Ultra-high energy neutrino simulations

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Chapter 3

Neutrino event generators

In this chapter two different neutrino Monte Carlo event generators, ANIS and GENHEN are described. These generators are used to simulate neutrinos of all flavors and their interactions in the seabed rock and the water surrounding the neutrino detector ANTARES, in the energy range covered by the telescope. A comparison in performance of both neutrino event generators is presented.

Monte Carlo simulations are of prime importance when studying the performance of a Cherenkov neutrino telescope as it enables the evaluation of the response of the telescope to neutrino interactions. Two distinct stages of simulation can be recognised: the neutrino event generation and the detector response simulation. Event generators accurately model the neutrino interactions in the media surrounding the Cherenkov neutrino telescope of interest, in the energy range covered by the telescope. The resulting secondary particles, such as muons, are propagated through the surrounding media towards the telescope using separate computer programs or subroutines. Neutrino event generation is the subject of the present chapter. In the second stage, the detector response to the Cherenkov light produced by the secondary leptons within the instrumented volume of the telescope is simulated. This second part is discussed in Chapter 4.

The chapter is organised as follows. In Section 3.1 the general concepts of neutrino event generators are explained. In 3.2 the neutrino generator GENHEN or ‘GENerator of High Energy Neutrinos” is presented. The neutrino generator ANIS, or “All Neutrino Interaction Simulation” is the subject of Section 3.3. When using ANIS, the produced secondary leptons need to be propagated towards the neutrino telescope using the lepton propagation code MMC or “Monte Carlo Muon Code”. MMC is also described in Section 3.3. Both ANIS and MMC
Neutrino event generators

were primarily designed for use within the AMANDA collaboration but the programs have been adapted for ANTARES. A comparison of the performance of the two neutrino generators is presented in Section 3.4.

3.1 Event Generators and Propagators

3.1.1 Neutrino Generators

Neutrino interactions of interest for ANTARES

Neutrino generators are used to simulate neutrino interactions with nuclei and atomic electrons for each of the three neutrino flavors: $\nu_\mu$, $\nu_e$ and $\nu_\tau$. Both channels of the neutrino-nucleon weak interaction, charged current (CC) and neutral current (NC) interactions are supported.

Over the energy range of interest for ANTARES, the interactions of $\nu_e$, $\nu_\mu$ and $\bar{\nu}_\mu$ with electrons can generally be neglected in comparison to the neutrino interactions with nuclei since the corresponding cross sections are much smaller than the neutrino-nucleon cross sections at high energies ($m_e \ll m_N$). The reactions $\bar{\nu}_e e^- \rightarrow W^- \rightarrow \nu_\mu \mu$ and $\bar{\nu}_e e^- \rightarrow W^- \rightarrow$ (hadrons) form important exceptions, as an intermediate $W^-$ boson is produced which decays in detectable secondary particles [34]. This channel dominates over the $\bar{\nu}_e$–nucleon scatterings in a narrow region around the energy of the resonance ($E_{\nu}^{res} \approx 6.3 \cdot 10^6$ GeV) and needs to be taken into account by neutrino generators for high energy neutrinos (and anti-neutrinos). The resonant scattering of anti-neutrinos is named after physicist Sheldon Glashow who discovered this phenomenon. A detailed discussion of this process can be found in [35].

Tau neutrinos in CC interactions with nuclei produce tau leptons which can decay again into tau neutrinos. The secondary tau neutrinos may on their turn interact with nuclei. This is the tau neutrino generation chain. The decay of taus is often simulated in neutrino generators using the package TAUOLA [36] (see Sections 3.2 and 3.3).

Predominant interaction

The three neutrino flavors are usually assumed to be produced in their astrophysical sources in the ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 1$. While propagating from their source over cosmological distances, neutrinos oscillate between the three flavors. This results in a ratio when arriving on Earth of $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ [37]. For muon neutrinos (and muon anti-neutrinos) the detection probability is higher, due to the long absorption length of muons produced in the charged-current (CC) interactions. The primary interaction of interest for the ANTARES telescope is therefore the CC muon neutrino scattering with nuclei.
Various scattering processes must be taken into account while generating neutrino interactions with matter: deep inelastic scattering (DIS), quasi-elastic nucleon (QE) scattering, several nucleon N and Δ resonance (RES) channels (with mass values below 2 GeV). In the QE channel of the CC muon neutrino interaction with nuclei,

\[ \nu_\mu + N \rightarrow CC \, \mu^- + N' \] (3.1)

the final nucleon \( N' \) acquires some momentum but remains intact. The nucleon and Δ resonance channels are given by

\[ \nu_{\mu \nu} + N \rightarrow CC \, \mu^- + N^* / \Delta \rightarrow \text{hadrons}. \] (3.2)

In this case, a nucleon resonance \( (N^*) \) or Delta resonance \( (\Delta) \) is produced that decays into hadrons.

High energy neutrino generators often neglect the QE and RES channels since their contribution is only significant at low energies \( (E \leq 10 \text{ GeV}) \). Hence, the DIS neutrino-nucleon CC-scattering is the dominant interaction of neutrinos (and anti-neutrinos) in conventional matter in the energy range covered by ANTARES \( (E \geq 10 \text{ GeV}) \). The DIS channel of the CC muon neutrino interaction with nuclei can be expressed as

\[ \nu_\mu + N \rightarrow CC \, \mu^- + X \rightarrow \text{hadronisation} \rightarrow \mu^- + \text{hadrons} \] (3.3)

reflecting the disintegration of the struck nucleon N into partonic fragments X that hadronize into various hadrons. Figure 3.1 shows the corresponding Feynman diagram. The outgoing muon is scattered at the interaction vertex over a certain angle. The average angular difference between the initial neutrino direction and the emerging muon direction [24] is bound by the following inequality

\[ \bar{\theta}_{\nu-\mu} < \frac{1.5^\circ}{\sqrt{E_\nu (\text{TeV})}} \] (3.4)

where \( E_\nu \) represents the neutrino energy. For muons below 10 TeV, the angular resolution of the neutrino telescope ANTARES is dominated by the \( \nu_\mu-\mu \) scattering angle described by Equation 3.4. Above 10 TeV, detector effects such as the water quality or the timing resolution (relative and absolute) of the photomultiplier tubes prevail. Above 10 TeV, an angular resolution of about 0.3° can be achieved with ANTARES.

Propagation through the Earth

Also for the propagation process through the Earth, only DIS interactions are simulated. It is now well established [38] [39] that the deep inelastic CC interaction
Figure 3.1: Neutrino (or anti-neutrino) deep inelastic scattering (DIS) event. A charged-current interaction between a muon neutrino (or muon anti-neutrino) and a nucleon (proton or neutron) is depicted. The incoming neutrino (or anti-neutrino) creates a $W^-$ (or $W^+$) boson and turns into a muon. The $W^-$ interacts with an individual quark within the nucleon, resulting in its disintegration. The struck quark and the remaining two quarks shower into a variety of hadrons, dissipating the large amount of energy transferred to the nucleon.

