Martin Wolf

Indirect Searches for Dark Matter in the Milky Way with IceCube-DeepCore

Department of Physics
Stockholm University
2016
Abstract

Many astronomical observations, including rotational curve measurements of stars and the analysis of the cosmic microwave background, suggest the existence of an invisible matter density content in the Universe, commonly called Dark Matter (DM). Possibly, DM could be of particle nature, where Weakly Interacting Massive Particles (WIMPs) could be a viable DM candidate. The cubic-kilometer sized IceCube neutrino observatory located at the Earth’s South Pole can search indirectly for the existence of DM by detecting neutrino signals from WIMP self-annihilation in the Galactic center (GC) and the Galactic halo (GH). Two main physics analyses were developed and conducted to search indirectly for WIMP self-annihilation in the Milky Way’s GC and GH. Signal hypotheses for different WIMP annihilation channels, WIMP masses and DM halo profiles were tested. The results of both analyses were compatible with the background-only hypothesis for all tested signal hypotheses. Thus, upper limits at the 90% confidence level (C.L.) on the thermally averaged DM self-annihilation cross-section, \( \langle \sigma_A v \rangle \), were set. Dedicated atmospheric muon veto techniques have been developed for the GC search making such an IceCube analysis possible for the first time. The GC analysis utilized data from 319.7 days of live-time of the IceCube detector running in its 79-string configuration during 2010 and 2011, whereas the GH analysis utilized pre-existing data samples developed for point-like neutrino sources with a live-time of 1701.9 days between 2008 and 2013. The most stringent upper limits on \( \langle \sigma_A v \rangle \) were obtained for WIMP annihilation directly into a pair of neutrinos assuming a Navarro-Frenk-White (NFW) DM halo profile. Conducting the GC and GH analyses for this annihilation channel an upper limit on \( \langle \sigma_A v \rangle \) as low as \( 4.0 \cdot 10^{-24} \text{ cm}^3\text{s}^{-1} \) and \( 4.5 \cdot 10^{-24} \text{ cm}^3\text{s}^{-1} \) is set for a 65 GeV and 500 GeV massive WIMP, respectively. These galactic indirect neutrino searches for DM are complementary to the indirect gamma-ray DM searches usually performed on extra-galactic targets like dwarf spheroidal galaxies.
dedicated to me, my family and my friends
Sammanfattning på svenska

IceCube neutrino observatory är en kubik-kilometer stor detektor som observerar universum med hjälp av neutriner. Neutrinerna detekteras genom deras växelverkan med ismolekyler i vilka laddade myoner kan skapas. Dessa myoner producerar Cherenkovljus som detekteras av 5160 fotosensorer, så kallade DOM:ar (Digital Optical Module), som är fördelade på 86 strängar mellan 1.5 km till 2.5 km djup. I den mittersta delen av detektorn, bestående av 8 strängar, är strängarna tättare placerade. Detta utgör den så kallade DeepCore komponenten av detektorn med en låg energitröskel runt 10 GeV. IceCube-detektorn kan i stort detektera neutriner vars energi är flera PeV.

Många astronomiska observationer, där ibland mätningar av galaxers rotationskurvor och analyser av den kosmiska bakgrunden, antyder att det existerar en osynlig massdensitet i universum som vi kallar mörk materia. Om denna mörka materia har partikelegenskaper är de svagt växelverkande massiva partiklarna (WIMP av engelskans Weakly Interactive Massive Particles) intressanta mörk materiekandidater. När sådana WIMP:ar annihilerar med varandra, i Vintergatans Centrum eller i Vintergatans omgivningar, den så kallade halon, kan standardmodellpartiklar bildas, till exempel neutriner. IceCube kan detektera dessa neutriner vilket gör det möjligt att söka efter mörk materia, indirekt, med hjälp av neutriner.

Två analyser har utvecklats och genomförts, där målet varit att söka efter mörk materia i Vintergatans centrum (VC) och i dess halo (VH). Olika signalhypoteser med varierande annihilationsskanaler, WIMP-massor och mörkmatteriefördelningar i halon testades. Resultaten från båda analyserna var förenliga med bakgrundshypotesen. Därför beräknades övre gränser med 90% konfidensnivå för medelvärdet av det termiska tvärsnittet för självannihilerande mörk materia, $\langle \sigma_A v \rangle$. Nya myonvetometoder utvecklades specifikt för att kunna utföra den först nämnda analysen. I VC analysen användes data motsvarande 319.7 dagars detektortid insamlade under 2010 och 2011 då detektorn bestod av 79 strängar. VH analysen använde istället en dataselectie avsedd för punkttällor vars detektortid motsvarade 1701.9 dagar insamlade mellan 2008 och 2013. De starkaste övre gränserna på $\langle \sigma_A v \rangle$ erhölls för WIMP annihilation direkt till neutrinopar förutsatt en Navarro-Frenk-White (NFW) profil av mörk materie fördenlingen i halon. Dessa två analyser där man sökt efter mörk materia indirekt med hjälp av neutriner är komplementära till gamma-blixt analyser där man vanligtvis letar efter mörk materia i närbelägna dvärggalaxer.
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Acknowledgments

It is almost twelve years ago that I started studying physics. With the common belief about the difficulty of physics studies in mind, I decided to give it a try and to see how far I would make it. Apparently and fortunately, I made it quite far, yet. This was only possible due to a lot of great people I met and worked with. Many friendships were established and many places were explored during the last twelve years.

During the last four and a half years in Stockholm I had the wonderful opportunity to experience a professionally productive, friendly, and supporting working atmosphere, especially with the IceCube-Stockholm research group, which let me travel to the South Pole. Special thanks go to the senior members of that group, Klas Hultqvist, Christian Walck, Chad Finley and Jon Dumm. Sadly, Per-Olof Hulth past away beginning of 2015 leaving a big void hardly possible to fill. I want to thank all of you for the great time and the spirit you created needed for such an ambitious project like a PhD and in particular for the hunt for Dark Matter. Unfortunately, we have not found it yet, but everything is just a matter of time. So let’s keep up the spirit!

My main supervisor Chad deserves special thanks. I thank you for always being so supportive and productive. You taught me to focus on the relevant and important things, which was key to get me to this point in life with almost no delay. Your scientific and pedagogical skills are just amazing and I wish I could explain randomly asked things as clearly and understandably as you do. I enjoyed the numerous long and constructive discussions we had at the whiteboard in your office. At no time did I feel like I was your first PhD student and I hope you enjoyed supervising me as much as I was proud to have you as such a great supervisor.

I can say similar things about Klas, Christian, Per-Olof, and Jon. What I love about Klas is his thorough thinking about physics and finding the smallest logical mistakes, especially in the last seconds before something like this thesis is due to be done. Thanks all of you for your advice and support during the last years. Also thanks for proofreading this thesis very thoroughly.

Beside to the seniors, I owe a great deal of thanks also to my fellow PhD
students Matthias, Marcel, Samuel, and Maryon. Thanks to Matthias the “fast” Galactic center analysis was born and it took us “only” about two years to finish it with a publication. Your war cry “Focus, Determination, Success” was indeed helpful. Although, I do not really miss these moments when publications had to be finished by the next day. Special thanks to Samuel for being such a terrific colleague and friend. Your wedding party is hard to top, but I will do my best. Thanks Marcel for sharing the coffee milk with me and Jon and also the cherry liquor you made yourself. You are indeed a very special person and I am glad I have met you. Maryon, you joined the team more recently and I have not seen you much around because you were mainly busy with teaching, courses and your lovely child. I am sure you will be doing great, especially with Chad as your supervisor. The “unconditional support” from all of you was really great!

I always felt like I was at the right place in the “bub” corridor due to the great people additionally from the ATLAS group. I thank all of you, especially Pawel for being a great friend and Christophe for being my mentor.

I also want to thank the entire IceCube collaboration and all the people I worked with during my PhD studies. Special thanks to the Uppsala IceCube group. I really enjoyed the regular Scandinavian IceCube meetings.

Finally, I would like to thank my family and friends for respecting my great absence far away from home during the last years. I am always very thankful whenever I can spend some time with you during my special journey of life.

Martin
Preface

The ordinary matter as we experience it in our daily life contributes to the total energy content of the Universe by only about 5%. The nature of the remaining part is yet unknown, but cosmological observations suggest it consists of Dark Matter (DM) and dark energy. This Ph.D. thesis contributes to the enormous effort in particle physics and astrophysics to reveal the existence and nature of DM. This thesis focuses on the most experimentally accessible particle candidate for DM: The Weakly Interacting Massive Particle (WIMP) with masses\(^1\) in the range from a few GeV to several TeV. By means of two analyses I have been searching indirectly for DM in the Galactic center and the Galactic halo probing the DM thermally-averaged self-annihilation cross-section, \(\langle \sigma_A v \rangle\), for WIMP masses in the range 30 GeV – 100 TeV and several WIMP annihilation channels using observational data of several years from the IceCube Neutrino Observatory at the South Pole. The IceCube low-energy detector infill array DeepCore has been utilized to probe small WIMP masses in the GC providing the most stringent published upper limits on \(\langle \sigma_A v \rangle\) to date for the direct annihilation of low-mass WIMPs (\(\sim 65\) GeV) into pairs of neutrinos assuming the NFW DM halo profile in the Milky Way. The search for WIMPs in the GC has already been presented by me in my licentiate thesis [1], but the search used a cut-and-count analysis approach instead of a likelihood method as described in this Ph.D. thesis. However, some parts, in particular the atmospheric muon veto techniques (section 8.1) and the event selection (section 8.2) are similar in the two theses.

\(\text{1This thesis uses the system of natural units in particle physics, where } h = c = k_B = 1.\)
About this thesis

This thesis is divided into three parts and contains ten chapters. Part I – III of this thesis is written in monograph form. My publications and conference proceedings supporting this thesis are appended at the end of this thesis.

Part I with chapter 1 provides a theoretical overview and introduces the research field of Dark Matter physics, the WIMP as possible DM particle candidate, and the neutrino signal flux from possible WIMP self-annihilation in the Milky Way. Part II discusses the principles of neutrino detection in chapter 2 and the IceCube neutrino detector at the South Pole in chapter 3. Furthermore, it discusses expected backgrounds for indirect WIMP searches using neutrinos in chapter 4. The part finishes with chapter 5 describing background and signal event simulation in IceCube. Part III contains the analysis chapters describing the indirect search for DM in the GC and the GH. Chapter 6 provides a general overview of the two analyses by emphasizing their distinct and complementary features and chapter 7 introduces the statistical concepts used in both analyses. The DM searches in the GC and the GH are presented with their results in detail in chapter 8 and chapter 9, respectively. Chapter 10 provides a conclusion and a brief outlook for possible improved results using the future PINGU detector. It finishes the monograph-section of this thesis. Finally, four papers published during the time of my Ph.D. studies and supporting this thesis are appended. Their content and my contribution to them are described below.

Author’s contribution

Below, the content and my contributions to the attached papers are summarized. Furthermore, I list my main contributions to the IceCube collaboration during my Ph.D. studies. Being part of a large collaboration like IceCube, major achievements are usually the result of great team work where many people made small but essential contributions.

Contribution to Papers

Paper I is a conference proceeding for an oral presentation at the International Cosmic Rays Conference (ICRC) in 2013. In this paper, I and my colleagues S. Flis (presenter) and M. Danniger describe event selection and veto techniques to reject atmospheric muon background in IceCube, which have been developed by us for the search for WIMPs in the Sun [2] and the Galactic center [3]. In particular, the five veto methods presented in this paper have been utilized in the GC DM search (cf. chapter 8, esp. section 8.1). I contributed substantially to
the development of these veto techniques and the writing of this paper.

**Paper II** is a conference proceeding for an oral presentation at the International Cosmic Rays Conference (ICRC) in 2013, as well. This paper, presented by myself, describes the status of the search for low-mass DM in the GC as detailed in chapter 8 in combination with the search for high-mass DM in the GC performed by my collaborator M. Bissok at Rheinisch-Westfälische Technische Hochschule Aachen. Together with my colleagues S. Flis and M. Danniger I developed the low-mass DM analysis utilizing the DeepCore low-energy infill detector array of IceCube (cf. section 3.1) to probe WIMP self-annihilation in the GC for WIMP masses as low as 30 GeV. I also contributed substantially to the text writing of this paper.

**Paper III** is the peer-reviewed journal publication with the results of the combined IceCube DM searches in the GC performed by my colleague S. Flis and myself at Stockholm University, and by my IceCube collaborator M. Bissok at Rheinisch-Westfälische Technische Hochschule Aachen, Germany. Together with S. Flis, I developed the low-energy event selection of this combined analysis utilizing the veto techniques as presented in paper I. Furthermore I helped to develop and apply the analysis method for this low WIMP mass search in the GC. Together with S. Flis and M. Bissok I wrote and published this paper.

**Paper IV** is chapter 8 “Dark Matter” of the letter of intent for The Precision IceCube Next Generation Upgrade (PINGU), a possible future detector infill array into DeepCore allowing to decrease the neutrino detection energy threshold to \(\sim 1\) GeV. Such a dense detector would allow to search for WIMP DM with masses as low as \(\sim 5\) GeV. Together with M. Danniger I developed and performed two sensitivity studies for the search for WIMPs in the Sun and the GC using the PINGU detector. Chapter 8 of this paper describes these two studies in detail and is self-contained. These studies show that PINGU would be able to improve current low-mass WIMP searches in both targets. Depending on the actual final capability of the detector to reject atmospheric muons by using the surrounding DeepCore and IceCube arrays as an atmospheric muon veto, the improvements vary by several factors. The entire DM chapter 8 of this paper is written by myself with the help of M. Danniger.
Contribution to IceCube

I represented the IceCube collaboration through contributed talks at international conferences:

- 25th International Workshop on Weak Interactions and Neutrinos (WIN), Heidelberg, Germany, 2015. “Indirect Dark Matter Searches with the IceCube Neutrino Observatory” I presented an overview on Dark Matter searches and their results performed in IceCube.

- 33rd International Cosmic Ray Conference (ICRC), Rio de Janeiro, Brasil, 2013. “Results from Low-Energy Neutrino Searches for Dark Matter in the Galactic Center with IceCube-DeepCore” I presented the status of the low-energy DM search in the GC as described in paper II.

In addition to my data analysis work, I developed several IceCube software projects commonly used by other IceCube collaborators.

CommonVariables

Neutrino event selection in IceCube relies on the calculation of event observables based on the detected light pulses. These event observables are used to develop cuts to reject background events and retain signal events. The CommonVariables IceCube software project provides a central implementation of commonly-used event observables, avoiding the need for reimplementations of such common observables by each analyst. Thus, event selection can be developed more quickly and is less error-prone. CommonVariables is implemented in C++ and provides Python bindings through the boost::python library [4] to allow simple integration into event processing scripts usually written in Python. It has been code-reviewed by the IceCube collaboration and fully integrated into the IceCube software repository. It is widely used in all processing levels from online filtering at the South Pole to the final analysis event selection stage by individual IceCube analyzers.

STTools

An effective noise hit cleaning in IceCube can be achieved by selecting only hits of an event that are causally connected in space and time (cf. section 3.4.1). I developed the C++ template programming framework STTools to allow a fast
development of such selection algorithms in IceCube.

**BoostNumpy** The programming language Python has become very popular in science due to its versatility and simplicity. Together with the NumPy [5] package Python provides a powerful working environment for big data science. However, Python is an interpreted language with decreased performance compared to a compiled language like C or C++. Thus, performance-critical or often repeated calculations, *i.e.* for each event, are implemented in C++. In order to be able to access data in C++ that is stored in NumPy data arrays, I developed the BoostNumpy [6] extension to the boost::python library [4]. It allows one to write C++ functions operating on scalar input values and executing them on a large set of data with only a single line of Python code. Like boost::python, BoostNumpy utilizes the meta-programming technique through C++ templates to dynamically construct the required run-time code for the Python bindings of the scalar C++ functions already at compile-time. Hence, scalar C++ functions can be exposed to Python with a single and simple line of C++ code.
Part I

Introduction on Dark Matter
1 Dark Matter

The cover picture of this thesis shows what the human eyes see in the sky on a dark and clear night. They see light – light emitted mainly from stars within the Milky Way, our own galaxy, but also from other near-by galaxies like Andromeda. When the objects are visibly too faint because their light emission intensity is too low or they are just too far away, humans need to use optical telescopes that can resolve those objects. Beside the telescopes that measure the electromagnetic astrophysical spectra one can use also particle detectors functioning as telescopes detecting cosmic particles either in space or on Earth. Using the most sensitive telescopes available to mankind to date, scientists have looked very closely at the objects we can see nearby and deep in the Universe. It seems that the Universe does not only consist of visible baryonic matter but also consists of dark matter and dark energy. This introductory chapter highlights the historic observational evidence for the existence of DM and describes possible candidates for DM. Furthermore, it discusses DM detection methods and finishes with a discussion about the possible DM density profiles of the Milky Way and their neutrino signals from DM particle annihilation.

1.1 Evidence for Dark Matter

In the past astronomers have studied the motion of stars of our galaxy and found anomalies when they compared the measured rotational velocity of the stars to the expected one derived from the law of gravity. Back in 1932, Jan Oort studied the motion of nearby bright stars [7] and concluded that there is invisible mass located in the galactic plane. He used the term Dark Matter but suggested an explanation by the presence of faint unseen stars. One year later Fritz Zwicky studied the Coma galaxy cluster [8]. Due to the old age of that cluster he assumed that the galaxies have already virialized and determined the average velocity of the galaxies using the virial theorem and the estimated mass of their visible matter. He found that the calculated velocity is much less than the one inferred by Doppler measurements. He concluded that the mass of the Coma galaxy cluster must be 400 times higher than the mass of the seen stellar matter.
In the late 1960’s, measurements of the rotation curves of galaxies had become possible using optical and radio techniques. In 1970, Rubin & Ford published a paper [9] showing the rotational velocity of stars in the Andromeda galaxy (M31) using optical measurements of the Hα spectral lines from ionized hydrogen regions in M31. Their measurements extended in radial distance from M31’s center only up to about 23 kpc. However, in 1975 Roberts & Whitehurst [10] measured the rotation curve of atomic hydrogen regions in M31 using the hydrogen 21 cm radio line for radial distances up to 30 kpc. The combined results of the optical and radio measurements are shown in figure 1.1. At large radial distances the rotation curve flattens out, which is in contradiction with a Keplerian fall-off ($v \propto 1/\sqrt{r}$) based on only the enclosed luminous matter. Thus, a dark mass component must be present in the galaxy, even in the outer regions where little gas and few stars exist, leading to an increasing cumulative mass with increasing radial distance. Roberts & Whitehurst conclude that Dwarf M stars of number a few tenths per cubic parsec could be an explanation of the missing mass and the observed mass-to-luminous ratio. In 1980 a follow-up study by Rubin, Ford & Thonnard [11] was published, measuring the rotation curves of 21 Sc galaxies of various size (4 to 122 kpc) and luminosity. The rotation curves of all galaxies have a similar shape and are flattened out with increasing radial distance from their centers. But a conclusive evidence for DM was still pending.

More direct empirical evidence for DM can be obtained using gravitational lensing effects. Gravitational lensing in the Universe in general means that the light of background objects, like galaxies, are deflected by the big mass of a foreground object, i.e. the lens, like a cluster of galaxies. Two types of gravitational lensing exist: Strong and weak gravitational lensing. In the first case, the mass of the lens object is big enough that the image of a background object is distorted to an arc due to the space-time bending in general relativity. These arcs are then seen multiple times aligned on a ring around the lens object. The rings are also known as Einstein rings. In contrast, in weak gravitational lensing the mass of the foreground lens object is too weak to cause significant distortions of a single background object but the distortion effect of the background objects is still present. So a statistical analysis of the distortion of many of the background objects have to be performed in order to deduce the properties of the lens.

The merging galaxy cluster 1E 0657-558 – the “Bullet cluster” – is an example of the usage of the weak gravitational lensing technique. By observing the weak gravitational lensing effects of background galaxies due to its total mass and by measuring its X-ray emission [12, 13], a direct hint for the existence of DM can be inferred. During the collision of two galaxy clusters, the galaxies can be regarded as collisionless particles, while the X-ray emitting in-
1.1 Evidence for Dark Matter

Figure 1.1: Rotation curve of the Andromeda galaxy (M31) measured optically by Rubin & Ford [9] and via the 21 cm radio line along the galaxy’s major ellipsoid axis by Roberts & Whitehurst [10]. The rotation curve flattens out at large radial distance from the galaxy’s center given rise to an increasing cumulative mass with increasing distance, while the surface density from luminous matter decreases with distance. Figure taken from [10].

The intracluster plasma behaves like a fluid and experiences ram pressure. Thus, the galaxies get spatially segregated from the plasma. The Bullet cluster has a high mass-to-luminous ratio indicating a high DM concentration. The luminous matter consists of the stellar component (1-2% [14]) and the intracluster plasma component (5-15% [15, 16]). If the DM would not be present the total mass of the cluster would be dominated by the plasma component and the gravitational map contour lines would follow the mass distribution of that plasma. Only in merging galaxy clusters, where the plasma component gets separated from the DM and stellar components, also a separation of the gravitational potential from the plasma mass distribution is observable, providing a very strong and direct evidence for the existence of DM.

Recently, it has been possible to determine the rotation curve of our own galaxy, the Milky Way, especially for regions of the galaxy inside the solar circle [17]. By comparing state-of-the-art baryonic mass distribution models to a compilation of observed data from 2780 individual measurements of gas kinematics, star kinematics and masers, the disagreement of these models with the data for the innermost regions of the galaxy by more than 5σ significance can be regarded as an other tremendous peace of evidence for the existence of DM even in our own galaxy.
On cosmological scales, the density of the individual mass-energy components of the universe, $\rho_i$, can be expressed in terms of the critical density of the universe, $\rho_c$, that would lead to a flat universe:

$$\rho_c = \frac{2H_0^2}{8\pi G_N};$$  \hfill (1.1)

$$\Omega_i = \frac{\rho_i}{\rho_c},$$  \hfill (1.2)

where $H_0$ and $G_N$ is the Hubble constant and Newton’s gravitational constant, respectively. In the $\Lambda$-Cold-Dark-Matter ($\Lambda$CDM) model of the universe the total density in terms of $\rho_c$ of the universe, $\Omega_{\text{tot}}$, consists of the baryonic matter density, $\Omega_b$, the cold DM density, $\Omega_c$, and the dark energy density, $\Omega_{\Lambda}$. For a flat universe $\Omega_{\text{tot}} = \rho/\rho_c = \sum_i \Omega_i$ would have the value one and the value $\Omega_i$ of the individual density components would be equal to their fractional abundance in the universe.

The different matter-energy density components leave imprints in the Cosmic Microwave Background (CMB). In the radiation dominated era of the early Universe, photons were not yet decoupled from the baryonic matter. Thus, the density distribution of the baryonic matter was influenced by the radiation pressure and the gravity arising from baryonic and dark matter. The baryonic density fluctuations are known as Baryonic Acoustic Oscillations (BAOs) and were in-
1.1 Evidence for Dark Matter

Figure 1.3: Foreground-subtracted CMB temperature power spectrum measured by Planck [18]. Upper panel: A precise measurement of seven acoustic peaks. The gray dots are the individual multipole measurements and the blue dots are the average values over 31 consecutive $l$-values together with their 1$\sigma$ uncertainties. Lower panel: The power spectrum residuals. The green lines show the ±1$\sigma$ uncertainties on the individual power spectrum estimates for high multipole values. Figure from [18].

The acoustic oscillations can be measured through a multipole expansion analysis of the CMB. The first satellite based CMB measurements were performed by the Wilkinson Microwave Anisotropy Probe (WMAP) [19] which provided a detailed map of the CMB temperature fluctuations. Up to date, the successor satellite experiment Planck provided the most accurate map [18]. Both data are compatible. The Planck temperature power spectrum for different angular scales (i.e. different multipole values, $l$) is shown in figure 1.3. The first and successive peaks carry information about the amount of baryonic and non-baryonic matter, respectively. The $\Lambda$CDM model can be fitted to that spectrum. Table 1.1 contains the density values of the $\Lambda$CDM model and the value of the Hubble constant obtained from the combined Planck and WMAP data. The red line in figure 1.3 shows the best fit of the $\Lambda$CDM model. The $\Lambda$CDM model fits also well to data obtained from 557 high redshift type Ia
Table 1.1: Composition of the Universe. Values of the baryonic matter ($\Omega_b$), cold Dark Matter ($\Omega_c$), dark energy ($\Omega_\Lambda$) densities, and the Hubble constant of the universe, measured by the Planck collaboration using combined Planck and WMAP data [18]. The dimensionless Hubble parameter $h$ is defined as $h \equiv H_0 / (100\text{km}\text{s}^{-1}\text{Mpc}^{-1})$.

<table>
<thead>
<tr>
<th>$\Omega_b h^2$</th>
<th>$\Omega_c h^2$</th>
<th>$\Omega_\Lambda$</th>
<th>$H_0$ ($\text{km}\text{s}^{-1}\text{Mpc}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.02205 \pm 0.00028$</td>
<td>$0.1199 \pm 0.0027$</td>
<td>$0.685^{+0.018}_{-0.016}$</td>
<td>$67.3 \pm 1.2$</td>
</tr>
</tbody>
</table>

One of the latest methods to observe DM is through the utilization of Type Ia supernovae [20] by the Supernova Cosmology Project.

1.2 Dark Matter Candidates

In order to explain the observational evidence of DM three main theory categories exist describing what DM is supposed to be. The first category makes faint Massive Compact Halo Objects (MACHOs), e.g. planets, brown dwarfs, or primordial black holes, the cause of the invisible mass. It has been searched for gravitational micro-lensing effects caused by MACHOs in the Magellanic Clouds, but the observed number density of such objects is too small to solve the flat rotation curve problem [21, 22, 23]. The second category is the set of theories that modify Newton’s law of gravity at large scales (Modified Newtonian Dynamics (MOND) theories [24]) and thus do not require the existence of new types of particles. However, one should note that the Bullet cluster provides a gravity model independent evidence for the existence of DM [12]. The third category consists of theories that assume DM to be new types of massive particles. Thus, such theories require an extension of the Standard Model (SM) of particle physics. In this case the observational evidence constrain the properties of such new particles. DM particles must be cold, i.e. non-relativistic, and non-baryonic particles. Otherwise the small-scale density fluctuations of the early universe could not have been grown via the BAO observed today in the CMB. The formation, evolution, and clustering of galaxies can also be simulated using $N$-body simulations. Such simulations prefer a cold DM scenario rather than a hot DM scenario [25]. The non-baryonicity of DM require it to be color-neutral, hence it must not interact with the strong force. The fact that the DM is “dark” means it should also be electrically neutral, thus with no electro-magnetic interactions. Interactions via the weak-force are still possible, however, the weak cross-section of the DM particles with baryonic matter must be lower than the one between the ordinary matter. Otherwise direct detection experiments (see section 1.3) would have most-probably already discovered the DM particles.
1.2 Dark Matter Candidates

The observational evidence does not constrain the spin of the DM particle, thus DM particles can be fermionic or bosonic. The stability of the lightest DM particle must be high, or conversely for Majorana typed DM particles, the self-interactions rather weak. Astrophysical lower limits on the lifetime of the DM particles can be set depending on their SM decay products, and are currently in the order of $\sim 10^{26}$ s using, e.g., satellite-based $\gamma$-ray observations [26]. DM self-annihilation must also be rare, however, not forbidden, when assuming that the DM particles were in thermodynamic equilibrium in the early universe. During the expansion of the early hot universe, its expansion rate became larger than the DM self-annihilation rate causing the DM particles to fall out of their thermodynamic equilibrium. One says the DM particles freeze out and a relic DM particle abundance freeze in. In this simple picture one can formulate the relation between the DM abundance at freeze-out time and the thermal averaged product of the self-annihilation cross-section and the relative velocity, $\langle \sigma_{A}v \rangle$, of the DM particles by solving the appropriate Boltzmann equation for the time evolution of the number density of WIMPs [27]:

$$\Omega_{DM}h^{2} \approx \frac{3 \times 10^{-27} \text{cm}^{3}\text{s}^{-1}}{\langle \sigma_{A}v \rangle}.$$  

(1.3)

Using the value $\Omega_{c}h^{2}$ from the CMB measurements as given in table 1.1 for the relic DM density, the DM self-annihilation strength is in the $\mathcal{O}(10^{-26})\text{cm}^{3}\text{s}^{-1}$, which is commonly referred to as the “natural scale”. This also implies, that if the particle constitute to all or part of the unseen dark matter, its self-annihilation strength is equal, or higher than the natural scale, respectively.

