

Theoretical modeling of charged current $\nu_\mu(\bar{\nu}_\mu) - {}^{40}\text{Ar}$ DIS at DUNE energies

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The charged current $\nu_\mu(\bar{\nu}_\mu)$ -induced deep inelastic scattering (DIS) from an ${}^{40}\text{Ar}$ target is studied using a microscopic framework that incorporates nuclear medium effects due to Fermi motion, binding energy, nucleon correlations, mesonic (π and ρ) contributions, and nuclear shadowing and antishadowing across the relevant Bjorken- x region. The nuclear structure functions $F_{iA}(x, Q^2)$ ($i = 1 - 3$) are evaluated using a relativistic nucleon spectral function (S_h) within the local density approximation employing the free nucleon structure functions, $F_{iN}(x, Q^2)$ ($i = 1 - 3$). These $F_{iN}(x, Q^2)$ ($i = 1 - 3$) are calculated using the parton distribution functions from the MMHT 2014 parametrization, including higher-order perturbative QCD corrections up to the next-to-next-to-leading order, along with the nonperturbative target mass corrections. The resulting nuclear structure functions $F_{iA}(x, Q^2)$ ($i = 1 - 3$) are subsequently used to compute the differential DIS cross sections for the ${}^{40}\text{Ar}$ nucleus. Numerical results are presented for $\nu_\mu(\bar{\nu}_\mu)$ beam energies $E = 4$ GeV and $E = 6$ GeV for the differential scattering cross sections $\frac{d^2\sigma}{dx dy}$ and $\frac{d\sigma}{dx}$, relevant to the ongoing and upcoming liquid-argon neutrino experiments such as DUNE and the Fermilab short-baseline neutrino program.

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I. INTRODUCTION

The study of (anti)neutrino interaction cross sections off free nucleons as well as nucleons bound inside a nuclear target is required to be carried out with a better theoretical understanding and improved statistics in the experimental measurements in order to minimize the present uncertainties in the extraction of the oscillation parameters, viz., the mixing angles θ_{12} , θ_{23} , θ_{13} ; the Dirac CP -violating phase δ_{CP} ; the mass-squared differences Δm_{21}^2 and $|\Delta m_{31}^2|$; etc., to a few percentage level, and to resolve the neutrino mass hierarchy problem. Since the (anti)neutrino-nucleon/nucleus cross sections are small, neutrino experiments in general require large-volume detectors filled with medium-to-heavy nuclear targets such as carbon, oxygen, argon, iron, and lead. For example, the next-generation experiments such as the deep underground neutrino experiment (DUNE) at Fermilab in the USA [1,2] and the Hyper-Kamiokande (HyperK) in Japan [3] which are designed to measure the CP -violating phase δ_{CP} in the leptonic sector, the neutrino mass hierarchy, matter-antimatter asymmetry,

etc., with enhanced precision. These neutrino experiments are planned with different nuclear targets, such as the multikiloton liquid-argon time projection chambers (LArTPCs) in DUNE ($\langle E \rangle = 2.5\text{--}3$ GeV) and 260,000 metric tons of ultrapure water in HyperK ($\langle E \rangle = 0.6$ GeV), and focus specifically on understanding the (anti)neutrino-nucleus cross sections in the few GeV energy region, which is sensitive to some of the oscillation parameters. Moreover, the short-baseline neutrino program—comprising ICARUS [4,5], SBND [6,7], and MicroBooNE [8] experiments—employs LArTPC technology to perform high-resolution measurements of neutrino-argon interaction cross sections in the few-GeV energy regime. Hence, the understanding of (anti)neutrino-nucleus interactions in this energy region is important in order to interpret the presently available and the upcoming data from the aforementioned experiments.

In the few-GeV energy region, the (anti)neutrino-nucleon scattering cross sections receive contributions from the quasielastic, inelastic, and deep inelastic scattering (DIS) processes, and provide an important probe of nucleon structure over a wide range of four momentum transfer square Q^2 and the invariant hadronic mass W . The (anti)neutrino-nucleon cross sections for the inelastic scattering are generally described in terms of the cross sections arising due to the resonant ($P_{33}(1232)$, $P_{11}(1440)$, $S_{11}(1535)$, etc.) production amplitude, nonresonant production amplitude, and interference between them. In this resonance region, $\nu_l(\bar{\nu}_l)$; $l = e, \mu$ interactions with the nucleon target produce

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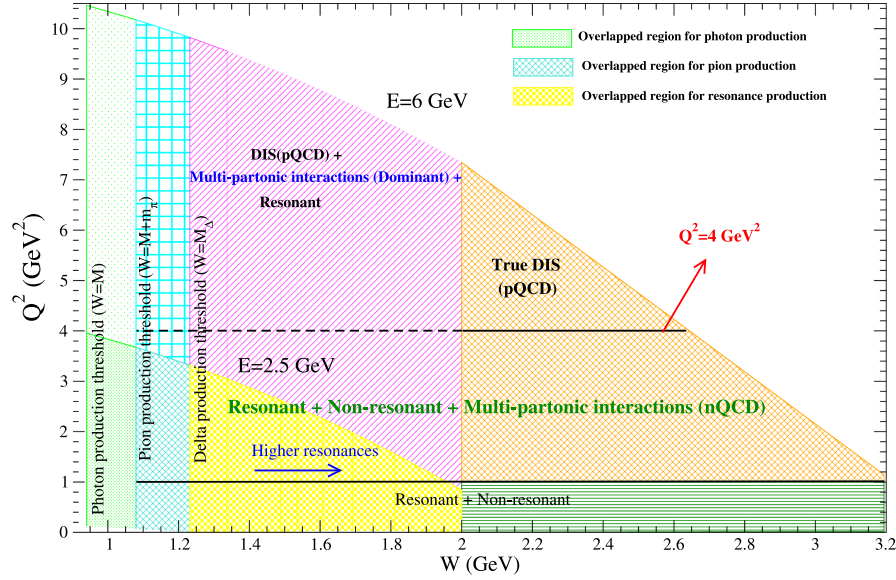


FIG. 1. The W - Q^2 plane showing the indicative kinematic boundaries for the various possible processes at the different neutrino energies, viz., $E = 2.5$ GeV and $E = 6$ GeV [17].

various final states with mesons like πN , $\pi\pi N$, ηN , ΛK , etc. states. In the case of resonance production, the vector form factors, for the $N \rightarrow R$ transition are used which are derived using helicity amplitudes, determined from the real and/or virtual photon scattering experiments [9]. However, for the $N \rightarrow R$ axial-vector transition form factors, the available information is very limited except for the $\Delta(1232)$ for which there are different parametrizations. It has been strongly felt that precise $\nu(\bar{\nu}) - N$ scattering cross sections in the Δ -resonance region is required. The description of (anti)neutrino-nucleon scattering in this kinematic region becomes progressively uncertain at higher invariant masses, where several overlapping resonances contribute and experimental constraints on the transition form factors for the $N \rightarrow R$ transitions remain limited.

