Neutrino Event Generators*

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Abstract

For the world-wide neutrino community, neutrino event generators provide one of the key interfaces between theory and experiment. In this note I will describe improvements to four generators that simulate neutrino interactions in the few-GeV regime: GENIE, GiBUU, NEUT, and NuWRO. I will conclude with some thoughts on how research in this area has evolved over the past decade, and what some of the outstanding challenges are.

I. INTRODUCTION

This paper will have two objectives. The first is to describe briefly recent developments in the four main neutrino event generators that are in use around the world: NEUT, GiBUU, NuWRO, and GENIE. At the same time, I will use a somewhat wider lens, and examine how this tool has evolved over the past decade, and where it might be headed. This will highlight, I believe, recent successes as well as some significant challenges.

For experimentalists, generators need no introduction. The play a number of roles in the analysis of data and the production of our scientific results. If one is performing a cross section analysis, the goal is to produce a result that is as model (i.e. generator)-independent as possible, often achieved by making data-based corrections. Nonetheless generators, combined with full detector simulations, are used for background estimation, acceptance corrections, and connecting true to observed quantities (typically encoded in an unfolding matrix). These necessarily introduce systematic errors associated with the generators and the models they contain.

For oscillation experiments, the role played by generators is less obvious, since these measurements typically involve near/far comparisons. In this case, generators are often tuned to near detector data, and residual uncertainties on model parameters then impact the precision of oscillation results. In this context, of primary concern to the experiment is the question of how wrong the model could potentially be.

I would point out that while generators are indeed used in other branches of physics, in particular electron scattering and collider physics, neutrino generators are unique in a number of ways. They lack of a simple factorization of hard and soft processes that allows simplifications in collider simulations, and many of the quantities that we are attempting

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to calculate are, from a theoretical perspective, extremely complicated, requiring relativistic nuclear many-body theory for an accurate *ab initio* treatment.

A. The Components

If we view an Event Generator as a piece of software, than its inputs are a neutrino (of specified flavor and energy) and a nucleus, and the output is a set of outgoing particle four vectors. These codes typically attempt to (imprecisely) factorize the task:

1. The initial nuclear model which describes the energy-momentum distributions of nucleons in the target nucleus.
2. Models for the fundamental nucleon-level scattering processes.
3. For inclusive interactions, the generator runs an appropriate hadronization algorithm, many of which are tuned to free nucleon data.
4. The effect of the nuclear medium on final state hadrons is computed.

In all cases, one has a range of options for the modeling, often going from the very simple (Relativistic Global Fermi Gas), to the extremely complicated, and one of the practical challenges in developing this software is balancing the computational requirements against the desire for detailed microscopic calculations. This factorization relies on the applicability of the Impulse Approximation - a valid approach for scattering at GeV energies, however relying entirely on this assumption is incorrect, as it neglects the important role played by 2p-2h scattering processes. Generators are benchmarked against a wide range of data, including electron scattering, neutrino scattering - from the bubble chamber era as well as experiments from the past decade - and hadron probes.

II. RECENT PROGRESS

In this section we will review recent improvements in four of the most widely used generators in the few-GeV regime: GENIE, GiBUU, NEUT, and NuWRO.

A. NuWRO

NuWRO was the first neutrino event generator to be developed by a theory group (Wroclaw University)[1]. Careful attention is paid to making smooth transitions between models, for instance in the treatment of the transition region between resonance production and

DIS, or in the transition between low mass hadronization and PYTHIA. The final models are benchmarked against data, and good agreement is shown [1, 2]. The NuWRO collaboration has investigated the difficult and important problem of hadronization in nuclei, an area where generators apply very different approaches [3].