The SM of particle physics has been very successful predicting the existence of all the elementary particles that we have also already discovered. But none of these particles has the properties of the a DM particle as described above. Thus, an extension of the SM is required if DM particles do exist. At this point we just want to mention three popular types of extensions of the SM.

The first type is the supersymmetric extension of the SM, called SUperSYmmetry (SUSY). SUSY introduces a symmetry between forces and matter [28]. For each SM boson a fermionic super-partner with spin 1/2, and for each handedness SM fermion a scalar bosonic super-partner with spin 0 is introduced. Weakly interacting supersymmetric particles with masses above a few GeV, commonly called WIMPs might be perfect candidates for Cold Dark Matter (CDM). The analyses presented in this thesis assume WIMPs in general to be the DM particles. For simplicity they are denoted just as $\chi$. The SUSY model with the smallest possible field content giving rise to all the fields of the SM is called the Minimal Super-symmetric Standard Model (MSSM) [29]. Supersymmetry in the MSSM introduces the quantum number $R$-parity, $R$, which
is assumed to be conserved. The SM particles have the R-parity $+1$ assigned, whereas the super-particles (sparticles) have R-parity $-1$. $R-parity$ is a multiplicative quantum number, thus sparticles can only decay into an odd number of lighter sparticles plus any kinematically allowed number of particles. Beside the decay, self-annihilations into SM particles are also possible if the sparticle has a Majorana character. In the MSSM a few particles, such as neutralinos, sneutrinos, axinos, and gravitinos, would fulfill the DM particles requirements. Among these the neutralino has the highest interaction probability and is therefore of particular interest to detection from a phenomenological point of view. The neutralino is a linear combination of the super-partners of the $B$, $W_3$, and the two neutral Higgs fields, $H_1^0$ and $H_2^0$, forming four neutralino mass eigenstates ($\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, and $\tilde{\chi}_4^0$), where $\tilde{\chi}_1^0$ is denoted as the lightest one:

$$\tilde{\chi}_1^0 = n_{11} \tilde{B} + n_{12} \tilde{W}_3 + n_{13} \tilde{H}_1^0 + n_{14} \tilde{H}_2^0.$$ (1.4)

The super-symmetric partners are called gauginos ($\tilde{B}$ and $\tilde{W}_3$) and higgsinos ($\tilde{H}_1^0$ and $\tilde{H}_2^0$). The lightest neutralino mass eigenstate, $\tilde{\chi}_1^0$, could be the Lightest Super-symmetric Particle (LSP) of the MSSM and thus the DM particle.

The second type of SM extensions results from theories of Universal Extra Dimensions (UEDs). Within the minimal UED theories an extra dimension of size $O(\text{TeV}^{-1})$ featuring a tower of Kaluza-Klein (KK) states [30]. The first excitation of the hyper-charge gauge boson, $B^{(1)}$, is generally the lightest Kaluza-Klein particle (LKP). Usually it is denoted as KK-photon, $\gamma^{(1)}$. The LKP is supposed to be stable due to the KK-parity quantum number conservation arising from the momentum conservation in the higher dimensional space. Other KK particles, e.g. the KK-graviton, the KK-neutrino, or the $Z^{(1)}$-boson, might also be possible DM particle candidates. In general, the masses of the KK particles are found to be in the GeV-scale, making them a subset of WIMPs.

The third type of SM extensions is the introduction of Axion Like Particles (ALPs). Originally, the axion was introduced to solve the strong-CP problem in Quantum Chromodynamics (QCD). The strong-CP problem arises because experimentally no CP-symmetry violating process has been observed in the QCD sector, unlike in electroweak theory. Theoretically, there is no reason why the CP-symmetry should be conserved in strong interactions. Such a CP-violation would cause e.g. an electric dipole moment (EDM) of the neutron, that has not been yet observed. Its 95% C.L. upper limit has been determined as low as $3.6 \cdot 10^{-29} \text{ e}\text{m}$ [31] virtually excluding the neutron EDM. In order to accomplish CP-symmetry conservation in QCD, specific parameters of QCD, e.g. the vacuum angle $|\theta| \lesssim 10^{-11}$ [32], need to be chosen very precisely without a more fundamental theory behind these choices, also known as the fine-tuning problem of the universe. The most well-known proposed solution to the strong-CP problem is the Peccei-Quinn theory [33]. There new pseudo-scalar particles
called axions are introduced. In a presence of a magnetic field axions can couple to two photons, $g_{a\gamma\gamma}$, but the coupling is suppressed by the high Peccei-Quinn symmetry breaking scale, $f_a$. This coupling, and thus the conversion of axions to photons, and vice versa, is often used for experimental searches, e.g. light-shining-through-a-wall experiments. In such experiments laser light is directed into the bore of a dipole magnet in front of a wall. Since axions are only weakly interacting particles in vacuum they are traveling through the wall and might reconvert to photons inside a second dipole magnet at the other side of the wall. The typical mass of axions is at the sub-eV scale. They are not produced through thermal freeze-out like the WIMPs. Instead they form a Bose-Einstein condensate with very high number density. Due to their properties, axions are candidates for a DM particle.

In the following we want to focus on the class of WIMP DM particles and describe briefly different detection principles of those. In the analyses presented in this thesis, we have concentrated our research exclusively on the class of WIMP DM particles, due to their high mass expectation at the GeV and TeV energy scale, probeable by the IceCube neutrino experiment (see chapter 3).

### 1.3 Dark Matter Detection

DM particles can be detected using different detection principles. Based on the orientation of the Feynman-diagram describing the general DM particle interaction with SM particles, three main principles can be distinguished. Figure 1.4 shows the three orientations leading to three types of detection: Direct detection, indirect detection, and production. In the following sub-sections we will focus on the detection methods for WIMPs using these three techniques.

![Figure 1.4](image.png)

**Figure 1.4:** Simplified Feynman diagrams for WIMP-SM particle interactions for different time orderings (time line always from left to right). (a) Direct detection through WIMP-SM scattering; (b) Indirect detection through WIMP self-annihilation into SM particles; (c) WIMP pair production through a collision of SM particles. Figure from [34].
1.3.1 Direct Detection

Direct detection experiments aim to measure the WIMP-nucleon cross-section, $\sigma_{\chi N}$, through the detection of WIMPs scattering off target nuclei. When WIMPs scatter off nuclei, the nuclei experience a recoil, that can be measured either via its heat deposition (phonons), its produced scintillation light (photons), or its ionization (electrons) inside the fiducial volume of the experiment. Usually an experiment is able to utilize two of these recoil measurements to discriminate background from signal events. Since the signal is expected to be very small because of the weak-scale cross-section, such experiments must be kept background free from thermal noise, or cosmic rays induced muons. Thus, such experiments are put underground deep inside a mountain or kilometers deep into the ice. In order to keep the thermal noise at a minimum, cryogenic apertures are usually required. To veto the atmospheric muon background usually active veto volumes filled with water and containing Photo-Multiplier Tubes (PMTs) measuring the muon’s produced Cherenkov light are used. If the WIMP has a spin, the WIMP-nucleon cross-section is composed of a spin-independent (scalar interaction), $\sigma_{\chi N,SI}$, and spin-dependent (axial-vector interaction), $\sigma_{\chi N,SD}$, cross-section. The former one scales with the square of the atomic number, $A$, of the target material. Thus, to increase the experiment’s sensitivity to the WIMP-nucleon cross-section, target material with high atomic numbers are usually chosen. Experiments using liquid noble gases to measure recoil scintillation and ionization are e.g. XENON [35, 36, 37], LUX [38], ZEPLIN [39], Dark-Side [40] and DEAP [41]. Other experiments like CDMS [42, 43, 44, 45], CoGeNT [46, 47], EDELWEISS [48] and CRESST [49] use semi-conductor materials in a cryostat to measure phonons from the recoil energy deposition together with ionization or scintillation. A complementary approach is to utilize the metastability of a superheated liquid composed of carbon and fluorine pursued by e.g. the COUPP [50], PICASSO [51], PICO [52], and SIMPLE [53] experiments.

A more distribution-based, rather than event-by-event based, detection technique is to look for annual modulations of the WIMP-nucleon recoil rate in a crystal when Earth travels around the Sun, and thus passes through different DM velocity distributions. The DAMA/LIBRA experiment [54] utilized this technique and claimed a found annual modulation at $> 8\sigma$ significance [55, 56] that is consistent with the presence of a 60 GeV WIMP in the galactic halo. With a significance of 2.8$\sigma$ results from CoGeNT [57] support this annual modulation. However other experiments like CDMS, XENON, COUPP, or EDELWEISS exploring the same parameter space were not able to confirm this claim. Thus, the DAMA results remain highly controversial. A compulsory test could be made by the proposed DM-ICE experiment [58] deep in the South Pole ice.
using the same detector material (NaI) as DAMA but located at the opposite hemisphere. Hence, seasonal variations and environmental effects could be excluded as possible backgrounds currently being the explanation of the observed DAMA modulation.

### 1.3.2 Indirect Detection

Complementary to the direct detection is the indirect detection, where DM particles are detected via their annihilation or decay SM particle products. Usually indirect searches focus on astro-physical targets where the DM particle density is expected to be high. Such targets are the cores of celestial bodies like the Earth, the Sun or entire galaxies and clusters of galaxies. Within the Milky Way the galactic center and the surrounding galactic DM halo can also be dominating sources of particles from DM annihilation or decay due to their close distances to Earth. Existing indirect DM detection experiments are either ground-based or satellite-based particle detectors. Due to the size restrictions of the latter, satellite experiments are usually aiming at the detection of photons in the keV to GeV energy range, *i.e.* being X-ray and $\gamma$-ray detectors. Ground-based detectors can be built bigger and thus can be sensitive for higher particle energies up to the TeV energy scale. Via telescope dishes they detect the Cherenkov light produced by charged particles induced by cosmic $\gamma$-rays interacting in the upper atmosphere. Examples are H.E.S.S. [59], Veritas [60], and the future CTA [61] experiment. Neutrino detectors at Earth, *e.g.* the IceCube neutrino observatory (see chapter 3), can even probe energy scales above a PeV. Satellite-based experiments aim to detect X-rays, *e.g.* XMM-Newton [62], or $\gamma$-rays, *e.g.* Fermi [63].

In 2014 an unidentified 3.5 keV X-ray line was observed in galaxy clusters and the Andromeda galaxy that might be explainable with DM particle decay [64, 65]. But instrumentation effects or an atomic transition line could be an explanation as well. A similar anomaly has been observed in 2012 when analyzing Fermi data in the galactic center region [66]. There, a 130 GeV $\gamma$-line at $3.2\sigma$ significance had been observed possibly caused by DM particle annihilation. A follow-up analysis [67] by the Fermi collaboration using improved event processing and reconstruction techniques lowered the global significance of that $\gamma$-line and favored an instrumental effect for its cause.

Dwarf spheroidal galaxies in the vicinity of the Milky Way are favored targets for DM searches due to their high mass-light ratio, providing smaller systematic uncertainties in the foreground light emission modeling required in general for photon observation. The total dark matter content can also be estimated relatively accurately via stellar rotational curve or gravitational microlensing measurements. The fact that no line features, either in X-ray [68] or $\gamma$-ray [69], have been observed in dwarf spheroidal galaxies, weakens the argumentation of
a DM based explanation of the observed line features.

Satellite experiments like PAMELA [70], AMS-02 [71], or Fermi [72] measuring the antimatter fraction of cosmic-rays can also be used to search indirectly for DM particles. If DM particles decay or annihilate into pairs of charged leptons, e.g. $e^+e^-$, the energy distribution of the antimatter fraction can be used to search for DM. For instance the positron fraction is governed by cosmic-ray interactions with gas in the interstellar medium and should fall off at high energies ($\sim 10 \text{ GeV}$). In contrast to the expectations, the positron fractions measured by these experiments indicate a rise and a flattening-out at high energies. A possible explanation is the additional abundance of positrons from DM annihilation or decay if the DM is leptophilic, i.e. predominantly leptons as primary end products. Alternatives to a DM based origin from TeV WIMP annihilation [73] of the observed high energy positrons are astro-physical source objects like nearby pulsars and pulsar-wind nebulae [74] or supernova remnants [75] producing positrons by accelerated electron induced electromagnetic cascades.

In case of the existence of leptophilic DM, DM particles might also annihilate or decay predominantly into neutrinos. Thus, data from large neutrino detectors like Super-Kamiokande [76], ANTARES [77], or IceCube [78] can be analyzed in regard of excesses of neutrinos originating from WIMP annihilation in astro-physical targets like the Sun [2], galactic halo [79], and the galactic center [3]. Unlike charged particles, neutrinos are deflected only by the gravitational space-time bending. Scattering of neutrinos in the interstellar medium is also much weaker than for photons. Hence at time of neutrino detection at Earth, they point mainly directly back to their origin. This thesis presents two IceCube analyses searching for WIMP annihilation in the Galactic center (see section 8) and the Galactic halo (see section 9).

### 1.3.3 Production Detection

At accelerators, like the Tevatron at FermiLab or the Large Hadron Collider (LHC) at CERN, WIMPs can be produced in particle collisions but will escape the detector in the same way as neutrinos due to their weak interactions. Thus, the search for neutral weakly interacting particles can only be performed by measuring the missing transverse energy, $E_{T,\text{miss}}$, of a particular interaction. Usually, DM particle production interactions with distinct leptons or hadrons (jets) in the final state are searched for [80, 81, 82, 83]. Such interactions allow an accurate $E_{T,\text{miss}}$, and hence DM mass reconstruction. For direct DM particle production channels initial state radiation of quarks or gluons with single photons or hadrons in the final state can be used as detection channel [84, 85, 86]. The interpretation of such searches depends on the underlying effective theory and the mediator masses with weaker constraints for lighter mediator masses.
For a particular DM particle interaction with SM particles, detailed signal and SM background Monte Carlo (MC) predictions can be produced. Kinematic cuts then reduce the SM background contribution in the data and an excess of events on-top of the remaining SM background predictions would then hint for the existence of the DM particles in question. The SM background can also be inferred from control regions from the observed data itself and extrapolating to the signal region eliminating systematic uncertainties arising from the background simulations. But this procedure has the disadvantage that backgrounds like neutrinos are irreducible.

1.4 Galactic Dark Matter Abundance

The exact distribution of DM particles in galaxies is poorly known. In order to keep the mass of the galaxy finite the density profile of the DM should approach zero at large distances. For the outer regions of the DM halo profile various mathematical expressions can be fitted to the rotational curve measurements mentioned in section 1.1. The DM density distribution in the inner part of a galaxy is more difficult to determine and is subject to debates. Measurements of rotational curves of dwarf galaxies and their fits to various DM density profiles suggest a cored DM density in the center regions of the galaxies, whereas numerical N-body simulations of DM particle distribution evolution [87] favor a cuspy central distribution, what is known as the cusp-core problem [88]. Possible explanations of that problem could be the neglect of baryons in the N-body simulations [89] and the influence of gas outflow on the DM distribution during star formation and supernovae explosions in the galaxy’s past [90].

Following Ref. [91], a broad set of DM density profiles can be formulated as

$$\rho_{DM}(r) = \frac{\rho_0}{\left(\delta + \frac{r}{r_s}\right)^\gamma \cdot \left(1 + \left(\frac{r}{r_s}\right)^\alpha\right)^{(\beta - \gamma)/\alpha}},$$

(1.5)

where $r_s$ is the scale radius, where the mass density profile changes slope between the inner and outer parts of the galaxy. The distribution is parameterized via the dimensionless profile parameters $\alpha, \beta, \gamma$, and $\delta$. We have introduced the parameter $\delta$ in eq. 1.5 in order to represent an even broader set of DM halo profiles. The normalization $\rho_0$, usually in units of GeV cm$^{-3}$, can be determined by solving this equation for $\rho_0$, when setting $r = R_{sc}$ and $\rho_{DM}(R_{sc}) = \rho_{sc} \equiv \rho_{local}$, where $R_{sc}$ and $\rho_{sc}$ denotes the radius of the solar orbiting circle around the GC and the (local) DM mass density at that radius, respectively.

Depending on the underlying data, i.e. either simulations or astro-physical observations, specializations of eq. 1.5 have been used to propose different DM
halo shapes fitting the considered data appropriately. The widely used Navarro-Frenk-White [92] shape \((\alpha, \beta, \gamma, \delta) = (1, 3, 1, 0)\) fits the data from N-body simulations best, while the Burkert [93, 94] shape \((\alpha, \beta, \gamma, \delta) = (2, 3, 1, 1)\) has been fitted to observed universal mass profiles obtained from measurements of the Milky Way terminal velocities at inner Galactic radii, the circular velocity of maser star forming regions at intermediate radii, and the velocity dispersions of stellar halo tracers for the outermost region of the Milky Way [95], resulting in a purely phenomenological model. A cored isothermal shape as proposed by Ref. [88] can also be realized by setting the parameters to \(\alpha = 2, \beta = 2, \gamma = 0,\) and \(\delta = 0.\) As model we denote a complete set of specific halo density profile parameter values of equation (1.5), i.e. including values for \(\rho_0\) and \(r_s.\) The same fits have been performed for the NFW profile as well [95]. Table 1.2 summarizes the fitted model parameter values \(\rho_0, r_s,\) and \(\rho_{\text{local}}\) of equation (1.5) obtained through these fits, together with their model parameter uncertainties. These model definitions are used throughout the analyses presented in this thesis.

Table 1.2: DM halo model parameters of the NFW and Burkert density profiles as given in [95] and used in the analyses presented in this thesis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NFW</th>
<th>Burkert</th>
</tr>
</thead>
<tbody>
<tr>
<td>((\alpha, \beta, \gamma, \delta))</td>
<td>((1, 3, 1, 0))</td>
<td>((2, 3, 1, 1))</td>
</tr>
<tr>
<td>(\rho_0) (\left[10^7 M_\odot/kpc^3\right])</td>
<td>(1.40^{+2.90}_{-0.93})</td>
<td>(4.13^{+6.2}_{-1.6})</td>
</tr>
<tr>
<td>(r_s) ([kpc])</td>
<td>(16.1^{+17.0}_{-7.8})</td>
<td>(9.26^{+5.6}_{-4.2})</td>
</tr>
<tr>
<td>(\rho_{\text{local}}) ([GeV/cm^3])</td>
<td>(0.471^{+0.048}_{-0.061})</td>
<td>(0.487^{+0.075}_{-0.088})</td>
</tr>
</tbody>
</table>

1.5 DM signal intensity in the Galactic Halo

DM particles might be subject to self-annihilation or decay into SM particles [96]. This work considers exclusively WIMPs and their self-annihilation. The intensity of WIMP self-annihilation in the galactic halo depends on the WIMP density distribution in the galactic halo (cf. section 1.4) and scales with its square. Following the notation from Ref. [96, 97] we define the line of sight (los) integral of the DM density squared, \(J_\Psi,\) along a viewing line through the galactic halo:

\[
J_\Psi(\Psi) = \int_0^{l_{\text{max}}} \rho_{\text{DM}}^2 \left( \sqrt{R_{sc}^2 - 2lR_{sc} \cos \Psi + l^2} \right) dl. \tag{1.6}
\]
1.6 Neutrino Flux from Dark Matter annihilation

Here, $\Psi$ and $\rho_{DM}$ denotes the opening angle w.r.t. to the GC and the DM density profile as given by equation (1.5) and specialized for the NFW and Burkert DM halo models with their parameter values given in table 1.2, respectively. The quantity $l$ is the distance along the line of sight. The upper integration limit

$$l_{\text{max}} = \sqrt{R_{\text{halo}}^2 - \sin^2 \Psi R_{\text{sc}}^2 + R_{\text{sc}} \cos \Psi}$$

depends on the radius of the galactic halo, $R_{\text{halo}}$. Due to the rapid decreasing behavior of equation (1.5) for radii larger than the scale radius $r_s$, such radii do not contribute significantly to the total value of $J_a$. This can be seen in figure 1.5a, that shows the DM density profile as a function of radial distance for the NFW and Burkert halo models as defined in table 1.2. Hence, we use $R_{\text{halo}} = 50$ kpc. The corresponding los integral for WIMP self-annihilation, $J_a$, is shown in figure 1.5b. Obviously, the NFW model describes a cuspy profile, whereas the Burkert model provides a cored galactic DM density profile. In order to avoid a divergence of the DM density, and thus for the los integral, for the NFW profile at $r = 0$ (since $\delta = 0$), we use a flat density core for $r < 0.015$ kpc, which corresponds to opening angles $\Psi < 0.1^\circ$. This procedure is similar to the one described in Ref. [97], that uses a constant $J_a$ value for $\Psi < 0.1^\circ$, but is more motivated from a physical point of view. However, there is no difference between both procedures for the analyses presented in this thesis due to their angular resolutions being greater than $0.1^\circ$. Since the intensity of DM annihilation is proportional to the los integral $J_a$, cusp models like the NFW model, with overall more DM in the galactic center region, will imply more stringent limits on the DM thermal averaged self-annihilation cross-section, $\langle \sigma_A v \rangle$ (cf. section 1.6), than cored DM models like the Burkert model.

1.6 Neutrino Flux from Dark Matter annihilation

When WIMPs self-annihilate in the galactic halo they are expected to produce SM particles, i.e. leptons, quarks, or bosons. Produced muons and tauons will decay weakly into lighter ones producing neutrinos. The bosons decay either leptonically, or into quarks and the quarks will hadronize into mesons, e.g. pions, which then decay into leptons or photons. At the end of the entire chain of particle decays a fraction of all produced SM particles are neutrinos that will propagate from the annihilation site to Earth, where they can be detected in large neutrino detectors like IceCube (cf. chapter 3).

The energy-differential flux of neutrinos resulting from DM annihilation, $d\Phi_\nu/(dA d\Omega dt dE)$, is proportional to the WIMPs’s thermal averaged annihilation cross-section, $\langle \sigma_A v \rangle$, the inverse of the WIMP mass squared, $m_\chi^2$, the yield of neutrinos of each annihilation process, $dN_\nu/dE$, and the los integral for DM
Figure 1.5: (a) DM mass density profile in the galactic halo as a function of the distance from the GC for the NFW and Burkert DM halo models (cf. table 1.2). (b) The corresponding los integrals $J_a(\Psi)$ for WIMP self-annihilation (cf. equation (1.6)) as a function of the opening angle, $\Psi$, from the GC.

annihilation, $J_a$. It can be formulated by [97]

$$\frac{d\Phi_{\nu}(\Psi)}{dA \, d\Omega \, dt \, dE} = \frac{\langle \sigma_A v \rangle \, J_a(\Psi)}{2 \, 4\pi m^2_\chi} \frac{dN_\nu}{dE}. \quad (1.8)$$

The factor $1/2$ accounts for the fact that there are two WIMPs per annihilation. Here we assume Majorana-type WIMPs, i.e. the WIMP is its own anti-particle. In scenarios where the WIMPs are not their own anti-particles, an additional factor $1/2$ would be required in equation (1.8). The isotropic emission of neutrinos is accounted for via the factor $1/(4\pi)$.

The exact branching ratio hierarchy of the WIMP, i.e. into which SM particles it annihilates in what fraction of all cases, is unknown and depends on the exact coupling constants of the WIMP to SM particles. Thus, in general $dN_\nu/dE$ is given by

$$\frac{dN_\nu}{dE} = \sum_{\text{ann. channels}} b_i \frac{dN_{\nu,i}}{dE}, \quad (1.9)$$

where $b_i$ stands for the actual branching ratio of the particular annihilation channel $i$. Due to the unknown branching ratios, it is common practice to consider different annihilation channels with 100% WIMP branching ratio. Annihilation channels resulting in soft and hard energy spectra of the detection particle in question, e.g. the neutrino, are usually chosen in order to bracket the real annihilation branching ratio hierarchy, which might be a mixture of different pure
annihilation channels. For neutrinos being the detection particle a soft channel is the annihilation into a pair of b-quarks, whereas the direct annihilation into a pair of neutrinos generates a very hard spectrum (essentially a line feature). In the analyses presented here, five different annihilation channels have been considered: \(\chi\chi \rightarrow b\bar{b}, \chi\chi \rightarrow W^+W^-, \chi\chi \rightarrow \mu^+\mu^-, \chi\chi \rightarrow \tau^+\tau^-,\) and \(\chi\chi \rightarrow \nu\bar{\nu}.)\)

The neutrino energy spectra, \(dN_\nu/dE\), have to be generated for each considered annihilation and WIMP mass using a software that simulates the WIMP annihilation and the resulting decay chain of the particle products. This work uses the Pythia software package [98] in version 8.175. In case of s-wave non-relativistic DM annihilation, as assumed exclusively here, a WIMP annihilation process can be seen as equivalent to the decay of a generic resonance, \(D\), with a mass of \(2m_\chi\), as discussed e.g. in Ref. [99]. The generic resonance is forced to decay into the annihilation particle products, e.g. \(b\bar{b}\), with a branching ratio of 100%. All neutrinos produced during one simulated annihilation process are recorded in a one-dimensional histogram according to their energies, constituting the neutrino energy spectrum of that particular annihilation process and WIMP mass. We produced neutrino energy distributions with a constant resolution of 1 GeV for all WIMP masses. In order to produce a smooth neutrino energy distribution, many annihilations (\(\mathcal{O}(10^7) - \mathcal{O}(10^9)\)) need to be generated producing a smooth neutrino energy distribution.

In general all neutrino spectra of the considered annihilation channels are subject to electroweak correction effects, that is the creation of additional virtual photons and real W and Z bosons within the annihilation/decay process resulting in additional low energy final neutrinos. This is discussed in great detail e.g. in Ref. [100] and converts the line feature of the neutrino spectrum for the annihilation process \(\chi\chi \rightarrow \nu\bar{\nu}\) into a continuous spectrum. The electroweak correction effect occurs for WIMP masses higher than the \(W/Z\) mass, i.e. around 90 GeV. In general, the detection efficiency of large neutrino detectors degrade with decreasing energies. Since the additional neutrinos are found to be most prominent at low energies (\(\lesssim 10\) GeV) such neutrinos do not contribute much to the signal detection capability. The neutrino energy threshold of the IceCube neutrino detector is \(\sim 10\) GeV. In this work we do not consider electro-weak corrections. Thus, the neutrino spectrum of the direct annihilation of WIMPs into a pair of neutrinos leads to a line spectrum with a line energy at the mass of the WIMP. Practically, a line features can cause technical difficulties. Since we are using general IceCube simulated neutrino data (cf. section 5.1.1) to create WIMP signal probability density functions (p.d.f.s), the analysis would suffer from too little simulated data statistics when selecting simulated neutrino events with only one exact energy. Thus, we are using a Gaussian shaped spectrum centered around the WIMP mass with a standard deviation of 5% the mass of
the WIMP. The normalization is fixed so that the energy integrated neutrino yield is $1/3$ for each individual (anti-)neutrino flavor per WIMP annihilation.

