Ultra-high energy neutrino simulations

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Summary and conclusions

Extremelly energetic cosmic particles, with energies as high as 10^{20} eV have been observed in extensive air shower arrays [11] [12] [7]. The origin of these ultra high energy cosmic rays is one of the intriguing puzzles of astroparticle physics. In order to solve this problem, the astrophysical objects which are the source of cosmic rays and the processes involved in the production of particles with such extreme energies need to be unraveled.
In the last several years, considerable advances have been achieved in the field of cosmic ray research. Even though uncertainties remain and alternative models can be envisaged [12], evidence may be emerging for a diffuse shock acceleration scenario, involving extragalactic sources [11] [7]. Further information on the origin of ultra high energy cosmic rays can be obtained by searching for ultra high energy neutrinos. Ultra high energy neutrinos originate from the interactions of cosmic rays with ambient photons at the sites where they are produced [2]. Since neutrinos are stable neutral particles which interact very weakly with matter, they can travel across extragalactic distances to reach the Earth without being deflected by the electromagnetic fields of the Universe. Neutrinos thus point back to their sources and may provide essential information on the inner workings of ultra high energy cosmic ray accelerators.

The small interaction probability of neutrinos make them difficult to detect. Neutrino telescopes overcome this issue by observing the products of their interactions through the Cherenkov effect in a transparent medium such as sea water or ice. The main topic of this thesis is to study whether neutrino detectors can be used to search for ultra high energy neutrinos.

A correlation between ultra high energy cosmic rays and the several nearby active galactic nuclei (AGN) has recently been reported [13] which suggests that AGN are likely sources of ultra high energy neutrinos as well. The sensitivity of the ANTARES neutrino telescope to ultra high energy neutrino events above 10^{16} eV (and up to 10^{20} eV) has been estimated in the framework of this thesis. At these ultra high energies, the Earth is opaque to neutrinos and only downward-going and horizontal neutrinos can arrive at the detector. Since neutrino telescopes such as ANTARES are optimized for the detection of upward-going neutrinos in the energy range from 10^{11} to 10^{16} eV, it needs to be investigated whether downward-going neutrinos of energies in excess of 10^{16} eV can be observed. This is of relevance not only for the ANTARES telescope but also for the future cubic kilometer-scale detector KM3NeT. Moreover, the present study will provide information for the optimisation of the geometry of the KM3NeT telescope and the technologies required.

A non-localised flux of high energy neutrinos has been considered in order to enhance the probability of detection. As muon neutrinos are more easy to detect, only this neutrino flavor has been taken into account in the data analysis. The diffuse flux of muon neutrinos from AGN has been modelled by a generic E^{-2} spectrum with units of $10^{-6}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ [2].

The performance of ANTARES relies on the timing resolution of the signals recorded in the photo-sensors of the telescope and the proper operation of the various mechanical and electronic components of the telescope. A time calibration method and a diagnostic tool to determine if components are functioning as espected have been developed. The time calibration method has been tested with the MILOM prototype instrumentation line of ANTARES to provide preliminary information on the time calibration of the entire telescope. The method consists of the determination of the time offsets between the responses of the front-end chips of the line to a flash of an optical beacon. All electronics and calibration systems were found to contribute less than 0.5 ns to the overall timing resolution. This result enables us to predict an angular resolution of less than 0.3° for the ANTARES telescope.

The sensitivity of ANTARES to ultra high energy neutrinos has been evaluated in terms of Monte Carlo simulations. Three distinct stages of simulation can be recognised: the neutrino event generation, the propagation of the produced leptons towards the telescope and the detector response simulation. The simulation programs used to simulate events in ANTARES accept neutrino events within a limited range of energies only, i.e. below 10^{16} eV and thus cannot be exploited for the study of ultra high energy neutrino events. Improvements of already existing packages and the development of new programs have thus been required.

The neutrino event generator ANIS [74] was initially designed for use with the AMANDA neutrino telescope but it has been adapted to ANTARES to generate ultra high energy neutrino interactions in the surrounding water and seabed. The produced secondary leptons have been propagated towards and through ANTARES using the lepton propagator MMC [50] which is interfaced with ANIS and can process ultra high energy events. The telescope geometry and the sea water properties at the ANTARES site have been implemented in MMC. The output format of ANIS and MMC has been modified such that the software packages could be integrated into the ANTARES Monte Carlo simulation chain. This enabled a comparison with GENHEN [55], a neutrino event generator that includes lepton propagation. When suitably tuned, both programs were found to require roughly the same amount of CPU time and give comparable event rates. Nevertheless, only ANIS can be used in association with MMC above 10^{16} eV to generate ultra high energy neutrino events in the telescope.

A fast and flexible detector simulation program for neutrino telescopes has been developed to simulate the hits from Cherenkov photons at ultra high energies. The software package, named SIRENE was primarily designed for the future cubic kilometer-sized detector KM3NeT [79], but it has been applied to ANTARES as the program allows the use of alternative geometries belonging to other neutrino telescopes. SIRENE is capable to model the detector response for neutrino events with energies as high as 10^{20} eV. The program does not only allow the simulation of variable telescope geometries but also of different configurations and characteristics of the photo-multiplier tubes inside the optical modules of the telescope. SIRENE has been integrated into the ANTARES Monte Carlo simulation chain, thus enabling a comparison with the detector simulation package KM3 which is commonly used for ANTARES simulations. The ANTARES event library has been modified to take the characteristics of SIRENE into account.

