Neutrino Event Generators

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CompF Topical Groups:

☐ (CompF1) Experimental Algorithm Parallelization
■ (CompF2) Theoretical Calculations and Simulation
☐ (CompF3) Machine Learning
☐ (CompF4) Storage and processing resource access
☐ (CompF5) End user analysis
☐ (CompF6) Quantum computing
☐ (CompF7) Reinterpretation and long-term preservation of data and code
■ (Other) NF6 (Neutrino cross sections), TF11 (Theory of neutrino physics)

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Abstract: (200 Words)
Monte Carlo event generators are ubiquitous tools for experimental collaborations across the neutrino community, yet remain years behind the exceptional progress of many theoretical groups. Here, we discuss some potential and actively developing ways for the event generator community to further bridge the gaps between current theory and future experiment, permitting fast development of neutrino-nucleus scattering simulations required for proper experimental measurements. Such developments will be key initiatives to ensure the success of future precision neutrino oscillation experiments.

In the coming decade, the accelerator neutrino community will pursue definitive oscillation measurements focused on answering fundamental questions in high-energy physics: understanding the degree to which CP violation exists in the lepton sector, determining the neutrino mass ordering, and extensively testing the three-flavor framework to search for one or more *sterile* neutrino species proposed as an explanation for several experimental anomalies [1]. As the field moves into the precision era with the DUNE [2], SBN [3], and Hyper-Kamiokande [4] experiments, an unprecedented level of control over systematic uncertainties, including those associated with the simulation of neutrino interactions [5], will become necessary for success. Neutrino event generators, including GENIE [6], GiBUU [7], NEUT [8], and NuWro [9] among others [10, sec. 42], play an indispensable role in the analysis and interpretation of neutrino oscillation data [11]. Given their importance to the entire oscillation effort, generators should be supported, scrutinized, and treated with the same level of care as the experimental apparatus.

More detailed models of neutrino-nucleus scattering and new neutrino cross section measurements will both be required to improve neutrino generators going forward. We anticipate multiple LOIs on these related topics and ask the Snowmass conveners to consider connections to those efforts carefully. This LOI will discuss development of the generators themselves, highlighting several focus areas to address the needs of experiments. This LOI builds on extensive discussions held at recent workshops at ECT* [12, 13] and Fermilab [14, 15]. These meetings identified community challenges, explored prospects for addressing them, and planned an initial phase of related work. We encourage the Snowmass conveners to carefully review the output of those workshops in addition to this short document.

Streamlining theory improvements

In recognition of the importance of cross-section modeling to the neutrino oscillation program, the theory community has developed a significant number of new neutrino interaction models. Many of these remain unimplemented in event generators. As the number and sophistication of these models continue to increase, the prevailing development practices for adding new theory content to generators are cause for concern. Direct re-implementation within a single generator's code base is the norm. Despite the past successes of this approach, it is labor-intensive and slow, often taking multiple person-years for a single model. This leads to a bottleneck which adversely impacts all parties: theorists are less able to exercise their models against data, and neutrino experiments cannot fully benefit from the latest model improvements in a timely manner. Due to a limited number of generator experts and a diversity of relevant models, the neutrino community's ability to support a wide-ranging program for physics beyond the Standard Model may be particularly affected by this situation. A technical solution to this problem, the creation of a common theory interface to facilitate addition of new models to generators, is being actively explored by a joint working group of theorists and experimentalists led by Fermilab [14, 16]. Expanded effort and further input from other communities will help in finding an optimal solution.

Standardizing software interfaces

In addition to the interaction modeling itself, there are a number of generator tasks required by experiments which are technically demanding but theoretically straightforward. Examples of these include (1) interpreting the output of beam simulations to calculate the full energy, flavor, direction, and position dependence of the neutrino flux, (2) propagating simulated neutrinos through a realistic detector geometry and sampling locations for interaction vertices, and (3) storing a detailed representation of each neutrino interaction for downstream processing. The generator components that handle each of these tasks are called the *flux driver*, *geometry driver*, and *event record*, respectively. At present, each generator implements each of these tools independently with no common standard, and the completeness of the flux and geometry drivers varies widely. This situation results in significant duplication of effort between generators. It also creates unnecessary barriers (1) to the adoption of more than one generator in experimental production workflows (e.g., for uncertainty assessments in which an alternate generator is used to produce "pseudo-data") (2) to the creation of new "mini-generators" for specific processes, and (3) to generator interoperability, e.g., simulation of the primary neutrino interaction in one generator and hadronic final-state interactions in another.[1]

Developing universal, maintainable tools for systematic uncertainties and tuning

Reliable and efficient assessment of systematic uncertainties associated with generator modeling is crucial for all neutrino experiments. Due to the high computational cost of brute-force methods (e.g., rerunning the entire simulation chain for each varied model parameter), current techniques in this area typically involve scaling (or *reweighting*) existing Monte Carlo events. The weight calculators used for this task are typically custom-made and reliant on the details of a particular implementation. In most cases, they cannot be applied to multiple generators or even to sufficiently different models available within the same generator. Additionally, only a subset of model uncertainties may be addressed via reweighting, e.g., because events in unpopulated regions of phase space cannot be reweighted into existence. Long-term maintainability and full coverage of model uncertainties will likely require a more flexible

[1] While "mixing and matching" generators in this way must be handled carefully to avoid inconsistent theoretical assumptions, the community's ability to do so is currently limited by software, not physics.

approach with support for multiple generators. Early investigations into adapting solutions from other fields, e.g., the use of the Professor [17] tuning framework by GENIE [18], are underway and must continue.

