

Test of the *GENIE* neutrino event generator against reduced cross sections extracted from $^{16}\text{O}(e,e'p)$ data

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The reduced cross section of the semiexclusive $(l, l'p)$ lepton scattering process irrespective of the type of interaction is determined mainly by the bound nucleon momentum distribution in the target and nucleon final state interaction with the residual nucleus. These cross sections can be identified with distorted nuclear spectral functions and therefore, they are similar up to Coulomb corrections for neutrino and electron scattering on nuclei. In this article, we exploit this similarity and use data with precise kinematics and large statistics for semiexclusive electron scattering on an oxygen target to test models employed in the *GENIE* neutrino event generator. We find that these models cannot reproduce well the measured reduced cross sections in all allowed kinematic regions and the *GENIE* event generator needs to describe better both the nuclear ground states and nucleon final state interaction. The approach presented in this paper provides a great opportunity to better test the accuracy of nuclear models of quasielastic neutrino-nucleus scattering, employed in neutrino event generators.

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I. INTRODUCTION

In current [1,2] and future [3–5] accelerator-based neutrino experiments the probabilities of neutrino oscillations as functions of neutrino energy are measured to evaluate the oscillation parameters and to test the three-flavor paradigm. The accuracy to which neutrino oscillation parameters can be extracted depends on the ability of experiments to determine the individual energy of each detected neutrino. These experiments rely on neutrino event generator codes, which are simulations of neutrino-nucleus interactions used to estimate efficiencies, backgrounds, and systematic uncertainties for the obtained result.

The neutrino beams have broad distributions that range from tens of MeVs to a few GeVs. The incident neutrino energy is not known *a priori* and can only be deduced by measuring the leptonic and hadronic energy of the final state particles. The energy and scattering angle of the outgoing muon can be directly measured. To determine the hadronic energy ϵ_h a calorimetric method is used, which relies not only on the visible energy E_{vis} measured in the detector, but on a fit of ϵ_h as a function of E_{vis} , obtained from simulation. Thus, the accuracy of the neutrino energy reconstruction depends on the models of the neutrino-nucleus interactions

that are implemented in neutrino event generators. The systematic uncertainties of this procedure affect significantly the determination of the incident neutrino energy. For instance, the estimated muon and hadronic energy resolutions are 3.5% and 25%, respectively, giving an overall energy resolution for neutrino events in the NOvA detector [6] of about 7%.

In addition, the neutrino-nucleus scattering model is critical for obtaining background estimates in analyses aimed at determining the neutrino oscillation parameters. Further progress in reducing systematic errors in neutrino oscillation experiments requires a more extensive use of measurements of final-state protons. It is needed for neutrino energy reconstruction because a more exclusive final-state measurement allows us to better estimate the neutrino energy and provide information about the multi-nucleon contribution to the inclusive cross section. Inclusive reactions are relatively insensitive to the details of the final nuclear states.

Neutrino- and electron-nucleus interactions are similar due to their shared origin in electroweak theory. Electrons interact via a vector current, and neutrinos interact via vector and axial-vector currents. The nuclear structure and final state interactions of the outgoing hadrons they are expected to be identical for both leptons. These similarities can be used to test models of neutrino-nucleus interaction. Neutrino event generator *GENIE* [7–10], has been extended to electron scattering, and their results were compared with measured inclusive cross sections of electron-nucleus (eA) interaction. Note that inclusive reactions are relatively

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insensitive to the details of the final nuclear states. Therefore, rather simple phenomenological and factorized models and event generators that employ them are able to describe inclusive and total cross sections but cannot make predictions on both leptons and hadrons in the final states. Theoretical models attempting to describe the semiexclusive ($l, l'p$) lepton scattering process must be macroscopic and unfactorized models, and simultaneously account for various nuclear effects, including nuclear ground states, i.e., shall structure of nuclei, nucleon-nucleon (NN) correlations and final state interaction (FSI) of the knocked-out nucleon with the residual nucleus. The semiexclusive ($l, l'p$) lepton scattering process involves the specific asymptotic states and allows us to test the nuclear in model more in detail. The reduced cross section, obtained from the measured differential semiexclusive electron scattering cross section divided by the kinematic factor and the off-shell electron-proton cross section, can be identified as the distorted spectral function. Thus, irrespective of the type of interaction (electromagnetic or weak), the distorted spectral function is determined mainly by the intrinsic properties of the target and the ejected nucleon's interaction with the residual nucleus and depends upon the initial and ejectile nucleons' momenta and the angle between them. Microscopic and unfactorized the relativistic distorted wave impulse approximation (RDWIA), initially designed for the description of exclusive ($e, e'p$) data [11–13] was used [14–17] for the calculation of the charged-current (CC) quasielastic (QE) neutrino scattering reduced cross sections as a function of the missing nucleon momentum. The results were compared with those obtained from measurements of ($e, e'p$) scattering on oxygen, carbon, calcium, and argon targets. It was shown that these cross sections are similar to those of electron scattering data and agree with electron scattering data. This approach provides novel constraints on nuclear models of the CCQE scattering and can be applied to test spectral functions and FSI employed in neutrino event generators. A systematic comparison of the CCQE reduced cross sections calculated within the models employed in the *GENIE* event generator [18,19] with those measured in electron scattering on carbon targets was carried out in Ref. [20]. The goal of the present paper is to test the *GENIE* models against semiexclusive electron scattering data on oxygen. This target is the main detector component in water Cherenkov neutrino detectors, and for oxygen, there are high-precision datasets with different monochromatic electron beams.

The outline of this article is as follows. In Sec. II we briefly present the formalism for the CCQE semiexclusive scattering process, the calculation of the reduced cross sections with a neutrino event generator, and regard basic aspects of comprehensive model configurations employed in the *GENIE* version 3 simulation framework. Results are presented and discussed in Sec. III. The conclusions are summarized in Sec. IV.

II. FORMALISM OF QUASIELASTIC SCATTERING AND NEUTRINO EVENT GENERATOR AS A TOOL IN REDUCED CROSS SECTION STUDY

A. CCQE lepton-nucleus cross sections

In the laboratory frame, the differential cross section for exclusive electron (σ^{el}) and (anti)neutrino (σ^{cc}) CC scattering can be written as

$$\frac{d^6\sigma^{el}}{d\varepsilon_f d\Omega_f d\varepsilon_x d\Omega_x} = \frac{|\mathbf{p}_x| \varepsilon_x \varepsilon_f \alpha^2}{(2\pi)^3 \varepsilon_i Q^4} L_{\mu\nu}^{(el)} \mathcal{W}^{\mu\nu(el)} \quad (1a)$$

$$\frac{d^6\sigma^{cc}}{d\varepsilon_f d\Omega_f d\varepsilon_x d\Omega_x} = \frac{|\mathbf{p}_x| \varepsilon_x |\mathbf{k}_f|}{(2\pi)^5 \varepsilon_i} \frac{G^2 \cos^2 \theta_c}{2} L_{\mu\nu}^{(cc)} \mathcal{W}^{\mu\nu(cc)}, \quad (1b)$$

