\text{cascade}} &gt; -0.124$</td>
</tr>
</tbody>
</table>
12. Final cut

The final cut is defined as an OR between cuts on each of the 3 data stream BDT scores.

12.1 Unbiased optimization

In counting experiments the final event selection commonly optimizes the limit setting or discovery capabilities of the experiment. IceCube analyses performed on earlier data sets have not seen a convincing UHE neutrino signal which motivated the decision to optimize the final cut for high sensitivity.

The model rejection potential technique [104] is used. The method relies only on signal and background expectations derived from simulation, so no bias is introduced by looking at experimental data. The average upper limit that would be observed after hypothetical repetition of an experiment with expected background $n_b$ and no true signal ($n_s = 0$), is the sum of individual experiment upper limits weighted by their Poisson probability of occurrence

$$\bar{\mu}_{90}(n_b) = \sum_{n_{obs}=0}^{\infty} \mu_{90}(n_{obs}, n_b) \frac{(n_b)^{n_{obs}}}{n_{obs}!} e^{-n_b}$$  \hspace{1cm} (12.1)$$

Over the hypothetical experimental ensemble, the strongest expected constraint on a test signal flux $\Phi(E, \theta)$ corresponds to the set of cuts that minimizes the model rejection factor

$$\frac{\bar{\mu}_{90}}{n_s}$$  \hspace{1cm} (12.2)$$

and hence minimizes the average flux upper limit

$$\Phi(E, \theta)_{90} = \Phi(E, \theta) \frac{\bar{\mu}_{90}}{n_s}$$  \hspace{1cm} (12.3)$$

Here, the assumed test signal flux $\Phi(E, \theta)$ corresponds to the Waxman-Bahcall upper bound on astrophysical neutrinos. The expected background is the sum of the contributions from atmospheric muons and atmospheric neutrinos. At high levels of the analysis, experimental data seem to lie between the background prediction from poly-gonato and 2-component CORSIKA. For this reason the atmospheric muon background was estimated from the mean of these predictions. Figure 12.1 shows the remaining number of events as a
Table 12.1: Summary of the cuts giving the lowest model rejection factors (MRFs).

<table>
<thead>
<tr>
<th>MRF</th>
<th>$BDT_{\text{trackdown}}$</th>
<th>$BDT_{\text{trackup}}$</th>
<th>$BDT_{\text{cascade}}$</th>
<th>$N_{bg}$</th>
<th>$N_{sig}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.19982</td>
<td>0.48</td>
<td>0.48</td>
<td>0.17</td>
<td>1.22</td>
<td>17.21</td>
</tr>
<tr>
<td>0.20037</td>
<td>0.49</td>
<td>0.48</td>
<td>0.17</td>
<td>1.19</td>
<td>17.05</td>
</tr>
<tr>
<td>0.20138</td>
<td>0.47</td>
<td>0.48</td>
<td>0.17</td>
<td>1.32</td>
<td>17.41</td>
</tr>
<tr>
<td>0.20161</td>
<td>0.5</td>
<td>0.48</td>
<td>0.17</td>
<td>1.18</td>
<td>16.93</td>
</tr>
<tr>
<td>0.20208</td>
<td>0.48</td>
<td>0.49</td>
<td>0.17</td>
<td>1.19</td>
<td>16.91</td>
</tr>
<tr>
<td>0.20256</td>
<td>0.48</td>
<td>0.47</td>
<td>0.17</td>
<td>1.48</td>
<td>17.82</td>
</tr>
<tr>
<td>0.20257</td>
<td>0.49</td>
<td>0.49</td>
<td>0.17</td>
<td>1.16</td>
<td>16.75</td>
</tr>
<tr>
<td>0.20311</td>
<td>0.49</td>
<td>0.47</td>
<td>0.17</td>
<td>1.45</td>
<td>17.66</td>
</tr>
<tr>
<td>0.20373</td>
<td>0.47</td>
<td>0.49</td>
<td>0.17</td>
<td>1.29</td>
<td>17.11</td>
</tr>
<tr>
<td>0.20376</td>
<td>0.47</td>
<td>0.47</td>
<td>0.17</td>
<td>1.58</td>
<td>18.02</td>
</tr>
</tbody>
</table>

function of a cut on the BDT score for each data stream, for simulated signal and background as well as experimental data.

The final cut was optimized to minimize the model rejection factor using a grid search, where cuts have been evaluated within a specified range of values for each BDT score. In the optimization procedure, the average 90% confidence level Feldman-Cousins upper limit was calculated without taking uncertainties into account. The final cut is indicated in figure 12.1 and shown at the top of table 12.1.

12.2 Passing rates

The predicted number of surviving events for a live time of 345.7 days is summarized in table 12.2. A total of 1.2 background events is predicted, and a signal flux on the level of the Waxman-Bahcall upper bound predicts 17.2 events. The most signal efficient stream is the cascade stream. This might seem counterintuitive since cascade-like energy deposit is localized whereas tracks are extended and can therefore be detected even if the interaction vertex is far away. There are several factors that contribute to cascade-like signal efficiency:

- Background is mostly track-like, which enables background rejection with small signal loss for the cascade stream.
- The analysis is optimized for very bright events. UHE tracks are typically significantly longer than the effective size of the detector, which implies that only part of the event will be detected. Cascade-like events are localized which implies that they could appear brighter than track-like events with similar energy.
(a) Downgoing track stream.

(b) Upgoing track stream.

(c) Cascade stream.

Figure 12.1: Number of events remaining after a cut on the BDT score. Statistical errors are shown. Note that the “bumps” occur when low energy events with large weight drop out. The smooth region around the final cut implies good statistics at final level.
Table 12.2: Predicted number of events passing the final cut. Signal is normalized to the Waxman-Bahcall upper bound.

<table>
<thead>
<tr>
<th>Data stream</th>
<th>Atm $\mu$</th>
<th>Atm $\nu_\mu$</th>
<th>Atm $\nu_e$</th>
<th>$E^{-2} \nu_\mu$</th>
<th>$E^{-2} \nu_e$</th>
<th>$E^{-2} \nu_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>0.17</td>
<td>0.62</td>
<td>0.43</td>
<td>5.59</td>
<td>6.68</td>
<td>4.94</td>
</tr>
<tr>
<td>Track down</td>
<td>0.01</td>
<td>0.05</td>
<td>0.01</td>
<td>1.03</td>
<td>0.57</td>
<td>0.54</td>
</tr>
<tr>
<td>Track up</td>
<td>0</td>
<td>0.27</td>
<td>0.00</td>
<td>2.60</td>
<td>0.02</td>
<td>0.42</td>
</tr>
<tr>
<td>Cascade</td>
<td>0.17</td>
<td>0.30</td>
<td>0.43</td>
<td>2.14</td>
<td>6.63</td>
<td>4.20</td>
</tr>
</tbody>
</table>

- All neutral-current neutrino interactions will be cascade-like.
- Up to 13% of signal events possibly arise thanks to the Glashow resonance.
- The cascade stream allows more uncontained and non-throughgoing events than the track streams, increasing the effective volume.

Furthermore, the cascade stream has received a more sophisticated treatment than the track streams, because of the initial disagreement between experimental and simulated data.

Note that the cascade stream also lets in most background.

12.3 Sensitivity and effective area

The effective area is shown in figure 12.2. The energy distribution for surviving signal events is shown in figure 12.3. The central 90% energy region is $5.45 < \log_{10}(E_{\nu}/GeV) < 8.33$, or 282 TeV to 214 PeV.

Systematic uncertainties are described in chapter 14. A relative gaussian error of 16% is estimated for the signal prediction and 42% for background. Uncertainties are taken into account by using the profile likelihood method implemented in the class TRolke [105, 106] within the data analysis framework ROOT. Including uncertainties, the resulting sensitivity to an $E^{-2}$ all-flavor neutrino flux becomes $1.15 \times 10^{-8} E^{-2}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. This sensitivity, shown in figure 12.4, probes several interesting astrophysical neutrino flux models.
Figure 12.2: Neutrino effective area. The Glashow resonance peak is clearly visible for electron neutrinos. Note that electron neutrino simulation is lacking between $10^{10}$ and $10^{11}$ GeV.