The mean free path for neutrinos in rock is comparable with the diameter of the Earth at approximately 40 TeV. Above this energy, the Earth becomes gradually opaque to neutrinos. Below this energy, the Earth is getting more and more transparent to neutrinos. Deep inelastic scattering with nuclei is therefore also the major source of the attenuation of the neutrino flux while passing through the Earth. Electron neutrinos and muon neutrinos are absorbed in CC interactions and are driven to lower energies in NC interactions. Given the energies involved, QE and RES neutrino-nucleon and interactions can also in this case be safely neglected for the calculation of the neutrino attenuation.

Tau neutrinos are a particular case. They are never absorbed in CC interactions as they regenerate: $\nu_\tau \rightarrow \tau \rightarrow \nu_\tau$, as was already mentioned above. The Earth is thus transparent to tau neutrinos at all energies.

To quantify the phenomenon of absorption of the neutrinos in the Earth with more precision, neutrinos are propagated through the Earth using various den-
3.1 Event Generators and Propagators

Density profiles which model the interior of our planet. The most widely used density profile is taken from the Preliminary Reference Earth Model [40] [34], which is shown in Figure 3.2. In this model, the Earth consists of concentric spheres with different densities depending on the radial distance \( r \) to the center of the planet.

![Density profile of the Earth as a function of the distance from the center of the Earth.](image)

**Figure 3.2:** Density profile of the Earth as a function of the distance from the center of the Earth.

**Kinematics**

The kinematic variables describing the \( \nu_\mu - \mu \) deep inelastic scattering (DIS) are the total center-of-mass energy \( \sqrt{s} \), the square of the (negative) invariant momentum transfer between the incoming neutrino and the outgoing muon \( Q^2 \), the energy transfer in the target frame \( \nu \), the Bjorken scaling variable \( x \), the relative energy transfer or inelasticity \( y \) and the total energy of the outgoing hadrons in their center-of-mass frame \( W^2 \). The basic relations between the kinematic variables are presented in the following equations

\[
s = (p + p_N)^2 = 2ME_\nu + M^2 \approx 2ME_\nu \tag{3.5a}
\]

\[
Q^2 = -q^2 = -(p - p')^2 = -(E_\nu - E_\mu)^2 = 4E_\nu E_\mu \sin^2 \frac{1}{2} \Theta_\mu > 0 \tag{3.5b}
\]

\[
\nu = \frac{q \cdot p_N}{M} = E_\nu - E_\mu = E_X - M \tag{3.5c}
\]

\[
x = \frac{-q^2}{2q \cdot p_N} = \frac{Q^2}{2M\nu} \quad \text{with} \quad 0 \leq x \leq 1 \tag{3.5d}
\]
Neutrino event generators

\[ y = \frac{q \cdot p_N}{p \cdot p_N} = \frac{\nu}{E_\nu} = 1 - \frac{E_\mu}{E_\nu} = \frac{Q^2}{2ME_X} \] (3.5e)

\[ W^2 = E_X^2 - p_X^2 = (E_\nu - E_\mu + M)^2 - (p - p')^2 = -Q^2 + 2M_\nu + M^2 \] (3.5f)

where \( E_\nu \) and \( p \) are the energy and the four-momentum of the incident neutrino, respectively. \( E_\mu \) and \( p' \) are the energy and the four-momentum of the outgoing muon. The variables \( q = p - p', p_N \) and \( p_X \) are the four-momenta of the exchanged boson \( W^-(\text{or } W^+) \), the incoming nucleon \( N \) and the outgoing hadronic final states \( X \), while \( p_h \) is the four-momentum of one single hadron. The basic kinematic relations (3.5d) and (3.5e) lead to

\[ xy = \frac{Q^2}{2ME_\nu} = \frac{Q^2}{s - M^2} \] (3.6)

which shows that for a given energy \( E_\nu \), DIS neutrino-nucleon scatterings can be characterized by two variables such as \((x, y)\) or \((x, Q^2)\).

Cross section

To calculate the rate of high energy events in a neutrino detector, the differential DIS neutrino-nucleon cross sections needs to be evaluated in the whole range of the kinematic variables \( 0 \leq x \leq 1 \) and \( 0 \leq Q^2 \leq \infty \). For an isoscalar nucleus of mass \( M \), i.e. a nucleus with an equal number of protons and neutrons \( N = \frac{n^2 + p^2}{2} \), the leading order electroweak theory predicts the differential cross section for neutrino-nucleon DIS scattering as described by

\[ \frac{d^2\sigma}{dxdy} = \frac{2G_F^2ME_\nu}{\pi} \left( \frac{M_W^2}{Q^2 + M_W^2} \right)^2 \left[ xq(x, Q^2) + x\bar{q}(x, Q^2)(1 - y)^2 \right] \] (3.7)

where \( M_W \) is the mass of the intermediate boson \( W^- \) and \( G_F = 1.16632 \times 10^{-5} \text{ GeV}^{-2} \) is the Fermi constant. This differential cross section is expressed per nucleon and differential in terms of the Bjorken scaling variables \( x \) and \( y \). It is specific for neutrinos; for anti-neutrinos, \( q(x, Q^2) \) and \( \bar{q}(x, Q^2) \) need to be exchanged.

The hadronic part of the neutrino-nucleon interaction leads to the appearance of the parton distribution functions \( q(x, Q^2) \) and \( \bar{q}(x, Q^2) \) in Equation 3.7. The PDFs represent the probability density for finding a particle with a certain longitudinal momentum fraction \( x \) and momentum transfer \( Q^2 \). The differential cross sections in Equation 3.7 depend on both the PDFs of quarks \( q(x, Q^2) \) and antiquarks \( \bar{q}(x, Q^2) \). The known PDFs are obtained by using experimental data [41]. Experimentally determined PDFs are available from various groups worldwide such as the CTEQ [42], MRS/MRST/MSTW [43], H1 [44] and ZEUS [45] [46] collaborations.
3.1.2 Lepton propagators

Muon energy losses in matter at high energies

Only high energy muons originating from neutrino interactions in matter in or around ANTARES have a range long enough to reach the telescope. As a muon travels through matter it looses energy due to ionization, including delta ray production and excitation processes, bremsstrahlung, photo-nuclear interaction and pair production. The relative importance of these processes depends on both the target material and the muon energy. The process of muon pair production in muon propagation is usually neglected due to the very small cross sections involved [47]. The energy loss of a muon in matter below a few hundred GeV is continuous and dominated by ionisation as described in the Bethe-Bloch relation [48]. The energy transferred to the free electrons during a collision is rather small, but knock-on electrons, also called delta rays can be emitted. At high muon energies ($E \geq 1$ TeV) the radiative processes become prevalent. In some rare cases, the radiative energy loss can be very large. As this happens only rarely, the energy loss cannot be treated as a uniform and continuous process. Instead, a division between a continuous and a discrete energy loss regime is usually introduced in the lepton propagation programs via an energy cut ($E_{\text{cut}}$) and a relative energy loss cut ($n_{\text{cut}}$) (see Sections 3.2.3 and 3.3.3). Below these cuts all losses are considered as continuous [49]. While $E_{\text{cut}}$ is preferably used in the evaluation of the transport of muons and taus down to the detector location, $n_{\text{cut}}$ is applied to simulate the leptons passing through the Cherenkov telescope to obtain the detector response. The energy thresholds are artificial and depend upon characteristics of the muon propagation algorithm but also on the configuration of the detector. The energy thresholds should therefore be chosen carefully in order to get the best accuracy within a reasonable calculation time since the stochastic treatment of the energy can lead to a very large number of separate energy loss events [50].

