The Search for Neutralino Dark Matter with the AMANDA-B10 Detector

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Abstract

If dark matter in the Universe is constituted by super-symmetric particles in the form of neutralinos then these can accumulate gravitationally in the center of the Earth and annihilate therein. This annihilation process generates a neutrino flux that can be measured as up-going near-vertical muons in a detector like AMANDA. These up-going muons will result in an excess on top of the atmospheric neutrinos coming through the Earth from the northern hemisphere.

An original analysis is presented for the search with AMANDA data for muons induced by neutralino annihilation in the center of the Earth. The comparison of the number of observed data events with the number of expected atmospheric neutrinos is used to calculate an upper limit on both the annihilation rate of neutralinos and the corresponding muon flux.

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Chapter 1

Introduction

The study of the Universe using detectors sensitive to the arrival of neutrinos from space, called neutrino astronomy, began in the 1960s. The theorist John Bahcall and experimenter Ray Davis developed a detector using chlorine to monitor the arrival of neutrinos from the Sun. The Davis detector, which began operating in 1967, found only about one-third of the expected number of solar neutrinos. Discussions of the significance of this discovery sometimes overlook the fact that it was a great triumph to detect any neutrinos from space at all, and that the success of the Davis detector established neutrino astronomy as a new branch in the investigation of the Universe.

Since neutrinos mainly interact via the nuclear weak interaction, the neutrino beam can travel cosmological distances before being attenuated. They are not absorbed by ambient matter like photons and, since they are electrically neutral, they are not deflected by magnetic fields as they travel through space. Therefore, neutrinos always point directly back to their source¹. As neutrinos are so extremely reluctant to interact with other forms of matter, the detectors have to be very sensitive, which means that they have to be shielded from the influence of other particles, such as cosmic rays. Therefore the neutrino telescopes are buried in deep mines, or in tunnels underneath mountains, where layers of solid rock on top screen out the unwanted particles.

The analysis presented in this work has been performed with data taken in 1999 by the Antarctic Muon And Neutrino Detector Array (AMANDA) situated near the South-Pole. This neutrino telescope is designed to detect the secondary charged particles produced in neutrino interactions. It is attempted to infer the direction of the parent neutrino, the type of neutrino and its origin from the detected particle.

A wide range of scientifically interesting areas can be studied using the AMANDA detector. Its potential of high-energy neutrino detection has been proven [1] and the spectrum of expected atmospheric neutrino events has been observed [2]. Furthermore, the AMANDA collaboration has been able to put limits on the flux from hypothetical neutrino point sources [3], neutrino-induced cascades [4], the diffuse flux of high-energy neutrinos [6], neutrinos from Gamma Ray Bursts [7] and magnetic monopoles [8].

The AMANDA detector is also sensitive to another interesting area, namely, the search

¹Note however that gravitational lensing can bend the path of the traveling neutrino.

for dark matter in the Universe. In this dissertation a search for a neutrino signal coming from the annihilation of neutralinos in the center of the Earth will be presented. No evidence for the existence of neutralinos has been found and upper limits on the muon flux induced by the annihilation of the hypothetical neutralinos are presented.

Chapter 2 describes the dark matter candidates and in particular the neutralino, the lightest stable particle provided by the Minimal Super-symmetric extension of the Standard Model. An overview of how such particles can be detected is given as well. The different high-energy neutrino sources and the physical processes for neutrino detection in such an experiment are reviewed in chapter 3. The AMANDA detector, as configured in 1999, is described in chapter 4. Details about the electronics, the trigger system and the calibration techniques are also provided. In chapter 5 the experimental data, the simulation of the neutralino signal and of the atmospheric muon and neutrino events are discussed. Chapter 6 is devoted to the muon track reconstruction techniques used in this work. In chapter 7 attention is given to the cleaning and processing techniques of the data. The method developed in this work for the selection of the neutralino-induced muon tracks is explained and its results are discussed. The resulting effective volumes and upper limits on the muon flux from neutralino annihilation are revealed in chapter 8. Sources of systematic uncertainties and their impact on the results are discussed in chapter 9. The comparison with the results obtained by other experiments are discussed as well. Finally, the analysis is summarized in chapter 10.

Chapter 2

Dark Matter in the Universe

2.1 Introduction

Astronomers know that there is more to the Universe than meets the eye. The bright stars and galaxies are the obvious components of the Universe to creatures such as ourselves. Until the 1980s, it was widely accepted that most of the matter in the Universe could be studied by its emission of light or other forms of electro-magnetic radiation. However, it is now clear that much less than half of the mass of the Universe is in the form of matter that the Sun and the Stars, the Earth and ourselves are made of.

Astronomers have known since the 1930s that there is at least some dark matter in our own Milky Way galaxy [10]. Although most of the stars in the galaxy orbit in a relatively thin disc about 100000 light years across, but only some 2000 light years thick (thicker near the center; thinner at the edge), they bob up and down within the confines of the disc as they orbit around the center of the galaxy. This motion is constrained by the amount of matter there is in the disc. The more matter there is, the smaller the amplitude of the bobbing is, because gravity holds the stars more tightly in its grip. Statistical studies show that there is more matter in the disc than can be seen in the form of bright stars.

More recently, studies of the way galaxies like our own rotate (using spectroscopy and measurements of the Doppler effect) have shown the presence of even more dark matter. Across the entire disc of a galaxy like the Milky Way, the rotation speed is independent of the radius from the center of the galaxy to a much higher degree than expected, as illustrated in figure 2.1. This can only mean that the entire disc of bright stars is embedded in a much bigger halo of dark material, which carries the bright galaxy around in its gravitational grip.

By the middle of the 1980s, it was clear that overall our galaxy contains up to ten times as much dark matter as the matter that can be seen in the form of stars. At about the same time, studies of the Universe at large had shown that there is much more dark matter in the depths of the inter-galactic space, holding galaxies together in clusters.

The speed with which individual galaxies are moving within a cluster can be found using the Doppler effect. The overall red-shift for the cluster is caused by the expansion



Figure 2.1: The rotation curve for the spiral galaxy M33. The points represent the measured circular rotation velocities as a function of distance from the center of the galaxy. The dashed curve is the contribution to the rotational velocity due to the observed matter. If there was only luminous matter, the rotation curve would drop for a large distance from the center of the galaxy. The existence of dark matter is inferred by the discrepancy between the observed rotation curve and the rotation curve due to the luminous disk. Figure from [11].

2.2. DARK MATTER CANDIDATES

of the Universe, but the individual galaxies within the cluster show slightly different redshifts, because of their random motions adding to (or subtracting from) this cosmological red-shift. It turns out that the galaxies are moving too fast within the clusters to be held in place by the gravity of the material that can be seen in the form of galaxies. The presence of clusters proves that there must be additional dark matter present. There is about ten times more of this cosmological dark matter than the amount of matter in galaxies themselves, including the dark component of galaxies.

On the largest scale of all, the Universe as a whole, there may be additional dark matter. If the inflationary model of the Big Bang is correct, then the spacetime of the Universe must be nearly flat. The results of the analysis of cosmic microwave background radiation and high red-shift type Ia supernovae favor an energy density of the universe [9],

$$\Omega_0 = \Omega_M + \Omega_\Lambda = 1 \tag{2.1}$$

where Ω_M is the matter component and Ω_Λ is the cosmological constant component.

Measurements of galaxy masses from gravitational effects in large scale structures e.g. rotation velocity distributions, as described earlier, indicate that the matter density should be at least [10]:

$$\Omega_M \ge 0.2 \div 0.3 \tag{2.2}$$

However, observations of high red-shift type Ia supernovae estimating the expansion rate of the Universe [12], the anisotropies in the cosmic microwave background radiation [13] and theories of structure formation in the Universe [14] increase this value to:

$$\Omega_M \sim 0.3 \div 0.4. \tag{2.3}$$

Comparing with the estimates of the luminous matter content of the Universe, Ω_{lum} , taking into account the visible light output from galaxies and the inter-galactic medium,

$$\Omega_{lum} \le 0.016, \tag{2.4}$$

the conclusion is that the total matter content is larger than expected from luminous matter alone.

2.2 Dark Matter Candidates

All the matter known from direct observations - stars, planets and people - is made of baryonic material. More examples of baryonic matter exist in the form of dwarves, black holes and other "Massive Astronomical Compact Halo Objects" (MACHOs). The amount of baryonic material in the Universe has been determined by the conditions in the cosmic fireball of the Big Bang, in which the Universe was born. Studies of the cosmic microwave background radiation power spectrum [13], [15], regarded as the afterglow of the Big

Bang, and spectroscopic measurements of the relative abundances of light elements (2 H, 3 H, 4 He, 7 Li) in old stars, formed when the Universe was young, provide tight constraints on the amount of baryonic material that could have been produced. The baryon density is restricted to 5 % of the total matter.

Thus, the major part of the dark matter has to be non-baryonic. These dark matter particles must meet some requirements, i.e. they must be electrically neutral, have a nonzero mass, interact weakly with ordinary matter and have a relic abundance which is in accordance with theoretical predictions of the dark matter mass density. They are called "Weakly Interacting Massive Particles" (WIMPs) and they come in two varieties. "Hot Dark Matter" is the name given to hypothetical WIMPs that emerge from the Big Bang traveling at speeds close to the speed of light. "Cold Dark Matter" is the name given to particles that emerge from the Big Bang traveling much more slowly than the speed of light.

There is one known candidate for the role of Hot Dark Matter particle, the neutrino. It was originally assumed that neutrinos have zero mass. However, in early 1996, laboratory experiments only set an upper limit on its mass of ~ 5.6 electron volts. Today there are independent experimental indications that neutrinos do have mass [16], [17], [18], [19]. However, constraints given by the Pauli exclusion principle together with modern understanding of galaxy creation, restrict the fraction of hot dark matter to $\Omega_{\nu} \cdot h^2 < 0.0076$ [20]¹.

Hence, one needs another non-baryonic cold dark matter relic from the Big Bang epoch to explain the high value of the observed mass density in the Universe. These hypothetical particles also have to be sufficiently massive (i.e. non-relativistic at the time of galaxy formation) in order to undergo gravitational effects. There are several candidates from various extensions of the Standard Model (SM) of electroweak interactions, e.g. galactic dark matter axions [21], axinos [22] and gravitinos [23]. However, the most attractive ones are the neutralinos, the lightest stable particles provided by the Minimal Super-Symmetric extension of the standard Model (MSSM).

2.3 MSSM Phenomenology and Neutralinos

Super-symmetry (SUSY), which is an extension to the Standard Model of electroweak interactions, is a development of grand unified theories which suggests that there is a symmetry between bosons and fermions, so that in the particle world there should be a bosonic counterpart for every fermion, and a fermionic counterpart for every boson.

The minimal super-symmetric standard model has many free parameters, but with some simplifying assumptions the number of free parameters can be reduced. In this dissertation, the same MSSM with seven free parameters is used as in [24], [25], [26], [27] and [28]. In particular, a very general set of models imposing no restrictions from supergravity other than gaugino mass unification is investigated. The free parameters are the

¹ Ω is the energy density in units of the critical density and *h* is the Hubble parameter in units of 100 kms⁻¹Mpc⁻¹.

Higgsino mass parameter μ , the ratio of the Higgs vacuum expectation values $\tan\beta$, the gaugino mass parameter M_2 , the mass m_A of the CP-odd Higgs boson and the quantities m_0 , A_t and A_b from the ansatz on the scale of super-symmetry breaking. The parameters and the full set of Feynman rules are described in detail in [24] and [29]. Extensive scans of the model parameter space have been made, both general ones and others specialized to specific regions². The model parameters have been varied within the generous ranges listed in table 2.1.

Parameter	Unit	Min	Max
μ	GeV	-50000	50000
M_2	GeV	-50000	50000
$\tan \beta$	1	1.0	60.0
m_A	GeV	0	10000
m_0	GeV	100	30000
A_b/m_0	1	-3	3
A_t/m_0	1	-3	3

Table 2.1: The ranges of parameter values used in the scans of the MSSM parameter space. Note that several special scans aimed at interesting regions of the parameter space have been performed. In total ~ 100000 parameter sets have been generated that are not excluded by accelerator searches [30], [31].

The MSSM is based on the assumption that the *R*-parity, defined as $R \equiv (-1)^{3B+L+2S}$ (where *B* and *L* are baryon and lepton numbers respectively and *S* is the spin), is conserved. This assumption within the MSSM is of great importance for the SUSY dark matter hypothesis. By definition, R = +1 for the standard model particles and Higgs bosons and R = -1 for their super-partners. In the case of *R*-parity conservation, the lightest (*R*-odd) super-symmetric particle (LSP) is stable and becomes a likely candidate for cold dark matter.

In this dissertation it is assumed that the WIMP is the lightest neutralino in the MSSM. The lightest neutralino, $\tilde{\chi}_1^0$, is defined as the lightest mass eigenstate obtained from the superposition of four spin-1/2 fields, the Bino and the Wino gauge fields, \tilde{B} and \tilde{W}^3 , and two neutral CP-even Higgsinos, \tilde{H}_1^0 and \tilde{H}_2^0 :

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0.$$
(2.5)

In this notation, the gaugino fraction of the neutralino can be defined as

$$f = |N_{11}|^2 + |N_{12}|^2 \tag{2.6}$$

where particles with $f \rightarrow 0$ are more higgsino-like (annihilate mostly in heavy quarks) and with $f \rightarrow 1$ are gaugino-like (annihilate mainly into gauge bosons). The actual composition of the neutralino can have cosmological consequences since its annihilation

²These scans have been made in the parameter space corresponding to a set of parameter values that predict a detectable muon flux induced by the annihilation of neutralinos in the center of the Earth (see also chapter 9).

cross-section depends on it. In [32] it has been discussed that a mainly Wino type neutralino would not be cosmologically relevant in the present epoch since it would have annihilated too fast in the early Universe to leave any relevant relic density.

For each generated model, defined by the particular values for the 7 parameters mentioned in table 2.1, it is checked whether it is not excluded by current accelerator constraints and if it is cosmologically interesting, meaning that $0.025 < \Omega_{\chi} h^2 < 1$, i.e. where the neutralinos can make up most of the dark matter in our galaxy without overclosing the Universe.

Unsuccessful searches for SUSY particles at accelerator experiments have set a lower limit on the neutralino mass $m_{\chi} > 31$ GeV [33], while theoretical arguments based on the requirement of unitarity set an upper limit of 340 TeV [32]. Imposing in addition the condition on $\Omega_{\chi} h^2$ mentioned above, only models with $m_{\chi} \lesssim 10$ TeV [26] become cosmologically interesting.

2.4 Detection of Neutralinos

2.4.1 Introduction

In the early stages of the Universe, when the temperature T exceeded the WIMP mass m_{χ} , these particles were in thermal equilibrium [14]. This equilibrium abundance was maintained by the annihilation of WIMPs into lighter particles and by other particles annihilating into WIMPs. When the temperature fell below the WIMP mass their density became suppressed by the factor $\exp(-m_{\chi}/T)$. Their density would be exponentially small today if it were not for the expansion of the Universe. At some point the thermal equilibrium was violated and WIMPs dropped out of the equilibrium, remaining at a certain relic abundance. From the freeze-out condition an approximate estimation of the WIMP relic density is found [14]:

$$\Omega_{\chi} h^2 \simeq \frac{3 \cdot 10^{-27} \text{cm}^3 \cdot \text{s}^{-1}}{<\sigma_A v >}$$
(2.7)

where $\langle \sigma_A v \rangle \simeq G_F^2 m_{\chi}^2$ is the thermally averaged product of the total cross-section of the WIMP annihilation into light particles, multiplied with their relative velocity v; G_F is the Fermi constant and h is the Hubble constant. Under the assumption that the WIMPs exist, the averaged product of their annihilation cross-section and their relative velocity is estimated to be $\langle \sigma_A v \rangle \sim 10^{-25}$ cm³s⁻¹. This leads to a value for $\Omega \chi h^2$ which agrees within one order of magnitude with the necessary value of the dark matter density (see section 2.1).

The search for WIMPs as remnants from the Big Bang epoch is very important as their existence may be the explanation, at least partially, for the dark matter density observed today. This is very surprising, knowing that WIMPs were initially introduced in the framework of the super-symmetric standard model as a theoretical solution in the grand unification theory without the intention to solve the dark matter problem. Many methods have been proposed to search for evidence of particle dark matter. In addition to accelerator experiments [30], [31], direct and indirect dark matter experiments have been performed. Direct dark matter searches attempt to measure the recoil of dark matter particles scattering elastically off the detector material. Indirect dark matter searches have been proposed to observe the products of dark matter annihilation including γ -rays, positrons, anti-protons and neutrinos.

2.4.2 Direct Detection

The general idea behind these experiments is that relic neutralinos (or other possible WIMPs) could scatter off the nuclei in some material, depositing typically tens of keV of energy. The energy deposited by the recoil nucleus has a characteristic exponential spectrum and depends on the WIMP mass and its relative velocity through the galactic halo. Some examples of how the thermal energy could be detected include:

- i) via changes in resistance due to a slight temperature increase (bolometry)
- ii) via a magnetic flux change due to a super-conducting granule phase transition, or
- iii) via ionization.

The technical challenge is to build detectors that could pick out the relatively rare, low energy neutralino scattering events from backgrounds mainly due to cosmic rays and radioactivity in surrounding matter. The detectors pursue a sensitivity of 0.1-0.01 events/kg/day [36], [37]. The detector energy resolution must therefore be good enough in order to distinguish genuine WIMP recoils from background electron ones.

Another possible signal comes from the seasonal variation in the dark matter detection rate, caused by accounting for the Earth's velocity about the sun, while at the same time accounting for the sun's velocity about the galactic center. Very high counting rates would be necessary to detect this, since the seasonal variation amounts to less than a per cent. It should also be noted that if dark matter detectors are sensitive to the direction of collision products, this should also depend on the time of day and season of the year.

IGEX [38] and HDMS [39] are two germanium ionization detectors, which obtain excellent energy resolution and the highest event rate of all direct WIMP searches. Their main difficulties come from distinguishing WIMP-induced recoils from electron recoils, induced by β - and γ -radioactivity. The GENIUS project [40] will have even more germanium to its disposal than the above mentioned experiments. These experiments will explore a large part of the super-symmetric parameter space in the future.

The DAMA experiment [41] is based on a scintillator (CsI(Tl), NaI) detector. This kind of detector has the additional advantage in the γ -background rejection because electron and nuclear recoils have different scintillation times. However, this technique is not applicable for energies close to the detector threshold. The DAMA collaboration claims to have a region in parameter space where a neutralino signal is allowed at the 90% confidence level. They reported a detection of a statistically significant annual fluctuation in the total rate based on four years of data taking. These signal variations correspond to a neutralino mass $m_{\chi} = 52 \pm_{8}^{10} \text{GeV/c}^2$ and a WIMP nucleon cross-section of

 $\sigma = (7.2 \pm 0.4)_{0.9} 10^{-6} \text{pb} [42], [43].$ Other experiments have not yet confirmed these results.

CDMS [44], [45], CRESST [46] and EDELWEISS [47], [48] use bolometric detectors in combination with ionization detectors. They measure the temperature fluctuations caused by the interaction of particles in the absorber (Ge, silicon, saphire). This method is applicable in a wide energy range and provides a high precision recoil identification. The published results of the CDMS group and the EDELWEISS experiment exclude at 90 % confidence level the WIMP candidate as reported by the DAMA collaboration.

2.4.3 Indirect Detection

The MSSM neutralinos are Majorana particles, i.e. they are their own anti-particles, and are therefore able to annihilate pair-wise. The annihilations of two neutralinos into standard model particles could leave unique signs, which can not be mismatched with particles from other known sources.

Balloon experiments like BESS [49], CAPRICE [50] and HEAT [51] and the satellite experiment AMS [58] have searched for a neutralino induced anti-proton and positron flux from the galactic halo. Anti-protons and positrons are produced in equal amounts to protons and electrons in neutralino annihilations.

The anti-proton flux from neutralino annihilations could be distinguished from the cosmic ray anti-proton flux at low energies, because the latter flux is expected to drop substantially at low energies, due to kinematic constraints, whereas the neutralino induced anti-proton flux is more flat. However, according to detailed calculations, the differences between conventional sources and anti-protons from neutralino annihilations are small. So far, no indications of an excess in the anti-proton flux due to WIMP annihilations have been observed [50].

Positrons are produced in pion and kaon decays in hadron jets from the pair of annihilating neutralinos. The expected fluxes of positrons from neutralino annihilations are very small, compared to the cosmic ray positrons. The absolute flux of positrons has been measured by the HEAT detector [51], but no significant signature from the annihilation of neutralinos has been detected.

Another channel for detection of neutralino annihilations in the halo is to search for monochromatic gamma rays $\chi\chi \rightarrow \gamma\gamma$. This line signal is expected to be very faint as well. Therefore, instruments with good energy and angular resolution are required. Both ground based Air Cherenkov Telescopes (Veritas [52], Milagro [53], MAGIC [54] and Celeste [55]), which are limited to 100 GeV - TeV neutrinos, and satellite detectors (GLAST [56], EGRET [57]), which are most sensitive to neutrinos with energies below 100 GeV, can probe this field.

One of the most promising methods for the discovery of neutralinos in the halo is the observation of energetic neutrinos from their annihilation in heavy objects. The ideal situation would be the search for such a secondary signal from the galactic center. If very high densities of dark matter are present in the galactic center, as expected for very cuspy halo profiles [59] or density spikes [60], sizable neutrino fluxes could be produced. For most particle dark matter candidates, however, very large fluxes of γ -rays would accompany such neutrinos and it would be unlikely that neutrinos would be observed in the absence of a γ -ray signal. However, neutrino experiments could help confirm that a γ -ray signal was the result of dark matter annihilations rather than a more traditional astrophysical source. Unfortunately, the AMANDA neutrino telescope at the South Pole is not sensitive to neutrinos from the galactic center.

Heavy objects like the Earth or the Sun are also very interesting to search for highenergy neutrino signals coming from annihilations of neutralinos. The neutralinos have a non negligible probability of scattering off atomic nuclei in the Earth or the Sun. They can lose enough energy as to fall below the escape velocity and become gravitationally trapped. Trapped neutralinos sink to the core of the Earth or the Sun where they annihilate into ordinary particles:

$$\chi\chi \to \begin{cases} l\bar{l}, q\bar{q}, W^+W^-, Z^0Z^0, H_1^0H_3^0, H_2^0H_3^0, Z^0H_1^0, \\ Z^0H_2^0, W^+H^-, W^-H^+, gg, Z\gamma, \gamma\gamma \end{cases}$$
(2.8)

Because of the absorption in the terrestrial or solar medium, only neutrinos are capable of escaping to the surface. Neutralinos do not annihilate into neutrinos directly, but energetic neutrinos may be produced via hadronization and/or decay of the direct annihilation products. The density of the trapped neutralinos will increase until their annihilation rate becomes half of their capture rate.

This method has the advantage that the neutralino-induced neutrinos have a welldistinguished angular spectrum in the direction of the center of the celestial body. The reconstruction of the neutrino direction allows to search for an excess in the event rate of the detector in a specific direction. In this work the data taken by the AMANDA detector in 1999 have been analyzed for the search for neutralino annihilations in the center of the Earth.

The neutrino flux coming from the annihilation of neutralinos in the center of Earth can be written as follows [61]:

$$\frac{d\phi}{dE_{\nu}} = \frac{\Gamma_A}{4\pi R^2} \sum_F B_F \frac{dN}{dE_{\nu}}$$
(2.9)

where Γ_A is the annihilation rate, R is the distance from the source to the detector and F stands for the annihilation channel with branching ratio B_F and differential neutrino flux dN/dE_{ν} .

The annihilation rate depends on the annihilation cross-section, the capture rate, the age of the capturing object and the neutralino density distribution inside the Earth. The capture rate depends on the elastic cross-section for neutralino scatterings on atomic nuclei in the Earth, the escape velocity of the Earth, the local relic density of neutralinos and their velocity distributions.

Many theoretical calculations of the expected neutrino flux coming from the annihilation of neutralinos in the center of the Earth and the Sun have been made [29], [62], [63]. For the majority of particle physics models, the WIMP capture and annihilation rates reach or nearly reach equilibrium in the Sun. This is often not the case for the Earth, because of two reasons. First, the Earth is less massive than the Sun. Therefore the Earth provides fewer targets for WIMP scattering and a less deep gravitational well for capture. Secondly, the Earth accretes WIMPs only by scalar (spin-independent) interactions. Therefore, it is obvious that the Earth will provide less observable neutrino signals from WIMP annihilations than the Sun. However, due to the vertical geometry of the AMANDA detector, it is very difficult to reconstruct horizontal muon tracks. As a result, the detector is not very sensitive in the direction of the Sun (horizon)³. The detection of the neutralino-induced flux from the Sun in the underground detector will therefore be strongly polluted by the atmospheric background. Moreover, the working period of the detector is limited to the period during which the Sun is below the horizon.

The operating experiments AMANDA [64], Baksan [65], Super-Kamiokande [16], MACRO [66] and Baikal [67] and the planned experiments ANTARES [69], NEMO [70], NESTOR [71] and ICECUBE [72] are all capable of detecting neutrinos from annihilating WIMPs. None of these experiments have detected a neutralino signal so far. The present neutrino experiments have established upper limits on the neutralino-induced muon flux [75], [76]. The AMANDA collaboration already analyzed the data taken in 1997 and set upper limits on the muon flux coming from the annihilation of neutralinos in the center of the Earth [77] and the Sun [80], [81]. In this dissertation, the data taken in 1999 have been investigated for neutralino signals coming from the center of the Earth.

2.5 WIMP Diffusion in the Solar System

A new study was performed very recently, in which a new estimate of the velocity distribution of WIMPs at the Earth was made, taking into account the diffusion of WIMPS in the solar system. In this section an overview is given of the theoretical models predicting the capture of WIMPS by the Earth.

In 1985 Press and Spergel [82] calculated the capture rate of heavy particles by the Sun. This prompted them to calculate the flux of high-energy neutrinos coming from the center of the Earth [83]. The capture rate in the Earth (see also section 2.4.3) depends on the mass and the velocity distribution of the WIMPs. The higher the mass of the WIMP, the lower the required velocity to facilitate capture.

The calculations of [82] were refined by Gould in [84],[85],[86]. The exact formulae required to calculate the capture of WIMPs by a spherically symmetric body were derived by Gould in 1987 [84]. In a later paper [85], Gould implemented the fact that the Earth is well inside the gravitational potential of the Sun. The velocities of the incoming particles are increased when these approach the potential of the Sun. Thus the WIMPs will have gained velocity when they reach the Earth. This reduces capture substantially. However, Gould also realized that particles scattered by the Earth can become bound to the solar system⁴.

³Note that this is true for the AMANDA-B10 detector, which is used in this work. The AMANDA-II detector is sensitive to horizontal tracks. See also chapter 4.

⁴There are two sorts of scattering. "Gravitational scattering" conserves the velocity of the scattered particles and can thus be referred to as elastic scattering. "Weak scattering" of a particle reduces its velocity

In 1991 Gould realized [86] the importance of the gravitational diffusion caused by other planets. He considered the combined diffusion effect of Jupiter, Venus and the Earth and concluded that it makes the velocity distribution isotropic near the Earth. WIMPs will diffuse in the solar system both between different bound orbits, but also between unbound and bound orbits. The net result of all this is that the velocity distribution at the Earth will effectively be the same as if the Earth was in free space. In other words, the phase space density of unbound and bound particles would be the same. Specifically, for the most important parts of the velocity space, this would happen on time scales shorter than the age of the solar system. This would lead to an enhanced capture rate of heavy WIMPs by the Earth.

In 1999 Gould and Alam [87] implemented the results of Farinella et al. [88] in their calculations. Farinella calculated, numerically, the fates of about 50 asteroids of which most were considered to be "Near Earth Asteroids" (NEAs). They concluded that about one third of the considered asteroids will be ejected to hyperbolic orbits or will be driven into the sun in less than 2 million years. If the results of Farinella et al. also apply to general Earth crossing orbits of WIMPs, the part of velocity space corresponding to bound solar orbits would be effectively empty, since the typical time scales at which such orbits are populated from unbound orbits are generally much longer [86]. This, in turn, would reduce the expected capture and annihilation rates in the Earth and thus reduce the neutrino fluxes. The basic results of Farinella et al. were confirmed by Gladman et al. [89] and Migliorini et al. [90].

In [87] Gould and Alam investigated the implications of the idea that bound WIMPs would actually be thrown into the Sun. They considered two different scenarios: an "ultra conservative scenario", where all bound WIMPs are depleted, and a "conservative scenario", where all bound WIMPs, that do not have Jupiter-crossing orbits, are depleted. In the ultra-conservative view, solar depletion is assumed to be so efficient that no bound WIMPs exist. In this case, WIMPs with masses above about 325 GeV could not be captured by the Earth at all. In the conservative view, Jupiter is assumed to be faster at diffusing WIMPs into the solar system than solar depletion is at throwing them into the Sun. The conservative approach allows WIMPs up to about 630 GeV to be captured. Both views significantly reduce the neutrino fluxes from the Earth for heavier WIMPs.

However, these results are based on the results of Farinella et al [88], but can these results be applied to all Earth-crossing WIMP orbits? The orbits of asteroids ejected from the asteroid belt are, after all, rather special as they typically arise from resonances. Therefore, it is not necessarily so that these results apply to all bound WIMPs. The true answer probably lies somewhere between the conservative view and the assumption that solar depletion is very inefficient. This means that some WIMPs on bound orbits in the inner solar system will survive, but solar capture will somewhat diminish their numbers.

In section 9, the implications of the effect of solar capture on the expected neutrino fluxes from the Earth will be discussed.

and can therefore lead to capture by Earth or make the particle bound to the solar system.