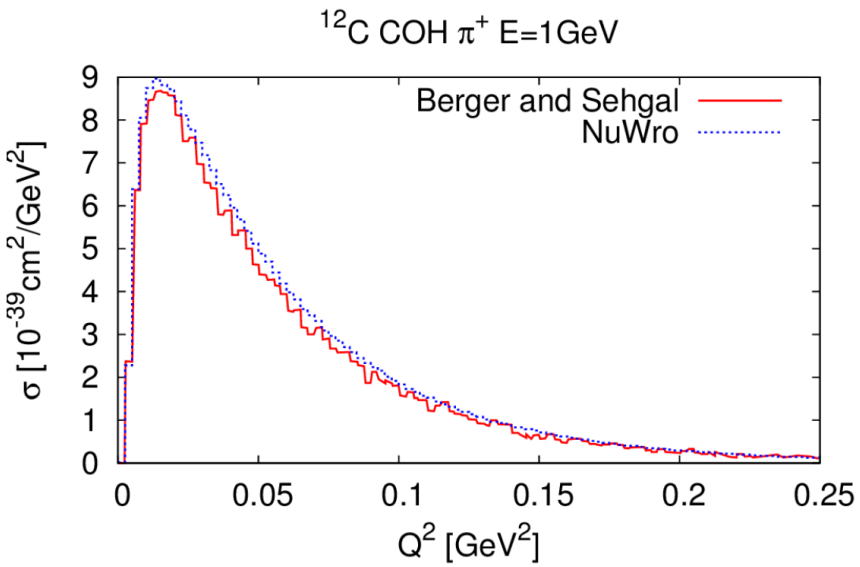

FIG. 1: Berger-Sehgal calculation (red) and NuWRO prediction (blue) of the Q^2 distribution of muon neutrino CC coherent interactions off carbon at E_ν=1 GeV.

Recently, several improvements have been made. The Berger-Sehgal model for coherent production [4], in both NC and CC channels, has been added. Figure 1 shows the good agreement between the NuWRO implementation and the original theory calculation for the Q^2 distribution of CC coherent interactions on carbon at 1 GeV. Modifications have been made to the angular distribution of pions in delta decays, which are now based on ANL/BNL bubble chamber measurements. Another major development has been eWRO - the ability to run the NuWRO models in electron scattering mode, which makes possible a wide variety of comparisons to electron scattering data. One example is shown in Figure 2.

B. GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) model is a semiclassical transport model in coupled channels [6] that takes into account numerous nuclear effects: the local density approximation, mean-field and Coulomb potentials, off-shell particle transport, 2p2h excitations, and in-medium spectral functions. It is the only generator that uses transport theory, the others all rely on intranuclear cascade Monte Carlos. It has been extensively

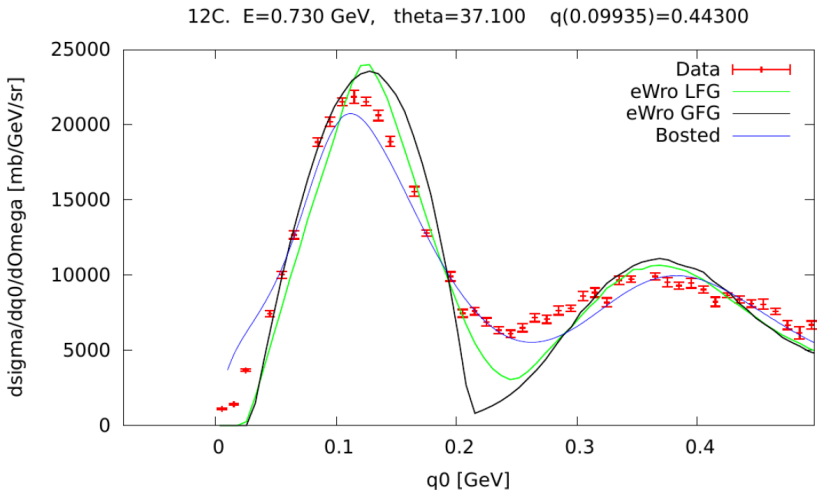

FIG. 2: Electron inclusive scattering comparison using eWRO. Shown are results from a global fermi gas (black), local Fermi gas (green), and using the Bosted parametrization of the inclusive response [5].

checked against data for heavy-ion collisions, electron scattering, photo-production, and hadron-nucleus collisions. GiBUU describes a wide range of data with a single, self-consistent microscopic model, ensuring consistency between nuclear effects in the initial state (such as Fermi motion, Pauli blocking, hadron self-energies, and medium-modified cross sections) and the final state (such as particle reinteractions). GiBUU is best viewed as a theoretical framework, which has now found application in photo-, electon-, neutrino-, pion-, nucleon-, and heavy-ion reactions, giving it considerably broader scope than most neutrino generators.