In the region of high Q^2 and W , the dominant contribution to the scattering cross sections arises from the DIS process, where the interaction is described in terms of the incoherent scattering of (anti)neutrinos from partonic constituents of the nucleon. In this regime, perturbative QCD (pQCD) offers a well established theoretical framework, in which the structure functions are expressed in terms of the parton distribution functions (PDFs). However, of the current generation of (anti)neutrino experiments which are using (anti)neutrino beams in the region of a few GeV energies like NO ν A [10,11], MINER ν A [12,13], ArgoNeuT [14,15], etc., and the next generation experiments like DUNE and HyperK, etc., most of the events do not lie inside the strict kinematic domain of the applicability of the pQCD. Particularly, the kinematic region of moderate W , i.e., $W \lesssim 2$ GeV and $Q^2 \lesssim 2$ GeV² is important, as it lies in the transition region between the resonance production and the deep inelastic scattering. In this domain of Q^2 and W , nonperturbative quantum chromodynamics

(QCD) effects like the target mass corrections, higher twist effects, multiparton correlations, etc., become important. Owing to the lack of a comprehensive theoretical framework for describing the resonance to DIS transition region, it has become common in phenomenological studies to extend DIS-based prescriptions to include regions of lower values of Q^2 and W . This provides a practical and consistent description of inclusive cross sections across a broad kinematical range. Nevertheless, one must exercise caution when extrapolating the DIS description to low Q^2 and W . In this context, kinematical constraints on W become important; for example, cuts such as $W \geq 1.7$ GeV or $W \geq 2$ GeV are applied to exclude the regions that are theoretically understood to be dominated by contributions from the excitation of higher resonances [9,16].

In Fig. 1, we have indicated the kinematically allowed regions in the W - Q^2 plane for the resonant, nonresonant, and deep inelastic scattering processes. We broadly classify the interactions into the traditional DIS and the shallow inelastic scattering (SIS) regions. It is important to point out that the direct meson production in the nonresonant region and the meson production through quark-quark interactions (not describable by the perturbative QCD) at energies lower than the SIS region intermix with the resonant meson production, and there is no practical way to separate experimentally, individual events that include mesons produced by these processes. Therefore, in practice, it is difficult to experimentally have a well-defined SIS region, clearly separated from the perturbative DIS region or the resonance region. The physics of this complex region has to be understood better, both theoretically and experimentally. The current neutrino experimental community often takes $Q^2 \geq 1$ GeV² and $W \geq 2$ GeV to define the “DIS” region [12]. These limits on Q^2 and W are below the conventional

limits, generally taken for defining a clean DIS region to be described by the perturbative QCD. This phenomenological separation of events between the DIS and SIS reflects distinct theoretical and experimental challenges. Both kinematic regions are highly relevant for DUNE, where more than 50% of events are expected to originate from the kinematic region of higher resonance excitations and DIS [1,2].

In oscillation experiments, the mismodeling of the interaction cross sections in the transition region directly impacts the neutrino energy reconstruction and contributes substantially to the systematic uncertainties. Reducing these uncertainties is essential for achieving the precision goals of DUNE, particularly in the measurements of δ_{CP} and the neutrino mass ordering.

To date, substantial effort has been devoted to improving the neutrino event generators, which are indispensable tools for the experimental analyses and serve as a bridge between the theoretical and experimental sectors. Presently, GENIE MC [18] is the most widely used neutrino event generator, which employs leading-order (LO) parton model cross sections with phenomenological corrections, based on the Bodek-Yang model [19] for obtaining the DIS cross sections. The transition region is handled through empirical prescriptions in the invariant mass W with several limitations, as discussed in Ref. [16]. In the kinematic region of low-to-moderate Q^2 and high x , the separation between the DIS and non-DIS processes becomes blurred, and the partonic descriptions must be supplemented by nonperturbative corrections. These effects are particularly relevant for DUNE, where a substantial fraction of events populate the kinematic region of non-DIS events. Therefore, a better theoretical understanding of the (anti)neutrino-nucleon/nucleus deep inelastic scattering cross sections, and their modifications in the presence of higher order perturbative and nonperturbative QCD corrections, the nuclear medium effects as well as the kinematic phase-space constraints such as a cut on the hadronic invariant mass (center-of-mass energy) W and the four momentum transfer square (Q^2), is required. In the electromagnetic sector, the importance of nuclear medium effects in the DIS region was clearly established by the European Muon Collaboration (EMC) [20] at CERN. It was observed that the ratio of the nucleon structure functions for iron to deuterium, $\frac{F_2^N(\text{Fe})}{F_2^N(\text{D})} \neq 1$. This is known in the literature as the EMC effect. Subsequently, in many more experiments at SLAC, CERN, and FNAL, similar observations were made using different nuclear targets [21,22]. These nuclear medium effects exhibit a clear dependence on Bjorken x . At large x ($\gtrsim 0.7$), they are predominantly governed by Fermi motion; in the intermediate region $0.3 \leq x \leq 0.7$, they arise from nucleon-nucleon correlations and mesonic contributions, collectively known as the EMC effect, while at low x , they are driven by coherent nuclear phenomena, namely shadowing ($x \leq 0.1$) and antishadowing ($0.1 \leq x \leq 0.3$). In

(anti)neutrino-nucleus scattering, however, the interaction involves not only a vector component but also an axial-vector contribution, implying that the corresponding nuclear medium effects need not be identical in the two cases. Therefore, an independent understanding of nuclear medium effects in the weak sector for deep inelastic scattering processes is required. At present, it is recognized that insufficient understanding of these effects leads to approximately 25% uncertainty in the (anti)neutrino-nucleus cross sections, contributing significantly to systematic errors. Hence, for improved precision in the measurement of (anti)neutrino-nucleus interaction cross sections—relevant for the determination of oscillation parameters, the extraction of nuclear structure functions in the electroweak sector, and other related observables—it is essential to achieve a better understanding of the nuclear medium effects, particularly in the low-to-moderate Q^2 region (1–5 GeV²).

