Neutrino event generators

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April 12, 2017

1 Event generators and neutrino physics

The physics of neutrino mass is a window to the highest energy scales in nature, providing glimpses well beyond what we may currently access directly. The Particle Physics Project Prioritization Panel ("P5") report [1] highlights neutrino mass as one of the five Science Drivers for structuring the mission of high energy physics (HEP) in the United States, and the importance given to the program internationally is visible in the robust international participation in DUNE [2]. We additionally have the opportunity in the near future to settle lingering questions surrounding a number of measured anomalies that hint at the existence of a sterile neutrino.

Establishing the existence of "CP-violation", whether neutrinos and antineutrinos oscillate differently, and fully testing the three-flavor neutrino framework at a long baseline experiment is a daunting task. Results in the short baseline program could overthrow the three flavor framework entirely but require extraordinary experimental controls to substantiate such a discovery. Both of these programs require very fine controls on systematic uncertainties. Event generators play a mission-critical role in neutrino experiments and require the same level of attention as the experimental apparatus. GENIE (Generates Events for Neutrino Interaction Experiments) [3] is the most widely-used event generator in neutrino experiments today. It is a core component of the software stack for every running and planned neutrino beam experiment in the United States. The newest results from neutrino-nucleus cross section experiments must be coupled to the latest developments in nuclear theory within GENIE if we are to obtain the largest possible return on our investments in the neutrino program.

2 The neutrino simulation software stack

In accelerator neutrino experiments, observables are a convolution of the flux, interaction physics, and detector response. Three corresponding pieces combine to form the software stack, as illustrated in Figure 1. The flux simulation covers proton interactions with the target, the focusing horns, and the decay volume, and its output models the neutrino beam energy, shape, and direction. Geant4 [4] and FLUKA [5, 6] are the most popular simulation toolkits for this

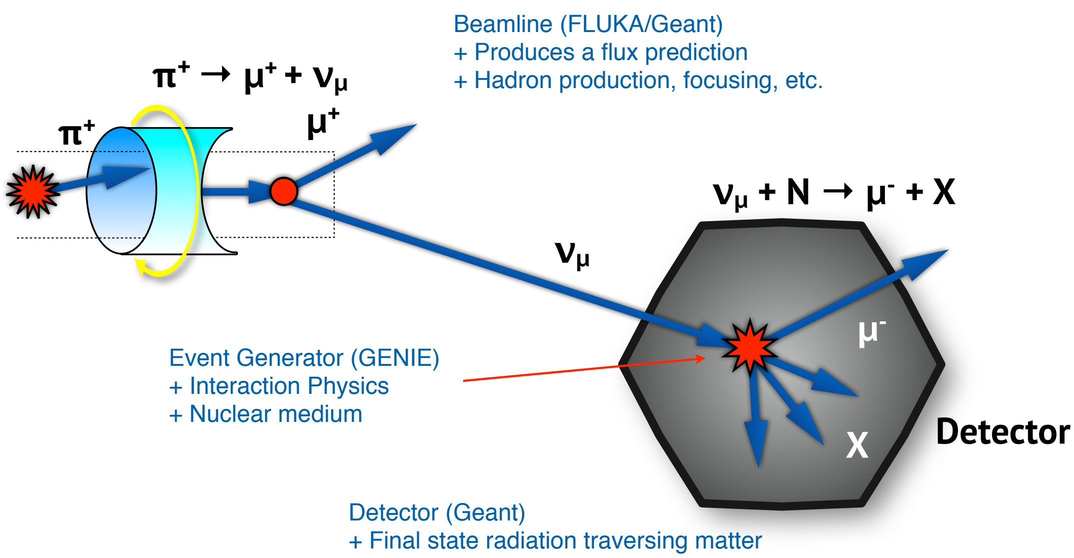

Figure 1. The accelerator neutrino experiment software stack.

purpose. Event generators simulate the primary interaction of the neutrino with nuclei in the detector and propagating reaction products out of the struck nucleus. The detector simulation takes over at the boundary of the nucleus. Geant4 [4] is the leading solution for detector response. It is the middle "layer" that is our primary concern here though. Event generators give experimenters access to the physics of the neutrino interaction, and GENIE is the primary code at ArgoNeuT [7], DUNE [2], MicroBooNE [8], MINERνA [9], NOνA [10], and SBND [11], because of its flexible framework and fully-featured geometry and flux drivers.

3 The role of the event generator in an accelerator neutrino experiment

Experiments use event generators to connect observed event topologies to the true underlying kinematics. Two features define the way generators are deployed at experiments. First, we do not know the kinematic details of beam neutrinos on an event by event basis, and, even worse, the *statistical* description of the flux is generally constrained only at the 10% level. Second, driven by a low absolute cross section, the economics of neutrino experiments force us to use heavy nuclear targets (that typically double as the detection medium as well). This exposes analysis of the reactions to very complex nuclear physics. Because we lack a complete theory that can describe from first principles the neutrino interaction with a nuclear target and the subsequent evolution of the reaction products, event generators must use ad-hoc and phenomenological models. This distinguishes event generators in neutrino experiments from the usual situation at colliders. For collider experiments, generators, like MadGraph [12] and Pythia [13] are really computation aids for theorists. GENIE is not.