The signal neutrinos are subject to neutrino oscillations on the way from their creation site in the Milky Way to Earth. The existence of neutrino oscillations has been discovered by the Super-Kamiokande and the Sudbury Neutrino Observatory (SNO) neutrino underground detector experiments. Super-Kamiokande detected a zenith angle dependent disappearance of atmospheric muon neutrinos which is consistent with the two-flavor oscillation of muon and tauon neutrinos with $\Delta m^2 > 0$ [101]. The SNO experiment measured the total flux of $^8\text{B}$ solar neutrinos and found a deficit of electron neutrinos consistent with the oscillation of electron neutrinos into muon and tauon neutrinos [102]. IceCube has measured the atmospheric muon neutrino flux in dependence on the zenith angle and was able to confirm the Super-Kamiokande results [103, 104]. For a two-neutrino oscillation hypothesis the probability that a neutrino flavor state $a$ has oscillated to flavor state $b$ depends on the mixing angle $\theta$ between the neutrino flavor states, the mass squared difference of the neutrino mass eigenstates, $\Delta m^2$, and the ratio of propagation length $L$ over the energy of the neutrino $E_\nu$ [101]:

$$P_{a \rightarrow b} = \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/\text{eV}^2)(L/\text{km})}{(E_\nu/\text{GeV})}$$  \hspace{1cm} (1.10)

With values for $\Delta m^2$ and $E_\nu$ of $10^{-4}$ and 1 TeV, respectively, the oscillation length is well below 1 AU, i.e. the Sun–Earth distance. Hence, this work assumes a neutrino flavor ratio of

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$$  \hspace{1cm} (1.11)

at Earth.
Part II

Neutrino Detection & The IceCube Neutrino Observatory
Neutrinos are neutral weakly interacting elementary paricles. They are fermions with spin 1/2 and belong to the family of leptons. They exist in three different flavors: electron-neutrino ($\nu_e$), muon-neutrino ($\nu_\mu$), and tauon-neutrino ($\nu_\tau$). Compared to their massive counterparts the electron, muon, and tauon, their masses are tiny but non-vanishing. First hints that neutrinos could have a mass and thus flavor oscillate, have been seen by the Homestake experiment that measured the electron-neutrino flux from the Sun [105]. The measured flux was substantial suppressed with respect to theoretical predictions. The fact that neutrinos have mass has finally been confirmed by the discovery of neutrino flavor oscillation of solar and atmospheric neutrinos by the SNO [106] and Super-Kamiokande [107, 108] experiments, respectively.

2.1 Neutrino Interactions with Matter

The interaction of neutrinos with matter can only happen through the exchange of the weak $W^\pm$ and $Z^0$ bosons. Depending on the exchanged boson one distinguishes between Charged Current (CC) (i.e. $W^\pm$) and Neutral Current (NC) (i.e. $Z^0$) interactions. Due to charge conservation, CC interactions of a neutrino with a nucleon produce a charged lepton in the final state, whereas NC interactions result in neutrino scattering:

\[
\nu_\ell (\bar{\nu}_\ell) + N \rightarrow \ell^- (\ell^+) + X \quad \text{(CC)} \quad (2.1)
\]

\[
\nu_\ell (\bar{\nu}_\ell) + N \rightarrow \nu'_\ell (\bar{\nu}'_\ell) + X \quad \text{(NC)} \quad (2.2)
\]

Here, $N$ denotes a nucleon, $\ell$ a lepton flavor (i.e. $e$, $\mu$, $\tau$), and $X$ the remnant of $N$, procuding a hadronic cascade. Depending on the momentum transfer in the interaction and thus on the energy of the incident neutrino, the neutrino can undergo three different main types of scattering processes with a nucleon. In Quasi-Elastic Scattering (QES), the target nucleon remains mainly unchanged and most of the incident momentum is transfered to the out-going lepton. For
Figure 2.1: Measurements of the $\nu_\mu$-nucleon and $\bar{\nu}_\mu$-nucleon CC scattering cross-section for neutrino energies between 0.1 GeV and 350 GeV. Neutrino-nucleon cross-sections are about twice as large as anti-neutrino-nucleon cross-sections due to the domination of valence quarks over sea quarks in the nucleon at this energy scale. In contrast to the CC cross-sections, NC cross-sections are in general smaller but non-neglectible. Figure adapted from [110].

At neutrino energies relevant for IceCube, i.e. $\gtrsim 10$ GeV, DIS is the dominating interaction process, thus each detected neutrino interaction constitutes at least one hadronic cascade at the interaction vertex.

The CC muon neutrino-nucleon scattering cross-section has been measured by several experiments in the past [110]. Figure 2.1 shows the measurements for different neutrino energies. Above $\sim 100$ GeV the cross-sections have a linear dependence on energy. The cross-sections depend heavily on the parton distribution functions of the nucleon that can be parametrized according to CTEQ6 [111], which is used also in this work. As can be seen in figure 2.1 the neutrino cross-sections are about a factor two higher than the ones for anti-neutrinos. This is due to the domination of valence quarks over the sea quarks in the nucleon’s parton distributions and the resulting helicity dif-
ferences for matter and anti-matter interactions, \textit{i.e.} helicity suppression for anti-neutrinos. Laboratory measurements of the neutrino cross-sections for high neutrino energies, \textit{i.e.} several hundred GeV, are difficult to conduct due to their large neutrino production costs. However, they can be calculated using perturbative QCD for neutrino energies up to $10^{12} \text{ GeV}$ [112]. At neutrino energies above $\sim 10^5 \text{ GeV}$ the sea quarks with symmetric quark and anti-quark abundances dominate in the nucleon. Thus, at high energies the cross-sections for neutrinos and anti-neutrinos become equal. Up to $\sim 10^6 \text{ GeV}$, the neutrino-cross sections rise linearly with the neutrino energy. For even higher neutrino energies the rising of the cross-section can be approximated by a power-law in the neutrino energy [109]. Because of the rising neutrino cross-section with neutrino energy, matter becomes opaque for very high energy neutrinos. The Earth becomes opaque for neutrinos with energies above a few PeV, at which energy more than 70\% of the neutrinos get absorbed before traversing one Earth diameter [113].

In the case of a CC-interacting muon-(anti-)neutrino, $\nu_\mu$, a muon (anti-muon) will be present in the final state that will propagate through the detector and will lose its energy through different energy loss mechanisms. For high muon energies above $\sim 1 \text{ TeV}$, stochastic energy losses like $e^+e^-$-pair production, bremsstrahlung, and photo-nuclear interaction dominate with a linear dependence in muon energy. Figure 2.2 shows the contribution of the different energy loss mechanisms for muons in ice. The average energy losses per unit length in ice can be approximated by [115]

$$-\left\langle \frac{dE}{dx} \right\rangle = a + bE.$$  

The coefficients $a$ and $b$ with values $0.249 \text{ GeV mwe}^{-1}$ and $0.422 \cdot 10^{-3} \text{ mwe}^{-1}$, respectively, have been determined by performing a detailed simulation of the muon energy losses by taking into account all the energy loss processes mentioned above [115]. Along the path of the propagating charged muon, Cherenkov radiation (\textit{cf.} section 2.2) is emitted allowing one to detect the muon via light sensors in the ice.

All NC neutrino interactions produce an hadronic cascade due to the nucleon disruption in the DIS process. The CC electron and tauon neutrino interactions produce an electron and tauon in the final state, respectively. Due to the short interaction range of the electron, the CC electron neutrino interactions create an electromagnetic cascade. The tauon has a very short life-time and its decay produces mainly an hadronic cascade. All cascade developments are quite localized around the interaction vertex. Due to that and the light scattering in the glacial ice at the South Pole (\textit{cf.} section 2.3), the recorded light pattern of the
Cherenkov radiation (cf. section 2.2) has a mostly spherical shape around the neutrino interaction vertex.

### 2.2 Cherenkov Radiation

The neutrino-induced charged particles emit Cherenkov radiation when propagating through the ice. Cherenkov radiation is produced when charged particles are moving in a dielectric medium faster than the speed of light in that medium. The charge of a fast moving particle polarizes the medium non-symmetrically along the travel axis resulting in momentary dipole fields along the axis which emit photons. The number of emitted photons of wavelength interval $d\lambda$ along the distance interval $dx$ that the charged particle traverses, can be expressed by
2.3 Light Propagation in the South Pole Ice

the Frank-Tamm formula [116]:

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

(2.4)

where \(\alpha = 1/137\), \(\lambda\), \(\beta = v/c\), \(n(\lambda)\), and \(z\) denotes the fine structure constant, the wavelength of the photon, the speed of the particle in terms of the speed of light in vacuum, the index of refraction of the medium, and the number of elementary charge quanta, respectively. The emitted photons constitute a light wavefront with an opening angle \(\theta_c\) with respect to the particle’s trajectory, that depends on the energy of the photons and the speed of the charged particle:

\[
\cos \theta_c = \frac{1}{n(\lambda) \cdot \beta}.
\]

(2.5)

The refractive index of ice for photons in the visible range of the electromagnetic spectrum is about 1.33. Thus, the opening angle for muons with a speed \(\beta \approx 1\) propagating through ice is 41.2°. The characteristic number of photons with wavelengths between 300 nm and 600 nm, i.e. the light acceptance range of the IceCube Digital Optical Modules (DOMs) (cf. section 3.2), emitted by a muon traveling one meter in ice is about 33,000 [117].

2.3 Light Propagation in the South Pole Ice

The Cherenkov photons from the neutrino-induced charged secondary particles are subject to absorption and scattering in the South Pole ice. The glacial ice at the South Pole has formed by accumulation of snow over the last \(\sim 165\) thousand years [118, 119].\(^1\) The effective scattering coefficient, \(b_e(400\text{nm})\), and absorption coefficient, \(a(400\text{nm})\), for light of 400 nm wavelength, where IceCube DOMs are most sensitive, are depth and ice-purity dependent. Impurities of the ice like dust degrade the optical properties of the ice. The depth profiles of \(b_e(400\text{nm})\) and \(a(400\text{nm})\) are also pressure and temperature dependent. At shallow depths smaller than \(\sim 1350\) m the ice contains air bubbles. At larger depths the air bubbles have been transformed by the high pressure into air-ice clathrates that have similar optical properties as pure ice. The scattering and absorption profiles are tabulated in 10 m steps for depths between 1300 m and 2600 m [120]. They are basically described by a six-parameter ice model introduced in Ref. [121]. However, the six-parameter ice model has been updated with a more sophisticated parameterization of Mie scattering of photons on ice impurities [122]. The parameters of the new ice model are determined through a

\(^1\)The age of the glacial ice at the depth of the deepest deployed IceCube DOMs is about 90 thousand years.
global fit of dust laser logger data [119] and detected events in IceCube induced by in situ LED light sources [120]. The resulting new ice model is called \textit{SPICE-Mie} and is an abbreviation for \textit{South Pole ICE - Mie}. It is an improvement on the previous ice model named Additionally Heterogeneous Absorption (AHA), that used an extrapolation for the parameters for depths greater than 2350 m from dust concentration measurements in ice cores from other Antarctic sites (Vostok & Dome Fuji). At depths between 1950 m and 2150 m the optical properties of the ice are worse due to a higher concentration of dust particles. This region of the ice is referred to as the \textit{dust layer}. However, below the dust layer the absorption and scattering decrease significantly, constituting the clearest ice with average absorption and scattering lengths of of 172.0 m and 53.3 m, respectively [120]. Figure 2.3 shows the effective scattering and absorption of the SPICE-Mie and the earlier AHA ice model as a function of depth.

### 2.4 Light Detection with PMT Arrays

Arrays of Photo-Multiplier Tubes (PMTs) can be used to detect the Cherenkov light produced by the secondary charged particles (\textit{cf.} section 2.2) induced by the neutrino interaction in matter (\textit{cf.} section 2.1). Obviously, a transparent medium has to be chosen in order to be able to measure Cherenkov radiation emitted at a distance. To increase the probability for a detectable interaction, the volume of the neutrino detector must be maximized. A natural interaction material for such a neutrino detector is water or ice. Liquid scintillator materials like linear alkylbenzene with a high scintillation photon yield can also be used, \textit{e.g.} by the SNO+ experiment [123] that is currently under construction. In order to be able to detect single Cherenkov photons, PMTs are usually used. Several neutrino detectors utilizing this neutrino detection principle exist. For instance the SNO [124] and Super-Kamiokande [125] neutrino detectors use a two-dimensional grid of PMTs mounted at the walls of a sphere filled with water and deployed in mines. The ANTARES neutrino detector [77] uses water as detection medium as well but arranges the PMTs in a three-dimensional grid in the Mediterranean Sea south of France. IceCube is currently the largest neutrino detector, with one cubic kilometer of instrumented detector volume, and is deployed as a three-dimensional array of PMTs in the glacial ice at the South Pole (\textit{cf.} chapter 3).
Figure 2.3: Effective scattering (top) and absorption (bottom) of the glacial South Pole ice as a function of depth. The solid line shows the SPICE-Mie model [120] with estimated systematic uncertainties shown as a grey band. The dashed lines show the optical properties of the earlier AHA ice model [121] as comparison. Figure from [120].
3 The IceCube Detector

With one cubic kilometer of instrumented detection volume IceCube is the largest neutrino detector on Earth. The detector was deployed at the geographical South Pole by drilling 86 2.5 km deep boreholes into the glacial ice. Each borehole was equipped with a support cable called string with 60 attached Digital Optical Modules (DOMs) (cf. section 3.2) detecting Cherenkov radiation. IceCube was constructed during seven Austral summer seasons from 2004/05 to 2010/11 at a depth between 1450 m and 2450 m below the surface of the glacier. The 5160 DOMs are arranged in a three-dimensional array shaped like a hexagonal cylinder with a surface area of $\approx 1 \text{ km}^2$ and a height of 1 km, constituting the $1 \text{ km}^3$ of instrumented volume. On average the strings are placed about 125 m from each other and the spacing between DOMs is about 17 m. With this layout the lower neutrino energy detection threshold of the IceCube in-ice array is about 100 GeV. In addition to the in-ice detector array, an on-ice surface air-shower detector array, named IceTop, exists. It is used to detect air-showers produced by Cosmic Ray (CR) particles hitting the atmosphere at the South Pole with energies above $10^5 \text{ TeV}$. Across the $1 \text{ km}^2$ IceCube surface area 81 IceTop stations with 2 tanks equipped with 2 DOMs each are distributed. Thus, in total IceTop consists of 324 DOMs in addition to the 5160 in-ice DOMs.

In analyses the fully constructed IceCube detector is usually denoted as IceCube-86 or simply IC86. However, during the seven year construction phase of IceCube, data have been recorded using partial detector configurations. Data taken with partial configurations are denoted according to the number of deployed strings, e.g. IceCube-79 for the data taking period between May 2010 and May 2011. Figure 3.1 shows a three-dimensional schematic overview of the IceCube detector array. Furthermore, figure 3.2 illustrates the footprint and the seasonal construction of IceCube.

3.1 The DeepCore infill array

The eight center strings of IceCube have a denser instrumentation than all the other strings. They constitute the DeepCore infill array [126]. The string spacing
of DeepCore is reduced to $\sim 72$ m to decrease the lower neutrino energy detection threshold to about 10 GeV. To accomplish this the DOM spacing on each string has been reduced as well. Due to the presence of the dust layer at the lower third of the detector, the DeepCore DOMs have been grouped into two sections, one with 10 DOMs above and one with 50 DOMs below the dust layer with a DOM spacing of 10 m and 7 m, respectively. Furthermore, the PMTs of six of the strings are High Quantum Efficiency (HQE) PMTs with a 35% increased photon detection efficiency [126]. The other two infill strings have a mixture of HQE and regular IceCube DOMs. The innermost IceCube string numbered 36 and the six DeepCore surrounding IceCube strings constitute together with the eight DeepCore strings the extended DeepCore fiducial volume. It is often used in low energy analyses where the outer IceCube strings can be used as veto against the atmospheric muon background (cf. chapter 8).
Figure 3.2: The footprint of the IceCube detector. The different colors of the string positions (circles) indicate the string’s deployment season completing a new detector configuration: **Yellow**: 2004/05 (IC1), **Green**: 2005/06 (IC9), **Red**: 2006/2007 (IC22), **Magenta**: 2007/08 (IC40), **Purple**: 2008/09 (IC59), **Blue**: 2009/10 (IC79), and **Orange**: 2010/11 (IC86). The two “missing” strings 79 and 80 in the upper right corner were deployed in the center of IceCube, because of constructional remains in the ice at their original position from the former South Pole station. The thirteen strings with a black circle in the middle of the detector indicate the DeepCore fiducial volume used in the GC analysis (cf. chapter 8). The arrows at the lower left corner show the orientation of the cartesian IceCube coordinate system, which has its origin in the center of the detector.
Figure 3.3: Photograph of an IceCube Digital Optical Module (DOM). Its individual components are annotated. Figure taken from [34].

3.2 Digital Optical Module

The smallest detection unit of IceCube is the Digital Optical Module (DOM). The DOM aims to measure the Cherenkov light emitted by a charged particle propagating through the ice. Figure 3.3 shows a photograph of an IceCube DOM with its components annotated. Its main component is the downward facing 10-inch Hamamatsu R7081-02 PMT [117] powered by an in-DOM 2 kV high voltage (HV) generator. All electronics of the DOM are encapsulated in 13 mm thick glass sphere, strong enough to withstand the high pressure of 2.5 km water equivalent mass. Silicon gel between the glass sphere and the PMT provides an optimal coupling between both. The combination of glass and gel is transparent for light with wavelengths between 350 nm and 650 nm. The peak quantum efficiency of the PMT alone is about 25% at wavelength of 390 nm [117]. However, the maximum number of Cherenkov photons is detected by the DOM for wavelengths of about 405 nm due to characteristics of the Cherenkov light spectrum folded with the transmission efficiency of the DOM [120] (cf. section 2.3). The PMT has 10 dynodes and a total amplification of $10^7$ allowing the detection of single photons. When a single photon hits the photo-cathode of the PMT an electron might be emitted through the photo-electric effect. This electron gets accelerated by the electric field between the photo-cathode and the first dynode, hitting the first dynode and ejecting successive electrons from that dynode. This amplification process repeats several times until the electrons hit the anode pro-
3.2 Digital Optical Module

Producing a measurable electric current. In order to avoid an influence of the Earth’s magnetic field on the electron’s flight path due to the Lorentz force, a magnetic shield cage surrounds the PMT. The time evolution of the output signal voltage of the PMT, which is proportional to the PMT’s anode load current, is registered by electronics located on the DOM DOM Main Board (MB) and constitutes the waveform. Whenever the analog waveform signal crosses the discriminator threshold equivalent to 1/4 Photo Electron (p.e.), a so-called DOM launch is issued and the analog waveform gets digitalized by an analogue Transient Waveform Digitizer (ATWD) and one fast Analog Digital Converter (fADC), and that DOM is called a hit DOM. In order to allow the ATWDs to digitize the entire beginning of the waveform, the analog waveform signal is delayed by \( \sim 75 \text{ ns} \) due to initialization time of the ATWDs. Thus, the analog signal is passed through a serpentine strip line located on the delay board. The sampling rate of the ATWD and the fADC is 303 MHz and 40 MHz, respectively. The ATWD operates in three different gains (0.25, 2, and 16) to ensure accurate pulse height measurements for different signal strengths. It samples the waveform into 128 3.3 ns wide time bins (422 ns total time coverage). The fADC provides a longer time coverage of up to 6.4 \( \mu \text{s} \) but with a coarser time binning of 25 ns.

In addition to the DOM MB, the DOM hosts a flasher board with 12 Light Emitting Diodes (LEDs) for in-situ detector calibration. Half of the LEDs are horizontal oriented and the other half tilted with an angle of 45°. The power and thus the duration and brightness of the LED flashes can be regulated to generate a well defined light pattern.

In conjunction with the main pulse from the detected Cherenkov photon the recorded waveform is a superposition of waveforms caused by different physical side processes inside the PMT. Such processes lead to pre-pulses, late-pulses, and after-pulses. Pre-pulses are caused by dynode skipping electrons and occur a couple of nanoseconds before the main pulse. Due to inelastic scattering of electrons with the dynode material possible late-pulses occur right after the main pulse. Finally, due to the ionization of the residual gas inside the PMT by the amplification electrons, after-pulses might occur. Because the slow moving ions need to propagate back to the photo-cathode where they eject secondary electrons creating the after-pulse signal, such after-pulses occur late after the main pulse, here typically in a time window between 300 ns and 11 \( \mu \text{s} \) after the main-pulse. In addition to the three discussed pulse signals, the PMT has a dark noise rate caused by the thermal evaporation of electrons from the photo-cathode and the dynodes, as well as from radioactive decays in the DOM’s glass sphere.

\footnote{For redundancy purposes a second ATWD exists which is used in cases where the first ATWD is still occupied with the digitization of a previous waveform.}
The in-situ measured maximal dark noise rate of standard and HQE DOMs is about 650 Hz and 750 Hz, respectively [126]. In order to reduce the amount of data that would have to be sent to the surface due to the high noise rate, coincident conditions, called Local Coincidence (LC), between adjacent DOMs on the same string are implemented. The DOMs on a string can communicate to each other via dedicated LC cables querying their hit status. When at least one of the next or next-to-next neighboring DOMs w.r.t. to the hit DOM is hit as well, i.e. LC-span 2, within a time window of \( \pm 1 \mu s \) the hit of the DOM is marked as Hard Local Coincidence (HLC) hit. For HLC hits the entire waveform of the ATWD and fADC are sent to the surface for later feature extraction by software. All other hits are marked as Soft Local Coincidence (SLC)\(^2\) hits. For such hits only the waveform bin with the maximal value and its two neighboring bins are sent to the surface and used for feature extraction. All DOMs are individually time-synchronized utilizing Global Positioning System (GPS) taking signal time delays due to different cable lengths of the DOMs into account.

### 3.3 Data Acquisition System

The DOM launches are collected in the counting house named IceCube Lab (ICL) at the surface. ICL is located at the center of the IceCube array and contains string hub computers, which are connected to the string cables. Each string hub computer handles one string and hence the readout of 60 DOMs. The IceTop DOMs are connected to computers as well, which are called IceTop hubs. The hubs report the DOM launches to IceTop and in-ice trigger handlers. The trigger handlers implement several trigger conditions. An example for an in-ice trigger is the Simple Multiplicity Trigger (SMT) requiring a certain amount of HLC hits within a predefined trigger time window. For instance the SMT-8 trigger requires 8 HLC hits within 5 \( \mu s \) occurring anywhere in the in-ice detector array. In order to be able to trigger low-energy events in DeepCore the SMT-3 DeepCore trigger requires at least 3 HLC hits within the DeepCore fiducial volume (cf. section 3.1) and in a 2.5 \( \mu s \) time window. This trigger defines a data readout time window of \( \pm 6 \mu s \) centered around the time of the first of the three HLC hits fulfilling the DeepCore trigger condition. The types, the start times, and the durations of all individual triggers are reported to the global trigger handler forming a global trigger hierarchy object containing all individual triggers and a \( \pm 10 \mu s \) expanded data readout time window with respected to the first and last trigger time. It is passed-on to the event builder that creates an event by pulling the DOM launch data from the string and IceTop hubs. Figure 3.4 illustrates the event construction in a schematic flowchart. The events are stored as a

\(^2\)The naming is historical. No coincidence requirement is involved for SLC hits.
3.4 Event Reconstructions

stream of event frames in an IceCube specific binary file format, i.e. an .i3-file. Together with the detector geometry, calibration, and status information frames, the triggered event frames of a data run\(^3\) are stored on hard-drives for Processing and Filtering (PnF) as well as on tape for archiving. For the completed IceCube detector, i.e. IC86, the global trigger rate is about 2.4 kHz. The trigger rate is seasonally dependent due to the atmospheric muon production rate by CR interactions being dependent on the atmospheric pressure and hence correlating with the atmospheric temperature. A ±10% change in the trigger rate can be observed due to this effect [127] (cf. chapter 8).

Data runs are usually eight hours long.

The recorded events are calibrated, e.g. the baseline of the waveforms are subtracted, and individual photo-electron pulses with their timing and charge information are extracted from the waveforms (i.e. feature extraction). The processing is performed in several incremental steps called levels. The levels are numbered. At the South Pole the first level with number 1, i.e. the online level, is run. The online level includes the mentioned event calibration and feature extraction as well as the filtering of recorded events (cf. section 3.6).

3.4 Event Reconstructions

Event filters and event selections in general require event reconstructions of different kinds. Since the reconstruction algorithms are based on the hits in the detector the reconstruction quality gets degraded by noise hits. Noise hit cleaning before performing the reconstruction algorithms minimize badly reconstructed events. An effective noise cleaning algorithm is the search for causal clustering

\(^3\)Data runs are usually eight hours long.
of hits based on the time and distance between the hits. Propagating muons tend to produce hits that are connected with the speed of light in vacuum and the hits have a track-like hit pattern. The produced hits from localized particle cascades, on the other hand, tend to be connected with the speed of light in ice. Noise hits occur randomly in the detector. Hence, most noise hits can be cleaned-out from an event by requiring hits to be clustered in space and time.

The muon filter (cf. section 3.6.2) for instance requires a track reconstruction with a muon hypothesis. It performs a log-likelihood reconstruction based on the hit time distribution of an event [128]. Only the first extracted pulse of each DOM waveform is used in this reconstruction, hence, it is denoted as single-photo-electron (SPE) reconstruction and described below in more detail. It can be seeded with the result of a first guess reconstruction to improve its performance. The used first guess reconstruction is called line-fit. Finally, the energy of the muon event can be reconstructed via different sophisticated methods briefly described below as well.

3.4.1 Noise Hit Cleaning with SeededRT

As mentioned above, random distributed noise hits in the detector can be cleaned using a space-time hit clustering algorithm. Before that the extracted PMT pulses are cleaned by a time-window (TW) cleaning selecting only pulses within \( \pm 4 \, \mu s \) around the trigger time. This is roughly the time a particle of speed \( c \) would take to traverse the entire IceCube detector diagonally. The remaining pulses are further cleaned using the SeededRT hit clustering algorithm. Initially, it selects, \( i.e. \) is 'seeded' with, all HLC pulses. For each selected pulse it looks for additional, \( i.e. \) SLC, pulses in its space and time vicinity. For the space and time condition it uses a sphere of radius \( R = 150 \, \text{m} \) and a time-window of \( T = \pm 1.5 \, \mu s \), respectively. It is an iterative algorithm and repeated until no additional causally connected pulses can be found, or a maximum number of iterations is reached. The relative large time-window with respected to the radius \( R \) accounts for light scattering and the lower speed of light in the ice. After the two cleanings, the resultant pulse series has isolated noise hits removed and is denoted as TWSRT-pulses. Because of the removed noise pulses, the reconstruction results are improved by the usage of TWSRT-pulses.

3.4.2 Line-Fit

The line-fit reconstruction [129] is the fastest but also the least accurate track reconstruction available in IceCube. It fits a line along the hit DOMs in space and time using the least-squares method. For a given set of recorded hits in space, \( \vec{x}_i \), and time, \( t_i \), it solves for the line, parameterized by position \( \vec{x}_0 \) and
3.4 Event Reconstructions

time \( t_0 \), and the particle speed \( \vec{v} \) by minimizing the least-squares sum:

\[
\min_{t_0, \vec{x}_0, \vec{v}} \sum_{i=1}^{N} \rho_i^2(t_0, \vec{x}_0, \vec{v})
\]  

(3.1)

with

\[
\rho_i(t_0, \vec{x}_0, \vec{v}) = \| \vec{v}(t_i - t_0) + \vec{x}_0 - \vec{x}_i \| .
\]

(3.2)

It does not take into account any Cherenkov cone topology of the particle’s photon emission, or ice properties. Due to the quadratic behavior of the expression 3.1 the method is strongly affected by hit outliers from scattered photons and noise. To account for that the improved line-fit [130] removes the very scattered hits, i.e. late hits with respect to the hit times of the closest neighboring hits, and uses an intermediate Huber fit [131] with a linear dependence on \( \rho \) in the least-squares sum for \( \rho > 153 \) m. The advantage of the line-fit and improved line-fit algorithms is their robustness and computational speed. Thus it can be used as initial guess for more sophisticated likelihood track reconstructions like the SPE log-likelihood reconstruction.