In the literature, various phenomenological groups [23–28] have proposed nuclear parton distribution functions which may provide direct information about the nuclear modifications of the nucleon structure functions and the scattering cross sections. These nuclear parton distribution are obtained by applying nuclear correction factors to the free-nucleon PDFs while analyzing the experimental data from charged-lepton DIS, Drell-Yan production in proton-nucleus collisions, and high-energy collider data from the proton-nucleus and nucleus-nucleus collisions. The global fitting groups such as those led by Hirai *et al.* [23], Eskola *et al.* [24], and de Florian-Sassot [25], have included a wide range of charged-lepton and hadronic data in their analysis, often assuming that the same nuclear correction factors apply to both the electromagnetic and the weak DIS processes. In contrast, the nCTEQ Collaboration [26,28] has performed dedicated fits to neutrino-nucleus DIS data, extracting nuclear PDFs directly without relying solely on the constraints from the analysis of charged-lepton DIS data. Their analyses indicate potential differences between nuclear modifications in the electromagnetic and the weak structure functions, particularly in the low- x region. This tension remains an open issue, underscoring the need for high-precision data as well as the need for developing a better theoretical understanding of the neutrino-nucleus DIS process [16].

In the present work, we have studied the effects of various nuclear medium effects on the (anti)neutrino-argon DIS cross sections, such as the Fermi motion, the binding energy, and the nucleon correlations. The nuclear medium effects are incorporated through the use of a spectral function of the nucleon in the nuclear medium [29,30]. The effect of mesonic contribution has been included which is found to be significant in the low and intermediate region of x [29]. We have also included the effect of the shadowing and antishadowing corrections following the works of Kulagin and Petti [31]. Moreover, we have discussed the effect of a cut on the center of mass energy on the

differential scattering cross sections. The nucleon structure functions which are used as an input to evaluate the nuclear structure functions required to determine the (anti)neutrino-nucleus differential cross sections are evaluated by using the Martin-Motylinski-Harland-Lang-Thorne (MMHT) parametrization of PDFs [32] up to the next-to-next-to-leading order (NNLO) in the four flavor (u , d , s , and c) modified minimal subtraction (MSbar) scheme following Ref. [33–35]. The target mass correction (TMC) is included following the work of Schienbein *et al.* [36].

In Sec. II, we present the formalism in brief for describing the charged current induced (anti)neutrino-nucleon DIS process, followed by the (anti)neutrino-nucleus DIS process. In Sec. III, the numerical results for the double and single differential scattering cross sections are presented and discussed. In the last section, Sec. IV, we summarize our findings.

II. DEEP INELASTIC SCATTERING OF (ANTI) NEUTRINO FROM NUCLEON (N)/NUCLEI (A)

A. $\nu_\mu/\bar{\nu}_\mu - N$ DIS

For the charged current (anti)neutrino deep inelastic scattering off a free nucleon target (depicted in Fig. 2),

$$\nu_\mu(k)/\bar{\nu}_\mu(k) + N(p) \rightarrow \mu^-(k')/\mu^+(k') + X(p'), \quad (1)$$

the invariant matrix element is given by

$$-i\mathcal{M} = \frac{iG_F}{\sqrt{2}} l_\mu \left(\frac{M_W^2}{q^2 - M_W^2} \right) \langle X | J^\mu | N \rangle, \quad (2)$$

where $k(k')$ are the four momenta of incoming(outgoing) lepton, and p and p' are the four momenta of the target nucleon and the jet of hadrons produced in the final state, respectively. G_F is the Fermi coupling constant, M_W is the mass of the W boson, and $q^2 = (k - k')^2 = -Q^2$ ($Q^2 \geq 0$) is the four momentum transfer square. l_μ is the leptonic current and $\langle X | J^\mu | N \rangle$ is the hadronic current for the (anti) neutrino induced reaction. The differential scattering cross section corresponding to the reaction given in Eq. (1) in the lab frame is expressed as [37]

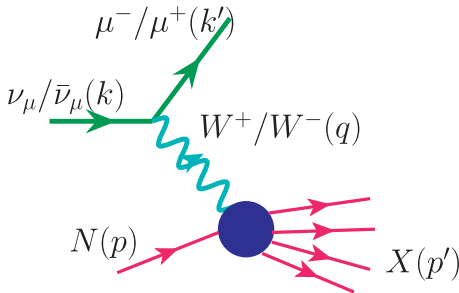


FIG. 2. Feynman diagram representing the deep inelastic scattering induced by the $\nu_\mu/\bar{\nu}_\mu - N$ interaction processes.

$$\frac{d^2\sigma_N}{dx dy} = \frac{yM_N E}{\pi E'} \frac{|\mathbf{k}'|}{|\mathbf{k}|} \overline{\sum} \sum |\mathcal{M}|^2, \quad (3)$$

where $x = \frac{Q^2}{2M_N \nu}$ is the Bjorken scaling variable, $y = \frac{p \cdot q}{p \cdot k} (= \frac{\nu}{E}$ in the lab frame) is the inelasticity, $\nu = E - E'$ is the energy transfer, M_N is the nucleon mass, and $E(E')$ is the energy of the incoming(outgoing) lepton. The invariant matrix element square $\overline{\sum} \sum |\mathcal{M}|^2$ is given in terms of the leptonic ($L_{\mu\nu}$) and hadronic ($W_N^{\mu\nu}$) tensors as

$$\overline{\sum} \sum |\mathcal{M}|^2 = \frac{G_F^2}{2} \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2 L_{\mu\nu} W_N^{\mu\nu}. \quad (4)$$

The leptonic tensor $L_{\mu\nu}$ is given by

$$L_{\mu\nu} = 8 \underbrace{(k_\mu k'_\nu + k_\nu k'_\mu - k \cdot k' g_{\mu\nu})}_{\text{symmetric}} \pm \underbrace{i\epsilon_{\mu\nu\rho\sigma} k^\rho k'^\sigma}_{\text{antisymmetric}}, \quad (5)$$

which consists of both the symmetric and antisymmetric terms arising due to the contribution from the vector and the axial-vector components. In the antisymmetric term the “+” sign corresponds to the antineutrino case and the “−” sign is for the neutrino case.

