

MODELING NUCLEAR EFFECTS IN NuWro MONTE CARLO EVENT GENERATOR*

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In this article, I discuss recent advancements made by the Wrocław Neutrino Group in neutrino–nucleus interaction modeling, focusing on the implementation of an exclusive model for meson-exchange current-driven interactions in the NuWro Monte Carlo event generator and on NuWro’s performance against recent MINER ν A CC1 p 0 π measurements. I also briefly describe the fine-tuning of final-state interactions in NuWro. These improvements have a significant impact on exclusive observables.

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The upcoming long-baseline accelerator experiments, such as DUNE [1] and T2K-HK [2], aim to measure the neutrino oscillation parameters, leptonic charge parity (CP) violation phase, and constraints on the neutrino mass hierarchy. These ambitious programs require a comprehensive understanding of neutrino-nucleus interactions. One of the leading sources of systematic uncertainty in oscillation analyses is the limited knowledge of interaction cross sections and final-state interactions (FSI). The incident neutrino energy (E_ν) is unknown, and the beams used in most accelerator-based neutrino experiments are not mono-energetic and have broad spectra. As neutrino energies are reconstructed, rather than directly measured, via final-state observables, any mis-modeling of the interaction dynamics biases the reconstructed energy and, in turn, the measured oscillation parameters. Accurate, well-validated neutrino–nucleus interaction models that account for detailed nuclear effects and hadronic final states are therefore essential [3].

While the neutrino community is fortunate to have several Monte Carlo (MC) event generators, such as GENIE, NEUT, NuWro, and GiBUU, this article focuses exclusively on the NuWro MC event generator [4, 5]. The article is organized as follows: In Section 1, I introduce the NuWro MC generator. In Section 2, I briefly discuss transverse kinematic (TKIs) [6], which are observables with minimal dependence on E_ν that were proposed

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to directly constrain nuclear effects in (anti-)neutrino–nucleus interactions. In Section 3 and Section 4, I discuss recent improvements within NuWro that have a significant impact on TKIs and other exclusive observables. Finally, I conclude this article in Section 5.

1. NuWro

NuWro [5, 7] is an MC event generator for lepton–nucleus interactions developed at the University of Wrocław, with the focus on simulating neutrino–nucleus interaction in an accelerator-based neutrino experiment. It provides a flexible, and user-friendly platform for simulating neutrino–nucleus interactions across a broad energy range. Within NuWro, one can simulate quasielastic (QE), quasielastic hyperon production (HYP), meson-exchange currents (MEC), resonance production (RES), and deep inelastic scattering (DIS) processes for both charged-current (CC) and neutral-current (NC) interactions. NuWro has been used as the primary MC tool in two experiments: the KamLAND measurement of the strange axial form factor [8] and the JSNS² study of missing energy with a KDAR monoenergetic neutrino flux [9].

NuWro version 25.11 includes improvements in three channels, namely QE, MEC, and RES, the details of which can be found in [10–13]. In this article, I focus on the NuWro implementation of the 2020 Valencia model [12], including np – nh and isospin decomposition, as well as two-nucleon kinematics within the MEC channel; see Ref. [12]. The fine-tuning of NuWro’s cascade module [14] using reweighting tools and its impact on exclusive observables is discussed in Section 4.

2. Transverse kinematics

Consider the scenario of a neutrino scattering off a free and stationary nucleon shown in Fig. 1 (a). The momentum conservation in the plane transverse to the incoming neutrino direction implies that the momenta of the outgoing charged lepton and the struck nucleon perfectly balance each other (*i.e.*, zero transverse kinematic imbalance) assuming there is no FSI. The scenario becomes complicated when a neutrino scatters off a bound nucleon within the nucleus. To elaborate on it, consider the processes of the form

$$\nu + A \rightarrow \mu^- + p + X, \quad (1)$$

where A is the target nucleus and X is the final-state hadronic system, which consists of the remnant nucleus and may include additional protons or neutrons, but no mesons or heavy baryons. The momentum of the struck nucleon (which is unknown), the binding energy, and FSI disrupt this balance, see Fig. 1 (b). In this case, one defines the transverse projection of

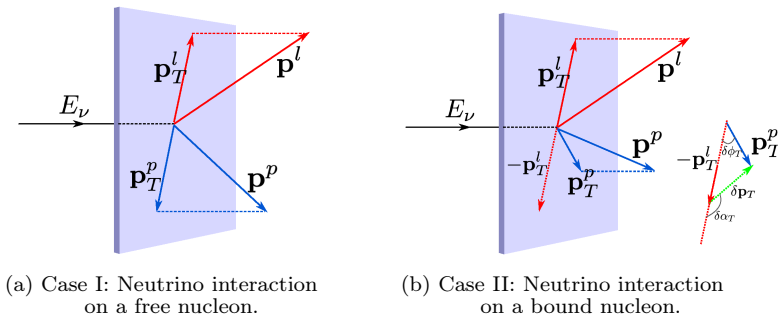


Fig. 1. Schematic definition of the transverse kinematics [6].

