# NuWro MONTE CARLO GENERATOR OF NEUTRINO INTERACTIONS — FIRST ELECTRON SCATTERING RESULTS*

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`NuWro` Monte Carlo generator of events is presented. It is a numerical environment containing all necessary ingredients to simulate interactions of neutrinos with nucleons and nuclei in realistic experimental situation in wide neutrino energy range. It can be used both for data analysis as well as studies of nuclear effects in neutrino interactions. The first results and functionalities of `eWro` — module of `NuWro` dedicated to electron–nucleus scattering — are also presented.

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## 1. Introduction

For the past twenty years, there has been a growing interest in the neutrino oscillations. Since the confirmation of this phenomenon in Super-Kamiokande and Sudbury experiments, a lot of effort has been made towards precise measurement of lepton mixing angles and mass differences. More challenging studies of neutrino mass hierarchy, leptonic CP violation as well as existence of sterile neutrino are addressed by a series of new experiments. We pay here a special attention to the ones using accelerator neutrino beam sources, including MINOS+, T2K, NovA, MicroBooNE and planned DUNE and Hyper-Kamiokande. A large part of systematic uncertainties comes from a lack of precise knowledge about neutrino–nucleus interaction physics. Complexity of this problem is largely due to difficulties in modeling nuclear structure effects in large energy range spanned by neutrino beams. This requires the use of different theoretical formulations for various pieces of the

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phase space, starting from the nonrelativistic quantum mechanics through effective hadronic field theories up to quark jet fragmentation routines for deep inelastic scattering. All particles created and participating in the scattering propagate through atomic nucleus, where they are subject to strong final state interactions (FSI). It is desirable for the systematic error in new oscillation experiments to be reduced to 1–3%. It is a very challenging goal because the knowledge of neutrino–nucleus cross sections is not better than 10–20%. Beside the oscillation studies, accelerator neutrinos are a probe to test the weak interaction of hadrons and atomic nuclei, which makes the physical program even richer and more interesting.

Monte Carlo generator of events such as `NuWro` [6] helps in analysis of experimental measurements. `NuWro` has been developed since $\sim$ 2004. Even though, it is not an official Monte Carlo of any experiment, it is widely used as a tool for development and testing new physical models in MC generators. This includes *e.g.* implementation of the IFIC model of two-nucleon currents [7] and the Berger–Sehgal model of coherent pion production [8]. `NuWro` is also used as a benchmark and reference for experimental collaborations [9, 10]. Overview and references to other MC generators (such as `GENIE`, `NEUT` and `GiBUU`) can be found in [11].

Recently, a new electron scattering simulation module was added to `NuWro`. It allows for comparisons with accurate electron–nucleus scattering data and extensive tests of implemented physical models. This makes `NuWro` a fully-fledged and versatile tool for theoretical and experimental physicists. Its main interaction channels and implemented physical models will be outlined in the following sections.

## 2. `NuWro`

`NuWro` generator is capable of simulating neutrino interactions taking into account beam profile and composition, detailed detector geometry as well as FSI in the nuclear target. It can be applied to a neutrino energies ranging from around 100 MeV, implied by the requirement of validity of the impulse approximation, up to the TeV energy range. In between, the possible physical channels change from charged-current quasielastic (CCQE), neutral current elastic (NCE) scattering, through multi-nucleon meson exchange currents (MEC), coherent (COH) and resonant (RES) pion production up to deep inelastic scattering (DIS), which stands here for processes more inelastic from RES. A description of nuclear system in `NuWro` can be chosen from a variety of options: global or local Fermi gas models (FG or LFG), hole spectral function [12–14], effective momentum and density-dependent potential [15]. The object-oriented `C++` code is very flexible and allows one to easily introduce new theoretical models and modify the existing ones. The choice of physical interaction channels, model parameters and variants, such as nucleon and resonance form factor sets, is made within the universal parameter file. The output is written in three separate files containing respectively: the simulations parameter set, the integrated cross sections for each interaction mode and target, and the `ROOT` tree of equally weighted events with information about initial, intermediate and final state particles. The `NuWro` is an open source code and can be downloaded from [16]. A prototype of a `NuWro` On-line service is also available there.

The CCQE and NCE scattering processes are very important for neutrino experiments with beam energy range up to few GeV [17, 18]. In `NuWro`, the FG/LFG model has been improved by implementing relativistic ring random phase approximation (RPA) [19] with effective nucleon mass (only for CCQE). `NuWro` contains also an implementation of the spectral function approach [20]. For both CCQE and NCE interactions, one can choose between multiple form factor sets describing neutrino–nucleon vertex structure.

Importance of MEC in neutrino experiments has been first pointed out by Martini *et al.* in [21] in connection with MiniBooNE CCQE cross section measurement publication [22]. The latter analysis did not consider the MEC contribution, which lead to abnormally large measured nucleon axial mass parameter, whereas the models including MEC tend to reproduce its standard value from the MiniBooNE data [23]. In `NuWro`, there are two MEC implementations available: the effective transverse enhancement model [24], which parametrizes MEC effects as an enlargement of magnetic nucleon form factors, and the microscopic IFIC model [7] (only for charge current interactions).

The RES channel includes pion production processes in the invariant mass range $W < 1.6$ GeV. It consists of the $\Delta(1232)$ resonance excitation [25] and effective background extrapolated from the DIS contribution down to $W = 1.4$ GeV. There are multiple $\Delta$ form factor sets available including the fits to ANL/BNL bubble chamber data from [25]. The lack of heavier resonances is justified by the quark–hadron duality hypothesis [26] and Fermi motion effects, which wash out the distinct resonance signal. Recently, pion angular correlations measured in the ANL and BNL experiments were included [27, 28] as well as an approximate implementation of the $\Delta(1232)$ self-energy in nuclear matter from [29].