The nucleon hadronic tensor $W_N^{\mu\nu}$ is expressed in terms of the nucleon structure functions $W_{iN}(\nu, Q^2)$; ($i = 1-5$) as [37]

$$\begin{aligned} W_N^{\mu\nu} = & \left(\frac{q^\mu q^\nu}{q^2} - g^{\mu\nu} \right) W_{1N}(\nu, Q^2) \\ & + \frac{W_{2N}(\nu, Q^2)}{M_N^2} \left(p^\mu - \frac{p \cdot q}{q^2} q^\mu \right) \left(p^\nu - \frac{p \cdot q}{q^2} q^\nu \right) \\ & - \frac{i}{2M_N^2} \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma W_{3N}(\nu, Q^2) \\ & + \frac{W_{4N}(\nu, Q^2)}{M_N^2} q^\mu q^\nu + \frac{W_{5N}(\nu, Q^2)}{M_N^2} (p^\mu q^\nu + q^\mu p^\nu). \end{aligned} \quad (6)$$

In the massless lepton limit ($m_l \rightarrow 0$), when the leptonic tensor [Eq. (5)] is contracted with the hadronic tensor [Eq. (6)], the contributions from the terms associated with $W_{4N}(\nu, Q^2)$ and $W_{5N}(\nu, Q^2)$ vanish.

Generally, the cross sections [Eq. (3)] are expressed in terms of the dimensionless nucleon structure functions $F_{iN}(x, Q^2)$; ($i = 1-3$), which are related to the nucleon structure functions $W_{iN}(\nu, Q^2)$; ($i = 1-3$) as

$$F_{1N}(x, Q^2) = M_N W_{1N}(\nu, Q^2), \quad (7)$$

$$F_{2N}(x, Q^2) = \nu W_{2N}(\nu, Q^2), \quad (8)$$

$$F_{3N}(x, Q^2) = \nu W_{3N}(\nu, Q^2). \quad (9)$$

Using these dimensionless nucleon structure functions, the differential scattering cross section is given by [37]

$$\begin{aligned} \frac{d^2\sigma_N}{dx dy} = & \frac{G_F^2 M_N E}{\pi} \left(\frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[xy^2 F_{1N}(x, Q^2) \right. \\ & + \left(1 - y - \frac{M_N xy}{2E} \right) F_{2N}(x, Q^2) \\ & \left. \pm xy \left(1 - \frac{y}{2} \right) F_{3N}(x, Q^2) \right]. \end{aligned} \quad (10)$$

In the above expression, the $+$ ($-$) sign associated with the F_3 structure function applies to the neutrino(antineutrino)-induced process. In the quark parton model, the dimensionless nucleon structure functions ($F_{2N}(x)$ and $xF_{3N}(x)$) are in turn written in terms of the parton distribution functions at the leading order of perturbative QCD as [38]

$$F_{2N}(x) = \sum_i x[q_i(x) + \bar{q}_i(x)], \quad (11)$$

$$xF_{3N}(x) = \sum_i x[q_i(x) - \bar{q}_i(x)], \quad (12)$$

where i runs for the different flavors of (anti)quark, and $q_i(x)$ ($\bar{q}_i(x)$) corresponds to the probability density of finding a quark(antiquark) with a momentum fraction x . Assuming massless and collinear spin- $\frac{1}{2}$ partons, the structure functions in charged current (anti)neutrino-nucleon DIS satisfy the Callan-Gross relation [39]:

$$F_{1N}(x) = \frac{F_{2N}(x)}{2x}. \quad (13)$$

Therefore, the differential scattering cross section [Eq. (10)] may be written as

$$\begin{aligned} \frac{d^2\sigma_N}{dx dy} = & \frac{G_F^2 M_N E}{\pi} \left(\frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[\left(1 - y - \frac{y^2}{2} - \frac{M_N xy}{2E} \right) \right. \\ & \left. \times F_{2N}(x) \pm xy \left(1 - \frac{y}{2} \right) F_{3N}(x) \right]. \end{aligned} \quad (14)$$

However, in realistic (anti)neutrino-induced processes, the Callan-Gross relation is modified due to higher-order QCD effects, target mass corrections, and higher-twist contributions associated with multiparton correlations at low to moderate values of Q^2 , and is given at the LO by

$$\begin{aligned} F_{1N}(x, Q^2) = & \frac{1}{2x} [(1 + r^2)F_{2N}(x, Q^2) - F_{LN}(x, Q^2)], \\ r^2 = & \frac{4M^2 x^2}{Q^2}, \end{aligned} \quad (15)$$

where $F_{LN}(x, Q^2)$ is the longitudinal nucleon structure function which is evaluated following the work of Moch *et al.* [34]. In our study, we incorporate higher-order QCD effects, target mass corrections, and higher-twist contributions in evaluating the nucleon structure functions. In the literature, different parametrizations are available for

the parton density distribution functions, namely, Gluck-Reya-Vogt (GRV) [40], 2010 CTEQ PDF release (CT10) [41], coordinated theoretical-experimental project on QCD (CTEQ)18 [42], MMHT14 [32], mass scheme hessian tolerance (MSHT)20 [43], Alekhin-Blumlein-Moch-Placakyte (ABMP)16 [44], neural network parton distribution functions (NNPDF) [45], etc., to evaluate the nucleon structure functions.

In the present work, we study the dependence of the (anti)neutrino-nucleon scattering cross sections on the choice of different PDFs parametrizations in the few-GeV energy region, which are currently used in many studies. We have evaluated the results for the total scattering cross sections (σ_N) for the neutrino—as well as the antineutrino—induced charged current DIS processes off free nucleon target at the LO of perturbative QCD by using some of the recent PDF parametrizations like CT18 [42], NNPDF [45], MSHT20 [43], and MMHT14 [32] as shown in Fig. 3. We have obtained the numerical results by incorporating the uncertainty in the PDFs at the 68% confidence level which is shown by the symmetric band around the central value. It may be observed from the figure that the numerical results for the total scattering cross sections using these PDFs parametrizations overlap among themselves within the uncertainty bands. However, the results corresponding to their central values have some variation which is about 5%–6% for the neutrino and 2%–4% for the antineutrino induced processes over the considered energy region. This uncertainty in the total scattering cross section for $\nu_\mu/\bar{\nu}_\mu - N$, arising from the PDFs dependence, propagates into the evaluation of scattering cross sections for $\nu_\mu/\bar{\nu}_\mu - A$, where additional uncertainty arises due to the limited understanding of the nuclear medium effects. In the next subsection, we briefly discuss the formalism for the (anti)neutrino induced DIS processes on nuclear targets and the various nuclear medium effects such as Fermi motion, binding energy, nucleon correlations, mesonic contributions, and (anti)shadowing effect which have been taken into account using a microscopic many-body field theoretical approach.

