Ultra-high energy neutrino simulations

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Chapter 5

High Energy Simulations Results

The sensitivity of the ANTARES telescope to a diffuse flux of cosmic neutrinos with energies above $10^7$ GeV has been estimated using the newly developed chain of simulation programs. An average upper limit of the event rate is determined and the corresponding effective areas for neutrinos are presented.

The study of the diffuse neutrino flux that originates from discrete sources which cannot be individually resolved, or from interactions of cosmic rays with intergalactic matter or radiation, may yield important cosmological information. Such measurements are of particular interest for neutrino energies in excess of $10^{16}$ eV, in the so-called ultra high energy (UHE) range. Indeed, the origin of UHE neutrinos and the associated high energy cosmic rays has remained a mystery for many years (see Chapter 1). Recent results appear to correlate extragalactic supermassive black holes at the center of nearby active galaxies with the observation of UHE cosmic rays on Earth. The detection of UHE neutrinos will provide crucial information on the sources of UHE cosmic rays and the processes involved in the production of such extremely energetic particles.

Above $10^7$ GeV, the Earth is opaque to muon neutrinos. At the same time the neutrino interaction probability is still insufficient for the limited mass of sea water above the telescope to yield a reasonable event rate. Hence, only horizontally traveling neutrinos have a chance of being detected in an underwater neutrino telescope.

When searching for neutrinos in the UHE domain, the background consists of atmospheric muons which can reach the detector. They are produced in large air showers by interactions of cosmic ray primaries with the Earth’s atmosphere. Especially multiple atmospheric muons in a short time slot can be mis-reconstructed
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as secondary leptons from charged-current deep-inelastic neutrino scattering interactions. The distribution and intensity of the atmospheric muons therefore need to be known in order to discriminate this large background from the UHE neutrino signal.

The techniques usually employed for neutrino searches (see Chapter 2) need to be reconsidered when looking for UHE neutrinos. The Earth cannot be used as a shield against downward-going atmospheric muons. Moreover, the reconstruction algorithms typically used by ANTARES are optimised for muon energies lower than $10^5$ GeV and not necessarily suited for the reconstruction of UHE muon tracks. However, trigger selections and cuts on the energy and zenith angle can be applied, based on the expectation that the signal is dominated by the downward-going, almost horizontal direction, while the background is mostly vertically downward-going.

The generation of UHE neutrino interactions and the subsequent response of the detector to these events are simulated using the dedicated high energy Monte Carlo programs described in the previous chapters of this thesis. Details on the actual simulations for UHE neutrinos are given in the next section. The proposed strategy to discriminate between the penetrating UHE neutrino events and the atmospheric background is presented in Section 5.2 which also includes a calculation of the upper limit for UHE neutrino detection with ANTARES and a comparison to existing upper limits. The chapter is concluded with a discussion on these results.

5.1 Monte Carlo simulations

5.1.1 Ultra high energy neutrino simulation

The Pierre Auger Observatory has found evidence suggesting that Active Galactic Nuclei (AGN) are likely sources of the highest energy cosmic rays [13]. The present study therefore focuses on diffuse neutrino fluxes from AGN and the simulations are based on assumed AGN-like neutrino spectra.

At the energies of interest for this analysis, the values of the interaction cross section for neutrinos and anti-neutrinos are nearly identical (see Chapter 4). Hence, only neutrinos need to be considered. The Monte Carlo program ANIS [74] has been used to generate a flux of $10^5$ muon neutrinos and their interactions in the media surrounding the ANTARES telescope. The simulation assumes a generic AGN-like spectrum of the form $E^2 \Phi = 10^{-6}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$, for energies ranging between $10^4$ GeV and $10^{11}$ GeV. Muons produced in charged-current interactions are propagated towards the telescope using the program MMC [50].

\footnote{The Probability Density Functions (PDFs) describing the signal distribution accounting for uncorrelated background hits are empirical fits to Monte Carlo simulations of muons with energies between $10^5$ and $10^6$ GeV. See Chapter 4.}

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5.1 Monte Carlo simulations

In Figure 5.1, the distribution of the cosine of the zenith angle of the generated muon neutrinos is shown, for various energy ranges. Only events which can produce a muon able to reach the detector are shown. As can be seen in the figure, the generated neutrino events concentrate near the horizon as the energy increases. This is expected as the Earth becomes opaque to UHE neutrinos and the path length through the atmosphere and the sea water is longest in the horizontal direction. A major fraction of muons from UHE neutrinos will therefore reach the detector in the downward-going, horizontal direction. In the present analysis, only downward-going events will thus be considered.