Bremsstrahlung, also known as decelerating radiation, is electromagnetic radiation which is produced by the acceleration of the muon when deflected by an atomic nucleus. Muons can also radiate a virtual photon which can interact with a nucleus and create a positron-electron pair. This is the direct pair production interaction. Bremsstrahlung and pair production are the dominant processes at high energy ($E \geq 1$ TeV) as they contribute up to 40% and 50% of the average muon energy loss, respectively. The inelastic interaction of muons can be described via the exchange of a quasi-real photon between the muon and a nucleon. It is often referred to as photo-nuclear interactions of the muons. Its contribution is rather small but it becomes more important at high energy. This process contributes up to 10% of the total energy loss around 1 TeV. The photo-nuclear interaction is essentially a low $Q^2$ process ($Q^2 \ll 1$ GeV$^2$) and its description is model dependent. Simplifications can be made in the theoretical considerations of the process to obtain convenient and simple formulae for the cross section. The most commonly used are the expressions given by Bezrukov and Bugaev [51] or
Neutrino event generators

Borog and Petrukhin [52] which lead to results agreeing within 10% for the differential cross section and within about 5% for the average energy loss, provided that the same photo-nuclear cross sections are used in the calculations [53].

The total energy loss is determined by the summation of all individual contributions. The average rate of muon energy loss can be described by

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

(3.8)

with $a(E)$ the muon energy loss by ionization, and $b(E)$ the summation of bremsstrahlung, photo-nuclear interaction and pair production. Below 1 TeV, the first term dominates. As can be seen from Equation 3.8 it is (approximately) independent of the muon energy. Above 1 TeV the second term of the equation becomes dominant, where the energy loss is proportional to the energy of the muon.

3.2 GENHEN

The Monte Carlo event generator GENHEN generates high-energy neutrino interactions in the media surrounding the instrumented volume of the ANTARES neutrino telescope. An extensive description of the lastest version of the program can be found in an ANTARES internal note [54] and a Ph.D. thesis [55]. In Figure 3.3 an example is shown of a diffuse AGN-like flux of muon neutrinos assuming $E^2 \Phi = 10^{-6}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ which has been generated with GENHEN. A summary of the main characteristics of the program is given in the following sections.

3.2.1 Program summary

GENHEN simulates neutrino and anti-neutrino interactions with conventional matter for high-energy neutrinos up to $10^9$ GeV. This upper limit on the neutrino energy is due to the lepton propagator programs which are used in GENHEN (see Section 3.2.3). For the propagation of the neutrinos through the Earth, the Preliminary Reference Earth Model [40] [34] is used to calculate the density profile. Details on this Earth model as implemented in GENHEN can be found in [56]. The detector reference system of ANTARES that is used by GENHEN is centered at the center of gravity of the telescope such that $(x, y, z) = (\text{North, West, Up})$ with $z = 0$ at the seabed level. Straight upward-going (vertical) events are characterized conventionally by a zenith angle $\Theta = 0$. Upward-going events therefore have a zenith angle $\Theta$ such that $0 \leq \cos(\Theta) \leq 1$. The code is written in the programing language Fortran [57]. The particle identification numbers follow the scheme used in the GEANT [58] detector simulation program. Since different event topologies require different input conditions to be generated, GENHEN
Figure 3.3: Upward-going muon neutrino energy spectrum simulated with GENHEN, assuming a diffuse AGN-like flux with energies between $10 \text{ GeV}$ and $10^9 \text{ GeV}$. Events with a neutrino or secondary muons which could reach the Can were selected for further processing with a detector simulation. Few events can be seen at high energies due to the absorption of neutrinos in the Earth.

GENHEN simulates one neutrino or anti-neutrino flavor at a time assuming only one type of interaction, essentially to improve the speed of the simulation.

A package based on the Monte Carlo programs LEPTO [59] and RSQ [60] has been implemented to simulate the neutrino interactions [54]. The total cross sections and event kinematics of neutrino-nucleon CC and NC interactions in the matter surrounding ANTARES are computed with the help of LEPTO for the DIS channel. LEPTO integrates the differential cross section given by Equation 3.7 over the full range of neutrino interactions relevant to ANTARES. As the LEPTO program is accurate up to neutrino energies of 10 TeV, GENHEN uses an extrapolation of the model to calculate the neutrino-nucleon cross sections and kinematics to generate DIS interactions up to an energy of $10^9 \text{ GeV}$ [55]. GENHEN uses various parton density parametrizations of the C-TEQ group [42], provided by the library PDFLIB [61] for the DIS channel. The recommended (and used) parametrization is the last tested version CTEQ6D. The nucleon and $\Delta$ resonant (RES) and the low energy quasi-elastic (QE) parts of the neutrino-nucleon interaction are generated with the program RSQ. GENHEN simulates the Glashow resonance using an internal routine [62].
3.2.2 Generation method

Geometry

The instrumented volume of ANTARES is represented as a cylinder centered on the center of gravity of the telescope and containing all the photo-multiplier tubes (PMTs). A larger cylinder referred to as the Can

\[ V_{\text{Can}} \]

1

encompasses the instrumented volume of the detector. The Can defines the volume within which Cherenkov light is produced in the Monte Carlo detector simulation when evaluating the response of the telescope. The Can is surrounded by a third cylinder: the Generation Volume in which neutrino interactions with nuclei and atomic electrons in the matter surrounding the telescope are simulated. The Generation Volume therefore represents the neutrino interaction volume. This volume \( (V_{\text{gen}}) \) corresponds to the Can expanded with the maximum lepton range in the appropriate medium (rock or sea water) for the maximum value of the energy range \( (E_{\text{max}}) \) to be generated. The range \( R_{l\text{max}} \) (with \( l = \mu, e, \tau \)) is determined for the simulated neutrino topology assuming that the lepton takes all the neutrino energy \[54\]. In the downwards direction \( V_{\text{gen}} \) is determined by the maximum lepton range in rock \( (R_{\text{max}}(\text{rock})) \). The lower bound of the Can only extends to the seabed as leptons below this point won’t be able to produce detectable light. Horizontally \( V_{\text{gen}} \) is calculated using the maximum lepton range in sea water \( (R_{\text{max}}(\text{water}) \times \cos \theta_{\text{max}}) \) with \( \theta_{\text{max}} \) the upper edge of the range of the zenith angle. In the upward direction the extension of the Can is either determined by the maximum lepton range in sea water, or by the sea surface whichever is the smallest for downward-going neutrinos. If upward-going events are simulated, the Generation Volume stops at the top of the Can.

The Can and the Generation Volume are tools used in the generation method. The final result of the simulation should not depend on the details of \( V_{\text{gen}} \) or the Can, of course. The generation process is statistical and encompasses the entire generation volume \( V_{\text{gen}} \).