Using neutrino cross section data

The experimental community is producing a growing literature of high-statistics neutrino cross section measurements useful to constrain generator modeling. In the coming years, the quantity and quality of available data will continue to improve rapidly, and generator work to leverage these data toward model improvements must expand accordingly. A key ingredient in this effort is the ability to compare and tune models to multiple datasets. These tasks are non-trivial due to many technical details, such as flux predictions and signal definitions, that must be considered. Individual groups sometimes develop their own comparison and tuning tools, e.g., GENIE's proprietary Comparisons product [18]. An open-source solution called NUISANCE [19] has emerged as a *de facto* community standard, with support for all widely-used generators and a large and expanding number of cross section datasets. Maintenance and further development of standardized software tools for model comparisons and tuning, usable by experiments and theorists alike, will be essential as the field enters the precision era.

Using data from non-neutrino probes

Due to many similarities between the interaction processes from a theoretical standpoint, relevant information for understanding and controlling neutrino–nucleus scattering uncertainties can be obtained from a variety of non-neutrino sources: electron-nucleus scattering; pion-nucleus or pion-nucleon scattering; and photon-nuclear scattering. For example, electron scattering experiments have some useful capabilities which are difficult to achieve for the neutrino case (e.g., a known and precisely controllable beam energy). As a result, growing attention is being paid to the potential for electron cross-section measurements to inform generator modeling of neutrino scattering [20, 21] and a dedicated collaboration, Electrons for Neutrinos (e4ν) [22], has been formed to pursue related work. With the exception of GiBUU, neutrino generator support for simulating electron interactions has historically been incomplete and not fully compatible with the modeling for neutrinos. To make best use of electron scattering data to support neutrino experiments, consistent generator implementations of both processes, software tools for model comparisons and tuning, and analyses to interpret results and improve models will all be needed. Similar efforts to make pion-nucleus scattering measurements are underway [23–26], but efforts to integrate this information into generators and common analysis tools are even less well-developed than the electron-neutrino case. With a few exceptions [27], existing photonuclear scattering datasets have generally not been integrated into common frameworks or used for model development.

Computing resources & techniques

At present, event generation and related activities are not often among the most resource-intensive tasks needed by neutrino experiments. However, as the sophistication of generator models, tuning, and systematic uncertainty calculations grows, this is likely to change. A notable recent example, which may be indicative of future trends, is the creation of a custom GENIE tune by the NOvA experiment [28] using high-performance computing resources at NERSC [29]. Discussion of future computing needs for neutrinos should be pursued during Snowmass in consultation with LHC experiments and other parties. New computing techniques, including the use of GPUs, machine learning [30], and quantum computers, may also become increasingly useful to neutrino event generation.

Human factors

Development of neutrino event generators requires a diversity of expertise and close collaboration between theorists, experimentalists, and computing professionals. While the nature of the work creates many opportunities, it also poses some sociological challenges. Many of these, related to training, communication, career incentives, etc., are similar to those encountered by the LHC generator community [31, sec. 3.2]. Some unique challenges, e.g., that neutrino generators bridge the traditional HEP/NP funding divide, are briefly explored in ref. [32]. Some mission-critical generator tasks are not well-suited for university research groups, and we anticipate that Fermilab and other national laboratories will need to play an important role in supporting the full range of needed activities. Expanding opportunities for junior scientists in this space will also be critical to maintain continuity of expertise and to scale effort to meet growing demands.

Conclusions and Outlook

Here we have presented a short summary of the ongoing developments across the neutrino event generator community, with some topical explanations of ideas both in their infancy and currently under construction. We hope this informs the broader field within and outside the Snowmass Neutrino and Computational Frontiers of our collective progress and growing needs. This document also serves as a call for funding agencies to recognize our increasingly complex requirements. Neutrino generator development will be crucial for the success of the precision oscillation program, and we welcome further discussion on this topic during the Snowmass process.

[1] C. Giunti and T. Lasserre, *eV-Scale Sterile Neutrinos*, *Annual Review of Nuclear and Particle Science* **69** (2019) [1901.08330].

[2] DUNE collaboration, *Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) : Conceptual Design Report, Volume 2: The Physics Program for DUNE at LBNF*, *arXiv preprint* (2015) [1512.06148].

[3] P. A. Machado, O. Palamara and D. W. Schmitz, *The Short-Baseline Neutrino Program at Fermilab*, *Annual Review of Nuclear and Particle Science* **69** (2019) 363 [1903.04608].

