The GENIE neutrino event generator

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☐ (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:

Event generators provide nothing less than the single interface between theory and experiment and, as such, they are an essential ingredient throughout the lifetime of an experiment, from its design and optimization phases till the end of its physics exploitation phase. GENIE is an international collaboration of theorists and experimental physicists spanning several major experiments. It was initiated following a *call to arms* at the start of the NuINT conference series, in 2001, for the development of a universal event generator with broad community support. Today, the GENIE collaboration plays a central role in the development of such a universal event generator, through the careful and critical amalgamation of recent theories and data into reliable and predictive comprehensive Monte Carlo models, and the development of an advanced global analysis of scattering data for the evaluation of model uncertainties and the derivation of physics tunes. GENIE places a substantial emphasis in the development of software tools addressing the unique simulation and analysis requirements of neutrino experiments, and, via its *Incubator*, it cultivates connections with several theoretical and experimental groups. The wide adoption of GENIE, which is integrated in the simulation and analysis chain of all experiments, and its broad pool of expert users and developers, are a testament to the success of the GENIE development model and its unique position in delivering tangible benefits to the neutrino community. GENIE was developed to be a *universal generator* and it is the ideal platform for delivering physics modelling improvements to the experimental community, in the most economical way, using mature experimental interfaces and existing workflows.

Event generators provide nothing less than the single interface between theory and experiment and, as such, they are an essential ingredient throughout the lifetime of an experiment, from its design and optimization phases till the conclusion of its physics exploitation program. In the precision measurement era, as systematic errors start to dominate the total error budget, and biases due to model dependencies start to dominate the systematic error budget, development work in that theory-experiment interface takes centre stage. In the field of neutrino physics, the lack of a universal event generator amalgamating the latest theory and data into reliable and predictive comprehensive models, addressing the unique requirements of neutrino experiments, and providing standardised tools to support simulation and analysis related tasks was flagged more than 20 years ago. The 1st International Workshop on Neutrino-Nucleus Interactions in 2001 was a *call to arms* for such a universal event generator.

GENIE [1] is the neutrino community response to that call to arms. It is a vertically-integrated event generator designed and developed *from scratch* by a **large international collaboration of theorists and experimental physicists** spanning several major experiments. Today, some 20 years later, GENIE is **fully integrated in the simulation chain and analysis chain of all current and future accelerator-based neutrino experiments** using neutrino beams in the GeV energy range. Increasingly, GENIE is also being used by experiments using both lower (reactor $\bar{\nu}$, COHERENT, CAPTAIN-Mills, etc.) and higher energy (km3net, IceCube/PINGU, SHiP, FASER-nu, etc.) neutrinos. The broad adoption of GENIE was facilitated by **popular off-the-shelf tools for the realistic simulation of a host of complex experimental setups**, including tools for the complete description of the neutrino source and detector geometry, and tools supporting analysis-related tasks, such as software for the propagation of systematic errors. Several experiment-specific codes have been written on top of the GENIE framework, which is an irreplaceable element of a modern neutrino experiment software stack. Frequently, these experiment-specific codes are too GENIE-specific that use of alternative generators (if so wished) is far from trivial.

Through the popular and standardised GENIE tools, users have access to **several alternative state-of-the-art comprehensive models for the simulation of the interactions of neutrinos**, charged leptons and hadrons with nucleons and nuclei. These comprehensive models are built carefully from a rich constellation of alternative physics model implementations, paying special attention to physics consistency and full coverage of processes and kinematic space, and using data to decide how to best extrapolate theoretical models beyond the region of their validity, and to address double-counting issues. Within the same software and physics framework, GENIE core developers and contributors have been developing and releasing a **growing suite of physics modules for the simulation of BSM physics signatures** (nucleon decay, neutron-antineutron oscillations, boosted dark matter, neutral heavy leptons) that play central role in the expansion of the physics program of many neutrino experiments.

