Snowmass2021 - Letter of Interest

Event Generators for Accelerator-Based Neutrino Experiments

Snowmass Topical Groups: (check all that apply □/■)
■ (NF3) Beyond the Standard Model
■ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
■ (CompF2) Theoretical Calculations and Simulation
■ (TF05) Lattice Gauge Theory
■ (TF11) Theory of neutrino physics

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Abstract:
Upcoming accelerator-based neutrino experiments present a challenging theoretical problem for the event generator community. In this letter, we highlight some of the unique challenges and suggest some possible solutions. We believe that important lessons, both technical and organizational, can be learned from the great success of the hadronic event generator community at the LHC.

Current and upcoming accelerator-based neutrino experiments like NOvA [1], T2K [2], DUNE [3] and T2HK [4] will provide sensitive tests of the three-flavor paradigm for neutrinos. A key difficulty in these experiments is that neutrino energies are never measured directly. Instead, the neutrino energy is reconstructed from the energies of the final-state particles of the scattering process.

In these experiments, the target materials include water, liquid scintillator, and liquid argon, and therefore one of the main theoretical challenges is understanding neutrino-nucleus scattering. Neutrino-nucleus scattering is a difficult multi-scale problem, particularly at the few-GeV energies of accelerator neutrino experiments. Figure 1 gives an overview of processes contributing to the cross section at these energies. Despite all difficulties, understanding neutrino-nucleus scattering at the few-GeV scale is key to the success of future experiments. As argued, for instance, in the DUNE Conceptual Design Report, "uncertainties exceeding 1% for signal and 5% for backgrounds may result in substantial degradation of the sensitivity to CP violation and the mass hierarchy." [3]. Such remarkable uncertainties may only be achieved by combining experimental efforts (e.g., using SBND, the near detector in the Fermilab SBN program [5, 6], and the DUNE near detector to measure neutrino-argon interactions precisely) with better theoretical control in order to meet upcoming experimental demands (see Refs. [7, 8] for discussions on the current predictions of different neutrino event generators).

Neutrino physics spans a staggering range of energy scales, from 10^{-6} eV for the cosmic neutrino background to 10^{15} eV for ultra-high-energy events observed by the IceCube experiment. Nevertheless, we believe efforts to understand neutrino-nucleus interactions should focus on the specific energy region relevant to a given experimental setup. Therefore, specialized event generators are necessary for accelerator neutrino experiments working in the 100 MeV to few GeV energy range [9–14].

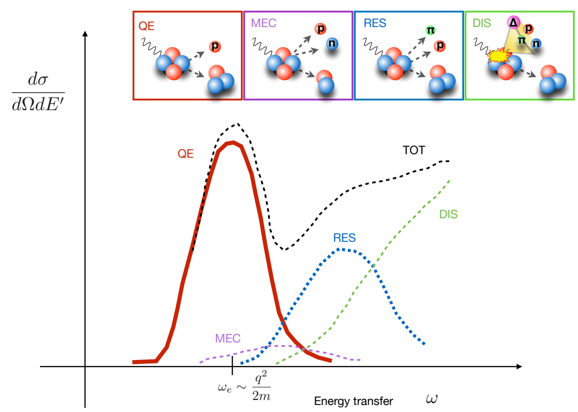

Figure 1: A schematic diagram of the various processes contributing to the neutrino-nucleus cross section.

To some extent, the situation in neutrino physics parallels that of hadronic event generators used at the LHC, where modular general-purpose Monte Carlo (GPMC) generators allow physicists to combine theoretical predictions from different simulation frameworks. For instance, one might generate a hard scattering process in `Sherpa` [15], use the parton shower algorithm of `PYTHIA` [16], and hadronize the colored products of the shower using `Herwig` [17]. Key to this modular approach has been the Les Houches Accord [18], which defines a generic user process interface for event generators. Concrete examples of these standards include the Les Houches Event File (LHEF) [19] and Supersymmetry Les Houches Accord (SLHA) format [20]. Additionally, the biannual Les Houches meetings have regularly led to studies comparing generators and working in collaborative ways to understand and reduce theoretical uncertainties associated with different implementations (e.g., see Refs. [21–23] and especially the phenomenological and Monte Carlo studies).