B. $\nu_\mu/\bar{\nu}_\mu - A$ DIS

The basic reactions for the (anti)neutrino induced charged current DIS off a nuclear target, depicted in Fig. 4 (with the four momenta of the particles mentioned in the corresponding parenthesis) are given by

$$\nu_\mu(k)/\bar{\nu}_\mu(k) + A(p_A) \rightarrow l^-(k')/l^+(k') + X(p'_A),$$

for which the differential scattering cross sections are generally expressed in terms of the leptonic and nuclear hadronic tensors as [46]

$$\frac{d^2\sigma}{dx dy} = \frac{G_F^2 M_N y}{2\pi} \frac{E}{E'} \frac{|\mathbf{k}'|}{|\mathbf{k}|} \left(\frac{M_W^2}{M_W^2 + Q^2} \right)^2 L_{\mu\nu} W_A^{\mu\nu}. \quad (16)$$

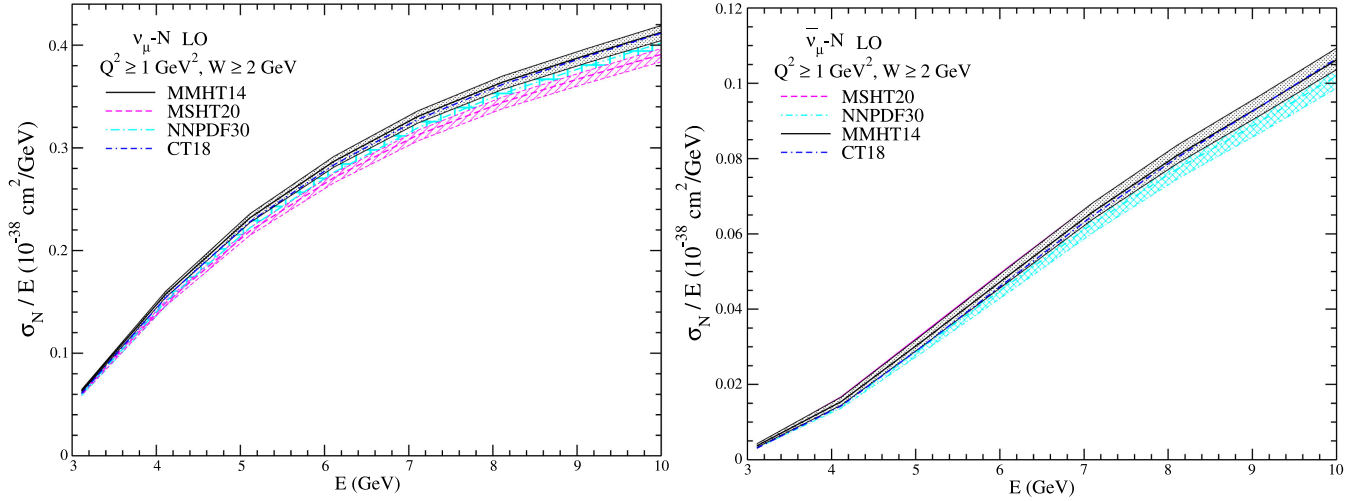


FIG. 3. $\frac{\sigma_N}{E}$ as a function of E for the charged current $\nu_\mu - N$ (left panel) and $\bar{\nu}_\mu - N$ (right panel) DIS processes. The results are computed at LO using different nucleonic PDFs [32,42,43,45]. The associated PDF uncertainties, shown as bands, correspond to a symmetric 68% confidence level about the central value. A cut of $W \geq 2$ GeV is applied in the calculations of total scattering cross sections.

The leptonic tensor $L_{\mu\nu}$ is already defined in Eq. (5). For the $\nu_\mu(\bar{\nu}_\mu) - A$ DIS process, the nuclear hadronic tensor $W_A^{\mu\nu}$ is written in terms of the weak nuclear structure functions $W_{iA}(\nu, Q^2)$ ($i = 1-5$) as [37]

$$\begin{aligned} W_A^{\mu\nu} = & \left(\frac{q^\mu q^\nu}{q^2} - g^{\mu\nu} \right) W_{1A}(\nu, Q^2) \\ & + \frac{W_{2A}(\nu, Q^2)}{M_A^2} \left(p_A^\mu - \frac{p_A \cdot q}{q^2} q^\mu \right) \left(p_A^\nu - \frac{p_A \cdot q}{q^2} q^\nu \right) \\ & - \frac{i}{2M_A^2} \epsilon^{\mu\nu\rho\sigma} p_{A\rho} q_\sigma W_{3A}(\nu, Q^2) \\ & + \frac{W_{4A}(\nu, Q^2)}{M_A^2} q^\mu q^\nu + \frac{W_{5A}(\nu, Q^2)}{M_A^2} (p_A^\mu q^\nu + q^\mu p_A^\nu), \end{aligned} \quad (17)$$

with M_A as the nuclear target mass. In the massless lepton limit, terms associated with $W_{4A}(\nu, Q^2)$ and $W_{5A}(\nu, Q^2)$ vanish when contracted with the leptonic tensor.

These nuclear structure functions $W_{iA}(\nu, Q^2)$; ($i = 1-3$) are generally expressed in terms of the dimensionless

nuclear structure functions $F_{iA}(x, Q^2)$; ($i = 1-3$) defined as follows:

$$F_{1A}(x, Q^2) = M_A W_{1A}(\nu, Q^2), \quad (18)$$

$$F_{2A}(x, Q^2) = \nu W_{2A}(\nu, Q^2), \quad (19)$$

$$F_{3A}(x, Q^2) = \nu W_{3A}(\nu, Q^2). \quad (20)$$

Using the above relations and Eqs. (17) and (5) in Eq. (16), the differential cross section is written in terms of the first three dimensionless nuclear structure functions $F_{iA}(x, Q^2)$; ($i = 1-3$) as [37]

$$\begin{aligned} \frac{d^2\sigma}{dx dy} = & \frac{G_F^2 M_N E}{\pi} \left(\frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[xy^2 F_{1A}(x, Q^2) \right. \\ & + \left(1 - y - \frac{M_N xy}{2E} \right) F_{2A}(x, Q^2) \\ & \left. \pm xy \left(1 - \frac{y}{2} \right) F_{3A}(x, Q^2) \right]. \end{aligned} \quad (21)$$