Both programs were found to give comparable results in the energy range below 10^{16} eV, although differences remain that can be attributed to the tracking algorithms employed and the parametrisation of the muon total cross section. Moreover, in contrast to KM3, SIRENE can be used to process ultra high energy neutrino events. An interface with the trigger software of ANTARES has been developed to simulate the effect of the detector electronics and trigger the events produced by SIRENE. In order to validate the quality of the events simulated by SIRENE, they have been subjected (after digitization) to two distinct track reconstruction programs, known as Aart Strategy and Scanfit, which are available in the ANTARES collaboration. It was found that SIRENE cannot easily be used with either reconstruction algorithm. This can be partly attributed to the probability density functions adopted by both reconstruction programs that correspond to muon energies less than 10^{14} eV. These probability functions are therefore not suitable for simulating ultra high energy neutrino events with SIRENE. Moreover, the reconstruction programs were primarily designed for use with KM3 which involves a specific tracking algorithm that is not especially adequate for SIRENE. Therefore, new probability density functions for describing the ultra high energy range need to be developed and further tuning is required to improve the performance of the reconstruction programs in conjunction with SIRENE. However, the program that is used for energy reconstruction was found to perform well with SIRENE in the energy range below 10^{16} eV. None of the available reconstruction algorithms was found suitable at ultra high energies and a different approach has been envisaged to estimate the ANTARES sensitivity in this domain.

When searching for neutrinos in the ultra high energy domain, the background consists of atmospheric muons which can reach the detector. They result from interactions of cosmic ray primaries in the Earth's atmosphere and can be mis-interpreted as secondary leptons from cosmic neutrinos. The program MU-

PAGE [100] has been used to simulate the atmospheric muons impinging on the ANTARES detector surface. MUPAGE is a parametrisation of the atmospheric muon flux, based on HEMAS [101], simulating single and multiple underwater muons at the depth of the detector. A dedicated data analysis method has been developed in order to reduce the atmospheric muon background while preserving sensitivity to the ultra high energy signal. The method relies on differences between the signal and the atmospheric muon background regarding the energy of the muons and the direction from which they arrive at the detector. The amount of light emitted by the muons and the associated electromagnetic showers provide an indirect measure of the muon energy. As it depends on the position of the track relative to the telescope, it contains position and direction information and can be used to estimate the muon energy without having to rely on a full geometrical reconstruction. To include the simulation of the front-ends electronics, the total charge of the hits has been chosen as an estimate of the muon energy for the data analysis. It was found that the atmospheric background can be rejected by excluding events with low charge values and vertical directions. A model rejection potential method has been applied to optimise the experimental cuts and place the strongest constraints on the simulated AGN-like diffuse neutrino flux. The optimised selection criteria lower the effective area for neutrinos at energies below 10^{16} eV as compared with the standard effective area of the ANTARES telescope. However, the effective area is enhanced at higher energies up to 10^4 m^2 at 10^{20} eV. The obtained effective area is comparable to the one of the neutrino telescope AMANDA-II for the same flux model and energy range [111].

An estimate of the average flux upper limit that can be obtained with ANTARES for the simulated AGN-like diffuse muon neutrino flux has been placed at the 90% confidence level at

$$E^2\phi \leq 1.2 \times 10^{-7}\mathrm{GeVcm^{-2}s^{-1}sr^{-1}} \quad \text{(after 1 year)}, \tag{5.2a}$$

$$E^2\phi_{\nu_\mu+\nu_{e^-}+\nu_\tau} \leq 4.1 \times 10^{-8}\mathrm{GeVcm^{-2}s^{-1}sr^{-1}} \quad \text{(after 3 years)}. \tag{5.2b}$$

This limit is valid for neutrino energies between 10^{17} eV and 10^{20} eV. It was compared with the currently most competitive upper bounds made on the diffuse flux of ultra high energy neutrinos. The upper limit predicted after one year of observation with ANTARES is about on order of magnitude above the theoretical bound calculated by Waxman and Bahcall [107] and about a factor of four above the upper limit placed by the AMANDA-II [111] telescope. The expected sensitivity after three years of operation is enhanced to about a factor of two above the Waxman and Bahcall limit. Compared with the results reported by AMANDA-II, the sensitivity of ANTARES expected after three years of data taking shows an improvement of almost a factor two. These results are encouraging. However, it should be noted that the present study is aimed at an order of magnitude estimate. No full energy nor track geometry reconstruction was included. Nonetheless, a fairly competitive upper limit for the neutrino event rate has been found.

It is anticipated that the cubic kilometer sized KM3NeT [79] project will lead to an event rate increase of about a factor twenty, and hence a substantical reduction in the upper limit allowing to probe the Waxman and Bahcall range.