Chapter 3

High-Energy Neutrinos and Detection Principle

3.1 Introduction

AMANDA [64] is a neutrino telescope, capable of detecting neutralinos indirectly, as mentioned in chapter 2, by measuring the high-energy neutrino flux from WIMP annihilations inside heavy objects. The detection principle consists of registering the muons that are produced in the charged current interactions between the neutrinos and the bedrock below or the ice surrounding the detector by means of their Cherenkov emission. This method was developed some time ago [91] and is now successfully implemented in large under-water/under-ice Cherenkov telescopes like Baikal [67] and AMANDA [64]. Besides searching for neutralino dark matter, these detectors probe the sky to search for high-energy extra-terrestrial neutrino sources. In this chapter the different high-energy neutrino sources are discussed and the detection principle of AMANDA is explained.

3.2 Cosmic Rays

All stable charged particles and nuclei originating from outside the Earth are considered cosmic rays. Those particles, which are accelerated at astrophysical sources, are called "primary cosmic rays". The particles originating in interactions with interstellar gas or with the Earth atmosphere are considered "secondaries".

The cosmic rays dominantly consist of ionized atomic nuclei, in particular protons and helium. Elements such as Li, B, C, O and Fe are also present. Since their discovery in 1912 the cosmic rays have been studied extensively. The knowledge gained on their exact composition, in collaboration with photo-spectroscopic information from distant celestial objects, has been very important for the understanding of nucleosynthesis at the Big Bang, in stars and supernovae.

Figure 3.1 shows the energy spectrum of the cosmic rays. The energy of the cosmic radiation goes from tens of MeV to about 10^{20} eV and thus covers a dozen orders of

magnitude in energy. The intensity of the primary nucleons I_N can be represented by the following expression:

$$I_N(E) \sim 1.8 E^{-\alpha} \frac{\text{nucleons}}{\text{cm}^2 \cdot \text{s} \cdot \text{sr} \cdot \text{GeV}}$$
(3.1)

where E is the energy per nucleon in GeV and α is the differential spectral index. This "near perfect" power law of the energy spectrum spans 30 orders of magnitude in flux.



Figure 3.1: The energy spectrum of cosmic ray primaries. These have a spectrum of $\sim E^{-2.7}$ between $E \sim 10^{10}$ eV and $E \sim 5.10^{15}$ eV. At the "knee", the spectrum steepens to $\sim E^{-3.0}$ reflecting the composition change to heavier elements. Beyond $E \sim 5.10^{18}$ eV, the so-called ankle, the spectrum flattens again and the composition seems to shift back to lower mass nuclei. The dots represent the results of several experiments. The line is just to show that there is some difference from a constant power law. Figure from [92].

The differential spectral index α is equal to 2.7. Around 5.10^{15} eV the slope changes to $\alpha \sim 3.0$, in the zone of the spectrum known as the "knee". Above this energy, the cosmic rays are probably of extra-galactic origin. At about $E \sim 5.10^{18}$ eV, the slope changes again, due to the different origin of the particles.

In general the power law behavior as well as the composition can be interpreted in terms of shock accelerations and propagation through the interstellar medium. A quantitative proposal for the origin of the cosmic radiation was drawn by Biermann and Stanev [93]. A nice feature of that theory is that it makes specific and quantitative predictions about the origin, the energies, the detailed shape of the spectrum and the chemical composition of the particles. In this proposal the origin of the cosmic rays can be traced from three different sources: supernovae explosions into the interstellar medium, supernovae explosions into a predecessor stellar wind and radio galaxies. The overwhelming success of this proposal is based on the prediction of the knee due to an upper energy limit of the first source type.

During the last years a broad spectrum of various other source-theories has been developed. Although the supernovae mechanism explains the sub-knee regime very well, the energy range between the knee and the ankle, and even more above the ankle, is not well understood. Thus the discussion about the single contributions of the proposals is still going on.

It is expected that cosmic ray interactions with the Cosmic Microwave Background Radiation (CMBR) should produce a sharp cutoff in the observed spectrum. The reason is that nucleons above $5 \cdot 10^{19}$ eV lose energy drastically during their propagation from the source to the Earth via photo-pion production in nucleon collisions with the photons of the CMBR. This so called GZK-cutoff¹ in the cosmic ray spectrum at about 70 EeV is characteristic for models with extra-galactic sources that are homogeneously distributed. The energy spectra of ultra-high energy cosmic rays reported by the AGASA [94], Fly's Eye [95] and HiRes [96] experiments are all shown to be in agreement with each other for energies below 10^{20} eV. The data from Fly's Eye and HiRes are consistent with the expected flux suppression above the GZK-cutoff and are inconsistent with a smooth extrapolation of the observed cosmic ray energy spectrum to energies above the GZK-cutoff. AGASA data, however, show an excess of events above 10^{20} eV, compared to the predicted GZK suppression and to the flux measured by other experiments. Although the GZK problem is still debated today, the future Pierre Auger observatory [35] offers the possibility of addressing the GZK question.

3.3 Atmospheric Muons and Neutrinos

The analysis presented in this dissertation has two types of background events: atmospheric muons and atmospheric neutrinos. The origin of these background events and the general method used to reduce the flux of these events as much as possible are discussed in this section. More details on the reduction of the background events can be found in chapters 7 and 8.

The primary cosmic rays interact in the atmosphere and produce charged and neutral mesons. These particles decay and give rise to muons, electrons and neutrinos:

¹Greisen, Zatsepin and Kuzmin, 1966.

$$p + N \to \pi, K, \dots \tag{3.2}$$

$$\pi^{\pm}, K^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
 (3.3)

$$\mu^{\pm} \to e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_{\mu}(\nu_{\mu})$$
 (3.4)

This is the only decay channel for the pion, while the kaon only decays in 63.5% of the cases following this mode. The energy of the produced muons amounts on average to 79% of the meson energy in case of the pion and 52% of the meson energy in case of the kaon.

Atmospheric muons and neutrinos are the most abundant particles originated by cosmic rays in the atmosphere. Atmospheric muons can only reach the AMANDA detector from above² since they can only travel several thousands of meters through the Earth before being absorbed. The Earth is used as a "shield" against atmospheric muons produced in the northern hemisphere.

However, a significant part of the atmospheric muons produced in the southern sky is also rejected by the thick ice layer and the downward orientation of the AMANDA optical modules (see also chapter 4). Nevertheless, even at the depth of the AMANDA detector (~ 2000 meter), the triggered atmospheric muon flux (see section 4.4) is a factor of ~ 10^6 larger than the triggered muon flux induced by atmospheric neutrinos. Hence, a further elimination of these atmospheric muons is necessary. Since these atmospheric muons travel downwards³, they will be separated from the atmospheric neutrinos by means of their reconstructed track direction. On the other hand, the atmospheric muons can be used to calibrate the detector and study the detector response.

The atmospheric neutrinos can penetrate the Earth from all directions and form an irreducible background for experiments like AMANDA. It is very important to measure the flux originating from atmospheric neutrinos, since these neutrinos are a source of background in the search for neutralino dark matter and in the search for cosmic high-energy neutrino sources. The location of these signal sources require the detection of an excess of neutrinos above the background of atmospheric neutrinos coming from a given angular bin. It is thus important to measure the angular spectrum of atmospheric neutrinos very precisely. Furthermore, atmospheric neutrinos can be used to test the detector capabilities as well.

3.4 High-Energy Neutrino Sources

Apart from the atmospheric neutrinos (described in section 3.3), originating in the cosmic ray interactions in the Earth's atmosphere, there are other classes of high-energy neutrinos

²These muons are produced in the southern hemisphere above the AMANDA detector.

³From the point of view of the AMANDA detector, "downwards" means from the ice surface to the detector.

coming from different sources. In this chapter the galactic neutrinos, the active galactic nuclei, the gamma ray bursters and the super nova remnants are discussed. Magnetic monopoles, binary systems, cosmic strings, ... are other, more exotic, sources of high-energy neutrinos. More information on these sources can be found in [36].

3.4.1 Galactic Neutrinos

The interaction of the galactic cosmic rays with the interstellar matter results in a diffuse neutrino flux, called "galactic neutrinos". The resulting neutrino intensity can be estimated from the known cosmic ray spectrum and the matter distribution in our galaxy [97], [98], [99], [100]. However, the interstellar matter density is not known very precisely, introducing uncertainties in the neutrino intensity estimation.

Large clusters of galaxies are another important, but yet uncertain, source of galactic neutrinos. In this case neutrinos are produced by proton-proton interactions of high-energy cosmic rays with the inter-cluster gas. The diffuse neutrino flux coming from these galaxies has been estimated in [101].

3.4.2 Active Galactic Nuclei

Active Galactic Nuclei (AGN) are galaxies that emit a large amount of energy from their central regions, known as their nuclei. Since long they have been considered as a possible source of high-energy neutrinos, nowadays all thought to be powered by essentially the same process, involving the accretion of matter on to a super-massive black hole at the center of the active galaxy. As material from the galaxy falls into the black hole, gravitational energy associated with its mass is released and converted into electro-magnetic radiation and radio waves.

Energy from the central source is often beamed out from the powerhouse to either side of the galaxy, probably from the "poles" of the black hole, as illustrated in figure 3.2. The energy cannot escape in other directions because it is blocked by the accretion disc. Where the beamed radiation interacts with the material in the galaxy and its surroundings, it can produce thin jets or extended regions called lobes, which radiate at radio wavelengths.

There are two different models of γ -ray emission in the AGN-jets. One model includes electron acceleration and inverse Compton scattering. However, this model does not expect a neutrino flux. The other model, called the proton blazar model, assumes the acceleration of protons. Proton interactions with matter or radiation can lead to neutrino production. See also figure 3.3. In [104], [105] more information can be found on the estimation of the diffuse neutrino background from AGNs.

The "Compton Gamma Ray Observatory" [106] has observed high-energy γ -rays from active galactic nuclei. The luminosities of these AGNs vary from 10^{42} erg/s to 10^{48} erg/s.



Figure 3.2: Schematic representation of a radio-loud AGN. The AGN observation is determined by different phenomena, depending on the angle between the AGN jet and the line of sight. At small angles (observer looks into the jet), the relativistically boosted jet dominates the observation. AGNs are now called blazars. At intermediate angles (observer looks into the gap between the torus and the jet), the hot broad line region is observed. AGNs are called quasars in this case. At large angles, the narrow line region is observed as the torus obscures the AGN core. AGNs are called narrow line radio galaxies. Figure taken from [102].



Figure 3.3: Schematic representation of AGN acceleration processes. The origin of gamma ray photons in a leptonic picture is indicated in the inner part of the jet. The outer jet shows their origin in a hadronic picture. The charged pion production and the subsequent neutrino production is not shown. Figure from [103].

3.4.3 Gamma Ray Bursters

Gamma Ray Bursters (GRBs) were first detected in the late 1960s by satellites sent up by the US Air Force to monitor nuclear explosions on Earth linked with atomic weapons testing, but the discovery was not declassified and made public until 1973. GRBs are short but very intense flares of ~ 100 keV - 1 MeV photons. These powerful sources appear and fade away again in a matter of a few seconds, but during its brief life time a gamma ray burster can shine as brightly at gamma ray energies (~ $10^{52} - 10^{53}$ erg) as all the other gamma ray objects in the sky put together.

Gamma ray bursters are the best motivated transient sources of high-energy neutrinos. The energy sources of GRBs may be associated with compact neutron stars, hyperaccreting black holes or supernova explosions of very massive stars [107]. The bursts are believed to be produced by the dissipation of the kinetic energy of a relativistically expanding fireball. The "Relativistic Fireball Model" [108] provides estimations of neutrino fluxes from GRBs, describing the explosion as a result of the large amount of energy released within a small volume⁴. The relativistic fireball allows electrons to be shock accelerated and produce γ -rays by synchrotron radiation. Existing protons will also be accelerated and may interact with γ -rays producing neutrinos through pion photo-production. On average the BATSE detector [34] detects one such gamma ray burst per day.

3.4.4 Supernova Remnants

Supernova remnants (SNRs) are expanding shells of material formed from the outer layers of a star blown apart during a supernova explosion. Some supernova remnants can be seen through the glow of visible light that they radiate, while others are only seen at X-ray or radio wavelengths. As the shock wave from the supernova races out through the interstellar matter, it heats the gas between the stars and produces a reflected shock, which bounces back and heats the material in the supernova remnant as well. This heating raises the material to temperatures where X-rays can be emitted. Within the shock waves, electrons are accelerated and emit radio waves in the form of synchrotron radiation. SNRs send out large fluxes of low-energy neutrinos as well. These neutrinos are produced in the interactions of protons, accelerated inside the supernova remnants, with the supernova shell.

On the 23rd of February 1987 several detectors around the world recorded a burst of neutrinos associated with the explosion of Supernova 1987A. In fact, this supernova was seen in visible light which had been traveling towards the Earth from the Large Magellanic Cloud for more than 160000 years, since the star that created the supernova exploded. When the records of the various neutrino detection experiments that were running around the world at the time were examined, they showed that a pulse of neutrinos had arrived at the Earth just before the light from the supernova. These were explained as neutrinos from the dying star, produced at the moment its core collapsed, some 3 hours before the energy released by that collapse was able to blast away the outer layers of the star and

⁴This volume is typically of the order of $\sim 10^7 \text{ m}^3$.

produce the glare of the visible light.

In large Cherenkov telescopes, like the AMANDA detector, these neutrinos can be detected by fluctuations in the detector noise. A special "supernova trigger system" has been set up by the AMANDA collaboration for the detection of these SNRs. The AMANDA-B10 detector configuration (see chapter 4) can monitor about 68 % of the stars in our galaxy, while the AMANDA-II detector (see chapter 4) can reach 95 % of the stars in our galaxy. The AMANDA collaboration is working with SNEWS (SuperNova Early Warning System) members to provide timing information to help pinpoint the position of the supernova by triangulation.

3.5 Detection Principle

3.5.1 Introduction

The AMANDA (Antarctic Muon And Neutrino Detector Array) detector (see chapter 4) is an ice-Cherenkov detector made for the detection of high-energy neutrinos. The detection principle is based on the interaction of the neutrino, coming from any source, with the rock below the detector or with the ice surrounding the detector. The charged leptons that result from this interaction can be identified by specific signatures that can be measured by the detector. In this section the basic physical processes for the indirect detection of high-energy neutrinos are explained in more detail.

3.5.2 Neutrino-Nucleon Interaction

Neutrinos or anti-neutrinos that travel through matter (in this case the rock or the ice of Antarctica) have a finite probability of interacting with a target nucleus and produce a lepton. The interaction can be a neutral current interaction or a charged current interaction.

The neutral current interaction:

$$\nu + N \to \nu + N \tag{3.5}$$

is characterized by a hadronic cascade. Especially abundant is the following process:

$$\nu + N \to \nu + N + \pi^0. \tag{3.6}$$

The dominant reaction for atmospheric neutrinos is the charged current interaction:

$$\nu_l(\bar{\nu}_l) + N \to l^-(l^+) + X$$
 (3.7)

where N is the target nucleon, l is the charged lepton and X is the combination of the final state hadrons. The signature of the interaction depends on the flavor of the neutrino. The two basic signatures are illustrated in figure 3.4.



Figure 3.4: Neutrino detection with the AMANDA detector. On the left: a muon track induced by a muon-neutrino. As the muon passes through the detector, light is emitted along its path at a constant rate. On the right: a cascade produced in the detector by an electron (tau), induced by an electron-neutrino (tau-neutrino).

An interacting ν_{μ} produces a muon that can travel long distances through the detector depositing energy continuously by ionization and stochastic interactions, mainly by bremstrahlung and pair production processes (see section 3.5.3). The ν_e and ν_{τ} channels are somewhat different. The electron from a ν_e -interaction will generate an electro-magnetic cascade, which is confined to a volume of a few cubic meters. The electro-magnetic cascade coincides with the hadronic cascade X of the primary interaction vertex. The optical characteristic of this type of event is an expanding spherical shell of Cherenkov photons with a larger intensity in the forward direction. The tau produced in a ν_{τ} interaction will immediately decay and also generate a cascade. At energies > 1 PeV this cascade is separated by several tens of meters from the cascade of the primary interaction vertex, connected by a single track. This signature of two extremely bright cascades is unique for a high-energy ν_{τ} and is called a "double bang" event [109].

Due to the limited size of the cascades, the detection of cascade-like events is restricted to interactions close to or inside the detector. The accuracy of the direction measurement is worse for cascades than for long muons tracks. Cascades have a typical directional error of 30° to 40° , while the directional error of a reconstructed muon track is $\sim 3^{\circ}$ in AMANDA-B10.

However, cascades from a diffuse flux of ν_e and ν_{τ} have advantages as well. The energy resolution of these events ($\sigma[\log_{10}(E/\text{TeV})] = 0.1 - 0.2$) is better than the energy resolution of track-like events ($\sigma[\log_{10}(E/\text{TeV})] = 0.3 - 0.4$), thanks to the limited size of the cascade, which makes the full energy to be mostly completely deposited inside the detector volume. Another advantage is that the cascade channel is sensitive to all neutrino flavors because the neutral current interactions also generate cascades. Furthermore, cascades are sensitive to the full space angle 4π , while the reconstruction of neutrino-induced muon tracks are limited to the northern hemisphere representing a space angle of 2π .

The search for neutralino dark matter is primarily based on the identification of muons induced by muon-neutrinos. The muons resulting from the charged current interaction have large path lengths, significantly simplifying the particle track reconstruction in the detector.

The muon that is created in the high-energy ν_{μ} charged current interaction carries approximately 60% - 80% of the neutrino energy. The deviation angle between the muon and the neutrino flight line can be parameterized as [110]:

$$\psi = 0.7^{\circ} \times (E_{\nu}/\text{TeV})^{-0.7}.$$
 (3.8)

The scattering angle is smaller for more energetic events. In the TeV-energy range, where the AMANDA-B10 detector is most sensitive, the scattering angle between the neutrino and the resulting muon is $\sim 1^{\circ}$. Taking the muon track reconstruction accuracy of $\sim 3^{\circ}$ into account, the deviation angle between the neutrino and the muon can be neglected.

The cross-section for the charged current neutrino-nucleon interaction can be written as follows [104]:

$$\frac{d^2\sigma}{dxdy} = \frac{2G_F^2 M_N E_\nu}{\pi} \left(\frac{M_W^2}{Q^2 + M_W^2}\right)^2 \left[xq(x, Q^2) + x\bar{q}(x, Q^2)(1 - y^2)\right]$$
(3.9)

where $-Q^2$ is the invariant momentum transfer squared from the neutrino to the outgoing muon, q and \bar{q} are the parton distribution functions of the nucleon, G_F is the Fermi constant for weak interactions and M_N and M_W are the respective masses of the nucleon and the W boson. The Bjorken scaling variables x and y are given by

$$x = \frac{Q^2}{2M_N(E_{\nu_l} - E_l)}$$
(3.10)

and

$$y = 1 - \frac{E_l}{E_{\nu_l}}$$
(3.11)

where x is the fraction of the nucleon's four-momentum carried by the interacting quark and y is the fraction of the neutrino energy carried away by the gauge boson, also called the in-elasticity.

In figure 3.5 the neutrino-nucleon cross-section is shown as function of the neutrino energy. In the search for neutralino dark matter, the energy range of interest starts from tens of GeV to a few TeV (see section 2.3). At these low energies, $Q^2 \ll M_W^2$ and the term in parentheses in equation 3.9 can be neglected. In this region the charge-current interaction cross-sections for an isoscalar target are almost directly proportional to the neutrino energy and can be analytically expressed as:

$$\sigma(\nu N) = 9.63 \cdot 10^{-39} \left(\frac{E_{\nu}}{1 \text{GeV}}\right)^{0.92} \text{cm}^2$$
(3.12)



Figure 3.5: Charged current neutrino interaction cross-sections divided by the neutrino energy as function of the neutrino energy.

$$\sigma(\bar{\nu}N) = 4.03 \cdot 10^{-39} \left(\frac{E_{\bar{\nu}}}{1 \,\text{GeV}}\right)^{0.97} \,\text{cm}^2.$$
(3.13)

For higher neutrino energies $(Q^2 \approx M_W^2)$, the cross section grows more slowly as can be seen in figure 3.5. However, in the same energy range, the average value of y begins to fall, which leads to an increase in the momentum transfer to the muon and, hence, a longer muon range. The longer muon range helps to offset the slower growth in the neutrinonucleon cross-section. The average inelasticity of the charged current neutrino-nucleon interaction is shown in figure 3.6.

3.5.3 Ionization and Stochastic Energy Loss

When a muon travels through matter it continuously looses energy via ionization and in a discrete way via e^+e^- or $\mu^+\mu^-$ pair production, bremsstrahlung (and a small contribution of Cherenkov radiation, see also section 3.5.4), photo-nuclear interactions and the production of δ -electrons. All these processes lead to Cherenkov photons from secondary particles that can be detected. These photons are much more numerous than the Cherenkov photons of the muon itself (see section 3.5.4) and therefore play an important role in the detection of high-energy neutrinos.

The average rate of the muon energy loss can be written as [111]:

$$-\frac{dE}{dx} = a(E) + b(E)E \tag{3.14}$$

where a(E) is the ionization energy loss and b(E) is the sum of the stochastic energy



Figure 3.6: Energy dependence of the average in-elasticity of neutrino-nucleon interactions.

losses. In figure 3.7, the rate of the muon energy loss as function of the muon energy is shown.

Below the critical energy, $E_c \approx 650$ GeV for muons in ice, which is defined as the energy at which radiative and ionization losses are equal, a(E) dominates the energy loss. In this case, the muon energy loss is given by the Bethe-Bloch equation [113]:

$$-\frac{dE}{dx} = K\frac{Z}{A}\frac{1}{\beta^2} \left(\frac{1}{2}ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta}{2}\right)$$
(3.15)

with

$$\frac{K}{A} = \frac{4\pi N_A}{Ar_e m_e c^2} = 0.307075 \text{MeV g}^{-1} \text{ cm}^2 \text{ for } A = 1 \text{ g mol}^{-1}$$
(3.16)

where A and Z are the atomic mass and atomic number of the medium respectively, β , γ , c are the usual relativistic factors, m_e is the electron mass, r_e is the classical electron radius, T_{max} is the maximum energy transfer per collision, I is the mean excitation energy, N_a is Avogadro's number and δ is the density effect correction to ionization energy loss. The density correction term introduces a correction for the fact that the atoms in a dense medium will react coherently to the incident particle, i.e. this correction takes the effect of macroscopic polarization of the medium into account.

Above the critical energy E_c , the term b(E)E dominates the energy loss i.e. discrete losses start to dominate over continuous ones and the muon energy can be estimated by the secondary Cherenkov emission along the track.

In the muon energy range of meaning for AMANDA ($E_{\mu} > 100 \text{ GeV}$), the functions a(E) and b(E) can be considered constant. In ice, $a \approx 0.2 \text{ GeV} \cdot \text{m}^{-1}$ and $b \approx 3 \cdot 10^{-4} \text{ m}^{-1}$ [116].


Figure 3.7: The qualitative behaviour of the average rate of the muon energy loss in ice as function of the muon energy. Figure from [112].

The range of the muon as function of the muon energy results from the integration of equation 3.14:

$$R_{\mu}(E) \sim \frac{1}{b} ln \left(\frac{E}{E_c} + 1\right). \tag{3.17}$$

3.5.4 Cherenkov Radiation

In this work it is important to reconstruct the muon tracks induced by the atmospheric muons, the atmospheric neutrinos and the annihilation of neutralinos very accurately. The reconstruction technique (see also chapter 6) is based on the Cherenkov light emitted by the muon.

A charged particle radiates photons if its velocity \vec{v} is greater than the local phase velocity of light:

$$\left|\overrightarrow{v}\right| = \beta c > \frac{c}{n} \tag{3.18}$$

where n is the index of refraction of the medium in which the particle travels.

The Cherenkov radiation is caused by the interaction of the incident particle with the atoms of the surrounding medium. The latter get polarized by this interaction, but subsequently depolarise, resulting in an electro-magnetic wave. The propagation velocity of this wave will be equal to the speed of light in the medium. The condition that the particle moves faster than this speed is needed so that constructive interference is possible. If the condition is not fulfilled, the radiation will exponentially decay. The condition for observing Cherenkov radiation expressed in equation 3.18, puts a threshold on the energy for the incident muon given as:

$$E_{thr}(\lambda) = \frac{m_{muon}}{\sqrt{1 - \left(\frac{1}{n(\lambda)}\right)^2}}.$$
(3.19)

The photo-multiplier tubes (see chapter 4) of the AMANDA detector are most sensitive in the wavelength range of 300 nm - 600 nm. For these wavelengths, the refraction index of the ice is considered constant n = 1.33. The dependency of n on phase- or group velocity, wavelength, pressure and temperature is discussed in detail in [118]. Taking the mass of the muon $m_{muon} = 105$ MeV into account, the energy threshold $E_{thr} = 160$ MeV.

The light is emitted under a fixed angle so that a moving light cone, also called Cherenkov cone, pointing to the particle, is formed. The characteristic Cherenkov angle depends on the wavelength of the emitted radiation and the velocity of the particle. The Cherenkov angle is given by [117]:

$$\cos\theta_C = \frac{1}{\beta n(\lambda)} \tag{3.20}$$

For ultra-relativistic particles ($\beta \approx 1$) in ice, the Cherenkov angle $\theta_C = 41.2^{\circ}$.

The number of photons emitted can be described by the Frank-Tamm formula [113]:

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha}{\lambda^2} \cdot \left(1 - \frac{1}{\beta^2 n^2}\right) \tag{3.21}$$

where $\alpha \approx 1/137$ is the fine structure constant, yielding ~ 215 photons/cm expected from Cherenkov radiation.

The energy loss due to Cherenkov radiation is part of the radiative muon energy loss and is defined per unit length and per unit wavelength as:

$$-\frac{d^2E}{dxd\lambda} = \frac{\alpha}{hc}sin^2\theta.$$
(3.22)

This energy loss is of the order of 2 MeV/m and is thus negligible compared to the energy losses described in section 3.5.3.

Chapter 4

The AMANDA Neutrino Telescope

4.1 Introduction

Neutrino detectors are always installed deep under ground or in deep lakes in order to suppress the muon background caused by the enormous flux of cosmic rays interacting with particles in the atmosphere¹. These muons can penetrate deeply into the Earth, even down-to the deepest mines, but the number of events decreases strongly with increasing depth.

Most of the cosmic neutrino detectors are based on the Cherenkov radiation detection in a pure and homogeneous medium. As a result, most of these detectors are installed in water or ice as these are cheap detection media. There are mainly two different types of Cherenkov detectors: detectors using closed water tanks (Super-Kamiokande [16] and SNO [114]) and open detection volume detectors (ANTARES [69], NEMO [70], NESTOR [71], Baikal [67], DUMAND [115], AMANDA [64] and ICECUBE [72]).

The closed water tank detectors have a high concentration of photomultiplier tubes in the detector volume and an artificial purification of the medium. This has the advantage that neutrino fluxes can be measured with an extreme accuracy. Another advantage of these detectors is their low energy threshold. This has resulted in the observation of neutrino oscillations in solar and atmospheric neutrinos [114]. The disadvantage of closed tank detectors is that the detection of the high-energy neutrino flux is not possible. The combination of the limited detector mass and the small neutrino interaction cross-sections (see chapter 3) results in a low neutrino rate in these detectors.

The open Cherenkov detectors have reached a compromise between the accuracy and the energy range. The initial project, called DUMAND [115] was canceled in 1995, due to the slow progress and budget difficulties. The project nevertheless managed to make great headway in pioneering techniques, such as exploring background designs, studying backgrounds and - most importantly - stimulating the community to study high-energy neutrinos. Another project that has been running for a long time is the BAIKAL experiment [67]. The detector has been installed in lake Baikal, one of the world's largest

¹Note that the Earth itself is the best shield against the flux of cosmic rays.

and deepest lakes and mainly consists of ~ 200 large light detectors (0.4 m diameter) installed on cables. The BAIKAL project has reached the level enabling it produce interesting physics results. They have observed neutrino-induced events and published limits on the muon flux induced by WIMPs in the center of the Earth [67], [68].

The AMANDA (Antarctic Muon And Neutrino Detector Array) detector is continuing the idea of neutrino detection by instrumenting a large underground volume with Cherenkov light detectors, but it is the first one to use ice as detector medium. The telescope is located deep in the ice of the glacier at the Amundsen-Scott South Pole station. The idea is to detect Cherenkov light produced in the ice by highly relativistic muons and other charged particles coming from neutrino interactions. The arrival time and intensity of the light are used to reconstruct the trajectory of the charged particles and relate it to that of the original neutrino.

The detector consists of a three dimensional array of photomultiplier tubes (PMTs), arranged in 19 strings and buried between 1000 and 2350 meters below the ice surface. In the near future, the AMANDA detector will be extended to a 1 km³ detector, ICECUBE, for which most of the technology has already been tested in AMANDA. A plot of the present detector is shown in figure 4.1.

4.2 History

The first major deployment took place in the austral summer of 1993/1994 when four strings were deployed at a depth of 800 to 1000 meters. This part is called AMANDA-A. It was found that AMANDA-A was deployed at a depth where a large residual population of air bubbles was situated, inducing very short scattering lengths at these depths. It was thought that these bubbles would be absent at 800 m as a result of the phase transition that occurs as the increasing pressure transforms the air bubbles into air hydrate crystal. However, due to the low temperatures at the south pole, the diffusion of air molecules into the ice crystalline structure slows down. Thus, the bubbles only completely disappear at about 1300 m. Although the data taken with the AMANDA-A detector were not very useful for track reconstruction, the detector was used for a long period as a good calorimeter.