In the above expression, the $+$ ($-$) sign associated with the F_{3A} structure function applies to the neutrino(antineutrino)- induced process. As the interaction takes place with a nuclear target, the nucleons bound inside it are off shell and continuously moving with nonzero Fermi momentum. For the present numerical calculations, we choose the three momentum transfer $\mathbf{q}$ to be along the z axis, and therefore $q^\mu = (q^0, \mathbf{q}) = (q^0, 0, 0, q^z)$, where q^0 is the energy transferred to the nuclear target. The Bjorken variables for the nuclear target (x_A) and the bound nucleon (x_N) are defined as

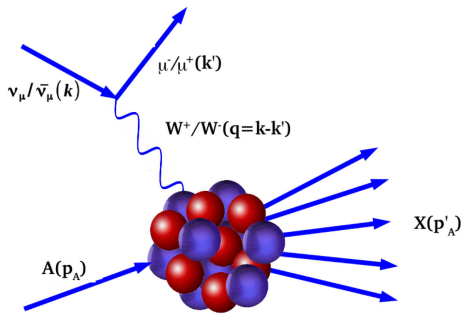


FIG. 4. Feynman diagram showing the deep inelastic scattering induced by the $\nu_\mu/\bar{\nu}_\mu - A$ interaction processes.

$$x_A = \frac{Q^2}{2p_A \cdot q} = \frac{Q^2}{2M_A q^0} = \frac{Q^2}{2AM_N q^0},$$

$$x_N = \frac{Q^2}{2p \cdot q} = \frac{Q^2}{2(p^0 q^0 - p^z q^z)}. \quad (22)$$

The nucleons bound inside a nucleus may also interact among themselves via the strong interaction, which we incorporate by taking the nucleon-nucleon correlations into account using a microscopic field theoretical approach. The effects of the Fermi motion, the binding energy, and the nucleon correlations are included through the relativistic nucleon spectral function (S_h), which is obtained by using

the Lehmann representation for the relativistic nucleon propagator. The properties of the spectral function have been discussed in Refs. [30,47]. The dressed relativistic nucleon propagator in an interacting Fermi sea in infinite nuclear matter is calculated using the technique of many body theory. To obtain the results for a finite nucleus, the local density approximation is then applied, in which the Fermi momentum of an interacting nucleon is not considered to be a constant quantity but the function of position coordinate (r) [30]. Following our earlier work [37], the expressions for the weak nuclear structure functions, which are used to evaluate the differential scattering cross sections, are given by

$$F_{1A,N}(x_A, Q^2) = 4AM_N \int d^3r \int \frac{d^3p}{(2\pi)^3} \frac{M_N}{E_N(\mathbf{p})} \int_{-\infty}^{\mu} dp^0 S_h(p^0, \mathbf{p}, \rho(r)) \left[\frac{F_{1N}(x_N, Q^2)}{M_N} + \left(\frac{p^x}{M_N} \right)^2 \frac{F_{2N}(x_N, Q^2)}{\nu_N} \right], \quad (23)$$

$$F_{2A,N}(x_A, Q^2) = 4 \int d^3r \int \frac{d^3p}{(2\pi)^3} \frac{M_N}{E_N(\mathbf{p})} \int_{-\infty}^{\mu} dp^0 S_h(p^0, \mathbf{p}, \rho(r)) \left(\frac{M_N}{p^0 - p^z \gamma} \right) \times F_{2N}(x_N, Q^2) \\ \times \left[\frac{Q^2}{(q^z)^2} \left(\frac{|\mathbf{p}|^2 - (p^z)^2}{2M_N^2} \right) + \frac{(p^0 - p^z \gamma)^2}{M_N^2} \left(\frac{p^z Q^2}{(p^0 - p^z \gamma) q^0 q^z} + 1 \right)^2 \right], \quad (24)$$

$$F_{3A,N}(x_A, Q^2) = 4A \int d^3r \int \frac{d^3p}{(2\pi)^3} \frac{M_N}{E_N(\mathbf{p})} \int_{-\infty}^{\mu} dp^0 S_h(p^0, \mathbf{p}, \rho(r)) \times \frac{q^0}{q^z} \left(\frac{p^0 q^z - p^z q^0}{p \cdot q} \right) F_{3N}(x_N, Q^2), \quad (25)$$

where $\nu_N = \frac{p \cdot q}{M_N} = \frac{p^0 q^0 - p^z q^z}{M_N}$, $\gamma = \sqrt{1 + \frac{4M_N^2 x^2}{Q^2}}$ and E_N is the relativistic energy of an on shell nucleon. It is notable that $F_{1A,N}(x_A, Q^2)$ has been evaluated without using the Callan-Gross relation at the nuclear level [37]. The results obtained by using Eqs. (23), (24), and (25) are labeled as the results with the spectral function(SF) only.

In the case of the bound nucleons, which interact among themselves via the exchange of virtual mesons such as π , ρ , etc., there is a finite nonzero probability that the intermediate vector boson may interact with these mesons instead of the nucleon. Therefore, we also incorporate the mesonic contribution by using a many-body field theoretical approach similar to that used in the case of the bound nucleons, following Ref. [29]. The expressions for the mesonic structure functions $F_{1A,i}(x, Q^2)$ and $F_{2A,i}(x, Q^2)$ for pions and rho meson are given by [37]

$$F_{1A,i}(x, Q^2) = -6 \times a \times AM_N \int d^3r \int \frac{d^4p}{(2\pi)^4} \theta(p^0) \delta \text{Im} D_i(p) 2m_i \left[\frac{F_{1i}(x_i)}{m_i} + \frac{|\mathbf{p}|^2 - (p^z)^2}{2(p^0 q^0 - p^z q^z)} \frac{F_{2i}(x_i)}{m_i} \right], \quad (26)$$

$$F_{2A,i}(x, Q^2) = -6 \times a \int d^3r \int \frac{d^4p}{(2\pi)^4} \theta(p^0) \delta \text{Im} D_i(p) 2m_i \left(\frac{m_i}{p^0 - p^z \gamma} \right) F_{2i}(x_i) \\ \times \left[\frac{Q^2}{(q^z)^2} \left(\frac{|\mathbf{p}|^2 - (p^z)^2}{2m_i^2} \right) + \frac{(p^0 - p^z \gamma)^2}{m_i^2} \left(\frac{p^z Q^2}{(p^0 - p^z \gamma) q^0 q^z} + 1 \right)^2 \right], \quad (27)$$

where subscript $i = \pi/\rho$, m_i is the mass of the pion/rho meson, $x_i = \frac{Q^2}{-2p \cdot q}$, with an extra minus sign arising due to the direction of the mesonic four momentum p , and $a = 1$ for the pion and $a = 2$ for the rho meson [29]. $D_i(p)$ is the meson ($i = \pi$ or ρ) propagator in the nuclear medium [37]. Notice that $F_{2A,\rho}(x, Q^2)$ has an extra factor of 2 compared to pionic contribution because it has two transverse

polarization states [48]. For the numerical calculations, we use the GRV PDF parametrization [49] for both the pion and the rho meson. It is worth recalling that the parity violating nuclear structure function $F_{3A}(x_A, Q^2)$ has no mesonic contribution, as it depends mainly on the valence quark distribution which averages to zero when the three charge states of the pion and the rho mesons are taken into consideration.