Figure 12.3: Energy distribution for signal events passing the final cut.
Figure 12.4: Sensitivity and astrophysical neutrino flux models. For a description of the models see section 2.3.
13. Non-signal events

13.1 Tagging of flasher-type events

In three high energy analyses performed with AMANDA-II using data from 2000–2003, at least twelve very similar events were found. The events all exhibit spherical light emission that seems to originate from the region around a particular optical module (OM). For this reason it seems likely that these events spring from some sort of detector artefact.

These events are in many ways similar to high energy cascade-like signal events which makes it important to characterize and if possible exclude them from the signal search. Here, a selection is devised with the purpose of tagging events for further investigation. Any event tagged is not included in the search for signal.

13.1.1 Light originates from the same region

The light seems to originate from the region around OM 531. OM 531, number 19 on AMANDA string 16, has position \((x, y, z) = (296.5 \text{ m}, 30.5 \text{ m}, 187.1 \text{ m})\). Table 13.1 shows the reconstructed vertex position for as many events of this type that could be found, along with the distance from OM 531. The mean reconstructed vertex position is \((x, y, z) = (296.5 \text{ m}, 29.9 \text{ m}, 184.4 \text{ m})\) with standard deviations \((\Delta x, \Delta y, \Delta z) = (2.4 \text{ m}, 4.2 \text{ m}, 4.1 \text{ m})\). The largest distance from OM 531 is 13.1 m.

One further event of this type was found in a high energy analysis performed with IceCube in the 22-string configuration, using data from 2007. Owing to differing geometry and DOM sensitivity this type of event will appear slightly different in IceCube than in AMANDA. The reconstructed \(z\)-position for the icecube event is 12 m above the mean, at 196.6 m. The DOM that detected most light is the DOM closest to and above OM 531, at \(z\)-position 201 m.

13.1.2 Stationary source

If the light originates from OM 531 and the light emission is spherical this should be reflected in a low value of the LineFit velocity. The IceCube event yields \(v_{\text{LF}} = 0.02\), in agreement with this expectation.
Table 13.1: Reconstructed vertex position for flasher type events, along with distance d from OM 531. Note that only distances were available for data sample Wiedemann. The events in data sample Ackermann and Wiedemann may be overlapping.

<table>
<thead>
<tr>
<th>Data sample</th>
<th>x/m</th>
<th>y/m</th>
<th>z/m</th>
<th>d/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gerhardt (AMANDA-II 2001)</td>
<td>295.4</td>
<td>32.3</td>
<td>184.3</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>295.5</td>
<td>30.1</td>
<td>183.8</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>295.5</td>
<td>31.4</td>
<td>183.5</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>295.1</td>
<td>27.9</td>
<td>182.1</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td>293.7</td>
<td>28.8</td>
<td>183.5</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>297.2</td>
<td>31.0</td>
<td>182.4</td>
<td>4.8</td>
</tr>
<tr>
<td>Ackermann (AMANDA-II 2003)</td>
<td>301.1</td>
<td>32.8</td>
<td>183.7</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>294.5</td>
<td>18.5</td>
<td>182.2</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td>300.7</td>
<td>32.4</td>
<td>182.3</td>
<td>6.7</td>
</tr>
<tr>
<td>Wiedemann (AMANDA-II 2003)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>Seo (IceCube-22 2007)</td>
<td>296.2</td>
<td>34.1</td>
<td>196.6</td>
<td>10.2</td>
</tr>
</tbody>
</table>
13.1.3 Bright events

All of the events for which there is information about brightness are bright events. The AMANDA events have more than 2000 hits, where one hit can correspond to many photoelectrons. The IceCube event has an estimated number of photoelectrons of around $5 \cdot 10^4$.

The events were all found in high energy analyses, which might be the reason they are all very bright. That is, there might be dimmer events of this type that were removed from these analyses at a lower level. However, the similarity among the events seems to indicate a general regularity to their expression. Furthermore, this type of events has not been found in lower energy analyses. Stricter quality cuts are generally used in lower energy analyses though, and since these events appear artificial they may have been removed by quality cuts.

13.1.4 Timing

For the AMANDA events the hit time distribution was investigated. A possible conclusion was that light was produced over a longer time scale than for events of particle origin. The event duration for each of the AMANDA events is more than $10 \mu s$. The Icecube event has a duration of more than $27 \mu s$. A typical event of particle origin has a duration of less than $6 \mu s$, bounded by the geometry of the detector and absorption of photons in the ice.

13.1.5 Event hypotheses

One hypothesis for the production of light in these events is a discharge in the PMT or from the PMT base board in OM 531. However, the brightness of these events might not be compatible with a discharge. Furthermore, one might expect a damaged PMT to stop functioning, which has not been observed.

OM 531 is equipped with a UV flasher board and given the brightness of the events another hypothesis is that the flasher was triggered. The designer of the flasher board deems this hypothesis unlikely though. This investigation remains unconclusive.

13.1.6 Event selection

Since AMANDA was still powered and active for the data sample used in this analysis, an event selection was devised to tag this type of events.

A study of the performance of cascade reconstruction methods shows that there is often a systematic shift in reconstructed vertex position of flasher events. For this reason events were selected in relation to the reconstructed vertex for the 2007 IceCube event rather than OM 531. The resulting selection is showed in table 13.2.
Table 13.2: Event selection for tagging of flasher type events. The cuts are combined with a logical AND.

<table>
<thead>
<tr>
<th>Selection criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from IceCube event vertex &lt; 30 m</td>
</tr>
<tr>
<td>Total number of photoelectrons &gt; $10^3$</td>
</tr>
<tr>
<td>Linefit velocity &lt; 0.1</td>
</tr>
<tr>
<td>Event duration &gt; 8 $\mu$s</td>
</tr>
</tbody>
</table>

Any event tagged is not used in the search for signal. The fraction of signal removed by this selection is $1.5 \times 10^{-5}$.

13.2 IceTop coincidences

A high energy downgoing atmospheric muon event with fairly vertical direction is very likely to be registered by the IceTop detector. Such IceTop coincidences thus indicate cosmic-ray induced background events and could serve as a powerful veto. Unfortunately IceTop coincidences are not implemented in the simulation used in this analysis and a veto can therefore not be applied. It was decided a priori that any surviving events from experimental data would be checked for IceTop coincidences. If the timing is compatible with a downgoing air shower the event would not be considered signal. This would not affect the upper limit in the case a significant excess is not found.
14. Systematic uncertainties

Two main types of analyses performed within IceCube are point source and diffuse analyses. Point source analyses look for a resolved flux, signal is localized and background can be estimated from experimental data. Diffuse analyses look for an unresolved flux, signal is not well localized and background must be estimated based on simulated data. Systematic errors arise from imperfect description of the detector, the environment and the physical processes behind event generation, propagation and energy loss. Many systematic uncertainties can be avoided in point source analyses, while a comprehensive investigation of uncertainties is required for diffuse analyses.

A common technique for estimating the impact of systematic uncertainties is to vary relevant parameters in simulation within a reasonable range and propagate the effects through the analysis. Here, this technique was used extensively. This approach is computationally intensive and was possible largely thanks to the national computational resource SweGrid. Much work was spent incorporating SweGrid in the standard IceCube simulation production framework.

For this approach to be feasible, benchmark data sets used to investigate systematics were generated with less statistics than for data sets serving as the baseline for most analyses. Where statistics is severely limited at final level, the impact on the analysis was estimated at a slightly lower level. Furthermore, the effect on all-flavor neutrino data was estimated using $\nu_\mu$ neutrino simulation only. This was considered reasonable since $\nu_\mu$ neutrino simulation probes all data streams of the analysis and the final passing rate is similar between neutrino flavors.

Note that the neutrino cross sections used in the benchmark data sets are based on CTEQ5 PDFs [59,61], except in the absolute energy scale and neutrino cross section uncertainty investigations. Also note that in the following sections the signal neutrino component is often indicated by the energy spectrum, $E^{-2}$, and is normalized to the Waxman-Bachall upper bound. Number of events are listed assuming a livetime corresponding to the blinded experimental data set, 345.7 days, unless otherwise noted.

The systematic uncertainties are summarized in the last section.
Table 14.1: Number of events passing the final cut for different DOM efficiencies and neutrino components.

<table>
<thead>
<tr>
<th>DOM efficiency</th>
<th>$E^{-2} \nu_{\mu}$</th>
<th>Conv atm $\nu_{\mu}$</th>
<th>Prompt atm $\nu_{\mu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>90%</td>
<td>5.55</td>
<td>0.41</td>
<td>0.23</td>
</tr>
<tr>
<td>100%</td>
<td>6.03</td>
<td>0.69</td>
<td>0.27</td>
</tr>
<tr>
<td>110%</td>
<td>6.45</td>
<td>1.25</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Figure 14.1: Number of photoelectrons for neutrino components and for atmospheric muons at final level.