The detector simulation program SIRENE (see Chapter 5) has been used to determine the photon field and the hits in the telescope. In Figure 5.2, the event rates are shown (with a solid line), as a function of the muon energy for those events which could produce a detectable signal. In the figure, only downward-going events are shown.

\[ E^{-2.7} \]

The energy spectrum of cosmic rays primaries follows an \( E^{-2.7} \) spectrum for energies below \( 10^{15} \text{ eV} \) (the knee) and above \( 10^{19} \text{ eV} \) (the ankle). In between these two limits, it is proportional to an \( E^{-3} \) spectrum. Since this work focuses on the highest energies, the cosmic ray energy spectrum has been approximated with an \( E^{-2.7} \) energy spectrum.

3The energy spectrum of cosmic rays primaries follows an \( E^{-2.7} \) spectrum for energies below \( 10^{15} \text{ eV} \) (the knee) and above \( 10^{19} \text{ eV} \) (the ankle). In between these two limits, it is proportional to an \( E^{-3} \) spectrum. Since this work focuses on the highest energies, the cosmic ray energy spectrum has been approximated with an \( E^{-2.7} \) energy spectrum.
Figure 5.2: Energy distribution of muons from downward-going ultra high energy (UHE) astrophysical neutrino (solid) and cosmic ray (dashed) interactions in the atmosphere. Only events which can reach the detector are shown. The UHE events have been simulated using ANIS, assuming an AGN-like spectrum. The atmospheric muons have been simulated using MUPAGE. The atmospheric spectrum has been extrapolated beyond 500 TeV, assuming an $E^{-2.7}$ spectrum.

 atmospheric muon background simulation

The spectrum of atmospheric muon bundles impinging on the ANTARES detector surface has been simulated with the program MUPAGE [100] or MUon GEnerator from PArametric formulas. MUPAGE is a parametrisation of the atmospheric muon flux at the depth of the detector, simulating single and multiple underwater muons between 20 GeV and 500 TeV and up to 85° zenith angle. All kinematic parameters of the muons are tuned with a Monte Carlo simulation of primary cosmic ray interactions and shower propagation in the atmosphere, based on the program HEMAS [101]. It allows the calculation of the high energy muon component ($E \geq 500$ GeV) in extensive air showers (EAS) assuming a primary total energy between $10^{12}$ and $10^{20}$ eV. Hadronic interactions are handled with DPMJET [102] which embodies a phenomenological model [103], using results from direct and indirect measurements of cosmic rays in the energy range between 10 GeV and 1 EeV. Direct observations are used to extrapolate the energy spectra of each element to high energies. The muons which could reach the sea
5.2 Data selection and analysis

A total number of $10^5$ downward-going atmospheric events, consisting of bundles of at most 1000 muons have been generated with MUPAGE, in the energy range 20 GeV - 500 TeV at the default ANTARES Can (see Chapter 4), for zenith angles with $-1 \leq \cos \theta \leq -0.087$. The detector simulation program SIRENE has been used to determine the resulting photon hits in the telescope. In Figure 5.2, the event rates are shown (with a dashed line), as a function of the muon energy, for those events which could produce a detectable signal. As can be seen in the figure, the distribution drops rapidly with increasing energy.

In Figure 5.3 the distribution of the cosine of the zenith angle is shown for atmospheric muons which could produce a detectable signal. As can be seen in the figure, most atmospheric muons reach the detector from the vertical downward-going direction. Such a spectrum is limited to an angular range of approximately $\cos \theta \leq -0.10$.

5.2 Data selection and analysis

A dedicated data analysis method needs has been developed in order to reduce the amount of atmospheric muon background while preserving sensitivity to the
ultra high energy (UHE) signal. Using this analysis method, an estimate can be made of the upper limit that can be achieved with ANTARES on the assumed astrophysical neutrino flux.