GiBUU has been used extensively over the past several years to illuminate areas where nuclear effects can play significant roles in experimental analyses [7–9]. These papers have described the issues generally, discussing the model choices in GiBUU, for instance, while also studying their implications in the context of specific experimental programs and measurements. As an example, the consequences for experiment of 2p2h scattering and final-state interactions, in terms of neutrino energy reconstruction, kinematic reconstruction, usefulness of topological separation based on final state observables, and others, have been explored. By providing fast turnaround for implementation of new theoretical ideas, theory-led generator groups are able to quickly provide tools to assess the impact on experiment. This stands in contrast with generators developed by experimentalists, which incorporate new theory more slowly, and are most often used as the front end to full Monte Carlo simulations. This is often a slow process, but one that is needed for experiments to assess exactly how their measurements are impacted. In this way, generators developed by theory- and experiment-led teams play complementary roles.

C. GENIE

The GENIE [10] neutrino event generator utilizes a software design which emphasizes extensibility, modularity, and flexibility. This design lowers the bar to development work, and over the past two years the collaboration has been re-organized to better facilitate model contributions by the broader community to GENIE. Fermilab has also taken on a larger role in GENIE activities, serving to support the large user base at the lab and acting as a hub for GENIE work. GENIE also has a new release strategy, where major releases (the next being GENIE 3.0) incorporate changes to the default set of models, and minor releases (the most recent being 2.10) incorporate new models as optional elements.

GENIE 2.10 offered a number of enhancements, which are described in detail elsewhere [11]. They include improvements to the intranuclear rescattering simulation to better characterize the A dependence of rescattering processes, the inclusion of an Effective Spectral Function model [12] that combines a new nuclear model based on super-scaling phenomenology with modeling of multi-nucleon scattering processes, the inclusion of a model for neutrino production of single kaons [13], and extensions to run to TeV scales, among others. Results from the new intranuclear rescattering model are shown in Figure 4, and the muon energy distribution from 1.5 GeV CC reactions producing single kaons is shown in Figure 3.

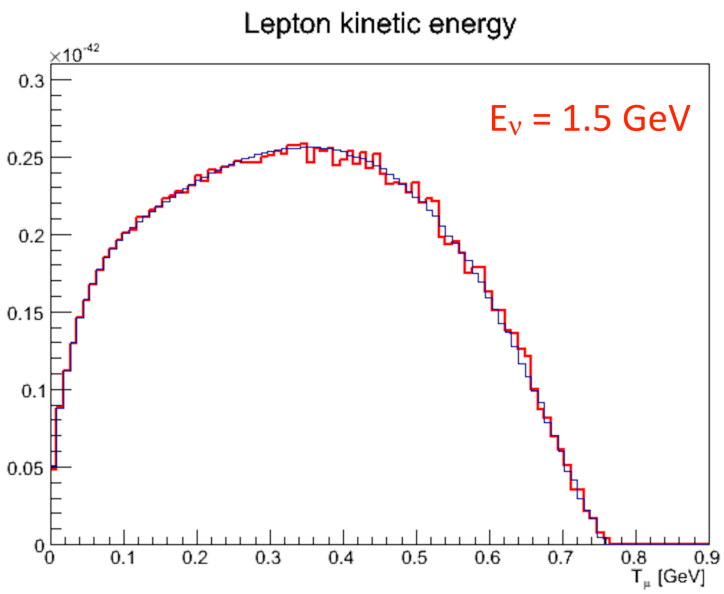

FIG. 3: Muon energies from 1.5 GeV CC $\Delta S = 1$ single pion reactions. The predictions from the full theory calculation [13] are shown (blue), together with a standalone C++ implementation that is identical to the GENIE prediction (red).