14.1 DOM efficiency

The photon detection efficiency of a DOM depends on the quantum efficiency of the PMT, transmittance of the optical gel and glass housing, and shadowing from the mu-metal shield and various cables outside the DOM. Furthermore, because of the way simulation is set up, effects from properties of the local hole ice surrounding the DOM are included in the definition of DOM efficiency.

The uncertainty on the PMT detection efficiency is 7.7% [64]. Including other components, the uncertainty on the DOM efficiency is estimated to be 10%.

$\nu_{\mu}$ neutrino simulation was generated with DOM efficiency set to 90% and 110%. The surviving number of events for different neutrino flux components is shown in table 14.1.

There was no atmospheric muon simulation with varied DOM efficiency available. The DOM efficiency is directly related to the number of detected photoelectrons, $N_{\text{pe}}$. The $N_{\text{pe}}$ distribution for different neutrino components and for atmospheric muons is shown in figure 14.1. Atmospheric muons agree best with $E^{-2}$ neutrino simulation and the impact on atmospheric muons is therefore estimated to be the same as for $E^{-2}$ neutrinos.
### 14.2 Ice model

The AHA ice model (see section 4.6) is used as baseline in this analysis. A different ice model, SPICE1 [107], derived in an independent fashion, is used as an estimate of a reasonable variation of ice properties in one direction. \( \nu_\mu \) neutrino simulation and 2-component CORSIKA was generated using the SPICE1 ice model. The surviving number of events for different data components and ice models is shown in table 14.2.

2-component CORSIKA predicts almost the same number of events for AHA and SPICE1 after the final cut. The statistics for the SPICE1 data set is 10% of that of the AHA data set and the statistical error on the prediction at final level is large. For this reason, the effect on atmospheric muon background is estimated at a slightly lower level. A looser, signal efficient, cut was evaluated with the intention of increasing statistics by at least 10 times. The cut is described in table 14.3. The number of events surviving this cut is shown in table 14.4. If the cut is tightened or loosened slightly the resulting systematic uncertainty becomes similar or smaller.

### 14.3 Absolute energy scale

For variables based on the number of detected photoelectrons, background and signal extend to higher values than the burn sample experimental data. This means that experimental data cannot be used to constrain the uncertainty

<table>
<thead>
<tr>
<th>Ice model</th>
<th>( E^{-2} \nu_\mu )</th>
<th>Conv atm ( \nu_\mu )</th>
<th>Prompt atm ( \nu_\mu )</th>
<th>Atm ( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHA</td>
<td>6.03</td>
<td>0.693</td>
<td>0.275</td>
<td>0.0316 ± 0.0127</td>
</tr>
<tr>
<td>SPICE1</td>
<td>5.30</td>
<td>0.484</td>
<td>0.246</td>
<td>0.0313 ± 0.0227</td>
</tr>
</tbody>
</table>

Table 14.3: A signal efficient cut giving at least 10 times the final level statistics for atmospheric muon simulation.

\[
(BDT_{\text{trackdown}} > 0.386) \text{ OR } (BDT_{\text{trackup}} > 0.414) \text{ OR } (BDT_{\text{cascade}} > 0.108)
\]

<table>
<thead>
<tr>
<th>Ice model</th>
<th>( \text{Atm } \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHA</td>
<td>3.94 ± 1.00</td>
</tr>
<tr>
<td>SPICE1</td>
<td>2.52 ± 1.10</td>
</tr>
</tbody>
</table>

Table 14.4: Number of events passing a looser-than-final cut for different ice models.
on the number of detected photoelectrons, or the absolute energy scale, in this region. This uncertainty is investigated by manually shifting the detected number of photoelectrons by an appropriate amount, then re-evaluating the BDT scores and final cut passing rates.

The estimation of a reasonable shift is based on an analysis of standard candle (SC) data. A standard candle is a laser module with absolutely calibrated light output. There are two standard candles installed inside the in-ice detector volume. A disagreement in number of detected photoelectrons between experimental and simulated data was seen for the standard candles. The disagreement is mainly attributed to uncertainties on the ice model, DOM efficiency, DOM saturation behavior and possibly a miscalibration of ATWD channel 2 gain. In the SC analysis, DOMs are divided into saturated and unsaturated, and the two categories are studied separately.

In this analysis, systematic uncertainties on the ice model and DOM efficiency are taken into account by other means. The error on detected number of photoelectrons is therefore estimated based on the SC analysis results using saturated DOMs. The burn sample data extends to about $\log_{10}(N_{pe}) = 5.2$. The SC light output setting corresponding to the number of detected photoelectrons closest above this value shows a shift of -11.6% for simulation in relation to experimental data.

The impact of shifting the number of detected photoelectrons by -11.6% is shown in table 14.5, for all-flavor neutrino components and 2-component CORSIKA.

### 14.4 Neutrino-nucleon interaction cross sections

The baseline neutrino simulation within IceCube uses neutrino-nucleon interaction cross sections based on CTEQ5 PDFs \[59, 61\]. At a late stage of the analysis it was pointed out that these PDFs do not fit modern data, and that there were state-of-the-art calculations available based on HERA data performed by A. Cooper-Sarkar and S. Sarkar (CSS) \[4\]. The CSS calculations account for PDF uncertainties deriving from both model uncertainties and from the experimental uncertainties of the input data sets. The new CSS cross sections are lower than the ones based on CTEQ5 PDFs, as shown in figure 14.2.
Figure 14.2: The ratio between CSS and CTEQ5-based neutrino cross sections. The band reflects the errors provided with the CSS cross sections. Figure by A. Franckowiak.

Table 14.6: Number of events passing the final cut for different neutrino cross sections.

<table>
<thead>
<tr>
<th>Cross sections</th>
<th>$E^{-2} \nu$</th>
<th>Conv atm $\nu$</th>
<th>Prompt atm $\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTEQ5-based</td>
<td>6.03</td>
<td>0.69</td>
<td>0.27</td>
</tr>
<tr>
<td>CSS</td>
<td>5.56</td>
<td>0.37</td>
<td>0.25</td>
</tr>
</tbody>
</table>

For this analysis, neutrino simulation using the new CSS cross sections was generated and used as a baseline. The impact of using different cross sections is shown in table 14.6.

When studying the effect of using old and new cross sections for $\nu_\mu$ neutrinos it was noticed that the rate is lower for CSS simulation in the downgoing and horizontal region. In this region neutrinos traverse the ice and those interacting have a large probability of being detected. A lower rate could be expected since the CSS interaction cross sections are lower.

In the upgoing region the rates are similar. In this region neutrinos traverse the Earth. Secondary particles produced by neutrinos interacting far from the detector will be absorbed. Neutrinos interacting close to the detector on the other hand have a large probability of being detected. The lower CSS cross sections reduce the risk of absorption as well as the chance of interaction close to the detector. The two effects seem to be of roughly the same order and effectively cancel out between CSS and CTEQ5-based simulation.

The rate is lower for CSS simulation at high energies, where the difference is largest between CTEQ5-based and CSS cross sections. However, for events with zenith angle $> 110$ degrees, CSS simulation shows a higher rate at high energies.
Table 14.7: Number of events passing the final cut for CSS neutrino cross sections varied within uncertainties.

<table>
<thead>
<tr>
<th>Cross sections</th>
<th>$E^{-2}\nu$</th>
<th>Conv atm $\nu$</th>
<th>Prompt atm $\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS min</td>
<td>5.36</td>
<td>0.36</td>
<td>0.23</td>
</tr>
<tr>
<td>CSS</td>
<td>5.56</td>
<td>0.37</td>
<td>0.25</td>
</tr>
<tr>
<td>CSS max</td>
<td>5.71</td>
<td>0.47</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Cross section uncertainties are given with the CSS cross sections. Table 14.7 shows the impact on the analysis of varying the CSS cross sections within uncertainties.

14.5 Atmospheric neutrino flux normalization

The baseline model for the conventional component of the atmospheric neutrino flux is derived by Honda et al [47]. The estimated uncertainty on the normalization in the paper is $\pm 25\%$ at 1 TeV. Here, the uncertainty is estimated from experimental data.