5.2.1 Track energy estimate

As can be seen in Figure 5.2, the muon energy spectrum expected from an AGN-like neutrino flux at the detector extends to larger values than that of the atmospheric muons. Thanks to the steeper slope of the atmospheric spectrum, the signal over background ratio improves with energy. In principle, it is thus possible to search for an excess of astrophysical neutrinos at higher energies. Since for ANTARES no reconstruction program is available for ultra high energy muons, the reconstructed muon energy cannot be easily used to distinguish muons induced by cosmic neutrino interactions from atmospheric muons. On the other hand, the muon energy can be estimated [89] from the muon energy loss on its way to and through the telescope (see Chapter 5). In fact, the amount of light emitted by the muons and the associated electromagnetic showers provides an indirect measure of the muon energy. It should be realized though that the number of photons hitting the photo-multiplier tubes (PMTs) in the telescope depends strongly on the position of the track relative to the telescope (see Chapter 5). The amount of light observed in the telescope thus needs to be combined with position and direction information to estimate the muon energy, without having to rely on a full geometrical reconstruction.

As discussed in Chapter 3, the trigger software simulates the digitisation of the hits by the front-end chips (ARS) of the PMT. It also translates the recorded amplitude (AVC), time (TVC) and position of the digitised hits into calibrated information which can be used for further analysis. The calibrated amplitude is determined using a linear dependency of the recorded AVC value on the number of photo-electrons [25]. The calibrated signal amplitude in the PMT is thus proportional to the number of detected photo-electrons.

In Figure 5.4, the distribution of the estimated total charge of the hits induced in the telescope by the simulated AGN-like muon neutrino spectrum is shown, as a function of the (true) initial muon track energy. The distribution is also shown for a generic $E^{-1}$ spectrum, for comparison. The muon energy considered in the figure is the energy of the incoming muon at the surface of the default Can volume of ANTARES (see Chapter 2). The total charge of the hits in an event has been estimated by taking the sum of the calibrated hit amplitudes in every PMTs of the telescope. As expected, the distribution shows a correlation between the true muon energy and the digitised charge of the signal. Despite the width of the distribution, the total charge is seen to increase proportionally with the energy up to about $10^6$ GeV. Above this energy, the distribution becomes flatter due to the signal integration of the front-end chips of the PMT. The ensemble of PMTs which constitute the telescope is seen to saturate when receiving a charge...
5.2 Data selection and analysis

Figure 5.4: Distribution of the total charge of the hits produced by one event as a function of the (true) muon track energy. The energy distribution is assumed to follow an AGN-like spectrum (bottom). The same distribution is also shown for a generic $E^{-1}$ spectrum (top), for illustrative purposes. Downward-going events simulated with SIRENE are shown at the trigger level.
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larger than about $10^6$ photo-electrons (p.e). The performance of the PMT thus limits the readout of a large charge. However, the true muon energy is still a determining factor in the observed charge. The total charge of the digitised hits is therefore chosen as an estimate of the muon energy, without having to rely on track reconstruction.

5.2.2 Uncorrelated background and triggering

ANTARES does not only record hits from astrophysical and atmospheric muons, but also from the decay of $^{40}$K and bioluminescence (see Chapter 2). While hits from high energy muons are related in time and position, as a consequence of the properties of Cherenkov light emission, hits due to $^{40}$K and bioluminescence are uncorrelated. The trigger software is used to separate these isolated hits from the ones created by astrophysical and atmospheric muons. In this work, a background rate of 70 kHz due to $^{40}$K and bioluminescence has been added to the ultra-high energy (UHE) signal and the atmospheric background (see Chapter 5 for details). A three-dimensional trigger (trigger 3D) is used to search for time correlated hits. A hit is in local coincidence if it is within 20 ns of another hit, on a different optical module (OM), at the same storey. These coincident hits are referred to as “L1” events. Only events with a sufficient number of correlated hits are selected for further analysis, while the others are being discarded. This is motivated by the assumption that high energy muons induce multiple hits in the telescope, while uncorrelated background will mainly produce single hits. Since a muon track is defined by five independent parameters, a minimum of five local coincidences (“5L1”) is required. Coinciding hits on the same photo-multiplier tube (PMT) will generally result in a single hit with a large charge of typically 2.5 photo-electrons (p.e.) or more. Consequently, events with hits having a large charge are also included in the aforementioned L1 events.