Because they are tools for understanding efficiencies and backgrounds, event generators must simulate all of the types and momenta of every particle that appears in the final state of an interaction on an event-by-event basis. The ideal input theory would provide internally consistent and fully-differential neutrino-nucleus cross sections in the kinematics of every final-state particle, over all reaction mechanisms, over the full energy range, for all combinations of neutrino flavor and helicity, and for every nucleus in the experiment. However, modern theory typically provides only the kinematics for the final state lepton, with minimal guidance on the hadronic side, and generally only for a subset of the experimentally accessible phase space. Thus, neutrino-nucleus interactions, as implemented in event generators, are usually factorized as a product of a scattering off individual nucleon (in the impulse approximation regime), hadronization, which may be followed by formation zone, and final state interactions, usually modeled in a very effective (approximated) way. This makes estimating systematics quite challenging. Furthermore, calculations are always performed in real kinematic variables like four-momentum transfer, neutrino energy, inelasticity, etc. However, none of these quantities are directly observable at a neutrino experiment.

Neutrino experiments measure final state particle spectra, after transport through the nucleus. Relating these observable quantities to the true, underlying kinematics can only be done through a model, as implemented through an event generator.

For sociological reasons, neutrino event generator groups are comprised almost entirely of experimentalists. GENIE and NEUT [14] are the two most widely used generators and they are staffed by experimentalists. NuWro [15–17] and GiBUU [18] are organized by theorists, but they lack some of the tools and support required by experimenters, e.g., geometry and re-weighting utilities (although recently, NuWro has begun to include some of these features). Experimenters are heavily involved in generators because we require full final state descriptions - which most theories are unable to provide and most theorists are not interested in calculating. For example, while a relatively large amount of attention has been paid to final state lepton kinematics, theory groups are very hesitant to compute final state hadron information. This is due to the fact that the total cross section is a much more tractable problem (while still being incredibly challenging) and due to the complications of FSI.

4 The main challenges for neutrino event generators

The primary problem facing neutrino event generators is to have a consistent physics model for the large number of processes that must be included. Due to a lack of theoretical models experimental data are often used to tune generators. One must be very careful when these data were obtained using the generator being tuned, or when using different released set of data which share a subset of events used in the analysis. This is a challenging task requiring well-established experimental knowledge of neutrino physics. There are also computationally intensive issues facing us (particularly for nuclei larger than carbon), but they are properly nuclear physics topics and are being addressed within that community [19]. Fundamentally, while neutrino event generators could benefit from faster integrators, vectorized math libraries, and the ability to run on new and different computing architectures, these are sub-dominant concerns. If nuclear (NP) and high energy physics (HEP) were not separated into silos, large scale computation problems would be more central for generators like GENIE. Changes that made it easier to collaborate across the HEP and NP divide would be welcome and it would make it easier for us to contribute to the very computationally intensive pieces.

In fact, within the HEP landscape today, the major problem neutrino event generators face actually looks more like a data analysis issue. We need manpower to implement models and study their various combinations and tunes. Because we do not have a single theoretical framework with which to reliably work and because neutrino cross section data sets are complicated to handle - difficult-to-understand correlations between data sets due to flux modeling and nuclear effects, difficult-to-ascertain levels of model dependence injected by the generator used to produce the analysis, disparate signal definitions and observables, etc. - there are complicated tensions when combining data sets to tune an event generator. We need support to make it easier to work directly with theorists in the form of travel and workshops, as working through new model implementation without their direct input is challenging.

Neutrino event generators need people with the right mix of computation and physics skills to tackle these problems, but there is little support to do the actual work. As a consequence, development is carried forward by individuals with other dominant responsibilities, slowing down overall progress and making the task of keeping the code base well-organized, well-vetted, and performant even more challenging.

5 Conclusions

Neutrino event generators face different challenges as compared to codes that are widely used in collider physics. We operate in a regime that lacks a coherent, first-principles description of the complete set of physics that are applicable to the experiments we cover. At the same time, neutrino experiments are very sensitive to the physics modeling in the generator, making the details of how the global physics model is constructed extremely important.

These problems do not map well onto “computing” problems; instead, physics concerns dominate the neutrino generator development landscape. Moreover, these physics challenges are not well supported by the theory community, orphaning experimentalists who depend on generators’ output but who lack both the intellectual and financial resources to fully support them. Because of the physics developments required for progress in neutrino generator work, we regard a funding model which confines that work to computing channels as unlikely to be successful. Instead, we encourage support for a fully collaborative effort between theorists and experimentalists, and between nuclear and particle physicists. We feel that a model that recognizes the significant physics problems remaining in neutrino generator development is essential for the substantial progress needed for future neutrino experiments to be realized.

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