Because the analysis is optimized for high energies, atmospheric muons dominate background until very close to the final cut. However, for the upgoing track stream it is possible to select a neutrino sample, as can be seen in the BDT score distribution in figure 11.12. A cut to select atmospheric neutrinos is chosen as $BDT_{trackup} > 0.20$. This results in 88 events from the burn sample. These events have been visually inspected to confirm that they look like neutrino events. Figure 14.3 shows direction and energy at this cut level.

The simulated conventional atmospheric neutrino component describes the shape of experimental data well but shows a rate deficit of about 24%. This deficit is considered within systematic uncertainties and the simulation is therefore renormalized to match experimental data. The rate ratio between experimental and simulated data as a function of cut on the BDT score is shown in figure 14.4, after renormalization of the conventional atmospheric neutrino component. At the highest cut values the statistical error on experimental data is large. Furthermore, the Waxman-Bahcall signal rate is becoming significant. The absolute value of the local rate ratio extremum at cut value 0.305, 18%, is used as the systematic uncertainty on the normalization of the conventional atmospheric neutrino flux.

The baseline model for the prompt component of the atmospheric neutrino flux is derived by Enberg, Sarcevic et al [48]. The uncertainty on this model is implemented within the weighting scheme of the IceCube software framework. The number of surviving events for the model is shown in table 14.8.
Figure 14.3: Distributions at neutrino level. Real data is shown with a solid black line with a shaded area, and atmospheric muon neutrinos is shown with a dashed green line.

Table 14.8: Number of events passing the final cut for the baseline prompt neutrino flux model, plus and minus uncertainties. Note that the assumed live time here is 375.5 days.

<table>
<thead>
<tr>
<th>Model</th>
<th>Prompt atm ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sarcevic min</td>
<td>0.46</td>
</tr>
<tr>
<td>Sarcevic std</td>
<td>0.79</td>
</tr>
<tr>
<td>Sarcevic max</td>
<td>1.02</td>
</tr>
</tbody>
</table>
Figure 14.4: The rate ratio between experimental and simulated data, \((R_{\text{exp}} - R_{\text{sim}})/R_{\text{sim}}\), as a function of cut on the BDT score, for the upgoing track stream at neutrino level. The absolute value of the local rate ratio extremum at cut value 0.305, 18%, is used as the systematic uncertainty on the normalization of the conventional atmospheric neutrino flux. Statistical errors are shown.

14.6 Cosmic ray flux normalization

In the paper describing the poly-gonato model by Hörandel [14], a 20% uncertainty in cosmic ray flux normalization is quoted. A difference between experiments up to a factor of 2 in the knee region is shown in the 2010 PDG review of cosmic rays by Gaisser and Stanev [9].

Here, experimental data is used to constrain the uncertainty on normalization. The considered data region is after the level 3 track stream coincidence.

Figure 14.5: The ratio between Monte Carlo (MC) simulation and experimental data, \((R_{\text{sim}} - R_{\text{exp}})/R_{\text{exp}}\), as a function of the experimental data rate as a cut on the three data stream BDT scores is tightened. Note that the systematic uncertainty is based on the ratio \((R_{\text{exp}} - R_{\text{sim}})/R_{\text{sim}}\).
Table 14.9: Number of atmospheric muon events passing the final cut for different cosmic ray composition models. Note that the assumed live time here is 375.5 days.

<table>
<thead>
<tr>
<th>Composition model</th>
<th>Atm $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-component</td>
<td>0.034 ± 0.014</td>
</tr>
<tr>
<td>Mean</td>
<td>0.19</td>
</tr>
<tr>
<td>Poly-gonato</td>
<td>0.34 ± 0.25</td>
</tr>
</tbody>
</table>

cuts and cascade stream quality cuts. The region is dominated by atmospheric muon background and the difference in rate between experimental and simulated data can be attributed to the uncertainty on cosmic ray flux normalization. The rate ratio between simulated and experimental data as a function of cut on the three data stream BDT scores is shown in figure 14.5. The maximum rate difference, 12.4%, is taken as the systematic uncertainty.

14.7 Cosmic ray composition

The atmospheric muon background rate is estimated by the mean of poly-gonato and 2-component CORSIKA. The difference between these 2 composition models are taken as a reasonable variation of cosmic ray composition. The surviving number of events after the final cut for the 2 composition models is shown in table 14.9.

14.8 Seasonal variation

Figure 14.6 shows the level 3 rate for data taking runs as a function of modified Julian date. The atmospheric muon background simulation assumes an October atmosphere. The mean data rate in October is 3.94 Hz. The minimum rate is around 3.35 Hz and the maximum around 4.68 Hz. The atmospheric neutrino models assume average atmospheric conditions. The systematic uncertainty due to seasonal variation is bounded by the maximum and minimum rates.

14.8.1 Data quality assurance

An official “good run list” is put together by the monitoring and verification working groups. The good run list criteria are based on the most fundamental data quality requirements, which underly the majority of physics analyses. A good run is a run for which data was acquired in a standard physics run configuration, as opposed to test or calibration, with the nominal or partial detector being active, and which satisfies a minimum length requirement. There can
be no external light sources active in the detector during data taking. The rate should be stable over the run and no severe problems should be observed by the run coordinator or in further offline checks by monitoring and verification. Furthermore, no general problem should be reported by standard offline processing.

It is the responsibility of each analyzer to further assure data quality. A few runs in the good run list were excluded from this analysis because a previous point source analysis found anomalous zenith distributions. Here, the rate of each run was compared with the mean of the surrounding 10 runs. All runs with a rate that differed more than 3 standard deviations from the mean were investigated. The majority of these runs either had a partial detector configuration or were less than an hour long. A partial detector configuration means that fewer than the nominal number of strings were active, which naturally affects the data rate. There is a short period at the beginning and possibly at the end of each run where data rate deviates from the nominal value. If the runs are short it will affect the rate of the run.

Three runs differed more than 3 standard deviations, had a long run length and a nominal detector configuration. In one of these runs a significant number of DOMs dropped out. For the other two runs, no problems were found. Since no problems were found for the runs with deviating rates, none were excluded.

### 14.9 Neutrino coincidences

Coincidences between atmospheric muon and neutrino events were not simulated. Given a neutrino event, the most likely coincidence is with a low energy atmospheric muon event. Since the analysis is optimized for high energy neutrino events, this implies that the majority of this type of events will be
dominated by the neutrino event. Atmospheric neutrino simulation describes the experimental upgoing neutrino data sample well. Variables that were seen to be highly sensitive to coincident activity in the detector were not used in the analysis. This indicates that neutrino coincidences do not constitute a large problem for the analysis.

14.10 Summary

The systematic uncertainties resulting from different sources of uncertainty are summarized in table 14.10. Individual uncertainties are summed in quadrature to give a total systematic uncertainty. The largest sources of uncertainty are DOM efficiency, the ice model, and the normalization of the atmospheric neutrino flux.

Statistical uncertainties for the samples passing the final selection are shown in table 14.11.
### Table 14.10: Summary of systematic uncertainties.

<table>
<thead>
<tr>
<th>Source</th>
<th>$E^{-2}\nu$</th>
<th>Conv atm $\nu$</th>
<th>Prompt atm $\nu$</th>
<th>Atm $\mu$</th>
<th>Tot bg</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOM efficiency</td>
<td>−7.9%, +7.1%</td>
<td>−40.3%, +80.1%</td>
<td>−15.2%, +22.0%</td>
<td>−7.9%, +7.1%</td>
<td>−15.5%, +28.6%</td>
</tr>
<tr>
<td>Ice model</td>
<td>± 12.0%</td>
<td>± 30.1%</td>
<td>± 10.6%</td>
<td>± 36.1%</td>
<td>± 12.4%</td>
</tr>
<tr>
<td>Abs energy scale</td>
<td>−3.9%</td>
<td>−15.6%</td>
<td>−8.4%</td>
<td>−29.2%</td>
<td>−7.9%</td>
</tr>
<tr>
<td>$\nu$ cross section</td>
<td>−3.7%, +2.6%</td>
<td>−2.4%, +27.1%</td>
<td>−6.2%, +5.5%</td>
<td>−</td>
<td>−3.4%, +9.3%</td>
</tr>
<tr>
<td>Atm $\nu$ flux norm</td>
<td>-</td>
<td>± 18%</td>
<td>−40.9%, +30.1%</td>
<td>−</td>
<td>−22.6%, +17.1%</td>
</tr>
<tr>
<td>CR flux norm</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>± 12.4%</td>
<td>± 1.7%</td>
</tr>
<tr>
<td>CR composition</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>± 81.5%</td>
<td>± 11.4%</td>
</tr>
<tr>
<td>Seasonal variation</td>
<td>-</td>
<td>± 16.6%</td>
<td>± 16.6%</td>
<td>−15.0%, +19.0%</td>
<td>−10.6%, +10.7%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>−15.4%, +14.2%</td>
<td>± 16.6%</td>
<td>± 16.6%</td>
<td>−15.0%, +19.0%</td>
<td>−35.0%, +40.0%</td>
</tr>
</tbody>
</table>