[4] Hyper-Kamiokande Proto- collaboration, *Hyper-Kamiokande design report*, *arXiv preprint* (2018) [1805.04163].

[5] NuSTEC collaboration, *NuSTEC White Paper: Status and challenges of neutrino–nucleus scattering*, *Prog. Part. Nucl. Phys.* **100** (2018) 1 [1706.03621].

[6] C. Andreopoulos et al., *The GENIE Neutrino Monte Carlo Generator*, *Nuclear Instruments and Methods* **A614** (2010) 87 [0905.2517].

[7] O. Buss, T. Gaitanos, K. Gallmeister et al., *Transport-theoretical description of nuclear reactions*, *Physics Reports* **512** (2012) 1.

[8] Y. Hayato, *A neutrino interaction simulation program library NEUT*, *Acta Physica Polonica B* **40** (2009) 2477.

[9] T. Golan, J. Sobczyk and J. Żmuda, *NuWro: the Wrocław Monte Carlo generator of neutrino interactions*, *Nuclear Physics B - Proceedings Supplements* **229-232** (2012) 499.

[10] M. Tanabashi, K. Hagiwara, K. Hikasa et al., *Review of particle physics*, *Physical Review D* **98** (2018) 030001.

[11] U. Mosel, *Neutrino event generators: foundation, status and future*, *Journal of Physics G: Nuclear and Particle Physics* **46** (2019) 113001 [1904.11506].

[12] "Modeling neutrino-nucleus interactions." https://indico.ectstar.eu/event/19/, 2018.

[13] "Testing and Improving Models of Neutrino Nucleus Interactions in Generators." https://indico.ectstar.eu/event/53/, 2019.

[14] J. Barrow, M. Betancourt, L. Cremonesi, S. Dytman, L. Fields, H. Gallagher et al., *Summary of workshop on common neutrino event generator tools*, 2008.06566.

[15] "Generator Tools Workshop." https://indico.fnal.gov/event/22294/, 2020.

[16] https://npc.fnal.gov/neutrino-joint-theory-experiment-working-group/.

[17] A. Buckley, H. Hoeth, H. Lacker et al., *Systematic event generator tuning for the LHC*, *Eur. Phys. J. C* **65** (2010) 331 [0907.2973].

[18] GENIE collaboration, C. Andreopoulos et al., "GENIE Physics & User Manual." https://genie-docdb.pp.rl.ac.uk/cgi-bin/ShowDocument?docid=2.

[19] P. Stowell, C. Wret, C. Wilkinson, L. Pickering et al., *NUISANCE: a neutrino cross-section generator tuning and comparison framework*, *J. Instrum.* **12** (2017) P01016 [1612.07393].

[20] A. M. Ankowski, A. Friedland, S. W. Li, O. Moreno, P. Schuster, N. Toro et al., *Lepton-nucleus cross section measurements for DUNE with the LDMX detector*, *Phys. Rev. D* **101** (2020) 053004 [1912.06140].

[21] A. M. Ankowski and A. Friedland, *Assessing the accuracy of the GENIE event generator with electron-scattering data*, *arXiv preprint* (2020) [2006.11944].

[22] e4ν collaboration, A. Ashkenazy et al., "Electrons for neutrinos: addressing critical neutrino-nucleus issues." https://www.jlab.org/exp_prog/proposals/18/C12-17-006.pdf.

[23] DUET Collaboration collaboration, *Measurement of $\sigma_{\rm abs}$ and $\sigma_{\rm cx}$ of π^+ on arbon by the dual use experiment at TRIUMF (DUET)*, *Phys. Rev. C* **95** (2017) 045203.

[24] E. Pinzon Guerra et al., *Using world charged $\pi^\pm$−nucleus scattering data to constrain an intranuclear cascade model*, *Phys. Rev. D* **99** (2019) 052007 [1812.06912].

[25] LArIAT collaboration, *The Liquid Argon In A Testbeam (LArIAT) Experiment*, *JINST* **15** (2020) P04026 [1911.10379].

[26] DUNE collaboration, *First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform*, 2007.06722.

[27] O. Lalakulich, K. Gallmeister and U. Mosel, *Neutrino- and antineutrino-induced reactions with nuclei between 1 and 50 GeV*, *Physical Review C* **86** (2012) .

[28] NOvA collaboration, *Adjusting neutrino interaction models and evaluating uncertainties using NOvA near detector data*, 2006.08727.

[29] https://www.nersc.gov.

[30] S. Pina-Otey, F. Sánchez, T. Lux and V. Gaitan, *Exhaustive neural importance sampling applied to Monte Carlo event generation*, *Phys. Rev. D* **102** (2020) 013003 [2005.12719].

[31] A. Valassi et al., *Challenges in Monte Carlo event generator software for high-luminosity LHC*, 2004.13687.

[32] G. N. Perdue, S. Dennis, S. Dytman, H. R. Gallagher, T. Golan and J. Wolcott, "Neutrino event generators." https://hepsoftwarefoundation.org/cwp/hsf-cwp-017-CWP_neutrino_event_generators.pdf.