where $k_i = (\varepsilon_i, \mathbf{k}_i)$ and $k_f = (\varepsilon_f, \mathbf{k}_f)$ are the initial and final lepton 4-momenta, $p_A = (\varepsilon_A, \mathbf{p}_A)$, and $p_B = (\varepsilon_B, \mathbf{p}_B)$ are the initial and final target 4-momenta, $p_x = (\varepsilon_x, \mathbf{p}_x)$ is the ejectile nucleon 4-momentum, $q = (\omega, \mathbf{q})$ is the 4-momentum transfer carried by the virtual photon (W-boson), and $Q^2 = -q^2 = \mathbf{q}^2 - \omega^2$ is the photon (W-boson) virtuality. In Eqs. (1a) and (1b) Ω_f is the solid angle for the lepton momentum, Ω_x is the solid angle for the ejectile nucleon momentum, $\alpha \simeq 1/137$ is the fine-structure constant, $G \simeq 1.16639 \times 10^{-11} \text{ MeV}^{-2}$ is the Fermi constant, θ_c is the Cabibbo angle ($\cos \theta_c \simeq 0.9749$), $L^{\mu\nu}$ is the lepton tensor, and $\mathcal{W}_{\mu\nu}^{(el)}$ and $\mathcal{W}_{\mu\nu}^{(cc)}$ are respectively the electromagnetic and weak CC nuclear tensors [14].

For exclusive reactions in which only a single discrete state or a narrow resonance of the target is excited, it is possible to integrate over the peak in missing energy and obtain a fivefold differential cross section of the form

$$\frac{d^5\sigma^{el}}{d\varepsilon_f d\Omega_f d\Omega_x} = R \frac{|\mathbf{p}_x| \tilde{\varepsilon}_x \varepsilon_f \alpha^2}{(2\pi)^3 \varepsilon_i Q^4} L_{\mu\nu}^{(el)} \mathcal{W}^{\mu\nu(el)} \quad (2a)$$

$$\frac{d^5\sigma^{cc}}{d\varepsilon_f d\Omega_f d\Omega_x} = R \frac{|\mathbf{p}_x| \tilde{\varepsilon}_x |\mathbf{k}_f|}{(2\pi)^5 \varepsilon_i} \frac{G^2 \cos^2 \theta_c}{2} L_{\mu\nu}^{(cc)} \mathcal{W}^{\mu\nu(cc)}, \quad (2b)$$

where R is a recoil factor

$$R = \int d\varepsilon_x \delta(\varepsilon_x + \varepsilon_B - \omega - m_A) = \left| 1 - \frac{\tilde{\varepsilon}_x \mathbf{p}_x \cdot \mathbf{p}_B}{\varepsilon_B \mathbf{p}_x \cdot \mathbf{p}_x} \right|^{-1}, \quad (3)$$

in which $\tilde{\varepsilon}_x$ is the solution to the equation $\varepsilon_x + \varepsilon_B - m_A - \omega = 0$, where $\varepsilon_B = \sqrt{m_B^2 + \mathbf{p}_B^2}$, $\mathbf{p}_B = \mathbf{q} - \mathbf{p}_x$ and m_A and m_B are masses of the target and the recoil nucleus, respectively. Note that the missing momentum is $\mathbf{p}_m = \mathbf{p}_x - \mathbf{q}$ and missing energy ε_m are defined by $\varepsilon_m = m + m_B - m_A$ [14].

The leptonic tensor is as written in Ref. [14]. The electromagnetic and the weak CC hadronic tensors, $\mathcal{W}_{\mu\nu}^{(el)}$ and $\mathcal{W}_{\mu\nu}^{(cc)}$ are given by bilinear products of the

transition matrix elements of the nuclear electromagnetic or CC operator $J_\mu^{(el)(cc)}$ between the initial nuclear state $|A\rangle$ and the final state $|B_f\rangle$ as

$$\mathcal{W}_{\mu\nu}^{(el)(cc)} = \sum_f \langle B_f, p_x | J_\mu^{(el)(cc)} | A \rangle \langle A | J_\nu^{(el)(cc)\dagger} | B_f, p_x \rangle \delta(\varepsilon_A + \omega - \varepsilon_x - \varepsilon_{B_f}), \quad (4)$$

where the sum is taken over undetected states.

The reduced cross section is given by

$$\sigma_{\text{red}} = \frac{d^5 \sigma^{(el)(cc)}}{d\varepsilon_f d\Omega_f d\Omega_x} / K^{(el)(cc)} \sigma_{IN}, \quad (5)$$

where $K^{el} = R p_x \varepsilon_x / (2\pi)^3$ and $K^{cc} = R p_x \varepsilon_x / (2\pi)^5$ are phase-space factors for electron and neutrino scattering and σ_{IN} is the corresponding elementary cross section for lepton scattering from the moving free nucleon [20]

The single-nucleon charged current has the $V - A$ structure $J^\mu^{(cc)} = J_V^\mu + J_A^\mu$. For calculation of the vertex function $\Gamma^\mu^{(cc)} = \Gamma_V^\mu + \Gamma_A^\mu$ of a moving but free nucleon we employ the CC1 de Forest prescription for the off-shell vector current vertex function [21]

$$\Gamma_V^\mu = G_M(Q^2) \gamma^\mu - \frac{\bar{P}^\mu}{2m} F_M(Q^2) \quad (6)$$

and the axial current vertex function

$$\Gamma_A^\mu = F_A(Q^2) \gamma^\mu \gamma_5 + F_P(Q^2) q^\mu \gamma_5, \quad (7)$$

where $\bar{P} = (\varepsilon_f + \bar{\varepsilon}, 2\mathbf{p}_x - \mathbf{q})$ and $\bar{\varepsilon} = \sqrt{m^2 + (\mathbf{p}_x - \mathbf{q})^2}$. The weak vector form factors F_V and F_M are related to corresponding electromagnetic ones for proton $F_{i,p}^{(el)}$ and neutron $F_{i,n}^{(el)}$ by the hypothesis of conserved vector current

$$F_i = F_{i,p}^{(el)} - F_{i,n}^{(el)} \quad (i = V, M). \quad (8)$$

The experimental momentum distribution is also obtained using Eq. (5) with the off-shell electron-nucleon cross section σ_{cc1} developed by de Forest [21] that are normally used for σ_{eN} . For the axial F_A and pseudoscalar F_P form factors, we use the dipole approximation.

The reduced cross section σ_{red} effectively represents the distorted spectral function where final-state interactions (FSI) introduce dependencies on the ejectile momentum, the angle between the initial and final nucleon momentum and the incident lepton energy. In the nonrelativistic PWIA limit, σ_{red} reduces to the bound-nucleon momentum distribution. These cross sections for (anti)neutrino scattering off nuclei are similar to those for electron scattering apart from small differences at low beam energy due to effects of Coulomb distortion of the incoming electron wave function

as shown in Refs. [14–16]. With the reduced cross section the factorization approximation to the semiexclusive cross section Eqs. (2a) and (2b) can be written as [20]

$$\frac{d^5 \sigma^{(el)(cc)}}{d\varepsilon_f d\Omega_f d\Omega_x} = K^{(el)(cc)} \times \sigma_{IN} \times \sigma_{\text{red}}(\varepsilon_m, \mathbf{p}_m, \mathbf{p}_x). \quad (9)$$

Such factorization is not strictly valid relativistically because the binding potential alters the relationship between lower and upper components of a Dirac wave function [22].