the momentum imbalance $\delta\mathbf{p}$ from the kinematics of the observed final-state particles as follows:

$$\delta\mathbf{p}_T = \mathbf{p}_T^\mu + \mathbf{p}_T^p, \quad (2)$$

where $\mathbf{p}_T^{\mu(p)}$ is the transverse projection of the outgoing muon (proton) momentum. In cases where only Fermi motion of initial-state nucleons is considered with no other nuclear effects, $\delta\mathbf{p}_T$ peaks around the Fermi momentum value. Processes such as multi-nucleon ejection and FSI can distort the shape by accumulating on the right tail of this distribution. Transverse kinematics, which have minimum dependence on E_ν , are referred to as TKI observables and are sensitive to nuclear effects and intranuclear momentum transfer. This technique was first proposed in [6] and was later adopted by many neutrino experiments to directly compare models of nuclear effects with experimental data, and to constrain different neutrino-interaction models [15, 16].

3. The 2020 Valencia model

Neutrino scattering off a nucleus via the MEC mechanism is significant at sub-GeV energies. In MEC, typically more than one nucleon is knocked out from the nucleus. The new NuWro version 25.11 comes with several MEC models. These are the Nieves *et al.*, Marteau *et al.*, SuSAv2, the Transverse-Enhancement (TE) Model, and the 2020 Valencia model [17]. These models differ in their implementation and cover different phase spaces.

The TE model is implemented using analytic formulas. The Marteau *et al.* model uses a hybrid approach: tabulated response functions $W^{\mu\nu}(\omega, |\mathbf{q}|)$ are used in a specified kinematic region, while analytic formulas are used outside this region. The Nieves *et al.* and SuSAv2 models instead tabulate all five response functions $W^{\mu\nu}(\omega, |\mathbf{q}|)$. The 2020 Valencia model adopts a similar strategy, but with separate tables for different final-state nucleons and different *event topologies* to preserve the information about individual contributions.

Figure 2 compares the total cross sections from these models. While their predictions for the inclusive cross section differ, most do not predict the kinematics of the outgoing nucleons, except for the 2020 Valencia model. MC generators address this by combining *inclusive* and *exclusive* parts, using the latter to simulate the kinematics of the outgoing nucleon states. Up until NuWro v21.09, the *exclusive* part of all MEC models was modeled in the same way, using the phase-space prescription proposed in Ref. [18]. NuWro 25.03 and later v25.11 comes with implementation of the 2020 Valencia model and improvements in the treatment of the *exclusive* part of the MEC models.

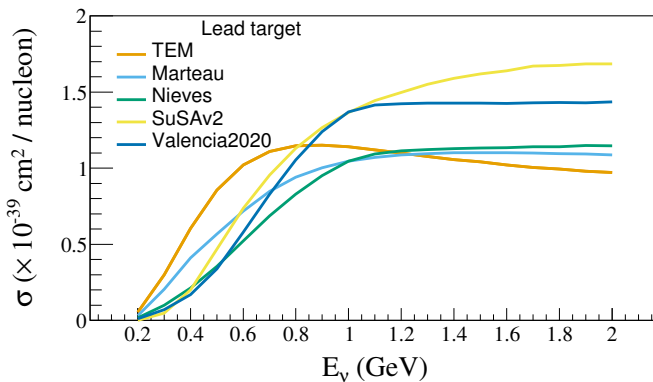


Fig. 2. Total MEC cross-section predictions from various MEC models implemented within the NuWro MC generator on the lead target.

The exclusive MEC model developed by the Valencia group, known as the 2020 Valencia model, separates the total MEC cross section into distinct $2p2h$ and $3p3h$ contributions. The $2p2h$ component is further subdivided into three categories based on the isospin of the outgoing nucleon pair: pp , np , and pn (nn , pn , and np in case of anti-neutrino). For each case, the model predicts the momenta of the outgoing states.

The correlation between the two nucleons is treated differently for each nucleon-pair configuration. For example, Fig. 3 illustrates these correlations for neutrino scattering off a lead nucleus. In NuWro, this correlation is incorporated by separating the response-function tables for each outgoing state, and approximating the correlations between outgoing nucleon states using a nucleon-sampling function with two adjustable parameters. These parameters are tuned to reproduce a nucleon phase space similar to that of the 2020 Valencia model. Currently, NuWro implementation of the 2020 Valencia model includes tables for four targets: carbon, oxygen, iron, and lead. The parameters in the nucleon-sampling function are fine-tuned for carbon and extrapolated to other targets.

