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# The GENIE neutrino Monte Carlo generator

C. Andreopoulos [a,*], A. Bell [b], D. Bhattacharya [b], F. Cavanna [c], J. Dobson [d], S. Dytman [b], H. Gallagher [e], P. Guzowski [d], R. Hatcher [f], P. Kehayias [e], A. Meregaglia [g,h], D. Naples [b], G. Pearce [a], A. Rubbia [g], M. Whalley [i], T. Yang [j]

[a] Rutherford Appleton Laboratory, STFC, Oxfordshire OX11 0QX, UK
[b] Physics Department, Pittsburgh University, Pittsburgh, PA 15260, USA
[c] Physics Department, L'Aquila University, 67100 L'Aquila, Italy
[d] Physics Department, Imperial College London, Blackett Lab., London SW7 2BW, UK
[e] Physics Department, Tufts University, Medford, MA 02155, USA
[f] Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[g] Physics Department, ETH Zurich, CH-8093 Zurich, Switzerland
[h] IPHC—Strasbourg, F-67037 Strasbourg Cedex 2, France
[i] Physics Department, Durham University, Durham DH1 3LE, UK
[j] Physics Department, Stanford University, Stanford, CA 94309, USA

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ABSTRACT

GENIE [1] is a new neutrino event generator for the experimental neutrino physics community. The goal of the project is to develop a 'canonical' neutrino interaction physics Monte Carlo whose validity extends to all nuclear targets and neutrino flavors from MeV to PeV energy scales. Currently, emphasis is on the few-GeV energy range, the challenging boundary between the non-perturbative and perturbative regimes, which is relevant for the current and near future long-baseline precision neutrino experiments using accelerator-made beams. The design of the package addresses many challenges unique to neutrino simulations and supports the full life-cycle of simulation and generator-related analysis tasks.

GENIE is a large-scale software system, consisting of $\sim$120000 lines of C++ code, featuring a modern object-oriented design and extensively validated physics content. The first official physics release of GENIE was made available in August 2007, and at the time of the writing of this article, the latest available version was v2.4.4.



## 1. Introduction

Over the last few years, throughout the field of high energy physics (HEP), we have witnessed an enormous effort committed to migrating many popular procedural Monte Carlo Generators into their C++ equivalents designed using object-oriented methodologies. Well-known examples are the GEANT [2], HERWIG [3] and PYTHIA [4] Monte Carlo Generators. This reflects a radical change in our approach to scientific computing. Along with the eternal requirement that the modeled physics be correct and extensively validated with external data, the evolving nature of computing in HEP has introduced new requirements. These requirements relate to the way large HEP software systems are developed and maintained, by wide geographically spread collaborations over a typical time-span of $\sim$25 years during which they will undergo many (initially unforeseen) extensions and modifications to accommodate new needs. This puts a stress on software qualities such as re-usability, maintainability, robustness, modularity and extensibility. Software engineering provides many well proven techniques to address these requirements and thereby improves the quality and lifetime of HEP software. In neutrino physics, the requirements for a new physics generator are more challenging for three reasons: the lack of a 'canonical' procedural generator, theoretical and phenomenological challenges in modeling few-GeV neutrino interactions, and the rapidly evolving experimental and theoretical landscape.

Neutrinos come from many sources and a variety of experiments have been mounted to measure their properties. These experiments have complicated detectors composed of many elements and the neutrinos have many flavors and a wide energy spectrum (from

* Corresponding author.
*E-mail address:* costas.andreopoulos@stfc.ac.uk (C. Andreopoulos).

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$\sim 1$ MeV to $\sim 1$ PeV). Our long-term goal is for GENIE to become a 'canonical' neutrino event generator with wide applicability. The origins of the code come from the Soudan experiment [5] and recent application has been primarily to MINOS [6]. Thus, emphasis has been given to the few-GeV energy range, the challenging boundary between the non-perturbative and perturbative regimes. These are relevant for current and near future long-baseline precision neutrino oscillation experiments using accelerator-made beams, one of the focuses of high energy physics. GENIE development over the next five years will be driven by the upcoming generation of accelerator experiments including T2K [7], NoVA [8], Minerva [9], MicroBooNE [10] and ArgoNEUT [11]. These developments are well underway and the code is being used successfully in each of these experiments. The present version provides comprehensive neutrino interaction modelling in the energy from $\sim 100$ MeV to a few hundred GeV. Results can be obtained and will be qualitatively correct for any nuclear target.

GENIE[1] is a ROOT-based [12] Neutrino MC Generator. It was designed using object-oriented methodologies and developed entirely in C++ over a period of more than three years, from 2004 to 2007. Its first official physics release (v2.0.0) was made available on August 2007 and, at the time of writing this article, the latest available version was v2.4.4. It also describes v2.6.0 which will be released shortly. GENIE has already been adopted by the majority of neutrino experiments, including those using the JPARC and NuMI neutrino beamlines, and will be an important physics tool for the exploitation of the world accelerator neutrino program.