Algorithm

The energy \( E \) and the direction of the neutrinos that need to be simulated are chosen to reflect the ANTARES neutrino telescope properties or specific interests of the user. The direction is defined by the zenith angle \( \theta \) and the azimuth angle \( \chi \). It is sampled uniformly in the cosine of the zenith angle range \( [\theta_{\text{min}}, \theta_{\text{max}}] \), and in the azimuth angle range \( [0, 2\pi] \). For the energy spectrum, only power law spectra of the type \( \phi(E) \propto E^{-\gamma} \) are supported in GENHEN. Such an energy spectrum is motivated by the theory of Fermi shock acceleration (see Introduction) which

\[ 1 \text{The default Can which is commonly used in ANTARES simulations was also exploited in this work. It is defined by the lower extend } dZ_{\text{min}} = -278.15 \text{ m, the upper extend } dZ_{\text{max}} = 341.47 \text{ m, and the radial extend } dR = 266.11 \text{ m.} \]
is commonly used to describe the production of high energy neutrinos. The energy is sampled in the range \([E_{\text{min}}, E_{\text{max}}]\) such that \(E^{-\gamma}\) is uniformly distributed. The event generation in \(E\) and \(\cos \theta\) is therefore made such that the events are uniformly (flat) distributed over phase space.

The energy spectrum from which the events are drawn corresponds either to the flux of neutrinos at the interaction vertex close to the telescope or to the flux of primary neutrinos entering the opposite side of the Earth. A typical value of the spectral index \(\alpha\) is 1.4 for the interacting neutrino flux, as it gives reasonable statistics in all energy ranges. This value corresponds to a spectral index \(\gamma \approx \alpha + 1 = 2.4\) for the neutrino flux at the surface of the Earth \(^2\). In the case that the drawing spectrum is the primary neutrino spectrum, a full propagation through the Earth is required. If no full propagation through the Earth is performed, the shadowing effect of the Earth is contained in event weights (see next section) in the form of a transmission probability, taking only charged-current (CC) scatterings into account \([54]\). For a neutrino \(\nu\) with an energy \(E_\nu\) and a zenith direction \(\theta\), the probability of survival through the Earth or the transmission probability \(P_{\text{trans}}\) can be expressed by

\[
P_{\text{trans}}(E_\nu) = \exp \left[ -N_A \sigma_\nu(E_\nu) \int \rho_\theta(l) dl \right] \quad (3.9)
\]

\(^2\)In the energy range covered by GENHEN, the neutrino-nucleon interaction total cross-section is considered to rise linearly with the energy \([63]\) \([64]\).
Neutrino event generators

with \( N_A \) the Avogadro number, \( \sigma_v \) the neutrino CC-cross section, and \( \rho_0 \) the Earth column depth in the neutrino direction defined by the zenith angle \( \theta \). This approximation is reasonable for muon and electron neutrinos [54], but NC interactions need to be taken into account when simulating tau neutrinos and their regeneration chain. Therefore a full simulation of the propagation through the Earth is necessary for tau neutrinos.

In order to limit the time required to simulate events within a large range of energies and obtain sufficient statistics at high energies, the total energy range is divided into a number of equal divisions in \( \log_{10}(E_n) \), with \( E_n \) the energy of the neutrino. This makes it possible to define a different Generation Volume \( V_i \) for each energy bin \( i \), and prevent large numbers of events from being generated at low energies in an interaction volume determined by the high energy range.

The number of events \( N_i \) generated in each energy bin \( i \) is calculated by weighting the events with the chosen neutrino generation spectrum

\[
N_i(E_{i,\text{min}}^\text{min}, E_{i,\text{max}}^\text{max}) = N_{\text{gen}} \times \frac{\int_{E_{i,\text{min}}^\text{min}}^{E_{i,\text{max}}^\text{max}} E^{-a}dE}{\int_{E_{\text{min}}^\text{min}}^{E_{\text{max}}^\text{max}} E^{-a}dE}
\] (3.10)

where \( E_{i,\text{min}}^\text{min} \) and \( E_{i,\text{max}}^\text{max} \) are the extremes of the energy bin \( i \), and \( E_{\text{min}}^\text{min} \) and \( E_{\text{max}}^\text{max} \) are the extremes of the entire energy range of the neutrinos to be simulated. In Equation 3.10, \( N_{\text{gen}} \) is the total number of events to be generated. As a next step, the number of events \( N_i \) per bin \( i \) is scaled by the ratio of the corresponding Generation Volume \( V_i \) for that bin \( i \) and the entire Generation Volume \( V_{\text{gen}} \) corresponding to the total generated spectrum. The obtained value is smeared with a Poisson distribution \( P \) in order to account for the fluctuations in the generated spectrum

\[
N_i^{\text{scaled}}(E_{i,\text{min}}^\text{min}, E_{i,\text{max}}^\text{max}) = P \left( N_i \times \frac{V_i}{V_{\text{gen}}} \right).
\] (3.11)

At initialisation, the GENHEN program computes the interaction cross sections of the neutrinos with the surrounding matter for the topology chosen and initialises the lepton propagation code (see Section 3.2.3). Once the information is available the event loop starts. The energy \( E_i \) of the neutrino is sampled from the chosen generation spectrum. If the propagation through the Earth is not activated, the energy is drawn from the neutrino flux at the interaction vertex close to the telescope, accounting for the different densities of the media around ANTARES. If a full propagation is required, the energy is taken from the neutrino flux at the surface of the Earth. The coordinates and direction cosines of the neutrino interaction vertex are generated uniformly in the Generation Volume \( V_i \) depending on the value of \( E_i \). If the interaction vertex is generated outside the Can volume, cuts on the distance of closest approach to the Can and the neutrino direction are performed to exclude events with secondaries which will not reach the Can and therefore cannot create detectable light and events with secondaries...
that can reach the telescope but with insufficient energy to pass the detection threshold. If the event survives the cuts, or if the vertex is generated inside the Can, the interaction is taking place close to the detector, choosing a specific reaction channel based on the relative cross sections at the sampled energy. If a full propagation through the Earth is required, it is checked whether the event has an energy, vertex and direction that allow the neutrino to make at least one interaction in the propagation through the Earth, otherwise that event is discarded. If the neutrino undergoes a charged current (CC) interaction with nuclei deep in the Earth, the event is discarded as no emerging muon will survive the propagation. If it undergoes a neutral current (NC) interaction with nuclei, the final energy when leaving the Earth and entering the sea water is calculated. This becomes the energy at the interaction vertex close to the telescope.

As was mentioned before, the interaction channel is chosen based on the relative cross sections at the sampled energy. If leptons are produced in the interaction, they are propagated to determine whether they reach the Can, using one of the available lepton propagator programs. If an event contains a neutrino or a lepton which reaches the Can volume, a weight is associated to it, which depends on the energy bin. The event weights are described in the next paragraph and calculated using the prescriptions of References [65] and [66]. The weights are stored along with the events. This can be used to adapt the generated sample and obtain physical spectra. The final energy of the neutrino that propagates through the Earth is also recorded.

**Neutrino event distribution**

To obtain a distribution corresponding to a model, specified by a given neutrino flux \( \phi_{\nu}^{\text{model}}(E_\nu, \theta_\nu) \) at the surface of Earth, the sample of generated events needs to be weighted by the ratio of the model neutrino flux to the generated flux. The differential flux of neutrinos (in units of \( \text{GeV}^{-1} \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \)) that is simulated at the surface of Earth \(^3\) can be expressed by

\[
\phi_{\nu}(E_\nu, \theta_\nu) = \frac{N_{\text{gen}}}{V_{\text{gen}} I E l_\theta \sigma(E_\nu) \rho N_A E_\nu P_{\text{trans}}(E_\nu, \theta_\nu) F}
\]

where

- \( V_{\text{gen}} \) (in \( \text{m}^3 \)) is the volume in which the neutrino interactions were generated.