B. Neutrino event generator as a tool in reduced cross section study

Reduced cross sections calculated for the oxygen nucleus within the *GENIE* version 3.4.0 framework are compared with data to test the nuclear models that are employed in the *GENIE* event generator. Several models for the nuclear ground state and several models for FSI are offered within this framework. We simulated only CCQE neutrino interactions with the oxygen nucleus. The events with one proton and any number of neutrons which did not undergo final state interactions are selected as a $1\mu 1p$ signal. This event selection is performed using two methods: one is based on a specific event topology in the final state and the other relies only on the knowledge of the kinematics of events [20].

In the Saclay experiment Ref. [23] the $^{16}\text{O}(e, e'p)$ measurements have been performed in the perpendicular kinematics for $-100 \leq p_m \leq 300$ MeV/c and the reduced cross section has been integrated in the intervals of missing energy $\varepsilon_m = 10\text{--}15$ MeV and $15\text{--}20$ MeV, where the $p_{1/2}$ and $p_{3/2}$ hole strengths are mostly centered in two peaks with separation energies of 12.2 and 18.5 MeV, respectively. In perpendicular kinematics, the incident energy and energy transferred are fixed, as are the electron scattering angle and the outgoing proton energy, whereas the missing momentum changes with the proton angle. It is necessary to choose the electron angle and outgoing proton energy such that $|\mathbf{p}_x| = |\mathbf{q}|$. The vectors $\mathbf{p}_m$ and $\mathbf{q}$ are almost perpendicular.

In the NIKHEF experiment Refs. [24–26] the ^{16}O reduced cross section has been measured in the range $0 \leq \varepsilon_m \leq 40$ MeV and $-180 \leq p_m \leq 270$ MeV/c. The reduced cross sections for removal of nucleons from $1p_{1/2}$ and $1p_{3/2}$ shells in $^{16}\text{O}(e, e'p)^{15}\text{N}$ were measured in quasielastic parallel kinematics at three different beam energies: $\varepsilon_i = 304, 456$, and 521 MeV. In this kinematics, $\mathbf{p}_x$ is parallel or antiparallel to $\mathbf{q}$. The data were obtained by keeping $|\mathbf{p}_x|$ constant and changing the transferred momentum, i.e., by varying the scattering angle of the two detected particles. The total kinetic energy in the center-of-mass system between the outgoing proton and the recoiling ^{15}N nucleus was kept constant at 90 MeV. In Table II of Ref. [25] are listed the relevant kinematic parameters of the

TABLE I. Summary of data for the $^{16}\text{O}(e, e'p)$ reaction. ε_i is the beam energy, ε_f is the central electron energy, θ_e is the central electron angle, T_p is the central proton kinetic energy, θ_p is the central proton angle, and $\Delta\varepsilon_m$ is the range of the missing energy.

Data set	ε_i (MeV)	ε_f (MeV)	θ_e (deg)	T_p (MeV)	θ_p (deg)	$\Delta\varepsilon_m$ (MeV)	Notes
Saclay [23]	500	372	59	102	35–88	10	Perpendicular; 1s is not available
NIKHEF [24,25]	304–521	188–406	29–81	89–99	36–49	40	Parallel; 1s is not available

TABLE II. Table of the experimental cuts that are used in simulation. $\Delta\varepsilon_f$ is the electron energy acceptance, $\Delta\theta_e$ is the electron angle acceptance, ΔT_p is the proton kinetic energy acceptance, $\Delta\phi_p$ is the proton angle acceptance, and $\Delta\phi_e$ is the electron plane angle acceptance.

Data set	$\Delta\varepsilon_f$ (%)	$\Delta\theta_e$ (deg)	ΔT_p (%)	$\Delta\theta_p$ (deg)	$\Delta\phi_e$ (deg)	$\Delta\phi_p$ (deg)
Saclay [23]	[−7, +25]	2	8	2	6	6
NIKHEF [24,25]	[−4, +6]	4	[−5.4, +5]	6	6	6

experiment. The missing momentum is positive for $|\mathbf{q}| < |\mathbf{p}_x|$.

In electron scattering experiments, the lepton and hadron spectrometers are set in-plane, and therefore the out-of-plane angles are fixed to $\phi_e = 0^\circ$ and $\phi_p = 180^\circ$. The sixfold exclusive cross section can be written as [20]

$$\frac{d^6\sigma}{d\varepsilon_\mu d\Omega_\mu dT_p d\Omega_p} = \frac{N_{1\mu 1p}}{N_{\text{tot}}} \frac{\sigma_{\text{tot}}(\varepsilon_\nu)}{\Delta\varepsilon_\mu \Delta T_p \Delta\Omega_\mu \Delta\Omega_p}, \quad (10)$$

where N_{tot} is the total number of generated CCQE neutrino events with a total CCQE cross section $\sigma_{\text{tot}}(\varepsilon_\nu)$ at energy ε_ν . $N_{1\mu 1p}$ is the number of selected $1\mu 1p$ events in the differential phase-space volume bin $\Delta V = \Delta\varepsilon_\mu \Delta T_p \Delta\Omega_\mu \Delta\Omega_p$ with the central values $\varepsilon_\mu, T_p, \Omega_\mu, \Omega_p$ and with size of differential bins $\Delta\varepsilon_\mu, \Delta T_p, \Delta\theta_\mu, \Delta\theta_p, \Delta\phi_\mu, \Delta\phi_p$. The central values and sizes of the differential bins of kinematic variables are given in Tables I and II, respectively, for every dataset that is analyzed in this work.

To transform from measured variables ε_μ and T_p to phase-space (ε_m, p_m) [20]

$$\varepsilon_m = \omega - T_p - \varepsilon_B \quad (11)$$

and

$$p_m = [p_x^2 + k_\nu^2 + k_\mu^2 - 2k_\mu k_\nu \cos \theta_\mu - 2p_x k_\nu \cos \theta_p + 2k_\mu p_x \cos \theta_{\mu p}]^{1/2} \quad (12)$$

we use the formula Ref. [27]

$$\frac{d^6\sigma}{dp_m d\varepsilon_m d\Omega_\mu d\Omega_p} = \frac{d^6\sigma}{d\varepsilon_\mu dT_p d\Omega_\mu d\Omega_p} / J(\theta_p), \quad (13)$$

where the Jacobian $J = \partial(\varepsilon_m, p_m) / \partial(\varepsilon_\mu, T_p)$ is equal to [20]

$$J(\theta_p) = \frac{1}{p_m} (k_\mu - k_\nu \cos \theta_\mu + p_x \cos \theta_{\mu p}) - \frac{\varepsilon_x}{2p_m} \frac{p_x^2 + p_m^2 - |\mathbf{q}|^2}{p_x^2}. \quad (14)$$

and is determined at the bin centers of the kinematic variables. In Eq. (13), $\cos \theta_{\mu p} = \cos(\theta_\mu + \theta_p)$, and we assess positive (negative) values to p_m for the condition $\theta_p < \theta_q$ ($\theta_p > \theta_q$), where $\cos \theta_q = \mathbf{p}_x \cdot \mathbf{q} / (|\mathbf{p}_x| |\mathbf{q}|)$. Then, we can determine the distorted spectral function as

$$S^D(p_m, \varepsilon_m) = \frac{d^6\sigma}{dp_m d\varepsilon_m d\Omega_\mu d\Omega_p} / K^{(el)(cc)} \sigma_{\nu N}, \quad (15)$$

where $K^{(el)(cc)}$ is phase-space factor [20]. All nuclear models which are implemented in the *GENIE* version 3 generator do not take into account the shell structure of ^{16}O and use the nucleon momentum distribution as a function of missing momentum at the fixed value of missing (binding) energy ε_m . Therefore, we can evaluate only

$$\sigma_{\text{red}}(p_m) = \int S^D(p_m, \varepsilon_m) d\varepsilon_m \quad (16)$$

as a function of p_m , integrated over the range $\Delta\varepsilon_m$, that is given in Table I. Then, the reduced cross section can be written as

$$\sigma^{\text{red}}(p_m) = \Delta\varepsilon_m S^D(p_m). \quad (17)$$

We calculate the $\sigma_{\nu N}$ using the same nucleon form factors as in the *GENIE* cross section calculation and the CC1 de Forest prescription [21].