3.4.3 SPE Log-Likelihood

A more powerful track reconstruction than line-fit is the single-photo-electron (SPE) log-likelihood reconstruction [128] that is based on the photon hit time probability density function at a distant receiving DOM. It uses only the first photon pulse of each DOM launch. Given the hit data points in space, \( \vec{x}_i \), and time, \( t_i \), for the \( N_{\text{hit}} \) hit DOMs, the log-likelihood function for observing hits at distances \( d_i \) with residual times \( t_{\text{res},i} \) from a hypothetical track with parameters \( \vec{a} \) can be constructed:

\[
\log L(t_{\text{res}}, d \mid \vec{a}) = \sum_{i=1}^{N_{\text{hit}}} \log p(t_{\text{res},i}, d_i \mid \vec{a}),
\]

(3.3)

where the hit time residual, \( t_{\text{res}} \), specifies the time difference between a scattered and an unscattered photon traveling from the point of emission on the hypothesized track at time \( t_0 \), to the hit recording DOM, recorded at time \( t_{\text{hit}} \), in ice with refractive index \( n_{\text{ice}} = 1.31 \). It is given by

\[
t_{\text{res}} = t_{\text{hit}} - t_{\text{geo}}
\]

(3.4)

\[
= t_{\text{hit}} - \left( t_0 + r_{\text{geo}} \frac{n_{\text{ice}}}{c} \right).
\]

(3.5)

The shortest distance between the light emitting point on the track and the recording DOM is denoted as \( r_{\text{geo}} \). The p.d.f. of the photon arrival times, \( p(t_{\text{res}}, d) \),
is the so-called Pandel distribution [132, 128] and is given by the expression

\[ p(t_{\text{res}}, d) = \frac{1}{N(d)} \frac{\tau(-d/\lambda), t_{\text{res}}^{(d/\lambda)-1}}{\Gamma(d/\lambda)} \cdot e^{-\left(\frac{t_{\text{res}}}{\tau + ct_{\text{res}}/(n_{\text{ice}}\lambda_a) + d/\lambda_a}\right)}, \] (3.6)

with the normalization

\[ N(d) = e^{-d/\lambda_a} \left(1 + \frac{\tau c}{n_{\text{ice}}\lambda_a}\right)^{-d/\lambda}. \] (3.7)

The parameters $\tau$ and $\lambda$ are unspecified functions of $d$ and the scattering length $\lambda_s$ [132]. Studies by the Antarctic Muon And Neutrino Detector Array (AMANDA) collaboration [128] showed that an approximation by constant values yields a good agreement of performed detailed MC simulations with the Pandel distribution. For ice the parameter values are chosen to be $\tau = 557$ ns, $\lambda = 33.3$ m, and $\lambda_a = 98$ m [128]. A shortcoming of the parameterization of the Pandel distribution as given by equation (3.6) is the assumption of bulk ice with constant scattering and absorption lengths. In order to account for the finite timing resolution of the detector (i.e. PMT jitter) and the unphysical narrowness of equation (3.6) for small distances ($d < \lambda$), a Gaussian convoluted Pandel distribution, called $\text{CPandel}$, is used [133], where the width, $\sigma_{\text{jit}}$, of the gaussian function matches the PMT jitter time. The probability for random noise hits to occur is taken into account by simply adding a constant p.d.f. $p_0$ to equation (3.3) [128].

### 3.4.4 MPE Log-Likelihood

Similar to the SPE log-likelihood reconstruction, the multi-photo-electron (MPE) log-likelihood reconstruction is based on the Pandel p.d.f. of a single photon as given in equation (3.6). However, the information about the number of recorded photons at each DOM can be incorporated into the photon arrival time p.d.f. as well. The first recorded photon at each DOM can be assumed to have undergone less scattering than the remaining photons. Thus, the MPE-Pandel photon arrival time p.d.f. can be formulated for $N$ recorded photons at a hit DOM as [132]

\[ p_N(t_{\text{res}}, d) = Np(t_{\text{res}}, d) \left( \int_{t_{\text{res}}}^{\infty} p(t', d) dt' \right)^{N-1} \] (3.8)

and used in the likelihood function equation (3.3).

### 3.4.5 SplineMPE Log-Likelihood

Instead of using an analytical expression for the photon arrival time p.d.f. in equation (3.3), muon simulation with individual photon propagation simulation
can be performed to create $p_N(t_{res}, d)$. The advantage of this method is the ability to incorporate the dependence of the scattering and absorption lengths on the orientation and depth of the light emitting source, i.e. the ice model [120]. The photon arrival times for photons of differently oriented muon tracks of different depths and distances from the receiving DOMs were simulated and fitted with a multi-dimensional spline surface [134] constituting the splined p.d.f. for equation (3.3).

### 3.4.6 Angular Uncertainty Estimator

The angular uncertainty of the likelihood SPE reconstruction of each event can be estimated by fitting its likelihood space with an elliptic paraboloid around the best fit point [135]. The shape of the paraboloid can be parameterized by an error ellipse in the azimuth-zenith angular plane by a major and minor axis $\sigma_1$ and $\sigma_2$, respectively, and an orientation angle $\alpha$. The error ellipse is inferred from the likelihood function, when its negative logarithmic value has changed by one half with respect to its maximum. The addition of both axes in quadrature defines the paraboloid uncertainty estimator, $\sigma_{\text{para}}$:

$$\sigma_{\text{para}} = \sqrt{\frac{\sigma_1^2 + \sigma_2^2}{2}}. \quad (3.9)$$

It is a measure of the quality of the track reconstruction and can be used to select well reconstructed events.

### 3.4.7 Vertex Reconstruction

After the reconstruction of the direction and the position of the event (cf. section 3.4.2 and section 3.4.3), the interaction vertex point of a muon event inside the detector can be reconstructed using detector geometrical hit and non-hit patterns via a likelihood algorithm called finite-reco [136]. It takes a pre-calculated track hypothesis as seed and fits for its interaction and stopping points using the probabilities to produce hit DOMs and non-hit DOMs for a muon obtained from MC simulation via a maximum likelihood method. The reconstructed vertex position can be used to distinguish between through-going atmospheric muon events and neutrino induced starting events in the detector. Low-energy events below $\sim$100 GeV can be fully contained inside the detector. The selection of such events provides a low-energy event selection as used in the Galactic Center WIMP search described in chapter 8.
3.4.8 Energy Reconstructions

The simplest energy proxies of an event are the number of hit DOMs and the total registered PMT charge, $Q_{tot}$, of that event. In general, the more energy an event has, the more DOMs are hit and the more energy is deposited in the detector. Hence, more Cherenkov light is produced and thus more PMT charge gets registered.

A more sophisticated muon energy reconstruction using a maximum likelihood approach is called MuE. In order to determine the muon energy, MuE reconstructs the Cherenkov photon density of the track at its closest approach to the Center of Gravity (COG) of the hits inside the detector and compares it to the one obtained from simulation [137, 138] using a bulk ice model. The number of Cherenkov photons per unit track length, $N_c$, can be expressed as linear function of the muon energy, $E_\mu$, for muon energies above $\sim 10$ TeV [137]:

$$N_c = 3 \cdot 10^4 m^{-1} \left( 1.22 \cdot 10^{-3} \frac{E_\mu}{GeV} \right)$$

(3.10)

As described in section 2.3, the optical properties of the ice vary with depth. To account for that the light yield from a muon at a distance $r$ from its track has been remodeled via an analytic expression depending on the depth and the orientation of the muon track and thus on the absorption and scattering lengths of the ice at various depths [138]. Further on in this thesis this approach is denoted as MuEx energy reconstruction.

3.5 Event Observables

An event in IceCube is described by event observables constructed from obtained hit pulse information and reconstruction results as described in section 3.4. The observables used in the analyses presented in this thesis and their definition are listed in table 3.1.

3.6 Event Filtering

The event filtering aims to select interesting physics candidate events. In order to decide if an event is interesting, first basic reconstructions of the event, e.g. direction and position in the detector, are performed.

The filters take the results of the online reconstructions and decide if the event should be kept or discarded. Different filters have been implemented targeting specific event topologies or types of analyses. If an event passes at least one of the filters, it is kept and transferred via satellite to the IceCube data processing center at UW-Madison/USA in the North, where further processing is
### Table 3.1: Event observables used in the Galactic center and Galactic halo analyses.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{ch}$</td>
<td>The number of hit DOMs, referred to as <em>channels</em> in IceCube.</td>
</tr>
<tr>
<td>$n_{str}$</td>
<td>The number of strings with hit DOMs.</td>
</tr>
<tr>
<td>$t_{obs}$</td>
<td>The observation time of the event used to calculate its right ascension.</td>
</tr>
<tr>
<td>$\Theta_{zen}$</td>
<td>The reconstructed zenith angle, using the SPE track reconstruction.</td>
</tr>
<tr>
<td>$\Phi_{azi}$</td>
<td>The reconstructed azimuth angle, using the SPE track reconstruction.</td>
</tr>
<tr>
<td>$\sigma_{\text{para}}$</td>
<td>The uncertainty of best fit log-likelihood estimate obtained by the <em>paraboloid</em> uncertainty estimator, cf. section 3.4.6.</td>
</tr>
<tr>
<td>$r_{llh}$</td>
<td>The reduced log-likelihood value, defined as $-\ln(L/n_{ch})/(n_{ch} - 5)$.</td>
</tr>
<tr>
<td>$\sigma_z$</td>
<td>The spread, <em>i.e.</em> RMS, of the collected charge along the vertical detector direction $z$.</td>
</tr>
<tr>
<td>$t_{accu}$</td>
<td>The time elapsed from the event start time until 75% of the total event charge is accumulated.</td>
</tr>
<tr>
<td>$v_{\text{LF},z}$</td>
<td>The vertical velocity component, <em>i.e.</em> $z$-direction, of the track reconstructed with the line-fit algorithm, cf. section 3.4.2.</td>
</tr>
<tr>
<td>$\Delta \log (L)$</td>
<td>The difference of the best fit log-likelihood value, $L$, for a starting and infinite track hypothesis using the <em>finite-reco</em> algorithm cf. section 3.4.7.</td>
</tr>
<tr>
<td>$P_{\text{FR}}$</td>
<td>The starting vertex point of the event reconstructed by the <em>finite-reco</em> algorithm, cf. section 3.4.7.</td>
</tr>
<tr>
<td>$L_{\text{FR}}$</td>
<td>The reconstructed track length using the <em>finite-reco</em> algorithm, cf. sec. 3.4.7.</td>
</tr>
<tr>
<td>$r_{\text{FR}}$</td>
<td>The horizontal radial distance of the starting vertex position from the center vertical axis of the detector. The vertex position is reconstructed using the <em>finite-reco</em> algorithm, cf. section 3.4.7. The position of the center-most string, numbered 36, is used as position of the central vertical axis of the detector.</td>
</tr>
<tr>
<td>$z_{\text{trav}}$</td>
<td>The average drift of the hits in vertical direction, $z$, from the average vertical position of the first quartile of all hits. Hence, it is defined as $\sum_{i}^{n_{ch}}(z_i - &lt;z_{1\text{st}\text{quartile}}&gt;) / n_{ch}$.</td>
</tr>
<tr>
<td>$L_{\text{dir}}$</td>
<td>The projected distance along the reconstructed track between the first and last direct hit. Hits are considered as direct when they have a residual time, $t_{\text{res}}$ cf. equation (3.4), within the interval $[-15\text{ns}, +75\text{ns}]$.</td>
</tr>
<tr>
<td>$n_{\text{dir}}$</td>
<td>The number of DOMs with direct pulses as defined for $L_{\text{dir}}$.</td>
</tr>
<tr>
<td>$L_{\text{sep}}$</td>
<td>The distance along the reconstructed track between the COG positions of the first and the last quartiles of hits projected onto the reconstructed track, referred to as <em>separation</em>.</td>
</tr>
</tbody>
</table>
performed. A collaboration wide identical base processing called offline level 2 is provided by the IceCube data processing center. In addition to the online level, the offline level 2 provides more sophisticated event reconstructions that would have been computationally too expensive to run on the small computer cluster at the South Pole. In addition to the offline level 2 base processing, the IceCube collaboration maintains a common level 3 muon event selection based on muon filter events, that targets well reconstructed muon track events, induced by muon neutrino CC interactions.

The search for DM in the Galactic Center as described in chapter 8 uses the DeepCore filter in order to select low-energy events starting inside the DeepCore fiducial volume. In contrast the search for DM in the Galactic Halo targets higher WIMP masses and thus more energetic events. This analysis, as discussed in detail in chapter 9, uses events from the common level 3 muon event selection as a basis.

3.6.1 The DeepCore Filter

The DeepCore filter [126] aims to select events starting inside the DeepCore fiducial volume and to reject atmospheric muon events by applying a veto criterion for IceCube hits. The input of the filter is DeepCore SMT-3 triggered events (cf. section 3.3). The rate of such triggered events in the IceCube-79 detector is about 185 Hz. For each event the average position of DeepCore HLC hits, with times within one standard deviation of the average time of all DeepCore HLC hits, is calculated, and referred to as COG vertex position. As COG vertex time the average of the DeepCore HLC hit times is taken, where the HLC hit times are subtracted by the propagation times of unscattered light propagating from the hit positions to the COG vertex position, equivalent to equation (3.4). For each HLC hit in the IceCube veto region the speed, \( \Delta r / \Delta t \), of a hypothetical particle connecting the COG and that hit is calculated. If the speed is consistent with the speed of a muon, i.e. close to the speed of light in vacuum, it can be assumed that the hit in the IceCube veto region is caused by a muon traveling through DeepCore and leaving a hit in IceCube. Hence, the event can be rejected. Figure 3.5 illustrates this veto algorithm. The rate of DeepCore filtered events for IceCube-79 is \( \sim 18 \) Hz.

3.6.2 The Muon Filter

The muon filter aims to select well reconstructed muon neutrino induced muon events from the northern hemisphere as well as muon events from the southern hemisphere. Since events from the southern hemisphere are atmospheric muon background dominated a zenith angle dependent cut on the deposited energy in
Figure 3.5: Schematic illustration of the atmospheric muon veto algorithm applied by the DeepCore filter. A COG vertex position of the DeepCore event inside the DeepCore fiducial volume is calculated (cf. text in section 3.6.1). Each HLC hit in the IceCube veto region is compared with the speed of a hypothetical particle connecting the veto hit with the COG. Events with veto hits having compatible muon particle speeds (cut region) are rejected. The colors represent the hit times following the natural rainbow colors with red and violet being the first and last hits, respectively. Figure taken from [126].

<table>
<thead>
<tr>
<th>Zenith Region</th>
<th>Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^\circ \leq \Theta_{zen} \leq 60^\circ$</td>
<td>$\log_{10}(Q_{tot}/PE) \geq 0.6 \cdot \cos(\Theta_{zen}) + 2.3$</td>
</tr>
<tr>
<td>$60^\circ &lt; \Theta_{zen} &lt; 78.5^\circ$</td>
<td>$\log_{10}(Q_{tot}/PE) \geq 3.9 \cdot \cos(\Theta_{zen}) + 0.65$</td>
</tr>
<tr>
<td>$78.5^\circ \leq \Theta_{zen} \leq 180^\circ$</td>
<td>$-\ln(L_{SPE}/ns^{-n_{ch}})/n_{ch}-3 \leq 8.7$</td>
</tr>
</tbody>
</table>

Table 3.2: Muon event filter passing conditions for IceCube-86. The cuts depend on the zenith angle $\Theta_{zen}$ of the SPE muon track reconstruction, the total registered charge $Q_{tot}$ of the event, and the reduced negative logarithm of the likelihood value $L_{SPE}$ of the SPE track reconstruction.

the detector, i.e. the sum of registered PMT charges, is made. Thus, the filter selects events with energies above the energy of most atmospheric muons. The cut settings of the filter have been adjusted for the different detector configu-
rations during the construction of IceCube. Table 3.2 shows the event passing conditions of the muon event filter for the completed IceCube-86 detector configuration.
4 Expected Backgrounds

The main backgrounds for the analyses of this work are atmospheric muons and neutrinos created through interactions of CR primary particles in the upper atmosphere. CRs were discovered by Victor Hess through balloon flight experiments in 1912 [139]. Since then many air-borne and ground-based experiments have been conducted to measure the flux and the composition of the CR spectrum. Figure 4.1 shows the primary CR spectrum over 13 orders of magnitude in energy per nucleus. As shown in figure 4.1a, the primary CR flux consists mainly of protons, and helium nuclei. Heavier ions up to iron as well as non-hadronic components like electrons, positrons, γ-rays, and neutrinos [140] are present as well, however in a much lower abundance. The differential intensity, \( i.e. \) the flux, of the primary CR nucleons follows the power law

\[
\frac{dN(E)}{dE} \propto E^{-\gamma_{\text{CR}}} \tag{4.1}
\]

with the differential spectral index \( \gamma_{\text{CR}} \) varying for different energy ranges. Figure 4.1b shows the high energy part of the spectrum. For energies per nucleon below the ‘knee’ at \( \approx 4 \cdot 10^{15} \text{ eV} \) the index \( \gamma_{\text{CR}} \) is 2.7. This is the energy range relevant for the analyses in this thesis. Above the ‘knee’, the spectrum softens to \( \gamma_{\text{CR}} \approx 3.0 \). At the ankle \( (E \approx 3 \cdot 10^{18} \text{ eV}) \) the spectrum hardens slightly again.

The primary incident CR particles interact with the nuclei of the atmosphere and create hadronic and electromagnetic air showers. The created secondary particles like pions and kaons are highly energetic and ultra-relativistic. They will either interact with other atmospheric molecules or decay into lighter particles like muons or neutrinos. A list of possible CR particle interaction processes
and the decay modes of their products with given branching ratios is:

\[ p^+(\alpha^{2+}, \text{etc.}) + N \rightarrow \pi^{\pm}(K^\pm) + X \]  

(4.2)

\[ \pi^- (\pi^+) \rightarrow \mu^- (\mu^+) + \bar{\nu}_\mu (\nu_\mu) \quad (\text{b.r.} \approx 100\%) \]  

(4.3)

\[ K^- (K^+) \rightarrow \mu^- (\mu^+) + \bar{\nu}_\mu (\nu_\mu) \quad (\text{b.r.} \approx 64\%) \]  

(4.4)

\[ \rightarrow \pi^- (\pi^+) + \pi^0 \quad (\text{b.r.} \approx 21\%) \]  

(4.5)

\[ \rightarrow \pi^0 + e^- (e^+) + \bar{\nu}_e (\nu_e) \quad (\text{b.r.} \approx 5\%) \]  

(4.6)

\[ \rightarrow \pi^0 + \pi^- (\pi^+) + \bar{\nu}_\mu (\nu_\mu) \quad (\text{b.r.} \approx 3\%) \]  

(4.7)

\[ \mu^- (\mu^+) \rightarrow e^- (e^+) + \bar{\nu}_e (\nu_e) + \nu_\mu (\bar{\nu}_\mu) \quad (\text{b.r.} \approx 100\%) \]  

(4.8)

where \( N \) and \( X \) denotes an initial atmospheric hadron and its hadronic remains after the interaction, respectively. The created muons and neutrinos may reach the surface of the Earth and propagate further to the IceCube detector constituting the main backgrounds for IceCube and thus the analyses presented in this thesis.

### 4.1 Atmospheric Muon Background

Atmospheric muons are predominantly produced by leptonic and semi-leptonic decays of charged pions and kaons as given for instance in equation (4.3) & equation (4.4) and equation (4.7), respectively. Due to the high energies and the relatively long lifetime of the muons, they can reach the surface of the Earth and the IceCube detector 1.8 km deep in the Antarctic ice. Figure 4.2 shows the vertical flux of atmospheric muons (\( \mu_{\text{atm}}^{-} \)) as function of the atmospheric depth and altitude. The CR primary particles like protons interact via equation (4.2) creating pions in the upper atmosphere, that decay along the path to the Earth surface. Hence, the proton and pion flux decreases with atmospheric depth, while the flux of atmospheric muons increases very fast in the upper atmosphere and decreases only slightly due to the decay of the muons. At the surface of the Earth the flux of negative charged muons is about 20 m\(^{-2}\)s\(^{-1}\)sr\(^{-1}\). Thus, atmospheric muons (together with atmospheric neutrinos cf. section 4.2) are the dominant background for the IceCube underground experiment. Fortunately, muons get absorbed by matter and their maximal penetration distance is about 20 km w.e. [140]. At the depth of IceCube, i.e. 1.8 km w.e., the muon inten-
4.1 Atmospheric Muon Background

(a) CR energy spectrum and composition for $E/\text{nucleus} < 1\text{ PeV}$

(b) CR all-particle energy spectrum for $E/\text{nucleus} > 10\text{ PeV}$

Figure 4.1: The primary CR spectrum over 13 orders of magnitude in energy per nucleus. For energies below $\sim 1\text{ PeV}$ (a) the composition of the primary CR spectrum as been measured by several experiments. It consists mainly of protons and $\alpha$-particles but heavier nuclei up to iron are present as well in much lower abundance. At very high energies the spectrum follows several power laws concatenated by the ‘knee’, the ‘second knee’, and the ‘ankle’ as shown in figure (b). Data points are from several CR air shower experiments. Figures from [140].
Figure 4.2: Atmospheric vertical particle fluxes as a function of atmospheric depth and altitude. At the surface of the Earth muons and neutrinos dominate. All particles except protons and electrons near the top of the atmosphere, are created by CRs interacting with atmospheric nucleons. The data points show measurements of the negatively charged atmospheric muons ($\mu^-$ atm) performed by balloon experiments. Figure taken from [140].

Intensity from the southern sky atmosphere is about $2 \cdot 10^{-3}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$ [140]. For IceCube located at the South Pole, muons created in the atmosphere of the northern hemisphere get all absorbed by the Earth leaving atmospheric neutrinos the only background for northern hemisphere analyses. For southern hemisphere analyses like the Galactic Center WIMP search analysis described in chapter 8, atmospheric muons from the southern hemisphere produce a $10^6$-times higher trigger rate than atmospheric neutrinos. Dedicated atmospheric muon vetoes have been developed (cf. section 8.1) to address this additional background for such analyses. However, at final analysis cut level the background consists still predominantly of muons ($\sim 90\%$). The remaining background ($\sim 10\%$) are atmospheric neutrinos. The Galactic halo WIMP search described in chapter 9 is a predominantly northern hemisphere analysis, where atmospheric neutrinos are the dominating background. The data sample utilizing the southern hemisphere applies a high energy cut and a veto cut in order to reject basically the entire atmospheric muon background (cf. chapter 9 for more details).
4.2 Atmospheric Neutrino Background

As illustrated in figure 4.2, the vertical flux of atmospheric neutrinos increases monotonically with atmospheric depth. They are produced in the decays of the pions, kaons and muons through leptonic (e.g. equation (4.3), equation (4.4) & equation (4.8)) and semi-leptonic (e.g. equation (4.7)) decay processes and referred to as conventional flux. The spectral index of the atmospheric neutrino energy spectrum, \( \gamma_{\text{atm}, \nu} \), is related to \( \gamma_{\text{CR}} \) of the CR particles. Due to the long lifetime of the charged pions, their interaction length is shorter than their decay length. Thus, the pions interact with the atmosphere before decaying leading to an increased spectral index for atmospheric neutrinos by about one:

\[ \gamma_{\text{atm}, \nu} \approx \gamma_{\text{CR}} + 1 \]  

At energies above \( \approx 1 \text{ TeV} \) the atmospheric neutrino energy spectrum is proportional to \( E^{-3.7} \). The production of charmed hadrons, like the \( D \)-mesons and \( \Lambda_c \) baryons containing a \( c \)-quark, by the CR interaction is also possible [141, 142, 143]. Due to the very short lifetime (< \( 10^{-12} \text{ s} \)) of charmed hadrons, they decay quickly before losing energy. Hence, neutrinos from charmed hadron decays are called ‘prompt’ neutrinos and their spectral index follows the one of the CRs. Compared to pions and kaons, the production energy threshold of charmed hadrons is much higher (\( \sim 10 \text{ TeV} \)). Hence, an atmospheric neutrino background from charm meson decays is negligible for the here discussed analyses.

The atmospheric electron and muon neutrino flux has been measured by IceCube and other experiments. Together with their theoretical fluxes they are shown in figure 4.3. The analyses presented in this thesis use the flux parameterization by Honda [144] which is shown as solid red and blue lines in figure 4.3 for electron and muon neutrinos, respectively (cf. also section 5.2).

In contrast to muons, only very high energy neutrinos (\( E_\nu \sim \mathcal{O}(\text{PeV}) \)) get absorbed by the Earth (cf. section 2.1). Thus, atmospheric neutrinos from all directions constitute a relevant background for the analyses of this thesis which address neutrino energies below 100 TeV.

4.3 Astrophysical Neutrinos

Evidence for the existence of an isotropic astrophysical neutrino flux has been recently reported by IceCube [149, 150] making neutrino astronomy a new observation window to the Universe. The analysis of Ref. [150] analyzed three years of IceCube data and observed 37 astrophysical neutrino candidates of all flavors with energies ranging from 100 TeV to PeV, where the highest energy neutrino candidates of these measured events are inconsistent with a pure terrestrial atmospheric neutrino flux hypothesis by 5.7\( \sigma \). Recently, IceCube has searched for astrophysical neutrinos with energies as low as 1 TeV [151] and
Figure 4.3: Atmospheric electron neutrino (red filled triangles) [145] and muon neutrino (black filled circles) [146, 147] flux measurements by IceCube and their theoretical predictions. The predictions by Honda [144] (solid lines) and Bartol [148] (dashed lines) for the conventional $\nu_e$- and $\nu_\mu$-flux are shown in red and blue lines, respectively. The predicted prompt component from charm-meson decays [142] is shown as magenta band. Figure taken from [145].

conducted a search for astrophysical muon neutrinos in the northern hemisphere [152] in the energy range 100 GeV – PeV. This latest search observed 35,000 muon neutrinos of mainly atmospheric origin. However, the highest energy muon neutrinos of this sample ($\sim 10$ events) ($\gtrsim 330$ TeV) are as well inconsistent with a pure atmospheric muon neutrino hypothesis at a level of $3.7\sigma$ and constitute a possible additional background of astrophysical muon neutrinos for the analyses presented in this thesis. The origin of the astrophysical neutrinos is still unknown. They might be created by Gamma Ray Bursts (GRBs), Active Galactic Nuclei (AGNs), supernova explosions, and pulsars. Another possible origin could be the annihilation or decay of DM particles, leaving the astrophys-
4.3 Astrophysical Neutrinos

Astrophysical neutrinos a signal rather than a background for the in chapter 9 presented galactic halo WIMP search analysis. A combined maximum likelihood analysis of the measured high-energy astrophysical neutrino flux from the previous discussed analyses has been performed by IceCube [153]. The best fit spectral index for an assumed unbroken power-law energy spectrum of astrophysical neutrinos with energies between 25 TeV and 2.8 PeV was found to be $-2.50 \pm 0.09$, resulting in a flux at 100 TeV of $(6.7^{+1.4}_{-1.2}) \times 10^{-18}$ GeV$^{-1}$s$^{-1}$sr$^{-1}$cm$^{-2}$.
5 Event Simulation in IceCube

Simulated detector events are required in order to develop event selections for the analyses presented in this thesis. Beginning with the primary particle generation the entire particle interaction and detector response chain has to be simulated to generate simulated event information in a form as provided by measured data. Due to the computational complexity of the IceCube simulation framework, simulated data sets for atmospheric muons and neutrinos are produced centrally by the collaboration. Despite the fact that background event simulation is available, the analyses described in this thesis use right ascension scrambled experimental data as background in order to minimize the systematic effects from simulation in the analyses. Simulated background is solely used to understand the detector and to identify better background rejection efficiencies through dedicated veto techniques (cf. section 8.1).