Modular GPMCs bring several benefits to the community. First, they streamline the user experience and reduces the technical expertise and cognitive overhead necessary to use the various programs. Second, a common output format makes it easier to compare results. Finally, the first two points create a positive feedback loop, which in turn makes it easier to improve and refine the

GPMCs for the benefit of the whole community.

Physics requirements dictate important features for GPMCs for accelerator-based neutrino experiments. First of all, generators should establish common validation benchmarks using existing experimental data. For instance, one of the key ingredients of a cross section is the product of leptonic and hadronic tensors, $d\sigma(E_\nu) \propto L^{\mu\nu} H_{\mu\nu}$, and the neutrino physics of $L^{\mu\nu}$ largely decouples from the nuclear physics of $H_{\mu\nu}$. Structuring the problem this way has significant advantages, specially for validation purposes. For example, the simulation of final state interactions (e.g. elastic and inelastic scattering of nucleons, in-medium effects, pion production and absorption, etc...) after the initial hard scattering is largely independent of the nature of the probe. To take full advantage of this structure, it is crucial that generators validate their results first against the large body of electron scattering data before applying them to the neutrino sector. The modular approach makes this task easier, more robust, and more transparent.

In addition to validating the nuclear effects, this separation would also play a vital role in studies ranging from rare Standard Model processes to new physics. The separation would create an opportunity to automate the purely perturbative leptonic tensor through the use of tools developed by the LHC community [24–26]. For instance, around 100 events of the muonic neutrino trident $\nu_\mu \to \nu_\mu \mu^+ \mu^-$ (the hadronic scattering target is left implicit) have been observed at CHARM II [27], CCFR [28] and NuTeV [29]. So far only the muonic channel has been observed, although the Standard Model also predicts tridents like $\nu_\mu \to \nu_\mu e^+ e^-$ and $\nu_\mu \to \nu_e e^+ \mu^-$ and similarly for antineutrinos. Recent studies estimated that DUNE should see hundreds to thousands of events from these processes [30, 31]. Reliably calculating processes like these is a clear goal for GPMCs for neutrino experiments. Furthermore, this interface would provide an easy-to-use method for studying BSM models. To highlight the importance of BSM searches, we note that at ATLAS and CMS the number of BSM searches surpass standard model studies [32, 33]. Given the unprecedented capabilities of the DUNE multi-purpose near detector complex, modular GPMCs would help realize DUNE's potential as a new-physics discovery tool (see e.g. Ref. [34]).

Third, it is critical to quantify systematic uncertainties associated with theoretical models. To this end, users must be able to vary the relevant model input parameters to determine their effects. A similar situation arises in hadronic event generators for the LHC, where systematic effects are included from scale variations or from the choice of the PDF dataset. The goal is for the community to reach a consensus for the correct way to deal with these uncertainties.

Fourth, at least in principle, neutrino-nucleus scattering is ultimately a problem in nonperturbative QCD. Therefore, it is desirable that our understanding of these processes be consistent with QCD wherever possible. For instance, experimental extractions of the isovector axial nuclear form factor $F_A(q^2)$ recently shifted to a model-independent analysis, imposing only the known analytic structure required by QCD [35]. This shift removed an underestimated and uncontrolled systematic effect, which led to better agreement across experiments. The generator community should also be aware of upcoming benchmark calculations from lattice QCD, e.g., vector and axial form factors, and pion production and resonant form factors for single nucleons. For a recent overview, we refer the reader to the USQCD whitepaper highlighting connections between lattice QCD and upcoming neutrino experiments [36].

We want to end by reiterating that both friendly competition and collaboration between hadronic event generators have been instrumental in the success of the experimental program at the LHC. There is every reason to believe that the neutrino community would benefit from a similar setup. For this reason, we advocate that the neutrino community support several generators as well as efforts to standardize and streamline communication between researchers in this area.

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