TABLE III. Table of *GENIE* configurations and models of momentum distribution of nucleons, corresponding to these configurations.

<i>GENIE</i> configuration	Nuclear model
G18_02a	Relativistic Fermi gas
G18_10a	Local Fermi gas
G21_11v2	Local Fermi gas
effsf	Effective spectral function

C. *GENIE* simulation framework

The *GENIE* version 3 simulation framework utilizes several different models of nucleon momentum distribution in the nuclear ground state. It also offers several models of quasielastic lepton-nucleus interactions and several intra-nuclear cascade models for FSI. We use *GENIE* version 3.4.0 and consider four distinct sets of *GENIE* models for CCQE scattering on oxygen (see Table III), namely, the G18_2a, G18_10a, G21_11 (SuSAv2), and effsf (effective spectral function) models [28–30]. These models are accompanied by the FSI models hA2018 and hN2018 available in *GENIE* [28] and the hA2018 model [31] is used for each of our four considered CCQE scattering models.

The G18_02a configuration of the *GENIE* relies on implementation of the relativistic Fermi gas model (RFG), which has been modified to incorporate short-range nucleon-nucleon correlations [32]. The CCQE scattering is simulated by the Llewellyn-Smith model [33]. The G18_10a model set includes the full Valencia model [34–36] for the local Fermi gas (LFG) nucleon momentum distribution. It also utilizes the random phase approximation (RPA) which is a description of long-range and short-range NN correlations.

The G21_11 (SuSAv2) model [37] is based on a super-scaling model that accurately describes QE inclusive

scattering on a variety of targets ($A \geq 10$) for a wide range of electron energies. The version *GENIE* v3 describes struck nucleon momenta with a mean-field model (similar to LFG) at low momentum transfer and with a relativistic Fermi gas at high momentum transfer. To describe the outgoing nucleon kinematics the LFG nuclear model is used. The effective spectral function (effsf) model with or without enhancement of the transverse contribution [38,39] is implemented in *GENIE* as the option EffectiveSF.

The bound nucleon momentum distributions in oxygen for the genuine CCQE events produced using the *GENIE* and the RFG, LFG, and effsf representations of the target nucleus are shown in Fig. 1. It is clearly visible that in the range $150 \leq p_m \leq 220$ ($p_m \leq 50$) (MeV/c) the probability density function (PDF) dP/dp_m calculated with the RFG is much larger (smaller) than the PDFs used in the other models, and correlation tails are observed in the RFG and effsf distributions. The missing energy $E_{mis} = \varepsilon_\nu - \varepsilon_\mu - T_p$ distribution for two sets of events in which neutrino knocks out a proton, calculated with neutrino energy $\varepsilon_\nu = 0.5$ GeV using four *GENIE* models is shown in Fig. 2. The first set contains events with a muon and only one proton ($1p + 0n$) in the final state. Such events are selected in electron scattering experiments ($e, e'p$), where events with one or more low energy neutrons are only excluded through kinematic cuts. The events from ($1p + 0n$) set are used to measure reduced cross sections. The second set contains events with a muon, one proton, and at least one neutron ($1p + Nn$) in the final state. This set also includes the events in which a knocked out protons produce neutrons in inelastic interactions with the residual nucleus, i.e., events with large missing energy. In neutrino experiments these two sets of events are not distinguished, because the incident neutrino energy is unknown. For all models (except G21_11 model), the maximum of distribution is located in the range $E_m \leq 40$ MeV. For the

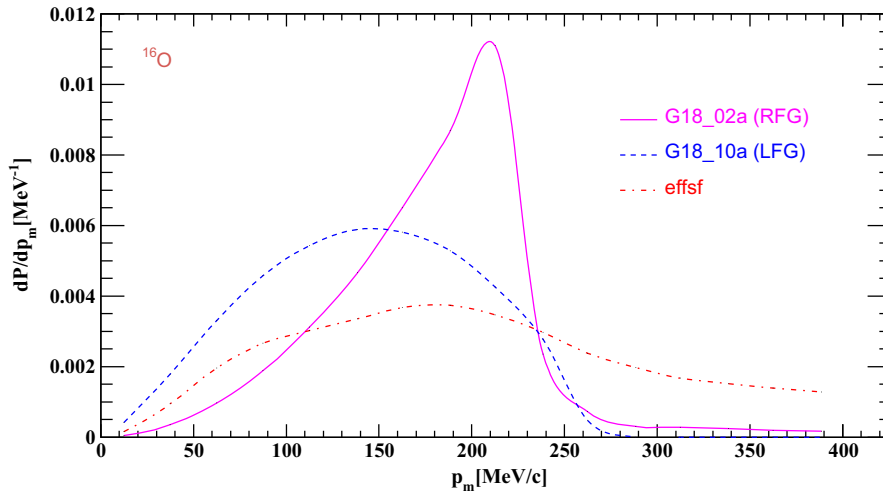


FIG. 1. Initial nucleon momentum distribution for ^{16}O according to the *GENIE* implementation of G18_02a (FG, solid line), G18_10a (LFG, dashed line), and effsf (dot-dashed) models.