The project is supported by a group of physicists from all major neutrino experiments operating in this energy range, establishing GENIE as a major HEP event generator collaboration. Many members of the GENIE collaboration have extensive experience in developing and maintaining the legacy Monte Carlo Generators that GENIE strives to replace, which guarantees knowledge exchange and continuation. The default set of physics models in GENIE have adiabatically evolved from those in the NEUGEN [13] package, which was used as the event generator by numerous experiments over the past decade.

This article will discuss the paradigm shift brought about by GENIE in neutrino physics simulations. In Section 2 we describe the unique challenges facing neutrino simulations in more detail. Section 3 gives a brief overview of the physics models available in GENIE. Section 4 gives a brief discussion of upgrades in progress. Section 5 describes the object-oriented design of GENIE. Section 6 describes the GENIE applications and utilities available for simulation and analysis tasks. Section 7 describes the structure of the GENIE collaboration and Section 8 describes code availability, distribution, supported platforms, external dependencies, releases, and license.

## 2. Neutrino interaction simulation: challenges and significance

Neutrinos have played an important role in particle physics since their discovery half a century ago. They have been used to elucidate the structure of the electroweak symmetry groups, to illuminate the quark nature of hadrons, and to confirm our models of astrophysical phenomena. With the discovery of neutrino oscillations using atmospheric, solar, accelerator, and reactor neutrinos, these elusive particles now take center stage as the objects of study themselves. Precision measurements of the lepton mixing matrix, the search for lepton charge-parity (CP) violation, and the determination of the neutrino masses and hierarchy will be major efforts in HEP for several decades. The cost of this next generation of experiments will be significant, typically tens to hundreds of millions of dollars. A comprehensive, thoroughly tested neutrino event generator package plays an important role in the design and execution of these experiments, since this tool is used to evaluate the feasibility of proposed projects and estimate their physics impact, make decisions about detector design and optimization, analyze the collected data samples, and evaluate systematic errors. With the advent of high-intensity neutrino beams from proton colliders, we have entered a new era of high-statistics, precision neutrino experiments which will require a new level of accuracy in our knowledge, and simulation, of neutrino interaction physics [14].

While object-oriented physics generators in other fields of high energy physics were evolved from well established legacy systems, in neutrino physics no such 'canonical' MC exists. Until quite recently, most neutrino experiments developed their own neutrino event generators. This was due partly to the wide variety of energies, nuclear targets, detectors, and physics topics being simulated. Without doubt these generators, the most commonly used of which have been GENEVE [15], NEUT [16], NeuGEN [13], NUANCE [17] and NUX [18], played an important role in the design and exploration of the previous and current generation of accelerator neutrino experiments. Tuning on the basis of unpublished data from each group's own experiment has not been unusual making it virtually impossible to perform a global, independent evaluation for the state-of-the-art in neutrino interaction physics simulations. Moreover, limited manpower and the fragility of the overextended software architectures meant that many of these legacy physics generators were not keeping up with the latest theoretical ideas and experimental measurements. A more recent development in the field has been the direct involvement of theory groups in the development of neutrino event generators, such as the NuWRO [19] and GiBUU [20] packages, and the inclusion of neutrino scattering in the long-established FLUKA hadron scattering package [21].

Simulating neutrino interactions in the energy range of interest to current and near-future experiments poses significant challenges. This broad energy range bridges the perturbative and non-perturbative pictures of the nucleon and a variety of scattering mechanisms are important. In many areas, including elementary cross-sections, hadronization models, and nuclear physics, one is required to piece together models with different ranges of validity in order to generate events over all of the available phase space. This inevitably introduces challenges in merging and tuning models, making sure that double counting and discontinuities are avoided. In addition there are kinematic regimes which are outside the stated range of validity of all available models, in which case we are left with the challenge of developing our own models or deciding which model best extrapolates into this region. An additional fundamental problem in this energy range is a lack of data. Most simulations have been tuned to bubble chamber data taken in the 70's and 80's. Because of the limited size of the data samples (important exclusive channels might only contain a handful of events), and the limited coverage in the space of $(\nu/\overline{\nu}, E_\nu, A)$, substantial uncertainties exist in numerous aspects of the simulations.

The use cases for GENIE are also informed by the experiences of the developers and users of the previous generation of procedural codes. Dealing with these substantial model uncertainties has been an important analysis challenge for many recent experiments. The impact of these uncertainties on physics analyses have been evaluated in detailed systematics studies and in some cases the models have been fit directly to experimental data to reduce systematics. These 'downstream'

[1] *GENIE* stands for *G*enerates *E*vents for *N*eutrino *I*nteraction *E*xperiments.