5.1 The Simulation Chain

The chain of event simulation in IceCube involves particle generators, lepton & photon propagators, and detector response simulation. Each component is briefly discussed in the following sections.

5.1.1 Particle Generators

Two main particle generators are used in IceCube to generate atmospheric muon and neutrino background events: \texttt{COSmic Ray SImulation for KAscade (CORSIKA)} [154] and \texttt{neutrino-generator} [155]. The latter one is also used for IceCube neutrino signal simulation.

\textbf{CORSIKA}

Cosmic Ray (CR) particle interactions following the Hörandel CR spectrum [156] and full shower development in the upper atmosphere can be simulated
with CORSIKA. Primary particles from light electrons to heavy ions like iron are injected into the upper atmosphere and propagated until they interact hadronically\(^1\) or electromagnetically with molecule nucleons of the atmosphere, decay, or reach a minimum energy. For IceCube and IceTop only the muons of the created secondary particles are of interest because they can penetrate the atmosphere and the glacial ice deep enough to reach the in-ice detector array. Thus, only these muons are tracked and recorded down to the surface of the Earth.

**Neutrino-Generator**

For atmospheric neutrino background and neutrino signal flux predictions, weighted neutrino data sets are produced using the *neutrino-generator* particle generator which is based on the All Neutrino Interaction Simulation (ANIS) generator [155]. Neutrinos of a certain generation energy spectrum (usually \(E^{-1}\) or \(E^{-2}\)) are injected at the surface of the Earth and propagated near to the detector volume and forced to interact in order to save computational resources. The neutrino interaction probability is provided by an interaction weight, \(W\), that includes the interaction volume and the neutrino cross-section (*cf.* section 2.1), and hence the neutrino absorption effect in matter. The composition of the Earth required for this effect is modeled through the Preliminary Earth Model (PREM) [158]. The injection weight includes also neutrino oscillation effects. Its unit is GeV cm\(^2\) sr. It can be used to weight the neutrino data set to any desired initial flux of neutrinos by multiplying \(W\) with the neutrino flux \(d\Phi_\nu/(d\Omega dA dt dE)\). Using this weighting scheme angular and energy dependent signal data sets for any given initial neutrino flux can be obtained.

### 5.1.2 Lepton & Photon Propagators

After the secondary charged leptons are produced (*cf.* section 5.1.1), they have to be propagated through the detector volume. The software module *Muon Monte Carlo (MMC)* [159] propagates the leptons through the detector medium and simulates their energy losses due to ionization, bremsstrahlung, photo-nuclear interactions, \(e^+e^-\)-pair production, decay and Cherenkov photon production. Further secondary leptons created by those interactions are propagated as well. Recently, the *PRopagator with Optimal Precision and Optimized Speed for All Leptons (PROPOSAL)* [115] has replaced the Java implemented MMC code by a C++ implementation incorporating updated photon yield tables for the various lepton energy loss processes. Separate photon yield tables are used for hadronic cascades, but hadrons are not propagated explicitly through the detec-

---

\(^1\)Hadronic interactions are handled in CORSIKA through the SIBYLL [157] hadronic interaction model.
The individual photons produced are propagated through the ice via a direct photon propagation code named Photon Propagation Code (PPC) [160]. Absorption and scattering variations with depth of the ice as provided by the South Pole ICE (SPICE)-Mie ice model (cf. section 2.3) are taken into account. Because the propagation processes of the individual photons are independent of each other, the simulation is parallelized utilizing Graphics Processing Units (GPUs), which have a much higher number of compute cores than Central Processing Units (CPUs). PPC uses the Compute Unified Device Architecture (CUDA®) programming framework for NVIDIA graphics cards. In order to use also non-NVIDIA graphics devices an independent propagation code named CLsim has been implemented. It is based on the OpenCL programming framework and thus runs also on non-NVIDIA graphics devices. It has been shown within the IceCube collaboration that both codes perform interchangeably.

5.1.3 Detector Response Simulation

Whenever a simulated photon hits the DOM surface, the DOM’s angular acceptance and efficiency determine if the photon produces a photo-electron. The DOM efficiency is a convolution of the PMT collection efficiency, the transmission of the glass-sphere with the optic gel between the sphere and the PMT, and the local hole ice properties around the DOM. After a photo-electron is produced all the DOM electronics including the PMT response, DOM logic and main-board electronics are simulated using the PMTResponseSimulator and DOMLauncher software modules. Finally the IceCube trigger logic is simulated constructing a trigger hierarchy object and building an actual event containing the same type of information as a real data event.

5.2 Background Simulation

CORSIKA and neutrino-generator event simulation (cf. section 5.1.1) is used to develop background rejection cuts and to determine the background rejection efficiency of the event selections. The flux of background atmospheric neutrinos is calculated using the generic neutrino-generator data sets weighted by the Honda atmospheric neutrino flux model [144], providing a neutrino purity determination of the final data samples. In the final analyses right ascension scrambled experimental data is used as background estimate in order to make the analyses robust against systematic effects in the simulation.
5.3 Signal Simulation

For signal neutrino data sets, the analyses in this work use the neutrino data sets produced with neutrino-generator (cf. section 5.1.1). The injection weight \( \mathcal{W} \) is multiplied with the neutrino flux expected from WIMP annihilation in the Milky Way given by equation (1.8). The neutrino energies of the neutrino data sets range from 10 GeV up to \( 10^9 \) GeV.
Part III

Indirect Searches for Dark Matter in the Milky Way
6 Analyses Overview

The indirect search for DM annihilation in the Milky Way is based on the flux of DM annihilation products. For a neutrino detector like IceCube (cf. chapter 3) it is the flux of neutrinos as described in section 1.6 and expressed in equation (1.8). Such searches aim to measure or, upon non-detection, to set upper limits on the thermal averaged DM self-annihilation cross-section, \( \langle \sigma_A v \rangle \), in dependence of the DM particle mass, \( m_\chi \). As mentioned in section 1.2 the analyses presented in this thesis focus exclusively on the WIMP as candidate for DM. The strategy is to probe a wide range of different WIMP masses. Due to the large variation in the neutrino detection efficiency of a single event selection in dependence of the neutrino energy and thus on the WIMP mass, it is advisable to develop different event selections targeting different neutrino energy ranges. The two analyses described in chapter 8 and chapter 9 target WIMP mass ranges of 30 GeV – 10 TeV and 300 GeV – 100 TeV, respectively. In combination the two analyses span the widest possible WIMP mass range currently probed by the IceCube detector. At the low-mass boundary the analysis is limited by the neutrino detection threshold of IceCube-DeepCore. The high-mass boundary is given by the unitarity bound of WIMPs [161] which relates \( \langle \sigma_A v \rangle \) to the WIMP freeze-out temperature of the early universe and gives an upper bound on the DM particle mass of about 340 TeV for \( \langle \sigma_A v \rangle \) being \( \mathcal{O}(3 \cdot 10^{-26} \text{cm}^3\text{s}^{-1}) \). Both here presented analyses search for WIMPs in the Milky Way but target different regions of it for observation. The low-energy analysis described in chapter 8 observes the Galactic Center which is located in the southern sky and thus for IceCube always above the horizon. On the other hand, the high-energy analysis presented in chapter 9 targets mainly the galactic halo in the northern hemisphere as seen by IceCube at the South Pole, but also in the southern hemisphere for neutrino energies above 10 TeV. In order to overcome the large atmospheric muon background (cf. section 4.1) for southern hemisphere searches with IceCube, the low-energy Galactic Center analysis utilizes the DeepCore infill detector array, cf. section 3.1, to select neutrinos interacting within this densely instrumented detection volume and uses the surrounding IceCube array as veto against incoming atmospheric muons. The galactic halo search for higher WIMP
masses, however, uses the energy spectrum of the atmospheric muons and places an energy cut to remove most of the atmospheric muon background. Both analyses test the same WIMP annihilation channels. As described in section 1.4 and section 1.6 we consider the two complementary DM density profiles NFW [92] and Burkert [93] and five different WIMP annihilation channels for a variety of different WIMP masses best suited for the particular analysis. Table 6.1 summarizes the WIMP signal hypotheses that are tested by the two analyses. The statistical analysis method of both analyses is a maximum log-likelihood frequentist analysis with confidence intervals constructed using the Feldman-Cousins prescription [162]. Chapter 7 will introduce the statistical methods used by the two analyses before they are described in detail in chapter 8 and chapter 9.

**Table 6.1:** The WIMP signal hypotheses that are tested in the analyses presented in this thesis.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Low-E GC</th>
<th>High-E Galactic Halo</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WIMP density profiles</strong></td>
<td>NFW</td>
<td>Burkert</td>
</tr>
<tr>
<td><strong>WIMP annihilation channels</strong></td>
<td>$\chi \chi \rightarrow b\bar{b}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\chi \chi \rightarrow W^+W^-$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\chi \chi \rightarrow \mu^+\mu^-$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\chi \chi \rightarrow \tau^+\tau^-$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\chi \chi \rightarrow \nu\bar{\nu}$</td>
<td></td>
</tr>
<tr>
<td><strong>WIMP masses</strong></td>
<td>30 GeV</td>
<td>300 GeV</td>
</tr>
<tr>
<td></td>
<td>65 GeV</td>
<td>500 GeV</td>
</tr>
<tr>
<td></td>
<td>100 GeV</td>
<td>1 TeV</td>
</tr>
<tr>
<td></td>
<td>200 GeV</td>
<td>3 TeV</td>
</tr>
<tr>
<td></td>
<td>300 GeV</td>
<td>10 TeV</td>
</tr>
<tr>
<td></td>
<td>400 GeV</td>
<td>30 TeV</td>
</tr>
<tr>
<td></td>
<td>500 GeV</td>
<td>100 TeV</td>
</tr>
<tr>
<td></td>
<td>1 TeV</td>
<td></td>
</tr>
</tbody>
</table>
7 Statistics

As mentioned in chapter 6 the two WIMP analyses use the same statistical concepts to determine the signal strength in the measured data samples. This chapter is dedicated to introduce these concepts.

7.1 The Mixture Model

The data sets used in the analyses presented in this thesis are supposed to consist of signal and background events. Thus, a mixture model with two components is a reasonable choice for constructing the probability density function (p.d.f.) for the measured observables of the data set events. This model consists of a signal and a background component. Each is represented as a p.d.f. and can be a product of individual p.d.f.s for each independent observable. The signal and background p.d.f.s are weighted to each other to form the composite p.d.f. \( f(x; \mu) \) for the measured observables \( x \) for each event given the hidden parameter \( \mu \). In the case here the parameter \( \mu \) is the number of signal events \( n_s \) in the data set.

The weights of both components, \textit{i.e.} the signal and background p.d.f.s, can be parameterized by the signal fraction, or signal strength, \( \xi \),

\[
\xi = \frac{n_s}{n_s + n_{bg}},
\]

(7.1)

where \( n_s \) and \( n_{bg} \) are the mean number of signal and background events in the data set, respectively.

7.2 Maximum Likelihood Estimator

Suppose the hypothesis is represented by a p.d.f., \( f(x; \mu) \), for observables with an unknown parameter \( \mu \), \textit{e.g.} the number of signal events in a data set, where \( x \) denotes a set of observables (event variables), like direction or energy proxy of an event of the data set of size \( N \). The a-priori probability that event \( i \) is within a small multi-dimensional space of the observables, \( dV_i \), centered on \( x_i \),
is $f(x_i; \mu) dV_i$. The probability of this happening for all $i$ is the product
\[
\prod_{i=1}^{N} f(x_i; \mu) dV_i. \quad (7.2)
\]
The maximum likelihood estimator for $\mu$ is the value which maximizes this probability. The constant factor $\prod_i dV_i$ is of no interest, so the function to be maximized is the likelihood function $L(\mu)$:
\[
L(\mu) = \prod_{i=1}^{N} f(x_i; \mu). \quad (7.3)
\]
It is a function of $\mu$ for the fixed measured observables $x_i$ of the data set.

### 7.3 Confidence Intervals

The confidence interval $[\mu_1, \mu_2]$ provides a statistical uncertainty for the unknown parameter $\mu$. The values $\mu_1$ and $\mu_2$ provide a lower and upper limit on $\mu$ at a predefined confidence level of probability $\alpha$.

#### 7.3.1 General Construction

The general construction procedure for confidence intervals is illustrated in figure 7.1. In this figure $x$ refers to the estimate $\hat{\mu}$ for the (unknown) parameter $\mu$ in the case here. The goal is to construct an interval $[\mu_1, \mu_2]$ of the parameter values so that the true parameter value $\mu_{\text{true}}$ is covered with a certain probability $\alpha$:
\[
P(\mu \in [\mu_1, \mu_2]) = \alpha. \quad (7.4)
\]
This probability defines the confidence level (C.L.). The confidence interval is a function of the measured quantity $x$, thus different for each (observed) value of $x$. It can be obtained by constructing acceptance intervals $[x_1, x_2]$ for each possible value $\mu$, such that
\[
P(x \in [x_1, x_2]; \mu) = \alpha. \quad (7.5)
\]
The simple connected region of the intersections of a vertical line at $x_0$ (indicated as dashed line in figure 7.1) with the acceptance intervals for all $\mu$ defines the confidence interval $[\mu_1, \mu_2]$, where $\mu_1$ and $\mu_2$ is the lowest and highest value of $\mu$ of all intersections, referred to as lower and upper limit, respectively.

The selection of values $x$ for a given value $\mu$ to cumulate $P(x; \mu)$ until equation (7.5) is fulfilled is arbitrary. An intuitive choice proposed by Neyman [163]...
Figure 7.1: Illustration on the general confidence interval construction for a hypothesis with one measured quantity and one unknown parameter. An acceptance interval \([x_1, x_2]\) is selected for the measured quantity using a chosen procedure, \textit{i.e}. Neyman-Pearson or via the Feldman-Cousins ordering principle, illustrated as horizontal lines. For a given outcome of the experiment \(x_0\) shown as the dashed vertical line, the confidence interval \([\mu_1, \mu_2]\) is the simple connected region of the intersections of the vertical line with the acceptance intervals. By construction, the confidence interval satisfies equation (7.4). Hence, the probability that the true parameter value \(\mu_{\text{true}}\) is covered by the values of the confidence interval for the particular measured value \(x_{\text{obs}}\) is \(\alpha\). Figure taken from Ref. [162].

and known as the classical confidence interval construction, is to satisfy one of the conditions

\[
P(x < x_1; \mu) = 1 - \alpha, \tag{7.6}
\]

which leads to one-sided upper confidence limits with \(P(\mu > \mu_2) = 1 - \alpha\); and

\[
P(x < x_1; \mu) = P(x > x_2; \mu) = \frac{1 - \alpha}{2}, \tag{7.7}
\]

leading to central confidence intervals with upper and lower confidence limits satisfying \(P(\mu < \mu_1) = P(\mu > \mu_2) = (1 - \alpha)/2\). The drawback of this acceptance interval selection procedure is that one needs to decide what limits to determine, \(\textit{i.e}.\) one-sided or central limits, before performing the measurement, commonly known as the flip-flopping problem.

Another selection method has been proposed by Feldman and Cousins [162] that involves an ordering principle for the selection of \(x\) values and prevents the
flip-flopping problem. It is the one used in the analyses presented in this thesis and is described in section 7.3.2.

7.3.2 Acceptance Intervals via the Feldman-Cousins Ordering Principle

Feldman and Cousins [162] proposed the selection of the $x$ values based on the likelihood ratio $R$ given by

$$R = \frac{P(x; \mu)}{P(x; \mu_{\text{best}})}, \quad (7.8)$$

where $\mu_{\text{best}}$ is the value of the parameter $\mu$ that maximizes $P(x; \mu)$ for the fixed value $x$, i.e. $P(x; \mu)$ along a vertical line at $x$ in figure 7.1 (the maximum likelihood estimate for $\mu$). By construction $R$ has the value range $[0, 1]$. The values of $x$ for a given $\mu$, i.e. along the horizontal line, are selected for the acceptance interval in decreasing order of $R$ until the sum of $P(x; \mu)$ is equal or greater than the predefined confidence level. In this way the construction algorithm decides between upper limits and double-sided confidence intervals intrinsically. One may note that in order to get statistically stable results using this ordering principle, one needs to calculate $P(x; \mu)$ for a wide range of $\mu$ values and a large amount of independent experiments to cover the tails of the $x$-distribution for each $\mu$ with sufficient statistics.

7.4 Basic Hypothesis Testing

In order to make a statement about how well the measured data stand in agreement with given probabilities, i.e. a hypothesis $\mathcal{H}$, one constructs a function $t(x)$ of the measured data, called the test statistic (TS), that provides a measure how much the measured data deviate from the hypothesis. Possible TS functions are likelihood ratios that involve the parameter estimate $\hat{\mu}$ in case of composite hypotheses (cf. section 8.3.1 and section 9.2.1 for the TS function used in the GC and GH analysis, respectively). Repeated experiments, i.e. randomly generated data sets, for a given hypothesis, e.g. $\mathcal{H}_0$: the data sample consists of only background events, hence, $\mu = 0$, would provide different values for $t$ constituting a p.d.f. $g(t | \mathcal{H}_0)$ given that hypothesis. A $p$-value can be defined as the probability to get a $p$-value smaller than the $p$-value for the observed data set, $p_{\text{obs}}$, which corresponds to the $t$-value of the observed data set, $t_{\text{obs}}$, and hence for $t > t_{\text{obs}}$. Thus, it is defined as

$$p = \int_{t_{\text{obs}}}^{\infty} g(t' | \mathcal{H}_0) \, dt'. \quad (7.9)$$
Hence, the $p$-value provides the probability of how likely it is to observe the measured data when the null-hypothesis is true. In no way it provides a certainty of the observed data in terms of any alternative hypothesis $H_1$. An alternative hypothesis $H_1$ defines which deviations from the $H_0$ expectation one should look for, i.e. the choice of TS. In case of the analyses of this thesis $H_1$ represents a given DM hypothesis producing signal neutrinos.
8 Indirect Search for DM in the Galactic Center

The first of the two analyses presented in this thesis searches for muon neutrinos originating from WIMP self-annihilation in the Galactic Center. The analysis and its results were published in paper III in the European Physics Journal C. The analysis as described there is a composite of two individual IceCube Galactic Center analyses targeting different ranges of WIMP masses. One analysis, optimized for very small WIMP masses in the range 30 GeV – 1 TeV, was carried out by the author of this thesis and his colleague Samuel Flis at Stockholm University. The other analysis was optimized for higher WIMP masses in the range 300 GeV – 10 TeV and performed by Martin Bissok at the Rheinisch-Westfälische Technische Hochschule Aachen (RWTH Aachen) in Germany. For paper III the two analyses were combined in terms of their sensitivity. Hence, for each WIMP hypothesis the results were presented for the analysis that had the better sensitivity for the particular signal hypothesis. The cross-over point of the two analyses in terms of WIMP mass is around 300 GeV, depending on the particular DM profile density and WIMP annihilation channel. It is lower for hard annihilation channels like $\nu\bar{\nu}$ and higher for soft channels like $b\bar{b}$. The cross-over points can be nicely seen in figure 8.1, that is part of paper III. It shows the sensitivity (dashed lines) and observed upper limits (solid lines) at the 90% confidence level (C.L.) for three different WIMP annihilation channels assuming a NFW DM halo profile. Since both analyses observed a statistical under-fluctuation of data towards the Galactic Center, the upper limits are below the sensitivity lines for all WIMP masses. However, the low-energy analysis observed a stronger under-fluctuation than the high-energy analysis, leading to upper limit lines further below the sensitivity lines than in the high energy analysis case. Thus, the transition between the two analyses is nicely visible in this figure. This thesis describes solely the low energy analysis performed by the author and his colleague at Stockholm University. This low-energy analysis was initially motivated by the possible observed 130 GeV gamma-ray line feature in the Fermi Large Area Telescope (LAT) data as described in section 1.3.2.
Thus, the analysis focuses on WIMP masses around and below this energy. Initially, two event selections, optimized on WIMPs with masses of 65 GeV and 130 GeV annihilating into $b\bar{b}$ and $W^+W^-$, respectively, were developed for the Stockholm analysis. After combining the Stockholm and Aachen analyses for publishing paper III only the 65 GeV event selection contributed significantly to the sensitivity of the combined GC analysis. Thus, the 130 GeV event selection was not pursued further. Hence, this thesis will describe solely the 65 GeV event selection denoted as low-energy event selection in paper III.

![Graph](image)

**Figure 8.1**: Sensitivity (*dashed*) and observed upper limits (*solid*) at 90% C.L. of the GC analysis including detector systematics for the $b\bar{b}$ (*stars*), $\tau^+\tau^-$ (*squares*), and $\nu \bar{\nu}$ (*triangles*) WIMP annihilation channel assuming a NFW DM halo profile. The shaded areas are eye-guides for the reader, connecting corresponding sensitivities and observed upper limits. Figure taken from [3].

In general, an IceCube analysis searching for neutrinos originating from the direction of the Galactic Center has to deal with a huge atmospheric muon background (*cf. section 4.1*) because the Galactic Center at declination $-29^\circ$ is seen by IceCube always above the horizon at the South Pole. In order to reduce the down-going atmospheric muon data rate, dedicated veto techniques have
been developed for the low-energy Galactic Center analysis. The strategy to select muon neutrinos with energies below \( \sim 100 \text{ GeV} \) is to utilize the low-energy DeepCore infill array of IceCube (cf. section 3.1) and to select neutrino-induced starting-track events inside the DeepCore fiducial volume. The outer parts of the IceCube array are used as an active veto region for incident atmospheric muons. These developed veto techniques are described in more detail in section 8.1 before the overall event selection of the low-energy Galactic Center analysis is described in section 8.2. Finally, the analysis method, its sensitivity, the systematic uncertainties, and the results are presented in section 8.3, section 8.4, section 8.5, and section 8.6, respectively.

## 8.1 Atmospheric Muon Background Veto Techniques

Paper I describes the methods to extend IceCube low energy neutrino searches for Dark Matter with DeepCore. In order to address low WIMP masses, a dedicated low-energy (LE) event selection using the DeepCore infill array of IceCube is required. Since neutrino events in DeepCore with energies below \( \sim 100 \text{ GeV} \) have different event topologies than higher energy events interacting in IceCube, this dedicated LE event selection is able to exploit these differences. As mentioned above, this LE selection requires events to start inside the DeepCore fiducial volume and uses the surrounding IceCube array as a veto against incoming atmospheric muons. Five veto techniques are utilized in this Galactic Center analysis.

The first technique aims to select starting events inside DeepCore by requiring that the first four hits of an event occur inside the DeepCore fiducial volume. The used hits for this *pulse-time containment veto* are noise-cleaned TWSRT hits using the space-time clustering cleaning algorithm described in section 3.4.1. These noise-cleaned hits are also used to remove down-going coincident muons accompanying atmospheric neutrinos by rejecting all events with hits above the DeepCore fiducial volume, *i.e.* at depths below 2100 m, a region referred to as *detector-top veto* in the following. However, low-energy faint atmospheric muons will leave single hits in the IceCube veto region that would be cleaned away by the noise-clustering cleaning algorithm, mimicking starting events in the fiducial volume. Thus, the following techniques are based on the entire hit series of an event and were developed for the first time for this Galactic Center analysis.

The *RTVeto* veto algorithm identifies such faint incoming muons by searching for clusters of causally connected hits in space and time around each hit in the veto region prior to the first fiducial volume hit. The size of the largest found cluster of an event is correlated with the occurrence of an incoming muon. Figure 8.2 shows the size of these RT hit clusters for atmospheric muons (solid
line), low-energy signal neutrino events (dashed line), and data (circles). The error bars of the data points indicate the statistical uncertainty based on the number of events. With a rejection cut set to RT cluster size $\geq 3$, more than 80% atmospheric muons can be rejected while keeping 90% of signal neutrinos starting inside the fiducial volume.

The third technique for identifying atmospheric muons entering the fiducial volume is to look at the vertical position $z$ of the first hit of an event and the radial distance $r$ of its vertex position from the center axis of the detector. The vertex position is calculated by the vertex reconstruction algorithm described in section 3.4.7 using the noise-cleaned event hits. The distance $r$ is defined as $r = \sqrt{x^2 + y^2}$, where $x$ and $y$ are the horizontal coordinates of the vertex position. By constructing the two-dimensional $r$-$z$-space with the signal fraction per bin, a cut can be defined to disentangle signal and background events. The signal fraction is defined as $f_s/(f_s + f_b)$, where $f_s$ and $f_b$ are the two-dimensional signal and background p.d.f.s, respectively. This technique will be denoted as $RZCut$ further on in this thesis. Figure 8.3 shows the signal fraction in the $r$-$z$-plane applicable for this analysis.

The fourth veto technique utilizes the fact that a muon produces light with
Figure 8.3: Signal fraction $f_s/(f_s + f_b)$ in the $r$-$z$-plane for the RZCut. The radius is the horizontal distance of the vertex position of an event to the central detector vertical axis, whereas $z$ is the vertical position of the first hit of an event. Signal events start predominately deep at the center of the detector (i.e. left and lower-left part of the plot), while background events enter the DeepCore fiducial volume at the top and the outer parts. This analysis uses the rejection criteria \{($z > -300$ m and $z > -2.333r + 80$ m) or ($z \leq -300$ m and $r > 160$ m)\}, which is illustrated as a gray-shaded region.

a Cherenkov cone pattern and is referred to as ConeCut. Using a reconstructed track hypothesis and the reconstructed interaction vertex of the event, one can place a cone with its tip at the vertex position and its axis along the incoming track direction, i.e. time-wise before the vertex time, and count the hits, $n_{\text{cone}}$, inside this cone prior to the vertex time. The number of hits must be optimized with respect to the opening angle of the cone and an optimal veto efficiency was found for rather small opening angles between $20^\circ$ and $30^\circ$.

The fifth and last veto technique aims to catch incoming faint muons that have not been identified by the previous applied techniques, because the very few hits, $\mathcal{O}(< 5)$, in the veto region are too far apart or too distant from the reconstructed track hypothesis. By using all the hits in the veto region that can be found around a certain distance from the initial reconstructed track hypothesis and prior to the vertex time, the hit-normalized negative log-likelihood value, $r_{llh,0} = -\ln(L/n_{\text{ch}}^{\text{ns}})/n_{\text{ch}}$, for that track hypothesis based on solely these veto hits can be calculated. Hence, it determines how likely the hits are to be associated with a muon track. This technique is referred to as likelihood veto and denoted LHVeto. Hits originating from an actual muon tend to produce higher log-likelihood values than random distributed noise hits. Thus, additional muon
background events can be rejected by placing a lower bound on $r_{llh,0}$.

## 8.2 Event Selection

The search for WIMP self-annihilation in the Galactic Center uses 319.7 days of IceCube live-time during May 31 2010 and May 13 2011. During this time, IceCube was operated in its 79-string configuration with six DeepCore strings. Starting from level 2 (L2) that contains all events passing any IceCube filter with an event rate of 183 Hz, the analysis uses only events passing the DeepCore filter (cf. section 3.6.1), with an event rate of $\sim 18$ Hz. Through a series of levels of straight cuts, the data rate is reduced to 6.8 mHz. The sets of straight cuts for this analysis were developed successively and individual cuts were refined as the event selection was developed. An additional multivariate step using the Boosted Decision Tree (BDT) method leads to the final analysis level with a final data rate of 1.4 mHz. Thus, the data volume is reduced by five orders of magnitude while the signal efficiency with respect to all filters, *i.e.* L2, is kept at 21.4%. The details of the individual cut levels are described in the following sections. The overall evolution of the data rate and signal efficiency of the LE event selection of this analysis is shown in figure 8.4.