This was followed by the deployment of four strings at a depth of between 1500 and 1980 meters in 1995-1996 (AMANDA-B4). The AMANDA-B4 detector operated some time in coincidence with the AMANDA-A detector to permit the study of vertically down-going muons. The optical modules² (OMs) of AMANDA-B4 are connected by coaxial cables to the surface to prevent influence from cross-talk (see section 7.3.2). As the coaxial cables are highly dispersive, the problem of pulse resolution has to be dealt with, e.g. 10 ns pulses are dispersed to 400 ns pulses during their transition to the surface. Another disadvantage of coaxial cables is their relative thickness, limiting the amount of cables that can be bundled together in a string.

Six strings were added around AMANDA-B4 using twisted pair cables in 1996-1997

²See section 4.3 for the definition.



Figure 4.1: Schematic view of the geometry of the AMANDA-II (see section 4.2) detector. The Eiffel Tower is shown to illustrate the scale. The AMANDA-A configuration and the AMANDA-B10 configuration are marked by the shaded cylinder at a depth of 810 m - 1000 m and 1500 m - 2000 m respectively. In the center an up-going muon track is illustrated. This figure shows how the reconstruction program (see chapter 6) interprets the signals recorded by the detector to reconstruct the muon track. Each dot represents an optical module. Hit optical modules are marked by solid circles. The size of the circles is proportional to the number of photo-electrons detected. The shade of the circles indicates the time. Light shades correspond to early times and dark shades indicate late times. The arrow indicates a first guess of the direction of the muon using the linefit (see chapter 6). On the right an optical module (see section 4.3) is enlarged.

(AMANDA-B10). These cables produce less dispersion (a 10 ns signal is now stretched to the surface to 150-200 ns) and are thinner. However, a great deal of electronic cross-talk was observed in these strings. The AMANDA-B10 detector has a total of 302 optical modules.

Three additional strings were deployed in 1997-1998 (AMANDA-B13). The deployment of these three strings is somewhat special since they lie at a depth of between 1150 m - 2350 m. This is done in order to study the optical properties above and below the detector.

During the antarctic summer of 1999-2000, a deployment of six strings completed AMANDA-II, a detector with AMANDA-B10 as core and 9 strings (placed between 1150 and 2350 meters in depth) surrounding it. A problem arose during the deployment of string 17, which caused it to finally be placed at a maximum depth of 1520 meters. It is operative and can be used for calibration. The new strings (string 11 - string 19) incorporate new transmission technologies like additional optical fiber for pulse transition. The signal is emitted from the PMT through a LED or laser diode and transmitted over the fiber to an optical receiver at the surface. The optical fibers are essentially cross-talk free. This allows also for a dispersion-free propagation, but one has to face the problem that roughly 10 % of all optical channels are damaged during the freezing of the holes. In 1999/2000 another technology using Digital Optical Modules (DOMs) was tested. These modules contain analog transient waveform digitizers (ATWDs), recording and digitizing the pulses in situ and transmitting them synchronously to the surface. This technology results in the full retention of waveform information without the need for optical fibers. However, the digitization electronics are buried with the DOMs in the ice, hence, with no possibility of repair and limited possibility of upgrade.

The complete AMANDA-II detector contains 677 OMs spread over 19 strings, which are arranged in three concentric circles and separated by 30 m - 60 m. The cylindrical instrumented volume has a diameter of 200 m and a height of 500 m. The modules on each string are separated by 10 m - 20 m, depending on the string.

The origin of the AMANDA coordinate system almost coincides with string 4. Historically, the origin of the coordinate system was defined at the position of OM 70 (OM 10 on string 4). So x=y=0 were defined as the position of string 4 at the surface, and z=0 was -1730 m with respect to the surface. More recent and accurate geometry measurements have established that this OM is actually a bit away from (0,0,0). It was decided not to change the coordinate system definition, so now OM 70 lies (1.80,-1.48,-25.90) m away from (0,0,0). The X axis is defined as grid east, the y axis is defined as grid north and the Z axis is the normal to the surface at the location (1.80,-1.48) m away from string 4, according to the latest determination of the string 4 (x,y) coordinates.

Track angles theta and phi point to the origin of the track, backwards from the direction of travel. Theta is measured from the z-axis to the vector connecting the origin to the track's starting point. Thus a track pointing straight down into the Earth has an angle theta = 0 degrees; a track pointing directly upwards has a angle theta = 180 degrees. The azimuth angle is measured counterclockwise from the x axis, with the resulting point again referring to the origin of the track. In this dissertation the data taken during 1999 have been analyzed (see section 5.2). In 1999 the AMANDA detector consisted of 13 strings. However, string 11-13 were not used under optimal conditions that year. Therefore, the AMANDA collaboration decided to analyze the 1999 data using the AMANDA-B10 configuration.

The main goal of the detector is to identify up-going muons, originated by a neutrino interaction in the ice or in the bedrock below the detector. Therefore it is important to reconstruct up-going tracks accurately so that they can be distinguished from down-going muons, which are 10^6 times more abundant at trigger level (see section 4.4) and induced by cosmic ray interactions in the atmosphere (see section 3.3).

4.3 The Optical Modules

Each optical module consists of a hemispherical 8" Hamamatsu R5912-2 photomultiplier, a 14-dynode version of the standard 12-dynode R5912 tube, mounted inside a spherical glass pressure vessel. The photocathode is in mechanical and optical contact with the sphere glass through a silicon gel (General Electric RTV6156). The whole set is often referred to as optical module (OM), as shown in figure 4.1.

The OMs are operated at a somewhat high gain of 10^9 , to make it possible to transport the electrical output pulses through more than 2 km of cable. The gain can be reduced to about 10^8 in the case of DOMs. This is due to the pulse digitization inside the DOM, which allows numeric transmission to the surface without losses. Although the gain is high, it is necessary to amplify the pulses at the surface. This will be explained in a more detailed way in section 4.4. In all OMs the electrical cable is used both to transport the high voltage to the photomultiplier and to bring the output signal to the surface. The advantage of this design is that only one single penetrator is needed on each glass sphere.

The majority of the optical modules has been deployed with their photocathodes facing down, i.e. towards the center of the Earth. These OMs are referred to as "down looking" modules. Some of the OMs have been deployed "up looking". These optical modules can be used to study the absolute and angular sensitivity of the light collection. They are 1 and 10 in string 1, 21 and 30 in string 2, 41 and 50 in string 3 and 61, 62, 70, 79, 80, 81, 83 and 85 in string 4.

Every string is installed inside a hole made in the polar ice by melting it using pressurized hot water. The drill is composed of a hose and a drill head attached to it. Water is pumped through the end of the drill at a speed of 150 liters per minute. The head is equipped with instruments that measure the drilling direction, the hole diameter and water flow. The hole diameter is about 50-60 cm and its depth is larger than 2 km. It takes about 3.5 days to complete each hole.

The period between the installation of the string and the drilling procedure is limited by the re-freezing of the water inside the hole. The whole string must be in its final position within 35-40 hours after the completion of the hole drilling. Winches are used to slowly release the main cable and the optical fibers, which are rolled in reels. Every OM is attached to the main cable using cable breakouts placed at regular distance intervals. Once all the OMs are in place, the cable is deployed faster until the string reaches the foreseen depth. The complete deployment is monitored by pressure sensors placed at the bottom and top of the string.

4.4 Surface Electronics and Trigger System

The AMANDA detector trigger can come from a variety of sources. The main trigger of AMANDA-B10 is a majority trigger. For the AMANDA-B10 1999 data set, eighteen OMs are required to fire within a trigger window of 2.2 μ s. This corresponds to a true detector trigger rate of ~ 100 Hz. Taking into account the dead-time, the trigger rate is reduced to ~ 85 Hz. The detector data taking rate is 33kB per second, corresponding to ~ 1 TB recorded in 1999. Apart from the majority trigger, the detector could also be triggered by 4 external triggers from AMANDA-A, the South Pole Air Shower Experiments SPASE-1 and SPASE-2³ [73] and the Cherenkov telescope GASP⁴ [74] (the latter pointing in the direction of AMANDA-B10).

The data acquisition (DAQ) system, located on the surface, is responsible for reading out event information and storing it onto a disk. An event is resulting from light produced in or nearby the detector and producing hits in the OMs, which give a series of pulses. The data recorded consists of the time at which the pulse gets below a constant threshold level, called the leading edge (LE) and when it gets back to that level, called the trailing edge (TE). This allows for the calculation of the time over threshold (TOT). After a trigger is formed, the leading edge time and the trailing edge time of up to eight pulses for each OM will be recorded in a time window $\sim 22 \ \mu s$ before and $\sim 10 \ \mu s$ after the trigger time by Time-to-Digital Converters (TDCs).

The DAQ also records the amplitude of the pulses arriving from the OMs during a time window starting 2000 ns before and ending 2270 ns after the recorded trigger time. The amplitude of the pulse is measured by a voltage sensitive Analog-to-Digital Converter (ADC) which measures the largest amplitude reached during the time the gate is opened. So in case several photo-electrons are produced, the information will consist of as many (max 8) leading and trailing edges as there are resolved pulses and the largest amplitude of them all. In the analysis it is assumed that each hit inside the gate may have caused the measured amplitude. The absolute event time is obtained from a Global Positioning System (GPS) module.

Figure 4.2 shows the procedure for trigger formation and the read out of ADC and TDC. The SWedish AMPlifiers (SWAMPs) decouple the OM signal from the high voltage (around 1750 V) and amplify it. Copies of the signal that are amplified by a factor of 100 are provided to discriminators, while 20 times amplified signals are fed into the ADCs. The latter signal is delayed by 2 μ s. Discriminator outputs are fed into the TDCs and into the Digital Multiplicity Adder (DMAD), which produces the multiplicity trigger.

³SPASE-1 and SPASE-2 are two 'South Pole Air Shower Experiments' based at the surface of the South Pole glacier. They are respectively at a zenith angle of 27° and 12° with respect to AMANDA.

⁴GASP is a Cherenkov telescope that has been installed at the surface of the antarctic glacier near the South Pole.



Figure 4.2: The surface electronics of the AMANDA-B10 detector: amplifier, discriminator, trigger unit, ADC, TDC and DAQ. Figure from [174].

The trigger logic is an OR of the multiplicity trigger and the triggers from AMANDA-A, SPASE-1, SPASE-2 and GASP. As soon as a trigger is received, the formation of new triggers is stopped until all data have been read out and the system has been reset.

A separate DAQ is available for supernova monitoring. Scalers monitor the trigger rate of every individual OM for excesses in the scale of ~ 1 s. The detection of a supernova could manifest itself in the increase in the OM counting rate as a consequence of the multiple low-energy neutrino interactions close to every OM.

The AMANDA-II detector contains a Transient Waveform Recorder System (TWR) [175], which is designed to extend the integrated dynamic range of each OM in AMANDA-II by approximately a factor of 100, relative to the standard AMANDA DAQ. The TWR system can handle the normal muon trigger rates with virtually no dead time. The added capability should improve the energy resolution and background rejection for high energy phenomena and it should also help to improve the angular resolution of higher energy muons (muons that cross the array with an excess of 100 TeV).

4.5 Calibration

The analysis presented in this dissertation fully depends on the data taken by the AMANDA detector. This implies that the calibration of the detector is the first step in the analysis, just like in any other experiment. The calibration of the detector corresponds to the

determination of the position of every OM and the different delays introduced by the cables transmitting the signals to the surface. Special position measurement techniques are required because the optical modules are no longer accessible once they are being deployed⁵.

4.5.1 Calibration Tools

Several light sources have been deployed in the ice in order to calibrate the detector. An example of these light sources are Nitrogen lasers. Four powerful pulsed nitrogen lasers have been deployed in the ice at different depths. The lasers operate at a wavelength of 337 nm and inject up to 10^{12} photons per pulse at a rate of the order of 10 Hz. Other examples of light sources installed in the ice are DC Halogen lamps and Light Emitting Diodes (LEDs). Three lamps have been provided so far, one producing 10^{18} photons per second and the two others 10^{14} photons per second. Approximately 70 LEDs have been installed in the optical modules of which most have been installed on strings 11 - 19.

Another important calibration tool is operating on the surface of the polar ice cap. It is the pulsed Nd:YAG laser which sends light at 532 nm through optical fibers to nylon diffuser balls. These light diffusers have been installed just below every even (odd) numbered⁶ optical module. The laser, which is able to deposit up to 10^9 photons per pulse in the ice at a frequency of 500 Hz, has turned out to be the most efficient tool to be used for detector calibration, thanks to its capability of depositing a high amount of photons close to the different optical modules.

4.5.2 Time Calibration

The time calibration is done by sending light through the optical fiber to the sphere placed in the neighborhood of a given OM and taking data with the same OM. Considering the scattering length value of about 30 m, it is safe to assume that all photons, traveling a distance of ~ O(1) m between the light emitting sphere and the OM, have not scattered in the ice. The experimentally measured leading edges LE_{RAW} (ns) (see section 4.4) contain various time-off sets, which are different for each OM. The so-called T_0 calibration, or time calibration, determines these time offsets in order to reconstruct the true arrival time of the photons LE_{CAL} (ns), using the following formula:

$$LE_{CAL} = LE_{RAW} - T_0 - \frac{\alpha}{\sqrt{ADC}}$$
(4.1)

where T_0 (ns) and α (ns $\cdot \sqrt{mV}$) are the two correction constants for the OM being calibrated and ADC refers to the peak ADC value of the measured signal pulse (the height of the pulse in mV, see also section 4.4).

The offset T_0 is defined as:

⁵During the deployment the position of the strings is controlled, but the data are not sufficiently accurate. ⁶The position of installation (even or odd) depends on the string.

$$T_0 = T_{PMT} + T_{cable} + T_{surface} - T_{norm} \tag{4.2}$$

where T_{PMT} is the PMT transit time⁷, T_{cable} is the propagation time of the pulse along the cable, $T_{surface}$ are timing delays in the surface electronics and T_{norm} is an arbitrary normalization constant. Since only the relative time offsets between the PMTs are needed for the T_0 calibration, one usually defines the T_0 for one reference OM to be 0 ns and calculates the other T_0 's relative to this PMT. This has the advantage that different calibration sets can be compared easier.

In practice the problem is solved statistically. An example can be seen in figure 4.3. The leading edge time is plotted as a function of the inverse of the square root of the ADC measurement for every hit in the given OM. Then a fit is done using the following function:

$$LE_{RAW} = \frac{\alpha}{\sqrt{ADC}} + C \tag{4.3}$$

with α and $C = LE_{CAL} + T_0$ as the two constants to be determined. The constant α is easily determined from the slope of the fit, while C can be calculated from the extrapolation of the fit.

Another important quantity in the determination of T_0 is the measurement of the period, T_{total} , between the firing of the laser at the surface and the arrival of the pulse, coming from the OM, at the surface:

$$T_{total} = T_{fiber} + T_{PMT} + T_{cable} + T_{surface}$$

$$\tag{4.4}$$

The optical fiber transit time, T_{fiber} , has previously been measured using an OTDR (Optical Time Domain Reflectometry) device and is known for every individual OM. All elements to determine T_0 are now known. Given the experimentally measured leading edge LE_{RAW} and signal peak ADC, the true arrival time of the photons LE_{CAL} can be calculated.

The constant α is the correction for a known effect in signal processing called 'amplitude time walk'. A large pulse will be seen as arriving earlier than a small pulse, even if they were actually produced at the same time. This problem is due to the fact that a constant level discriminator is used. Figure 4.4 shows how the recorded time is modified by the amplitude of a pulse.

Typical α values are 600 ns $\sqrt{\text{mV}}$ for the optical modules connected to the surface electronics via coaxial cables and 250 ns $\sqrt{\text{mV}}$ for those installed along twisted pair cables. The range of T_0 's in AMANDA-B10 is 0 ns to 3000 ns. The time resolution of this calibration method is ~ 5 ns. This result has been obtained by comparing the time calibration parameter values calculated over several years.

An independent alternative time calibration procedure is based on the iterative reconstruction of experimentally measured down-going atmospheric muons. This method

⁷This transit time depends on the high voltage.





Figure 4.3: The leading edge times (ns) as function of the inverse of the square root of the signal amplitude ADC (mV)^{-1/2} for the calibration data of OM 5 on string 4. The fitted line provides the calibration constants α and C for this particular optical module. The distribution of the corrected leading edges (ns) is also shown.



Figure 4.4: The experimentally determined leading edge of a pulse LE_{RAW} has to be corrected according to its amplitude. This is necessary in case a constant level discriminator is used in order to avoid time walk. Pulse B passes the discriminator level later than pulse A, although in reality, they were produced at the same time.

provides T_0 -values that are in agreement with those obtained with the method explained above to about ~ 5 ns. Studies of simulated down-going muons also support this estimation of the time resolution. This method will probably be the main time calibration procedure in the future since it is much less time consuming and can be done at any time during the year.

4.5.3 Geometry Calibration

The relative location of the OMs within the array is determined by using the same setup as for the time calibration. Some OMs are equipped with a diffuse nylon sphere connected to the surface by an optical fiber. A dye laser at the surface generates light and transmits this light to the sphere. The relative positions of the OMs, which are illuminated in the neighboring strings, can be calibrated using this light. The pulse leading edges, signal amplitudes ADC and time-over-threshold values are measured. Assuming that some of these pulses correspond to direct hits, i.e. photons that arrived to the OMs without scattering in the ice, the distance between the modules can be estimated. The results coming from multiple source locations combined with the knowledge of the exact distance between OMs along a given string⁸, provides a precise determination of the horizontal distance as well as the relative depth shift between the strings. Relative positions of the OMs in the detector are determined with an accuracy of ~ 1 m.

The drilling data are used to define a reference system in order to know the relative positions of the OMs to fixed points on the ice surface. Data corresponding to drill head path length, orientation and local Earth's magnetic field have been taken every 10 cm

⁸OMs on stings 1-4 are separated by 20 m and OMs on strings 5-10 are installed every 10 m.

during the drilling of the holes. GPS measurements for each hole at the surface gives additional information to obtain the absolute horizontal position. The absolute depth of the array is determined with pressure sensors deployed with the strings and with the logs from the deployment. The estimated accuracy of the absolute position of the detector is ~ 2 m.

Chapter 5

Data Samples Analyzed

5.1 Introduction

In the analysis described in this work several samples of experimental and simulated data are used. The data samples can be divided into 4 categories. The recorded data events by the AMANDA detector are called "the 99 experimental data". The events looked for in this analysis are induced by the annihilation of neutralinos in the center of the Earth. These events will be referred to as the "WIMP signal events". In this chapter the main characteristics of these data samples are discussed.

The most abundant background events for this analysis are the down-going cosmic ray induced muons, which are referred to as "atmospheric muon events". The cosmic ray induced atmospheric neutrinos are much less numerous, but nonetheless very important since they can reach the detector from all directions. These events are called "atmospheric neutrino events". Note that only atmospheric muon-neutrinos are relevant to the analysis presented in this dissertation. The electron- and tau-neutrinos are less important in this work. The characteristics of these processes are described in chapter 3.

The simulation of the events is performed in several steps. The first step is the generation and the tracking of the particles, followed by the propagation of the Cherenkov light induced by these particles and finally the detector response to these Cherenkov photons is simulated. Each of these steps is described in this chapter. The difficulties that come with simulating the events, mainly caused by the incomplete description of the ice properties, are discussed as well.

5.2 Experimental Data

The experimental data used in this dissertation were collected by AMANDA-B10 from February 1999 to November 1999. The effective live time of the detector is reduced by selecting only runs for which the detector was running stably. This selection method is explained in more detail in section 7.3. Events in coincidence with AMANDA-A or the SPASE arrays were eliminated from the data sample because these events are produced

by down-going atmospheric muons. After selecting good runs and removing triggers in coincidence with other experiments, a total of $1.3 \cdot 10^9$ AMANDA-B10 triggers were recorded. The detector triggered a readout when at least 18 optical modules were hit within a time window of 2.2 μ s (see section 4.4). The preprocessing to level 2 (see also section 7.4) was done according to collaboration agreed methods and reduced the number of triggered events by a factor of ~110. The full chain of analysis cuts presented in this work reduces the data set further to a sample of O(1)-O(10) events, depending on the specific sub-analysis. This means that the number of triggered events is being reduced by a factor of ~ 10⁸ after all cuts have been applied. A complete description of the analysis is given in chapters 7 and 8.

In 1999 the AMANDA detector consisted of 13 strings (see chapter 4). However, strings 11-13 were not used under optimal conditions that year. Therefore the collaboration decided not to use these strings in the analyzes of the 1999 data. Instead, these strings were exclusively used for detector studies. In the analysis presented in this dissertation, the detector is limited to 10 strings, corresponding to 302 optical modules.

The effective live time of an experiment is the time during which the detector has been taking data corrected for the dead time of the detector. The effective live time of the recorded 1999 data set can be determined once all bad data taking runs have been removed. The files that have been produced by the AMANDA monitoring system during the data taking period of 1999 have been used to calculate the effective live time (see also section 7.3). The time difference distribution of each monitoring file has been fitted with an exponential:

$$exp\frac{\Delta t}{\tau}$$
. (5.1)

The true rate of the events can then be calculated as:

$$R_{true} = \frac{1}{\tau} \tag{5.2}$$

The measured rate of events, including the dead time, is calculated as:

$$R_{exp} = \frac{N_{file}}{t_{file}}$$
(5.3)

where N_{file} stands for the number of events in the monitoring file and t_{file} is the time span of the file.

The effective live time of the whole data taking period can be estimated as:

$$t_{effective} = \sum_{allgoodruns} t_{file} \times \frac{R_{exp}}{R_{true}}$$
(5.4)

The live time of the analyzed 1999 data set was calculated to be 221.4 days, corresponding to $1.3 \cdot 10^9$ AMANDA-B10 triggers. This effective live time is further reduced to 187.0 days or $1.1 \cdot 10^9$ triggered events taking into account the fact that the sub-sample

of 34.4 days, that has been used to tune the analysis cuts, can not be used for the final analysis results. This is necessary to respect blindness (see section 7.2).

5.3 Data Simulation of the Neutralino Signal

In chapter 2 the possibility of indirect neutralino detection has been discussed. It has been assumed that the dark matter in the halo consists, at least partly, of neutralinos. These particles have a non-negligible probability of scattering off particles of normal matter and lose kinetic energy. If this is the case, neutralinos can become gravitationally trapped inside heavy objects, like the Earth. They will sink towards the center of the Earth, where they will accumulate. Pair-wise annihilation of neutralinos can produce particles that decay into neutrinos. These neutrinos can be measured using large Cherenkov telescopes installed close to the surface of the Earth.

The neutrino flux will depend on the annihilation rate of the neutralinos, their relic density and the capture rate for the selected body. The evolution equation for N gravitationally captured neutralinos inside a heavy object is given by [29]:

$$\frac{dN}{dt} = C - C_A N^2 - C_E N \tag{5.5}$$

where C describes the neutralino capture, the second term stands for the neutralino annihilation rate $\Gamma_A = \frac{1}{2}C_A N^2$ and the third term is the neutralino evaporation, which is negligible for neutralino masses larger than 5 GeV [119].

The annihilation rate, Γ_A , can be expressed as:

$$\Gamma_A = \frac{C}{2} tanh^2 \frac{t}{\tau_A} \tag{5.6}$$

where t is the age of the object (about $4.5 \cdot 10^9$ years for the Earth) and $\tau_A = (CC_A)^{-1/2}$ is a measure of how fast capture and annihilation will come into equilibrium. The equilibrium time scale τ_A depends on the annihilation cross-section, the mass of the neutralino and the volume of the object where the neutralinos are captured. The ratio t/τ_A tells if an equilibrium density of neutralinos has been reached yet or not. For most super-symmetric models, equilibrium is not yet reached in the Earth.

The capture rate depends on the local halo mass density, the velocity dispersion of the neutralinos, the escape velocity from the Earth, the neutralino-nucleon cross-section and the body composition.

As discussed in chapter 2, the annihilation of two neutralinos results in the production of standard model particles. The most significant channels from the point of view of the resulting muon flux in the neutrino telescope are:

$$\chi\chi \to c\bar{c}, b\bar{b}, t\bar{t}, \tau^+\tau^-, W^+W^-, Z^0Z^0.$$
 (5.7)

The neutrino flux resulting from this annihilation will be different from each of these channels. Gauge bosons and τ -leptons can decay into neutrinos directly, whereas the neutrino flux from quark channels will be caused by their decay or their interaction with heavy hadrons.

The contribution of some other channels is negligible. Lighter quarks have a very small annihilation cross-section while light leptons will be absorbed in the celestial medium well before the decay into neutrinos can occur.

The neutrino energy spectrum will also be different for each annihilation channel. Since the AMANDA detector has an energy dependent efficiency, some annihilation channels will be easier to observe than others. The energy threshold of $\sim 10 - 30$ GeV of the AMANDA detector reduces the detection efficiency for the low mass neutralinos considerably. In chapter 8 the detection efficiency will be described in more detail.

In [29], a Monte Carlo study has been performed of the neutrino fluxes coming from the annihilations of neutralinos in the center of the Earth. This has been done for different neutralino masses and all interesting annihilation channels as mentioned in equation 5.7.

Two extreme annihilation channels, chosen to give a hard and soft neutrino spectrum, have been investigated in this dissertation. In this way a realistic estimate of the number of neutralino induced muons from any model is obtained. The channels are:

$$\chi\chi \to W^+W^- \tag{5.8}$$

and

$$\chi\chi \to bb$$
 (5.9)

These channels are referred to as the "hard" and "soft" channel respectively. Both channels have been simulated for 7 different neutralino masses: 50 GeV^1 , 100 GeV, 250 GeV, 500 GeV, 1000 GeV, 3000 GeV and 5000 GeV. These masses cover the mass range predicted by the different models as discussed in chapter 2.

Each simulated sample of muon-neutrinos induced by the annihilation of neutralinos in the center of the Earth consists of 500000 events randomly spread over the generation volume, which is a predefined cylindrical volume around the detector in which muonneutrinos coming from the annihilation of neutralinos in the center of the Earth are generated. The dimensions of the generated volume are defined in such a way that any muon track originating outside this volume can never reach, and therefore never trigger, the detector. This generation volume is defined differently for each neutralino mass since both the neutrino-nucleon interaction cross-section and the muon range are proportional to the muon-neutrino energy². In table 5.1, the height and the radius of the cylindrical generated volume, the generated volume itself and the number of triggered events for the different neutralino masses are shown.

¹In this case, the hard channel is $\chi\chi \to \tau^+\tau^-$ and the soft channel is $\chi\chi \to c\bar{c}$.

²In principle the generation volume of the 5 TeV neutralinos could have been used for all other neutralino Monte Carlo samples as well. However, this would not be very efficient with respect to the limited CPU time.



Figure 5.1: The energy of the triggered muons induced by the annihilation of neutralinos in the center of the Earth for different neutralino masses and for both the hard and soft channel. Note that the number of triggered events of the hard channel has been normalized to the number of triggered events of the soft channel for each neutralino mass.

WIMP mass	annihilation	Height of generated	Radius of generated	Generated volume (m ³)	Number of triggered
	channel	volume (m)	volume (m)		WIMPS
5000 GeV	hard	7600	380	3447709442	17173
5000 GeV	soft	7600	380	3447709442	4663
3000 GeV	hard	6150	290	1624878844	24924
3000 GeV	soft	6150	290	1624878844	7113
1000 GeV	hard	3500	260	743300822	22422
1000 GeV	soft	3500	260	743300822	6778
500 GeV	hard	2350	240	425245982	21040
500 GeV	soft	2350	240	425245982	6334
250 GeV	hard	1550	200	194778745	23032
250 GeV	soft	1550	200	194778745	6725
100 GeV	hard	950	160	76403533	16372
100 GeV	soft	950	160	76403533	4334
50 GeV	hard	800	140	49260173	4244
50 GeV	soft	800	140	49260173	965

Table 5.1: The height and the radius of the cylindrical generated volume, the generated volume itself and the number of triggered neutralino events are given for the different neutralino masses and annihilation channels.

Figure 5.1 illustrates the energy spectra of the triggered muon tracks induced by the annihilation of neutralinos in the center of the Earth for both the hard and soft annihilation channel and for several neutralino masses.



Figure 5.2: The angular distribution of the reconstructed muon tracks (fit 8, see chapter 6) coming from the annihilation of neutralinos in the center of the Earth. The neutralino masses and channels used are given in the plot.

Figure 5.2 shows that the angular spectra of reconstructed muon tracks coming from annihilations of heavy neutralinos are more peaked to the center of the Earth than the spectra with their origin in light neutralinos. There are mainly two reasons why models predicting heavy neutralinos show more centrally concentrated density distributions than models predicting light neutralinos.

When heavy neutralinos get gravitationally trapped, they will accumulate more closely to the center of the Earth than light neutralinos. In [29] the number density, N, is given as function of the distance, d, from the center of the Earth:

$$N(d) = N(0)exp(-d^2/2r_{\chi}^2)$$
(5.10)

with

$$r_{\chi} \simeq \frac{0.56 \cdot R_{\bigoplus}}{\sqrt{m_{\chi}}} \tag{5.11}$$

where m_{χ} is the mass of the neutralino (in GeV) and R_{\oplus} is the radius of the Earth. This explains the fact that heavy neutralinos annihilate more closely to the center of the Earth than light neutralinos.

The second reason is related to the neutrino-nucleon scattering angle (see also chapter 3). The higher the neutrino energy, the smaller this deviation angle. This results in muon fluxes more collimated towards the center for hard neutrino spectra than for soft ones.

Figure 5.3 shows the x-component versus the y-component of the interaction vertex for several "soft channel" neutralinos. For the low energy muons, e.g. muons coming from the annihilation of 100 GeV neutralinos, the vertex position is closely related to the location of the outer strings. This effect is clearly visible despite the larger spread of zenith angles at lower energies. The conclusion is that for vertical tracks at these energies, the spacing of optical modules on the inner four strings (20 m) is too large for these muons to trigger efficiently. The inner part is not densely enough equipped with photo-multiplier tubes for lower energies.