\(^3\)The flux corresponding to the events that are generated is the flux of neutrinos arriving at the telescope. The transmission probability through the Earth given in Equation 3.9 needs to be introduced in order to get the flux corresponding to the incoming neutrinos at Earth. If a full propagation through the Earth is simulated, there is no need to introduce the probability of transmission through the Earth in the weights. In this case \( P_{\text{trans}} \) is set to 1.
Neutrino event generators

- $I_E$ (in GeV) is the energy phase factor

\[
I_E = \begin{cases} 
\frac{E_{max}^{1-\gamma_{gen}} - E_{min}^{1-\gamma_{gen}}}{1-\gamma_{gen}} & \text{if } \gamma_{gen} \neq 1, \\
\ln \frac{E_{max}}{E_{min}} & \text{if } \gamma_{gen} = 1.
\end{cases}
\]

The energy phase factor results from the integration over the simulated energy range $[E_{min}, E_{max}]$ in which neutrinos were generated.

- $I_\theta$ (in sr) is the angular phase factor

\[I_\theta = 2\pi (\cos \theta_{max} - \cos \theta_{min}).\]

It results from the integration over the simulated angular range $[\theta_{min}, \theta_{max}]$, assuming that the event generation is isotropic. As the solid angle $\Omega$ is commonly specified by the zenith angle $\theta$ and the azimuth angle $\chi$, the angular distribution is flat in $\cos \theta$ and $\chi$.

- $\sigma(E)$ (in m$^2$) is the neutrino-nucleus interaction cross section.

- $\rho N_A$ (in m$^{-3}$) is the number of target nuclei per m$^3$, that is the target density.

- $P_{trans}$ is the probability of transmission through the Earth.

- $F$ is the number of seconds per year.

The weights $w_i$ to be assigned to each event $i$ are therefore

\[w_i = \frac{I_\theta I_E E_i^\gamma \sigma(E_i)\rho N_A V_{gen} P_{trans} F}{N_{gen}} \times \phi_v^{\text{model}}(E_i, \theta_i).
\]

In the GENHEN output tags, three types of weight can be distinguished, for each event. The weight $w1$ (in water equivalent m$^3$) is the Can volume $V_{gen}$. The so-called generation weight $w2$ (in units of GeV m$^2$sr s year$^{-1}$) does not depend on the flux model and is expressed as

\[w2 = I_\theta I_E E_i^\gamma \sigma(E_i)\rho N_A V_{gen} P_{trans} F.
\]

The global weight $w3$ (in year$^{-1}$) is defined as $w3 = w2 \phi_{atm}$ which corresponds to the generation weight $w2$ folded with a neutrino flux model $\phi_{atm}$ to give a rate of events per year. As a default the atmospheric neutrino flux due to Barthol is added to the event weight $w3$ but other models can be used as well (see [63]). For details on how to use the weights of GENHEN we refer to [67]. GENHEN directly links to the program NUFLUX to simulate the various atmospheric flux models. NUFLUX is described in detail in [66]. For more details on weights, we refer to [68] and [55].
3.3 ANIS: All Neutrino Interaction Simulation

3.2.3 Lepton propagator

GENHEN contains lepton propagation subroutines to calculate the maximum ranges which define the Generation Volume, i.e. the neutrino interaction volume, and the effective ranges that allow to compute effective areas (see Chapter 5). The main role of the subroutines is to propagate the produced leptons from the interaction vertex to the Can of the telescope simulating their energy losses and survival probabilities, including angular and lateral deflections due to multiple scattering.

The lepton propagator MUM

Three dedicated lepton propagators, MUM [49], PROPMU [69] and MUSIC [70] are included in GENHEN to calculate the cross sections, free paths and energy losses for lepton interactions and simulate the propagation of the muons over large distances in the media around ANTARES. While MUSIC and PROPMU include the angular and lateral deflections due to multiple scattering, MUM neglects muon scattering. It has been noted, however, that PROPMU is performing badly [71]: substantial numerical differences appear between the simulated and the predicted energy losses (up to 20%) for muon energy between 20 GeV and 10 TeV. MUM is the only lepton propagator available in GENHEN that can also propagate tau leptons, which loose energy differently than muons. The latest version of MUSIC also contains the propagation of taus (with the package TAUSIC), but this version has not yet been included in GENHEN. An ANTARES internal note details the comparison of the three lepton propagators [62]. As can be seen in that paper, MUM and MUSIC give comparable results for the muon propagation through matter, but the MUM algorithm is faster. Because of this, MUM has been chosen as the lepton propagator in this work. In this lepton propagator, the photo-nuclear cross sections according to Bezrukov-Bugaev [51] or the parametrization of the Zeus group [72] can be used. Bremsstrahlung is described according to Bezrukov-Bugaev-Andreev [73] or Koboulin-Kelner and Petrukhin (GEANT 4 [58]). The energy thresholds that determine the continuous and stochastic regimes (see Section 3.1.2 for their definition) are parameters for the initiation procedure of MUM and can be set to any value between $10^{-4} \leq \nu_{\text{cut}} \leq 0.2$ and $10 \text{ MeV} \leq E_{\text{cut}} \leq 500 \text{ MeV}$. A study of these energy cuts [49] leads to the choice of $\nu_{\text{cut}} = 0.01$ and $E_{\text{cut}} = 10 \text{ MeV}$.

3.3 ANIS: All Neutrino Interaction Simulation

ANIS is a Monte Carlo neutrino event generator for high-energy neutrino telescopes. It has been developed by Marek Kowalski and Askhat Gazizov for the AMANDA collaboration. A full description of the program is given in [74]. In Figure 3.5, an example is shown of a diffuse AGN-like flux of muon-neutrinos.
Neutrino event generators

generated with ANIS, assuming \( E^2 \Phi = 10^{-6} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \). Comparison between Figures 3.3 and 3.5 shows that the ANIS spectrum extends to higher energies. A summary of the properties of ANIS is discussed in the following sections.

![Number of events per year vs. \( \log_{10}(\text{Energy}[\text{GeV}]) \)](figure)

**Figure 3.5:** Upward-going muon neutrino energy spectrum generated using ANIS, assuming a diffuse AGN-like flux with energies between \( 10 \text{ GeV} \) and \( 10^{12} \text{ GeV} \). Events with a neutrino or secondary muons which could reach the Can were selected for further processing with a detector simulation. Few events can be seen at high energies due to the absorption of neutrinos in the Earth.

### 3.3.1 Program summary

ANIS can generate neutrinos and anti-neutrinos up to energies of \( 10^{12} \text{ GeV} \). The program is written in the language C++ which makes it flexible and allows new physics processes to be implemented easily at a later stage. ANIS is independent of any external software package. Instead the program uses pre-calculated tables to provide cross sections for various final states which consist of pairs of the variables \( x \) and \( y \), and rely on the type of interaction and the flavor of the neutrino that is generated. This makes the program fast and already implemented physics processes can be adapted by only modifying the cross section data in the tables without changing the code. The HepMC [75] Monte Carlo event record and the vector package of the CLHEP library, which is a set of high-energy physics utility classes, are used.