![Figure 8.4](image)

**Figure 8.4:** Data rate (*left ordinate*) and signal efficiency (*right ordinate*) for all cut levels of the LE event selection of the low-energy Galactic Center analysis. The signal efficiency is relative to the level 2 (L2) data that are all events passing any type of IceCube filter. At final level a signal efficiency of 21.4% is maintained while the data rate is reduced by five orders of magnitude to a final data rate of 1.4 mHz.
8.2 Event Selection

Table 8.1: Specifications of the dedicated monochromatic signal simulation data set used in the low-energy GC analysis for the event selection development.

<table>
<thead>
<tr>
<th>dataset</th>
<th>$E_\nu$ [GeV]</th>
<th>$N_{\text{gen. events}}^{\text{file}} \times N_{\text{file}}$</th>
<th>ice model</th>
<th>photon prop.</th>
</tr>
</thead>
<tbody>
<tr>
<td>signal</td>
<td>65</td>
<td>$2 \times 10^5 \times 92$</td>
<td>SPICE-Mie</td>
<td>ppc</td>
</tr>
<tr>
<td>$\nu_\mu + \bar{\nu}_\mu$</td>
<td>$3 \times 10^5 \times 97$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8.2: Specifications of the atmospheric background simulation data sets used in the low-energy GC analysis for the event selection development.

<table>
<thead>
<tr>
<th>dataset / ID</th>
<th>primary energy range [GeV]</th>
<th>$N_{\text{gen. events}}^{\text{file}} \times N_{\text{file}}$</th>
<th>ice model</th>
<th>photon prop.</th>
</tr>
</thead>
<tbody>
<tr>
<td>atm. $\nu_\mu + \bar{\nu}_\mu$ 6467</td>
<td>$E_\nu \in [10, 10^9]$</td>
<td>$2 \times 10^7 \times 286$</td>
<td>SPICE-Mie</td>
<td>ppc</td>
</tr>
<tr>
<td>atm. $\mu^- + \mu^+$ 6939</td>
<td>$E_{\text{pr.}} \in [600, 10^{11}]$</td>
<td>$25 \times 10^7 \times 10^4$</td>
<td>SPICE-Mie</td>
<td>ppc</td>
</tr>
</tbody>
</table>

The signal efficiency of figure 8.4 is based on a dedicated monochromatic muon neutrino signal data set generated with *neutrino-generator* (cf. section 5.1.1) and the usual IceCube detector simulation chain (cf. section 5). It represents the annihilation of 65 GeV massive WIMPs directly into a pair of neutrinos at the Galactic center. It has been used to develop the dedicated event selection of this analysis optimized for low-energy neutrinos below $\sim 100$ GeV in DeepCore as proposed also in paper I. The properties of this monochromatic signal simulation data set are specified in table 8.1. For atmospheric neutrino and muon background simulation the data sets given in table 8.2 have been used. These are used together with the experimental data to confirm the background rejection ability of the event selection.

In order to be able to constrain a broad spectrum of WIMP masses and annihilation channels, the final analysis, as described in section 8.3, uses the muon neutrino data set (row 1 of table 8.2) for WIMP signal simulation through the event weighting method as discussed in section 5.3.

In the following sub-sections the different levels of the event selection are described. They aim to select low-energy starting neutrino events inside DeepCore originating from DM self-annihilation several degrees around the Galactic Center, which itself is located at $-29^\circ$ declination and $266^\circ$ right ascension. During the development of the entire analysis the right ascension of the events
have been kept blind to avoid any confirmation bias by the analyzers. Only after the finalization of the analysis and its successful passing of the IceCube internal analysis review process, the data was unblinded and the real right ascension coordinates of the events were seen by the analysis.

8.2.1 Trigger & Filter Level – L1 & L2

This low-energy Galactic Center analysis uses solely data passing the DeepCore filter, which is run on events triggered by the SMT-3 DeepCore trigger as described in section 3.6.1. The overall IceCube-79 trigger rate is about 1,900 Hz while the DeepCore SMT-3 trigger rate is 185 Hz [126]. The level 2 filtered data are provided centrally by the IceCube collaboration. They contain all events passing any IceCube filter and have an event rate of 183 Hz as shown in figure 8.4. At level 2 the extracted PMT pulses of an event are noise cleaned using the time-window and SeededRT cleaning methods as described in section 3.4.1. After applying the DeepCore filter passing criteria by this analysis, the data rate is reduced to \( \sim 18 \text{ Hz} \).

8.2.2 Level 3

The first event selection level developed for the Galactic center analysis is based on the experience gained by the previous IceCube analysis searching for WIMPs in the Sun [2]. The Sun analysis utilized DeepCore for the selection of low-energy events as well, when the Sun is above the horizon during the austral summer time. Since the analysis is looking at a specific spot in the sky, \( \text{i.e.} \) the GC, it benefits from good angular resolution. Events with very few hit DOMs and strings and thus little hit information like position, time, and PMT charge, result generally in badly reconstructed tracks. Such events do not contribute much to the sensitivity of the analysis and are therefore removed by the level 3 cuts II & III as listed in table 8.3. In order to reduce the down-going atmospheric muon rate, the \textit{pulse-time containment} and detector-top vetoes are applied as described in section 8.1. After the applied level 3 cuts the data rate is reduced to \( \approx 1 \text{ Hz} \), whereas the signal efficiency is at the 70% level.

8.2.3 Level 4

The level 4 selection focuses on DeepCore contained events with good quality reconstructions. The passing conditions of the level 4 cuts are listed in table 8.4. The cuts I & II remove badly reconstructed events. The third cut selects events that are predominately contained in the DeepCore fiducial volume by requiring that the \textit{finite-reco} reconstructed event length is smaller or equal to 600 m, which is roughly the diagonal size of the DeepCore fiducial volume. Cut IV selects
events that start inside the DeepCore fiducial volume, thus the vertex starting position of such events should not be further away from the vertical center axis of the detector than 250 m. Atmospheric muons penetrate the detector from top to bottom leaving hits predominately along the vertical detector axis $z$, whereas signal neutrinos originate from a narrow zenith angle band centered at $61^\circ$, $\text{i.e.}$ $-29^\circ$ declination of the GC. Hence, the spread of hits along the $z$-axis tends to be larger for atmospheric muons than for signal neutrinos. Cut V addresses this. In order to reduce the overall amount of data the zenith angle interval cut VI selects events reconstructed within $\pm 20^\circ$ around the zenith angle of the GC. The most effective level 4 cut is the $RTVeto$ veto against faint atmospheric muons sneaking in as described in section 8.1. By rejecting all events with veto hit cluster sizes greater than two, the data rate is reduced by 80% while 90% of the signal is kept ($\text{cf.}$ also figure 8.2). After applying the level 4 cuts the data rate is reduced to 68 mHz and the signal efficiency is sustained at 38%.

Table 8.3: The level 3 cuts of the GC low-energy analysis and their event passing conditions.

<table>
<thead>
<tr>
<th>cut</th>
<th>event passing condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Event passed the DeepCore filter.</td>
</tr>
<tr>
<td>II</td>
<td>$n_{ch} \geq 11$</td>
</tr>
<tr>
<td>III</td>
<td>$n_{str} \geq 4$</td>
</tr>
<tr>
<td>IV</td>
<td>Event passed the pulse-time containment veto, $\text{cf.}$ section 8.1.</td>
</tr>
<tr>
<td>V</td>
<td>Event passed the detector-top veto, $\text{cf.}$ section 8.1.</td>
</tr>
</tbody>
</table>

Table 8.4: The level 4 cuts of the GC low-energy analysis and their event passing conditions.

<table>
<thead>
<tr>
<th>cut</th>
<th>event passing condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$\sigma_{\text{para}} \leq 13^\circ$</td>
</tr>
<tr>
<td>II</td>
<td>$r_{\text{llh}} \leq 11$</td>
</tr>
<tr>
<td>III</td>
<td>$L_{\text{FR}} \leq 600$ m</td>
</tr>
<tr>
<td>IV</td>
<td>$r_{\text{FR}} \leq 250$ m</td>
</tr>
<tr>
<td>V</td>
<td>$\sigma_z \leq 80$ m</td>
</tr>
<tr>
<td>VI</td>
<td>$41^\circ \leq \Theta_{\text{zen}} \leq 81^\circ$</td>
</tr>
<tr>
<td>VII</td>
<td>Event passed the $RTVeto$ veto, $\text{cf.}$ section 8.1</td>
</tr>
</tbody>
</table>
Table 8.5: The level 5 cuts of the GC low-energy analysis and their event passing conditions.

<table>
<thead>
<tr>
<th>cut</th>
<th>event passing condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Event passed the $RZCut$, cf. section 8.1.</td>
</tr>
<tr>
<td>II</td>
<td>Event passed the $LHVeto$ veto, cf. section 8.1, if $r_{lh,0} \geq 18$ for $r_{cyl} = 250$ m or $r_{lh,0} \geq 11$ for $r_{cyl} = 300$ m or $r_{lh,0} \geq 6.8$ for $r_{cyl} = 350$ m</td>
</tr>
<tr>
<td>III</td>
<td>Event passed the $ConeCut$ veto, cf. section 8.1, if $n_{cone} \leq 1$ for $\angle_{cone} = 20^\circ$</td>
</tr>
<tr>
<td>IV</td>
<td>$n_{ch} &lt; 80$</td>
</tr>
<tr>
<td>V</td>
<td>$51^\circ \leq \Theta_{zen} \leq 81^\circ$</td>
</tr>
</tbody>
</table>

8.2.4 Level 5

The main goal of the level 5 selection is to reject sneaking-in faint atmospheric muons. Thus, the three veto-like cuts $RZCut$ (cut I), $LHVeto$ (cut II), and $ConeCut$ (cut III), as described in section 8.1 are applied at this stage. The most effective veto cut is the $RZCut$, rejecting 62% of the data while keeping 91% of the signal with respect to level 4. Shallow events with their first hit being at vertical position $z$ above $-300$ m and above $-2.333r + 80$ m, or deep events with their first hit vertical position below $-300$ m and $r > 160$ m are rejected. Here, $r$ is the horizontal distance of the vertex position of the event to the central detector vertical axis. As described in section 8.1, the $LHVeto$ cut takes only pulses within a predefined cylinder radius around the reconstructed track. This analysis evaluates the $LHVeto$ for three different cylinder radii: 250 m, 300 m, and 350 m. For each cylinder radius setting a different cut on the hit-normalized negative log-likelihood value, $r_{lh,0}$, as listed in table 8.5 is used. High $r_{lh,0}$ values indicate bad fits to noise hits and such events are less likely to be atmospheric muons. Finally, the $ConeCut$ with a half-cone opening-angle of $20^\circ$ was used to reject atmospheric muons as well. Only if zero or one hits were found inside the cone, the event was kept. Because this analysis focuses on low-mass WIMPs and hence low-energy signal neutrinos, high energy events can be cut away by applying cut IV on the number of hit DOMs, which correlates with the energy of the event. The vast majority of the atmospheric muon events have reconstructed zenith angles less than the signal peak at $61^\circ$. By restricting the zenith angle range further by applying cut V, the background rate is reduced further by 27% while this cut affects the signal efficiency only by 4% with respect to level 4. All level 5 cuts, as listed in table 8.5, reduce the data by almost an...
order of magnitude to an event rate of $8 \text{ mHz}$.

### 8.2.5 Multivariate Final Analysis Level

The final selection level utilizes a multivariate technique through a BDT implemented in the Toolkit for Multivariate Data Analysis with ROOT (TMVA) software package [164]. BDTs calculate the signalness of an event, denoted as the BDT score. To determine how signal-like an event is, the BDT uses a signal and a background event sample with the same set of event property variables defined for both samples. It creates a binary cut decision tree based on these variables, where each decision node defines a cut on a variable. After the creation of the decision tree, i.e. after the BDT is trained, it is evaluated on the data sample in question, whose event property variables are supposed to be distributed for signal and background events the same as the ones of the signal and background training samples, respectively. Thus, a data event ‘flows’ along the decision line of the BDT from the root node to the leaf node, where a BDT score is assigned to each leaf node. Usually, BDT scores range from -1 (background) to 1 (signal). This GC analysis uses the signal simulation sample as given in table 8.1 and 10% of the experimental data for the signal and background training samples, respectively. As event property variables, providing selection power for starting events in DeepCore and originating from the direction of the GC, the following 12 event observables, as defined in table 3.1, are used: $\Theta_{\text{zen}}, \sigma_z, t_{\text{accu}}, v_{\text{LF},z}, P_{\text{FR},x}, P_{\text{FR},y}, \Delta \log (L), L_{\text{FR}}, r_{\text{FR}}, z_{\text{trav}}, L_{\text{dir}},$ and $L_{\text{sep}}$. The distributions of the event observables after applying the level 5 cuts are the input for the BDT. They are shown for experimental data, atmospheric muon and atmospheric neutrino simulation, as well as for the dedicated 65 GeV signal neutrino simulation in figure 8.5, figure 8.6, and figure 8.7. The rates of the atmospheric muon simulation in these figures are constantly about 20% higher than the data rates. This is due to an underestimated DOM photon detection efficiency of about 10% in simulation, that leads to less efficient vetoes and therefore higher event rates compared to experimental data. This has been investigated using a low statistic atmospheric muon simulation data set generated with a 10% increased DOM photon detection efficiency, resulting in good agreement of the two rates.

The LE sample BDT provides a BDT score distribution of the data and simulation events that is shown in figure 8.8. The bottom panel shows the ratio between data and total background MC. Again, the rate of the atmospheric muon simulation is constantly 20% higher than the data rate, due to the underestimated DOM photon detection efficiency in simulation mentioned above. The cut on the BDT score is optimized for best sensitivity (cf. section 8.3) for the signal hypothesis of 65 GeV massive WIMPs annihilating exclusively into a pair of bottom quarks ($b\bar{b}$) by calculating the sensitivity for different BDT cut values.
Figure 8.5: Distribution of the event observables $L_{FR}$, $P_{FR,x}$, $P_{FR,y}$, and $r_{FR}$ based on the finite-reco (FR) event reconstruction algorithm as defined in table 3.1 after level 5 cuts (cf. table 8.5) applied. Experimental data are shown as black squares. Atmospheric muon and neutrino simulation is shown as solid red and dash-dotted green lines, respectively. The 65 GeV monochromatic signal simulation is shown as blue dashed line and is normalized to the data rate. The yellow hatched band shows the total background simulation, i.e. atmospheric muons and neutrinos. Its width indicates the statistical uncertainty of the simulation defined as the square-root of the sum of the summed squared weights of the individual background simulations.
8.2 Event Selection

Figure 8.6: Same as for figure 8.5, but for the event observables $t_{\text{accu}}$, $L_{\text{sep}}$, $L_{\text{dir}}$, and $z_{\text{trav}}$. 

(a) Time required to accumulate 75% of the total event charge, $t_{\text{accu}}$.

(b) Separation length, $L_{\text{sep}}$, of the first and last quartile of pulses along the track.

(c) Projected distance along the reconstructed track, $L_{\text{dir}}$, between the first and last direct hit.

(d) Average drift, $z_{\text{trav}}$, of hits along the vertical detector direction $z$. 
Figure 8.7: Same as for figure 8.5, but for event observables $\Theta_{\text{zen}}$, $\sigma_z$, $v_{\text{LF},z}$, and $\Delta \log(L)$. 

(a) The reconstructed zenith angle of the event, $\Theta_{\text{zen}}$, using the SPE reconstruction.

(b) The RMS spread of the collected charge along the vertical detector direction $z$, $\sigma_z$.

(c) Reconstructed track velocity, $v_{\text{LF},z}$, using the line-fit reconstruction.

(d) Difference of the best fit log-likelihood value for a starting and infinite track hypothesis, $\Delta \log(L)$, using the finite-reco algorithm.
Figure 8.8: BDT score distribution of the LE event sample of the LE GC analysis. Experimental data are shown as black squares, atmospheric muons as solid red line, atmospheric muon neutrinos as green dash-dotted line, and the dedicated 65 GeV signal neutrino simulation, scaled to the data rate, as blue dotted line. The yellow hatched band indicates the total rate and the statistical uncertainty of the background simulation. The BDT score cut value 0.087 optimized on 65 GeV massive WIMPs annihilating exclusively into $b\bar{b}$ is indicated as vertical black dotted line. The bottom panel shows the ratio of data over total background MC. Due to an underestimated DOM photon detection efficiency by $\sim 10\%$, which leads to worse efficiencies of the veto techniques in simulation, the total simulated background rate is constantly 20% higher than the data rate.

Because of the softness of the neutrino spectrum of the $b\bar{b}$ annihilation channel, it is a reasonable choice to obtain an event selection sensitive to low-energetic neutrinos, and thus to low WIMP masses.

8.3 Analysis Method

The event selection as described in section 8.2, provides a low-energy data sample with reconstructed event zenith angles in the range [51°, 81°], or in declination [−39°, −9°], with the GC located at −29° declination. The data sample covers the entire right ascension range [0h, 24h]. Due to the location of IceCube at the South Pole, the background data rate in right ascension can be assumed
uniform, because the background is only zenith, \textit{i.e.} declination, dependent for IceCube and any detector geometry effects are averaged-out through the rotation of the Earth.

To estimate the signal strength of the dataset with respect to the different signal hypotheses listed in table 6.1, a binned maximum log-likelihood method with the two-component mixture model (\textit{cf.} section 7.1) is used. The analysis analyzes the distribution of events within a search window defined by the declination range and ±30° in right ascension around the GC location. However, the background estimation is based on all events of the declination range. The 90% confidence intervals for the median and observed upper limits are constructed using the Feldman-Cousins prescription as described in section 7.3.

8.3.1 Likelihood Function

The likelihood function of this analysis is constructed using the two-component mixture model. Due to the restriction of the search window in right ascension, a binomial factor in front of the likelihood function has to be introduced in order to take the probability into account that an event falls either into or outside the search window. Thus, the general likelihood function for this analysis can be defined as:

$$L(\xi) = \binom{N}{n} p^n (1 - p)^{N-n} \prod_{i=1}^{n} f(X_i | \xi),$$

where \(N\), \(n\), and \(\xi = n_s/N\) denote the total number of events of the data sample, the number of events observed inside the search window, and the signal fraction. The shape likelihood density function \(f(X_i | \xi)\) is a function of the direction \(X_i = (\alpha_i, \delta_i)\) of each event for a given signal fraction \(\xi\). The probability \(p\) defines how likely a particular event falls into the search window and depends on the signal fraction \(\xi\) and the probabilities \(\pi_s\) and \(\pi_{bg}\) of a signal and background event, respectively, to fall into the search window. Its functional form is given by:

$$p = \pi_s \xi + \pi_{bg} (1 - \xi).$$

Since the background estimation is based solely on the uniform distribution of the data events in right ascension, the probability \(\pi_{bg}\) is given by the size ratio of the signal to background window and thus equals 1/6. The probability \(\pi_s\) depends on the shape of the particular signal hypothesis and is calculated from the signal simulation. It is simply the signal p.d.f. fraction inside the search window compared to the entire declination band. Because the DM is supposed to be distributed across the entire galaxy, some signal events are expected to be
distributed within the entire sky. Thus, signal contamination in the background estimation needs to be addressed in the directional p.d.f. $f(X|\xi)$. This directional p.d.f. $f$ is constructed from a directional signal and background p.d.f. $f_s$ and $f_{bg}$, respectively, that are normalized to one over the search window. Since the background p.d.f. $f_{bg}$ is estimated from right ascension scrambled data, signal contamination of the background can be accounted for by subtracting the p.d.f. $f_{sc}$ from the background p.d.f. The $f_{sc}$ p.d.f. models the declination dependence of right ascension scrambled signal. Thus, $f(X|\xi)$ can be written as

$$f(X|\xi) = w f_s(X) + (1 - w)[(1 + w)f_{bg}(X) - w f_{sc}(X)],$$

where $w$ is the signal fraction inside the search window and is defined as

$$w = \frac{\pi_s \xi}{\pi_s \xi + \pi_{bg}(1 - \xi)}. \quad (8.4)$$

All p.d.f.s are constructed using the software package HEAL-Pix [165] to ensure equal solid-angle sized bins on the sphere. An example of the directional background and signal p.d.f.s is shown in figure 8.9. There, the signal p.d.f. assumes the NFW DM halo model and 100 GeV WIMPs annihilating exclusively into $W^+W^-$. The search window of this LE analysis is indicated with a dashed line. By maximizing the likelihood function $L(\xi)$ for a particular data set, e.g. a randomly generated one from background and signal events, or the real data set after unblinding, the best fit signal fraction, $\hat{\xi}$, and thus the best fit number of signal events, $\hat{n}_s = N\hat{\xi}$ can be inferred.

As test statistic, TS, the likelihood ratio, $R$, proposed by Feldman and Cousins as described in section 7.3 is used. For the likelihood function of this analysis as given in equation (8.1) it can be written as

$$R(\mu) = \frac{L(\mu)}{L(\mu_{\text{best}})}, \quad (8.5)$$

where $\mu$ denotes the number of signal events, $n_s$, and $\mu_{\text{best}}$ maximizes the likelihood function. By construction $R(\mu) \leq 1$. According to the ordering principle of Feldman-Cousins, the confidence intervals $[\mu_1, \mu_2]$ are inferred by constructing the acceptance intervals $[R_{\text{crit}}^\alpha(\mu), 1]$ for the confidence level $\alpha$, where $R_{\text{crit}}^\alpha(\mu)$ outlines the $1 - \alpha$ lower quantile of the ranked distribution of $R$, the so-called “critical region”, defined as a function of $\mu$. In order to construct $R_{\text{crit}}^\alpha(\mu)$ many pseudo-experiments for different values of $\mu$ have to be conducted. For a particular experiment the upper limit $\mu_2$ is calculated by finding the value $\mu$, that satisfies $R(\mu) = R_{\text{crit}}^\alpha(\mu)$ for $\mu > \mu_{\text{best}}$. The lower limit $\mu_1$ can be obtained analogously by requiring $R(\mu) = R_{\text{crit}}^\alpha(\mu)$ for $0 \leq \mu < \mu_{\text{best}}$. 
8.4 Sensitivity

The sensitivity of this analysis is defined as the median upper limit at the 90% C.L., \( \tilde{\mu}_{90} \), for background-only random data sets. Thus, \( R_{\text{crit}}(\mu) \) (cf. section 8.3.1) was derived from 10,000 pseudo-experiments for each signal hypothesis and number of signal events \( \mu \) ranging from 0 to 300 in steps of one.

Through equation (1.8) and the detector signal neutrino efficiency, obtained from the simulated energy-dependent and zenith-dependent neutrino effective area, \( A_{\text{eff}}(E_\nu, \Theta_{\text{zen}}) \), of the detector, a particular number of signal events \( \mu \), e.g. the median upper limit \( \tilde{\mu}_{90} \), for the analysis live-time \( T_{\text{live}} \) can be related to a thermally averaged WIMP self-annihilation cross-section \( \langle \sigma_A v \rangle_{\text{result}} \):

\[
\langle \sigma_A v \rangle_{\text{result}} = \mu \frac{8 \pi m_\chi^2}{T_{\text{live}} \int \int A_{\text{eff}}(E_\nu, \Theta_{\text{zen}}) \frac{dN_{\nu}}{dE_\nu} J_a(\Psi) dE_\nu d\Omega}.
\]

In practice, the integration of the denominator is a sum of the weights of the simulated signal neutrino events.
8.5 Discussion of Systematic Uncertainties

The sensitivity has been calculated for each combination of DM halo model, WIMP annihilation channel and WIMP mass. Figure 8.10 shows the sensitivity on $\langle \sigma_A v \rangle$ for the NFW (top) and Burkert (bottom) DM halo models and all considered WIMP annihilation channels. At WIMP masses $\geq 500$ GeV the sensitivity for the direct neutrino channel (solid lines) is based on less than 100 signal events, causing large statistical fluctuations. However, in the final publication (paper III) this mass region is covered by the high-energy (HE) GC analysis performed by the Aachen IceCube group.

8.5 Discussion of Systematic Uncertainties

The sensitivities and upper limits of this analysis are subject to systematic uncertainties that can be categorized into two classes: Detector systematics and astrophysical uncertainties. The detector systematics affect the signal detection efficiencies, whereas the astrophysical uncertainties describe the uncertainties on the initial amount of signal neutrinos from DM self-annihilation. Thus, astrophysical uncertainties include the choice of a particular DM halo model as well as uncertainties on the DM model parameters $\rho_{\text{local}}$ and $r_s$ as given in table 1.2. The relative effect of these model parameter uncertainties on $\langle \sigma_A v \rangle$ was estimated to be 60 – 100%. In general, the value of the local dark matter density, $\rho_{\text{local}}$, is poorly constrained by observations and is subject to large uncertainties of factors 2–3. The limits on $\langle \sigma_A v \rangle$ depend on $\rho_0^2$, resulting in variations on $\langle \sigma_A v \rangle$ by almost an order of magnitude. For this reason, astrophysical uncertainties are not included directly in the limits of this analysis, instead different limits on $\langle \sigma_A v \rangle$ are computed for the two different considered DM halo models NFW and Burkert.

The systematic uncertainties affecting the signal detection efficiency are predominantly governed by the optical properties of the glacial ice, in particular the light absorption and scattering lengths, and the photon detection efficiency of the DOMs. In order to estimate the effect of the systematic detector uncertainties on $\langle \sigma_A v \rangle$, the analysis was performed on different simulated data sets, that had the DOM efficiency, absorption, and scattering lengths varied by $\pm 10\%$. The individual effects on the sensitivity of the analysis were calculated for the different WIMP masses assuming the $b\bar{b}$ annihilation channel. Thus, a range of the relative effect on $\langle \sigma_A v \rangle$ was obtained caused by the individual detector systematic uncertainties and listed in table 8.6. Lower and higher uncertainty values result from higher and lower WIMP mass hypotheses, respectively. The total systematic uncertainty is a conservative estimate by adding the individual signal detection efficiency governing uncertainties in quadrature neglecting possible correlations between them.

The detector systematic uncertainties are incorporated into the final upper
Figure 8.10: Sensitivities at 90% C.L. on \( \langle \sigma_A v \rangle \) (without systematic uncertainties) for all WIMP annihilation channels of the LE GC analysis using the LE event selection for the NFW (top) and the Burkert (bottom) DM halo models. For WIMP masses \( \geq 500 \) GeV, the sensitivity for the direct neutrino channel (solid lines) lacks statistics and is based on less than 100 signal events in the final sample resulting into large statistical fluctuations.
8.6 Results

Table 8.6: Signal detection systematic uncertainties for the LE GC analysis caused by different types of uncertainties and their relative effect on the sensitivity of the analysis. The ranges result from the different WIMP masses assuming the $b\bar{b}$ annihilation channel. Lower and upper values are governed by large and small WIMP masses, respectively.

<table>
<thead>
<tr>
<th>Signal detection systematic uncertainty</th>
<th>relative effect on $\langle \sigma A v \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical DOM efficiency</td>
<td>$\pm 5 - \pm 30%$</td>
</tr>
<tr>
<td>Glacial ice scattering length</td>
<td>$\pm 1 - \pm 10%$</td>
</tr>
<tr>
<td>Glacial ice absorption length</td>
<td>$\pm 5 - \pm 50%$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$\pm 8 - \pm 60%$</td>
</tr>
</tbody>
</table>

limit results by increasing the baseline results by their relative variation due to the detection efficiency uncertainties mentioned above.