At first sight, one would assume that the inner (fiducial) part of the detector is the optimum place to search for low energy events. For geometrical reasons, it also has the best shielding against down-going muons. However, as is shown in figure 5.3, in this case a fiducial cut would make us blind for low energies. This could be a good argument to deploy extra strings in the middle of the detector with a much denser optical-module population.

Figure 5.4 shows some of the experimentally accessible observables: the y-component of the center of gravity of hits in the event $(C.O.G_{\cdot y})$ versus its x-component $(C.O.G_{\cdot x})$. The center of gravity of hits is defined as the average position of all hits in the event. Also this plot shows that the muons are dominantly detected by the outer strings, which have the densest population of optical modules. An analysis making use of a shielded fiducial volume is thus not efficient.

5.4 Simulation Tools

When analyzing experimental data it is necessary to compare these data to the expectation, which is in general, not calculable through analytical or numerical means. Rather, a statistical simulation of the relevant physical processes is needed. The simulations are based on Monte Carlo techniques. The simulated events will therefore often be referred to as Monte Carlo simulations or Monte Carlo (MC).



Figure 5.3: The X-component versus the Y-component of the neutrino-nucleon interaction vertex for the "soft channel" neutralinos. The thick dark points with numbers visualize the AMANDA string positions. The mass of the annihilating neutralinos is given inside the plot.



Figure 5.4: The Y-component versus the X-component of the center of gravity of hits for the "hard channel" neutralinos. The mass of the annihilating neutralinos is written inside the plot.

The simulation of the atmospheric muon events, atmospheric neutrino events and the WIMP signal events can be divided into different steps. The initial part is the generation of the cosmic ray muon and neutrino events and the neutrinos coming from the annihilation of the neutralinos. The next step is the propagation of these particles through the ice or rock to the detector. Finally, the detector response is simulated.

5.4.1 Event Generation

The generation of the atmospheric muon events is based on a given flux of primary cosmic rays. The generator simulates the interactions of the primaries with the Earth or its atmosphere and calculates the number of muons being produced. The spectrum of the primary particles, which are cosmic rays, is taken from other experiments. The generator that has been used in this dissertation to produce atmospheric muon events is called CORSIKA [120], [121].

CORSIKA is the standard program for the simulation of air showers in this kind of experiments. CORSIKA generates protons and heavier nuclei at the top of the atmosphere and propagates them down to the Earth's surface. CORSIKA is flexible enough to use various high- or low-energy interaction models. QGSJET is used by AMANDA for high-energy interactions while Gheisa is used for the low-energy interactions. The low-energy regime is defined to be below 70 GeV in CORSIKA which makes the choice for the low-energy interaction model irrelevant since AMANDA has an energy cut-off at ~ 800 GeV at the surface of the Earth. The cosmic ray spectrum was assumed to be isotropic with a spectral index of $\gamma = 2.73$ and energies between $8 \cdot 10^2$ to $1 \cdot 10^9$ GeVnucleon⁻¹.

Simulating air showers requires an enormous amount of computer resources. Since the flux of cosmic ray primaries is isotropic and muons with energies above 600 GeV are deflected less than 1 degree, an over-sampling technique has been applied. This means that an event, generated by CORSIKA, is used multiple times by randomizing the azimuth angle and horizontal coordinates with respect to the detector. An over-sampling factor of 100 has been used for this work. It has been proven in the past that over-sampling does not change the simulation results at any cut level. In total $20.4 \cdot 10^6$ AMANDA-B10 triggers have been simulated by CORSIKA, corresponding to a live time of 5.6 days.

Muons from atmospheric neutrino events with energies between 10 GeV and 10^8 GeV are generated using NUSIM [122], which is based on the theoretical prediction of the atmospheric neutrino flux performed by Lipari [123]. The events have been simulated in the zenith angular range of 80 to 180 degrees (i.e. no down-going atmospheric neutrinos, see chapter 4). NUSIM does not only generate events, but also propagates the neutrinos through the Earth and simulates their interactions with nucleons. The neutrino propagation takes the density profile of the Earth as given by the 'Preliminary Reference Earth Model' [127] into account, including the hadronic shower. This means that NUSIM also considers neutrinos that interact in the bedrock below the detector before they reach the ice. The neutrino interaction cross sections are taken from [124] and the MRSG parton distribution functions, described in [125] and [126], are applied.

NUSIM incorporates zenith angular and energy importance sampling. This means

that the same generated events can describe multiple arbitrary energy and zenith angular spectra by applying the appropriate weights. The concept of importance sampling is explained in more detail in [128], [129].

For the analysis presented in this work, $2 \cdot 10^7$ atmospheric neutrinos (muon neutrinos and anti-muon neutrinos) have been generated. A total of ~ 900000 of these atmospheric neutrinos resulted in muons that traveled in the direction of the detector and passed the level 2 criteria (see section 7.4).

The simulation of the annihilation of neutralinos and the decay or fragmentation of the produced particles, which give the neutrino flux, comes from [130]. The PYTHIA [131] program is used for the simulation of the decays and hadronizations of the particles produced in the annihilations. These simulations also include the neutrino charged current interaction. The muons generated with this program have been treated in a similar way as the atmospheric muons and the neutrino induced muons.

5.4.2 Muon Propagation

Muons from both neutrinos and cosmic rays are propagated through the rock below or the ice surrounding the detector using the program "Muon Monte Carlo (MMC)", a new high-precision tool for muon propagation through matter [132]. This program is capable of propagating muons by calculating the muon energy losses. The muon looses its energy via ionization of the ice, bremsstrahlung, the production of δ -electrons, muon-nucleus interactions and e^+e^- or $\mu^+\mu^-$ pair production (see also chapter 3). The energy loss due to the Cherenkov light, that is produced by the muon that propagates through the ice with a speed higher than the speed of light in ice, is relatively small.

MMC calculates the energy losses of muons that have energies from 105.7 MeV to 10^{11} GeV. As the simulation of these energy losses is CPU time consuming, the propagation process is split up in two parts. When the muon is far away from the detector, only average muon energy losses are calculated. The energy loss due to the light produced from secondaries is less important as this light will be absorbed in the Earth before reaching the detector. When the muon enters the cylindrical volume of 800 m in height and 400 m in radius defined around the detector, the so-called active volume, detailed information about the energy loss processes - including fluctuations - is calculated. MMC uses the latest muon interaction cross-sections available at this time [133]. The calculation of the muon's energy loss as it travels through ice is valid to within 1%.

5.4.3 Photon Propagation

All muon energy loss processes lead to the production of photons. However, the photon propagation simulation is not performed on an event-by-event basis. Instead the program PTD [134] is used to generate multi-dimensional tables of the probability density of an OM of observing a signal. These tables contain the probability that a PMT receives a signal from a muon energy loss process depending on the process itself, the distance to the light source, the time delay of the observed signal, the amount of energy loss and the

relative orientation of the OM with respect to the light source. PTD takes the following into account: the absorption by the pressure vessel glass, the absorption by the gel in the OM, the quantum efficiency of the PMT (see chapter 9 for definition), the angular response of the OM and the optical properties of the ice as described in section 5.4.5. However, the depth dependence of the optical properties of the ice can not be simulated by PTD intrinsically. This would require two additional dimensions to the PTD tables: the PMT depth and the depth of the energy loss vertex, which would make the PTD tables too large. Instead, all photons registered by an OM are assumed to travel only through ice that has a scattering coefficient close to that of the environment of the OM. Variations in the optical properties of the ice are accounted for by using different tables for different layers of ice.

Recently, a new program, called photonics [135], was developed by the AMANDA collaboration. Photonics has the advantage of being able to deal more accurately with the depth dependence of the ice properties than PTD. However, the production of photonics tables is very time-consuming. Unfortunately, the photonics tables were not yet available at the time the analysis, presented in this dissertation, was developed.

5.4.4 Detector Response

The program AMASIM (see [136], [137] and [138]) simulates the response of the detector to incoming photons, starting with the PMTs and ending with the DAQ system. AMASIM, which has been completely developed within the AMANDA collaboration, seeks the PMT hit probabilities in the tables produced by PTD. Saturation and afterpulsing are some of the effects that are taken into account for the PMT response simulation. Even the influence of the type of cable - co-axial or twisted pair cable - on the signal at the surface has been implemented in the software. The different trigger windows, the discriminator thresholds, the SWAMP gains, the TDCs, the peak sensing ADCs, the trigger logic and the different pulse shapes for the prompt and the delayed output of the SWAMPS are taken into account as well. A complete list of all detector parameters taken into account would be too long to draw up here. Despite the enormous effort that has already been invested in the development of the detector simulation, our understanding of the detector is still incomplete. More research in this field is required.

One of the main uncertainties (see also chapter 9) regarding the results obtained in this work comes from the uncertainties regarding the absolute and angular dependent acceptance of the AMANDA-B10 optical modules. The uncertainty regarding the acceptance is strongly related to the uncertainty in the muon propagation, in the description of the optical parameters of the re-frozen ice in the AMANDA drill holes and the sensitivity of the optical module itself. In [140] and [141] well-reconstructed down-going atmospheric muons have been used to measure the absolute and angular acceptance of the AMANDA optical modules. Moreover, comparisons between up-looking and down-looking optical modules have been performed. The result of this study is a correction factor for the optical properties of the ice immediately surrounding the OM and for the OM sensitivity. This correction changes the angular sensitivity of the modules, especially in the region that is sensitive to neutrino-induced events. This study will be further examined in the next

section.

5.4.5 Optical Properties of the Ice and Implementation in the MC

The AMANDA detector has been built in the ice of the South Pole glacier, as described in chapter 4. The ice is thus the only interaction medium used to detect high energetic neutrinos. The performance of the AMANDA detector critically depends on the optical properties of the ice that surrounds the detector. The photons are scattered and absorbed in the ice, affecting the timing and the number of photons that reach the optical modules respectively. Numerous studies using both in-situ light sources and atmospheric muons have been conducted to determine the ice properties. In [142] an overview is given of the ice optical properties between 140 m and 2300 m in depth at the South Pole.

The AMANDA collaboration uses the following parameters to approximate the optical properties of the ice: the scattering length λ_s (or the scattering coefficient $b = \frac{1}{\lambda_s}$), the absorption length λ_a (or the absorption coefficient $a = \frac{1}{\lambda_a}$) and the average of the cosine of the scattering angle $\tau_s = \langle \cos\theta \rangle$. It is customary to define the effective scattering length λ_s^{eff} as follows:

$$\lambda_s^{eff} = \frac{\lambda_s}{1 - \tau_s} \tag{5.12}$$

and its corresponding coefficient b_e as:

$$b_e = \frac{1}{\lambda_s^{eff}}.$$
(5.13)

The larger the effective scattering length is, the less photons will be delayed on their way from the emission point to the OM. The effective scattering length describes the following fact: small delays of the photons are obtained when there is few scattering and when the average scattering angle is small.

There are three agents that cause light to scatter or to be absorbed in ice: ice itself, air bubbles trapped in the ice and the insoluble impurities (dust) in the ice. The intrinsic absorption of ice is a result of its molecular and crystalline properties. Air bubbles do not contribute to the absorption in a significant way, but they can have a dramatic impact on scattering. Scattering due to air bubbles is independent of wavelength, but is directly related to the density of the bubbles and the bubble radius. The bubble radius decreases as the depth increases, due to the augmentation of the pressure with depth. Between \sim 400 m and \sim 1300 m of depth the air bubbles undergo a phase transition into air hydrate crystals, which have a refraction index that differs by no more than 0.4% from that of ice. This means that their contribution to scattering is negligible. The air bubbles do not completely disappear until \sim 1300 m of depth since the phase transition is significantly slowed down by low ice temperatures. The unexpected presence of air bubbles at the depth of AMANDA-A made it impossible to reconstruct muon directions.

An additional problem is caused by the presence of air bubbles in the re-frozen water holes in which the AMANDA optical modules have been deployed. During the analysis of AMANDA-B4 (1996) data (see also [143] and [144]) it has been suspected, e.g. due to the absence of a strong difference in hit rates between up- and down-looking OMs, that the re-frozen ice holes are filled with bubbles, which further modifies the optical ice model. This has been verified using a TV camera [145] and corresponding laboratory experiments [146].

A simulation of the effect of hole ice bubbles was carried out in [147]. It was found that hole-ice bubbles mostly affect the angular efficiency, while the timing is almost unaffected (except for the effects due to the changed angular efficiency). In a simplified picture one can think of the following model: in the forward direction the OM sees less light since photons with a direction towards the PMT are scattered away, the direct photon beam is being dispersed. From the backward direction photons which pass the PMT may be scattered back by bubbles just in front of the cathode to hit the PMT from its sensitive side. In the case of backward illumination, bubbles thus act like a little "mirror" below the photo-cathode [148].

Another point that must be taken into account is that the bubbles are probably not distributed in a homogeneous way inside the re-frozen hole. One has to assume a radial profile with more bubbles in the center as indicated by [146]. During refreeze, bubbles may accumulate below OMs leading to a larger density in front of the cathode of downlooking OMs. In [140], the necessary hole-ice correction using experimental muon data has been measured, based on a purely empirically approach.

The density of the impurities in the ice is correlated to the climatological conditions in the past, such as ice ages³. These climatological events have left layers of impurities in the form of dust, soot, ... Dust grains are the biggest contributors to scattering and absorption in the ice below 1400 meters.

The depth dependency of the scattering coefficient is shown in figure 5.5, as well as the fitted curves corresponding to the hydrostatic compression of air bubbles and the transition of bubbles into air hydrate crystals.

Figure 5.6 shows the absorption and effective scattering coefficient as function of the wavelength for 1690 m and 1760 m of depth (see also chapter 4).

The absorption and effective scattering coefficient are both measured using the same data set used to calibrate the detector geometry. The arrival time distribution of scattered hits and the number of hits are measured as function of the distance to the original light output. The results are compared to Monte Carlo simulations for various combinations of values for a and b_e . The combination of a and b_e that results in a Monte Carlo that agrees best with experimental data is taken as the best approximation of a and b_e . The depth dependency is determined by restricting the analysis to modules within certain depth layers. The wavelength dependency can be obtained by using many different laser/LED wavelengths for these measurements.

The implementation of the ice optical properties in the Monte Carlo introduces systematic uncertainties, as will be described in more detail in chapter 9. As discussed in section 5.4.3, the photon scattering and absorption are simulated by PTD. Several approx-

³AMANDA-B10 has been built in ice that is 25000 - 50000 years old.



Figure 5.5: The scattering coefficient *b* as function of depth in the ice. The results for the shallowest depths (140 m - 190 m) are obtained from measurements of the dimensions of the air bubbles inside ice core samples using a microscope [142]. The dashed curve illustrates the hydrostatic compression with constant density of air bubbles. The solid curve is the calculated scattering coefficient from residual air bubbles [149]. The data between 800 m and 1000 m were taken with a laser working at a wavelength of 515 ± 15 nm [150]. Data (dots) for depths greater than 1200 m were taken with a laser working at a wavelength of 532 nm [142]. Figure is taken from [142].



Figure 5.6: Absorption (lines on the bottom) and effective scattering (lines on the top) coefficients at 1690 m and 1760 m of depth as function of wavelength. The absorption curves are fits from the He and Price theory [151]. The data were taken with various in-situ light sources: the Extreme Ultraviolet module (EUV), working at ~ 310 nm, the Rainbow Module (RM) with variable wavelength and the Nd:YAG laser working at 532 nm. For $\lambda < 450$ nm the absorption is dominated by the impurities (dust) in the ice, for $\lambda > 450$ nm the absorption is dominated by intrinsic ice properties. Scattering is dominated by impurities for all wavelengths. Figure is taken from [142].

imations have been made when implementing the ice properties in PTD. The ice structure is assumed to be divided into layers of homogeneous ice, i.e. each OM sees only one sheet of ice and different OMs see different ice sheets. Furthermore, the wavelength-dependent absorption length and scattering length⁴ have been approximated.

However, these approximations appear to be insufficiently accurate. As a result the Monte Carlo does not agree well with experimental data, e.g. there is a discrepancy in the hit multiplicity distribution for down-going muons, due to the underestimation of the absorption in the simulation, resulting in a larger number of late photons to be observed in the Monte Carlo than in data. The Muon Absorption Model (MAM), takes care of this discrepancy by adjusting the absorption length such as to fit the observed hit multiplicity distribution. The newly-found absorption length is then used for the implementation of the MAM ice model in PTD. It has turned out that data and Monte Carlo show good agreement using the MAM ice model, see e.g. [152]. The MAM model has therefore been selected as "the standard ice model" by the AMANDA collaboration at the time this analysis was done.

Another ice model that has been used in this analysis is called the Kurt-Gary Model⁵ (KGM). This ice model has especially been used to compare with the MAM model and thus to check the systematic uncertainties. KGM uses measured properties of the ice and puts them into the simulation. It has not been combined with the measurements of the angular sensitivity [140], nor with the Sudhoff OM transmissivity measurements [153]. KGM and MAM both use the same layering of ice. The comparison of the results based on MAM and KGM will be discussed in more detail in chapter 9.

A new implementation method of the ice properties into the simulation of photon propagation is under investigation. This method is very promising, but was not available for the study presented in this thesis.

⁴The approximation of the scattering length has been done in every individual layer.

⁵This ice model is named after the two developers of the model, Kurt Woschnagg and Gary Hill.

Chapter 6

Event Reconstruction

6.1 Introduction

"The event reconstruction" is defined as the process of extracting the muon direction and the muon energy from the experimental or simulated data. Depending on how sparsely the AMANDA detector is instrumented, only a limited set of parameters can be constrained for each event. For muons these parameters are direction (θ, ϕ) , position (x,y,z) and time t. In this dissertation several reconstruction methods have been used. Two classes of reconstruction modes can be distinguished: "simple or first guess approximations" and "likelihood reconstructions".

A simple approximation is a fast analytical approximation of the track¹ parameters that does not need an initial hypothesis. In this work "the linefit" method (see section 6.2) has been used as a simple approximation. This linefit makes an ad-hoc assumption about the nature of the event, i.e. it assumes that the light recorded by the OMs is originating from a muon following a straight line trajectory. The linefit is not the most precise reconstruction technique available, but it has the advantage of being fast. It is therefore used in the first level data reduction, as explained in section 7.4.

The likelihood reconstructions are more accurate, but much more time-consuming than the simple approximations². They are based on algorithms maximizing multidimensional likelihood functions³ by minimizing $-\log(\mathcal{L})$ with respect to the parameters of the track, producing the best results if the minimization algorithms are initialized with reasonable starting values. The results of the linefit are used as the initial track parameters for the likelihood reconstruction. The likelihood used in this work is based on the hypothesis of the event being caused by a single muon track, which is infinitely long, and is therefore

¹A track is defined as the trajectory followed by a particle.

²As a result, likelihood reconstructions are always performed after an appropriate simple approximation and a first data reduction based on its results. Likelihood reconstructions are simply too time-consuming to be applied on all data.

³Parameter estimation by maximum likelihood is based on the assumption that a set of independently measured quantities x_i came from a probability density function $p(x;\alpha)$, where α is an unknown set of parameters. The method of maximum likelihood consists of finding the set of values, $\hat{\alpha}$, which maximizes the joint probability density for all the data, given by $\mathcal{L}(\alpha) = \prod_i p(x_i; \alpha)$, where \mathcal{L} is called the likelihood.

called "track likelihood".

The last step in the reconstruction framework is the production of "Data Summary Tape (DST)" information in the form of PAW N-tuples. See [154] and [155] for more information. All this has been implemented with the "recoos" program [156], which is based on the rdmc library [157] and the SiEGMuND software package [158]. The recoos program is very modular, i.e. it allows flexibility in the choice and combination of algorithms.

In section 6.2 the linefit is discussed in detail as a simple approximation for the likelihood reconstructions, discussed in section 6.3. The likelihood maximization and the iterative reconstruction technique are described in section 6.4. Finally, an overview is given of the reconstructions used in this work in section 6.5.

6.2 The Linefit

The linefit algorithm produces an initial set of track parameters solely on the basis of hit times. The fit ignores the geometry of the Cherenkov cone and the optical properties of the medium. It assumes a muon traveling with a velocity \vec{v}_{lf} through a 1-dimensional projection of the detector. The fit assumes that the locations of the PMTs, \vec{r}_i , which are hit at a time, t_i , can be connected by a line:

$$\overrightarrow{r}_i \approx \overrightarrow{r} + \overrightarrow{v}_{lf} t_i \tag{6.1}$$

with the origin of the light at t=0 being at \overrightarrow{r} .

The χ^2 to be minimized is defined as:

$$\chi^2 \equiv \sum_{i=1}^{N_{hit}} (\overrightarrow{r}_i - \overrightarrow{r} - \overrightarrow{v}_{lf} t_i)^2$$
(6.2)

where N_{hit} is the number of hit PMTs. The χ^2 is minimized by differentiation, first with respect to \overrightarrow{r} yielding

$$\overrightarrow{r} = \langle \overrightarrow{r}_i \rangle - \overrightarrow{v}_{lf.} \langle t_i \rangle \tag{6.3}$$

where $\langle x_i \rangle \equiv \frac{1}{N_{hit}} \sum_{i=1}^{N_{hit}} x_i$ denotes the mean of parameter x with respect to all hits. The differentiation of χ^2 with respect to \overrightarrow{v}_{lf} and taking equation 6.3 into account yields

$$\overrightarrow{v}_{lf} = \frac{\langle \overrightarrow{r}_i . t_i \rangle - \langle \overrightarrow{r}_i \rangle \cdot \langle t_i \rangle}{\langle t_i^2 \rangle - \langle t_i \rangle^2}$$
(6.4)

The result of the linefit is thus a vertex point \overrightarrow{r} , a speed $|\overrightarrow{v}_{lf}|$, a direction $\overrightarrow{e} = \frac{\overrightarrow{v}_{lf}}{|\overrightarrow{v}_{lf}|}$ and a χ^2_{lf} . The zenith angle is given by $\theta_{lf} \equiv \arccos(\frac{v_z}{|\overrightarrow{v}_{lf}|})$. The zenith angle θ_{lf} is used in the level 1 filtering, as described in section 7.4, as a first veto against atmospheric muons. The absolute speed $|\vec{v}_{lf}|$ of the linefit is the mean speed of the light propagating through the 1-dimensional detector projection. This variable has been used in the past by the collaboration in the first level filtering of the data since it can separate spherical events (cascades), which have low $|\vec{v}_{lf}|$ values, from long muon tracks, which have high $|\vec{v}_{lf}|$ values. However, this variable was not used in the filtering of the 1999 data set in order not to reject too many events based on the result of a fast but not so accurate reconstruction.

6.3 Likelihood Reconstructions

The likelihood track reconstruction [159] takes absorption and scattering of photons in the ice into account. The coordinate system used to reconstruct muon tracks is moving with the muon at the speed of light. The light emission only occurs at the Cherenkov angle, so that time delays are calculated with the muon at the position where the Cherenkov emission occurs, while distances are measured perpendicularly to the muon track.

The likelihood reconstruction is based on the minimization of the likelihood parameter L which is defined as

$$L \equiv -\frac{\log(\mathcal{L})}{N_{d.o.f.}} = \frac{-1}{N_{d.o.f.}} \log(\prod_{i=1}^{N_{ch}} p_i) = \frac{-1}{N_{d.o.f.}} \sum_{i=1}^{N_{ch}} \log(P(t_{res,i}|OM_i))$$
(6.5)

with $N_{d.o.f.} \equiv N_{ch} - 5$ the number of degrees of freedom⁴. \mathcal{L} is the likelihood and $P(t_{res,i}|OM_i)$ is the probability of observing a hit with a delay $t_{res,i}$ in OM "i". The term $t_{res,i}$ denotes a relative time, or "time residual"

$$t_{res} \equiv t_{hit} - t_{exp} \tag{6.6}$$

which is the difference between the observed hit time and the hit time expected for a "direct photon", a Cherenkov photon that travels, without delay, directly from the muon to an OM without scattering.

The expression $P(t_{res}|OM)$, sometimes referred to as "the Pandel Function" [160] within the AMANDA collaboration, is analytically calculable in the case of an isotropic and monochromatic point-like light source:

$$P(t_{res}|OM) \equiv \frac{1}{N(\rho)} \frac{\tau^{-(\rho/\lambda)} \cdot t_{res}^{(\rho/\lambda-1)}}{\Gamma(\rho/\lambda)} \cdot \exp(-(t_{res}/\tau) + c_{ice} \cdot t_{res}/\lambda_a + \rho/\lambda_a) \quad (6.7)$$

where

⁴"5" comes from the 5 reconstructed parameters.

6.3. LIKELIHOOD RECONSTRUCTIONS

$$N(\rho) = exp(-\rho/\lambda_a) \cdot (1 + \frac{\tau \cdot c_{ice}}{\lambda_a})^{-\rho/\lambda}$$
(6.8)

is the normalization coefficient. λ_a is the absorption length of the ice, ρ is the distance between the OM and the muon track, c_{ice} is the speed of light in ice, $\Gamma(\rho/\lambda)$ is the Gamma function while τ (unit time) and λ (unit length) are free parameters.

It describes the probability that a photon reaches the OM from a distance ρ from the track at a time delay of t_{res} compared to an un-scattered photon. This probability was generated by parametrizing the Monte Carlo simulations of light propagation in ice [161]. Other attempts to parameterize $P(t_{res}|OM)$ were performed in [162] and yielded comparable results.

For small distances the function has a pole at $t_{res} = 0$ for $\rho < \lambda$ corresponding to a high probability of an un-scattered photon. Going to larger values of ρ , longer delay times become more likely. For distances larger than the critical value $\rho = \lambda$, the power index to t_{res} changes sign, reflecting that the probability of un-delayed photons vanishes⁵.

The likelihood parameter, which is based on the pandel function, cannot be minimized numerically, due to the pole of the pandel function at $t_{res} = 0$. Moreover, the Pandel function ignores PMT and electronic jitter⁶, σ_{jitter} . To compensate all this, the Pandel function must be convoluted with a Gaussian with a width equal to the jitter. This convolution can not be done analytically and because a numerical convolution is CPU time-intensive, it is patched with a Gaussian $G(t_{res}, d)$. The patched pandel function is called "upandel function" $\hat{P}(t_{res}, d)$ and is defined as:

$$\widehat{P}(t_{res}, d) \equiv \begin{cases} G(t_{res}, d) = \frac{N_g(d)}{\sqrt{2\pi\sigma_g}} \cdot \exp{-\frac{(t_{res} - t_1)^2}{2\sigma_g^2}} & \text{for } t_{res} < t_1 \\ T(t_{res}, d) = \sum_{j=0}^3 a_j \cdot t_{res}^j & \text{for } t_1 < t_{res} < t_2 \\ P(t_{res}, d) & \text{for } t_2 < t_{res} \end{cases}$$
(6.9)

with d the "effective distance" which can be written as:

$$d = d_{\eta}(\eta) + d_{\rho}(\rho) \tag{6.10}$$

where $d_{\eta}(\eta)$ is related to the orientation of the track to the OM and $d_{\rho}(\rho)$ points to the real distance between the track and the OM.

The spline $T(t_{res}, d)$ interpolates between the Gaussian and the pandel function. The transition points are chosen to be at $t_1 \equiv 0$ and $t_2 \equiv \sqrt{2\pi} \cdot \sigma_g$. The a_j are chosen such that the upandel function and its first derivative are continuous at t_1 and t_2 . The normalization of $\hat{P}(t_{res}, d)$ yields a condition for N_g . The resulting equations for the a_j and N_g can be found in [159]. The parameter σ_g is the only free parameter left, describing the convolution of all timing uncertainties - in particular the PMT jitter. In this work it has been taken 15 ns.

⁵Essentially all photons are delayed due to scattering.

⁶Jitter is the deviation in or displacement of some aspect of the pulses in a high-frequency digital signal. The deviation can be in terms of amplitude, phase timing, or the width of the signal pulse. Another definition is that it is the period frequency displacement of the signal from its ideal location.

6.4 Likelihood Maximization and Iterative Reconstruction

The goal of the reconstruction is to find the track estimator that corresponds to the maximum likelihood. This is done by minimizing $-\log(\mathcal{L})$ with respect to the track parameters. The minimization algorithm that was used in this dissertation is called "Simplex" [163], which is one of the fastest and most accurate minimization algorithms available.

However, minimization procedures do not always yield the global minimum. Instead, local minima can arise due to symmetries in the detector, especially in the azimuth angle, or due to unexpected hit times caused by scattering. Once the global minimum is found, it is generally assumed that the true muon angle is known. This is, however, not always the case, due to the stochastic nature of light emission and detection. Since the reconstruction results cannot always be trusted, some events have to be rejected using different parameters, e.g. variables describing the "quality of the event" (see section 7.5).

The iterative reconstruction algorithm successfully deals with the problem of local minima by simply repeating the standard likelihood reconstruction algorithm on the same event several times. The procedure is the following: the result of the first minimization is saved as a reference. The point of the track which is closest to the center of gravity of hits is not modified, but both direction angles are randomly selected. The new track parameters are used as initial track parameters for the next minimization which is started in all five dimensions again. If the minimum of the likelihood is less than the reference minimum, it is saved as the new reference. This procedure is iterated n times, and the best minima found for zenith angles above and below the horizon are saved. These likelihood values are used to generate an important selection parameter that is used in this work as a quality variable (see section 7.5).

The algorithm does not often result in false minima, thanks to the iterations performed. After only 6 iterations, 95% of the reconstruction results are in the vicinity of the asymptotic optimum for $n \to \infty$. After 20 iterations > 99% of the results are at the global minimum. The reason for the improvement obtained with this iterative approach is that the minimization algorithms typically have more problems finding the correct direction than finding a vertex close to the center of the detector.