ANIS only simulates deep inelastic (DIS) neutrino interactions with matter as this channel is dominant at the energy range of interest for modern neutrino
3.3 ANIS: All Neutrino Interaction Simulation

Both charged-current (CC) and neutral-current (NC) scattering are implemented, as well as neutrino interactions with atomic electrons. In the latter case, as was explained in Section 3.2, only the Glashow resonant $\bar{\nu}_e e^- \rightarrow W^- \rightarrow \text{anything}$ interactions are relevant in the energy range of interest. All produced hadrons are considered to be pions since Cherenkov telescopes cannot distinguish between different types of hadrons.

ANIS also simulates the propagation of neutrinos through the Earth, using a density profile which follows the Preliminary Earth Model [40]. Neutrino absorption in CC scatterings with nuclei and energy loss in NC interactions with nuclei or Glashow scattering with electrons are simulated. The $\nu_\tau \rightarrow \tau \rightarrow \nu_\tau$ regeneration chain through the Earth is also included with the help of the program TAUOLA [36], which provides data tables with the final products of the decay chain.

Deep inelastic scattering is described using the CTEQ5 parametrization [42] for the parton distribution functions (PDFs). At high energies, up to $E \leq 10^{12}$ GeV, lepton-quark scattering occurs at small Bjorken $x$ ($x < 10^{-5}$), where no data exist. In the absence of any reliable PDF parametrization in this domain, extrapolations become inevitable. ANIS uses two approaches founded on different theoretical models that provide an extrapolation of the nucleon structure functions to small $x$ and large $Q^2$: one is based on the CTEQ5 parametrization and the other one on a non-standard hard pomeron enhanced model [76] inspired by A. Donnachie and P.V. Landshoff [77]. In Figure 3.6 the DIS neutrino-nuclear cross sections for CC and NC interactions for the two high energy extrapolations are compared.

Starting from the neutrino-nucleon interaction vertex, secondary muons and taus have to be propagated further towards the telescope using a dedicated lepton propagation program. ANIS does not include such a program but the muon propagator MMC [50] can be used to propagate the secondary muons towards the telescope. A description of the program MMC and its interface with the ANTARES software is given in Section 3.3.3.

The detector reference system in ANIS is centered at the center of gravity of the telescope. The coordinate system is right-handed with the x-axis directed eastward and the z-axis pointing away from the Earth center. By convention straight downward-going (vertical) events are characterized by a zenith angle $\Theta = 0$. Upward-going events therefore have a zenith angle $\Theta$ such that $-1 \leq \cos(\Theta) \leq 0$.

3.3.2 Generation method

Geometry

In ANIS, neutrinos that survived the propagation through the Earth are simulated to interact within a rotating cylinder whose z-axis is parallel to the neutrino direction, which is referred to as the Final Volume. The Final Volume is centered...
Figure 3.6: Differential neutrino-nucleon cross sections (in cm$^2$) used by ANIS. Both NC and CC $\nu - N$ interactions are represented. At high energy ANIS uses an hard-pomeron enhanced model (HP) or an extrapolation of the CTEQ5 paramatrization (pQCD). Both neutrino (solid line) and anti-neutrino (dashed) cross sections are shown [74]. The resonant $\bar{\nu}_e e^-$ reaction is also shown.

on the center of gravity of the telescope and two heights are defined: a positive height in the target region of the original neutrino-nucleon interaction and a negative height in the detector region. The size of the interaction volume is optimized by extending the positive height in the direction of the neutrino-nucleon interaction using the maximum muon range at the considered energy (currently this option is only available for muon neutrinos). The Final Volume is an auxiliary concept used in the generation method. Since it is defined for each event, it makes the generation process dynamic, but the final results should not depend on it.

Algorithm

Initially, the energy $[E_{\text{min}}, E_{\text{max}}]$ and directional ranges $[\cos \theta_{\text{min}}, \cos \theta_{\text{max}}]$ (with $\theta$ the zenith angle) of the neutrinos are chosen, together with the type of generation spectrum. Only power law spectra $F(E) \propto E^{-\alpha}$ are supported, but other
3.3 ANIS: All Neutrino Interaction Simulation

Figure 3.7: Definition of the telescope geometry assumed by the Monte Carlo event generator ANIS. The geometry is anchored to the detector center of gravity. A cylindrical Final Volume is defined for each neutrino event. The axis of the Final Volume is parallel to the direction of motion of the neutrino [74].

types could be added at a later stage. Neutrinos are generated uniformly on the surface of the Earth. Their energy is sampled from the chosen power law spectrum. Neutrinos are subsequently propagated through the Earth in small steps towards the telescope. Neutrinos that survive the propagation through the Earth are simulated to interact within the Final Volume.

All generated events are recorded or sampled according to their interaction probability. If all events are written to output, they need to be properly weighted in order to obtain distributions of physics variables. The weights used in ANIS for this purpose are defined below.

Neutrino event weights

Four event weights are defined in the program to produce a physical spectrum of the events once weighted with their interaction probability. These weights include a normalization constant $W_{\text{norm}}$, the interaction probability in the Final Volume $P_{\text{int}}$ and two weights, $R_{\text{atm}}^{\nu_e}$ and $R_{\text{atm}}^{\nu_{\mu}}$, that correspond to the atmospheric neutrino flux for electron and muon neutrinos. A detailed description of these weights and a tutorial on how to use them can be found in [74]. Here a brief description of these weights is given. The normalization constant $W_{\text{norm}}$ (expressed in GeV cm$^2$ sr s year$^{-1}$) is computed as

$$W_{\text{norm}} = \frac{I_{\Omega} \times I_E \times F \times A_{\text{gen}}}{N_{\text{gen}}}$$

where
Neutrino event generators

- $N_{\text{gen}}$ is the total number of generated neutrinos,
- $A_{\text{gen}}$ (in $\text{cm}^2$) is the surface of the cross section of the Final Volume with the detector instrumented volume,
- $F$ is the number of seconds per year,
- $I_E$ is the energy phase factor. It is defined as
  \[
  I_E = \begin{cases} 
  \frac{E_{\text{max}}^{1-\gamma_{\text{gen}}}}{1-\gamma_{\text{gen}}} & \text{if } \gamma_{\text{gen}} \neq 1, \\
  \ln \frac{E_{\text{max}}}{E_{\text{min}}} & \text{if } \gamma_{\text{gen}} = 1.
  \end{cases}
  \]
  $I_E$ is given in units of giga electron-volt (GeV).
- $I_\Omega$ is the angular phase factor. It is defined as
  \[I_\Omega = 2\pi (\cos \theta_{\text{max}} - \cos \theta_{\text{min}}).\]
  $I_\Omega$ is given in units of steradian (sr).

The normalization constant is chosen such that the event rate per year $R$ is given by
\[
R = W_{\text{norm}} \sum_{i=1}^{i=N_{\text{gen}}} P_{\text{int},i}.
\]

The probability of interaction $P_{\text{int}}$ (dimensionless) inside the Final Volume is defined as
\[
P_{\text{int}} = 1 - \exp (-\sigma_{\text{tot}} \times \tau)
\]
with $\sigma_{\text{tot}}$ the neutrino total cross section for the event, and $\tau$ the column depth.

