
High Energy Neutrino Generator for Neutrino Telescopes

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Abstract

We present the high energy neutrino Monte Carlo event generator ANIS (All Neutrino Interaction Simulation). The aim of the program is to provide a detailed and flexible neutrino event simulation for high energy neutrino detectors, such as AMANDA and ICECUBE. It generates neutrinos of any flavor according to a specific flux, propagates them through the Earth and in a final step simulates neutrino interactions within a specified volume. All relevant standard model processes are implemented. We discuss strength and limitations of the program, and provide as an example event rates for atmospheric and E^{-2} neutrino spectra.

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1. Introduction

The era of dedicated high-energy neutrino telescopes has just begun. The currently operating detectors AMANDA and BAIKAL will hopefully soon be joined by ANTARES, ICECUBE, NEMO and NESTOR. The unifying goal is to detect neutrinos of extraterrestrial origin. For the Monte Carlo (MC) simulation of atmospheric muons in such detectors, CORSIKA is frequently used. The subsequent muon propagation may be done using programs such as MMC, MUM or MUSIC. However, no standard for neutrino generators has yet emerged.

In this paper, the MC ν -event generator **ANIS** (**A**ll **N**eutrino **I**nteraction **S**imulation) is described. It generates ν -events of all flavors, propagates them through the earth and finally simulates ν -interactions within a specified volume around the detector. All relevant SM processes, i.e. CC and NC νN -interactions as well as resonant $\bar{\nu}_e e^-$ -scattering are implemented. Neutrino regeneration as expected in NC-scattering, $\nu + N \rightarrow \nu + X$, and in τ production and decay chains, $\nu_\tau + N \rightarrow \tau + X$, $\tau \rightarrow \nu_\tau + (\nu_i) + X$, are included in ANIS.

In the next sections a description of the characteristic features of ANIS is presented. As an application of ANIS, the event rates for atmospheric and astrophysical electron neutrinos (following an E^{-2} spectrum) are calculated.

2. The Signal Generator ANIS

ANIS is written in C++ and makes use of the CLHEP package [1]. The internal event record is derived from the CLHEP *HepMC* event class. There are currently two output formats implemented: i) the AMANDA specific event format *f2000* [2] and ii) the HepMC *ascii* format [1].

The program is controlled through a steering file which allows to enable specific interaction processes included in the simulation. The currently implemented interaction channels include CC, NC as well as resonant $\bar{\nu}_e e^-$ -scattering. The cross-section data for CC and NC reactions are provided through pre-calculated external tables. The total cross-section is obtained through interpolation. Large sets of possible final states, characterized by the Bjorken variable x and $y = E_h/E_\nu$, have been generated and are randomly sampled from during generation of neutrino events. The use of pre-calculated tables makes the program fast and independent of other packages. The cross-section data has been calculated up to 10^{12} GeV and is discussed in more detail in the following section.

Primary ν 's are randomly generated on the surface of the earth with energy spectrum $F_\nu(E) \propto E^{-1}$ and are then propagated to the detector. Interacting with matter they are either absorbed (CC case) or regenerated at lower energies (NC case) [3]. In the special case of CC $\nu_\tau N$ -interaction a short-living τ -lepton is produced. It propagates in matter, losing part of its energy, and finally decays giving rise to secondary ν_τ and, in $\sim 17\%$ of the cases, to secondary ν_μ or ν_e . The τ -decay in ANIS has been simulated using TAUOLA [4]. Thereby the practically full polarization of high energy τ 's was taken into account. Again, the previously generated decays of polarized τ -leptons are stored in tables, which are then sampled from by ANIS.

The density profile of the earth in ANIS is chosen according to the Preliminary Earth Model [5]. Regeneration effects are naturally accounted for by feeding the secondary ν 's back into the event record. These ν 's are assumed to be emitted parallel to the direction of the primary ν . This is justified, since regeneration effects become significant just at very high energies, where the accumulated deflection angle is generally smaller than the telescope angular resolution.

Once the detection volume is reached, a final vertex is sampled along the ν trajectory within the detection volume (specified through the steering file). In the case of a CC $\nu_\mu N$ -interaction, ANIS correctly simulates the muon scattering angle. Along with the full event, three weights for later use are written out: the normalization of the flux, a weight for the atmospheric flux [6], as well as a weight proportional to the total cross-section of the neutrino interaction.

Event rates for atmospheric and various extraterrestrial neutrino spectra are obtained by applying the appropriate weights to the events. This last step is to be done by a user defined energy dependent weight function during analysis of the events in PAW, ROOT or any other analysis programs.