A coherent pion production process leaves the nucleus in its ground state. In `NuWro`, it is simulated using two phenomenological PCAC based models described in Rein–Sehgal [30] and Berger–Sehgal [8] papers, the latter seemingly closer to recent MINERvA data [31].

The DIS channel contains inelastic interactions in a region of $W > 1.6$ GeV. The overall cross section is evaluated using the Bodek–Yang corrections [32]. Hadronic final states are obtained using PYTHIA 6 hadronization routines [33]. In a region of $W \in (1.4, 1.6)$ GeV, a smooth transition from RES to DIS is done.

The FSI algorithm in NuWro is based on an intranuclear cascade [34]. It uses phenomenological and experimental cross sections for elastic and inelastic pion–nucleon and nucleon–nucleon interactions, including the Oset model from [35] and finite $\Delta$ life-time effects. The nucleon–nucleon effective cross section includes in-medium modifications following the approach of Pandharipande–Pieper [36]. More detailed overview of NuWro FSI effects can be found in [37].

## 3. Electron scattering in NuWro

The work is under way on eWro — a new module for generating the electron–nucleus interactions. Due to the abundance and good precision of electron scattering data, eWro can serve as a testing ground of nuclear physics models which are common in eWro and NuWro.

Currently, in eWro the nucleus is modeled within FG/LFG. The quasielastic and single pion production processes are implemented. The latter channel contains $\Delta(1232)$ resonance and a nonresonant background from [38, 39] and an implementation of nonperturbative $\Delta(1232)$ self-energy following [29]. The RES model of eWro differs from that of NuWro with respect of treatment of the nonresonant background.

In Fig. 1, eWro predictions for inelastic electron scattering off carbon and oxygen targets are presented. We show results for FG and LFG models of the ground state of the nucleus. The binding energy following the de Forest prescription [40] is taken into account. In most of the plots, the quasielastic and $\Delta(1232)$ peaks are clearly visible. To describe $N \to \Delta(1232)$ transition recent fits of electromagnetic form factors from [41] have been used. The $\Delta$ propagator is fully dressed in medium effects following the approach described in [29].

## 4. Summary

NuWro is a versatile tool to study lepton–nucleus interactions. It produces MC data samples for experimental analysis purposes. It covers most important interaction modes. It is a flexible code ready for further developments and use in an actual data analysis.

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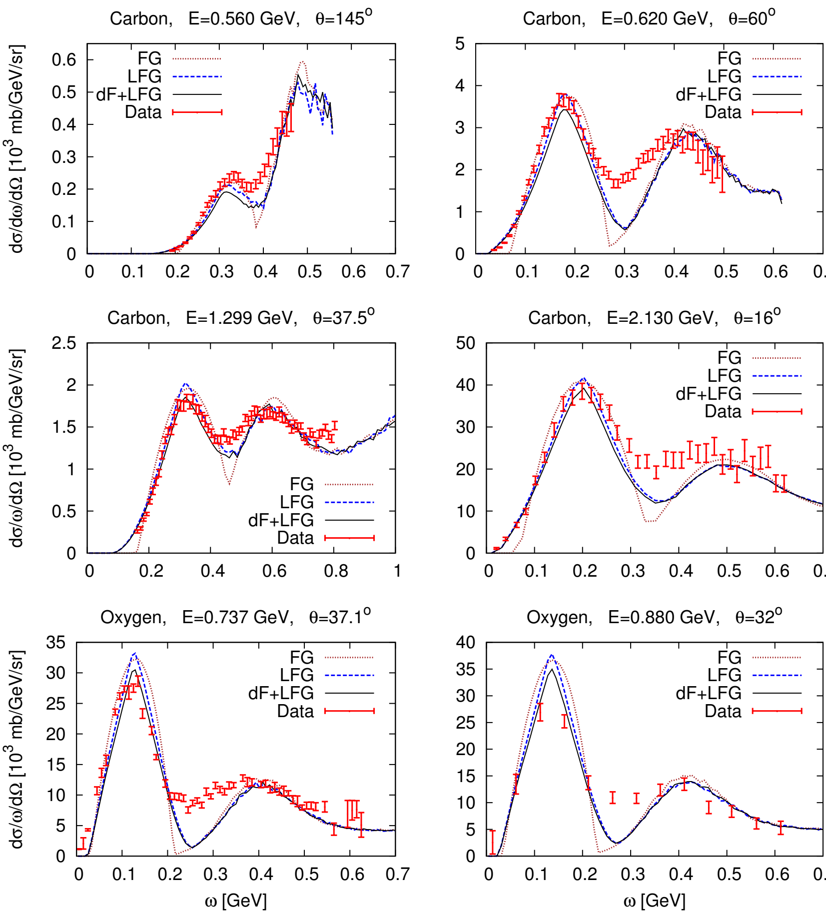


Fig. 1. Differential cross sections for electron scattering off carbon and oxygen obtained within `eWro` (for various beam energies, $E$, and scattering angles, $\theta$). The curves correspond to FG, LFG and LFG with de Forest treatment of binding energy (dF+LFG). The data are taken from [1] (top), [2] (middle left), [3] (middle right), [4] (bottom left), [5] (bottom right).

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