8.6 Results

After the analysis was finalized as described above and passed the IceCube collaboration internal analysis review process, the right ascension event information of the LE data sample was unblinded. The likelihood analysis was conducted on the unblinded data set for each signal hypothesis and the Feldman-Cousins upper limits at the 90% C.L. on the number of signal events $n_s$ and thus on $\langle \sigma A v \rangle$ were calculated and found to be within the $2\sigma$ statistical interval of expected upper limits around the median upper limit for the random background-only data sets. All upper limits are below the median upper limit and all lower limits on $n_s$ are zero, due to an observed under-fluctuation of the data within the search window. The results in terms of number of events are given in table 8.7. It lists the total number of observed events within the entire declination band ($N_{\text{tot}}$), the number of observed events in the search window ($n_{\text{obs}}$), the number of expected background events in the search window ($n_{\text{bg}}$), which equals $1/6 \cdot N_{\text{tot}}$, and the difference between $n_{\text{bg}}$ and $n_{\text{obs}}$ ($\Delta n$), which is negative. As an example, the likelihood analysis results for the $\tau^+ \tau^-$ annihilation channel assuming the NFW or Burkert DM halo model are shown in figure 8.11. The figure shows the median upper limits, i.e. sensitivities, as dashed lines and the observed upper limits as solid lines. Superimposed are the $\pm 1\sigma$ and $\pm 2\sigma$ range of expected upper limits in the case of no signal and only background as green and yellow bands, respectively. The upper limits at the 90% C.L. on $\langle \sigma A v \rangle$ for all considered WIMP signal hypotheses are listed in table 8.8 and include detector systematic uncertainties as outlined in section 8.5.

The background estimation of this analysis assumes a uniform right ascen-
Figure 8.11: Sensitivities (dashed line) and observed upper limit (solid line with markers) at 90% C.L. on $\langle \sigma A v \rangle$ for WIMPs annihilating into $\tau^+ \tau^-$ for the NFW (top) and Burkert (bottom) DM halo model. Systematic uncertainties are not included in this figure. The $\pm 1\sigma$ and $\pm 2\sigma$ range of upper limits obtained in simulated background-only trials are shown as green and yellow bands, respectively, around the median upper limit.
### Table 8.7: Results of the LE GC analysis using the LE event selection in terms of number of events. Listed are the total number of events at final cut level within the entire declination band ($N_{\text{tot}}$), the observed number of events within the search window ($n_{\text{obs}}$), the expected number of background events within the search window ($n_{\text{bg}}$), and the difference between $n_{\text{bg}}$ and $n_{\text{obs}}$ ($\Delta n$). The search window was 1/6 of the total declination band, thus $n_{\text{bg}} = 1/6 \cdot N_{\text{tot}}$.

<table>
<thead>
<tr>
<th>Event selection</th>
<th>$N_{\text{tot}}$</th>
<th>$n_{\text{obs}}$</th>
<th>$n_{\text{bg}}$</th>
<th>$\Delta n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LE</td>
<td>25,299</td>
<td>4,098</td>
<td>4,217</td>
<td>-119</td>
</tr>
</tbody>
</table>

### Table 8.8: Final upper limits (including detector systematics) on the self-annihilation cross-section, $\langle \sigma A v \rangle$, for different annihilation channels and WIMP masses, $m_\chi$, for the NFW (top) and Burkert (bottom) DM halo models.

\[
\begin{array}{cccccc}
\hline
m_\chi [\text{GeV}] & \langle \sigma A v \rangle [10^{-22} \text{cm}^3 \text{s}^{-1}] & \langle \sigma A v \rangle [10^{-22} \text{cm}^3 \text{s}^{-1}] & \langle \sigma A v \rangle [10^{-22} \text{cm}^3 \text{s}^{-1}] & \langle \sigma A v \rangle [10^{-22} \text{cm}^3 \text{s}^{-1}] & \langle \sigma A v \rangle [10^{-22} \text{cm}^3 \text{s}^{-1}] \\
\hline
b\bar{b} & W^+W^- & \tau^+\tau^- & \mu^+\mu^- & \nu\bar{\nu} \\
\hline
30 & 120.0 & 0.91 & 0.78 & 0.064 & 0.04 \\
65 & 9.7 & 0.21 & 0.17 & 0.068 & 0.31 \\
100 & 4.6 & 0.35 & 0.17 & 0.14 & 0.65 \\
200 & 2.8 & 0.58 & 0.26 & 0.23 & 1.7 \\
300 & 2.7 & 0.87 & 0.42 & 0.42 & 3.5 \\
400 & 2.8 & 1.4 & 0.61 & 0.67 & 11.0 \\
500 & 2.9 & 1.8 & 0.99 & 1.0 & \\
1000 & 4.0 & 3.4 & 2.5 & 4.0 & 11.0 \\
\hline
m_\chi [\text{GeV}] & \langle \sigma A v \rangle [10^{-22} \text{cm}^3 \text{s}^{-1}] & \langle \sigma A v \rangle [10^{-22} \text{cm}^3 \text{s}^{-1}] & \langle \sigma A v \rangle [10^{-22} \text{cm}^3 \text{s}^{-1}] & \langle \sigma A v \rangle [10^{-22} \text{cm}^3 \text{s}^{-1}] & \langle \sigma A v \rangle [10^{-22} \text{cm}^3 \text{s}^{-1}] \\
\hline
b\bar{b} & W^+W^- & \tau^+\tau^- & \mu^+\mu^- & \nu\bar{\nu} \\
\hline
30 & 4400.0 & 5.6 & 4.9 & 0.41 & 0.26 \\
65 & 61.0 & 1.3 & 1.1 & 0.43 & 2.1 \\
100 & 30.0 & 3.3 & 1.1 & 0.91 & 23.0 \\
200 & 18.0 & 4.8 & 1.7 & 1.5 & 4.8 \\
300 & 17.0 & 6.8 & 2.7 & 2.7 & 4.8 \\
400 & 18.0 & 8.8 & 4.0 & 4.5 & 12.0 \\
500 & 19.0 & 11.0 & 6.5 & 6.9 & 23.0 \\
1000 & 26.0 & 21.0 & 16.0 & 26.0 & 70.0 \\
\hline
\end{array}
\]
sion distribution of the background events and thus a uniform acceptance of the
detector for the right ascension coordinate of the events. The observed under-
fluctuation in terms of number of events could be generated by a non-uniform
right ascension detector acceptance. Such a non-uniformity could arise from
non-uniform data taking coverage in sidereal time, that could develop if the de-
tector would not take data in approximately the same time period of a sidereal
day during most of the live-time of the analysis, i.e. almost one year. For an ex-
periment like IceCube where detector operations depend on satellite availability,
such an occurrence could be possible. Thus, a Kuiper test \cite{166} was performed
on the right ascension coordinates of the data events comparing them to a uni-
form distribution. The resulting p-value of 77% indicates compatibility with the
uniform distribution null-hypothesis. A second cause for a non-uniform event
right ascension distribution could be a systematic asymmetry in the azimuthal
angular detection efficiency of the detector. With its hexagonal string geo-
metry, IceCube has six preferred azimuthal angles for which track reconstructions
have a better angular reconstruction quality than for other angles. Hence, the
right ascension coverage could become non-uniform for the recorded azimuth
coordinates and times of the events. Because for a given time the azimuth an-
gle of an event corresponds to a certain right ascension, the distribution of right
ascensions can be created, where all events got assigned manually the times of
all recorded events. This distribution constitutes the right ascension coverage.
In other words, the event azimuth distribution was folded with the distribution
of the detector orientations with respect to right ascension. The deviation from
the average of the right ascension coverage can be determined and was found
to be within ±0.4% and +0.3% at the location of the GC suggesting an over-
fluctuation instead of an actual under-fluctuation of the data. After these per-
formed cross-checks it was concluded that the observed data deficit is consistent
with a purely statistical under-fluctuation.

The obtained upper limits on \( \langle \sigma_A \rangle \) at 90% C.L. of this GC analysis can
be compared to other IceCube searches for DM in self-bound structures \cite{167, 79, 168} and to photon limits obtained through observations of dwarf spheroidal
galaxies by VERITAS \cite{169}, MAGIC \cite{170} and Fermi \cite{171}. Figure 8.12 shows
the upper limits for WIMP annihilation exclusively into \( \tau^+ \tau^- \) assuming the
NFW DM halo model with a local DM density of \( \rho_{\text{local}} = 0.471 \text{ GeV cm}^{-3} \).
The limit for this LE analysis is combined with the limit of the HE analysis
carried out by a collaborator at RWTH Aachen as described in the beginning
of this chapter. For this particular annihilation channel the cross-over point in
sensitivity of the two analyses is at about 200 GeV.

For WIMP masses below 1 TeV this combined GC analysis improves signif-

\footnote{A Kuiper test is a Kolmogorov-Smirnov test for cyclic distributions.}
icantly in sensitivity on previous IceCube analyses. This particular LE analysis using DeepCore probes the WIMP self-annihilation cross-section for WIMP masses below 100 GeV for the first time by IceCube.

The most stringent upper limits on $\langle \sigma_A v \rangle$ provided by this analysis are for the direct neutrino annihilation channel ($\chi \chi \rightarrow \nu \bar{\nu}$). At 65 GeV WIMP mass and assuming a NFW DM halo model it is as low as $4 \cdot 10^{-24}$ cm$^3$s$^{-1}$. Furthermore, due to the requirement that branching ratios need to sum to 100%, the upper limits of the direct neutrino annihilation channel provide an upper bound on the total annihilation cross-section for annihilations into SM final states [172] making the limits complementary to gamma-ray detection channels.
Figure 8.12: The upper limit on $\langle \sigma_A v \rangle$ at 90% C.L. of this GC analysis assuming DM annihilation into $\tau^+ \tau^-$ and the NFW DM halo model (solid black curve) are compared to other IceCube searches for DM in gravitational self-bound structures [167, 79, 168] and photon limits from observations of dwarf spheroidal galaxies by VERITAS [169], MAGIC [170] and Fermi [171]. The gray-shaded region shows a DM interpretation of the positron excess reported by the PAMELA collaboration. The green-shaded regions indicate the $3\sigma$ and $5\sigma$ preferred regions from the $e^+ + e^-$-flux excess observed by Fermi [173] and H.E.S.S. [174, 175]. All shaded region data are from Ref. [176]. To match the here assumed local DM density of $\rho_{\text{local}} = 0.471 \text{GeV cm}^{-3}$, the PAMELA and Fermi & H.E.S.S. shaded regions, and the IC22 halo limits are rescaled by the square of their local DM density ratio. The “natural scale” at the bottom is the self-annihilation cross-section region for WIMPs to be thermal relics from the Big Bang [177]. The black dotted line indicates the WIMP unitarity bound [161]. Figure taken from paper III.
9 Indirect Search for DM in the Galactic Halo

The second analysis of this thesis targets WIMP self-annihilation in the Galactic halo. It complements and extends the first search for WIMPs in the GC. The goal of this GH analysis is to extend the probed WIMP mass range to 100 TeV while increasing the sensitivity on the WIMP thermally averaged self-annihilation cross-section, $\langle \sigma_A v \rangle$, over the entire WIMP mass range of 300 GeV to 100 TeV. In order to accomplish this, the analysis needs to use a neutrino candidate data sample optimized for neutrino energies of the targeted WIMP mass range. The IceCube collaboration developed a muon neutrino data sample for point-like neutrino source searches using data from the partial 40-string detector configuration to the completed 86-string IceCube detector configuration [178, 179, 180]. The previous published IceCube GH analysis [79] used the one-year IceCube point-source $\nu_\mu$ data sample of the 79-string configuration to search for WIMPs in the GH via a multipole analysis approach. The analysis presented here supersedes the previous results by using five years of IceCube $\nu_\mu$ point-source data and a maximum likelihood analysis technique. The IceCube point-source data sets, utilizing the IceCube-40 to IceCube-86 string configurations, are full-sky data samples covering the northern and southern hemisphere. Due to the enormous muon background in the southern hemisphere, these data sets perform best mainly for the northern hemisphere, where muons are absorbed by the Earth. One advantage of the mainly northern hemisphere WIMP search is the smaller dependence on the assumed DM density profile due to the smaller variations between such profiles at large distances from the GC, which is the part of the halo visible in the northern sky. The analysis presented here gains additional sensitivity on $\langle \sigma_A v \rangle$ from a dedicated southern hemisphere point-source muon neutrino data set optimized for neutrino energies between 10 TeV and 100 TeV and named Medium Energy Starting Events (MESE). The event selections are briefly described in the next section of this chapter before the analysis method, its sensitivity and results are presented in section 9.2, section 9.3, and section 9.5, respectively.
9.1 Event Selection

This GH analysis uses a combination of all of the IceCube data sets optimized for directional searches with muon neutrinos that were available at the outset of the analysis. Four of these data sets span the four years from 2008 to 2012 of different IceCube string configurations: IC40, IC59, IC79, and IC86. The fifth data set consists of the additional MESE event selection that spans an IceCube data taking period of three years from 2010 to 2013. In the following these data samples are denoted as point-source (PS) data samples. The event selections of IC40, IC59, IC79, and IC86 are described in great detail in the IceCube publications about the search for point-like neutrino sources [178, 179, 180]. A publication about the MESE event selection is currently under preparation by the IceCube collaboration. Table 9.1 shows the characteristics of all utilized data sets in this GH analysis. The number of events, the data rate, and the median angular resolution for each data set is given separately for the northern and southern sky, i.e. up-going and down-going events, respectively.

In general, the PS event selections select recorded events passing the muon filter (cf. section 3.6.2). Cuts on event observables like $r_{\text{lhh}}$, $L_{\text{dir}}$, and $n_{\text{dir}}$ reduce the filtered data to the final analysis level in the northern hemisphere. Because atmospheric muons get absorbed by the Earth, the northern hemisphere provides a nearly pure neutrino sample with atmospheric neutrinos being the dominant background. The only atmospheric muon contamination in the northern hemisphere is caused by down-going events originating from the southern hemisphere and falsely reconstructed as up-going. Misreconstructed events can be rejected by dividing the hits of an event into two parts, performing a MPE track reconstruction (cf. section 3.4.4) for both individually, and requiring both sub-events to be up-going. Thus, after applying this requirement and cuts on event reconstruction quality observables like $r_{\text{lhh}}$, only a small number of misreconstructed events are left in the final event samples for the northern hemisphere [178]. Atmospheric muons are the dominating background in the southern hemisphere. Their energy spectrum is softer than the $\propto E^{-2}$-spectrum of assumed point-like neutrino sources. Thus, zenith dependent energy selection cuts are applied to reject the lower energy atmospheric muon background. As energy estimator the MuE (IC40 & IC59) and the MuEx (IC79, IC86 & MESE) algorithms (cf. section 3.4.8) have been utilized. Hence, only high-energy and well reconstructed events are selected in the southern hemisphere. Cuts are optimized for sensitivity (IC40) or discovery potential\(^1\) (IC59–IC86) on neutrino point-like source fluxes.

The IC40 event selection used only straight cuts. Starting with the develop-

\(^1\)Defined as the flux needed to make a 5$\sigma$ discovery in 50% of all performed pseudo-experiments of that signal strength.
9.1 Event Selection

Table 9.1: Characteristics of the point-source data samples used in the GH analysis. \(\uparrow\)-going and \(\downarrow\)-going denotes up and down going events reconstructed in the northern \((\delta > 0^\circ)\) and southern \((\delta \leq 0^\circ)\) hemisphere, respectively. The IC79, IC86, and MESE samples were made disjoint for the combined likelihood analysis, which is reflected in the number of events for the IC79 and IC86 data sample in this table. The median angular resolution was calculated for an energy spectrum \(\propto E^{-2}\) of muon neutrino events.

<table>
<thead>
<tr>
<th></th>
<th>IC40</th>
<th>IC59</th>
<th>IC79</th>
<th>IC86</th>
<th>MESE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>start year</strong></td>
<td>2008</td>
<td>2009</td>
<td>2010</td>
<td>2011</td>
<td>2010</td>
</tr>
<tr>
<td><strong>day</strong></td>
<td>Apr 5</td>
<td>May 20</td>
<td>May 31</td>
<td>May 13</td>
<td>May 31</td>
</tr>
<tr>
<td><strong>(MJD)</strong></td>
<td>(54,561)</td>
<td>(54,971)</td>
<td>(55,347)</td>
<td>(55,694)</td>
<td>(55,347)</td>
</tr>
<tr>
<td><strong>end year</strong></td>
<td>2009</td>
<td>2010</td>
<td>2011</td>
<td>2012</td>
<td>2013</td>
</tr>
<tr>
<td><strong>day</strong></td>
<td>May 20</td>
<td>May 31</td>
<td>May 13</td>
<td>May 16</td>
<td>May 2</td>
</tr>
<tr>
<td><strong>(MJD)</strong></td>
<td>(54,971)</td>
<td>(55,347)</td>
<td>(55,694)</td>
<td>(56,063)</td>
<td>(56,414)</td>
</tr>
<tr>
<td><strong>live-time [days]</strong></td>
<td>375.5</td>
<td>348.1</td>
<td>316.2</td>
<td>332.6</td>
<td>988.5</td>
</tr>
<tr>
<td><strong>number of data events</strong></td>
<td>14113</td>
<td>43339</td>
<td>50857</td>
<td>62534</td>
<td>—</td>
</tr>
<tr>
<td>(\uparrow)-going</td>
<td>22787</td>
<td>64230</td>
<td>59008</td>
<td>75785</td>
<td>549</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td>36900</td>
<td>107569</td>
<td>109865</td>
<td>138319</td>
<td>549</td>
</tr>
<tr>
<td><strong>data rate [mHz]</strong></td>
<td>0.435</td>
<td>1.441</td>
<td>1.862</td>
<td>2.176</td>
<td>—</td>
</tr>
<tr>
<td>(\uparrow)-going</td>
<td>0.702</td>
<td>2.135</td>
<td>2.160</td>
<td>2.637</td>
<td>0.006</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td>1.137</td>
<td>3.576</td>
<td>4.022</td>
<td>4.813</td>
<td>0.006</td>
</tr>
<tr>
<td><strong>median angular resolution [^\circ]</strong></td>
<td>0.9</td>
<td>0.8</td>
<td>0.7</td>
<td>0.6</td>
<td>—</td>
</tr>
<tr>
<td>(\downarrow)-going</td>
<td>0.6</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
<td>0.9</td>
</tr>
</tbody>
</table>

For events from the southern hemisphere the veto capability of the surface array IceTop was utilized. Down-going high-energy CR events with a shower axis close the IceTop detector can be removed for reconstructed zenith angles between 0° and 50° that are detected both in IceTop and IceCube. The veto allows an additional 90% reduction in background down-going events while losing less than 1% signal neutrinos for point-like neutrino source searches [179].

In the IC86 event selection the angular reconstruction of the muon tracks is improved by using the SplineMPE track reconstruction as described in section 3.4.5. The track seed for this SplineMPE fit is the Pandel-MPE reconstruction result seeded with the averaged result of four individual Pandel-MPE track fits, where for each fit the pulse series of the event was bootstrapped. The bootstrapping randomly selects pulses, based on a pulse-charge weighted multino-
mial distribution, from the original recorded pulse series. Thus, high-charged pulses are more likely to be drawn than lower-charged pulses, reducing the influence of noise hits on the reconstruction. Compared to the IC79 Pandel-MPE reconstruction this method improves the median angular resolution by 26% for 30 TeV neutrinos [180]. The BDT used for the southern hemisphere events utilizes variables exploiting the differences of single muon events and muon bundle events from signal neutrinos. Furthermore, a zenith dependent BDT score cut is applied to account for the strong zenith-dependent background of the southern hemisphere.

In contrast to the previously described PS event samples, the MESE event selection derives from the High Energy Starting Events (HESE) event selection designed to isolate a high purity sample of high-energy extraterrestrial neutrinos [149] by selecting starting events inside IceCube. Similar to the HESE event selection, it utilizes a veto region consisting of the outer strings of IceCube to reject incoming atmospheric muons. However, the HESE requirement, that an event has at least 6,000 p.e. is relaxed to 1,500 p.e.. This lowers the neutrino detection energy threshold to about 10 TeV for southern hemisphere searches while still maintaining a very low data event rate of $2 \mu$Hz, compared to the 1000 times higher data event rate of the conventional PS data sets (i.e. IC40–86).

To summarize the five individual PS event selections used in this GH analysis, figure 9.1 shows the Point Spread Function (PSF) of each sample separately for the northern (up-going) and southern (down-going) hemisphere. The best PSF is achieved by the IC86 selection. While IC40 appears to achieve better PSFs than some later selections, this is a pure selection effect. Low-energy events are under-represented in the IC40 sample due to its stricter cuts. The down-going MESE PS sample has poorer angular resolution than the other data samples. The requirement of starting events inside the IceCube detector, and thus the application of the outer string veto layer, means that all events have shorter lever arms than for the typical through-going track, limiting the reconstruction ability for tracks. However, the very low background rate of the MESE sample compensates for these reconstruction limitations in sensitivity estimations.

Figure 9.2 compares the neutrino effective areas for different declination bands in the northern (upper panel) and southern (bottom panel) hemisphere. Shown are the effective areas for the full detector for the conventional point-source and MESE event selections. The neutrino absorption in the Earth can be nicely seen in the upper panel for high-energy vertical up-going events (green dashed curve). The magenta dash-dotted curve in the bottom panel of figure 9.2 shows that the MESE event selection is efficient for neutrinos with energies above approximately 10 TeV. While the effective area is not very different from
Figure 9.1: Point Spread Functions (PSFs) at final analysis cut level for the data samples used in the GH analysis. The PSF is defined as the opening-angle, $\Psi_{\nu,\text{reco}}$, between the direction of the true neutrino and the reconstructed muon. The PSF is calculated for an assumed muon neutrino energy spectrum proportional to $E^{-2}$. Note, that the MESE sample is only defined for down-going events, i.e. lower plot.

the conventional down-going sample for most of the sky, the factor 1000 lower background, thanks to the veto, makes it more sensitive in the 10 TeV – 100 TeV range.

In order to be able to perform an analysis on all data samples combined, data sample overlap need to be eliminated. This is only an issue for the MESE
Figure 9.2: Solid-angle averaged effective area for $\nu + \bar{\nu}$-flux seen by the IC86 and MESE samples for different declination bands in the northern (top panel) and southern (bottom panel) hemisphere. Note, that the MESE sample is only defined for down-going events, i.e. lower plot. In the southern sky, most effective area for IC86 is found in a narrow declination band at the horizon ($0^\circ \geq \delta \geq -10^\circ$).

sample that overlaps with the IC79 and IC86 sample. Thus, MESE events found in these two samples (data and simulation) are removed, providing uncorrelated samples for IC79, IC86, and MESE.
9.2 Analysis Method

This GH analysis utilizes an unbinned maximum likelihood ratio test to search via the two-mixture model for signal neutrinos distributed in location and energy according to the particular tested DM hypothesis (cf. table 6.1). A new analysis framework has been developed to test the many individual DM hypotheses in an efficient and consistent way, which is described in more detail in section 9.2.2. The analysis is performed on the entire celestial sphere, i.e. including northern and southern hemisphere events, and using all the final selection data events of the five PS samples (cf. section 9.1). The likelihood function is described in section 9.2.1. The 90% confidence intervals for the median and observed upper limits are constructed using the Feldman-Cousins prescription as described in section 7.3.

9.2.1 Likelihood Function

The likelihood function for the $j$th single data set, e.g. IC86, is constructed using the two-component mixture model and is a function of its signal fraction $\xi^j = n^j_s / N^j$, where $n^j_s$ is the expected number of signal events in the $j$th data set of fixed size $N^j$:

$$L^j(\xi^j) = \prod_{i=1}^{N^j} f^j(X^j_i, \xi^j).$$

(9.1)

$X^j_i$ denotes the direction and energy in the $i$th event of the $j$th data set. Both direction and energy are used in this analysis to achieve the optimal sensitivity to $\langle \sigma_A v \rangle$. The combined likelihood function for all data sets can be defined as the product of the individual likelihood functions:

$$L(\xi) = \prod_j L^j(\xi^j),$$

(9.2)

where $\xi = n_s / N$ denotes the total signal fraction of the combined samples with total number of expected signal events $n_s$ and the fixed total number of events $N$ of all data sets. The p.d.f. $f^j$ of an individual data set represents the two-component mixture model. It consists of signal p.d.f.s $S^j_i$ and background p.d.f.s $B^j_i$:

$$f^j(X^j_i, |\xi^j) = \xi^j S^j_i(X^j_i) + (1 - \xi^j) B^j_i(X^j_i).$$

(9.3)

In general, the signal and background p.d.f.s can be different for each individual event. However, in this analysis the p.d.f. for signal and background are created numerically from signal simulation and experimental recorded data events,
respectively, and hence are binned. Thus, for some data events they provide
the same values making this analysis strictly speaking an unbinned maximum
likelihood analysis with binned p.d.f.s.

The background p.d.f. $B_i^j$ deserves special consideration. In general, it can
be created from the experimental data by scrambling the recorded time, and thus
the right ascension coordinate in the case of IceCube. It can also be created from
background simulation. The former method is used in this analysis. Due to the
fact that the DM halo density profile provides non-zero values for all directions
on the celestial sphere, signal is expected to be found for all directions on the ce-
lestial sphere if $\xi > 0$. Thus, the background p.d.f. $B_i^j$ has to account for signal
contamination in the background. $B_i^j$ can be constructed by taking the scram-
bled experimental data p.d.f. $\tilde{D}_i^j$ and subtracting the scrambled background-like
signal p.d.f. $\tilde{S}_i^j$. $\tilde{S}_i^j$ must describe the signal as it would be appearing in the back-
ground estimate. In this analysis $\tilde{S}_i^j$ is created from signal simulation events by
scrambling their time, hence by using the identical method as for creating $\tilde{D}_i^j$.

Because of the signal contamination the scrambled data p.d.f. $\tilde{D}_i^j$ is supposed
to consist of a scrambled signal $\tilde{S}_i^j$ and an actual background $B_i^j$ component,
where the latter one is assumed to be distributed uniformly in right ascension:

$$\tilde{D}_i^j(X_i^j) = \xi^j \tilde{S}_i^j(X_i^j) + (1 - \xi^j)B_i^j(X_i^j).$$  (9.4)

Solving this equation for $B_i^j$ yields

$$B_i^j(X_i^j) = \frac{1}{1 - \xi^j} \tilde{D}_i^j(X_i^j) - \frac{\xi^j}{1 - \xi^j} \tilde{S}_i^j(X_i^j).$$  (9.5)

Equation (9.5) thus describes how the background p.d.f.s can be constructed
from data and take into account the possible presence of signal. Even if no signal
is present in the real data, this is necessary for the simulated trials when signal
events are added to the generated data sets in order to estimate the sensitivity.
Inserting equation (9.5) into the likelihood p.d.f. $f^j$ as given in equation (9.3)

$$f^j(X_i^j, |\xi^j) = \xi^j S_i^j(X_i^j) + (1 - \xi^j) \left[ \frac{1}{1 - \xi^j} \tilde{D}_i^j(X_i^j) - \frac{\xi^j}{1 - \xi^j} \tilde{S}_i^j(X_i^j) \right],$$  (9.6)

which simplifies to the final expression for $f^j$:

$$f^j(X_i^j, |\xi^j) = \xi^j S_i^j(X_i^j) + \tilde{D}_i^j(X_i^j) - \xi^j \tilde{S}_i^j(X_i^j).$$  (9.7)

The signal and data p.d.f.s $S_i^j$, $\tilde{S}_i^j$, and $\tilde{D}_i^j$ are dependent on the direction
and energy of the events. The energy p.d.f.s, constructed from the reconstructed
muon energy of the events using MuE or MuEx (cf. section 3.4.8), vary with the zenith angle and thus with the declination coordinate, \( \delta \). Hence, different energy p.d.f.s for different declination bands are created. The p.d.f.s in equation (9.7) can be formulated in terms of declination dependent spatial \( (X) \) and energy \( (E) \) p.d.f.s:

\[
S^j_i \equiv X^j_s(\alpha^j_i, \delta^j_i) E^j_{s,\delta}(E^j_i)
\]

\[
\tilde{S}^j_i \equiv \tilde{X}^j_s(\delta^j_i) E^j_{s,\delta}(E^j_i)
\]

\[
\tilde{D}^j_i \equiv \tilde{X}^j_d(\delta^j_i) E^j_{d,\delta}(E^j_i)
\]

where the sub-script \( s \) and \( d \) denotes signal and data p.d.f.s, respectively. The spatial p.d.f. for data, \( \tilde{X}^j_d \), is only a function of the declination coordinate of the event because background will be assumed to be distributed uniformly in right ascension, \( \alpha \), for a time-integrated analysis. By construction, the spatial part of the background-like (i.e. time scrambled) signal p.d.f., \( \tilde{X}^j_s \), is also only dependent on \( \delta \).