The 3D trigger is suitable for UHE analysis. Since UHE muons induce large photo-electron hits in the PMTs, the trigger will select them irrespective of the number of local coincidences involved. The minimum of five correlated hits in the telescope has been shown to be sufficient to separate the hits due to atmospheric muons from those from uncorrelated background [21]. This selection will also improve the distinction between hits induced by UHE muons and the uncorrelated background. The resulting event rates are shown in Figure 5.5. Compared with the event rates shown in Figure 5.2, the background has been reduced as hits due to $^{40}$K decay and bioluminescence are now removed. However, at trigger level, no distinction can be made between events from atmospheric muons or cosmic neutrinos. Atmospheric muon bundles can spread over a large area and hit many optical modules (OMs) within a time window of a few nanoseconds [100], [104]. The trigger can therefore wrongly identify them as correlated

\footnote{The average uncorrelated background rate observed in situ.}
5.2 Data selection and analysis

Figure 5.5: Muon energy distribution at the trigger level induced by downward-going ultra high energy (UHE) astrophysical neutrinos (solid) and cosmic rays interaction in the atmosphere (dashed). SIRENE was used to simulate the UHE signal, while MUPAGE was used to generate the atmospheric muons. Events with a minimum of five local coincidences (at the same storey) or a large amplitude on one of the storeys are shown. The astrophysical neutrino flux corresponds to an AGN-like spectrum. The atmospheric spectrum has been extrapolated for energies above $10^5$ GeV with an $E^{-2.7}$ spectrum, following the primary cosmic ray spectrum at UHE.

hits from a single muon. Further analysis is necessary to improve the separation of the signal and the atmospheric background at the trigger level.

5.2.3 First event selection

Differences between the ultra high energy (UHE) signal and the atmospheric muon background can be exploited for data analysis. The main differences rely on the direction from which the muons arrive at the detector, and the energy of the muon which is estimated by the charge of the hits induced in the photomultiplier tubes (PMTs). In Figure 5.6, the distribution of the cosine of the zenith angle as a function of the total charge of the hits in an event is shown, for both the UHE signal and the background events. As can be seen in the figure, downward-going UHE muons concentrate near the horizon ($\cos \theta \approx 0$), whereas the direction of atmospheric muons is mainly vertical ($\cos \theta \approx -1$). Even though the charge induced by atmospheric muons is rather large (up to about $10^4$ photo-electrons), the hits from UHE muons give an even larger charge (up to about $10^{6.5}$ photo-
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electrons). These observations suggest that the atmospheric background can be rejected by excluding events with vertical directions and relatively low charge values.

Cut on the zenith angle

In figure 5.7, the distribution of the cosine of the muon zenith angle is shown for both signal and background events, at the trigger level.

As can be seen in the figure, atmospheric muons are peaking in the vertical direction and dominate over the astrophysical neutrino signal over almost the entire zenith angle range, with the exception of horizontal events in the range $-0.2 \leq \cos \theta \leq 0$. A loose cut is placed on the zenith angle at $\cos \theta \geq -0.6$ to reject the atmospheric vertical events while most signal events are kept.

Cut on the total charge of the hits

In Figure 5.8, the distributions of the total charge of the hits induced by ultra high energy (UHE) signal events and atmospheric background events are shown, at the trigger level. As for the muon energy spectrum, the distribution of atmospheric events has been extrapolated beyond $10^{4.5}$ photo-electrons (p.e.) with a power-law spectrum $E^{-2.7}$, following the primary cosmic ray spectrum. The distribution has thus been estimated up to $10^{6.5}$ p.e.

As can be seen in the figure, the distribution of UHE muons extends to a larger induced charge in the photo-multiplier tubes (PMTs) of the telescope than that of atmospheric muons. Both signal and background can induce a total charge up to $10^{6.5}$ p.e. A loose cut is placed at $10^4$ p.e. to reject events with low charge values which are mostly entirely due to atmospheric background.

5.2.4 Expected rates and neutrino flux limit

After selecting events with a charge larger than $10^4$ photo-electrons (p.e.) and a zenith angle such that $\cos \theta \geq -0.6$, the remaining simulated event rates per year have been determined. Figure 5.9 shows the event rates as a function of the estimated total charge of the hits (top) and the cosine of the zenith angle (bottom), after the cuts have been applied. As can be seen in the figure, the selection criteria reduce the number of background events but may require further optimisation.