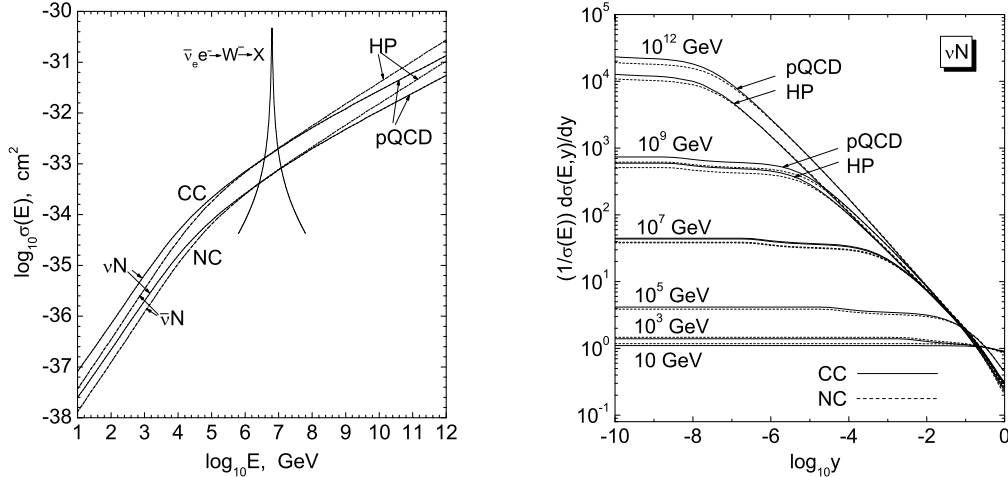


Fig. 1. a) νN - and resonance $\bar{\nu}_e e^-$ -cross-sections and b) normalized y -distributions.

3. Neutrino Cross Sections

At $E_\nu \lesssim 10$ PeV, deep inelastic νN -cross-sections may be successfully described in the framework of pQCD. Parameterization of the νN structure functions, $F_i^{\nu N}(x, Q^2)$, may be taken e.g. according to CTEQ5 [7]. At higher energies these cross-sections are dominated by scattering off small x quarks. The unknown behavior of the structure functions at $x \lesssim 10^{-6}$ makes the calculations model dependent. The uncertainty in extrapolations of $F_i^{\nu N}(x, Q^2)$ to small x and large Q^2 influence the expected cross-sections at high energies.

There are two possibilities presently included in ANIS: i) the smooth both in x and in Q^2 *power-law* extrapolation of the pQCD CTEQ5 parameterization to small x and large Q^2 , and ii) *hard pomeron* [8] enhanced extrapolation [9]. The cross-sections of the first case, denoted in the Fig. 1a as pQCD, practically coincide with [10], while the second model (HP, dash-dotted curves) predicts approximately 2 times higher cross-sections at $E_\nu \approx 1$ ZeV. The y -distributions, normalized to the corresponding cross-sections, are plotted in Fig. 1b; the solid and dashed curves stand for CC and NC νN -scattering, respectively.

The user can choose the desired model through the steering file. It is possible to add any new model to ANIS by providing the corresponding cross-section and final state tables.

Due to $m_e \ll m_N$, at high-energies practically all νe^- -cross-sections are negligible, with the only exception of $\bar{\nu}_e e^- \rightarrow W^- \rightarrow anything$ at $E_{\bar{\nu}_e} \approx 6.3$ PeV [11] (see Fig. 1a). This resonance process is also included in ANIS. Finally it should be noted, that ANIS can easily be extended to include new processes beyond the Standard Model.

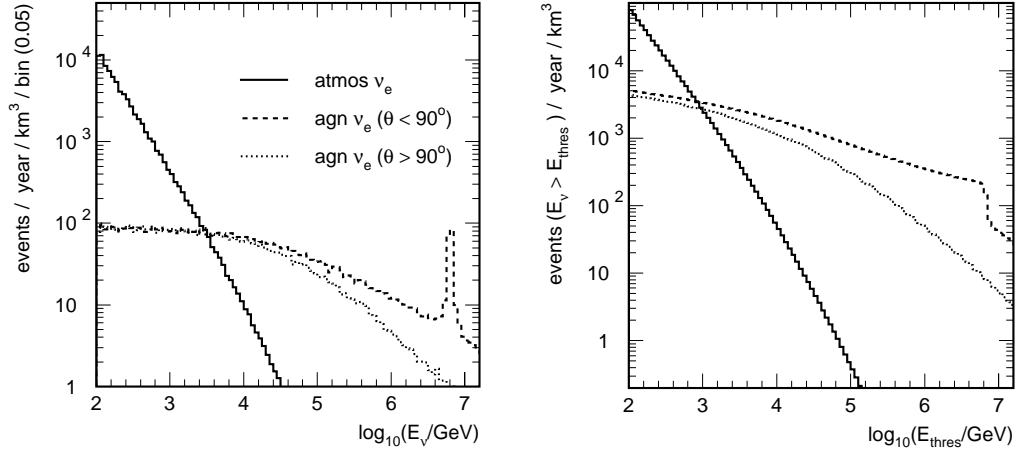


Fig. 2. Number of $\nu_e + \bar{\nu}_e$ events per ($\text{km}^3 \text{ year}$) are shown as a function of energy (left). The number of events above a threshold energy E_{thres} are shown in the right plot.

4. Discussion

As an application of ANIS, the resulting distributions of $10^5 \nu_e + \bar{\nu}_e$ events for an atmospheric spectrum and a diffuse AGN-like flux ($F_\nu(E) = 1 \times 10^{-6} E^{-2} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$) are shown in Fig. 2. In order to illustrate the effects of ν propagation through the earth, the contributions from the upper and lower hemisphere are shown separately. Alternatively, ν_μ and ν_τ can be simulated, however, muons produced in the reaction have to be propagated with a separate program, e.g. with those mentioned in the introduction. Concluding one can say, that the present version of ANIS allows the precise simulation of high-energy ν -events of all flavors in a wide energy range and designed flexible to allow incorporation of possible new physics processes.

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