The disadvantage of the iterative reconstruction technique is the enhanced CPU time, which is proportional to the number of iterations performed. Nevertheless, this iterative reconstruction algorithm was already used (with n=16) at cut level 3 in the analysis (see section 7.5).

The muon reconstruction performance strongly depends on the angle of the incoming muon. For up-going muons the predicted angular resolution is $\sim 3^{\circ}$. The angular resolution is worse for muons near the horizon because the AMANDA-B10 detector is a vertical detector⁷. The angular resolution of the up-going and horizontal tracks has been determined using simulations as described in [183].

For down-going muons, the situation is different. Experimental data can be used

⁷The detector diameter is significantly smaller than its height.
to determine the angular resolution. Using coincident data with the air shower arrays SPASE-1 and SPASE-2 (see also chapter 4), the spatial angular resolution for muons has been measured to be $\sim 3^{\circ}$ [164], [165]. Using coincident events with the GASP Cherenkov telescope (see also chapter 4), which has a lower energy threshold for air showers than the SPASE detectors, a similar angular resolution has been found [74].

6.5 Overview of the Used Reconstructions

In this dissertation several reconstructions have been performed. Some of these reconstructions have been implemented by the collaboration and need to be considered as "standard reconstructions". These reconstructions can be used in different types of analyzes, but they are not the most accurate reconstructions available. They are mainly used to make a first guess approximation and filter out the down-going atmospheric muons.

Additional to the standard reconstructions, 4 specific reconstructions have been added, all chosen to reconstruct up-going tracks very precisely, after cut level 2.

The standard reconstructions are:

- \rightarrow Fit 1: Tensor of Inertia fit
- \rightarrow Fit 2: Linefit
- \rightarrow Fit 3: Planewave fit
- \rightarrow Fit 4: upandel likelihood fit based on fit 2
- \rightarrow Fit 5: cascade fit.

The additional reconstructions are:

- \rightarrow Fit 6: upandel likelihood fit based on fit 4 using 6 iterations
- \rightarrow Fit 7: energy reconstruction based on fit 6
- \rightarrow Fit 8: upandel likelihood fit based on fit 6 using 16 iterations
- \rightarrow Fit 9: energy reconstruction based on fit 8.

The linefit (fit 2) and the upandel likelihood reconstruction (fit 4) are the standard reconstructions used in this dissertation and have been discussed in previous sections. The upandel likelihood reconstructions using both 6 (fit 6) and 16 (fit 8) iterations are the fits that were used most extensively in this work, as will be shown in section 7.5.2 and 8.3. They were also already described in this chapter.

The cascade fit (fit 5) has also been used in this analysis, but only in combination with the upandel likelihood reconstruction (fit 6) to form a quality variable (see also section 7.5.2). The basic approach of the cascade reconstruction is similar to the track reconstruction. It assumes events from a point light source with photons propagating spherically outside with a higher intensity in the forward direction. In chapter 3 the origin of these cascades is explained in detail. The cascade fit is discussed in more detail in [4], [5].

All the other reconstructions have not been used in this work. They have only been mentioned for completeness. More information about these fits can be found in [166].

Chapter 7

Analysis Techniques and Data Processing

7.1 Introduction

In this section the method developed for the search of a neutrino flux coming from the annihilation of neutralinos in the center of the Earth is described. The analysis technique is to identify an excessive flux of neutrinos on top of the atmospheric neutrino spectrum. The signal is assumed to manifest itself as long near-vertical tracks. The background on the other hand consists of a diffuse flux of atmospheric neutrinos and mis-reconstructed atmospheric muons. The atmospheric muon events, of which there are about 10^9 at trigger level in the 99 data set, outnumber the atmospheric neutrino events by a factor of 10^6 at this level. This makes data filtering very important. Due to the limited storage capacity and CPU time it is impossible to investigate every event in the same detail. A selection method has to be designed that rejects the down-going muons in an efficient and fast way.

To avoid any bias the analysis is initially performed blindly. This is described in section 7.2. Removing noisy optical modules, unstable data taking periods and cross-talk together with bad hits is described in section 7.3. The construction of filter level 1 and filter level 2 is explained in section 7.4. In section 7.5 a dedicated mechanism for the selection of neutralino dark matter is described and the final rejection and selection efficiencies are given in section 7.6.

7.2 Blind Analysis

The AMANDA detector has the potential to detect physical phenomena that have never been seen before. The danger is that the event selection, that has been designed to detect a signal, unintentionally produces an artificial signal or hides a true signal. The aim of a blind analysis is to design statistical tools which leave the result as unbiased as possible [167].

A systematic bias can be caused by the selection criteria which preferentially suppress

or enhance events in a particular region of parameter space. Or in other words, the cuts of the analysis can obscure or mimic a true signal. A blind analysis aims to design selection methods which are independent of the signal to be found. Note however that the detector itself can introduce measurement biases that are not eliminated by performing a blind analysis. The systematic bias is by definition independent of the total amount of data that has been investigated. This is of course only valid under the condition that the detector stays the same throughout the period during which the data were taken. In chapter 9 all possible sources of systematic uncertainties are discussed.

When cuts are tuned on a too small data sample they can be influenced by statistical fluctuations. This causes the selection of the wrong cut values and thereby introduces a statistical bias. This can result in the loss of true signal or the enhancement of a false signal. The problem of statistical bias can of course be solved by looking at additional fresh data. However, it is preferable, as with systematic bias, to reduce all biases from the start.

In this analysis "data sub-sampling" has been used to make the analysis blind and thereby reduce all possible biases. In practice this means that the analysis is tuned on a sub-sample of data. The final analysis is then applied on the remaining data sample at the last stage. Since there is an inevitable bias introduced in the sub-sample on which the cuts were tuned, that sub-sample is discarded after tuning and not used in the final result. This implies that the sub-sample has to be as small as possible. The argument against using such a small sub-sample is that it can introduce a statistical bias. The conclusion is that a compromise has to be found between these contradicting arguments.

In this analysis a sub-sample that corresponds to 15.5% of the full data sample has been used to tune the analysis cuts. This sample has an effective live time of 34.4 days (see chapter 5.2). In order to be sure that the sub-sample does not hide some dangerous systematic, the sample is drawn as uniformly as possible from the full data sample. This is done by picking out every fifth run in the list of all runs. This way the sub-sample contains data taken over the full data taking period.

7.3 Data Cleaning

Before the data can be reconstructed, several initialization steps are necessary. This can be divided into three parts: hit cleaning, cross-talk cleaning and OM and run selection.

7.3.1 Hit Cleaning

The hit cleaning [168] corresponds to 'removing' all hits which are not produced by the Cherenkov light, but result from the photo multiplier tube (PMT) noise, the noise produced by radioactive sources in the OM glass e.g. potassium [169], the electronic noise in the data acquisition system (DAQ) or other detector instrumentals. The ice itself is very quiet and also bioluminescense is not at all a problem for the AMANDA experiment. The hits are not really 'removed', they are being flagged so that they are not used in reconstructions or considered in cuts. Thus events always conserve all information as recorded by the DAQ. As these hits may confuse the reconstruction algorithms, it is important to reduce their number as much as possible.

The first concrete step of hit cleaning is the elimination of random noise at the beginning of the trigger window of the event, called pre-pulsing, and the after-pulsing at the end. See also chapter 4. Pre-pulsing rates are very low and after-pulsing has a characteristic time delay with respect to the primary pulse. This elimination is done by the reduction of the acquisition gate length to an interval of 4500 ns around the trigger time. See also section 4.4. This way all interesting hits are retained. The calibrated amplitude of the hit is required to be between 0.3 and 1000 photo electrons and the times over threshold (TOT) of all hits between 125 ns and 2000 ns. Furthermore, every secondary pulse in a single channel is discarded. These are most of the time caused by scattered photons which provide poor timing information. The reconstruction algorithms are presently not able to incorporate this information in an effective way. Finally, an isolation criterion is imposed eliminating a hit if no other tube within 70 meters fired within 500 ns. This cut is very efficient at eliminating random noise.

7.3.2 Cross-talk Cleaning

Another class of signals biasing the reconstruction results are electronic cross-talk hits [170]. Electronic cross-talk is the occurence of an electronic pulse in one OM caused by a signal in another OM on the same string. Cross-talk is the result of electro-magnetic coupling between different cables. It occurs mainly in the twisted quad cables (see chapter 4) of strings 5 to 10 and is not always rejected after the hit cleaning procedure, described earlier, has been applied [171], [172], [173].

The easiest way to improve the hit cleaning algorithm is to refine the TOT cut. In the standard hit cleaning it is required that 125 ns < TOT < 2000 ns. This condition is imposed on every OM. In this dissertation a cross-talk map of the detector has been used. This map has been produced using time calibration data and puts a constraint on each optical module individually.

During the time calibration, the high voltage of all OMs is turned off¹ with the exception of the OM that is being calibrated. The DAQ system however reads the full detector. The OM that is being flashed by the diffuser ball (see chapter 4) measures the radiated light. Any information coming from another OM reflects the presence of electronic cross-talk between these OMs.

Cross-talk occurs only between OMs located on the same string. There are three types of cross-talk, depending on the position of the OMs involved relative to the given string. The three categories are: top-bottom cross-talk, near-neighbor cross-talk and lobe cross-talk. In case of top-bottom cross-talk, the difference in OM position between the "talking" OM and the "receiving" OM is larger than 15 OM positions or larger than 150 m in distance. The near-neighbor cross-talk typically occurs between OMs that are 1 to 3 OM positions away. This corresponds to a physical separation of 10 to 30 meters.

¹The high voltage is in reality set to 300 V.

Lobe cross-talk is observable in the center of the string only. This type of cross talk is very similar to the near neighbor cross-talk, but OMs that are several positions away are affected as well in this case. This type of cross-talk is very much dependent on the way in which the two cables are wrapped together forming one bundle to go into the ice.

Cross-talk produces typically narrower pulses than the pulses produced by light. In figure 7.1 the pulse height versus TOT distribution is shown for light hits and cross-talk hits. Both the TOT and the pulse height depend on the characteristics of the pulse shapes. In the plot it is illustrated that the cross-talk is located in a different region than the light pulses.

The program "xt-filt" [173] has been designed to reduce cross-talk from data making use of the cross-talk map based on the fits of the pulse amplitude versus TOT.

7.3.3 OM and RUN Selection

A monitoring system [176] based on the ROOT data analysis framework [177] is operational since February 2001. The AMANDA data taking is split up in several runs. A typical run covers a period of 24 hours of data taking. Shorter run times are possible if interruptions occur and runs have to be started manually. During the data taking several parameters of the detector are written into monitoring files. These files typically contain noise rates, inclusive and exclusive trigger rates, TDC leading edge rates, ADC info rates and time difference distributions. As soon as a data taking run has been finalized, the corresponding monitoring file is sent over satellite to one of the AMANDA laboratories in the Northern hemisphere to be monitored.

The data that have been taken in 1999 do not have these monitoring files. However, a similar type of data stream has been produced after the actual data taking period [178]. The OM and run selection is based exclusively on the noise rates of the optical modules. The noise rates have the biggest influence on the reconstruction results for that matter. The selection is performed in two steps. In a first step a Gaussian fit is made to the noise rate distribution for each optical module and for each run. The results of these fits are used to classify optical modules according to the following criteria:

- \rightarrow an OM is considered bad for a given run if it has a deviation > 10 σ from its own mean (over the year) or the global mean (for that particular type of OM, see chapter 4).
- \rightarrow an OM is classified as bad for the complete data taking period if it has a deviation > 5 σ from its own or the global mean in > 50 % of all runs.
- \rightarrow an OM is declared dead in case its noise rate is below 10 Hz in >90% of all runs.
- \rightarrow a run is considered bad if more than 50% of the OMs exhibit a > 5 σ deviation of the noise rate or more than 20 % of all OMs a > 10 σ deviation.
- \rightarrow a run is considered short and consequently bad if it is shorter than 2000 seconds.



Figure 7.1: The signal peak ADC spectrum as function of the TOT values for both the time calibration data and the cross-talk data of optical module 149. The data on the right hand side of the solid curve was taken when OM 149 was illuminated by the closest diffuser ball. Hence the light produced pulses appear in the wing shaped region. The data on the left hand side of the solid line was taken when OM 130 was illuminated and thus with the high voltage of all other OMs, including OM 149, turned off (the high voltage is set to 300 V in practice). These pulses represent the cross-talk data. The vertical dashed line illustrates the cut TOT > 125 ns as part of the basic hit cleaning algorithm. In this analysis the pulses on the left side of the curved dashed line have been additionally removed. Figure from [174].

This method provides a data base for the identification of bad optical modules and unstable data taking periods. All OMs and runs that have been classified as bad are rejected from the analysis.

7.4 Filter Level 1 and Filter Level 2

The main goal of filter level 1 and filter level 2 is the rejection of the down-going atmospheric muon events. As mentioned in section 5.2, the experimental data consist of $1.1 \cdot 10^9$ events at trigger level. These events are mainly down-going atmospheric muon events. The idea is to identify the up going atmospheric neutrino events in this large data set in an efficient way.

Several analyzes are being performed using the 1999 data. In order to save disk space and CPU time, the AMANDA collaboration has decided to build general level 1 and level 2 data streams that can be used for different analyzes [179], [180], [166]. Since every analysis has its specific needs, these filter levels can only consist of loose selections.

The level 1 processing consists of the implementation of 5 reconstruction algorithms and an event selection depending on 1 of these reconstruction algorithms. The 5 muon fits (see chapter 6) are: the tensor of inertia fit (fit 1), the linefit (fit 2), the planewave fit (fit 3), the upandel likelihood reconstruction (fit 4) and the cascade reconstruction (fit 5). The events which have a reconstructed muon zenith angle, based on the linefit, of at least 70 degrees are selected. This level is called filter level 1.



Figure 7.2: Data at trigger level: reconstructed muon zenith angle based on the linefit (fit 2). On the left: the 99 experimental data are plotted as full line, the down-going atmospheric muon simulation sample as dashed line and the up-going atmospheric neutrino simulation sample as dotted line. The distributions of all samples have been normalized to each other. On the right: all WIMP simulation samples (7 different neutralino masses and 2 different annihilation channels) are illustrated combined as a dashed-dotted line.

In figure 7.2 the reconstructed muon zenith angle of the linefit is plotted before any cut has been applied. The experimental data consist at this level mainly of down-going atmospheric muons. These muons are about 10^6 times more abundant in data than the up-going atmospheric neutrinos at this level. However, the distributions show a not so good agreement between the experimental data and the simulated down-going atmospheric muon sample. The discrepancy is due to the fact that the linefit method uses only limited information with respect to the photon propagation (see chapter 6) and the incomplete description of the optical ice properties in the simulation (see chapter 5.4.5). The simulated upgoing atmospheric neutrino events have most of their tracks at large zenith angles. Note that the neutralino simulation evidently results in up-going muon tracks as the neutrinos are expected to come from the center of the Earth. The dominant fraction of all the data samples shown is reconstructed as to originate from the correct hemisphere. Nonetheless, an important fraction of the events is mis-reconstructed.

In order to reject as many atmospheric muons as possible, only events with a reconstructed muon zenith angle larger than 70 degrees are selected. The total passing rate after this cut is 3.2 % for experimental data, 8.1 % for the simulated down-going atmospheric muon sample, 72.5 % for the simulated up-going atmospheric neutrino sample and 99.8% for the simulated neutralino signal sample.

To summarize, the level 1 reconstructions and cut are:

- \rightarrow Fit 1: Tensor of inertia fit
- \rightarrow Fit 2: Linefit
- \rightarrow Fit 3: Planewave fit
- \rightarrow Fit 4: upandel likelihood reconstruction
- \rightarrow Fit 5: cascade reconstruction
- \rightarrow Zenith angle (linefit) > 70°.

In level 2 processing the cuts are based on the upandel likelihood reconstruction (fit 4). Only those events are selected which pass two basic quality cuts.

A cut on the reconstructed muon zenith angle has been set at 80 degrees. The zenith angle is the result of the upandel likelihood reconstruction. Simulated background events and experimental data agree well, as can be seen in figure 7.3. The background events that were wrongly reconstructed as up-going by the linefit, are now correctly identified as down-going. With this cut a lot of mis-reconstructed events are rejected.

The remaining data set was filtered to contain at least 4 direct hits. A direct hit is a hit with a small time residual t_{res} . The time residual is defined as $t_{res} \equiv t_{hit} - t_{exp}$ (see also section 6.3). This is the time difference between the recorded arrival time of the photon t_{hit} and the expected arrival time of the photon that has not been delayed by scattering-off particles t_{exp} . In this case it is required that -10 ns $\leq t_{res} \leq +25$ ns. In figure 7.4 the number of direct hits is plotted.

The simulated signal Monte Carlo shows the highest number of direct hits. The muon tracks coming from the annihilation of neutralinos in the center of the Earth are very vertical. Since the AMANDA-B10 detector is a "vertical detector" (height = 500 m, width = 120 m), the chance of having a lot of optical modules illuminated by the Cherenkov photons originating from the passing muon is very high. This explains the high number



Figure 7.3: Data after cut level 1: the reconstructed muon zenith angle based on the upandel likelihood reconstruction (fit 4). On the left: the 99 experimental data are plotted as full line, the down-going atmospheric muon simulation sample as dashed line and the up-going atmospheric neutrino simulation sample as dotted line. The distributions of all samples have been normalized to each other. On the right: all WIMP simulation samples (7 different neutralino masses and 2 different annihilation channels) are illustrated combined using a dashed-dotted line.



Figure 7.4: Data after cut level 1: the number of direct hits based on the upandel likelihood reconstruction (fit 4). It is required that -10 ns $\leq t_{res} \leq +25$ ns. On the left: the 99 experimental data are plotted as full line, the down-going atmospheric muon simulation sample as dashed line and the up-going atmospheric neutrino simulation sample as dotted line. The distributions of all samples have been normalized to each other. On the right: all WIMP simulation samples (7 different neutralino masses and 2 different annihilation channels) are shown combined with the dashed-dotted line.

of hit channels for muons coming from WIMPS. The fact that the muon track is most of the time parallel to the AMANDA strings results in a high number of direct hits in signal events.

There is a slightly larger number of direct hits in the experimental data than in the down-going atmospheric muon simulation. The up-going atmospheric neutrino simulation shows a larger number of direct hits than data but less than signal Monte Carlo.

The total passing rate including these cuts is 0.90 % for experimental data, 0.95 % for the CORSIKA atmospheric muon simulation sample, 40 % for the NUSIM simulated atmospheric neutrino sample and 74.5 % for the total simulated neutralino signal sample. See table 7.4 for a complete overview of the number of events passing the criteria at the different levels.

Thus the level 2 cuts are:

→ Zenith angle (upandel likelihood reconstruction) > 80° → $N_{direct}^{-10ns:25ns}$ (upandel likelihood reconstruction) ≥ 4.

7.5 Filter Level 3

At level 2 a large part of the mis-reconstructed events have already been rejected. Until now only simple variables have been used and the cuts have been straightforward. Since the size of the data sets has been reduced considerably, a more complicated selection method tuned to select WIMPs can now be applied on the remaining events. Additional reconstructions have been made at this stage on top of the 5 reconstructions available at level 1. The new reconstructions (see chapter 6) are:

- \rightarrow Fit 6: upandel likelihood reconstruction based on fit 4 using 6 iterations
- \rightarrow Fit 7: energy reconstruction based on fit 6
- \rightarrow Fit 8: upandel likelihood reconstruction based on fit 6 using 16 iterations
- \rightarrow Fit 9: energy reconstruction based on fit 8.

In this section a dedicated WIMP selection algorithm is explained. The selection quality of the method is also treated.

7.5.1 WIMP Selection Method

Analysing experimental data events looking for near-vertical tracks coming from the annihilation of neutralinos in the center of the Earth, starts with the identification and rejection of several types of background events. The most important type of background events are the down-going atmospheric muons. At level 2 the data are still strongly dominated by this type of background events (see table 7.4). Simulation of these events is very CPU time consuming. Therefore a part of the data itself is used as background sample in this early stage of the analysis. After having applied some strong cuts rejecting the downgoing events, the data start to be dominated by up-going atmospheric neutrino events. The neutrino events appear much later in the data since these are much less abundant than the atmospheric muon events. All this means that the type of background events changes as the cuts are being applied.

The analysis focuses first on the rejection of the down-going muon events and the identification of possible WIMP candidates on top of the expected atmospheric neutrino spectrum. As has been explained in section 5.4, there are 14 different simulations of neutralinos available in this work. The selection method has been applied on each WIMP Monte Carlo individually. This enhances the efficiency of the analysis considerably, especially for low neutralino masses.

The idea is to find a selection procedure that points out the most sensitive variable to cut on (among a chosen set of N=32 variables which parametrize the quality of an event) and, on top of that, also determines the most optimal cut value. The list of variables that have been investigated in this dissertation are summed up in table 7.1.

name of variable	definition			
zenith(8)	Zenith angle muon track (8)			
ldirb(8)	Length of direct $hits_{-15ns < t_{res} < 25ns}$ (8)			
ldirc(8)	Length of direct $hits_{-15ns < t_{res} < 75ns}$ (8)			
llen(8)	Length of hits projected on the track $-1000ns < t_{res} < 1000ns$			
nearly(8)	Number of hits too early $t_{res} \leq -15ns$			
ndira(8)	Number of direct $hits_{-15ns < t_{res} < 15ns}$ (8)			
ndirb(8)	Number of direct $hits_{-15ns < t_{res} < 25ns}$ (8)			
ndirc(8)	Number of direct $hits_{-15ns < tres < 75ns}$ (8)			
ndird(8)	Number of direct $hit_{s-15ns < t_{res} < 150ns}$ (8)			
nlate(8)	Number of late hits $t_{res} > 150 ns$			
$\sqrt{((smtdirc(8))^2 + (smtdircvan(8))^2)}$	Smoothness radius $R_{S,dir,iter}$ (8)			
jkchi(8)-jkprob(8)	$L_{up}(8)$ - $L_{down}(8)$			
smooth(8)/zenith(8)	$smoothness_{allhits}(8)$ /zenith angle(8)			
smoothdircvan(8)	Vanilla smoothness of direct $hits_{-15ns < t_{res} < 75ns}$ (8)			
smoothdirevan(8)	Vanilla smoothness of direct $hits_{-15ns < tres < 250ns}$ (8)			
smootallvan(8)	vanilla $smoothness_{allhits}$ (8)			
smoothdira(8)	Smoothness of direct $hits_{-15ns < t_{res} < 15ns}$ (8)			
smoothdirb(8)	Smoothness of direct $hits_{-15ns < t_{res} < 25ns}$ (8)			
smoothdirc(8)	Smoothness of direct $hits_{-15ns < t_{res} < 75ns}$ (8)			
jkrchi(5)/jkrchi(6)	$L_{cascade}$ (5) / $L_{muontrack}$ (6)			
pha(8)	Average hit probability per hit channel(8)			
pnha(8)	Average no hit probability per not hit channels (8)			
phnha(8)	Average hit + no hit probability per all channels (8)			
phe(8)	Hit probability of hit channels per event (8)			
pnhe(8)	No hit probability of not hit channels per event (8)			
nch	Number of hit channels			
nstr	Number of hit strings			
nhits	Number of hits			
energy (8)	Reconstructed energy (8)			
leng(8)	Reconstructed track length in meters (8)			
jksigth(2)	Speed of the linefit (2)			
dist(2)	Closest distance between track reconstruction and center of detector $(0,0,0)$			

Table 7.1: The names and definitions of all variables that were investigated by the algorithm designed for the selection of WIMPs. The number in between brackets corresponds to the number of the fit as defined in chapter 6. Note that these variables are listed for completeness. A detailed description of all variables used in the analysis is given in section 7.5.2.

Several possibilities like optimizing "signal to noise", "signal to square root of noise" or "choosing cuts to leave exactly n background events" have been investigated. These

methods however can easily lead to artificial cuts due to statistical limitations of the simulated data samples. It turned out that calculating the quantity

$$\epsilon_{signal}$$
(variable \leq cut value) $(1 - \epsilon_{background}$ (variable \leq cut value))

with

 ϵ_{signal} (variable \leq cut value) = the fraction of selected signal events after applying the cut $\epsilon_{background}$ (variable \leq cut value) = the fraction of background events passing the cut

is one of the best ways to determine efficient cut variables and cut values. This calculation is done for all N interesting variables and all their corresponding cut values.

In figure 7.5 the WIMP selection method is illustrated for the variable "number of hit channels". The number of hit channels is plotted for the WIMP signal (all 14 channels combined)², for the background of atmospheric muons and atmospheric neutrinos and the experimental data. The idea is to find a cut value for this variable so that as much as possible signal events are retained and as many background events as possible are rejected. It is also interesting to know whether this particular variable is an efficient variable to cut on compared to the other variables. The comparison of the distributions of signal and background indicates that the WIMP events have on average more hit channels than the atmospheric muons and the atmospheric neutrinos. Therefore the cut: variable > cut value has been investigated.

In figure 7.6 the selection efficiency for the signal and the background events is shown as function of the cut on the number of hit channels. Calculation of $\epsilon_{signal} \cdot (1 - \epsilon_{background})$ results in a function that peaks at a certain cut value (17 hit channels in this example). This value is considered to be the most optimal cut value for this particular variable. The corresponding value of $\epsilon_{signal} \cdot (1 - \epsilon_{background})$ is used as "weight of the variable". In other words, this weight tells us how efficient this variable is with respect to the other variables. After having investigated N variables, there is exactly one variable that comes out as being the most sensitive one. When the optimal cut has been applied on this variable, exactly the same procedure is iterated on all the N-1 remaining variables.

7.5.2 Results of the WIMP Selection Method

This section describes the 11 variables that come out of the above-described procedure as the most sensitive variables. As already mentioned, the analysis consists of 14 different series of cuts. Each of these series of cuts has been optimized for one of the 14 neutralino simulations available in this work. Every sub-analysis has therefore its own sample of cut variables and corresponding cut values used and a specific order in which the cuts have been applied. In order not to increase the complexity of describing 14 different

²Note that all 14 channels have been combined here as illustration. The analysis on the other hand has been performed for every signal Monte Carlo on an individual basis.



Figure 7.5: Top left: The number of hit channels for simulated signal (7 WIMP masses and both the hard and soft annihilation channel are included); Top right: The number of hit channels using simulated up-going atmospheric neutrino events; Bottom left: The number of hit channels for the simulated down-going atmospheric muon events; Bottom right: The number of hit channels for the 99 data. The vertical line indicates the optimal cut value.



Figure 7.6: Top left: Selection efficiency for simulated signal events (all 7 WIMP masses and both the hard and soft annihilation channel are included) as function of the cut on the number of hit channels; Top right: Selection efficiency for background events as function of the cut on the number of hit channels; Bottom left: Fraction of background events rejected as function of the cut on the studied variable; Bottom right: Selection efficiency for signal events \cdot (1- selection efficiency for background events) as function of the cut on the number of hit channels.

sub-analyzes, the order in which the variables have been used is not respected in this descriptive section.

The WIMP selection method has resulted in choosing several variables that have already been used in the level 1 and the level 2 filtering, be it based on different reconstructions. The cut on the muon zenith angle of the 16 iterations upandel likelihood reconstruction (fit 8) is tightened to 151° for the lowest neutralino mass and to 161° for the highest neutralino mass (see table 7.2 for the exact cut values). The neutralinos are gravitionally trapped inside the core of the Earth. Heavy neutralinos accumulate more closely to the center of the Earth compared to light neutralinos. This explains the tighter cuts for the high neutralino masses. This variable was the first and therefore most efficient cut variable used in each of the 14 sub-analyzes. It removes a large part of both the down going atmospheric muons and the up-going atmospheric neutrino events. This cut shows the importance of the vertical tracks in this analysis.

Figure 7.7 shows the angular distribution of the WIMP signal³, the down-going atmospheric muon simulation, the up-going atmospheric neutrino simulation and the experimental 99 data. The artificial peak at 80 degrees is due to the very strong correlation between this variable and the zenith angle of the upandel likelihood reconstruction (fit 4) on which a cut has been applied at 80 degrees in filter level 2.



Figure 7.7: Data after cut level 2: the reconstructed muon zenith angle of the 16 iterations upandel likelihood reconstruction (fit 8). On the left: Solid line: experimental data, dashed line: down going atmospheric muon Monte Carlo, dotted line: up-going atmospheric neutrino Monte Carlo. These distributions have been normalized to each other. On the right: all 14 WIMP simulations combined.

Another sensitive variable is "the length of the direct hits⁴". The length of the direct hits is defined as the total length covered by the projection of the positions of all OMs,

³In this illustration all 14 signal simulations are combined.

⁴definition of direct hit: see section 7.4.

detecting a direct hit, on the reconstructed track in question. In this case a hit is called a direct hit if -15 ns $\leq t_{res} \leq$ 75 ns. The track reconstruction used in this case is the 16 iterations upandel likelihood fit. In figure 7.8 this variable is plotted for the WIMP signal (all 14 signal simulations are combined), the down-going atmospheric muon simulation, the up-going atmospheric neutrino simulation and the experimental 99 data. The result of the WIMP selection method using this variable depends on the neutralino model. The optimal cut value ranges from 77 m for the lowest neutralino mass to 185 m for the highest neutralino mass (see table 7.2 for the exact cut values). Also the distribution of this variable shows a strange behaviour, due to the strong correlation with other variables that have already been cut on (same discussion as for the previous cut variable). The agreement between experimental data and atmospheric muon Monte Carlo is very good.



Figure 7.8: Data after cut level 2: the length of the direct hits of the 16 iterations upandel likelihood reconstruction (fit 8). It is required that -15 ns $\leq t_{res} \leq$ +75 ns (definition see section 7.4). On the left: Solid line: experimental data, dashed line: down-going atmospheric muon Monte Carlo, dotted line: up-going atmospheric neutrino Monte Carlo. These distributions have been normalized to each other. On the right: all 14 WIMP simulations combined.