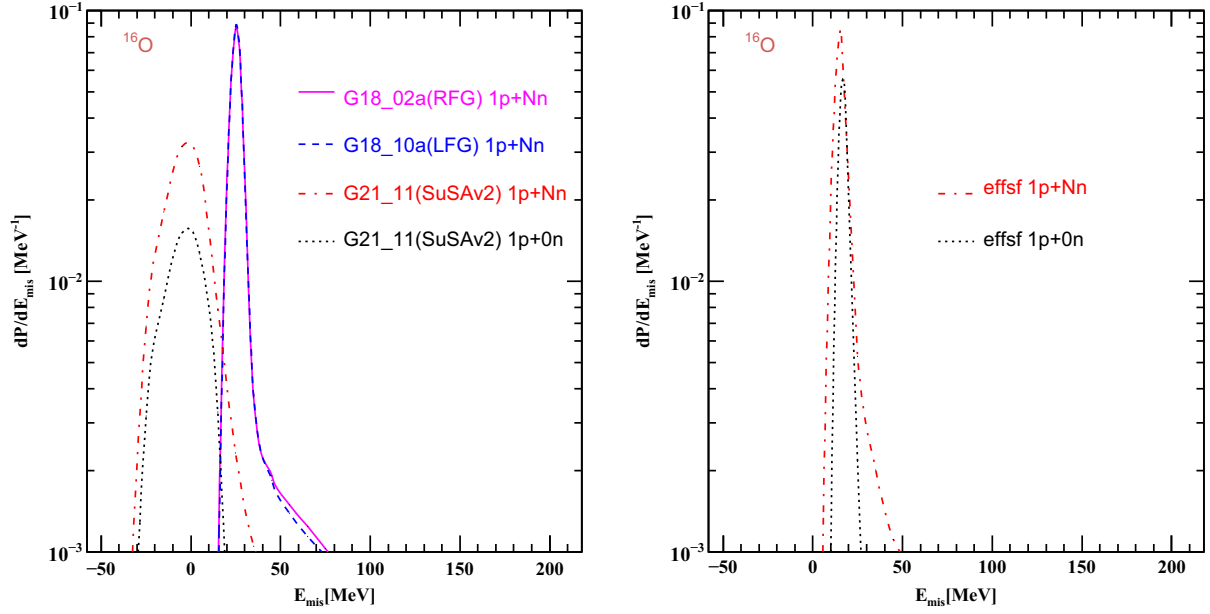


FIG. 2. Probability density distribution vs missing energy E_{mis} calculated for neutrino energy $\varepsilon_\nu = 0.5$ GeV. Left panel: PDF for $(1p+Nn)$ events calculated with the G18_02a (solid line), G18_10a (dashed line), and G21_11 (dot-dashed line) models and for $(1p+0n)$ events calculated within the G21_11 (dotted line) model. Right panel: PDF for the $(1p+0n)$ set calculated with the effsf (dotted line) model and PDF for the $(1p+Nn)$ set calculated within the effsf (dot-dashed line) models.

G18_02a and G18_10a models, the distributions of events in the $(1p+0n)$ set have narrow peak in the range $20 \leq E_m \leq 30$ MeV. The inelastic scattering changes the energy of the knocked-out protons significantly, and therefore the distributions of events in the $(1p+Nn)$ set are extend into the higher missing region.

III. RESULTS AND ANALYSIS

In Saclay and NIKHEF experiments the reduced cross sections were measured as a function of missing momentum for the removal of a proton from $1p_{1/2}$ and $1p_{3/2}$ shells of ^{16}O which correspond to the intervals of missing energy $\varepsilon_m = 10\text{--}15$ MeV and $15\text{--}20$ MeV, respectively. The models which are used in the *GENIE* generator to calculate the reduced cross sections do not take into account the shell structure of the ^{16}O nucleus. Therefore we cannot calculate the reduced cross sections for the removal of nucleons separately from the $1s$ and $1p$ shells.

The reduced exclusive cross sections for the removal of nucleons from $1p_{1/2}$ and $1p_{3/2}$ shells in $^{16}\text{O}(e, e'p)^{15}\text{N}$, $^{16}\text{O}(\nu, \mu^- p)^{15}\text{O}$, and $^{16}\text{O}(\bar{\nu}, \mu^+ n)^{15}\text{N}$ reactions calculated within the RDWIA [14] are shown in Fig. 3 together with Saclay data. The cross sections were calculated using the Saclay kinematic conditions with the normalization factors of data examined presented in Ref. [40]. The small difference between neutrino and antineutrino reduced cross sections for the removal of nucleons from $1p_{1/2}$ and $1p_{3/2}$ states is due to different nucleon's binding energies, that are higher for neutrons, and nucleon momentum distributions for these shells. The FSI effects are also

different between the cross sections due to interaction of the outgoing nucleons with different residual nuclei $p + ^{15}\text{O}$ for neutrino and $n + ^{15}\text{N}$ for antineutrino scattering off ^{16}O and Coulomb interaction of the knocked out protons. Moreover, the $1p_{1/2}$ orbit has spatial characteristics which are different from the $1p_{3/2}$ orbit. The RDWIA model predicts a stronger attenuation for proton emission

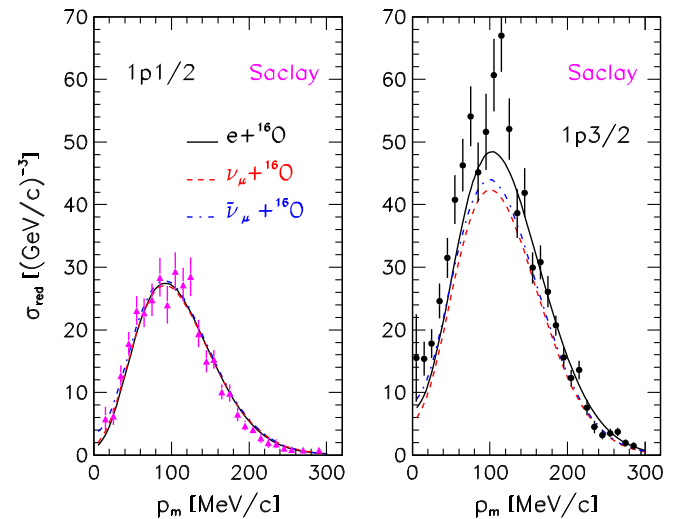


FIG. 3. Comparison of the RDWIA electron, neutrino, and antineutrino reduced cross sections [14] for the removal of nucleons from $1p_{1/2}$ and $1p_{3/2}$ shells of oxygen for Saclay [23] perpendicular kinematics. Saclay data for beam energy $E_{\text{beam}} = 500$ MeV, proton kinetic energy $T_p = 100$ MeV and $Q^2 = 0.3$ GeV².

from a level which has a larger fraction of its density in the nuclear interior [20]. The reduced cross sections for the removal of protons from the $1p = 1p_{1/2} + 1p_{3/2}$ shell in $^{16}\text{O}(e, e'p)^{15}\text{N}$ reaction together with Saclay data are shown in Fig. 4. Also shown are the reduced cross section calculated in the perpendicular Saclay kinematics for the knock out of protons from $1s$ ($\sigma_{\text{red}}(1s)$) and $1s + 1p$ [$\sigma_{\text{red}}(1p + 1s)$] shells in the $^{16}\text{O}(e, e'p)^{15}\text{N}$ reaction, and a ratio $R_{1p} = \sigma_{\text{red}}(1p)/\sigma_{\text{red}}(1p + 1s)$ as functions of missing momentum p_m . The contribution of the $1p$ shell to the reduced cross section calculated with the *GENIE* models can be evaluated using this ratio as

$$\sigma_{\text{red}}^{MC}(1p) = R_{1p} \cdot \sigma_{\text{red}}^{MC}(1p + 1s), \quad (18)$$

where $\sigma_{\text{red}}^{MC}(1p + 1s)$ is determined by Eq. (17). In the following, we compare $\sigma_{\text{red}}^{MC}(1p)$ with the measured reduced cross sections.