The atmospheric weights $R^{\text{ve}}_{\text{atm}}$ and $R^{\text{vm}}_{\text{atm}}$ (dimensionless) are defined as
\[
R^{\text{ve/vm}}_{\text{atm}} = \frac{F^{\text{ve/vm}}_{\text{atmo}}(E, \theta)}{F^{\text{gen}}_{\text{atmo}}(E, \theta)}
\]
with $F^{\text{atmo}}_{\text{atmo}}(E, \theta)$ ($\text{GeV}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$) the differential atmospheric flux for electron or muon neutrinos, and $F^{\text{gen}}_{\text{atmo}}(E, \theta)$ ($\text{GeV}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$) the generated differential flux at the surface of the Earth. The atmospheric neutrino flux contained in $R^{\text{ve}}_{\text{atm}}$ and $R^{\text{vm}}_{\text{atm}}$ has been derived from the Volkova flux using the Lipari parameters [78]. ANIS uses pre-calculated tables with the atmospheric neutrino flux data. The procedure on how to use these weights is described in detail in [74]. An example on how to use ANIS for simulating a neutrino flux in ANTARES is given in appendix A.
3.3.3 The Muon Propagator MMC

The muon propagator MMC propagates secondary charged leptons and neutrinos from neutrino-nucleon interactions towards the telescope. The program takes into account ionization losses, bremsstrahlung, photo-nuclear interactions and pair production, including effects such as Landau-Pomeranchuk-Migdal (LPM) and dielectric suppression, decay and Molière scattering. Several parametrizations for bremsstrahlung and photo-nuclear cross sections are available. All particles which have been produced during the propagation are also propagated until they disapear or exit the detector volume.

MMC can propagate leptons with energies from their rest mass up to $10^{30}$ eV, using extrapolations of the known cross sections at high energies. A full description of the program is given in [50]. MMC has been originally developed by Dmitry Chirkin for the AMANDA telescope. The program is written in the object-oriented language Java with a C++ interface to improve the flexibility and readability of the code. The current version of MMC (at the time of the writing of this thesis), i.e. version 1.4.6, contains the water properties at the ANTARES site so that ANIS and MMC can be used in the full ANTARES Monte Carlo chain. An example on how to use MMC for simulating a neutrino flux in ANTARES is given in appendix B.

Use of MMC for the ANTARES telescope

MMC can be used to propagate the secondary muon and tau leptons created at the neutrino vertices by ANIS towards the Can of the ANTARES telescope. As can be seen in Figure 3.8 the sea water at the ANTARES site is divided in three regions: one from the surface of the sea to the point where the track of the muon enters the cylindrical Can around the telescope. The second region starts here and ranges to the point where the muon trajectory exits the Can, while the rest of the track lies in the third region. We assume that the relative energy loss cut $v_{\text{cut}}$ and the energy cut $E_{\text{cut}}$ are interchangeable and related by $E_{\text{cut}} = m_{\mu}^2$, where $m_{\mu}$ is the energy of the propagated muon. The muons are propagated for a fixed $v_{\text{cut}}$ or $E_{\text{cut}}$ through the medium until the particle reaches a point where it looses an energy $\Delta E_{\mu}$ that is more than the cutoff energy $\Delta E_{\mu} \geq E_{\text{cut}}$ or $v = \Delta E_{\mu} / E_{\mu} \geq v_{\text{cut}}$. By default, in the first region, the muon relative energy loss cutoff is taken to be $v_{\text{cut}} = 0.05$ (dimensionless). In the second region the absolute energy cutoff is fixed at $E_{\text{cut}} = 500$ MeV, and finally in the third region the muon is propagated in one step with a relative cutoff of $v_{\text{cut}} = 1$ (all loss is continuous) to the point where it is lost. Only secondaries and interactions in the second region are recorded into the output. For more details on the implementation of the ANTARES main characteristics in MMC, see appendix B.

---

4 As defined in Section 3.2.
Neutrino event generators

Figure 3.8: Geometry used by the muon Monte Carlo propagator MMC [50] to propagate leptons through the media towards the ANTARES telescope. There are three propagation regions before the detector (the propagation is done with a fixed $v_{\text{cut}}$), inside the detector (the propagation is done with fixed $E_{\text{cut}}$), and after the detector (fast propagation with $v_{\text{cut}} = 1$).

Comparison with the ANTARES lepton propagator MUM

The performance of MMC has been compared with that of the lepton propagator MUM for the same settings ($v_{\text{cut}} = 10^{-3}$, ZEUS [72] parametrization of the photo-nuclear cross sections and Bezrukov-Bugaev-Andreev [73] parametrization of bremsstrahlung) for both standard rock and water. Figure 3.9 shows the final energy distributions of $5 \times 10^5$ muons with initial energy 100 TeV which were propagated through 1 km of water, calculated by MMC and MUM. The details of this comparison can be found in [50]. As can be seen in the figure, both programs give comparable results. The same settings were used in the framework of this thesis for the comparison of GENHEN(+MUM) and ANIS(+MMC) for the ANTARES telescope, described in the following section.

3.4 Comparison between ANIS and GENHEN

3.4.1 General differences

Both ANIS and GENHEN are Monte Carlo (MC) event generators for neutrino Cherenkov telescopes. While GENHEN has been developed specifically for AN-
3.4 Comparison between ANIS and GENHEN

Figure 3.9: Comparison of the final energy distributions of 500000 muons with initial energy 100 TeV which were propagated through 1 km of water, calculated by MMC (solid line) and MUM (dashed) with the same parametrizations of all cross sections and value of energy cutoff ($v_{cut} = 1 \cdot 10^{-3}$). Left: a close-up of the picture on the right [50].

TARES, ANIS can be used for any high-energy neutrino Cherenkov detector. Both algorithms can generate neutrinos of all flavors ($v_e, v_\mu, v_\tau$), taking into account all relevant interactions with atomic nuclei and electrons. GENHEN can simulate neutrino events up to $10^9$ GeV which is the usual energy range of interest for neutrino telescopes of the size of ANTARES. ANIS can generate events up to $10^{12}$ GeV with special emphasis on the simulation of the highest energy neutrinos. For this reason, quasi-elastic (QE) and resonant (RES) interactions are neglected in ANIS, while they are properly accounted for in GENHEN. Note that these processes are only relevant at low energies ($E < 10$ GeV).

GENHEN is written in the language Fortran whereas ANIS has been implemented in C++. The use of the C++ programming language makes the ANIS code fast and more flexible. GENHEN uses the ANTARES Monte Carlo event libraries while ANIS does not link to any library that is specific to a given detector. ANIS uses the HepMC and Vector packages of the CLHEP library to record the neutrino events energies, positions and directions.

The neutrino-nucleon interaction cross sections are described in ANIS using a parametrization for deep inelastic (DIS) scattering based on the CTEQ5 parametrization, whereas GENHEN can use various parametrizations of the CTEQ group [42]. In the framework of this thesis, CTEQ6, which is the latest parametrization available was used. As can be seen in Figure 3.10, there is a small dif-
Neutrino event generators

Figure 3.10: Differential neutrino-nucleon cross sections for the deep inelastic (DIS) channel of the charged-current (CC) interaction for the CTEQ6 parametrization (solid line) and the ANIS results based on the CTEQ5 parametrization (dashed).