Besides the mesonic contributions, the shadowing and antishadowing effects, which dominate in the low x region, have also been taken into account in the present numerical calculations, following the work of Kulagin and Petti [31] based on the Glauber-Gribov multiple scattering theory. The nuclear structure functions $F_{iA}^S(x, Q^2)$; ($i = 1-3$) including the shadowing effect, are given by

$$F_{iA}^S(x, Q^2) = \delta R(x, Q^2) \times F_{iN}(x, Q^2), \quad (28)$$

where superscript S corresponds to the nuclear shadowing effect and the correction factor $\delta R(x, Q^2)$ is taken from Ref. [31].

After taking the perturbative corrections up to NNLO [33–35] and the nonperturbative TMC [36] effect into account for the evaluation of free nucleon structure functions which are being used as an input to calculate the nuclear structure functions $F_{iA}(x, Q^2)$; ($i = 1, 2, 3$), the full expression for the nuclear structure functions $F_{iA}(x, Q^2)$ with the nuclear medium effects is given by

$$F_{iA}(x, Q^2) = F_{iA,N}(x, Q^2) + F_{iA,\pi}(x, Q^2) + F_{iA,\rho}(x, Q^2) + F_{iA}^S(x, Q^2), \quad i = 1-2 \quad (29)$$

and

$$F_{3A}(x, Q^2) = F_{3A,N}(x, Q^2) + F_{3A}^S(x, Q^2). \quad (30)$$

It should be noted that $F_{3A}(x, Q^2)$ has no mesonic contribution.

III. RESULTS AND DISCUSSION

We present the results for the double differential ($\frac{d^2\sigma}{dx dy}$) and single differential ($\frac{d\sigma}{dx}$) scattering cross sections for ν_μ and $\bar{\nu}_\mu$ induced DIS off a free nucleon (N) target, as well as for the nucleons bound inside the argon nucleus. The (anti) neutrino-nucleon scattering cross sections are calculated using Eq. (10), with the free nucleon structure functions $F_{iN}(x, Q^2)$; ($i = 1-3$) given by Eqs. (11)–(13). In our earlier works [37,46], we have demonstrated that the numerical results obtained for the structure functions at NNLO with the target mass corrections, and at next-to-leading-order (NLO) with the target mass corrections and higher-twist effects, are in agreement within a few percentages. Therefore, in this work, the structure functions $F_{iN}(x, Q^2)$; ($i = 1-3$) have been evaluated at NNLO following Refs. [33–35,37], using the MMHT14 PDF parametrization [32] in the four-flavor MSbar scheme, incorporating the TMC effect [36]. The corresponding results are labeled as “Free” in the curves shown in the various figures.

The differential scattering cross sections for $\nu_\mu(\bar{\nu}_\mu)$ induced deep inelastic scattering off an argon(^{40}Ar) target,

as given in Eq. (21), are obtained using the nuclear structure functions $F_{iA}(x, Q^2)$; ($i = 1-3$) defined in Eqs. (23)–(25). These $F_{iA}(x, Q^2)$; ($i = 1-3$), are calculated by convoluting the free nucleon structure functions $F_{iN}(x, Q^2)$; ($i = 1-3$) with the nucleon spectral function and integrating over the entire nuclear volume. This procedure accounts for the effects of Fermi motion, binding energy, and nucleon correlations. The corresponding results are labeled as “SF” in the text.

The effects of mesonic contributions arising from the pion and rho meson clouds are included using Eqs. (26) and (27), following a many-body field theoretical approach discussed in our earlier works [16,37,46]. Moreover, the shadowing and antishadowing corrections which are present in the case of scattering from nuclear targets, are incorporated [Eq. (28)] following Ref. [31]. The results, including the contributions from the spectral function, mesonic effects, and shadowing and antishadowing corrections, i.e., our full model, as defined in Eqs. (29) and (30), are labeled as “Total.” It may be further noted that ^{40}Ar is a nonisoscalar nuclear target; however, we have treated it as an isoscalar in view of the effect of nonisoscality being very small (1–3%) in ^{40}Ar [16] in the considered region of Bjorken x and inelasticity y .

The present numerical calculations are performed for $Q^2 \geq 1 \text{ GeV}^2$ at two different incoming (anti)neutrino beam energies, namely $E = 4 \text{ GeV}$ and $E = 6 \text{ GeV}$, under the following constraints on the center of mass energy W :

- (1) without applying any kinematical constraint on W ; these results are labeled as “No W_{cut} ”
- (2) by applying kinematical cuts on the center of mass energy W ; specifically $W \geq 1.7 \text{ GeV}$ and $W \geq 2 \text{ GeV}$, to study the effect of the W cut on the differential cross sections, which is relevant for understanding the transition region between the nucleon resonances and DIS.

In Fig. 5, we present the results for $\frac{1}{E} \frac{d^2\sigma}{dx dy}$ as a function of y for different values of Bjorken x in the case of $\nu_\mu - ^{40}\text{Ar}$ scattering at NNLO with the TMC effect for a neutrino beam energy of 4 GeV , corresponding to the spectral function only (dashed line) and to the full model (solid line), without applying any cut on the center of mass energy. These results are compared with those for a free nucleon target (dash double-dotted line) in order to study the effects of the nuclear medium corrections. We find that the inclusion of the nuclear structure effects through the nucleon spectral function leads to a reduction in the cross sections in the entire region of x and y . It is expected that the nuclear structure effects would lead to a reduction in the cross section. This reduction originates primarily from the restriction on nucleon momentum imposed by the Pauli blocking and the Fermi motion of the nucleons in the Fermi sea, together with nucleon-nucleon correlation effects, which have been taken into account through the use of spectral function. Such suppression has been consistently