The reduced cross sections together with NIKHEF data are shown in Fig. 5. The cross sections were calculated using the normalization factors for the data examined in Ref. [40]. The reduced cross sections for the knock out of protons from the $1p = 1p_{1/2} + 1p_{3/2}$ shell calculated in the parallel NIKHEF kinematics together with data are

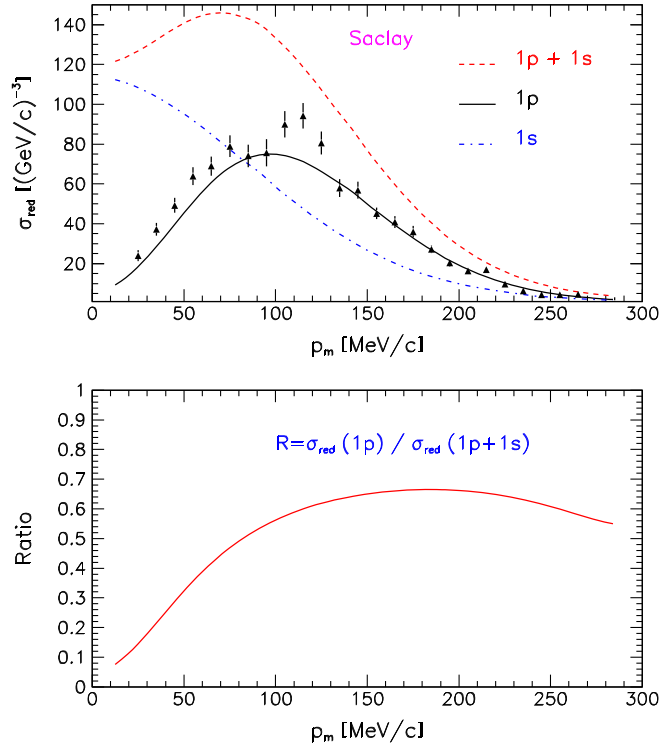


FIG. 4. The RDWIA electron reduced cross section [14] for the removal of protons from $1s$, $1p$, and $1s + 1p$ shells of ^{16}O for Saclay kinematics (upper panel) and ratio R_{1p} (lower panel) as functions of missing momentum. Also shown (upper panel) are Saclay data for the removal of protons from $1p = 1p_{1/2} + 1p_{3/2}$ shell.

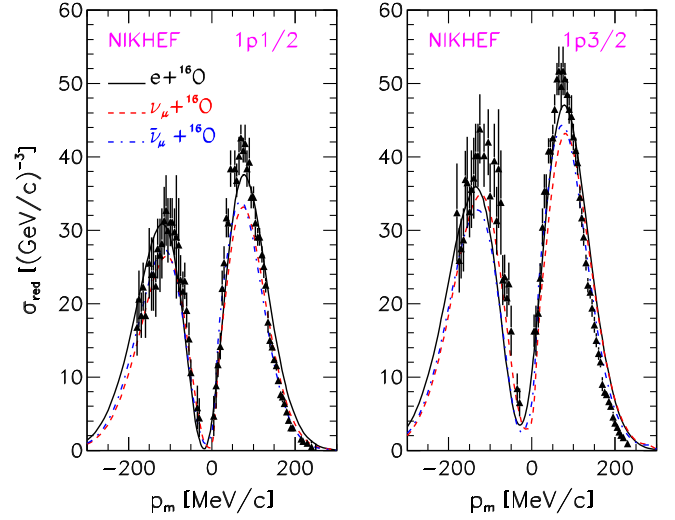


FIG. 5. The RDWIA calculation of electron, neutrino, and antineutrino reduced cross sections [14] for the removal of nucleons from $1p_{1/2}$ and $1p_{3/2}$ shells of ^{16}O for NIKHEF parallel kinematics [24,25] as function of p_m . NIKHEF data for beam energy $E_{\text{beam}} = 304\text{--}521$ MeV, proton kinetic energy $T_p = 89\text{--}99$ MeV and Q^2 is varied.

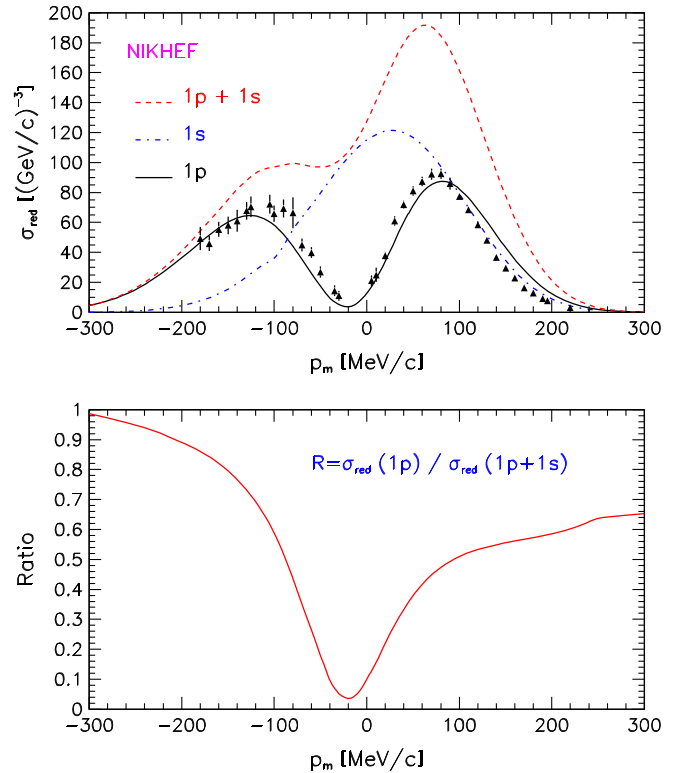


FIG. 6. The RDWIA electron reduced cross section [14] for the removal of protons from $1s$, $1p$, and $1s + 1p$ shells of ^{16}O for NIKHEF kinematics (upper panel) and ratio R_{1p} (lower panel) as functions of missing momentum. Also shown (upper panel) are Saclay data for the removal of protons from $1p = 1p_{1/2} + 1p_{3/2}$ shell.

shown in Fig. 6. Also shown in this figure is the ratio R_{1p} as a function of missing momentum. This ratio is minimal at $p_m = 0$, where the contribution to the reduced cross section by removal nucleons from 1s shell is dominant and increases with missing momentum up to 0.6–0.7 at $p_m = 150$ MeV/c. This range corresponds to the knock out of nucleons from 1p shell where the reduced cross sections measured at Saclay and NIKHEF kinematics reach maximum value of about 80 (GeV/c)³. There is an overall good agreement between calculated cross sections, but the value of electron cross sections at maximum is systematically higher (less than 10%) than (anti)neutrino ones with the exception of the $1p_{1/2}$ state for Saclay kinematics. The small difference between neutrino and antineutrino reduced cross sections is due to the difference in the FSI of protons and neutrons with residual nucleus.