The final expression for the combined likelihood function \( L(\xi) \) is given by

\[
L(\xi) = \prod_{j} \prod_{i=1}^{N_j} f^j(X^j_i, |\xi^j_i|)
\]

\[
= \prod_{j=1}^{N_j} \xi^j_i S^j_i(X^j_i) + \tilde{D}^j_i(X^j_i) - \xi^j_i \tilde{S}^j_i(X^j_i),
\]

where \( \xi = n_s/N \) is again the total signal fraction of the combined samples with total number of events \( N \) and the total number of expected signal events \( n_s \). The individual sample signal fractions \( \xi^j \) can be calculated for a given total signal fraction \( \xi \) by taking into account the relative signal weight

\[
\mathcal{W}^j_i = \frac{n^j_s}{\sum_j n^j_s} = \frac{n^j_i}{n_s}
\]

of each data sample \( j \) to all the other samples, where \( n^j_s \) is the expected number of signal events for the data sample \( j \) and is calculated from simulation for the particular DM hypothesis. Hence, \( \xi^j \) can be calculated with the number of events of the \( j \)th data sample, \( N^j \), through

\[
\xi^j = \frac{n^j_s}{N^j} = \frac{\mathcal{W}^j_i}{N^j} n_s = \frac{\mathcal{W}^j_i}{N^j} \xi N
\]

The likelihood ratio of the background-only (null) hypothesis over the best fitted signal-plus-background hypothesis, is used to define the test statistic (TS):
Indirect Search for DM in the Galactic Halo

\[ \text{TS} = -2 \log \left( \frac{L(\xi = 0)}{L(\hat{\xi})} \right), \]  

(9.15)

where \( \hat{\xi} = \hat{n}_s / N \) denotes the best fit signal fraction for the best fit total number of signal events \( \hat{n}_s \).

### 9.2.2 Spatial Template Analysis Approach

Considering all WIMP signal hypotheses as given in table 6.1, this GH analysis has to perform 70 different hypothesis tests. In order to automate this process in an efficient and error-robust way, the Spatial Template Analysis Approach has been developed for this analysis.

The implementation is based on the IceCube analysis software framework called \textit{psLab}, that is also used for point-like neutrino source searches. The psLab framework provides technical infrastructure for loading experimental data and simulation events, generating random data sets for pseudoexperiments, creating background p.d.f.s from experimental data, and infrastructure for maximizing the likelihood function. The framework makes use of an event generator and a likelihood function evaluation class. Both classes must be specialized for a particular analysis approach. The signal generator class provides the functionality to generate signal events with the desired signal properties, \textit{i.e.} spatial and energy distribution, used to create random data sets with non-zero signal strength. The likelihood function evaluator class defines the likelihood function and evaluates it for the events of a given data set. In case of a multi-data-set analysis psLab provides the general functionality to combine the likelihoods of the individual data sets based on their relative signal weight, which in fact is determined from the signal generator class.

For this GH analysis the specialized signal generator class, named \textit{I3SpatialTemplateGenerator}, and the dedicated likelihood function evaluator class, named \textit{I3SpatialTemplateLlh}, were developed, constituting the Spatial Template Analysis Approach. Figure 9.3 shows a flowchart of this approach. The neutrino signal flux, as given by equation (1.8), can be separated into a spatial, \textit{i.e.} \( J_\alpha(\Psi) \), and a neutrino-energy dependent part, \textit{i.e.} \( \propto dN / dE_\nu \). The spatial part constitutes a functional signal map \( M_{\text{astro}}(\alpha, \delta) \), whereas the neutrino energy dependent part is equivalent to \( F_{\text{astro}}(E) \) in figure 9.3. For each considered data set, \textit{i.e.} IC40 – IC86 & MESE, a functional detector acceptance map, \( A(\alpha, \delta) \), is created using a muon neutrino simulation with all selection cuts applied for that data set.

\footnote{We define a functional map to be a \( \mathbb{R}^2 \to \mathbb{R} \) mapping with discrete sampling points, \textit{i.e.} bin centers, in right ascension and declination. Moreover, we define a content map to be a functional map, where the bins are integrated taking the exact solid-angle of each bin into account.}
Figure 9.3: Flowchart of the Spatial Template Analysis Approach. An astrophysical neutrino flux expectation on the celestial sphere is split into a spatial \(M_{\text{astro}}(\alpha, \delta)\) and energy \(F_{\text{astro}}(E)\) component. Using a neutrino simulation with all event selection cuts applied a spatial detector acceptance map \(A(\alpha, \delta)\) and a detector-acceptance-corrected signal map \(G(\alpha, \delta)\) are created for each signal hypothesis. If the detector acceptance is uniform in right ascension, as for this analysis, \(A(\alpha, \delta)\) is effectively only a function of declination \(\delta\). \(G(\alpha, \delta)\) provides the p.d.f. for the signal generator. For the LH function evaluator \(G(\alpha, \delta)\) can be convolved with the PSF of the data sample constituting the spatial signal p.d.f., \(X_s(\alpha, \delta)\), for the LH function, if the spatial structure in the map is sensitive to the angular resolution of tracks.
by weighting the simulated events according to the signal neutrino energy spectrum \( F_{astro}(E) \). \( F_{astro}(E) \) includes all constants of equation (1.8) and the factor \( \langle \sigma_A \nu \rangle \) with a value of 1 cm\(^3\) s\(^{-1}\). The detector acceptance is assumed to be uniform in right ascension. Because the energy spectrum of signal neutrinos from WIMP annihilation is independent of the celestial direction, \( A \) is constant over right ascension for a given declination. \( A \) also includes the live-time of the data sample. By multiplying the detector signal acceptance map with the spatial signal template map, \( M_{astro} \), the detector acceptance corrected signal map \( G(\alpha, \delta) \) is produced. This map specifies the expected number of detected signal neutrinos from a certain celestial direction. By construction, the total signal weight of the particular data set is just the sum of all bins of the generator content map. A map for each combination of data set and signal hypothesis has to be generated in advance for this analysis approach. Thus, \( 5 \times 70 = 350 \) individual signal generator maps have been generated for this analysis.

For the generation of random data sets with injected signal events \( G(\alpha, \delta) \) is used by the signal generator class to draw events from the muon neutrino simulation. The drawing procedure generates a random spatial coordinate distributed according to the spatial signal map \( G(\alpha, \delta) \). For this coordinate it generates a signal energy p.d.f. using \( F_{astro}(E) \) and the detector response weight of the muon neutrino simulation. Finally, a signal event is drawn from the muon neutrino simulation following this signal energy p.d.f., and used for the random generated data set.

The generator map \( G(\alpha, \delta) \) is also the basis for the spatial likelihood p.d.f. \( \chi^2_s(\alpha, \delta) \) in equation (9.8). If the expected spatial signal distribution has detailed features, the likelihood signal hypothesis map should ideally be convoluted with the PSF of the data sample, \textit{e.g.} a two-dimensional Gaussian function with a width of the median angular resolution. A set of point-spread convoluted spatial likelihood maps can also be generated for different intervals of angular resolution. Based on the individual angular uncertainty estimate of an event (\textit{cf.} section 3.4.6), the appropriate likelihood map for that event can then be chosen by the likelihood function evaluator class when evaluating the likelihood function. In the GH analysis this convolution step is not necessary because the spatial map varies slowly on angular scales comparable to the PSF. Due to the smooth spatial signal distribution of the DM density profiles, a signal generator spatial map with a \( 2^\circ \times 2^\circ \) binning is used as the spatial likelihood map in this GH analysis.

For illustration purposes the functional signal template map \( M_{astro} \) for the NFW DM halo profile, the functional detector signal acceptance map \( A(\alpha, \delta) \) for the IC86 data sample and the \( \tau^+ \tau^- \) WIMP annihilation channel for WIMP masses of 100 TeV, and the functional signal generator map, \( G(\alpha, \delta) \), combining both maps are shown in figure 9.4. Because this signal hypothesis will lead to
high energy neutrinos, the analysis becomes also sensitive to signal events from the southern hemisphere. Thus, the GC can be nicely seen in figure 9.4c at \((\alpha, \delta) = (266^\circ, -29^\circ)\).

The energy information of the data and signal events are taken into account in the likelihood function via the energy p.d.f.s \(\mathcal{E}_{d,\delta}^j\) and \(\mathcal{E}_{s,\delta}^j\), respectively (cf. equations 9.8-9.10). An example for these energy p.d.f.s for the IC86 data sample is shown in figure 9.5. There, \(\mathcal{E}_{d,\delta}^j\) is shown as black solid curve and \(\mathcal{E}_{s,\delta}^j\) is shown for three different WIMP hypotheses annihilating exclusively into \(\tau^+\tau^-\); WIMP with a mass of 1 TeV (blue dashed), 10 TeV (green dotted), and 100 TeV (red dash-dotted). The higher the WIMP mass, the more high energetic neutrinos exceeding the atmospheric background spectrum, i.e. the data energy spectrum in this case, are expected. The ratio of \(\mathcal{E}_{s,\delta}^j\) and \(\mathcal{E}_{d,\delta}^j\) effectively functions as a signal energy weight for each data event for the test statistic, i.e. the likelihood ratio equation (9.15).

### 9.3 Sensitivity

By conducting the analysis for each signal hypothesis on 20,000 background-only random data samples generated by time scrambling, a median TS value, \(\tilde{\text{TS}}\), is obtained. The analysis is also performed on random data sets with different signal strength added, i.e. different number of signal events injected into the random background data set. For each signal strength 10,000 pseudoexperiments were performed. Together with the Feldman-Cousins likelihood ratio as given in equation (7.8), the median TS value, \(\tilde{\text{TS}}\), is related to a median upper limit at 90% C.L., \(\tilde{\mu}_{90}\), on the total number of signal events by constructing the Feldman-Cousins 90% confidence intervals as described in section 7.3. This median upper limit \(\tilde{\mu}_{90}\) defines the sensitivity of this analysis. The relation of \(\tilde{\mu}_{90}\) to the median upper limit on \(\langle \sigma_{Av} \rangle\) is again given by equation (8.6). Figure 9.6 shows the median upper limits on \(\langle \sigma_{Av} \rangle\) at 90% C.L., i.e. sensitivities, for all considered WIMP annihilation channels as a function of the WIMP mass, \(m_\chi\). The upper and lower panels show the sensitivities assuming the NFW and Burkert DM halo profile (cf. table 1.2), respectively.

### 9.4 Discussion of Systematic Uncertainties

The systematic uncertainties of this GH analysis arise from the same two classes of systematic uncertainties as for the GC analysis described in section 8.5, namely detector systematics and astrophysical uncertainties. Because the background is estimated from randomized data, uncertainties on the background estimation are minimal. The detector systematics affecting the signal detection efficiencies are mainly governed by the uncertainties on the light detection due to uncer-
Indirect Search for DM in the Galactic Halo

(a) Functional spatial template signal map $M_{\text{astro}} (\alpha, \delta)$ for the NFW DM model. It is $f_a$ in equation (1.8).

(b) Functional detector acceptance map $A(\alpha, \delta)$ for the IC86 data sample and $\tau^+ \tau^-$ annihilation channel for 100 TeV massive WIMPs. Included are also all constants in equation (1.8) and the live-time of the data sample. The detector acceptance is assumed to be uniform in right ascension.

(c) Functional spatial signal generator map $G(\alpha, \delta)$, which is the bin-wise product of $M_{\text{astro}} (\alpha, \delta)$ and $A(\alpha, \delta)$. For each celestial location it provides the expected number of signal muon neutrinos per solid angle in the IC86 data sample from 100 TeV massive WIMPs annihilating into $\tau^+ \tau^-$ assuming the NFW DM halo model and $\langle \sigma_A v \rangle = 1 \text{cm}^3\text{s}^{-1}$.

Figure 9.4: Example spatial template maps for the Spatial Template Analysis Approach using the IC86 data sample and the signal hypothesis of 100 TeV massive WIMPs annihilating into $\tau^+ \tau^-$ assuming the NFW DM halo model and $\langle \sigma_A v \rangle = 1 \text{cm}^3\text{s}^{-1}$. The functional spatial signal generator map (c) gets converted by the signal generator class of the analysis software framework psLab into a spatial content map, i.e. a map with solid-angle integrated bins, which then represents the number of signal events per bin, and used for selecting signal events according to the signal hypothesis and detector acceptance.
9.4 Discussion of Systematic Uncertainties

Figure 9.5: Detector energy p.d.f.s for IC86 data (black solid) and WIMP signal hypotheses for WIMPs of mass 1 TeV (blue dashed), 10 TeV (green dotted), and 100 TeV (red dash-dotted), annihilating into $\tau^+ \tau^-$. The shown p.d.f.s here are for events from the northern hemisphere. The energy p.d.f.s used in the analysis are similar, except, they are further subdivided in zenith ranges to account for the slowly varying energy distribution with zenith angle, $\Theta_{zen}$.

Uncertainties on the optical properties of the South Pole glacial ice, and the optical detection efficiency of the DOMs. To determine the signal detection uncertainty with respect to the baseline signal detection ability, spatial signal generator maps $G(\alpha, \delta)$ have been created for all combinations of WIMP mass and annihilation channel based on different muon-neutrino simulations, where the light scattering and absorption in the ice and the optical detection efficiency of the IceCube DOMs were varied by ±10%. As described in section 9.2.2, the signal generator map contains all information about the detector response and the signal hypothesis. Furthermore, the sum of the content map bins corresponds to the total signal weight of the data sample. By taking the ratio of the total signal weight of these maps to the baseline maps, the signal detection uncertainty can be calculated. A conservative estimate of the signal detection uncertainty for each annihilation channel and WIMP mass was obtained by adding the uncertainty from both
Figure 9.6: Median upper limits, \textit{i.e.} sensitivities, at 90% C.L. on $\langle \sigma_A v \rangle$ without systematic uncertainties for all WIMP annihilation channels of the GH analysis for the NFW (top) and the Burkert (bottom) DM halo models (\textit{cf.} table 1.2). The sensitivity at $\sim$100 TeV is improved by the usage of the MESE down-going event sample, resulting in a flatter curve at this energy, especially for the cuspy NFW DM model.
Table 9.2: Signal detection uncertainties for the GH analysis are listed for the NFW and Burkert DM halo model and all DM self-annihilation channels considered in this analysis. The uncertainty is energy and thus WIMP dependent. The lower and upper values for a particular annihilation channel correspond to high (100 TeV) and small (300 GeV) WIMP masses, respectively.

<table>
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<th>Burkert</th>
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components, i.e. ice properties and DOM detection efficiency, in quadrature. Table 9.2 shows the obtained ranges of the signal detection uncertainty for all considered WIMP self-annihilation channels and DM halo models. The uncertainties obtained here are similar to the uncertainties obtained by the previous IceCube GH analysis [79] performed with a multipole analysis technique on the IceCube-79 point-source data sample. The astrophysical uncertainties are the uncertainties on the amount of signal neutrinos from the DM self-annihilation, i.e. the choice of a particular DM halo model. Due to the smaller differences of the halo models in the northern hemisphere, where this GH analysis is mainly sensitive, the results are less dependent on the assumed DM halo model than they were for the GC analysis presented in chapter 8. This can be seen in figure 9.6, which shows the sensitivities for the NFW and Burkert DM halo models. Compared to figure 8.10, the sensitivities for the two models here are very similar. At high WIMP masses however the MESE sample improves the sensitivity in the southern hemisphere, where the DM halo models differ the most. Thus, the sensitivities at those masses differ more than at low masses.

Following the procedure of the GC analysis, the detector systematics, i.e. the signal detection uncertainties, are incorporated into the final upper limit results by increasing the baseline results by their relative variation due to the signal detection uncertainties described above and given in table 9.2.

9.5 Results

After finalizing and passing the IceCube internal analysis review process, this GH analysis was performed on the unblinded data sets. The obtained $p$-values (cf. equation (7.9)) for all considered signal hypotheses (cf. table 6.1) were
greater than 10%. Thus, upper limits on the thermally averaged DM self-annihilation cross-section, $\langle \sigma_A v \rangle$, at 90% C.L. were calculated using the Feldman-Cousins prescription (cf. section 7.3). Figure 9.7 and figure 9.8 show the obtained upper limits (solid black curves) together with the expected median upper limits (i.e. sensitivities) (dashed black curves) for the Burkert and NFW DM halo models, respectively. The $\pm 1\sigma$ and $\pm 2\sigma$ range of expected upper limits in the case of no signal and only background are shown as green and yellow bands, respectively. All obtained upper limits are within the $\pm 1\sigma$ range. The final results for all annihilation channels and DM halo models are given in table 9.3, table 9.4, and table 9.5. The sensitivities and upper limits on $\langle \sigma_A v \rangle$ given in these tables include the detector systematics as outlined in section 9.4 and given in table 9.2.

The results of this GH analysis can be compared to previous IceCube analyses and to other experiments. Figure 9.9 provides a comparison of the limits on $\langle \sigma_A v \rangle$ for the $\tau^+ \tau^-$ annihilation channel assuming the NFW halo model. The limit of this analysis is compared to the two previously performed GH analyses by IceCube using the 22-string [167] and 79-string [79] configuration. The best IceCube limits are provided by the IceCube-79 GC analysis [3] (cf. chapter 8) and this GH analysis. Shown in figure 9.9 is also the limit from the ANTARES neutrino telescope observing the GC [181]. This analysis assumes a local DM density $\rho_{\text{local}} = 0.471 \text{GeV cm}^{-3}$. Thus, all other limits obtained from galactic targets are scaled to this same density in order to make the comparison meaningful. Limits on $\langle \sigma_A v \rangle$ are also obtained by gamma-ray detection experiments like VERITAS, Fermi, and MAGIC from observations of spheroidal dwarf galaxies and are also shown in figure 9.9. However, due to imprecisely known $J_a$-factors by a factor of a few for dwarf spheroidal galaxies [182, 183], comparisons of limits obtained from galactic and extra-galactic targets involve large uncertainties. The most stringent upper limits on $\langle \sigma_A v \rangle$ set by this GH analysis assume the WIMPs annihilate directly into a pair of neutrinos and follow the NFW DM halo profile. As given in table 9.5 the upper limit for 500 GeV WIMPs is as low as $4.5 \cdot 10^{-24} \text{cm}^3\text{s}^{-1}$. The limits obtained for the direct neutrino annihilation channel are complementary to the limits obtained by the gamma-ray experiments. Because the annihilation branching ratios for a DM particle need to sum to 100%, the upper limits for the direct neutrino annihilation channels provide also an upper bound on the total annihilation cross-section for annihilations into SM final states [172].
Figure 9.7: Observed upper limits on $\langle \sigma A v \rangle$ at 90% C.L. (solid black lines) assuming the NFW DM halo model (cf. table 1.2) for different WIMP self-annihilation channels compared to the corresponding median upper limits, i.e. sensitivities, on $\langle \sigma A v \rangle$ (dashed black lines). The green and yellow shaded areas indicate the $\pm 1\sigma$ and $\pm 2\sigma$ range of upper limits obtained in simulated background-only trials, respectively. Systematic uncertainties are not included.
Figure 9.8: Observed upper limits on $\langle \sigma_A v \rangle$ at 90% C.L. (solid black lines) assuming the Burkert DM halo model (cf. table 1.2) for different WIMP self-annihilation channels compared to the corresponding median upper limits, i.e., sensitivities, on $\langle \sigma_A v \rangle$ (dashed black lines). The green and yellow shaded areas indicate the ±1σ and ±2σ range of upper limits obtained in simulated background-only trials, respectively. Systematic uncertainties are not included.
Table 9.3: Results for the $\chi\chi \rightarrow b\bar{b}$ and $\chi\chi \rightarrow W^+W^-$ WIMP annihilation channels. The median upper limit on the number of signal events ($\tilde{\mu}_{90}$), the observed upper limit on the number of signal events ($\mu_{90}$), the median upper limit on $\langle \sigma_A v \rangle$ ($\langle \tilde{\sigma}_A v \rangle_{90}$), and the observed upper limit on $\langle \sigma_A v \rangle$ ($\langle \sigma_A v \rangle_{90}$) at the 90% C.L. are shown assuming the Burkert (left) and NFW (right) DM halo model for different WIMP masses ($m_\chi$). $\langle \tilde{\sigma}_A v \rangle_{90}$ and $\langle \sigma_A v \rangle_{90}$ include systematic detection uncertainties and thus constitute the final results.

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Table 9.4: Results for the $\chi\chi \rightarrow \tau^+\tau^-$ and $\chi\chi \rightarrow \mu^+\mu^-$ WIMP annihilation channels. The median upper limit on the number of signal events ($\tilde{\mu}_{90}$), the observed upper limit on the number of signal events ($\mu_{90}$), the median upper limit on $\langle \sigma_A v \rangle$ ($\langle \tilde{\sigma}_{90} A v \rangle$), and the observed upper limit on $\langle \sigma_A v \rangle$ ($\langle \sigma_{90} A v \rangle$) at the 90% C.L. are shown assuming the Burkert (left) and NFW (right) DM halo model for different WIMP masses ($m_\chi$).

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Note: The effective cross section is given by $\sigma_{eff} = \langle \sigma A v \rangle_{90}$. The mass of the WIMP is $m_\chi$. The NFW and Burkert DM halo models are assumed. The upper limits are calculated at the 90% C.L. The results include systematic detection uncertainties and thus constitute the final results.
Table 9.5: Results for the $\chi\chi \rightarrow v\bar{v}$ WIMP annihilation channel. The median upper limit on the number of signal events ($\tilde{\mu}_{90}$), the observed upper limit on the number of signal events ($\mu_{90}$), the median upper limit on $\langle \sigma_A v \rangle$ ($\langle \sigma_A v \rangle_{90}$), and the observed upper limit on $\langle \sigma_A v \rangle$ ($\langle \sigma_A v \rangle_{90}$) at the 90% C.L. are shown assuming the Burkert (left) and NFW (right) DM halo model for different WIMP masses ($m_\chi$).

$\langle \sigma_A v \rangle_{90}$ and $\langle \sigma_A v \rangle_{90}$ include systematic detection uncertainties and thus constitute the final results.

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<th>$m_\chi$ [GeV]</th>
<th>$\tilde{\mu}_{90}$ [#]</th>
<th>$\mu_{90}$ [#]</th>
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<th>$\langle \sigma_A v \rangle_{90}$ [cm$^3$s$^{-1}$]</th>
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<td>$9.3 \times 10^{-24}$</td>
<td>1040</td>
<td>940</td>
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<td>230</td>
<td>$1.6 \times 10^{-23}$</td>
<td>$2.3 \times 10^{-23}$</td>
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Figure 9.9: The upper limit on $\langle \sigma_A v \rangle$ at 90% C.L. of this GH analysis (solid orange, down-pointing triangles) for the $\tau^+ \tau^-$ annihilation channel assuming the NFW halo model are compared to the IceCube-22 GH [167] (blue dashed, circles), the IceCube-79 GH [79] (red dashed, up-pointing triangles), and the IceCube-79 GC [3] (solid black, squares) analyses. Furthermore, the limit from ANTARES [181] (purple long dashed) are shown together with the most recent limits from spheroidal dwarf galaxy observations by gamma-ray detection experiments: VERITAS [169] (yellow dash-dotted) and Fermi plus MAGIC [184] (brown dash-dot-dotted). Due to imprecisely known $J_0$-factors for dwarf galaxies and the Milky Way, comparisons of limits from galactic and extra-galactic targets involve large uncertainties. The gray-shaded region shows a DM interpretation of the positron excess reported by PAMELA collaboration. The green-shaded regions indicate the $3\sigma$ and $5\sigma$ preferred regions from the $e^+ + e^-$-flux excess observed by Fermi and H.E.S.S. All shaded region data taken from Ref. [176]. To match the local DM density of $\rho_{\text{local}} = 0.471$ GeV cm$^{-3}$ assumed here, the region data and the IC22 halo limits are rescaled. The natural scale is the self-annihilation cross-section region for WIMPs to be thermal relics from the Big Bang [177]. The black dotted line (upper right) indicates the WIMP unitarity bound [161].
10 Conclusions & Outlook

Two searches for DM self-annihilation in the Milky Way have been performed targeting the Galactic center (cf. chapter 8) and the Galactic halo (cf. chapter 9) using data from the IceCube neutrino observatory at the South Pole. The results from both searches were compatible with the background-only hypothesis, thus upper limits on the thermally averaged DM self-annihilation cross-section, \( \langle \sigma_A v \rangle \), at the 90% C.L. have been set assuming different annihilation channels, WIMP masses and DM halo profiles of the Milky Way.

Dedicated atmospheric muon veto techniques have been developed for the GC analysis (cf. section 8.1), which made this low-energy neutrino search in the southern sky possible for IceCube for the first time.

The two analyses combined cover the widest range of WIMP masses probed by IceCube. Furthermore, they provide the most stringent upper limits on \( \langle \sigma_A v \rangle \) obtained by current IceCube searches. An improved version of the GC analysis that is based on the experience gained by the GC analysis presented here is currently under development by IceCube. It provides better sensitivity for low WIMP masses by utilizing improved event reconstructions. The results of both analyses are dependent on the assumed DM halo profile. However, due to the fact that the GH analysis is more sensitive to the northern hemisphere, where the DM halo profiles are more similar, the GH analysis is less dependent on the assumed DM halo profile than most indirect searches that look toward the GC. While gamma-based indirect searches for DM are generally more sensitive, neutrino-based searches can probe some otherwise inaccessible parameter space, such as annihilation directly into neutrinos.

Future analyses could improve by utilizing more live-time, i.e. more data, or more advanced event reconstructions. The utilization of cascade-like events, i.e. \( \nu_e \) and \( \nu_\tau \) CC interactions and all NC neutrino interactions, could increase the signal to background ratio by several factors. Furthermore, it is possible that the DM particle decays, which would also lead to a detectable neutrino signal. The analyses presented here are easy to adapt to test DM decay scenarios. However, due to the time constraints of this Ph.D. work only DM annihilation scenarios have been considered so far.
Future detectors like PINGU could also be used to search indirectly for DM in the Sun or the GC. PINGU is a proposed infill detector array to DeepCore, lowering the neutrino detection threshold to $\sim 1$ GeV. The author of this thesis has developed and performed two sensitivity studies searching for WIMPs in the Sun and the GC using PINGU. Paper IV, which is an excerpt of the PINGU letter of intent [185] covering chapter 8 “Dark Matter”, describes these searches in detail and is self-contained. It shows that competitive sensitivities could be reached for such searches for WIMP masses as low as 5 GeV. The exact sensitivity will depend however on the final design of the PINGU detector and the improvements gained by more sophisticated future analysis techniques and better angular reconstruction of the events than available today.
# Acronyms and Abbreviations

In alphabetical order:

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<tr>
<th>Acronym</th>
<th>Description</th>
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<td>AGN</td>
<td>Active Galactic Nucleus</td>
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<td>AHA</td>
<td>Additionally Heterogeneous Absorption</td>
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<td>ALP</td>
<td>Axion Like Particles</td>
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<td>AMANDA</td>
<td>Antarctic Muon And Neutrino Detector Array</td>
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<td>ANIS</td>
<td>All Neutrino Interaction Simulation</td>
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<td>ATWD</td>
<td>Analogue Transient Waveform Digitizer</td>
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<td>BAO</td>
<td>Baryonic Acoustic Oscillation</td>
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<td>CMB</td>
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Bibliography


