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# Neutrino Event Generator Review

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Neutrino event generators play an important role in the design and execution of neutrino experiments. In this paper I will review the state of the art in this field, with a focus on recent improvements to several widely used programs.

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## 1. Introduction

Neutrino event generators are an important tool for the analysis of experimental data, the design and optimization of detectors, and the evaluation of the systematic errors for measurements. The production of Monte Carlo samples for physics analyses is costly in terms of computing resources, time, and effort, and these place constraints on the level of computational complexity event generators can incorporate, and on validation. Simulating neutrino interactions in the energy range of interest to current and near-future experiments (roughly 0.5-10 GeV) poses particular challenges, as this broad energy range bridges the perturbative and non-perturbative pictures of the nucleon and a variety of scattering mechanisms are important. Figure 1 shows the broad kinematic range covered by the NuMI low energy and T2K beams (at the ND280 site), together with some characteristic values of $Q^2$ and invariant mass (W=1.2, 2, 4, 10 GeV) which are often considered to be cutoffs for the validity of particular theoretical approaches. For validation and uncertainty estimation data from previous neutrino experiments are used to evaluate cross sections and hadronization models, charged lepton scattering scattering are used to evaluate nuclear models and structure functions, and hadron scattering data are used in evaluating intranuclear rescattering models.

## 2. Review of Generators

The generators described in this brief review are largely assembled from common ingredients: descriptions of quasi-elastic/elastic scattering via nucleon form factors, models for single pion production via resonance production, modified parton-model based treatments of deep (and not-so-deep) inelastic scattering, impulse approximation treatments of nuclear dynamics, and intrancuclear cascade simulations. However they differ in many details, in particular in how the component cross sections are combined (while avoiding double counting), hadronization, and nuclear effects, and often lead to significantly different predictions [1]. In this section we will only mention a few key points about each program, while listing some new work that has been done in the past few years on certain packages. A more detailed review of the components of each generator can be found in Reference [2].

### 2.1 FLUKA

The FLUKA event generator has been widely used for twenty years to model a wide variety of physical processes, and has been used successfully in applications in a broad variety of areas [3], and versions incorporate the dominant neutrino scattering channels (quasi-elastic, delta production, and DIS) [4]. The DIS model incorporates the GRV98LO parton distributions with an extrapolation to $Q^2$=0 given by:

$$F_i(Q^2,x) = \frac{2Q^2}{Q_0^2+Q^2} F_i(Q_0^2,x). \tag{2.1}$$

The resonance production model (NunRes) is based on the model of Rein-Sehgal, with a non-resonant contribution determined from NunDIS. The transition from the resonance region to DIS is accomplished by a smooth linear transition of the cross section as a function of invariant mass. Hadronization is simulated using existing FLUKA routines.



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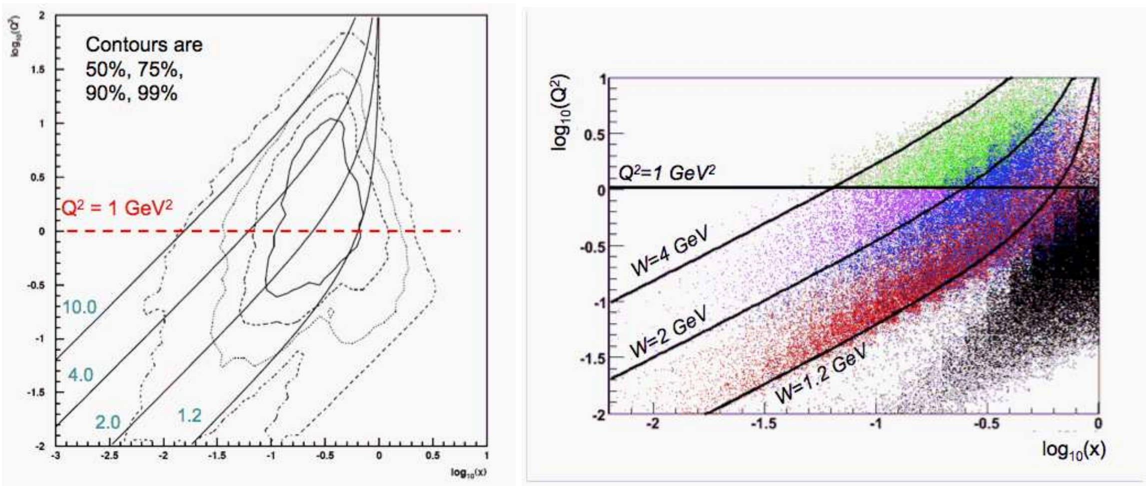


**Figure 1: Left:** Kinematic range probed by the Fermilab NuMI beam (low energy mode). Contour lines indicate regions of the kinematic plane containing the indicated fraction of events. **Right:** Kinematic range probed by the T2K beam at the ND280 site.