In order to determine an experimental limit on a flux, the (maximum) number of signal events needs to be known as a function of the number of observed events and expected background, after all selection cuts have been applied. The upper limit on a source flux $\phi(E_\nu)$ is thus calculated as

$$\phi(E_\nu)_{90\%} = \phi(E_\nu) \frac{\mu_{90}(N_{obs}, N_b)}{N_s}$$  \hspace{1cm} (5.1)
Figure 5.6: Event distribution as a function of the total charge observed in the neutrino telescope and the cosine of the zenith angle for downward-going UHE neutrino-induced muons (top) and atmospheric background muons (bottom), at the trigger level. Signal events were simulated with SIRENE. The atmospheric muon background was simulated with MUPAGE.
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Figure 5.7: Distribution of the cosine of the zenith angle (rates per year) for atmospheric muons (dashed) and muons induced by downward-going UHE astrophysical neutrinos (solid) at the trigger level.

Figure 5.8: Distribution of the total charge (in p.e.) of the digitised signal induced by downward-going ultra high energy (UHE) neutrinos (solid) and atmospheric muons (dashed) at the trigger level. The astrophysical neutrino flux corresponds to an AGN-like spectrum. The atmospheric spectrum has been extrapolated to higher charge values assuming an $E^{-2.7}$ spectrum, following the primary cosmic ray spectrum at UHE.
5.2 Data selection and analysis

Figure 5.9: Distributions of the cosine of the muon zenith angle (top) and the total charge of the hits (bottom) induced in the telescope by atmospheric muon background (dashed) and cosmic downward-going UHE neutrinos (solid). Only those events which survived both cuts mentioned in the text are shown.
where $\bar{\mu}_{90}(N_{\text{obs}}, N_b)$ is the 90% confidence interval as a function of the number of observed events $N_{\text{obs}}$ and the expected background $N_b$. The variable $N_s$ is the total number of signal events.

The event rates shown in Figure 5.9 need to be integrated to determine the number of expected signal events $N_s$ and background events $N_b$ above a given value of the total charge of the hits and the cosine of the zenith angle. These integrated distributions are shown for the cosine of the muon zenith angle in Figure 5.10 (top) and for the total charge of the hits in Figure 5.11 (top). The simulated background rates are relatively small and their fluctuations can be described by Poisson statistics. For this specific situation, the method proposed by Feldman and Cousins [105] can be used to calculate the average upper limit that would be observed after hypothetical repetition of the experiment. Table XII of reference [105] is used to determine the average upper limit of the signal (which Feldman and Cousins refer to as sensitivity) at the 90% confidence level (CL), that would be obtained over an ensemble of experiments with no true signal ($N_s = 0$), for each value $N_b$ of the simulated background. The resulting average upper limit at the 90% CL is shown as a function of the muon zenith angle in Figure 5.10 (bottom) and as a function of the total charge of the hits in Figure 5.11 (bottom). As can be seen in the figure, the average upper limit is enhanced towards 2.44 events ($N_b = 0$) at the highest zenith angle and charge values.

5.2.5 Model rejection potential

The method proposed by G. Hill and K. Rawlins [106] has been used to optimise the experimental cuts and develop a stronger upper limit on the AGN-like neutrino flux model studied. The method is based on signal and background expectations from Monte Carlo simulations. It is used to place the strongest constraints on theoretical signal models. It is therefore suitable for this analysis.

The final selection values are the ones which minimise the ratio of the average upper limit over the expected signal from the model, i.e. the “model rejection potential” or “model rejection factor”

$$MRF = \frac{\bar{\mu}_{90}(N_b)}{N_s}.$$ 

The model rejection factor is shown in figure 5.12 as a function of the muon zenith angle and the total charge of the hits, for the simulated signal and background. The model rejection factor reaches a minimum for $\cos \theta = -0.2$ and a total charge of the hits $N_{\text{PE}} = 10^5$ photo-electrons (p.e). The best constraints on the simulated

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The table gives upper limits for background rates up to 15. A linear interpolation has been used to determine the 90% upper limit within the range of given background rates. For values of the expected background larger than 15, an extrapolation has been used, assuming the statistical fluctuations are of order $\sqrt{N_b}$ [55].
5.2 Data selection and analysis

Figure 5.10: Integrated distribution of the cosine of the muon zenith angle for the flux shown in Figure 5.9. Signal (solid) events induced by the simulated AGN-like neutrino flux and atmospheric background (dashed) events are shown in the top figure. The average upper limit is shown in the bottom figure.
Figure 5.11: Integrated distribution of the estimated total charge of the hits for the flux shown in Figure 5.9. In order to place a more accurate constraint on the simulated neutrino flux, the atmospheric spectrum has been extrapolated to higher values assuming an \( E^{-2.7} \) spectrum. Signal (solid) events induced by the simulated AGN-like neutrino flux and atmospheric background (dashed) events are shown in the top figure. The average upper limit is shown in the bottom figure.
5.2 Data selection and analysis

Figure 5.12: Model rejection factor - as defined in the text - for the diffuse flux of downward-going UHE neutrinos as a function of the muon zenith angle (top) and total charge (bottom) cut variables.
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neutrino flux are therefore found by accepting events with $\cos \theta \geq -0.2$ and a total charge of the hits $N_{\text{PE}} \geq 10^5$ p.e.