In addition, a cut on the number of direct hits of fit 8 (16 iterations upandel likelihood reconstruction) has been performed, where it is required that -15 ns $\leq t_{res} \leq$ 75 ns. Figure 7.9 shows the corresponding distributions for the WIMP signal (all 14 signal simulations are combined), the down-going atmospheric muon simulation, the up-going atmospheric neutrino simulation and the experimental 99 data. Typical cut values are: number of direct hits > 8 for the high neutralino masses and > 7 for the low neutralino masses, depending on the annihilation channel. There is a good agreement between the experimental data and the simulated atmospheric muon data. The up-going atmospheric neutrino Monte Carlo and the neutralino simulation show a larger number of direct hits.

Also the number of direct hits of the 16 iterations upandel likelihood reconstruction (fit 8) for which -15 ns $\leq t_{res} \leq 15$ ns has been used. This variable looks only at photons



Figure 7.9: Data after cut level 2: number of direct hits of the 16 iterations upandel likelihood reconstruction (fit 8). It is required that -15 ns $\leq t_{res} \leq +75$ ns (definition see section 7.4). On the left: Solid line: experimental data, dashed line: down-going atmospheric muon Monte Carlo, dotted line: up-going atmospheric neutrino Monte Carlo. These distributions have been normalized to each other. On the right: all 14 WIMP simulations combined.

that hardly scattered on their way to the optical module, whereas the previous variable allowed a larger interval of time residuals. The distributions of these variables look similar but the distribution of the number of direct hits with the smaller time residuals is shifted towards smaller values. The variables are very strongly correlated, but nonetheless it is still efficient to use both in some of the sub-analyzes as can be seen in table 7.3. Figure 7.10 illustrates this variable for experimental data, signal Monte Carlo and background Monte Carlo. Also here there is a good separation between signal and background.

The cuts on the zenith angle, the length of the direct hits and the number of direct hits (-15 ns $\leq t_{res} \leq$ 75 ns) of the 16 iterations upandel likelihood reconstruction described so far are cuts number one, two and three respectively in all 14 sub-analyzes. The optimal cut values of these variables resulting from the WIMP selection method are summarized in table 7.2. This table also reveals the total passing rates with respect to filter level 2 for the signal and the background Monte Carlo after these three cuts have been applied. The selection efficiency of the signal is of the order of 70 - 80 % on average. The high mass neutralinos seem to be selected more efficiently than the low mass neutralinos. At the same time a rejection factor of the order of 10^3 - 10^4 is obtained for the background events. Note that in this case $\epsilon_s \cdot (1 - \epsilon_{bg}) \approx \epsilon_s$. See table 7.4 for a complete overview of the number of events passing the selection criteria described in this section.

The likelihood reconstructions used so far do not take correlations between hits into account. This means that tracks with clusters of hits at one end and those with smoothly distributed hits along the track may obtain equal likelihoods, despite the fact that the latter is more likely to be a well-reconstructed event. This observation resulted in the

WIMP mass	annihilation	$\operatorname{zenith}(8) >$	ldirc(8) >	ndirc(8) >	ϵ_s	ϵ_{bg}
	channel					
5000 GeV	hard	161	185	8	81 %	0.004 %
5000 GeV	soft	161	166	7	78~%	0.014~%
3000 GeV	hard	162	185	8	81 %	0.004~%
3000 GeV	soft	161	165	7	79 %	0.014 %
1000 GeV	hard	161	175	8	78~%	0.005~%
1000 GeV	soft	159	146	7	77 %	0.03 %
500 GeV	hard	161	157	8	79 %	0.013 %
500 GeV	soft	159	136	8	71 %	0.03 %
250 GeV	hard	159	146	8	77 %	0.02~%
250 GeV	soft	159	126	7	73 %	0.07~%
100 GeV	hard	157	125	7	73 %	0.09 %
100 GeV	soft	153	97	7	72 %	0.13 %
50 GeV	hard	150	96	7	68~%	0.1~%
50 GeV	soft	151	77	7	66~%	0.077~%

Table 7.2: The most efficient cut values of the first three variables used in the different subanalyzes. "zenith(8)", "ldirc(8)" and "ndirc(8)" respectively stand for the reconstructed muon zenith angle, the length of the direct hits (-15 ns $\leq t_{res} \leq$ 75 ns) and the number of direct hits (-15 ns $\leq t_{res} \leq$ 75 ns) of fit 8 (16 iterations upandel likelihood reconstruction). The last two columns show the fraction of signal events and the fraction of background events that pass these three cuts with respect to level 2. The cuts are the result of the WIMP selection method.



Figure 7.10: Data after cut level 2: the number of direct hits of the 16 iterations upandel likelihood reconstruction (fit 8). It is required that -15 ns $\leq t_{res} \leq +15$ ns (definition see section 7.4). On the left: Solid line: experimental data, dashed line: down-going atmospheric muon Monte Carlo, dotted line: up-going atmospheric neutrino Monte Carlo. These distributions have been normalized to each other. On the right: all 14 WIMP simulations combined.

definition of another interesting cut variable called "smoothness" [181], [182], [183]. The smoothness S of an event with respect to a certain parameter x, is motivated by a Kolmogorov-Smirnov comparison of the distribution of the observable x along the track to a reference template. Let's consider the location of hits for example. This can be compared to the linear template that corresponds to the expectation of a homogeneous occurrence of hits along the track. The typical step-widths are given by the granularity of the detector i.e. the density of the optical modules on the strings and the string structure. The smoothness parameter S is given by the largest difference between the normalized cumulative distribution of observed hits and the reference template. It is a characteristic measure if an observable is equally distributed along the track. The definition is illustrated in figure 7.11.

In other words, the smoothness parameter measures the deviation from a smooth distribution. S = -1/+1 corresponds to scenarios where all hits are at the end/beginning of the track and S = 0 when the distribution is perfectly homogeneous. Type and source of background events with large positive S values can be very different from events with large negative S values. This means that the distribution of S is not necessarily symmetric around 0 but can rather depend on the relative abundance and how efficient the individual sources of background have been rejected by other cuts. In this analysis the smoothness of the 16 iterations upandel likelihood reconstruction has been considered.

There exist several extensions and variations of the basic idea of smoothness. In this analysis the "vanilla smoothness" [181] has been investigated in addition to the "standard smoothness". The vanilla smoothness is defined as follows:



Figure 7.11: Illustration of the smoothness parameter. Figure from [182].

$$S^{van} = (S_j^{van})_{max}$$
 with $S_j^{van} = \frac{j-1}{N-1} - \frac{l_j}{l_N}$ (7.1)

 l_j is the distance between the points of closest approach (on the track) from the first hit photo multiplier tube to the j-th hit photo multiplier tube and N is the number of hits. The points of the closest approach from the track to the hit photo multiplier tubes are calculated. The vanilla smoothness is calculated for a template region between the first and the last hit. The definition of the vanilla smoothness is close to the original definition of smoothness.

Another parameter that influences the smoothness is the number of hits used. In this work two approaches are considered. The first case considers all hits i.e. all hits for which -1000 ns $< t_{res} < 2000$ ns. The second approach only uses hits with time residuals -15 ns $< t_{res} < 75$ ns.

Figure 7.12 shows the distribution of the vanilla smoothness using all hits for the experimental 99 data, the simulated down-going atmospheric muon events, the simulated up going atmospheric neutrino events and the WIMP Monte Carlo (14 models combined). Simulated signal events have better (smaller) smoothness values than simulated background events. Table 7.3 summarizes the most efficient cut values obtained using the WIMP selection method for this particular variable in the different sub-analyzes.



Figure 7.12: Data after cut level 2: the vanilla smoothness of the 16 iterations upandel likelihood reconstruction (fit 8) using all hits. On the left: Solid line: experimental data, dashed line: down-going atmospheric muon Monte Carlo, dotted line: up-going atmospheric neutrino Monte Carlo. These distributions have been normalized to each other. On the right: all 14 WIMP simulations combined.

Also combinations of variables were selected by the WIMP selection method. In this work the ratio between the smoothness using every hit and the reconstructed zenith angle turned out to be a sensitive variable. This ratio [183] has been calculated using the 16 iterations upandel likelihood reconstruction. The cut requires tighter smoothness values for horizontal events as compared to up-going vertical events. The corresponding distributions are shown in figure 7.13 and the cut values obtained from the WIMP selection method are given in table 7.3. It shows a nice separation between signal and background events. The experimental data are distributed similarly to the simulated background events.



Figure 7.13: Data after cut level 2: the ratio between the smoothness using every hit and the zenith angle from the 16 iterations upandel likelihood reconstruction (fit 8). On the left: Solid line: experimental data, dashed line: down-going atmospheric muon Monte Carlo, dotted line: up-going atmospheric neutrino Monte Carlo. These distributions have been normalized to each other. On the right: all 14 WIMP simulations combined.

A dedicated cut variable was developed using both the standard version and the vanilla version of smoothness. The new variable $R_{S,dir,iter}$ [183] is the radius in the plane spanned by the two smoothness flavors. Both are taken from the 16 iterations upandel likelihood reconstruction and have been calculated for direct hits only (-15 ns $< t_{res} < 75$ ns). The cut variable is defined as:

$$R_{S,dir,iter} = \sqrt{S_{dir,iter}(-15\text{ns} < t_{res} < 75\text{ns})^2 + S_{dir,iter}^{van}(-15\text{ns} < t_{res} < 75\text{ns})^2}$$
(7.2)

The optimal cut values on this variable for the different sub-analyzes can be found in table 7.3. The distribution of this variable is shown in figure 7.14 for the experimental data and the simulated background and signal data. From this figure it is obvious that the simulated background has larger smoothness radii than the simulated signal.

Other sensitive variables are related to the likelihood values of minimization processes of reconstructions. These likelihood values are calculated in the full parameter space. Likelihood values are always calculated under the assumption that the track is either down-going or up-going. Even for events that have already been identified as upgoing muons, likelihood values are also calculated under the assumption that these are



Figure 7.14: Data after cut level 2: the "smoothness radius" $R_{S,dir,iter}$ of the 16 iterations upandel likelihood reconstruction (fit 8). On the left: Solid line: experimental data, dashed line: down-going atmospheric muon Monte Carlo, dotted line: up-going atmospheric neutrino Monte Carlo. These distributions have been normalized to each other. On the right: all 14 WIMP simulations combined.

down-going muons. Both best likelihood values in the down- and in the up-going hypothesis are stored, one of them being the best overall likelihood. Comparing these 2 likelihoods gives an estimate of how much more likely the up-going track hypothesis is with respect to the down-going track hypothesis. A cut is applied on the difference of the likelihood parameters $L_{up} - L_{down}$, which is shown in figure 7.15 for the experimental data, the up-going atmospheric neutrino Monte Carlo, the down-going atmospheric muon Monte Carlo and the simulated WIMP events. Signal shows smaller likelihood parameter values for up-going tracks than for down-going tracks. The simulated down-going atmospheric muon spheric muon s, show similar distributions.

As a last likelihood cut, the ratio between the likelihood parameter values of the reconstruction with the shower hypothesis (cascade reconstruction 5, see also chapter 6) and the track hypothesis (upandel likelihood reconstruction 6, see chapter 6) has been selected. Figure 7.16 illustrates this ratio for background and signal Monte Carlo and for the experimental 99 data. The WIMP signal events are evidently much better described with a track hypothesis than with a shower hypothesis, resulting in relatively large ratios of the likelihood parameter values. The most efficient cut values for this variable for the different sets of cuts is shown in table 7.3. This cut has been applied at the end of some of the sub-analyzes. The events which are rejected by this cut are shower-like events. In reality these are mainly atmospheric muon events with associated bright bremstrahlung events.

Two more parameters, based on hit probabilities, have been used in the different subanalyzes [168]. The first variable is the hit probability of the hit channels. This variable



Figure 7.15: Data after cut level 2: the difference between the likelihood parameter of the up-going fit and the likelihood parameter of the down-going fit of the 16 iterations upandel likelihood reconstruction (fit 8). On the left: Solid line: experimental data, dashed line: down-going atmospheric muon Monte Carlo, dotted line: up-going atmospheric neutrino Monte Carlo. These distributions have been normalized to each other. On the right: all 14 WIMP simulations combined.



Figure 7.16: Data after cut level 2: the ratio of the likelihood parameter value of the cascade fit (fit 5) and the one of the muon track fit for the 6 iterations upandel likelihood reconstruction (fit 6). On the left: Solid line: experimental data, dashed line: down-going atmospheric muon Monte Carlo, dotted line: up-going atmospheric neutrino Monte Carlo. These distributions have been normalized to each other. On the right: all 14 WIMP simulations combined.

is formed by summing all hit probabilities of the optical modules which detect a hit. A well-reconstructed track has high values for this variable compared to a mis-reconstructed track. This is because a well-reconstructed event has its hits in the neighborhood of the track and these are uniformly distributed along the track. The probability that the hit optical modules indeed expect to see a hit is thus very high.

A different approach of hit probabilities is the probability that the not hit channels do not expect to detect a hit.

Both variables described are illustrated in figure 7.17 and figure 7.18 respectively for the signal Monte Carlo, the simulated up-going atmospheric neutrinos, the simulated down-going atmospheric muons and the experimental data. These variables have been used in some of the 14 sub-analyzes. More details about exact cut values can be found in table 7.3.



Figure 7.17: Data after cut level 2: the summed hit probabilities of the hit channels per event. The 16 iterations upandel likelihood reconstruction has been used (fit 8). On the left: Solid line: experimental data, dashed line: down-going atmospheric muon Monte Carlo, dotted line: up-going atmospheric neutrino Monte Carlo. These distributions have been normalized to each other. On the right: all 14 WIMP simulations combined.

7.6 Summary

The analysis has been focused so far on the rejection of the atmospheric muon background events. Each of the 14 sub-analyzes has been developed following the strategy described in section 7.5.1. This method has been followed until all the down going atmospheric muon events were rejected from the experimental data set. This is illustrated in figure 7.19. In this plot the relative selection efficiency is shown for the experimental data, the simulated signal events and the simulated background events as function of the cuts developed for the selection of the 250 GeV soft channel neutralinos. Also the number of

Hit probability of hit channels (8) >	*	*	*	*	*	*	0.25	*	*	*	*	*	*	0.4
Number of direct hits $_{-15ns < t_{res} < 15ns} >$	*	*	*	*	*	*	*	*	*	*	*	6	9	9
No-hit probability of not-hit channels (8) <	*	*	*	*	*	*	*	0.79	0.79	0.79	0.79	0.79	0.79	0.79
$L_{cascade}$ (5) / $L_{muontrack}$ (6) >	*	*	*	*	1.04	1.04	*	*	1.06	*	*	*	*	*
< vanilla smoothness _{allhits} (8) <	-0.25;0.22	-0.25;0.22	*	-0.17;0.26	*	*	*	*	*	*	*	*	*	-0.2;0.2
< smoothness _{allhits} (8)/zenith angle(8) <	*	*	-0.002; 0.0016	-0.002; 0.0016	-0.002; 0.0016	-0.0012; 0.0012	-0.0014; 0.0012	*	*	-0.0014; 0.0012	-0.0014; 0.0012	*	*	*
$L_{up}(8)$ - $L_{down}(8) <$	-15	-20	-18	-20	-11	6-	6-	*	-18	*	*	*	*	*
Smoothness radius $R_{S,dir,iter}$ (8) <	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.35	0.45	0.35	0.35	0.35	0.35	*
Number of direct hits _{$-15ns< t_{res}<75ns}$ (8) >}	8	7	∞	7	∞	٢	∞	∞	∞	٢	7	٢	٢	٢
Length of direct hits _{$-15ns < t_{res} < 75ns$} (8) >	185	166	185	165	175	146	157	136	146	126	125	76	96	LL
Zenith angle muon track $(8) >$	161	161	162	161	161	159	161	159	159	159	157	153	150	151
WIMP simulations (mass / channel)	5000 GeV hard	5000 GeV soft	3000 GeV hard	3000 GeV soft	1000 GeV hard	1000 GeV soft	500 GeV hard	500 GeV soft	250 GeV hard	250 GeV soft	100 GeV hard	100 GeV soft	50 GeV hard	50 GeV soft

Table 7.3: Overview of all cuts of the 14 different sub-analyzes. The order in which the cuts have been applied is not respected due to the complexity of combining 14 sub-analyzes in one table. The * denotes that no cut has been applied. The selection of the cut variables and the determination of the cut values is based on the calculation of $\epsilon_{signal} \cdot (1 - \epsilon_{background})$.



Figure 7.18: Data after cut level 2: the summed no-hit probabilities of the not hit channels per event. The 16 iterations upandel likelihood reconstruction has been used (fit 8). On the left: Solid line: experimental data, dashed line: down-going atmospheric muon Monte Carlo, dotted line: up-going atmospheric neutrino Monte Carlo. These distributions have been normalized to each other. On the right: all 14 WIMP simulations combined.

selected experimental data events and simulated atmospheric neutrino events is shown as function of the selection criteria. From this figure it is clear that the atmospheric muons are completely removed after application of the 5th cut at level 3 in this particular case. Although there is a limitation in the available number of simulated atmospheric muon events, the agreement between the expected number of atmospheric neutrino events and the number of selected experimental data events indicates that the data consist at this point exclusively of atmospheric neutrinos and a possible WIMP signal.

	DATA	trigger	L2	cut 1	cut 2	cut 3	cut 4	cut 5	cut 6
W	imps 100 GeV hard	16372	12898	11995	10755	9287	8757	8071	4971
	99 data	$1.1 \cdot 10^9$	$9.9 \cdot 10^{6}$	141900	7040	326	42	21	13
2	atmospheric muons	20360767	$19.1 \cdot 10^4$	1914	102	6	1	0	0
at	mospheric neutrinos	6110	2496	798.4	67.4	39.9	29.9	24.7	16.9

Table 7.4: The number of experimental and simulated data events passing the criteria of the analysis designed for the selection of 100 GeV hard channel WIMPs. The live time of the experimental data is 187.0 days. The number of simulated atmospheric neutrino events is normalized to the live time of the experimental data. The number of simulated atmospheric muon events corresponds to a live time of 5.6 days. The numbers of selected WIMP events have to be compared to each other on a relative basis."cut n" stands for the nth cut applied at level 3. All cut variables and cut values used are discussed in section 7.5.2.

Table 7.4 confirms this behaviour for the selection criteria of the 100 GeV neutralinos (hard channel). In this table the number of selected experimental and simulated data



Figure 7.19: The relative efficiency of the selection procedure (on the left) as function of the analysis cuts for the experimental data, simulated signal events (WIMP 250 GeV soft) and simulated background events (atmospheric muons and atmospheric neutrinos). All samples have been normalized to 1 at trigger level (cut 0), except for the atmospheric neutrinos that have been normalized to the effective live time of the experimental data. Also the number of experimental data and simulated atmospheric neutrino events (on the right) passing the respective selection criteria are given. "cut 1" contains all cuts applied at level 2. "cut n" (n > 1) corresponds to the (n - 1)th cut of the selection of the 250 GeV soft channel neutralinos applied at level 3. In this illustration the analysis cuts for the selection of 250 GeV soft channel neutralinos are taken as an example. In this plot any other neutralino model could have been chosen. These cuts can also be found in table 7.3.

events are given as function of these cuts. The experimental data and the simulated atmospheric neutrino events agree on a quantitative basis after application of the cuts rejecting the down-going atmospheric muon events as described in section 7.5.2.

The conclusion is that all down-going atmospheric muon events have been suppressed from the experimental data set which consists at this level exclusively out of up-going atmospheric neutrino events and a possible WIMP signal.

Chapter 8

Results

8.1 Introduction

The analysis has been focused so far on the rejection of the atmospheric muon background events, which have been completely removed from the data samples. The number of selected experimental data events and the number expected from simulated atmospheric neutrino Monte Carlo for the same live time correspond to each other after application of the cuts as described in chapter 7.

The next point in the search for neutralino dark matter is the investigation of the angular distribution of the experimental data. As discussed in section 5.3, the presence of a neutralino signal would manifest itself in an excess of near-vertical up-going neutrinoinduced muon tracks on top of the spectrum originating from atmospheric neutrino events.

In section 8.2 the study of the angular distribution of the experimental data events is described. Since no WIMP signal has been found, an upper limit on the muon flux coming from the annihilation of neutralinos can be calculated. A method has been developed to tune the next series of analysis cuts in such a way that the strongest upper limit is obtained on the theoretical signal model. This is explained in section 8.3. The effective volumes are shown for the different neutralino models in section 8.4. Finally, the upper limits are calculated in section 8.5.

8.2 WIMP Signal Excess ?

In the search for neutrinos, coming from the annihilation of neutralinos in the center of the Earth, it is very important to understand the angular spectrum of the selected events, since neutralino signals can be identified by an excess flux of near-vertical tracks on top of the expected atmospheric neutrino flux.

The analysis built up so far rejects the down-going atmospheric muons and concurrently selects the up-going neutrino-induced muons in a very efficient way. In section 7.5.1 the selection method is explained and section 7.5.2 describes the cut variables used. The first, and therefore most efficient, cut variable used in each of the 14 sub-analyzes is the reconstructed muon zenith angle obtained from the 16 iterations upandel likelihood reconstruction. In table 7.3 the cut values for this variable have been summarized.

In order to compare the angular distributions of the selected experimental data events and the expected atmospheric neutrino events, the cut on the reconstructed zenith angle has been omitted in each analysis while the other cuts remain the same. The comparison would otherwise not be statistically significant because the cut on the zenith angle reduces the angular window a lot.



Figure 8.1: The cosine of the reconstructed muon zenith angle for the experimental 99 data and the simulated atmospheric neutrino events. Both data samples have been subjected to the analysis cuts optimized for the selection of 5000 GeV neutralinos hard channel (top left), 3000 GeV neutralinos hard channel (top right) and 1000 GeV neutralinos hard channel (bottom left). The cut on the reconstructed zenith angle (see table 7.3) has been omitted.

Figures 8.1 and 8.2 illustrate the distribution of the cosine of the reconstructed muon zenith angle for the experimental and simulated¹ data passing all the selection cuts for

¹The simulated data consist of atmospheric neutrinos only. All down-going atmospheric muons have been rejected.



Figure 8.2: The cosine of the reconstructed muon zenith angle for the experimental 99 data and the simulated atmospheric neutrino events. Both data samples have been subjected to the analysis cuts optimized for the selection of 500 GeV neutralinos hard channel (top left), 250 GeV neutralinos hard channel (top right), 100 GeV neutralinos hard channel (bottom left) and 50 GeV neutralinos hard channel (bottom right). The cut on the reconstructed zenith angle (see table 7.3) has been omitted.

the hard annihilation channels, listed in table 7.3, except for the cut on the reconstructed muon angle. The shape of the angular distribution of the selected experimental data events is well described by the angular spectrum of the expected atmospheric neutrino events. The theoretically determined spectrum of atmospheric neutrino events shows a 30 to 40% excess in absolute normalization compared to the spectrum of experimental data. This discrepancy is investigated in more detail in chapter 9.



Figure 8.3: The cosine of the reconstructed muon zenith angle for the experimental 99 data and the simulated atmospheric neutrino events. Both data samples have been subjected to the analysis cuts optimized for the selection of 5000 GeV neutralinos soft channel (top left), 3000 GeV neutralinos soft channel (top right) and 1000 GeV neutralinos soft channel (bottom left). The cut on the reconstructed zenith angle (see table 7.3) has been omitted.

Figures 8.3 and 8.4 show the equivalent distributions for the soft channels. The distributions of the experimental and simulated data correspond as regards shape, but there is a discrepancy on the level of absolute normalization. This discrepancy is less pronounced for the soft channels than for the hard channels.

The number of events that pass the cuts of the 14 different sub-analyzes, with exception of the angular cut, are listed for both the experimental data and the simulated



Figure 8.4: The cosine of the reconstructed muon zenith angle for the experimental 99 data and the simulated atmospheric neutrino events. Both data samples have been subjected to the analysis cuts optimized for the selection of 500 GeV neutralinos soft channel (top left), 250 GeV neutralinos soft channel (top right), 100 GeV neutralinos soft channel (bottom left) and 50 GeV neutralinos soft channel (bottom right). The cut on the reconstructed zenith angle (see table 7.3) has been omitted.

data analysis	number of	number of
for the	expected	selected
selection of	atmospheric neutrinos	experimental data
wimps 5000 GeV hard	67.7	48
wimps 5000 GeV soft	69.0	60
wimps 3000 GeV hard	67.7	45
wimps 3000 GeV soft	55.3	49
wimps 1000 GeV hard	78.6	56
wimps 1000 GeV soft	76.7	89
wimps 500 GeV hard	74.5	58
wimps 500 GeV soft	27.3	36
wimps 250 GeV hard	68.8	44
wimps 250 GeV soft	22.2	25
wimps 100 GeV hard	22.2	28
wimps 100 GeV soft	19.5	18
wimps 50 GeV hard	19.5	19
wimps 50 GeV soft	18.2	20

Table 8.1: Number of expected atmospheric neutrino events and selected experimental data events passing the selection criteria optimized for the detection of the respective neutralino signals. The cuts used are summarized in table 7.3. The angular cut is not implemented as this cut reduces the statistical significance.

atmospheric neutrinos in table 8.1.

Although there is a relatively large discrepancy in the absolute normalization between the experiment and the theoretical prediction of the atmospheric neutrino spectrum, the shape of the distributions corresponds. The uncertainties on the absolute normalization of the simulated distribution is discussed in detail in chapter 9.

The conclusion of this verification is that no WIMP signal has been detected in any of the 14 different sub-analyzes. Instead, an upper limit on the muon flux coming from the annihilation of the neutralinos in the center of the Earth can be calculated. Therefore a further reduction of the background events, which at this point only consist of atmospheric neutrino events, is preferable². The important question is: how can the background events be rejected so that the most restrictive limit on the theoretical signal model is obtained ? The answer to this question is the model rejection factor [184], which is explained in the next section.

8.3 Model Rejection Factor

When an experiment fails to detect an expected flux, an upper limit on that flux is derived from experimental observation. Theoretical calculations provide a source flux $\Phi(E, \theta)$. After applying the cuts of the analysis and taking the detector response into account, the signal expectation n_s can be calculated. Applying the same analysis cuts on the background Monte Carlo results in an expected number of background events n_{bg} . When the experiment is performed, n_{obs} events are selected. Following the unified approach of Feldman and Cousins [185], the 90 %-confidence interval of the number of signal events μ_{90} =

²Note that all cuts mentioned in table 7.3 are now considered, including the cut on the zenith angle from the 16 iterations upandel likelihood reconstruction.

 (μ_1, μ_2) is calculated. In this experiment μ_{90} depends on both the number of background events n_{bg} and the number of observed events n_{obs} :

$$\mu_{90}(n_{obs}, n_{bg}) \tag{8.1}$$

The upper limit on the source spectrum $\Phi(E, \theta)$ at 90 % confidence level is defined as:

$$\Phi(E,\theta)_{90\%} = \Phi(E,\theta) \frac{\mu_{90}(n_{obs}, n_{bg})}{n_s}$$
(8.2)

In order to put the most restrictive limit on the theoretical signal model, the analysis cuts are optimized such that the ratio $\frac{\mu_{90}(n_{obs}, n_{bg})}{n_s}$ is as small as possible. However, this is not straightforward since μ_{90} depends on n_{obs} which is only known when the experiment has been performed and the cuts have been applied. This means that μ_{90} has to be replaced by something that does not depend on n_{obs} . Based on the concept of "an ensemble of experiments", an average upper limit³ is defined:

$$\bar{\mu}_{90}(n_{bg}) = \sum_{n_{obs}=0}^{\infty} \mu_{90}(n_{obs}, n_{bg}) \frac{(n_{bg})^{n_{obs}}}{(n_{obs})!} exp(-n_{bg})$$
(8.3)

The average upper limit is the infinite sum of upper limits with expected background n_{bq} and no true signal, weighed by their poisson probability of occurrence.



Figure 8.5: The average upper limit as function of the number of background events for the Feldman-Cousins unified 90 %-confidence level upper limits in the absence of a signal.

Figure 8.5 shows the average upper limit as function of the number of background events for the Feldman-Cousins unified 90 %-confidence level upper limits. The Model

³This quantity is called "sensitivity" by Feldman and Cousins.
8.3. MODEL REJECTION FACTOR

Rejection Factor (M.R.F.) [184] is defined as the ratio of the average upper limit and the number of expected signal events:

$$M.R.F. \equiv \frac{\bar{\mu}_{90}(n_{bg})}{n_s} \tag{8.4}$$

The number of signal events is not precisely known because the annihilation frequency of neutralinos in the center of the Earth depends on the 7 free parameters of the Minimal Super-symmetric extension of the Standard Model (MSSM) (see chapter 2). However, the value of the model rejection factor is not important in this analysis. The model rejection factor has not been used to calculate the upper limits (see section 8.5), but as an indicator of the most interesting cut value for the particular variable. In this dissertation, the number of signal events is replaced by the selection efficiency of the signal events. Over a set of identical experiments, the minimization of the model rejection factor will lead to the strongest constraint on the signal flux.

In each of the 14 sub-analyzes, the model rejection factor has been used. In a first attempt, the model rejection factor was calculated for several variables in order to select the variable that results in the best (lowest) average upper limit on the muon flux. It has turned out that, although every sub-analysis already contains a cut on the reconstructed muon zenith angle as described in chapter 7, an additional cut on the muon zenith angle is needed to obtain the lowest average upper limit on the muon flux.

In figure 8.6 the model rejection factor is shown as function of the cut on the reconstructed muon zenith angle. In this stage of the analysis, only atmospheric neutrino events (nusim Monte Carlo) are considered as background since all down-going atmospheric muons have been removed from the experimental data. The model rejection factor shows a clear minimum at 177° in this example.