Both ANIS and GENHEN generate neutrinos which follow a power law spectrum $E^{-\gamma}$ (with $\gamma$ the spectral index) at the surface of Earth. While in GENHEN fluxes are described in the unit GeV$^{-1}$ m$^{-2}$ sr$^{-1}$ s$^{-1}$, ANIS uses GeV$^{-1}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$. In order to compare event rates produced with ANIS and GENHEN, fluxes and atmospheric weights in GENHEN have been scaled with a factor $10^4$ to convert square meters into square centimeters.

GENHEN generates either neutrinos or anti-neutrinos for each run, while ANIS simulates 50% neutrinos and 50% anti-neutrinos. For ease of comparison, the ANIS code has been modified such that either neutrinos or anti-neutrinos are exclusively produced, similar to GENHEN.

GENHEN generates either charged-current (CC) or neutral-current (NC) neutrino interactions with nuclei for each run, while ANIS simulates both interaction channels. Only CC or NC events have therefore been selected with ANIS, after production for comparison with GENHEN. It is also possible to combine two runs of GENHEN with CC and NC events and to renormalize them, in terms of generated numbers of events so they can be compared with ANIS. In this thesis, the first method was chosen.

5In this comparison, the known anomalous behaviour of CTEQ5 (at very small $x \lesssim 10^{-6}$) has been overcome [74]. ANIS uses two different extrapolations for small $x$ and large $Q^2$ in order to correct for this anomaly in the CTEQ5 distribution sets.
3.4 Comparison between ANIS and GENHEN

ANIS only simulates DIS neutrino scattering with nuclei as the program focus on high energy neutrinos. Since GENHEN also generates the QE and RES channels, only DIS events have been selected after they were produced for comparison with the results of ANIS. When GENHEN propagates neutrinos through the Earth, only the DIS channel is simulated as absorption is important only at high energies.

3.4.2 CPU time Comparison

The Linux time command is used to acquire timing information about the high-energy neutrino event generators GENHEN and ANIS. The speed of both programs depends on the range of energies chosen and the drawing spectrum. On a single Linux machine (Intel(R) Pentium(R) 4 CPU 2.80 GHz) \(10^5\) muon neutrinos have been generated with GENHEN and ANIS, assuming a flux \(F(E) = E^{-2}\) at the surface of the Earth. Only Charged Current (CC) interactions at the neutrino-nucleon interaction vertex close to the detector are taken into account. All events are written to disk. The system CPU time used by the two programs are shown in Table 3.1. Since GENHEN is often used without the full simulation of the Earth for muon neutrinos, timing statistics for a run performed without the full propagation through the Earth are also shown. The amount of time

<table>
<thead>
<tr>
<th>Software</th>
<th>Number of events at the Can</th>
<th>Generation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANIS</td>
<td>44589</td>
<td>43’ 48.75</td>
</tr>
<tr>
<td>GENHEN</td>
<td>31095</td>
<td>49’ 27.53</td>
</tr>
</tbody>
</table>

Table 3.1: CPU usage of ANIS and GENHEN for the generation of \(10^5\) up-going events. The number of events with a neutrino or secondary muons which could reach the Can of the telescope are also given.

required for the simulation using ANIS is somewhat smaller compared to that required using GENHEN while it generates substantially more events at the detector. This is caused by the fact that GENHEN includes the propagation of the produced leptons towards the telescope, while ANIS does not include this process. However, the lepton propagator MMC which is used in conjugation with ANIS, takes only about 5 minutes to propagate the secondary muons produced in DIS neutrino-nucleon interactions with ANIS. ANIS in association with MMC is therefore slightly faster than GENHEN. This can be attributed to the use of pre-calculated tables which implies that ANIS does not need to make a link to any other package for tau decay simulation, cross section and atmospheric flux calculations. We conclude that ANIS and GENHEN require roughly an equal amount of CPU time per event generated.

69
Neutrino event generators

3.4.3 Event rate comparison

To compare the output of both codes, $10^5$ upward-going muon neutrinos were generated with ANIS assuming an $E^{-1}$ power law spectrum at the surface of Earth.

![Graph showing upward-going muon neutrino rates simulated with GENHEN (dashed) and ANIS (solid line), assuming a diffuse AGN-like spectrum, for energies between $10^2$ and $10^9$ GeV. Only events with a neutrino or secondary muons which could reach the telescope are displayed.]

Figure 3.11: Upward-going muon neutrino rates simulated with GENHEN (dashed) and ANIS (solid line), assuming a diffuse AGN-like spectrum, for energies between $10^2$ and $10^9$ GeV. Only events with a neutrino or secondary muons which could reach the telescope are displayed.

The produced muon secondaries were propagated towards the Can of the ANTARES telescope using the lepton propagator MMC and re-weighted to a diffuse AGN-like neutrino flux $E^2 \Phi = 10^{-6}$ GeV cm$^{-2}$ sr$^{-1}$ s$^{-1}$ at the surface of Earth. In parallel $10^9$ upward-going muon neutrinos were generated with GENHEN, assuming an $E^{1.4} \Phi = \text{GeV} m^{-2} \text{sr}^{-1} \text{s}^{-1}$ power law interacting spectrum. The produced muon secondaries were propagated towards the Can of ANTARES using the lepton propagator MUM and were re-weighted to a neutrino flux $E^2 \Phi = 10^{-6}$ GeV cm$^{-2}$ sr$^{-1}$ s$^{-1}$ at the surface of Earth.

In Figure 3.11, only charged-current (CC) neutrino interactions of the deep inelastic (DIS) channel are shown, with events occurring inside or at the Can and events with a secondary muon which could reach the Can. This event selection is done automatically with GENHEN as the program provides an option which
3.4 Comparison between ANIS and GENHEN

![Energy spectrum comparison between ANIS and GENHEN](image)

Figure 3.12: Atmospheric muon neutrino rates simulated with GENHEN (dashed) and ANIS (solid like). Only events with a neutrino or secondary muons which could reach the telescope are displayed. The parametrization from Lipari [78] was used.

allows to store events at or inside the Can. For ANIS, the program Atmflux\(^6\) which belongs to the MMC package was used to process the muons produced in neutrino-nuclei interactions.

As can be seen in Figure 3.11, the energy spectra obtained with ANIS and GENHEN are comparable. The remaining differences between the two spectra can possibly be attributed to the use of two different generation algorithms. The low event statistics at energies above \(E > 10^7\) GeV are due to the opacity of the Earth for very high-energy neutrinos (see Introduction). For a study of ultra-high energy (UHE) cosmic neutrinos with ANTARES, one therefore needs to focus on downward-going events. A method to select such events in order to arrive at an estimate of the sensitivity of ANTARES to these rare neutrino events is described in Chapter 5.

In Figure 3.12 the neutrino rates for an atmospheric neutrino flux are compared using either the Barthol model for GENHEN or the Lipari model for ANIS. The rates are comparable. The small differences are most likely due to the slightly different atmospheric flux model and the generation method used. It is concluded that - when suitably tuned - both GENHEN and ANIS can be used to simulate high energy neutrino spectra for ANTARES. However, for ultra-high energy downward-going neutrinos (of \(E_\nu \geq 10^9\) GeV), only ANIS can be used.

---

\(^6\)Atmflux allows to propagate leptons produced in neutrino-nuclei interactions, from the interaction vertex towards the Can of the telescope and gives an estimate of the energy lost along the path. If a muon reaches the Can or a neutrino interaction occurs inside the Can the energy is positive.