### Table 14.11: Summary of statistical uncertainties.

<table>
<thead>
<tr>
<th>Source</th>
<th>$E^{-2}\nu$</th>
<th>Atm $\nu$</th>
<th>Atm $\mu$</th>
<th>Tot bg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>± 0.97%</td>
<td>± 4.2%</td>
<td>± 66.8%</td>
<td>± 10.5%</td>
</tr>
</tbody>
</table>
15. Results

After unblinding the full experimental data sample three events passed the final cut. All three events passed through the cascade stream of the analysis. The events look like reasonable cascade candidate events. Event displays are shown in figures 15.1, 15.2 and 15.3.

Assuming no true signal the result is on the high side of expectation, but there is no real statistical tension between the result and a background only hypothesis. The background expectation was $1.22 \pm 0.51$ events. Based on a Poisson mean of 1.22 with a Gaussian uncertainty of 0.51, the probability of observing 3 or more events is 10%.

15.1 Upper limits on astrophysical neutrino fluxes

With three observed events, the 90% confidence level upper limit on an all-flavor $E^{-2}$ neutrino flux becomes $2.32 \times 10^{-8} E^{-2} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. Astrophysical neutrino models that do not predict an $E^{-2}$ spectrum from various source classes were tested in this analysis. Of the models considered, this analysis is sensitive to the AGN neutrino model derived by Mannheim [34], the blazar model derived by Stecker [31], and the radio galaxy neutrino model from Becker, Biermann and Rhode [33]. The latter two models are rejected at a 5 standard deviation confidence level, while the first is rejected at 99% confidence level. The analysis also excludes the Waxman-Bahcall upper bound [1] at a 3 standard deviation confidence level. The upper limit on an $E^{-2}$ spectrum is shown with various models in figure 15.4. Upper limits for different astrophysical neutrino flux models are summarized in table 15.1.

The upper limit derived in this work on an all-flavor astrophysical $E^{-2}$ neutrino flux is compared to other experimental results in figure 15.5.

15.2 Characterizing surviving events

The surviving events from any analysis will be scrutinized. This is especially true in the case of a significant excess of events, where a large enough number should be convincing neutrino induced events if a discovery is to be claimed. For the case of setting a limit it is not strictly required to categorize the events as neutrino induced or not, since any surviving events makes the resulting limit more conservative.
Figure 15.1: Display of event 1. This event is just above the main dust layer and is therefore asymmetric in depth.

Figure 15.2: Display of event 2. This event is in the very clean ice below the main dust layer, at the bottom of the detector but the development of the event starts a few DOMs above the very bottom.
Figure 15.3: Display of event 3. This event is in the very clean ice below the main dust layer, at the side of the detector.

Figure 15.4: The 90% confidence level upper limit derived in this work on an all-flavor $E^{-2}$ neutrino flux, compared to various astrophysical neutrino flux models described in section 2.3.
Table 15.1: Upper limits for different astrophysical neutrino flux models. The upper limits are expressed in terms of the model rejection factor [104], which is the fraction of the reference model rejected at the stated confidence level such that $\Phi_{CL} = MRF \times \Phi_{ref}$.

<table>
<thead>
<tr>
<th>Model</th>
<th>90% C.L.</th>
<th>3$\sigma$ C.L.</th>
<th>5$\sigma$ C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>W-B upper bound</td>
<td>0.34</td>
<td>0.68</td>
<td>1.70</td>
</tr>
<tr>
<td>Stecker Blazar</td>
<td>0.13</td>
<td>0.27</td>
<td>0.67</td>
</tr>
<tr>
<td>BBR II RQ AGN</td>
<td>0.11</td>
<td>0.22</td>
<td>0.55</td>
</tr>
<tr>
<td>Mannheim AGN</td>
<td>0.59</td>
<td>1.16</td>
<td>2.9</td>
</tr>
<tr>
<td>W-B prompt GRB</td>
<td>2.01</td>
<td>3.96</td>
<td>9.95</td>
</tr>
</tbody>
</table>

Figure 15.5: Experimental results. The upper limit derived in this work is labeled IC40 UHE. Upper limits from previous IceCube analyses include the IC22 cascade analysis [98], the IC22 diffuse UHE analysis (preliminary), the IC40 diffuse $\nu_\mu$ analysis [108] and the IC40 diffuse EHE analysis [109]. Upper limits from other experiments include Baikal [110], ANTARES [111], RICE [50], HiRes [112], PAO [55, 56] and ANITA [51, 52]. Differential limits are shown in thin solid lines. Note that for differential limits, the energy bin width assumed for the signal flux is given in decades in the legend. Where applicable, the assumed energy spectrum for signal is shown as well.
Distinguishing whether the surviving events are induced by neutrinos or atmospheric muons is difficult. For cascade-like events, any indication of a downgoing track is an indication that the event might be caused by an atmospheric muon. The events were studied in an event viewer, where it is possible to see the development of the event in the detector in detail. No indication of a track could be seen through visual inspection. Furthermore, event 1 starts on a string that is largely contained, which makes it unlikely that an incoming muon would go unnoticed.

15.2.1 Waveforms

Individual waveforms registered by DOMs hold information that does not resolve in the event viewer. In light of the flasher-type events described in section 13.1, the waveforms from the DOMs that detected most photoelectrons were inspected to search for any sign of detector artefacts. In previous flasher-type events there seemed to be an unusual light emission profile. For the flasher-type event seen in IceCube this was evident in the form of unusually long waveforms in the DOMs closest to the light source. Here, no indication of light of non-particle origin was seen.

For events 2 and 3, early pulses were noticed in two adjacent DOMs ∼80 m above the reconstructed cascade vertex. The waveforms can be seen in figures 15.6 and 15.7. The steep rise and large amplitude of the waveform following the early pulses indicate that the main pulse is caused by unscattered photons reaching the DOM from a point of emission of bright light, very likely the main cascade. Since no photons from the same light source could arrive at an earlier time, this implies that the early pulses stem from another source.

The early pulses are not consistent with pre-pulsing in the PMT. Pre-pulses are ascribed to photoelectrons ejected from the first dynode instead of the photocathode in the PMT. Pre-pulses in IceCube PMTs are typically between 1/10 to 1/20 of the single photoelectron (SPE) pulse size [64], below the threshold for triggering DOMs. They are rare, occurring at less than 1% of the SPE rate. The combined pre-pulses from many photons would only be observable for a large light pulse of more than 5000 photons detected within 30 ns. Pulses originating more than ∼25 m from a DOM would generally be broader than this, due to scattering in the ice [75]. Pre-pulses typically occur 30 ns before the main peak, whereas the early pulses seen here occurred 40 - 90 ns before the main peak.

The early pulses could indicate the presence of a muon, for which there are several compatible scenarios:

- A downgoing atmospheric muon dominated by a large stochastic energy loss.
- A neutrino induced muon dominated by a large stochastic energy loss.
- An outgoing muon from the hadronic part of the cascade.
Figure 15.6: Display of event 2, with waveforms for DOM 51 and 52 on string 46. The early pulses can be seen clearly. The DOMs are \( \sim 80 \) m above the reconstructed cascade vertex.

Figure 15.7: Display of event 3, with waveforms for DOM 47 and 48 on string 68. The early pulses can be seen clearly. The DOMs are \( \sim 80 \) m above the reconstructed cascade vertex.
A cascade induced by an atmospheric neutrino with a correlated muon from the same air shower.

The latter two scenarios are not currently being simulated. To state something more conclusive regarding the origin of these events, further study of waveforms in experimental and simulated data would be required. The importance of waveforms is clear in this case, and more generally for cascade analyses, where waveforms will be the subject of study for future analyses.