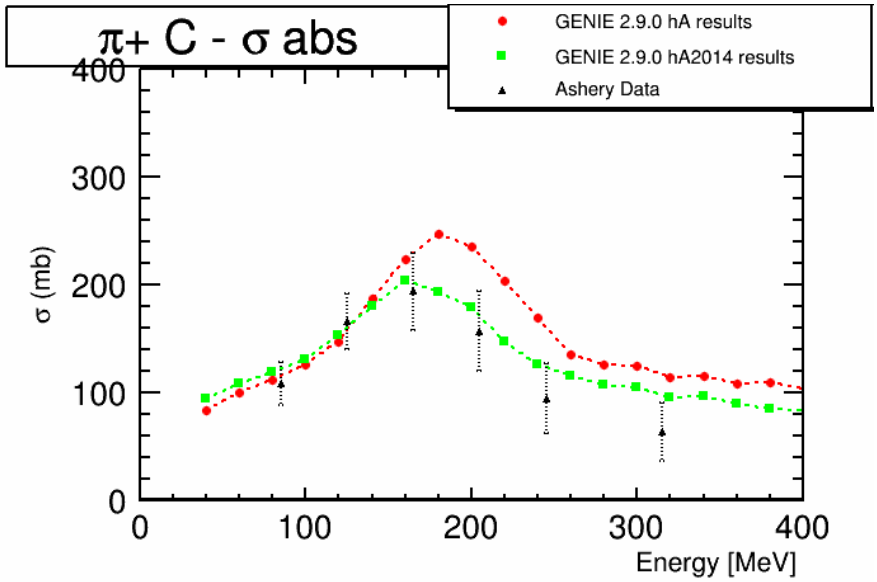

FIG. 4: Pion absorption on carbon, data compared with the GENIE default model (red) and the new intranuke model (green).

D. NEUT

The NEUT neutrino event generator was originally developed for the Kamiokande experiment, and has been used by the Super-Kamiokande, K2K, SciBoone, T2K, and Hyper-Kamiokande collaborations [14]. The primary goal of NEUT development is to meet the needs of this experimental program. Recent additions to NEUT include the Nieves model for multi-nucleon prodcution [15] and a returning of the single pion cross sections to the ANL/BNL data [16], both of which are on by default. In addition, the Nieves calculation of RPA correction [17] is available as a reweightable option, and radiative CCQE is also available as an optional process. Figure 5 shows the effect of including the RPA corrections on the CCQE cross section, and Figure 6 shows the multi-nucleon scattering cross sections. An extensive campaign of retuning using T2K near detector data, together with data from previous experiments in the same energy range, was carried out as part of their oscillation analyses, and is described elsewhere in these proceedings [19]. Other ongoing work includes re-tuning to pion multiplicity distributions, incorporation of the full CCQE model of Nieves, and improvements to the coherent model. More information about recent NEUT upgrades can be found in [19].

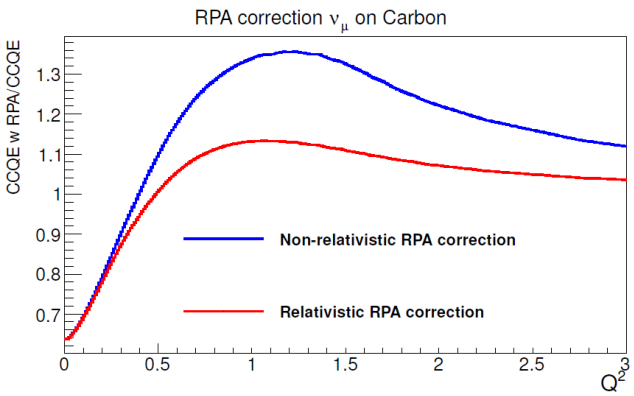

FIG. 5: Effect of relativistic (red) and non-relativistic (blue) RPA corrections on the shape of the Q^2 distribution for CCQE interactions (NEUT).