The resulting cut values for the 16 iterations upandel likelihood reconstruction, based on the model rejection factor, are summarized in table 8.2 for each sub-analysis. The cut values vary from 169° for the lowest neutralino masses to 177° for the highest neutralino masses. This behaviour is the reflection of the expected concentration of the neutralinos around the core of the Earth. As the neutralinos are gravitationally trapped, massive neutralinos are expected to accumulate more closely to the center of the Earth compared to the relatively light neutralinos. The deviation angle between the neutrino and the muon is, in addition, smaller for high-energy neutrinos. (see also chapter 3).

The number of experimental data and simulated atmospheric neutrino events that pass all selection criteria⁴ are given in table 8.2. The expected number of simulated background events and the selected number of experimental data events are, within the statistical uncertainty, in perfect agreement with each other in each sub-analysis.

⁴The final selection cuts include the cuts summarized in table 7.3 and the cut based on the model rejection factor.



Figure 8.6: Data after cut level 3 for the selection of 1 TeV hard channel neutralinos. Top left: The number of selected WIMP events as function of the cut on the reconstructed muon angle; Top right: The number of remaining atmospheric neutrinos (nusim Monte Carlo) as function of the cut on the reconstructed muon angle; Bottom left: The average upper limit as function of the cut on the reconstructed muon angle; Bottom right: The Model Rejection Factor as function of the cut on the reconstructed muon angle.

Data analysis	Cut value reconstructed	Number of	Number of
for the	zenith angle	selected experimental	expected atmospheric
selection of	muon track (8)	99 data events	neutrino events
wimps 5000 GeV hard	177	1	1.38
wimps 5000 GeV soft	177	2	1.28
wimps 3000 GeV hard	177	1	1.33
wimps 3000 GeV soft	177	1	1.21
wimps 1000 GeV hard	177	1	1.46
wimps 1000 GeV soft	177	1	1.61
wimps 500 GeV hard	176	3	3.70
wimps 500 GeV soft	175	4	4.15
wimps 250 GeV hard	175	3	5.17
wimps 250 GeV soft	175	4	3.94
wimps 100 GeV hard	175	5	3.94
wimps 100 GeV soft	169	9	10.27
wimps 50 GeV hard	169	9	10.34
wimps 50 GeV soft	169	10	9.39

Table 8.2: The optimal cut value based on the model rejection factor for the 16 iterations upandel likelihood reconstruction is shown for each of the 14 sub-analyzes. Also the number of experimental data events and atmospheric neutrino events that pass all selection cuts are given.

8.4 Effective Volumes

The effective volume is a useful tool to determine the detector performance and the cut efficiency as function of the neutralino mass. At trigger level the effective volume is calculated in the following way:

$$V_{eff_{trigger}} = \frac{n_{trigger}}{n_{gen}} V_{gen}$$
(8.5)

where $n_{trigger}$ is the number of events that have triggered the detector (see section 4.4) and n_{gen} is the number of events⁵ that have been generated in the cylindrical volume V_{gen} around the detector (see also section 5.3).

The effective volume is in fact a measure of how far a detector can see in the ice. This is of course mass dependent. The effective volume takes the effect of tracks starting or stopping within the detector volume in addition to through-going tracks into account.

The effective volumes at the final cut level are calculated in a similar way:

$$V_{eff_{cut}} = \frac{n_{cut}}{n_{gen}} V_{gen} \tag{8.6}$$

where n_{cut} is the number of events that passed all selection cuts, summarized in tables 7.3 and 8.2, and n_{gen} is the number of events that were generated in the volume V_{gen} around the detector.

The height and the radius of the cylindrical generated volume and the generated volume itself, used in this dissertation, are listed in table 5.1 for the different neutralino

⁵500000 events have been generated for each neutralino mass and annihilation channel.

WIMP simulation	Number of triggered WIMPS	Number of selected WIMPS
wimps 5000 GeV hard	17173	6609
wimps 5000 GeV soft	4663	1712
wimps 3000 GeV hard	24924	9941
wimps 3000 GeV soft	7113	2313
wimps 1000 GeV hard	22422	8660
wimps 1000 GeV soft	6778	2065
wimps 500 GeV hard	21040	8200
wimps 500 GeV soft	6334	1940
wimps 250 GeV hard	23032	8467
wimps 250 GeV soft	6725	1757
wimps 100 GeV hard	16372	3580
wimps 100 GeV soft	4334	1048
wimps 50 GeV hard	4244	957
wimps 50 GeV soft	965	177

Table 8.3: The number of triggered WIMPS and the number of WIMP events passing all selection criteria.

WIMP simulation	Effective volume at trigger level (m ³)	Effective volume at final cut level (m ³)
wimps 5000 GeV hard	$118 \cdot 10^{6}$	$45.6 \cdot 10^{6}$
wimps 5000 GeV soft	$322 \cdot 10^5$	$11.8 \cdot 10^{6}$
wimps 3000 GeV hard	$810 \cdot 10^{5}$	$32.3 \cdot 10^{6}$
wimps 3000 GeV soft	$231 \cdot 10^{5}$	$7.5 \cdot 10^6$
wimps 1000 GeV hard	$333 \cdot 10^5$	$12.9 \cdot 10^{6}$
wimps 1000 GeV soft	$101 \cdot 10^{5}$	$30.7 \cdot 10^{5}$
wimps 500 GeV hard	$179 \cdot 10^5$	$69.7 \cdot 10^5$
wimps 500 GeV soft	$539 \cdot 10^4$	$16.5 \cdot 10^{5}$
wimps 250 GeV hard	$897 \cdot 10^4$	$33.0 \cdot 10^{5}$
wimps 250 GeV soft	$262 \cdot 10^{4}$	$68.4 \cdot 10^4$
wimps 100 GeV hard	$250 \cdot 10^4$	$54.7 \cdot 10^4$
wimps 100 GeV soft	$662 \cdot 10^{3}$	$16.6 \cdot 10^4$
wimps 50 GeV hard	$418 \cdot 10^{3}$	$94.3 \cdot 10^3$
wimps 50 GeV soft	$951 \cdot 10^{2}$	$17.4 \cdot 10^{3}$

Table 8.4: The effective volumes at trigger level and at the final cut level for the 14 different sub-analyzes.

signal Monte Carlo samples. Table 8.3 lists the number of triggered WIMP events and the number of WIMP events passing all selection criteria.



Figure 8.7: Effective volumes as function of the neutralino mass at trigger level. The results are given for both the hard and soft annihilation channels and for both the 99 and 97 [77] data analyzes.

In table 8.4 the effective volumes are listed as function of the neutralino mass at trigger level. In figure 8.7 the results are shown for both the hard and soft annihilation channel and for both the 1997 [77] and 1999 (this work) data analyzes. The effective volumes are higher for all masses in the analysis of 1997 data compared to the results obtained in the 1999 data analysis. This difference can be explained. Part of the answer is related to the multiplicity trigger (see section 4.4). In 1999 the multiplicity trigger was set in such a way that an event was recorded as soon as at least 18 optical modules fired in a time window of 2.2 μ s. In the analysis of the 1997 data, this multiplicity trigger was set to 14 only. It is obvious that the latter condition results in a higher number of triggered data events. The second part of the answer relates to the muon propagator used in the Monte Carlo simulation. In the 1999 data simulation, the program "MMC" (see section 5.4) has been used to simulate the propagation of muons through the ice. This program simulates the energy losses, due to secondary processes, better than the muon propagator "MUDEDX" that has been used in the 1997 data simulations and uses tables calculated by Lohmann in

[186]. The events simulated by MMC show very bright tracks and relative high-energy losses, due to secondary processes, as observed in the experimental data events. This results in the generation of relatively short tracks. The MMC generated events finally pass the multiplicity trigger less efficiently than the events generated by mudedx.

From figure 8.7 it is also clear that the AMANDA-B10 detector is more sensitive to neutralinos with a larger branching ratio to annihilation channels which result in hard neutrino spectra than to models which preferentially give soft neutrino spectra, independent of the neutralino mass. The effective volumes increase for increasing neutralino masses until a saturation level is reached. High neutralino masses induce long muon tracks, which are easily detectable. The higher the neutralino mass, the longer the muon track.



Figure 8.8: Effective volume as function of the neutralino mass at the final cut level. The results are given for both the hard and soft annihilation channels and for both the 99 (this work) and the 97 [77] data analyzes.

Figure 8.8 and table 8.4 show the effective volumes of the 1999 data analysis at the final cut level. These seem to agree with the corresponding effective volumes of the 1997 data analysis [77] for the high neutralino masses. For the low neutralino masses the 99 data analysis seems to be more efficient. Especially for the 50 GeV and the 100 GeV channels, the gain in effective volume is 1-2 orders of magnitude, mainly due to the improved reconstruction algorithms available and an optimized analysis for each individual

signal Monte Carlo.

8.5 Flux Limits

8.5.1 Introduction

Since no statistically significant neutralino signal has been measured, an upper limit on the annihilation rate of the neutralinos in the center of the Earth can be calculated and translated into an upper limit on the muon flux coming from the annihilation of neutralinos. This section describes how these upper limits are calculated.

8.5.2 Limit on the Signal Expectation

Assuming there is only one Poisson distributed signal, the probability α of observing less than or the same number of events as observed in the experiment is given by:

$$\alpha = \sum_{n=0}^{n_0} P(n|\mu_s) \tag{8.7}$$

where $P(n \mid \mu_s) = \frac{\mu_s^n}{n!} e^{-\mu_s}$ corresponds to the probability of observing *n* events assuming that the Poisson distribution has a mean μ_s , and n_0 is the number of observed events in the experiment.

After choosing an α , usually 10%, the μ_s for which the above condition is fulfilled, is the $1 - \alpha$ confidence upper limit on the number of signal events, μ_s^{up} . This means that $1 - \alpha$ is the lower limit on the probability that the true number of signal events is lower than the calculated number μ_s^{up} , see also [188].

If there is a Poisson distribution of background events with mean μ_b in addition to the signal, equation 8.7 becomes:

$$\alpha = \frac{\sum_{n=0}^{n_0} P(n|\mu_s + \mu_b)}{\sum_{n=0}^{n_0} P(n|\mu_b)}$$
(8.8)

The probability of observing more events than the number of events measured in the experiment is then:

$$1 - \alpha = 1 - \frac{\sum_{n=0}^{n_0} P(n|\mu_s + \mu_b)}{\sum_{n=0}^{n_0} P(n|\mu_b)}.$$
(8.9)

In [188], [189], the unified approach for confidence belt construction used to calculate 90 %-confidence level limits is explained in more detail. From the number of expected atmospheric neutrino events and the observed number of experimental data events, mentioned in table 8.2, an upper limit on the number of signal events at 90 %-confidence level, N_{90} , has been calculated for each of the 14 sub-analyzes. In table 8.5 the results are

WIMP simulation	N_{90}
wimps 5000 GeV hard	2.93
wimps 5000 GeV soft	4.58
wimps 3000 GeV hard	2.93
wimps 3000 GeV soft	3.08
wimps 1000 GeV hard	2.93
wimps 1000 GeV soft	2.78
wimps 500 GeV hard	3.68
wimps 500 GeV soft	4.28
wimps 250 GeV hard	2.63
wimps 250 GeV soft	4.58
wimps 100 GeV hard	6.07
wimps 100 GeV soft	4.87
wimps 50 GeV hard	4.87
wimps 50 GeV soft	6.97

listed. They have been obtained using the "POLE" program [190] developed within the AMANDA collaboration.

Table 8.5: The upper limit on the number of signal events at 90 % confidence level, N_{90} , for the 14 different sub-analyzes.

8.5.3 Limit on the Conversion Rate

From the upper limits on the number of signal events and the effective volumes calculated in section 8.4, upper limits on the conversion rate of neutrinos to muons near the detector can be derived.

The number of muons from neutralino annihilation detected during the live time t is given by:

$$N_{\mu} = \Gamma_{\nu\mu} \cdot V_{\text{eff}} \cdot t \tag{8.10}$$

where $\Gamma_{\nu\mu}$ is the conversion rate per unit volume and time of neutrinos to muons near the detector. Using this formula, the upper limit on the conversion rate follows directly from the upper limit on the number of signal events N_{90} :

$$\Gamma_{\nu\mu}(E_{\mu} \ge E_{\mu,thr}) \le \frac{N_{90}}{V_{\text{eff}} \cdot t}$$
(8.11)

This is the limit on the number of muons produced in neutrino interactions per unit volume and time and with an energy higher than the muon energy threshold $E_{\mu,thr}$, which is equal to 10 GeV in these simulations. Since the effective volume and the upper limit on the number of signal events are unique for each neutralino mass and annihilation channel, the upper limits on the neutrino-to-muon conversion rates are model-dependent.

The conversion rates shown in table 8.6 are obtained using the effective volumes listed in table 8.4, the upper limits on the number of signal events mentioned in table 8.5 and taking a live time t of 187.0 days into account (see section 5.2).

Mass (GeV/c ²)	$\Gamma_{\nu\mu} (\mathrm{km}^{-3}\cdot\mathrm{year}^{-1})$	Annihilation rate (s^{-1})
wimp 5000 hard channel	125.4	$1.28\cdot 10^{10}$
wimp 5000 soft channel	756.0	$4.27\cdot10^{11}$
wimp 3000 hard channel	176.7	$3.00\cdot 10^{10}$
wimp 3000 soft channel	800.1	$6.41\cdot10^{11}$
wimp 1000 hard channel	444.2	$2.29\cdot 10^{11}$
wimp 1000 soft channel	1764.0	$3.40\cdot10^{12}$
wimp 500 hard channel	1030.1	$1.08\cdot10^{12}$
wimp 500 soft channel	5071.5	$1.87\cdot 10^{13}$
wimp 250 hard channel	1553.0	$3.37\cdot 10^{12}$
wimp 250 soft channel	13041.0	$1.04\cdot 10^{14}$
wimp 100 hard channel	21640.5	$1.32\cdot 10^{14}$
wimp 100 soft channel	57330.0	$1.80\cdot 10^{15}$
wimp 50 hard channel	100800.0	$2.42\cdot 10^{15}$
wimp 50 soft channel	781200.0	$4.40\cdot10^{17}$

Table 8.6: The 90 %-confidence level upper limits on the neutrino-to-muon conversion rates and on the annihilation rates of the neutralinos in the center of the Earth for the different neutralino masses and spectra.

8.5.4 Limit on the Annihilation Rate

The limits on the conversion rate can be translated into limits on the annihilation rate Γ_A of neutralinos in the center of the Earth, since the total neutrino-to-muon conversion rate can be written as (see also [130], [187]):

$$\Gamma_{\nu\mu} = \frac{\Gamma_A}{4\pi R_{\oplus}^2} \int dE_{\nu} \sum_F B_F \left(\frac{dN}{dE_{\nu}}\right)_F \cdot \sigma_{\nu N}(E_{\nu}) \cdot \rho_N \tag{8.12}$$

where R_{\oplus} is the radius of the Earth (the depth of the detector is negligible compared to R_{\oplus}), B_F is the branching ratio of the neutralino annihilation into the annihilation channel F with neutrino spectrum $\left(\frac{dN}{dE_{\nu}}\right)_F$, $\sigma_{\nu N}$ is the neutrino-nucleon cross-section and ρ_N is the density of nucleons in the ice surrounding the detector or in the bedrock below the detector. The muon energy threshold of 10 GeV used in the signal and background simulations has been taken into account through the muon production cross section.

Because each neutralino model has its unique neutrino spectrum, there is exactly one conversion factor c_i for each neutralino mass and annihilation channel:

$$\Gamma_{\nu\mu} = c_i \Gamma_A \tag{8.13}$$

This relation is used to convert the upper limits on the ν -to- μ conversion rate to upper limits on the neutralino annihilation rate. The results are given in table 8.6 and plotted in figure 8.9 for both the 1999 data analysis (this work) and the 1997 data analysis [77]. The resulting upper limits on the annihilation rate of this work are better than the results obtained in the 1997 data analysis for all masses and both the hard and soft annihilation channel. The upper limits for the 5000 GeV soft channel neutralinos and the 500 GeV hard channel neutralinos are a little bit higher than expected when compared to the upper limits for the other neutralino masses. This is due to the limited statistics of the final experimental data sample and the fact that the analysis cuts have been tuned on a subsample of experimental data (see section 7.2). The upper limits on the annihilation rate with the inclusion of systematic uncertainties will be shown in chapter 9.

The advantage of quoting limits on the annihilation rate is that the detector efficiency and threshold are included through equation 8.11. This implies that upper limits on the neutralino annihilation rate, published by different experiments, can be directly compared.

However, most experiments present their results as upper limits per unit area and time on the muon flux coming from the annihilation of neutralinos. This makes direct comparison between results of different experiments more difficult since the energy threshold enters in a non-trivial way in the calculation of the upper limit on the muon flux.

8.5.5 Limit on the Muon Flux

The upper limit on the total number of muons per unit area and time above an energy threshold $E_{\mu,thr} = 10$ GeV within a cone of half angle ϑ_c^6 can be written as a function of the upper limit on the annihilation rate (see also [130], [187]):

$$\Phi_{\mu}(E_{\mu} \ge E_{\mu,thr}, \vartheta \ge \vartheta_{c}) = \frac{\Gamma_{A}}{4\pi R_{\oplus}^{2}} \int_{E_{\mu,thr}}^{\infty} \int_{\vartheta_{c}}^{180^{\circ}} \frac{d^{2}N_{\mu}}{dE_{\mu}d\vartheta} dE_{\mu}d\vartheta$$
(8.14)

where the term $\frac{d^2 N_{\mu}}{dE_{\mu} d\vartheta}$ represents the number of muons per unit angle and energy produced in the neutralino annihilations and includes the decay of the particles created at the annihilation of the neutralinos, the neutrino-nucleon interactions and the muon energy losses from the production point to the detector. The upper limits on the muon flux, at any depth and above any arbitrary muon energy threshold and angular aperture, can be derived in this way from the upper limits on the annihilation rate.

The 90%-confidence level upper limits on the muon flux are shown in table 8.7 and plotted in figure 8.10. These upper limits have been calculated for a muon energy threshold of 1 GeV instead of 10 GeV. This makes the comparison with the results of other experiments (see chapter 9) possible. The upper limits on the muon flux resulting from the 1999 data analysis are lower than the upper limits achieved in [77] for all masses and both the hard and soft annihilation channel. The upper limits for the 5000 GeV soft channel neutralinos and the 500 GeV hard channel neutralinos are higher than expected compared to the upper limits for the other neutralino masses. This is due to the limited statistics of the final experimental data sample and the fact that the analysis cuts have been tuned on a sub-sample of experimental data (see section 7.2). In chapter 9 these upper limits will be calculated with the systematic uncertainties included.

⁶This is the angle of the muon with respect to the source (center of the Earth).



Figure 8.9: The 90 %-confidence level upper limits on the annihilation rate of neutralinos in the center of the earth as a function of the neutralino mass. No systematic errors are included in the limits (see chapter 9). The solid line corresponds to the hard annihilation channels, while the soft annihilation channels are represented by the dashed line. The results of both the 1999 data analysis (this work) and the 1997 data analysis [77] are illustrated.



Figure 8.10: The 90 %-confidence level upper limits on the muon flux coming from the annihilation of neutralinos in the center of the earth as a function of the neutralino mass. The muon energy threshold at the vertex is 1 GeV. No systematic errors are included in the limits (see chapter 9). The solid line corresponds to the hard annihilation channels, while the soft annihilation channels are represented by the dashed line. The results of both the 1999 data analysis (this work) and the 1997 data analysis [77] are illustrated.

Mass (GeV/c ²)	muonflux (km ^{-2} · yr ^{-1})
	$(E_{\mu,thr} = 1 \text{ GeV})$
wimp 5000 hard channel	432.7
wimp 5000 soft channel	834.8
wimp 3000 hard channel	447.5
wimp 3000 soft channel	651.4
wimp 1000 hard channel	512.0
wimp 1000 soft channel	680.7
wimp 500 hard channel	667.3
wimp 500 soft channel	1175.3
wimp 250 hard channel	540.8
wimp 250 soft channel	1876.8
wimp 100 hard channel	2924.5
wimp 100 soft channel	5595.4
wimp 50 hard channel	8901.5
wimp 50 soft channel	125073

Table 8.7: The 90 %-confidence level upper limits on the muon flux coming from the annihilation of neutralinos in the center of the Earth for the different neutralino masses and spectra. The muon energy threshold = 1 GeV.

Chapter 9

Systematic Uncertainties and Discussion

9.1 Introduction

The upper limits on the muon flux coming from the annihilation of neutralinos in the center of the Earth, determined in chapter 8, are affected by systematic uncertainties. Compared to those of traditional high-energy physics experiments, neutrino telescopes like AMANDA have large systematic errors, mainly because there is no precise calibration source of high-energy neutrinos available. Another difficulty is related to the fact that the AMANDA detector consists of strings of optical modules that are deployed in the ice of the antarctic glacier, as described in chapter 4. As these optical modules are not accessible once they are installed, their behaviour must be deduced from the signals received by the electronics. The optical properties of the ice (see section 5.4.5) have to be measured using deployed devices because no direct access to the ice at a depth of ~ 2000 m is possible.

The inclusion of the known theoretical and experimental systematic uncertainties in the calculation of the upper limit on the muon flux is not straightforward. The latter has been derived from the upper limit on the neutrino-to-muon conversion rate. Taking equation 8.11 into account, the uncertainties on the muon flux result from the uncertainties on the effective volumes V_{eff} for muons coming from the annihilation of neutralinos as well as the uncertainties on the estimation of the upper limit on the number of signal events, N_{90} . The uncertainties on N_{90} are in turn due to the uncertainties on the flux of atmospheric neutrinos and the uncertainties on the sensitivity of the detector.

In [191] a method has been proposed to incorporate systematic uncertainties into an upper limit. A similar approach [192] has been developed within the AMANDA collaboration in which systematic uncertainties are incorporated into the calculation of confidence intervals by integrating over the probability density functions parameterizing the uncertainties. Since negative efficiencies are un-physical, a log-normal distribution is used for the parameterization of the uncertainties. This method is well fitted to the specific case of this work as uncertainties in the prediction of background processes, uncertainties in the signal detection efficiency and background detection efficiency are taken into account. On top of that it allows for a correlation between the signal and the background

detection efficiencies. The method is a modified Feldman-Cousins-type confidence belt construction. More information can be found in [188], [192], [193] and [194].

In this chapter the different sources of systematic uncertainties are described. One section is devoted to an update of the signal Monte Carlo. The upper limits on the muon flux coming from the annihilation of neutralinos are re-calculated for the different neutralino masses and annihilation channels, taking these systematic uncertainties into account. The final results are compared to the results obtained by other indirect and direct detection experiments and the predictions of a set of relevant MSSM models. The effect of WIMP diffusion in the solar system is also explained. Finally the results of this work are discussed.

9.2 Sources of Systematic Uncertainties

As explained in section 5.4.5, the implementation of the measured optical properties of the ice are based on approximations made by the program PTD. However, these approximations appear to be insufficiently accurate. The Monte Carlo does not correspond well with experimental data due to the underestimation of the absorption in the simulation, resulting in a larger number of late photons to be observed in the Monte Carlo than in data. The Muon Absorption Model (MAM), which has been selected as the standard ice model, eliminates this discrepancy by adjusting the absorption length such as to fit the observed photon distributions.

In order to get some indication of how the implementation of the ice model affects the estimate of the detection efficiency, the MAM model is compared to the older ice model called the Kurt-Gary Model (KGM). KGM uses measured properties of the ice and includes them into the simulation. It has not been combined with the measurements of the angular sensitivity [140], nor with the Sudhoff OM transmissivity measurements [153] (see chapter 5). KGM does not include the effect of the OM sensitivity, unlike MAM, although they both use the same layering of ice. Thus comparing the simulations based on the MAM ice model with those based on the KGM ice model does not only give an indication on the detection efficiency uncertainty due to the implementation of the ice model in the simulation, but also on the detection efficiency uncertainty due to the uncertainty on the absolute and angular OM sensitivity.

Figures 9.1 and 9.2 illustrate the cosine of the reconstructed muon zenith angle for the experimental and simulated data passing the selection cuts for several hard and soft annihilation channels, listed in table 7.3, except for the cut on the reconstructed muon angle (see section 8.2). The simulated atmospheric neutrino events are based on the KGM ice model, whereas the corresponding figures 8.1, 8.2, 8.3 and 8.4 use atmospheric neutrino Monte Carlo based on the MAM ice model.

The behaviour of the KGM- and MAM-based atmospheric neutrinos seems to be comparable for this relatively large sample of selected events. The shape of the angular distribution of the KGM-based atmospheric neutrino events compares well with the shape of the angular spectrum of the selected experimental data and the atmospheric neutrinos based on MAM. The theoretically determined spectrum of KGM-based atmospheric



Figure 9.1: The cosine of the reconstructed muon zenith angle for the experimental 99 data and the simulated atmospheric neutrino events (KGM ice model). Both data samples have been subjected to the analysis cuts optimized for the selection of 3000 GeV neutralinos hard channel (top left), 1000 GeV neutralinos hard channel (top right), 500 GeV neutralinos hard channel (bottom left) and 250 GeV neutralinos hard channel (bottom right). The strong cut on the reconstructed zenith angle (see table 7.3) has been omitted.



Figure 9.2: The cosine of the reconstructed muon zenith angle for the experimental 99 data and the simulated atmospheric neutrino events (KGM ice model). Both data samples have been subjected to the analysis cuts optimized for the selection of 5000 GeV neutralinos soft channel (top left), 3000 GeV neutralinos soft channel (top right), 1000 GeV neutralinos soft channel (bottom left) and 100 GeV neutralinos soft channel (bottom right). The strong cut on the reconstructed zenith angle (see table 7.3) has been omitted.

neutrino events shows, as well as the spectrum of events based on MAM, an excess in absolute normalization, compared to the spectrum of experimental data, which is much more pronounced for the hard annihilation channels than for the soft channels.

WIMP MC	$ \Delta V_{effs} $ (MAM-KGM) %	$ \Delta V_{eff_{bg}} $ (MAM-KGM) %
wimp 5000 hard channel	28	23
wimp 5000 soft channel	31	18
wimp 3000 hard channel	30	8
wimp 3000 soft channel	34	23
wimp 1000 hard channel	32	16
wimp 1000 soft channel	38	28
wimp 500 hard channel	31	39
wimp 500 soft channel	39	20
wimp 250 hard channel	33	7
wimp 250 soft channel	38	22
wimp 100 hard channel	39	22
wimp 100 soft channel	24	6
wimp 50 hard channel	21	5
wimp 50 soft channel	57	9

Table 9.1: The difference in detection efficiency for signal and the difference in detection efficiency for background resulting from the comparison of the MAM based Monte Carlo with the KGM based Monte Carlo after the selection cuts, summarized in table 7.3, and the cut based on the model rejection factor have been applied for the 14 different sub-analyzes.

However, the difference between the simulations based on the MAM ice model and those based on the KGM ice model seems to be larger for near-vertical up-going muon tracks (see also [168]). In table 9.1 the absolute value of the difference in detection efficiency for background events resulting from the comparison of the MAM based Monte Carlo with the KGM based Monte Carlo is shown after all selection cuts have been applied, including the angular cut based on the model rejection factor. The differences vary from $\sim 10 \%$ to $\sim 30 \%$.

In figure 9.3 the effective volumes are illustrated for the muon tracks induced by the annihilation of neutralinos in the center of the Earth as a function of the neutralino mass at the final cut level¹ for both the MAM and the KGM ice model. The absolute value of the difference between the effective volumes based on MAM and KGM is listed in table 9.1 as well. The effective volumes based on KGM are systematically lower than those based on MAM, except for the 50 GeV soft channel where the statistics are very low. This can be partly explained by the fact that the analysis cuts have been tuned on a training sample that only consists of MAM simulated events, as that is the standard ice model used in AMANDA. Since the cuts cannot be changed in order to respect blindness (see section 7.2), they will implicitly favor events based on the MAM ice model. The differences in detection efficiency for signal events vary from $\sim 20 \%$ to $\sim 50 \%$.

Another, but not un-correlated, systematic uncertainty originates from the modeling of the absolute and angular sensitivity of the AMANDA optical modules. The absolute

¹The final selection cuts include the cuts summarized in table 7.3 and the cut based on the model rejection factor.



Figure 9.3: The effective volumes for the muon tracks induced by the annihilation of neutralinos in the center of the Earth passing the final cuts as a function of the neutralino mass for both the MAM and KGM ice model and both the hard and soft annihilation channel.

optical module sensitivity is a combination of the quantum and collection efficiency² of the photo-multiplier tube and the transmissivity of the OM glass and the optical gel, in between the PMT and the OM glass. These quantities can be measured in the laboratory prior to deployment. However, aging effects of the PMT or the gel inside the OM, as well as temperature or pressure effects can change in situ properties compared to those measured in the lab. The manufacturer specifications for the uncertainty in the quantum and collection efficiency are respectively 20 % and 10 % [195], while measurements of the transmissivity of the OM glass and optical gel of several optical modules result in an uncertainty of ~ 10 %. Since these uncertainties are considered un-correlated, they are added in quadrature to each other, resulting in an uncertainty of ~ 25 %. In [196] the impact of the OM sensitivity on the AMANDA-B10 results has been investigated. It has been shown that a 25 % change in the absolute sensitivity of all OMs leads to a ~ 10 % change in the rate of muons. This is of course an energy-dependent approximation. The uncertainty on the absolute OM sensitivity is estimated to be ~ 10 % in this work.