Professional continuous integration and validation suites developed over several years, a vast pool of experience in the development, validation and characterisation of comprehensive models, and a rigorous internal peer-review is a service to the community that minimizes the occurrence of mistakes that could invalidate the large MC productions produced by experiments and compromise the timely delivery of their physics results. Very extensive sets of codes and **vast data archives have been painstakingly curated by GENIE** to describe the scattering of neutrino, electron and hadron probes and to support the model validation and characterization tasks.

The extensive set of curated GENIE data archives and validation software, with the addition of a suitable interface to the Professor system [2], underpinned the recent development of the **powerful GENIE global analysis of neutrino scattering data**. In particular, the GENIE/Professor interface, enabled the efficient implementation of complex multi-parameter brute-force scans and removed substantial global analysis limitations by decoupling it from event reweighting procedures that, for all but the most trivial aspects of our physics domain, require substantial development time and are not exact, or even possible at all. Professor 'reduces the exponentially expensive process of brute-force tuning to a scaling closer to a power law in the number of parameters, while allowing for massive parallelisation' [3]. Using the GENIE global analysis, several new tunes of bare-nucleon cross-section and neutrino-induced hadronization models were performed for several distinct model configurations, and tunes of nuclear cross-sections are in progress.

Crucial in the GENIE's mission and development model is the **cultivation of collaborative efforts with stakeholder groups from across the neutrino community**. The open User Forum, maintains an active connection between the core GENIE group and the broader community. Through the *Incubator*, GENIE provides a well-defined and rigorously-managed procedure for the design, development, validation, peer review, integration and release of community contributions. Dozens of *incubator projects* were successfully completed over the past few years, harnessing community efforts to deliver sustainable software that meets stringent GENIE physics validation, software design, numerical efficiency and documentation requirements.

The core GENIE team has over 100 years collective experience in the delivery of neutrino Monte Carlo event generators, the development, validation, characterization and tuning of empirical comprehensive models, the development of a host of related software tools and frameworks, and the support of experimental communities. Over the past two decades, we played the leading role in the development of a universal neutrino event generator, and a very hands-on role in the coordination of community efforts, in particular via the GENIE Incubator. This LOI builds on this experience to highlight several areas which are central to the successful continued development of neutrino event generators:

Consolidation of an event generator framework and tools

We regret to see rudimentary discussions about the need for a *community-led neutrino event generator*, or discussions for a new common event generator framework and tools. These discussions did take place twenty years ago. GENIE is the community-led universal neutrino event generator produced in response to the NuINT01 *call to arms* for a universal neutrino generator. It was developed following best software design practises, and it has a mature and proven framework, tools and experimental interfaces. It is already integrated in the software chain of all neutrino experiments and, evidently, its design meets the requirements of these experiments. Within the neutrino community, there is a great degree of familiarity with the GENIE framework, tools and models, and the vast majority of developers target their developments for the GENIE platform. Re-engineering of event generator frameworks and tools will be disrupting and will deliver no tangible improvement over what is available now. Moreover, considering the scarce resources for neutrino generator development, such a re-engineering and will be hugely wasteful and will have a detrimental effect on the field[1]. GENIE has extended an invitation to anyone who wishes to be engaged in native model development to participate in the GENIE *Incubator*. In addition, GENIE has offered to provide all necessary technical support for the realization of interfaces to alternative neutrino event generators (mainly smaller legacy systems that lack GENIE's toolkit), so that experiments can be invoke these alternative generators as part of their established GENIE workflows. We welcome feedback from all groups on how GENIE can best fulfill its founding mission of serving as the common event generator for the neutrino community.

Development of universal neutrino Monte Carlo generator

GENIE is unique amongst neutrino generators as expressed mission is to serve the broader neutrino community, and it doesn't have a narrow focus on a specific experimental program. Recent developments in GENIE include both a new coherent elastic scattering generator for low energy experiments, and a new NLO DIS generator with validity range up to 10^9 GeV to serve the needs of neutrino telescopes. Similarly, GENIE framework and toolkit developments consider the requirements coming from the entirety of the experimental neutrino community. We encourage the Snowmass conveners to broadly consider neutrino event generation needs for the entire community, and we welcome feedback from all groups on how GENIE can best meet their needs going forward.