15.2.2 Energy

The energy resolution for contained neutrino induced cascade events has been estimated to $\sim 10\%$ in $\log_{10}(E_{\nu})$. The same performance was not seen at final level of this analysis. Figures 15.8 and 15.9 show the energy resolution for two different cascade reconstruction algorithms. There is a systematic shift in the reconstructed energy for both algorithms, most likely due to differing calibrations. The assumed neutrino energy spectrum has a significant impact on the calibration. Furthermore, there have been updates to the simulation that might impact the calibrations. The poor energy resolution is likely caused by the large fraction of uncontained events.

Table 15.2 shows reconstructed energy from the two cascade reconstructions, as well as separate estimations of primary energy for an astrophysical neutrino and a cosmic ray hypothesis. The primary energy was estimated by selecting events from simulation that are similar to the three surviving events. Events were selected from $\nu_e$ simulation weighted to an $E^{-2}$ spectrum, polygonato CORSIKA and 2-component CORSIKA. The selection was based on three variables relating to energy: the reconstructed energies $E_{\text{acer}}$ and $E_{\text{credo}}$, and the maximum current $I_{\text{max}}$; and three variables relating to cascade quality: the fill ratio, $R_{\text{fill}}$, linefit velocity, $V_{\text{LineFit}}$, and the reduced log-likelihood
Figure 15.9: Energy resolution for the cascade reconstruction Credo looking at signal $\nu_e$ neutrinos at final level.

Table 15.2: Reconstructed energy from the cascade reconstructions ACER and Credo. The two last columns show the estimated primary energy for an astrophysical neutrino and a cosmic ray hypothesis, based on similar events found in simulated data.

<table>
<thead>
<tr>
<th>Ev</th>
<th>Run</th>
<th>Ev ID</th>
<th>$E_{\text{acer}}$/TeV</th>
<th>$E_{\text{credo}}$/TeV</th>
<th>$E_{\nu_e}$/TeV</th>
<th>$E_{\text{CR}}$/PeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>111114</td>
<td>4722525</td>
<td>275</td>
<td>1030</td>
<td>782</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>111712</td>
<td>34368767</td>
<td>135</td>
<td>248</td>
<td>264</td>
<td>9 - 266</td>
</tr>
<tr>
<td>3</td>
<td>111788</td>
<td>28331601</td>
<td>244</td>
<td>643</td>
<td>452</td>
<td>635 - 2600</td>
</tr>
</tbody>
</table>

from the cascade reconstruction CLLH; and the fraction of DOMs with one hit only, $F_{1h}$; and for events 2 and 3, depth in the detector. While it was difficult finding similar CORSIKA events, similar $\nu_e$ events were easily found. For event 1, no CORSIKA events adequately similar were found. The sample size varied from 34 to 45 events for $\nu_e$ simulation and from 10 to 15 events for CORSIKA simulation. Based on the overall agreement between experimental and simulated data the estimates are deemed trustworthy.

15.2.3 Containment

The variable scale is used to describe containment. Scale is the factor by which you need to scale the IC40 detector in order to precisely contain the event, based on the vertex position from the cascade reconstruction CLLH. Events 2 and 3 are at the very edge of the detector. The most likely position for both signal and background at the final level is at the edge of the detector, as shown in figure 15.10. For signal this is mostly a geometrical effect, the volume corresponding to a step in scale increases with scale. It has also been seen that cascade reconstructions tend to pull the true vertex position closer to the detector for uncontained events.
The scale for event 1, 2 and 3 is 0.73, 1.26 and 0.96, respectively. Note that because of the asymmetrical shape of the IC40 detector, the scale varies differently depending on the location of the event in the horizontal plane. For example, since event 2 is outside a long edge of the detector, the scale is larger than if event 2 had been outside one of the short edges by the same amount.

15.3 Non-signal tags

None of the surviving events show activity in IceTop, which otherwise would have suggested an atmospheric muon background event.

No events were tagged as flasher-type by the selection described in section 13.1. However, to verify the robustness of the analysis the experimental data events just below the final cut were investigated. Removing Quality cut II but keeping the final cut on the BDT scores caused two more events to pass. These events are almost identical in expression and have a reconstructed vertex very close to the suspected flashing AMANDA OM, and are very likely flasher-type events. The reason they were not tagged as such is that the duration of each event was less than 3 \( \mu s \), while the tagging required a duration of 8 \( \mu s \), based on previous events of this type.

The events were removed from the analysis by the cut on fill ratio in Quality cut II. The events were otherwise rated highly cascade-like by the BDT. Since the fill ratio calculation is based on the hit time distribution this again indicates an unusual light emission profile. In retrospect, a better tagging selection would be based entirely on proximity to the suspected AMANDA OM. At the end of the IC40 data taking season AMANDA was shut down and no longer supplied with power. Assuming that the hypothesis of light originating from an AMANDA OM is true, this specific type of events should not pose a problem in future analyses.
16. Conclusions and outlook

An analysis structure with three streams based on signal and background topology was a novel approach within IceCube. This posed several challenges, the first of which was processing an analysis-specific filter level 2 in order to get a homogeneous data set. Secondly, by looking at both track-like and cascade-like events, a coherent picture describing the agreement between experimental and simulated data was required, to achieve a satisfactory degree of confidence in the predictions from simulation. Robustness was prioritized before signal efficiency.

Three events survived after unblinding. The events passed through the cascade stream of the analysis and look like reasonable cascade candidate events. There is no real statistical tension between the result and a background only hypothesis. The analysis structure proved efficient and the resulting upper limit on an astrophysical all-flavor neutrino flux with an $E^{-2}$ energy spectrum is the most strict to date.

For future analyses this type of approach could be made easier by including a “UHE filter” in the standard IceCube offline processing.

Sources of systematic uncertainty are continuously being investigated and the simulation being improved upon. More specifically, improvements are expected from better modeling and simulation of:

- The detector
- Ice properties
- Cosmic ray composition and flux normalization
- Atmospheric neutrino flux normalization and spectrum
- Neutrino-nucleon interaction cross sections

In this analysis a final cut was optimized for high sensitivity using the model rejection technique [104]. An alternate approach is to test the compatibility of a distribution from experimental data with simulated background and signal components. An suitable distribution could for example be a BDT score or an energy related variable. A frequentist approach suggested by Feldman [113, 114] was followed in a recent IceCube diffuse analysis, using the profile likelihood construction method to incorporate systematic uncertainties as nuisance parameters. This gave a better sensitivity than optimizing a final cut, especially for astrophysical neutrino flux models with distinctive energy spectra.

The final phase of construction of the 86-string IceCube detector was recently successfully completed, resulting in a detector volume of one cubic...
kilometer. With increased exposure, an improvement in sensitivity to an astrophysical UHE diffuse neutrino flux of more than an order of magnitude is anticipated.

16.1 Lessons learned

Initially an additional filter level was planned for the analysis. Early investigations indicated that an extra filter level would not improve signal efficiency significantly. Because of time constraints it was decided to simplify the structure of the analysis by evaluating a final cut at filter level 3. In hindsight, a possibly more efficient approach would have been to apply the cascade stream structure to the track streams as well. Applying harder quality cuts provides a limited phase space, relevant for signal, within which a multivariate classifier should perform efficiently.
Vår kunskap om universum kommer till stor del från observationer av fotoner, det vill säga elektromagnetisk strålning i olika våglängder. De mest ljusstarka och våldsamma objekten i universum, aktiva galaxkärnor och gammablixtar, har studerats noggrannt genom observationer av gammastrålning. Flödet av fotoner dämpas dock av gas och stoft i det interstellära mediet, och vid höga energier av kosmisk bakgrundsstrålning, vilket begränsar sikten. Astrofysikaliska källor med omgående regioner har ofta betydande optisk täthet, vilket gör att fotoner ger information om egenskaper på ytan av objekt.


Acceleration av hadroner ger upphov till stabila laddade kosmiska partiklar som färdas genom universum med hög energi. Dessa kosmiska partiklar kan också observeras. På grund av den elektriska laddningen böjs kosmiska partiklar av i inter- och extragalaktiska magnetiska fält, vilket gör att de inte pekar tillbaka till källan. Observationer av neutriner kan avslöja källor till kosmiska partiklar, och tillhandahålla en länk mellan observationer av gammastrålning och kosmiska partiklar.