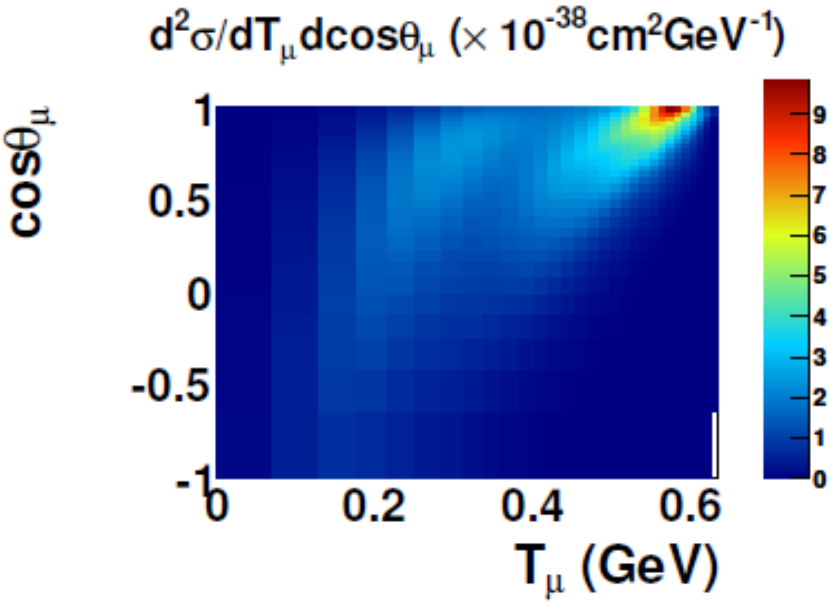

FIG. 6: Doubly differential distribution of $E_\nu = 0.65$ GeV QE-like interactions from oxygen, including 2p2h excitations (NEUT).

III. PROGRESS MADE AND CHALLENGES AHEAD

Experimentalists are fortunate to have access to four neutrino generators that are under active development. They have different emphases and perspectives, and play somewhat complementary roles, as they straddle the experiment/theory divide. Having multiple generators available to an experiment can be very helpful. For instance, being able to run multiple generators is a simple and (possibly) effective way to evaluate generator-related

systematic errors, but ONLY when: they incorporate different models and/or assumptions, are tuned to and constrained by relevant data, and the reasons for differences between the generators are well-understood (more work is needed here).

Over the past five years there has been continued and marked progress in the development and usage of neutrino generators. There has been a continuation of a trend towards open source, publicly available generator codes. Worldwide, there is an active theory community, and a number of theorists now work directly with experiments or generator developers. These direct experiment-theory conversations have produced new ideas about how to incorporate sophisticated (but slow) calculations into generators [18], and more experiments are now in a position to compare their results to multiple generators, and a variety of models within generators. Across the field there is now a broad recognition of the importance of close experiment-theory collaborations for progress in this area. Over the coming years, these efforts will naturally lead into conversations about the assignment of generator-related systematic errors, which can often be a difficult topic.

One of the largest challenges our field faces at the moment is in digesting the large amount of data that has been produced over the past decade, and building from it a consistent model of neutrino-nucleus interactions. To start with, there is a huge volume of data (γA, νA, eA, πA, pA), in principle. Deciding upon a strategy for incorporating this data into a coherent and consistent generator can in itself be a challenge, particularly as it has become clear that it is not possible to fit the entirety of the world's data using the models that are currently on the market. Progress often requires detailed understanding of an experiment's systematic errors, including correlations. Generator tuning campaigns, which also produce estimates of systematic errors, require large amounts of effort and require close collaboration between theorists, experimentalists, and generator authors.

Another challenge for generator developers stems from one of the largest theory challenges - how to correctly (or effectively) incorporate sophisticated nuclear physics into the needed calculations for neutrinos with energies around 1 GeV. There are a number of modeling issues that remain to be fully resolved, most significantly calculations related to np-nh processes, which for the purposes of generators, need to include modeling of the hadronic final state. And as always, trying to merge models that have applicability in separate kinematic domains will continue to be a challenge, as new models emerge.

Success in this area requires people working together across boundaries in our field: experiment/theory, particle/nuclear, High- vs. Medium- energy, and the neutrino-, electron-, and hadron-scattering communities. There are often challenges of geography, as the main experimental facilities in this field are currently running in Japan and the U.S., while the largest theory community is in Europe. These boundaries, unfortunately, define many of the funding mechanisms of our field, and finding creative ways to fund these collaborative

initiatives will be important. New ideas, effort, and collaborative structures will be required in order to make the feedback loop between theory and experiment, in which generators play an important role, operate more effectively in the coming years.

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