For each model considered we generated 10^8 CCQE neutrino events. The *GENIE* results are presented only with statistical errors. The reduced cross sections calculated with the *GENIE* G18_02a model that uses the RFG nucleon momentum distribution are shown in Fig. 7 together with Saclay [23] and NUKHEF [24–26] data. The cross sections were calculated using the kinematic conditions of the data examined that is presented in Tables I and II. At $|p_m| \leq 100$ MeV/c the values of the calculated cross sections are in agreement with the data and at higher missing momentum the calculated σ_{red} overestimates the measured ones significantly. This excess increases with missing momentum because of the uniform momentum distribution of the Fermi gas model. In Fig. 8 the comparison with data of the reduced cross sections calculated with the *GENIE* G18_10a

model are presented. We observe agreement between *GENIE* predictions and Saclay data at $|p_m| \geq 120$ MeV/c. At low missing momentum the calculation overestimates data significantly. On the other hand, the σ_{red} calculated within this *GENIE* model for NIKHEF parallel kinematics overestimates the measured electron scattering data in the range of $|p_m| \geq 50$ MeV/c. At $|p_m| \approx 100$ MeV/c where the maximum of the reduced cross section is observed the excess reaches up to 300%. Figure 9 shows the reduced cross sections calculated with the *GENIE* G21_11 model where the LFG nucleon momentum distribution is used. The σ_{red} calculated with this model for Saclay kinematics overestimates significantly measured cross sections at $p_m \leq 100$ MeV/c and underestimates the data in the range of $p_m \geq 150$ MeV/c. At NIKHEF kinematics the issue visible at $p_m \geq 150$ MeV/c resemble those for the G18_10a model seen in Fig. 8, but the excess is significant only in the range of $p_m \leq -100$ MeV/c. Approximately the same features are observed in Fig. 10, where the comparison with data of the reduced cross sections calculated with the *GENIE* effsf model is presented. The calculated cross sections overestimate the measured one at Saclay less than 60% at $p_m \leq 100$ MeV/c. The difference between the reduced cross sections calculated and measured at NIKHEF kinematics is significant at $|p_m| \geq 100$ MeV/c.

So, at Saclay perpendicular kinematics the agreement of the *GENIE* calculated reduced cross sections with data for neutrino scattering off oxygen and carbon [17] is approximately the same. For models considered (except the RFG), the issues are similar: the calculations overestimate data significantly at low missing momenta and underestimate

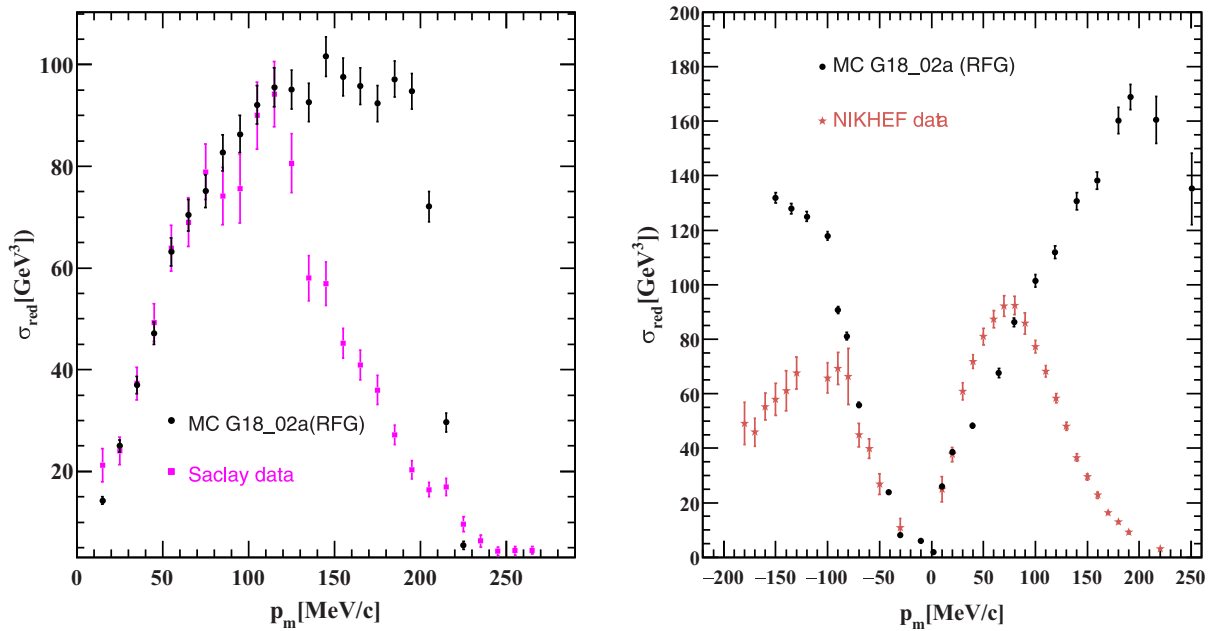
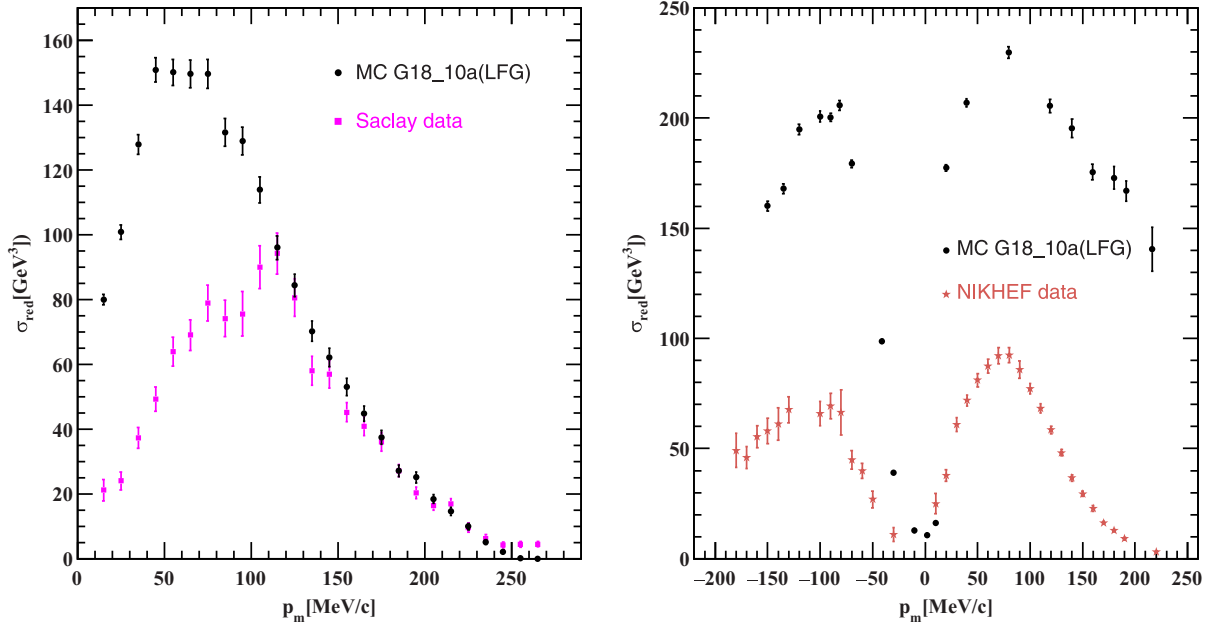
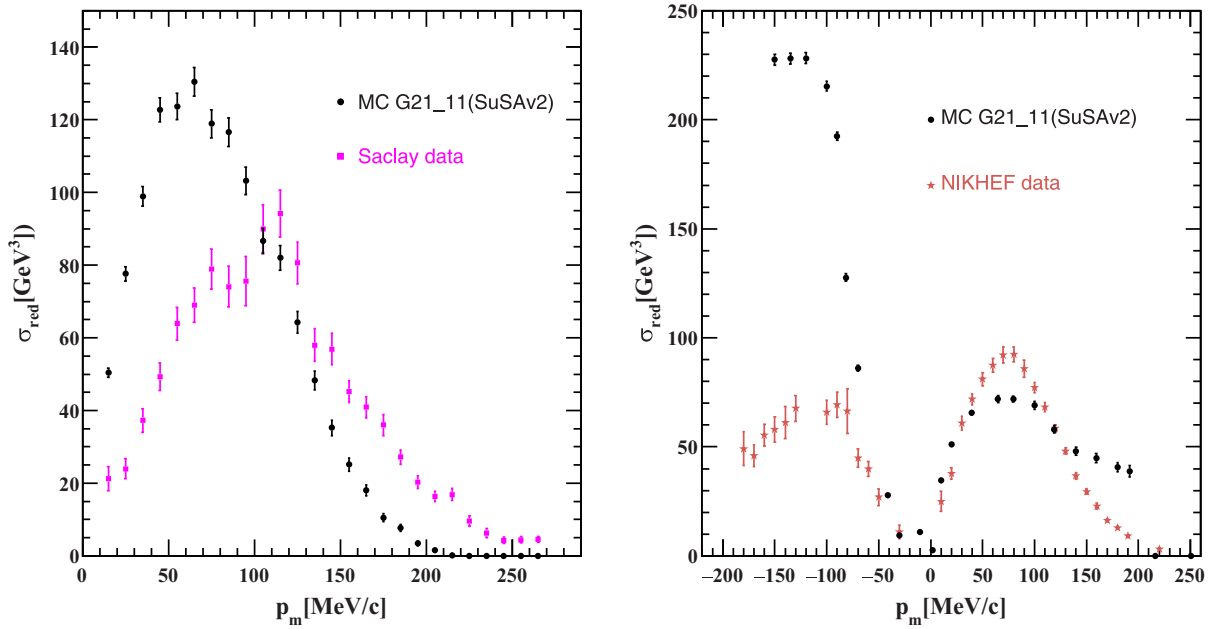
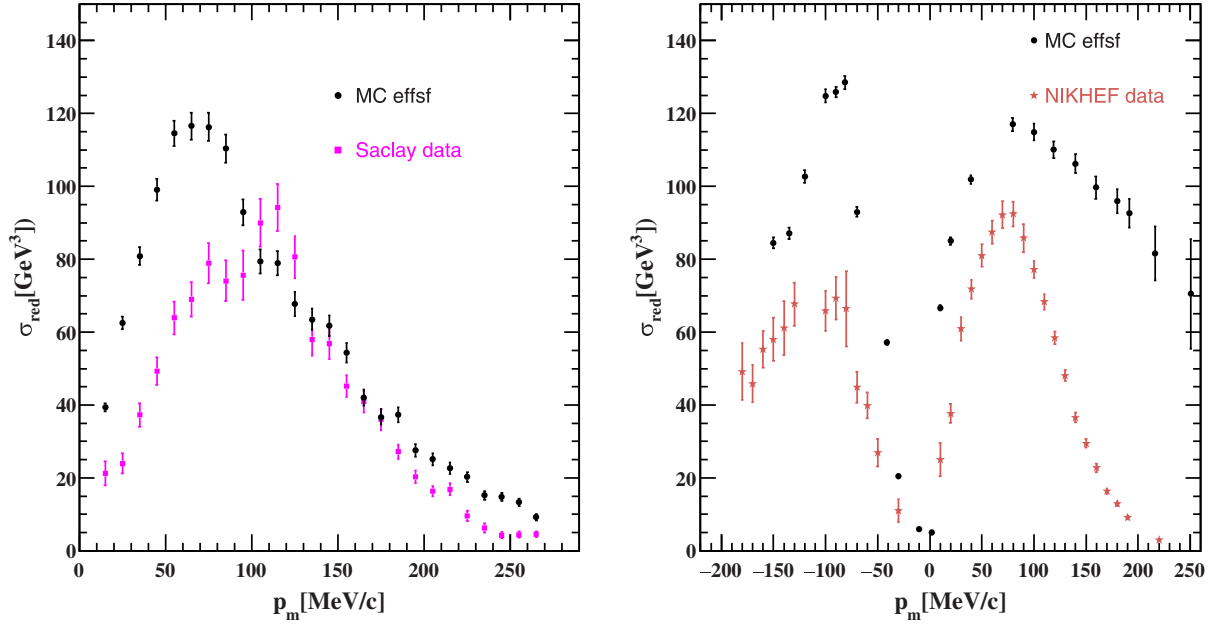


