Evaluating neutrino cross sections in the GENIE generator using comparisons with NOvA data

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October 15, 2024

Abstract

The NOvA experiment, primarily focused on neutrino oscillation studies [1], also provides a rich dataset for probing neutrino interaction models. In this project, we evaluate the performance of different models, whose tunes are integrated into the GENIE neutrino event generator [2], by comparing its predictions with several recent NOvA measurements [3, 4, 5]. The comparative analysis will be carried out in a similar way made in the recent publication [6].

1 Introduction

GENIE (Generates Events for Neutrino Interaction Experiments) [2] is a widely used neutrino event generator in the field of particle physics, designed to simulate neutrino interactions with various nuclear targets. It provides a comprehensive framework for modeling the complex processes involved in neutrino scattering, including quasielastic scattering, resonance production, and deep inelastic scattering, among others. GENIE incorporates multiple theoretical models and experimental data to simulate interactions across a wide range of neutrino energies, from a few MeV to several TeV. One of its key features is its flexibility, allowing researchers to apply different interaction models, to explore and compare various theoretical approaches. GENIE is an essential tool for experiments like NOvA, as it enables accurate predictions of neutrino cross sections, which are critical for interpreting experimental results and optimizing detector performance.

The NOvA experiment has recently published precise cross-section measurements [3, 4, 5], providing valuable insights into neutrino-nucleus interactions. These measurements are critical for understanding the underlying dynamics of neutrino scattering and for improving theoretical models used in neutrino event generators. NOvA's cross-section results include a range of interaction channels, such as charged-current quasielastic (CCQE) scattering, so-called CCQE-like and 2p2h, where a neutrino interacts with a nucleus, producing a lepton and hadronic system. Recent data sets from NOvA include measurements of the double-differential cross sections for muon neutrino and electron neutrino interactions, focusing on variables such as outgoing lepton energy and angle. Additionally, NOvA has measured the cross section as a function of transferred momentum and available energy, providing a more detailed look at hadronic energy and momentum transfer in charged-current interactions. These results offer new opportunities to test and refine neutrino interaction models and play a crucial role in reducing uncertainties in neutrino oscillation studies.

The comparative analysis will follow a methodology similar to that used in a recent publication [6], where the "Running Axial Mass" model was tested against experimental cross-section NOvA data [7]. This approach involves performing detailed simulations using the GENIE neutrino generator (v.3.4.0), incorporating the MArun model, and generating predicted cross sections for specific interaction channels. The simulated results will be compared with NOvA's experimental measurements, focusing on both total and differential cross sections across various kinematic variables such as lepton energy, angle, and/or transfered and visible energies. Statistical tools, such as chi-squared tests, will be employed to quantify the agreement between the model predictions and experimental data. By systematically comparing the results, we aim to evaluate the accuracy and limitations of the GENIE models in describing neutrino-nucleus interactions, providing a thorough cross-check and potential validation of the models across different interaction regimes.