Development of BSM event generators for neutrino experiments

Recent versions of GENIE support physics modules and event generation drivers for a number of BSM processes, such as nucleon decay, neutron-antineutron oscillations, and boosted dark matter interactions. Further developments for the simulations of neutral heavy leptons and other BSM models are in progress. Within GENIE, these BSM generators share the same software framework as the conventional lepton-nucleus event generators and, on many instances, they share common physics modelling elements (initial state nuclear environment, intranuclear hadron transport). The latter is crucial as conventional interaction channels are, typically, backgrounds to BSM channels. BSM searches form an important part of the physics program of modern neutrino experiments and we encourage the Snowmass conveners to consider the unique requirements they bring upon the development of Monte Carlo event generators, and we welcome feedback from all groups on how GENIE can best meet the needs of BSM searches.

Guided evolution of a comprehensive physics models

With the recent release of the GENIE Generator v3, a substantial change in the way that the GENIE Collaboration approaches the process of developing, validating, characterising, tuning and releasing comprehensive neutrino interaction simulations came into sharp focus. Previously, the GENIE Collaboration released a single, preferred ('Default') comprehensive model that reflected our understanding on the most predictive, robust, and self-consistent model that could be built out of GENIE neutrino interaction modelling elements. Over the last few years, driven by numerous theoretical developments, the community expressed a demand for the implementation of several alternative models that were, to a large extend, delivered (or are in the process of being delivered) by GENIE. Using that large constellation of models, GENIE has constructed, validated and tuned a number of alternative comprehensive models, and a much larger number of comprehensive models and tunes are being constructed. However, despite the demand for alternative models, experiments have a very limited capacity of consuming alternative models that is easily saturated. Limited by the long Monte Carlo production and analysis timescales, experiments are frequently tied to old GENIE releases, do not perform large scale productions more often than once every 1 or 2 years, and, to their long-term detriment, they do not provide timely feedback to drive the evolution of comprehensive models. More direct and constructive ways for two-way communication between experiments and GENIE Monte Carlo developers are crucial. The GENIE Forum and the appointment of experiment/GENIE liaisons is an important first step towards this direction. GENIE developments and release schedule can be influenced by experimental collaborations through the targeted support

[1] A recent analysis of the GENIE generator software base using the COCOMO model, reveals that a complete re-engineering of GENIE would require an effort of the order of 100 person-years! The underlying framework and tools are substantial parts of this code base.

of selected GENIE incubator projects. Several proprietary GENIE codes, for model validation, characterization and tuning, can be shared with experimental collaborations, to support common projects.

Development of a GENIE Argon tune

As it was mentioned in the introduction, the vast curated GENIE data archives, an auxiliary set extensive proprietary frameworks and tools, and an interface with the Professor tool that reduces the computation complexity of brute-force tuning while allowing for massive parallelisation, have underpinned the development of an advanced global analysis of neutrino scattering data. Several tunes were produced to date and were deployed seamlessly through the GENIE generator platform, and many more tunes are in progress. One of the medium-term goals of the GENIE collaboration is to develop GENIE Argon tunes for the early DUNE physics exploitation program, by building upon its current global analysis workflows and augmenting its data archives using Argon data from the SBN program. While such tunes may be attempted by other groups, we feel that the work carried out as part of the GENIE development process will provide lasting benefits for the community, as GENIE has that necessary long-term perspective to periodically revisit and update tunes in order to incorporate new models or other modelling improvements, and it has an established platform to seamlessly integrate tunes into new releases. This is a formidable task, but an essential one for the long-term utility of SBN data and the successful preparation for the early DUNE physics exploitation phase. This task could benefit from a joint venture between the GENIE and SBN collaborations, that beyond the current experimental data analysis and generator development paradigms.

[1] C. Andreopoulos et al., *The GENIE Neutrino Monte Carlo Generator*, *Nucl. Instrum. Meth. A* **614** (2010) 87 [0905.2517].

[2] A. Buckley, H. Hoeth, H. Lacker, H. Schulz and J. E. von Seggern, *Systematic event generator tuning for the LHC*, arXiv:0907.2973.

[3] *https://professor.hepforge.org*, 2020.