FIG. 7. Comparison of the *GENIE* G18_02a (RFG) model calculation reduced cross sections with data as functions of missing momentum. As shown in key, cross sections were calculated for Saclay [23] and NIKHEF [24,25] kinematics.

FIG. 8. Same as Fig. 7 but for the *GENIE* G18_10a (LFG) model calculation.FIG. 9. Same as Fig. 7 but for the *GENIE* G21_11 (SuSAv2) model calculation.

them slightly (except SuSAv2 model) at $p_m \geq 100$ MeV/c. The σ_{red} calculated at NIKHEF parallel kinematics demonstrates absolutely different behavior (except the RFG model) than measured ones. We observe persistent disagreement between the *GENIE* predictions of the reduced cross sections and electron scattering data at low beam energy. On the other hand, there is a good agreement

between the RDWIA calculated and measured cross sections and this approach can be used to model both lepton-boson and boson-nucleus vertices [41]. It is obvious that this model describes the semiexclusive ($l, l'p$) lepton scattering process better than the phenomenological models employed in the *GENIE* simulation framework.

FIG. 10. Same as Fig. 7 but for the *GENIE* effsf model calculation.

IV. CONCLUSIONS

In this article, we carried out a systematic comparison of the CCQE reduced cross sections calculated with models employed in the *GENIE* version 3 simulation framework with data measured in electrons scattering off the oxygen target. The reduced cross sections as functions of missing momentum were measured only for the removal of protons from $1p$ shells of ^{16}O as a whole, i.e., from the $1p + 1s$ shells. The reduced cross sections for the removal of proton from the $1p$ shells calculated with the *GENIE* models were evaluated using the relative contribution of the $1p$ shells R_{1p} predicted within the RDWIA model at Saclay and NIKHEF kinematics. We have observed persistent disagreement between the *GENIE* predictions and electron scattering data for the reduced cross sections. The σ_{red} calculated at NIKHEF parallel kinematics demonstrates absolutely different behavior than the measured ones. At Saclay perpendicular kinematics the agreement with data of the reduced cross sections calculated within the *GENIE* v.3 simulation framework for neutrino scattering on oxygen and carbon targets is

similar: the calculations overestimate the data at low missing momenta and underestimate the data at $p_m \geq 100$ MeV/c. Therefore, the *GENIE* event generator cannot simulate well two tracks CCQE events in the all allowed kinematic region. Neutrino event generators need to use more sophisticated models to simulate CCQE semexclusive processes. The direct comparison of spectral functions, implemented in neutrino event generators, with the precise electron reduced cross section data is an original and promising method for testing the quality of nuclear physics models implemented in Monte Carlo generators for neutrino interaction.

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DATA AVAILABILITY

The data that support the findings of the article are openly available [23–25].

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