The expected event rates, corresponding to the final event selection criteria defined above are shown in Figure 5.13 as a function of the cosine of the muon zenith angle direction and the total charge of the hits. A total number of $N_s \approx 20$

![Figure 5.13: Distributions of the cosine of the muon zenith angle (top) and the total charge (in p.e.) of the digitised signal (bottom) induced by downward-going ultra high energy (UHE) neutrinos, using optimised cut selections - as defined in the text. The astrophysical neutrino flux corresponds to an AGN-like spectrum.](image)

signal events remain and no background ($N_b = 0$). This corresponds to an average upper limit of 2.44 events for one year and 0.81 events per year for three years of observation with the ANTARES telescope.
5.2 Data selection and analysis

5.2.6 Average flux upper limits

The average flux upper limit or sensitivity of ANTARES to the diffuse flux of UHE muon neutrinos has been determined by scaling the assumed AGN-like neutrino flux by the ratio of the obtained average upper limit $\bar{\mu}_{90}(N_b)$ to the expected signal $N_s$.

$$\phi(E_\nu)_{90\%} = \phi(E_\nu) \times \frac{\bar{\mu}_{90}(N_b)}{N_s}.$$ 

The predicted average flux upper limit, regardless of systematic uncertainties is therefore given by

$$E^2 \phi \leq 1.2 \times 10^{-7} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1} \quad \text{(after 1 year)},$$

$$E^2 \phi \leq 4 \times 10^{-8} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1} \quad \text{(after 3 years)}.$$ 

It is valid for neutrino energies between $10^5$ and $10^{11}$ GeV. It applies to a pure flux of muon neutrinos.

Considering oscillations with a flavor composition at Earth such that $\nu_\mu : \nu_e : \nu_\tau = 1 : 1 : 1$, the equivalent average upper limit for an equally mixed neutrino flavors flux would be about three times the obtained value, that is

$$E^2 \phi_{\nu_\mu + \nu_e + \nu_\tau} \leq 3.6 \times 10^{-7} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1} \quad \text{(after 1 year)},$$

$$E^2 \phi_{\nu_\mu + \nu_e + \nu_\tau} \leq 1.2 \times 10^{-7} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1} \quad \text{(after 3 years)}.$$ 

5.2.7 Comparison with existing bounds

Theoretical upper bounds have been placed on the diffuse flux of neutrinos, based on observations of gamma-rays and cosmic rays. The level of sensitivity obtained for the ANTARES telescope can be compared to the limit predicted by Waxman and Bahcall [107] for diffuse high energy muon neutrinos at 

$$E^2 \phi = 0.9 - 4.5 \times 10^{-8} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

for energies above $10^4$ GeV. This bound was calculated with the assumption of a $\nu_\mu : \nu_e : \nu_\tau = 1 : 2 : 1$ ratio. The corresponding 90% confidence level (CL) upper limit on an equally mixed flavor neutrino flux is thus given by

$$E^2 \phi_{\nu_\mu + \nu_e + \nu_\tau} = 1.35 - 6.75 \times 10^{-8} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}.$$ 

The Waxman and Bahcall limit constrains the neutrino flux using measurements of the cosmic ray spectrum above $10^{19}$ eV. The model assumes that neutrinos are produced in interactions of protons with the ambient photons or matter, in sources which are optically thin for high energy protons to photo-meson and nucleon-meson interactions. The neutrino flux is taken to follow an $E^{-2}$ dependence, as expected from Fermi acceleration. The Waxman and Bahcall limit is
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Figure 5.14: Comparison of the calculated upper flux limits for diffuse muon neutrinos as derived from different experiments and model calculations. The limits are given as a function of the logarithm of the neutrino energy. The measured atmospheric muon flux is shown using AMANDA-II data [108] with the central values for different calculations [109]. The Waxman and Bahcall bound is from [107], the ANTARES limit from [99], the AMANDA B10 limit at ultra high energy from [110]. The AMANDA-II limit is from [108] and for ultra energy from [111]. The RICE limit is from [112] and the BAIKAL limit from [113]. The IceCube limit is from [114] and the KM3NeT limit from [79]. The assumption has been made that $\nu_\mu : \nu_\tau : \nu_e = 1 : 1 : 1$ at Earth.
interesting as it probes the sensitivity of the current and next generation of neutrino telescopes.