Analysen som beskrivs i denna avhandling eftersöker ett diffust flöde av utomjordiska neutriner med ett energispektrum som är typiskt för acceleration av hadroner i chockvågor, $E^{-2}$. Analysen är optimerad för ultra-högenergetiska neutriner, det vill säga neutriner med energi över 1 PeV. Data som samlats in med IceCube under 2008 och 2009 har undersökts. Under denna tidsperiod bestod detektorn av 40 strängar, och var ungefär hälften så stor som den nu färdigställda detektorn. Ett diffust flöde av neutriner är känsligt för egenskaper hos populationen av kosmiska acceleratorer i universum.

Neutrinosignalen är mycket svag i förhållande till bakgrunds­nivån i detektorn. Bakgrunden består av myoner och neutriner som produceras i atmosfären i skurar av partiklar som uppstår när kosmiska partiklar kolliderar med jordens atmosfär. Signal skiljer sig från bakgrund i framförallt två avseenden, signalen har högre energi och en annan typisk riktning.

Hela experimentet simuleras för att försäkra sig om att man förstår detektorn och insamlade data. En god överensstämmelse mellan simulering av bakgrund och insamlade data bekräftar god förståelse av detektorn och ger förtroende för beskrivningen av signalhypotesen. Analysen går ut på att filtrera bort bakgrunden och behålla så god acceptans för signalen som möjligt. I denna analys har förståelse för insamlade data prioriterats i störst möjliga mån. Under utvecklandet av analysen har ett mindre urval av insamlade data använts för att bekräfta simuleringsens validitet. Detta urval används inte i sökandet efter signal. Analysen är optimerad för att ge god känslighet för signal, baserat helt på simulerade data. Denna procedur skyddar forskaren mot omedveten påverkan i någon riktning, till exempel mot en teoretisk förutsägelse.

Denna analys letar efter neutrinoinducerade händelser som kan ta sig olika typ av uttryck i detektorn. En struktur med tre olika dataströmmar baserade på dessa uttryck har utvecklats. Det är första gången en sådan struktur har använts inom IceCube, detta medförde flera utmaningar men gav också god känslighet för signal.

Efter att analysen färdigställdes och godkändes av IceCube-kollaborationen applicerades den på data med en livstid på 345,7 dagar. Tre händelser överlevde analysens samtliga filtnivåer. De överlevande händelserna ser ut som rimliga neutrinoinducerade händelser men åtminstone två kan möjligtvis vara orsakade av atmosfäriska myoner. Resultatet är i rimlig överensstämmelse med bakgrund, och en gräns kan sättas för det maximala flödet av signalneutriner som är statistiskt förenligt med resultatet. Denna gräns är den mest strikta till dags dato och utesluter flera teoretiska modeller för flödet av utomjordiska neutriner.
A. Multivariate classifiers

In high energy physics a common problem is extracting a small signal from a very large data set. Multivariate classification algorithms based on machine learning techniques are able to utilize available information efficiently. Common for machine learning techniques is a training phase, where the algorithm learns how to classify events as signal-like or background-like based on data describing signal and background.

A.1 Boosted decision trees

A decision tree is a classifier that uses a binary tree structure. For an event, repeated left/right decisions are made based on a single variable at a time until a stop criterion is fulfilled, placing the event in a leaf node. In the phase space spanned by the variables used to characterize events, each leaf node corresponds to a hypercube defined by a series of straight cuts. Each leaf node is categorized as signal-like or background-like depending on the number of signal and background training events ending up in that node.

Boosting refers to an extension of the single decision tree. Several trees, a forest, are derived from the same training sample by reweighting events. The boosted decision tree (BDT) classifies events based on a weighted majority vote from the individual trees of the forest. Boosting stabilizes the response of the decision trees with respect to statistical fluctuations in the training sample. The weighted majority vote is referred to as the BDT score and lies in the range from -1 to 1, where low values indicate background-like events and high values signal-like events.

A classifier is said to be overtrained if statistical fluctuations in the training sample affect the classification of events. BDTs are pruned in order to reduce overtraining. The number of events in a leaf node decides the statistical significance of the classification as signal-like or background-like. The pruning removes leaf nodes with statistical significance lower than a specified value.

The BDT algorithm implemented in the TMVA toolkit [102] within the analysis framework ROOT [103] was used in this analysis. The TMVA toolkit provides several tools for evaluating the performance of BDTs. Overtraining is tested by comparing the BDT response between two independent data samples. Correlations between variables used to characterize events are provided to inform the variable selection process.
Table A.1: Configuration of the BDTs used in this analysis. Parameters not listed are used with values that are default in the TMVA toolkit.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTrees</td>
<td>400</td>
</tr>
<tr>
<td>BoostType</td>
<td>AdaBoost</td>
</tr>
<tr>
<td>SeparationType</td>
<td>GiniIndex</td>
</tr>
<tr>
<td>nCuts</td>
<td>20</td>
</tr>
<tr>
<td>PruneMethod</td>
<td>CostComplexity</td>
</tr>
<tr>
<td>PruneStrength</td>
<td>1.5</td>
</tr>
</tbody>
</table>

A.2 Evaluation of BDTs

A BDT was evaluated for each data stream at filter level 3. The variables used to characterize signal and background were required to show adequate agreement between real and simulated data. An understanding of which underlying physical properties a variable describes is required as well. The variables were selected based on separation power between signal and background. To reduce the phase space and thus the risk of overtraining, it was decided a priori to use no more than 10 variables in a BDT.

Many BDTs were evaluated for each data stream, based on different selections of variables. BDT scores were required to show adequate agreement between real and simulated data. A number of BDTs were then selected based on separation power between signal and background. The most signal-like events from the “burn sample” of real data (see chapter 8) were investigated in an event-viewer to make sure the BDT selected reasonable events. The most signal-like events from simulated background were investigated to see if there were other variables that might improve background rejection. This process was iterated until further change was not clearly justified.

In the process of selecting variables, it became clear that two variables can be highly correlated and still provide unique and crucial information. For example, the most accurate estimation of event energy is most often given by a sophisticated reconstruction. However, mis-reconstructions sometimes result in much too high event energies, resulting in an event classification as much too signal-like. Including a highly correlated and crude but robust energy estimator, such as total number of detected photoelectrons, protects against such unwanted behavior.

A BDT has many parameters that can be tuned for specific applications. Six different configurations were tested using a reasonable selection of variables for the downgoing track stream. Based on performance, one configuration was chosen and was then used for all data streams and variable selections. Table A.1 summarizes the chosen configuration.
Table A.2: Data components used in the training of the downgoing track stream BDT. \(-\Delta\) indicates the change in generation spectral index with regards to the poly-gonato model spectrum.

<table>
<thead>
<tr>
<th>Component</th>
<th>Sim</th>
<th>Gen spectrum</th>
<th>(N_{\text{files}})</th>
<th>(N_{\text{primaries/file}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>(\nu_\mu)</td>
<td>(E^{-1})</td>
<td>985</td>
<td>(5 \times 10^3)</td>
</tr>
<tr>
<td>Background</td>
<td>CORSIKA single</td>
<td>(\Delta = -1.0)</td>
<td>2897</td>
<td>(4 \times 10^5)</td>
</tr>
<tr>
<td>Background</td>
<td>CORSIKA double</td>
<td>(\Delta = -0.5)</td>
<td>2000</td>
<td>(2 \times 10^6)</td>
</tr>
<tr>
<td>Background</td>
<td>CORSIKA triple</td>
<td>(\Delta = 0)</td>
<td>200</td>
<td>(10 \times 10^6)</td>
</tr>
</tbody>
</table>

A.3 Downgoing track stream

For the downgoing track stream, \(\nu_\mu\) simulation with energy spectrum \(E^{-2}\) and energy greater than 1 PeV was used as signal in the BDT training phase. The downgoing track stream should be optimized for track-like events. \(\nu_\mu\) events also give rise to neutral-current interactions, which are cascade-like. Information about interaction type was unfortunately not saved in the simulation. Instead, track-like events were ensured by requiring that the directional MPE-reconstruction error was less than 5 degrees for signal. Furthermore, more convincing signal-like events were selected from real data if \(\nu_\mu\) signal was required to have a direct length greater than 300 m in the training phase.

Atmospheric \(\mu\) simulation was used as background in the training phase. Single events as well as double and triple coincident events were used, generated according to the poly-gonato model. Table A.2 shows the data components and statistics used for training. See chapter 6 for details on the simulation.