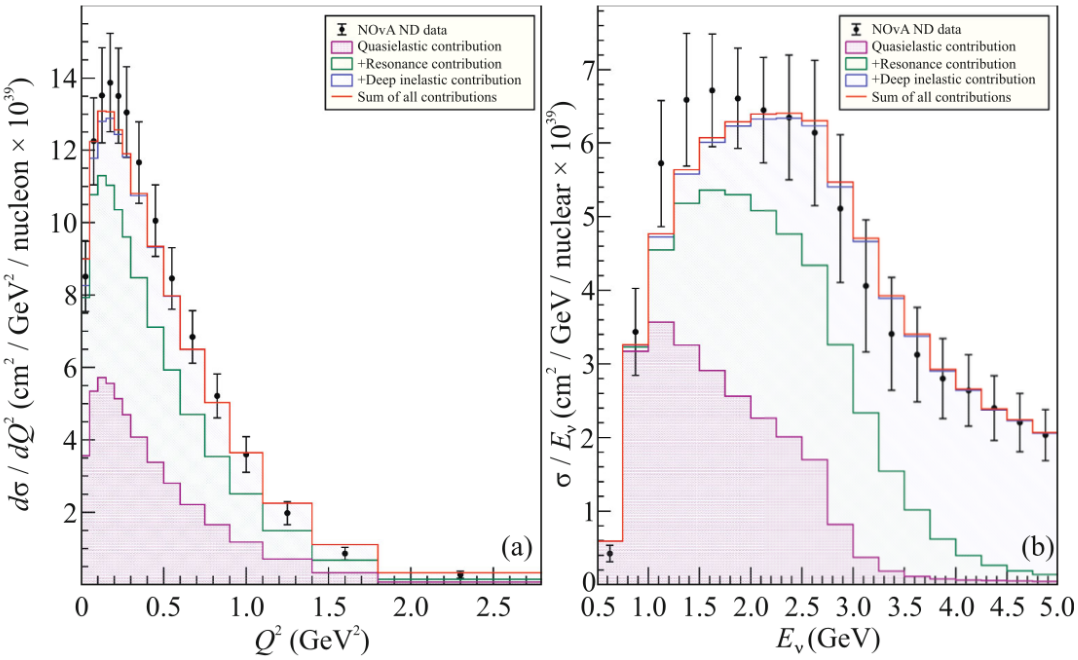

Figure 1: An example from [6] (a) Differential inclusive cross section $d\sigma/dQ^2$ for the charged-current scattering of ν_μ on nuclei and (b) the total cross section $\sigma(E_\nu)$ divided by the neutrino energy E_ν measured in the NOvA near detector [7] in comparison with the simulation using the GENIE neutrino Monte Carlo generator (v.3.4.0) with the MArun option.

1.1 Project Overview

Students will evaluate the performance of different neutrino interaction model, integrated into the GENIE neutrino generator, by comparing they with recent experimental measurements from the NOvA experiment. They will focus on the following three sets of data:

- Measurement of $d^2\sigma/d|\vec{q}|dE_{avail}$ in charged current neutrino-nucleus interactions at $E_\nu = 1.86$ GeV using the NOvA Near Detector [3].
- Measurement of the double-differential cross section of muon-neutrino charged-current interactions with low hadronic energy in the NOvA Near Detector [4].
- Measurement of the ν_e-Nucleus Charged-Current Double-Differential Cross Section at $E_\nu =$ 2.4 GeV using NOvA [5].

1.2 Project Objectives

- Understand neutrino interaction simulations within GENIE.
- Extract and analyze the experimental data from the above-listed NOvA publications, focusing on cross-section measurements.
- Simulate neutrino interactions using GENIE and compare the simulation outputs with the experimental results.
- Quantify the agreement between the models and experimental data by computing chi-squared metric including covariation.
- Interpret the differences and explore potential reasons for deviations between the model and the data, considering effects such as nuclear modeling, hadronic interactions, or systematic uncertainties.

2 Tasks

Each of suggested analysis could be done by individual analyzer (student) within the following workflow:

2.1 Literature Review

Students start by reviewing the published NOvA papers to understand the experimental results and cross-section measurements.

2.2 GENIE Simulations

Students will configure and run Monte Carlo simulations using GENIE with an included model. They will generate simulated neutrino events at the appropriate neutrino energies (based on each dataset).

2.3 Data Comparison

- For each dataset, students will plot the model predictions against the NOvA experimental data.
- Compute double-differential cross sections from simulation and compare them with the data in terms of key variables like muon kinematics (angle, energy) or transfered and visible energies.

2.4 Statistical Analysis

- Calculate chi-squared metric to quantify the agreement between the model predictions and the experimental data.
- Identify any discrepancies and hypothesize possible reasons for mismatches.

2.5 Presentation of Results

Students will prepare reports or presentations summarizing their findings, discussing the effectiveness of the model and any observed shortcomings. They can also propose further improvements or alternative models for future testing.

3 Preliminary schedule by topics/tasks

The duration of this project is 4-6 weeks. The work schedule will be agreed upon with the student(s).