Upper limits have also been reported by several existing neutrino experiments, assuming the same benchmark $E^{-2}$ dependence. In Figure 5.14, the 90% confidence level (CL) upper limits expected after one and three years of operation with ANTARES, for the diffuse flux of ultra high energy muon neutrinos are shown as a function of the neutrino energy. The most competitive experimental upper limits (at the 90% CL) for diffuse muon neutrinos are shown as well for comparison. The theoretical limit calculated by Waxman and Bahcall is also displayed. The sensitivity of ANTARES expected after one year of operation for diffuse UHE neutrinos is about a factor eight above the Waxman and Bahcall bound. After three years of data taking, the sensitivity is enhanced to about a factor two above the Waxman and Bahcall limit. As can be seen from the figure, the presented analysis predicts a sensitivity after one year of observation which is about a factor four above the upper limit placed by the AMANDA-II [111] telescope on the diffuse flux of UHE muon neutrinos. After three years of operation, the sensitivity of ANTARES improves to about a factor of two below that same upper limit. This upper limit has been determined by AMANDA-II using data from three years (2000 to 2002) with a livetime of 456.8 days. This is currently the most restrictive experimental bound placed by a neutrino telescope on a diffuse neutrino flux at UHE energies.

The upper limit calculated for ANTARES in this work is also about a factor two below the Radio Ice Cherenkov Experiment (RICE) bound [112] after one year of observation. After three years of data taking, the sensitivity of ANTARES increases to a factor of five below the RICE limit. This bound has been determined by RICE using data from seven years (1999 to 2005) with a livetime of 20500 hours that is around 854.1 days. This is currently the best limit at ultra high energies.

It should be noted that the present study is aimed at an order of magnitude estimate and does not account for systematic uncertainties. No full energy nor track geometry reconstruction was included. Nonetheless, a competitive upper limit has been found.

5.2.8 Effective detector area

The effective area for neutrinos represents the area of an ideal detector, capable of detecting neutrinos with full efficiency. It describes the performance of a telescope including its efficiency to observe neutrinos. The effective area $A_{\text{eff}}$ is defined as

$$\text{Nevents} = T \int dE \Phi A_{\text{eff}}(E, \theta)$$

where $\text{Nevents}$ is the number of events, $T$ the detector live-time and $\Phi$ the incoming neutrino flux. The effective area depends on the energy $E$ and the zenith
Figure 5.15: Muon neutrino effective area (in square meters) for ANTARES as a function of the neutrino energy (in GeV). The effective area for events which survive the selection cuts for UHE neutrino detection as described in Section 5.3.5 is shown (bottom). The standard effective area for (upward-going) neutrino energies below $10^7$ GeV is also shown for comparison (top).
angle $\theta_\nu$ of the neutrinos. In Figure 5.15, the effective area of the ANTARES telescope is shown as a function of the (true) incoming neutrino energy, for those events which could survive the optimised selection cuts described in the previous subsections. The optimised selection criteria lower the effective area at energies below $10^7$ GeV, as compared with the standard effective area of the ANTARES telescope. However, the effective area is enhanced at higher energies. As can be seen in the figure, the detection area increases with the neutrino energy up to $10^4$ m$^2$ at $10^{11}$ GeV. In the nearly horizontal angular range, a large area is covered by the muon tracks what yields an high detection efficiency. Moreover, high energy events produce a large amount of light which induce hits in the telescope, even when the neutrino interaction occurs far from the telescope.

5.3 Discussion

In the presented study, the flux of ultra high energy (UHE) diffuse muon neutrinos from downward-going and horizontal events has been simulated. Using new dedicated software packages and an optimised set of selection criteria, a fairly competitive upper limit for the neutrino event rate has been found. The event rates, however, remain low when using the neutrino telescope ANTARES. It is anticipated that the cubic kilometer sized KM3NeT [79] telescope will lead to an event rate increase with a factor twenty or more, and hence a reduction in the upper limit that probes the Waxman and Bahcall range (cf. Figure 5.14).