In section 5.4.5 it has been explained that the deployment of the AMANDA strings in the antarctic ice, i.e. drilling the holes using pressurized hot water and the re-freezing of the water after the installation of the strings, causes an enlarged density of air bubbles near the optical modules. The air bubbles lead to additional photon scattering, which changes the angular dependence of the OM sensitivity measured in ice [197]. This effect has been studied in [140] making use of both down-going muon tracks and up-going neutrinoinduced muon tracks. The result of this study is a correction of the angular sensitivity of the optical modules, which mainly consists of a reduction of the OM sensitivity in the "forward direction"³, the most sensitive angular range of the OM for the detection of upgoing muon tracks. A new hole-ice/angular sensitivity model⁴ has been derived from this angular sensitivity analysis. However, the latter has been performed using an ice model which is considered out-dated compared to the MAM and KGM ice models. Therefore the angular sensitivity model cannot be considered as an improvement of the OM angular response representation and will not be used in this dissertation. However, it does give an indication of the uncertainty on the detection efficiency, caused by the uncertainty in angular sensitivity, which is estimated to be $\sim 25 \%$ [165]. Adding this uncertainty in quadrature to the uncertainty due to the absolute OM sensitivity yields an uncertainty of ~ 27 % in the detection efficiency.

In section 5.4.2 the muon propagation code used in this work has been discussed. The propagation code MMC uses formulas for cross-sections which are valid within 1 % [199]. The coefficients a and b of equation 3.14 are known within 3 % and 5 % respectively in the muon energy range sensitive to AMANDA. In [200] the differences in the muon flux and the energy spectrum at the detector depth caused by the use of different muon propagation codes was examined and resulted in uncertainties of the order of ~ 10 %. In this analysis a systematic uncertainty of 10 % has been assumed due to the treatment of the muon propagation in the ice.

²The quantum efficiency is defined as the fraction of photons that yield a photo-electron, while the collection efficiency is defined as the fraction of photo-electrons that hit the first dynode.

³This concerns photons that hit the OM head-on.

⁴This model is often referred to as the "angsens" model.

9.2. SOURCES OF SYSTEMATIC UNCERTAINTIES

Several effects related to the detector hardware simulation generally result in very small systematic errors. A revision of the detector simulation has been performed in [137] yielding a change in the simulated trigger rate for atmospheric muons of the order of 6 %. As this increase in rate for atmospheric muons cannot be translated into a rate of neutrino-induced muons or muons coming from the annihilation of neutralinos, it is reasonable to assume that the effects caused by hardware simulation are not bigger for the signal simulation. Therefore the uncertainty resulting from hardware simulation is considered ~ 6 %.

In [201] the reconstruction uncertainties due to time calibration errors have been discussed. The uncertainties in the timing calibration and the geometry calibration are estimated to be ~ 5 %, which translates into a detection efficiency uncertainty of ≤ 2 %.

Not all sources of systematic uncertainties discussed in this section are independent. This makes it very difficult to combine all these effects into a final estimate of the total uncertainty in V_{eff} . As already stated above, the comparison of the simulations based on MAM with those based on KGM gives an estimate of how uncertainties on the ice models and the OM sensitivities are translated into uncertainties on the detection efficiency. This results from the fact that the MAM model has been obtained by fitting the Monte Carlo to data, while the KGM model is the result of actual measurements of ice properties which have been implemented in the simulation.

The absolute and angular OM sensitivity uncertainties were discussed separately as they were investigated several times in very different ways. They cannot be added quadratically to the uncertainties obtained from the comparison of MAM with KGM as the correlation is too strong. Instead the uncertainties due to the muon propagation (10 %), the hardware simulation (6 %) and the calibration (2 %) are quadratically added to the uncertainty due to the absolute and angular OM sensitivity (27 %) yielding a total systematic uncertainty of 29 % for both the signal detection efficiency and the background detection efficiency, defined as approach 1. This estimate of the systematic uncertainty can be compared to the systematic uncertainty obtained from the comparison of MAM and KGM, listed in table 9.1 and defined as approach 2.

In this analysis the nominal values of V_{eff} to be used in equation 8.11 are the effective volumes listed in table 8.4 based on the MAM ice model, since this is the standard ice model to be used. As a conservative estimate of the uncertainty on the detection efficiency, the largest difference between the effective volumes obtained, assuming approach 1 and approach 2 with respect to the nominal effective volumes, are chosen as the total systematic uncertainty.

In table 9.2 the number of experimental data events and atmospheric neutrino events passing all selection criteria are given (see also table 8.2) together with the systematic uncertainties on the signal detection efficiency and the background detection efficiency.

Further uncertainty in the number of expected atmospheric neutrinos comes from the uncertainties present in the calculation of the atmospheric neutrino flux. The atmospheric neutrino flux is a convolution of the primary cosmic ray spectrum with the yield of the neutrinos produced by the hadronic interactions of the cosmic rays in the atmosphere. The uncertainty of the atmospheric neutrino flux is mainly affected by the uncertainties in the

WIMP MC	N_{data}	N_{nusim}	$ \Delta V_{eff_s} $ %	$ \Delta V_{eff_{bg}} $ %	N_{90}
wimp 5000 hard channel	1	1.38	29	29	3.23
wimp 5000 soft channel	2	1.28	31	29	5.02
wimp 3000 hard channel	1	1.33	30	29	3.23
wimp 3000 soft channel	1	1.21	34	29	3.68
wimp 1000 hard channel	1	1.46	32	29	3.08
wimp 1000 soft channel	1	1.61	38	29	3.23
wimp 500 hard channel	3	3.70	31	39	5.02
wimp 500 soft channel	4	4.15	39	29	5.92
wimp 250 hard channel	3	5.17	33	29	3.68
wimp 250 soft channel	4	3.94	38	29	6.22
wimp 100 hard channel	5	3.94	39	29	8.97
wimp 100 soft channel	9	10.27	29	29	8.47
wimp 50 hard channel	9	10.34	29	29	8.47
wimp 50 soft channel	10	9.39	57	29	14.17

Table 9.2: The number of experimental data events and atmospheric neutrino events (based on MAM) passing all the selection criteria, the systematic uncertainty on the detection efficiency for signal, the systematic uncertainty on the detection efficiency for background and the upper limit on the number of signal events at 90 % confidence level, N_{90} , with the inclusion of the systematic uncertainties are given for the 14 different sub-analyzes.

primary cosmic ray spectrum and the properties of the hadronic interactions. In [198] the uncertainties on the present neutrino flux predictions have been investigated, leading to the conclusion that the absolute uncertainty is ≤ 30 %.

The program developed in [192], which calculates the upper limits on fluxes, takes the uncertainties in the prediction of the number of background processes and uncertainties in the signal detection efficiency and background detection efficiency into account. The resulting upper limits on the number of signal events, taking the uncertainties mentioned in previous paragraphs into account, are listed in table 9.2.

9.3 Update Signal Monte Carlo

The analysis presented in this dissertation has been continuously adapted and improved with respect to the evolution of the simulation tools and the description of the ice models. Since the Monte Carlo is continuously improving, several updates have been made since the experimental data have been un-blinded. However, the analysis cuts cannot be changed after the un-blinding of the experimental data as explained in section 7.2. In this work the latest versions of the simulations are used, although the analysis cuts have been tuned on older versions.

The neutralino signal simulation, described in chapter 5, assumes that all neutrinonucleon interactions take place in the ice surrounding the detector. The limited depth of the ice layer has not been considered in the simulation. In this work a new Monte Carlo has been developed including the bedrock below the ice surface. The center of the AMANDA detector is installed at a depth of 1730 m from the surface of the ice layer, which is 2810 m thick near the South Pole. This means that the ice-rock interface is

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located only 1080 m deeper than the center of AMANDA.

Figures 9.4 and 9.5 illustrate the depth of the neutrino-nucleon interaction vertices of the triggered WIMP events as a function of the muon energy. These figures clearly show that the triggered high-mass neutralinos annihilating into the hard channel have most of their neutrino-nucleon interaction vertices in the bedrock below the antarctic ice layer. However, the triggered low-mass neutralinos annihilating into the soft channel produce muons that originate all in the ice surrounding the detector.

The muon tracks originating in the bedrock will be shorter compared to those originating in the ice because the muon absorption is higher in rock than in ice, as illustrated in figure 9.6. On the other hand, the neutrino-nucleon cross-section is higher in rock than in ice. However, this effect is rather small compared to the effect caused by the difference in muon range.

Another improvement with respect to the signal simulation described in chapter 5 is the use of the neutralino-induced muon event generator "WimpSimp⁵" by J. Edsjö [130]. The main improvement concerns the inclusion of the cascades that arise at the neutrino-nucleon interaction vertices.

The signal simulation that includes the bedrock and the cascades at the interaction points is referred to as "the new signal Monte Carlo", while the signal simulation described in chapter 5 will henceforth be called "the old signal Monte Carlo". Note that the corrections discussed in this section were only applied on the signal simulation. The background Monte Carlo, described in chapter 5, includes the bedrock and the cascades by default.

Figure 9.7 shows the effective volumes for the old and new signal simulation as a function of the neutralino mass. The inclusion of bedrock and cascades in the simulation results in a decreased detection efficiency, especially for the high-mass neutralinos. In table 9.3 the number of WIMP events passing all selection criteria for both the old and new signal Monte Carlo and for each of the 14 different sub-analyzes has been listed, together with the corresponding effective volumes.

9.4 The Upper Limits with Inclusion of Systematic Uncertainties

Figures 9.8 and 9.9 illustrate the upper limits on the annihilation rate and the muonflux respectively as a function of the neutralino mass. The 1999 data results have been obtained using the method described in chapter 8 and taking the systematic uncertainties, listed in table 9.2, and the effective volumes based on the new WIMP simulation, listed in table 9.3, into account. The results of the 1997 data analysis have also been calculated with the inclusion of systematic uncertainties [77]. Table 9.4 lists the results of the 1999 data analysis. The interpretation of the results is covered in the following paragraphs.

⁵WimpSimp version 1.2 has been used in this dissertation.



Figure 9.4: The depth of the neutrino-nucleon interaction vertices of the triggered WIMP events, with respect to the center of the AMANDA detector, as a function of the energy of the muon resulting from the interaction of the neutralino-induced neutrino in the ice or rock. The mass and annihilation channel of the neutralinos are given inside the plots. The horizontal line represents the ice-rock interface.



Figure 9.5: The depth of the neutrino-nucleon interaction vertices of the triggered WIMP events, with respect to the center of the AMANDA detector, as a function of the energy of the muon resulting from the interaction of the neutralino-induced neutrino in the ice or rock. The mass and annihilation channel of the neutralinos are given inside the plots. The horizontal line represents the ice-rock interface.



Figure 9.6: The muon range in ice (full line on top) and rock (full line on bottom) as a function of the muon energy. The dashed lines indicate one standard deviation. Figure from [202].

WIMP MC	N_{WIMP} old MC	N _{WIMP} new MC	V_{eff} (m ³) old MC	V_{eff} (m ³) new MC
wimps 5000 GeV hard	6609	3579	$45.6 \cdot 10^{6}$	$24.7 \cdot 10^{6}$
wimps 5000 GeV soft	1712	1277	$11.8 \cdot 10^{6}$	$8.81 \cdot 10^{6}$
wimps 3000 GeV hard	9941	5956	$32.3 \cdot 10^{6}$	$19.4 \cdot 10^{6}$
wimps 3000 GeV soft	2313	2012	$7.5 \cdot 10^6$	$6.54 \cdot 10^{6}$
wimps 1000 GeV hard	8660	7126	$12.9 \cdot 10^{6}$	$10.6 \cdot 10^{6}$
wimps 1000 GeV soft	2065	2041	$30.7\cdot 10^5$	$3.03 \cdot 10^{6}$
wimps 500 GeV hard	8200	7930	$69.7 \cdot 10^{5}$	$6.74 \cdot 10^6$
wimps 500 GeV soft	1940	1996	$16.5 \cdot 10^{5}$	$1.70 \cdot 10^{6}$
wimps 250 GeV hard	8467	8474	$33.0 \cdot 10^{5}$	$3.30 \cdot 10^{6}$
wimps 250 GeV soft	1757	1781	$68.4 \cdot 10^{4}$	$6.94 \cdot 10^{5}$
wimps 100 GeV hard	3580	3636	$54.7 \cdot 10^{4}$	$5.56 \cdot 10^{5}$
wimps 100 GeV soft	1084	1076	$16.6 \cdot 10^{4}$	$1.64 \cdot 10^{5}$
wimps 50 GeV hard	957	898	$94.3 \cdot 10^{3}$	$8.85\cdot 10^4$
wimps 50 GeV soft	177	138	$17.4 \cdot 10^{3}$	$1.36\cdot 10^4$

Table 9.3: The number of WIMP events passing all the selection criteria defined in the different sub-analyzes, using the old (see also table 8.3) and the new signal Monte Carlo. The corresponding effective volumes are given as well (see also table 8.4).



Figure 9.7: The effective volume as a function of the neutralino mass for the new and old signal simulation and the hard and soft annihilation channels.



Figure 9.8: The 90 % confidence level upper limit on the annihilation rate of the neutralinos in the center of the Earth as function of the neutralino mass. The results of the 1999 data analysis take the systematic uncertainties, as well as the effective volumes based on the new signal Monte Carlo into account. The systematic uncertainties are also included in the results of the 1997 data analysis. [77].



Figure 9.9: The 90 % confidence level upper limit on the muonflux coming from the annihilation of neutralinos in the center of the Earth as function of the neutralino mass. The upper limits have been calculated for a muon energy threshold of 1 GeV. The results of the 1999 data analysis take the systematic uncertainties, as well as the effective volumes based on the new signal Monte Carlo into account. The systematic uncertainties are also included in the results of the 1997 data analysis [77].

Mass (GeV/c ²)	Annihilation rate (s^{-1})	Muonflux (km ^{-2} · yr ^{-1})
		$(E_{\mu,thr}=1 \text{ GeV})$
wimp 5000 hard channel	$2.57 \cdot 10^{10}$	869.8
wimp 5000 soft channel	$6.23 \cdot 10^{11}$	1217.4
wimp 3000 hard channel	$5.35 \cdot 10^{10}$	797.7
wimp 3000 soft channel	$8.83\cdot 10^{11}$	897.5
wimp 1000 hard channel	$2.92 \cdot 10^{11}$	653.6
wimp 1000 soft channel	$4.00 \cdot 10^{12}$	802.2
wimp 500 hard channel	$1.52 \cdot 10^{12}$	938.7
wimp 500 soft channel	$2.51 \cdot 10^{13}$	1576.8
wimp 250 hard channel	$4.72 \cdot 10^{12}$	756.9
wimp 250 soft channel	$1.38\cdot 10^{14}$	2493.3
wimp 100 hard channel	$1.75\cdot 10^{14}$	3873.8
wimp 100 soft channel	$3.16\cdot 10^{15}$	9838.1
wimp 50 hard channel	$4.47\cdot 10^{15}$	16412.2
wimp 50 soft channel	$1.14\cdot10^{18}$	325290

Table 9.4: The 90 %-confidence level upper limits on the annihilation rate and the muon flux, with the inclusion of the systematic uncertainties and taking the new signal simulation into account, coming from the annihilation of neutralinos in the center of the Earth for the different neutralino masses and spectra. The muon energy threshold = 1 GeV.

9.5 The Effect of WIMP Diffusion in the Solar System

In section 2.5 an overview was given of the theoretical models predicting the capture of WIMPs by the Earth. In [203] the velocity distribution of WIMPs near the Earth was estimated taking the gravitational diffusion due to the Earth, Venus and Jupiter and depletion due to solar capture into account. The result of this calculation is a smaller capture rate of neutralinos in the Earth, especially at higher neutralino masses, compared to the standard approximation [86], i.e. that the solar diffusion can be approximated by the Earth being in free space and seeing a Gaussian halo velocity distribution. This is mainly due to the fact that solar capture suppresses the velocity distribution by about an order of magnitude at low velocities and this suppression propagates into a suppression of the same order of magnitude in the capture rate.

The neutrino-induced muon flux does not directly depend on the capture rate, but rather on the annihilation rate as explained in chapter 8. In equation 5.6 the annihilation rate Γ_A is expressed in terms of the WIMP capture rate C, the age of the object t and the time scale for capture and annihilation equilibrium to occur τ_A . Since the annihilation rates depend on the capture rates, the annihilation rates are also suppressed. The amount of suppression depends on whether capture and annihilation are in equilibrium or not.

Equilibrium has most often not yet occurred in the Earth. As illustrated in figure 9.10 the typical equilibrium time scales, τ_A , for the set of MSSM models considered, are much longer than the age of the solar system, $t_{\odot} \simeq 4.5 \cdot 10^9$ years.

Assume the capture and annihilation rates in the usual Gaussian approximation are defined by C^{G} and Γ_{A}^{G} respectively, while the new estimates are denoted C and Γ_{A} . Using the equation 5.6 and the fact that the constant C_{A} remains the same in both the standard



Figure 9.10: The equilibrium time scales τ_A as a function of the neutralino mass for several MSSM models. The dashed horizontal line indicates the age of the solar system. All models considered have an equilibrium time scale longer than the age of the solar system. The dots correspond to models for which the neutrino-induced muon fluxes, with the standard Gaussian approximation, are larger than 10 km⁻²yr⁻¹ and the plus signs indicate models with smaller fluxes. Figure from [203].

and new scenario, the following can be written:

$$\frac{\Gamma_A}{\Gamma_A^G} = \frac{C}{C^G} \frac{\tanh^2\left(\sqrt{\frac{C}{C^G}} \frac{t_{\odot}}{\tau_A}\right)}{\tanh^2\left(\frac{t_{\odot}}{\tau_A}\right)} \simeq \begin{cases} \frac{C}{C^G} & \text{if } t_{\odot} \gg \tau_A\\ \left(\frac{C}{C^G}\right)^2 & \text{if } t_{\odot} \ll \tau_A \end{cases}$$
(9.1)

If the annihilation rate and the capture rate are in equilibrium, the annihilation rate suppression (and thus the neutrino-induced muon flux suppression) is equal to the capture rate suppression. However, should the equilibrium not be reached, which is the case for the Earth as shown by the set of MSSM models in figure 9.10, the annihilation rate suppression is equal to the capture rate suppression squared, i.e. the suppression is amplified.

Figure 9.11 shows for a set of MSSM models how the decrease in the capture rate C affects the annihilation rate Γ_A . Also the limiting cases for $t_{\odot} \gg \tau_A$ and $t_{\odot} \ll \tau_A$ are illustrated. From this figure it is evident that the suppression of the annihilation rate is close to $(C/C^G)^2$ for most models, as equilibrium has not occurred. The net result is that the suppression of the annihilation rates starts above about 100 GeV and reaches a maximal suppression of about 10^{-2} at around 1 TeV.

Given the relation between the neutrino-induced muon flux and the annihilation rate in equation 8.14, the neutrino induced muon flux will be suppressed by the same amount as the annihilation rate. In section 9.6 the suppression on the neutrino-induced muon flux due to the solar capture and the gravitational diffusion effects will be further discussed.

9.6 Final Results

Combining all the information discussed in the previous sections, the upper limits on the muon flux coming from the annihilation of neutralinos in the center of the Earth, including the systematic uncertainties, are shown in figure 9.12 as function of the neutralino mass. The results of the 1997 data analysis [77] are shown as well.

The dots show the predictions from the MSSM models using the usual Gaussian approximation. Only those models that do not violate present accelerator bounds and have a relic density in the range $0.05 \le \Omega_{\chi} h^2 < 0.2$ have been considered. A local dark matter density of 0.3 GeV/cm³ has been assumed.

The results obtained by other indirect detection experiments are illustrated for comparison. However, the effective live time of these experiments is much longer than the live time of the AMANDA 1999 (187.0 days of live time, see section 5.2) and 1997 (130.1 days of live time [77]) data sets. The result published by the MACRO experiment is based on an experimental data set with an effective live time of about 4 years [206], corresponding to the operational period 1989 - 2000. The Baksan experiment has been operational in the period 1978 - 1995 which has resulted in an experimental data set with a live time of 11.94 years [65]. The results of the Super-Kamiokande experiment correspond to an effective live time of 3.47 years [16], resulting from the data taking period 1996 - 2000. The sensitivity calculated for the future experiment Icecube is based on 10 years of data taking.



Figure 9.11: The suppression of the annihilation rate Γ_A/Γ_A^G as a function of the neutralino mass. The maximum suppression on the annihilation rate, which corresponds to the minimum value of the ratio Γ_A/Γ_A^G , is indicated by the dashed-dotted line, while the minimum suppression, which corresponds to the maximum value of the ratio Γ_A/Γ_A^G , is shown by the dashed line. The majority of the models have an annihilation rate suppression close to the lower curve since equilibrium has most often not occurred in the Earth. The dots correspond to models for which the neutrino-induced muon fluxes, with the standard Gaussian approximation, are larger than 10 km⁻²yr⁻¹ and the plus signs indicate models with smaller fluxes. Figure from [203].



Figure 9.12: The upper limits on the neutrino-induced muon flux coming from the annihilation of neutralinos in the center of the Earth, including the systematic uncertainties, as a function of the neutralino mass for the hard annihilation channels. The AMANDA results of the 1999 data analysis (this work) are shown in addition to the published AMANDA upper limits obtained in the 1997 data analysis [77]. Also the current upper limits from the neutrino telescopes Baksan [207], Macro [206] and Super-Kamiokande [16] and the anticipated sensitivity for the future neutrino telescope Icecube [72] are indicated. All upper limits have been calculated for a muon energy threshold of 1 GeV. The dots and crosses represent the model predictions from the MSSM, calculated with the DarkSUSY package [204], [205], assuming the usual Gaussian approximation of the WIMP velocity distribution. Models that are excluded by the current direct detection limit set by the Edelweiss experiment [48] are indicated by circles, while models that are not excluded are represented by crosses.



Figure 9.13: The upper limits on the neutrino-induced muon flux coming from the annihilation of neutralinos in the center of the Earth, including the systematic uncertainties, as a function of the neutralino mass for the hard annihilation channels. The AMANDA results of the 1999 data analysis (this work) are shown in addition to the published AMANDA upper limits obtained in the 1997 data analysis [77]. Also the current upper limits from the neutrino telescopes Baksan [207], Macro [206] and Super-Kamiokande [16] and the anticipated sensitivity for the future neutrino telescope Icecube [72] are indicated. All upper limits have been calculated for a muon energy threshold of 1 GeV. The dots and crosses represent the model predictions from the MSSM, calculated with the DarkSUSY package [204], [205], assuming the new estimate of the WIMP diffusion in the solar system [203]. Models that are excluded by the current direct detection limit set by the Edelweiss experiment [48] are indicated by circles, while models that are not excluded are represented by crosses.

Figure 9.13 shows the upper limit on the neutrino-induced muon flux as a function of the neutralino mass as illustrated in figure 9.12, but in this figure the new estimate of the WIMP velocity distribution, as described in section 9.5, is also taken into account. This figure shows that there is a significant suppression on the neutrino-induced muon flux for neutralino masses higher than 100 GeV. Neutralinos with masses above 2 TeV are not observable as the predicted muon fluxes are lower than the sensitivity estimated for future detectors, e.g. Icecube. The theoretical predictions lie below the scale of the plot since in this case the number density of neutralinos falls down rapidly if the dark matter density is kept fixed. In the range between 100 GeV and 2 TeV, future detectors still have a chance of detecting a neutralino signal coming from the center of the Earth. However, the prospects of doing so is clearly diminished with the new estimates of the fluxes. In addition, all models which could be tested by e.g. Icecube are already excluded by direct detection experiments in the mass range of interest.

9.7 Discussion

The results of this dissertation are shown in figures 9.12 and 9.13. Comparing these results with the results of the 1997 AMANDA data analysis, there is an improvement of a factor ~ 1.3 for the high neutralino masses to 1 order of magnitude for the low neutralino masses. However, the results are not directly comparable. The 1999 data analysis is based on 187.0 days of effective live time, while the 1997 data set is limited to 130.1 days of live time. Furthermore there are differences in the trigger settings and in the simulation tools used. The most important differences with respect to the simulation are the different ice models, the different muon propagator and the inclusion of the bedrock and the hadronic cascades at the neutrino-nucleon interaction vertices.

Comparing the AMANDA results presented in this work with the results of Macro, Baksan and Super-Kamiokande, it can be concluded that the AMANDA results are slightly better, especially for neutralino masses higher than 250 GeV. Note however that the live time of the 1999 AMANDA data set is much smaller than the live time of the other experiments (see section 9.6). Using the fact that the upper limits scale as $1/\sqrt{t}$, with t the effective live time of the experiment, the combination of the AMANDA 1997 and 1999 data sets would result in upper limits that are considerably lower than the upper limits set by the other indirect detection experiments so far.

In figures 9.12 and 9.13 the results of the indirect detection experiments are compared to the results of the Edelweiss experiment. The latter uses a direct detection technique, as explained in section 2.4.2, to set limits on the neutralino-nucleon cross-section as a function of the neutralino mass. The same scan over MSSM parameter space, used to generate the set of MSSM models shown in figures 9.12 and 9.13, is used to identify parameter combinations that are accessible by direct searches. However, there is no one-to-one correspondence between the results of the direct detection searches and the expected neutrino flux from the models probed. Thus the comparison of the results of the indirect detection experiments and the direct detection experiments is not straightforward.

In [208] it is noted that direct dark matter searches do not necessarily rule out all the
MSSM parameter space available to AMANDA. Direct and indirect searches are only comparable if the dark matter is uniformly distributed in space and time in the galactic halo. However, many-body simulations predict a clumpy dark matter distribution in the galaxy. In this case the direct detection experiments will indicate how densely populated the solar system is in the vicinity of the Earth at the moment the data are taken. Indirect detection experiments, however, are only sensitive to the past history of the solar system, e.g. if it passed through a dense dark matter region in the past, heavy objects like the Earth accumulated dark matter that can be detected today. Another difference is related to the velocity of the WIMPs. Direct searches are sensitive to the high velocity tail of the dark matter velocity distribution, where the direct neutralino-nucleon scattering gives a clear signal. Indirect searches, on the other hand, are more sensitive to the low-velocity tail, where gravitational capture is more efficient.

In [80] and [81] the search for neutralino dark matter inside the center of the Sun, using AMANDA data, has been described. The advantages and disadvantages of investigating the Sun for dark matter have already been discussed in section 2.4.3. The AMANDA results coming from the Sun are fairly competitive with the results of the direct searches on Earth. This can be explained by the fact that the Sun is sensitive to the spin-dependent WIMP-hydrogen interactions, which are effective in capturing WIMPs, while the Earth only accretes WIMPs by spin-independent interactions.

Chapter 10

Summary and Outlook

A search for neutralino dark matter in the center of the Earth has been conducted using the data taken with the AMANDA-B10 detector in 1999. A signature for neutralino annihilations in the center of the Earth would be observed as an excess of vertically up-going muons on top of the spectrum resulting from conventional sources. There are two types of background events in this search: down-going atmospheric muon events and up-going atmospheric neutrino events. Hard selection cuts have been designed to completely reduce the background of atmospheric muons, which are 10^6 times more abundant than the neutrino-induced muons. The latter can not be entirely rejected, but restrictive cuts on the reconstructed muon zenith angle improve the sensitivity to a hypothetical signal of neutralinos.

No statistical significant excess of near-vertical up-going muon tracks on top of the predicted atmospheric neutrino background has been observed. 90 % confidence level upper limits on the annihilation rate of neutralinos in the center of the Earth and the muon flux, induced by these annihilations, have been calculated. The derived limits on the annihilation rate vary from $2.42 \cdot 10^{15} \text{ s}^{-1}$ for 50 GeV neutralinos to $1.28 \cdot 10^{10} \text{ s}^{-1}$ for 5 TeV neutralinos, while the limits on the muon flux vary from 8901.5 km⁻²yr⁻¹ to 432.7 km⁻²yr⁻¹ for the same neutralino mass range. The inclusion in the derivation of the limits of the effect of the detector systematic uncertainties on the one hand, and the theoretical uncertainty in the expected number of background events on the other hand, results in upper limits on the annihilation rate of $4.47 \cdot 10^{15} \text{ s}^{-1}$ for 50 GeV neutralinos and $2.57 \cdot 10^{10} \text{ s}^{-1}$ for 5 TeV neutralinos. The limits on the muon flux change to 16412.4 km⁻²yr⁻¹ and 869.8 km⁻²yr⁻¹ respectively.

The upper limits derived in this dissertation for the high-mass neutralinos are better than the presently published limits set by other indirect detection experiments. The limits set for the low-mass neutralinos are slightly worse compared to the results of similar experiments, although a big improvement has been achieved in this work compared to the results based on the 1997 AMANDA data for the low-mass neutralinos. This improvement is thanks to the selection procedure, developed in this thesis, which treats every possible signal separately and optimizes the cuts in such a way that the most sensitive upper limit is obtained. There are still some possibilities left to improve the AMANDA results. The upper limits can be scaled down by combining the 1997 and 1999 AMANDA data sets and by analyzing the data taken by AMANDA-II. Furthermore, an additional improvement can be achieved by re-triggering the experimental data to lower trigger thresholds. This is especially suited for improvements of the sensitivity of low-mass neutralinos. More work is needed on the systematics as well, especially the systematic uncertainties due to the description of the ice models and the optical module sensitivity should be reduced.

However, the results obtained by the direct detection experiments rule out several sets of parameters of the MSSM that can not be probed with the presently available indirect detection experiments. In addition, a study of the velocity distribution of WIMPs near the Earth was made very recently, taking the gravitational diffusion due to the Earth, Venus and Jupiter and the depletion resulting from solar capture into account. As a result, the theoretically expected muon flux coming from the annihilation of neutralinos in the center of the Earth is considerably reduced and the probability that even a detector like Icecube detects a signal becomes very small. Note that the interpretation of these new results have to be handled with care as they are based on several approximations.

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