Figure A.1 shows the result of the overtraining check performed by the TMVA toolkit. The BDT response is evaluated on two independent data samples, the training sample and the test sample. A Kolmogorov-Smirnov test quantifies the distance between the two response distributions in a range from 0 to 1, where 1 indicates that the distributions are equal. The test and training samples are of equal size per default in TMVA, which means that the statistics used for training is reduced. After confirming that the Kolmogorov-Smirnov test did not indicate overtraining, the BDT was trained on close to the full signal and background data samples, with a much smaller test data sample.

A.4 Upgoing track stream

For the upgoing track stream, \(\nu_\mu\) simulation with energy spectrum \(E^{-2}\) and energy greater than 1 PeV was used as signal in the BDT training phase. Track-like events were ensured by requiring that the directional MPE-reconstruction error was less than 5 degrees for signal.
Figure A.1: Overtraining check for the downgoing track stream BDT.

Table A.3: Data components used in the training of the upgoing track stream BDT. $\Delta$ indicates the change in generation spectral index with regards to the poly-gonato model spectrum.

<table>
<thead>
<tr>
<th>Component</th>
<th>Sim</th>
<th>Gen spectrum</th>
<th>$N_{files}$</th>
<th>$N_{primaries/file}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>$\nu_\mu$</td>
<td>$E^{-1}$</td>
<td>1945</td>
<td>$5 \times 10^3$</td>
</tr>
<tr>
<td>Background</td>
<td>CORSIKA single</td>
<td>$\Delta = -1.0$</td>
<td>24201</td>
<td>$4 \times 10^5$</td>
</tr>
<tr>
<td>Background</td>
<td>CORSIKA double</td>
<td>$\Delta = -0.5$</td>
<td>2000</td>
<td>$2 \times 10^6$</td>
</tr>
<tr>
<td>Background</td>
<td>CORSIKA triple</td>
<td>$\Delta = 0$</td>
<td>200</td>
<td>$10 \times 10^6$</td>
</tr>
</tbody>
</table>

Atmospheric $\mu$ simulation was used as background in the training phase. Single events as well as double and triple coincident events were used, generated according to the poly-gonato model. Table A.3 shows the data components and statistics used for training. See chapter 6 for details on the simulation.

Figure A.2 shows the result of the overtraining check performed by the TMVA toolkit. After confirming that the Kolmogorov-Smirnov test did not indicate overtraining, the BDT was trained on close to the full signal and background data samples, with a much smaller test data sample.

A.5 Cascade stream

For the cascade stream, $\nu_e$ simulation with energy spectrum $E^{-2}$ and energy greater than 1 PeV was used as signal in the BDT training phase.

Atmospheric $\mu$ simulation was used as background in the training phase. Single events as well as double and triple coincident events were used, gen-
Figure A.2: Overtraining check for the upgoing track stream BDT.

Table A.4: Data components used in the training of the cascade stream BDT. $\Delta$ indicates the change in generation spectral index with regards to the poly-gonato model spectrum.

<table>
<thead>
<tr>
<th>Component</th>
<th>Sim</th>
<th>Gen spectrum</th>
<th>$N_{\text{files}}$</th>
<th>$N_{\text{primaries/file}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>$\nu_e$</td>
<td>$E^{-1}$</td>
<td>999</td>
<td>$5 \times 10^3$</td>
</tr>
<tr>
<td>Background</td>
<td>$\nu_\mu$</td>
<td>$E^{-1}$</td>
<td>1945</td>
<td>$5 \times 10^3$</td>
</tr>
<tr>
<td>Background CORSIKA single</td>
<td></td>
<td>$\Delta = -1.0$</td>
<td>24201</td>
<td>$4 \times 10^5$</td>
</tr>
<tr>
<td>Background CORSIKA double</td>
<td></td>
<td>$\Delta = -0.5$</td>
<td>2000</td>
<td>$2 \times 10^6$</td>
</tr>
<tr>
<td>Background CORSIKA triple</td>
<td></td>
<td>$\Delta = 0$</td>
<td>200</td>
<td>$10 \times 10^6$</td>
</tr>
</tbody>
</table>

erated according to the poly-gonato model. Because the cascade stream BDT was evaluated at a higher level than the track stream BDTs, atmospheric $\nu_\mu$ simulation was included in the background as well. Table A.4 shows the data components and statistics used for training. See chapter 6 for details on the simulation.

Figure A.3 shows the result of the overtraining check performed by the TMVA toolkit. After confirming that the Kolmogorov-Smirnov test did not indicate overtraining, the BDT was trained on close to the full signal and background data samples, with a much smaller test data sample.
Figure A.3: Overtraining check for the cascade stream BDT.
## List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACER</td>
<td>Atmospheric cascade energy reconstruction</td>
</tr>
<tr>
<td>AGN</td>
<td>Active galactic nucleus</td>
</tr>
<tr>
<td>AMANDA</td>
<td>Antarctic muon and neutrino detector array</td>
</tr>
<tr>
<td>ANIS</td>
<td>All neutrino interaction simulation</td>
</tr>
<tr>
<td>ATWD</td>
<td>Analog transient waveform digitizer</td>
</tr>
<tr>
<td>BDT</td>
<td>Boosted decision tree</td>
</tr>
<tr>
<td>CC</td>
<td>Charged-current</td>
</tr>
<tr>
<td>CDOM</td>
<td>Color DOM</td>
</tr>
<tr>
<td>COG</td>
<td>Center of gravity</td>
</tr>
<tr>
<td>CORSIKA</td>
<td>Cosmic ray simulations for Kascade</td>
</tr>
<tr>
<td>CSS</td>
<td>Cooper-Sarkar and Sarkar</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data acquisition</td>
</tr>
<tr>
<td>DOM</td>
<td>Digital optical module</td>
</tr>
<tr>
<td>DOR</td>
<td>DOM readout</td>
</tr>
<tr>
<td>EHE</td>
<td>Extremely high-energy</td>
</tr>
<tr>
<td>fADC</td>
<td>Fast analog-to-digital converter</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field programmable gate array</td>
</tr>
<tr>
<td>GRB</td>
<td>Gamma ray burst</td>
</tr>
<tr>
<td>GZK</td>
<td>Greisen-Zatsepin-Kuzmin</td>
</tr>
<tr>
<td>HLC</td>
<td>Hard local coincidence</td>
</tr>
<tr>
<td>HV</td>
<td>High voltage</td>
</tr>
<tr>
<td>ICL</td>
<td>IceCube laboratory</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>LC</td>
<td>Local coincidence</td>
</tr>
<tr>
<td>LPM</td>
<td>Landau-Pomeranchuk-Migdal</td>
</tr>
<tr>
<td>MB</td>
<td>Mainboard</td>
</tr>
<tr>
<td>MC</td>
<td>Monte Carlo</td>
</tr>
<tr>
<td>MMC</td>
<td>Muon monte carlo</td>
</tr>
<tr>
<td>MPE</td>
<td>Multi-photoelectron</td>
</tr>
<tr>
<td>MRF</td>
<td>Model rejection factor</td>
</tr>
<tr>
<td>MSPS</td>
<td>Mega-samples per second</td>
</tr>
<tr>
<td>NC</td>
<td>Neutral current</td>
</tr>
<tr>
<td>OM</td>
<td>Optical module</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability density function</td>
</tr>
<tr>
<td>PE</td>
<td>Photoelectron</td>
</tr>
<tr>
<td>PMT</td>
<td>Photomultiplier tube</td>
</tr>
<tr>
<td>PnF</td>
<td>Processing and filtering</td>
</tr>
<tr>
<td>PREM</td>
<td>Preliminary reference Earth model</td>
</tr>
<tr>
<td>SC</td>
<td>Standard candle</td>
</tr>
<tr>
<td>SLC</td>
<td>Soft local coincidence</td>
</tr>
<tr>
<td>SMT8</td>
<td>Simple majority trigger 8</td>
</tr>
<tr>
<td>SNR</td>
<td>Supernova remnant</td>
</tr>
<tr>
<td>SPADE</td>
<td>South Pole Archival and Data Exchange</td>
</tr>
<tr>
<td>SPE</td>
<td>Single photoelectron</td>
</tr>
<tr>
<td>SPE-32</td>
<td>SPE track reconstruction, 32 iterations</td>
</tr>
<tr>
<td>UHE</td>
<td>Ultra high-energy</td>
</tr>
</tbody>
</table>