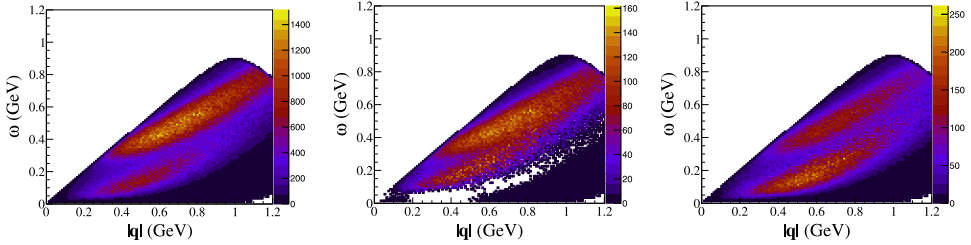


Fig. 3. Double differential cross section $d^2\sigma/dq d\omega$ for the lead ($^{208}_{82}\text{Pb}$) target produced by the NuWro implementation of the 2020 Valencia model (using the tables of response function for lead) for pp (left), np (middle), and pn (right) outgoing pair in the $2p2h$ mechanism.

The algorithm for this implementation is illustrated in Figs. 2 and 3 of Ref. [19], with a detailed description given in Ref. [12]. The current version of NuWro includes the 2020 Valencia model for four nuclear targets: carbon, oxygen, calcium, and lead. For other nuclei, the tables corresponding to the closest nucleus by atomic mass are used.

The impact on *exclusive* observables from experimental analyses using the 2020 Valencia model within NuWro, for the carbon target, is demonstrated in Ref. [12]. Using the newer MEC model in NuWro, the $\chi^2/\text{d.o.f.}$ reduces when compared with MINER ν A exclusive data [21, 22]. In Fig. 4, I

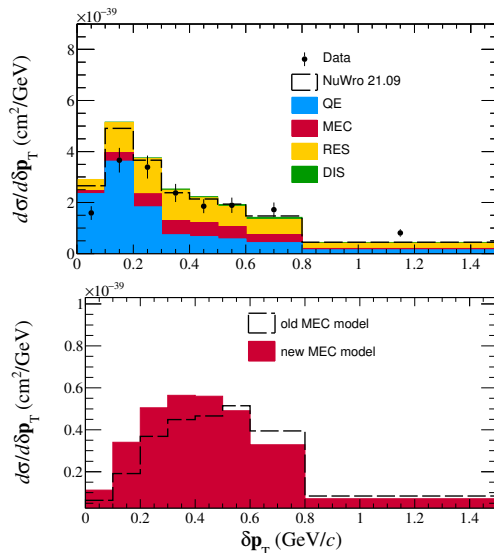


Fig. 4. Top: Comparison of $d\sigma/d\delta p_T$ with MINER ν A CC1 $p0\pi$ data [20] for lead. Bottom: Contribution of MEC to the differential cross section using the 2020 Valencia model and an earlier MEC model.

present a similar comparison, comparing the new and old MEC models, using more recent MINER ν A CC1 p 0 π [20] but for the lead target, since MEC contributions are higher for large atomic masses. Figure 4 shows the impact of modeling nucleon correlations on TKI variables like δp_T .

4. Modeling FSI in NuWro

NuWro includes a cascade module that simulates the FSI of hadrons produced at the primary interaction vertex. The basic framework is inspired by the MC approach proposed by Metropolis *et al.* [23]. The cascade module provides a semi-classical description of hadron propagation in the nuclear medium, incorporating nuclear effects such as in-medium modification of the hadron–nucleon cross section, Pauli blocking, and nucleon–nucleon correlations.

A dedicated sub-module of the NuWro cascade is the nucleon-FSI module, which simulates only nucleon (re)interactions. A previous study compared the nucleon-FSI module with proton transparency data and estimated an uncertainty in FSI effects of about 30%, expressed in terms of the nucleon mean free path [24]. This result implied that the nucleon (re)interaction probability could be scaled upto 30% in either direction. Modifying the (re)interaction probability changes the number of reinteractions, which in turn affects the kinetic energy of the propagating nucleons and, consequently, all exclusive observables.

Building upon this, the Wrocław group fine-tuned the nucleon-FSI module using recent MINER ν A CC1 p 0 π results [20] by fine-tuning the parameter which scales the nucleon mean free path. The fit was performed simultaneously on four nuclear targets: carbon, water, iron, and lead. To fit the neutrino data, new reweighting tools were developed to adjust FSI [14]. A global fit of the nucleon mean free path was carried out using all exclusive observables published by MINER ν A. The study concluded that the NuWro FSI strength should be increased by approximately 24%. The current NuWro version, v25.11, ships with the fine-tuned value of the scaling parameter obtained in [14] as the default, with an option to reweight FSI in the upcoming NuWro versions.

5. Summary

The upcoming versions of NuWro will have further improvements in QE channel, see Ref. [11], as well as a reweighting-tools to reweight NuWro's cascade module [14].

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