4 Required skills

- Basic knowlegde of neutrino interactions theory/phenomenology (helpful to start).
- Basic knowledge of Linux; programmimg on C++ and analyse HEP data with ROOT (helpful to start).
- A personal laptop or computer with a Linux system installed. A Linux virtual machine will be provided to computentional jobs.
- English or Russian language for communication.

5 Acquired skills and experience

As part of their work on neutrino interaction analysis using the GENIE generator and NOvA experimental data, the students are developing a broad set of valuable skills and gaining practical experience across several key areas of particle physics and data science. This project equips them with not only theoretical knowledge but also the ability to apply advanced analytical techniques to real-world experimental data. Below are the specific areas where students are building expertise:

5.1 Particle Physics

The students are acquiring a foundational understanding of particle physics, particularly in the realm of neutrino interactions. They are learning about how neutrinos interact with atomic nuclei and the intricacies of neutrino-nucleus scattering processes, such as charged-current quasielastic (CCQE) scattering, so-called CCQE-like, 2p2h and resonance production. In addition, they are gaining insights into how nuclear effects, such as final-state interactions and nuclear binding energy, influence the observed interactions. As they engage with NOvA's cross-section measurements, students are also becoming familiar with how experimental techniques are applied to measure and interpret these fundamental physical quantities, providing a clear link between theory and experiment in particle physics.

5.2 Monte Carlo Simulations

The project involves extensive use of Monte Carlo simulations, particularly through the GENIE neutrino event generator, which is widely used in the neutrino physics community. Students are learning how to configure GENIE to simulate neutrino interactions under various conditions, including different neutrino energies, interaction channels, and nuclear targets. This hands-on experience with GENIE allows students to understand the role of theoretical models in predicting interaction cross-sections and the importance of accurate simulations in experimental particle physics.

5.3 Data Analysis

A crucial component of the project is the comparison of simulated results with experimental data from NOvA. Through this process, students are developing critical data analysis skills. They are learning how to extract and process large datasets, compute relevant physical quantities, and generate cross-section measurements from both experimental and simulated data. They are also becoming proficient in statistical methods used to evaluate the performance of theoretical models, such as chi-squared tests and goodness-of-fit analyses. This allows them to quantitatively assess how well the simulation aligns with experimental observations. Furthermore, they are gaining experience in visualizing complex results, comparing multiple variables (such as energy and angle), and interpreting any discrepancies between the data and model predictions, honing their ability to critically analyze and communicate scientific findings.

6 You are welcome and good luck!

We hope you find this material very INTEREST and wish you best practice in JINR.

References

[1] M. A. Acero *et al.*, "Improved measurement of neutrino oscillation parameters by the NOvA experiment," *Phys. Rev. D*, vol. 106, no. 3, p. 032004, 2022.

[2] L. Alvarez-Ruso, C. Andreopoulos, A. Ashkenazi, *et al.*, "Recent highlights from GENIE v3," *Eur. Phys. J. ST*, vol. 230, no. 24, pp. 4449–4467, 2021.

[3] M. A. Acero *et al.*, "Measurement of d2sigma/d—q—dEavail in charged current neutrino-nucleus interactions at <Ev> = 1.86 GeV using the NOvA Near Detector," 10 2024.

[4] M. A. Acero *et al.*, "Measurement of the double-differential cross section of muon-neutrino charged-current interactions with low hadronic energy in the NOvA Near Detector," 10 2024.

[5] M. A. Acero *et al.*, "Measurement of the ν_e-Nucleus Charged-Current Double-Differential Cross Section at $\langle E_\nu \rangle = 2.4$ GeV using NOvA," *Phys. Rev. Lett.*, vol. 130, no. 5, p. 051802, 2023.

[6] I. D. Kakorin, V. A. Naumov, and O. B. Samoylov, "Test of the Model of "Running Axial Mass" Using NOvA Near Detector Data on Muon Neutrino Scattering on Nuclei," *JETP Lett.*, vol. 119, no. 11, pp. 813–822, 2024.

[7] M. A. Acero *et al.*, "Measurement of the double-differential muon-neutrino charged-current inclusive cross section in the NOvA near detector," *Phys. Rev. D*, vol. 107, no. 5, p. 052011, 2023.