### 2.2 GENIE

GENIE is a ROOT-based Neutrino MC Generator [5]. Numerous developments over the past several years have focused on software infrastructure needed by experimental users. These include speed improvements to software that interfaces neutrino cross sections, detector geometry, and output of neutrino beam simulations in order to correctly simulate event rates in complicated detector geometries located at near sites where the beam and detector sizes are comparable. GENIE can also do event-by-event reweighting, allowing experiments to make the efficient use of a single Monte Carlo sample for systematic error evaluation [6]. Currently under development for GENIE is a new intranuclear rescattering model that would incorporate a full hadron-nucleon cascade simulation, using two and three-body cross sections derived from data and a goal of accurately describing nucleon, pion, and kaon cross sections in nuclei up to 2 GeV KE [7].

### 2.3 GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) model is a semiclassical transport model in coupled channels applied in this case to neutrino interactions [8]. The BUU equation describes the space-time evolution of a many-body system in the presence of potentials and a collision term, and has been used for several decades as the basis for transport models which describe scattering over a broad range of incident energies. The computational task that this model undertakes is one of solving a set of eight-dimensional integral-differential equations which are coupled through the collision integral and mean-field terms. It takes into account numerous nuclear effects: the local density approximation, mean-field and Coulomb potentials, off-shell particle transport Pauli blocking, hadron self-energies, and modified cross sections, and the final state, such as particle reinteractions, since the two are derived from the same model. Recent work has gone into extending the GiBUU calculations to higher energies, through the incorporation of DIS scattering processes and comparisons with nuclear PDFs [9].

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### 2.4 NEUT

The NEUT neutrino event generator was originally developed for the Kamiokande experiment, and has been used by SuperKamiokande, K2K, T2K, SciBoone, among others [10]. Since NEUT was originally developed in the context of water Cerenkov nucleon decay experiments, particular attention was given to the rescattering and absorption of few-hundred MeV pions in oxygen nuclei.

In order to more accurately model backgrounds to relic neutrino searches, improvements have recently been made to the neutral current elastic cross section and the modeling of de-excitation photon emission from oxygen. Intranuclear rescattering is simulated using a custom built cascade model that has been extensively compared to hadron-nucleus (particularly $\pi$-$^{16}$O scattering) and pion photo-production data [11]. In pion absorption reactions, hadron emission is now simulated, with nucleon multiplicities taken from data, kinematic distributions for two-body final states taken from data, and kinematic distributions for other final states determined via phase space decays.

### 2.5 NUANCE

The NUANCE generator [12] was originally developed for the IMB experiment, and has subsequently been used by SuperKamiokande, MINOS, and MiniBooNE, among others. The program generates 99 exclusive final states for NC and CC processes. Numerous aspects have been modified by the MiniBooNE experiment in order to better describe their data. In the cross section model these include the addition of a parameter ($\kappa$) to control low $Q^2$ suppression of quasi-elastic scattering, adjustments in coherent/resonant $\pi$ production modeling, and updating form factors in the resonance production model [13]. The modeling of rare e-like events has been improved with the inclusion of non-isotropic $\Delta$ decays, radiative decays, and de-excitation photon emission from carbon. Reweighting capabilities within MiniBooNE MC have also been added, and a tuning of the final state interaction model for pion propagation (pion absorption and charge exchange cross section normalizations) based on external pion-carbon data.

### 2.6 NuWRO

The NuWRO generator is the first neutrino generator to be produced by a theory group (Wroclaw University) [14] and features careful treatment of transition regions in the cross section and hadronization model. The NuWRO generator uses a new hadronization model, which is able to accurately describe many features of the collected data, including total average multiplicities as a function of invariant mass, strange particle production rates, and forward and backward hemisphere multiplicities. NuWRO also features an ‘effective’ implementation of spectral functions in order to correctly describe the distribution of nucleon momenta and binding energies in the impulse approximation scheme [15]. This work therefore represents the most advanced effort to efficiently implement spectral functions in a neutrino event generator.

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