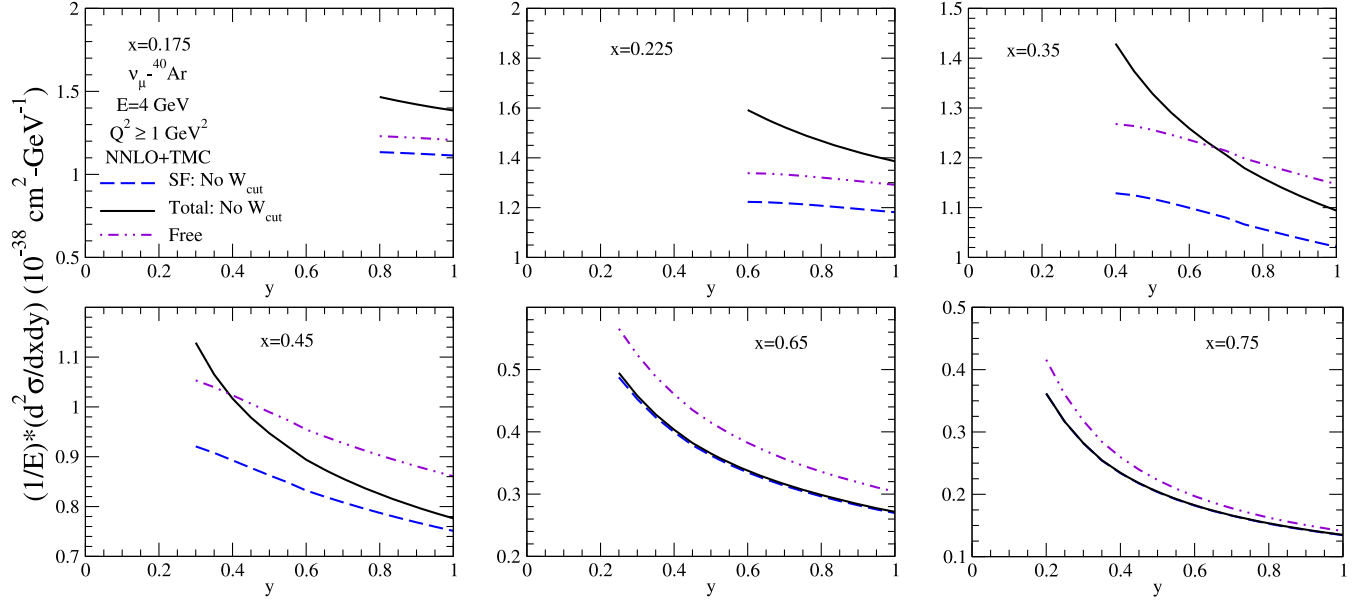


FIG. 5. $\frac{1}{E} \frac{d^2 \sigma}{dx dy}$ as a function of y at $E = 4$ GeV for the charged current $\nu_\mu - {}^{40}\text{Ar}$ DIS process at different values of x . The results are presented for $Q^2 \geq 1$ GeV², without applying any cut on W . The numerical calculations are performed at NNLO incorporating the TMC effect, using the spectral function only (dashed lines) and the full model (solid lines). For comparison, the results for a free nucleon target are also included (double-dot-dashed lines) without applying any cut on W .

observed in both quasielastic and inelastic reactions [9]. In the present case of deep deep inelastic scattering, we find that quantitatively, the reduction is about 10–13% at $y = 0.5$ and 6–12% at $y = 0.8$ for $0.35 \leq x \leq 0.75$ at $E = 4$ GeV.

Furthermore, in the nuclear medium, the bound nucleons are enveloped by a virtual mesonic cloud which interacts via the exchange of intermediate virtual bosons W , contributing to the neutrino-nucleus cross section. In the present work, this effect is explicitly incorporated through the contributions of low-lying mesons, namely pions and rho mesons, interacting with the W boson as described in Sec. II B. As a consequence, the cross section is enhanced in the intermediate Bjorken- x region, $0.3 < x < 0.6$. The effects of shadowing and antishadowing corrections are negligible in the considered kinematic region. Consequently, the results of the full model [using Eqs. (29) and (30) in Eq. (21)], are larger than those obtained with the spectral function alone for $x \leq 0.45$. For example, this enhancement from the results obtained with the nuclear structure effects is about 20% at $y = 0.5$ and 10% at $y = 0.8$ for $x = 0.35$. This enhancement decreases with increasing y , becoming about 10% at $y = 0.5$ and 5% at $y = 0.8$ for $x = 0.45$, and reduces further with increasing x . Furthermore, we find that, due to the inclusion of nuclear medium effects, the differential scattering cross sections using the full model increases about 6% at $y = 0.5$ and $x = 0.35$ relative to the results for the free nucleon case, while at $y = 0.8$ it decreases to $\sim 3\%$ for the same value of x .

In Fig. 6, the results for $\frac{1}{E} \frac{d^2 \sigma}{dx dy}$ as a function of y for $\nu_\mu - {}^{40}\text{Ar}$ are presented for $E = 6$ GeV. It may be noted from the figure that, with increasing energy, the scattering

cross sections also extend to the lower region of inelasticity y . Furthermore, the nuclear medium effects due to the nuclear structure effect are reduced with increasing beam energy. For example, at $E = 6$ GeV the suppression in the differential cross sections obtained using the spectral function alone is about 11–13% for $0.35 \leq x \leq 0.65$ and $0.5 \leq y \leq 0.8$, which decreases to about 7% at $y = 0.5$ and 4% at $y = 0.8$ for $x = 0.75$, as compared to the free nucleon case. Incorporating the mesonic contributions results in an enhancement in the differential cross sections, which is about 27% at $y = 0.5$ and 18% at $y = 0.8$ for $x = 0.225$, relative to the results with the spectral function only, while it becomes 14% and 8% for $x = 0.35$, and 7% and 4% for $x = 0.45$, respectively for the same values of y . We also find that the relative increase due to the mesonic contributions at $E = 6$ GeV is smaller than that observed at $E = 4$ GeV, with a reduction of about 2–5% for $0.225 \leq x \leq 0.45$ and $0.5 \leq y \leq 0.8$. The numerical results for $E = 6$ GeV are further compared with those obtained using the phenomenological nuclear PDFs parametrizations from the CTEQ group, namely nCTEQ15 [27], which includes data from charged-lepton as well as neutrino induced DIS experiments, and nCTEQnu [28], which includes data only from neutrino experiments. It may be observed that the results obtained using the nCTEQ15 and nCTEQnu PDF parametrizations are not mutually consistent, except in the region $0.35 \leq x \leq 0.45$ for intermediate-to-high values of y . Our numerical results using the full model are larger than those obtained using the nCTEQnu nuclear PDFs parametrization [28] in the low- to intermediate- x region, particularly

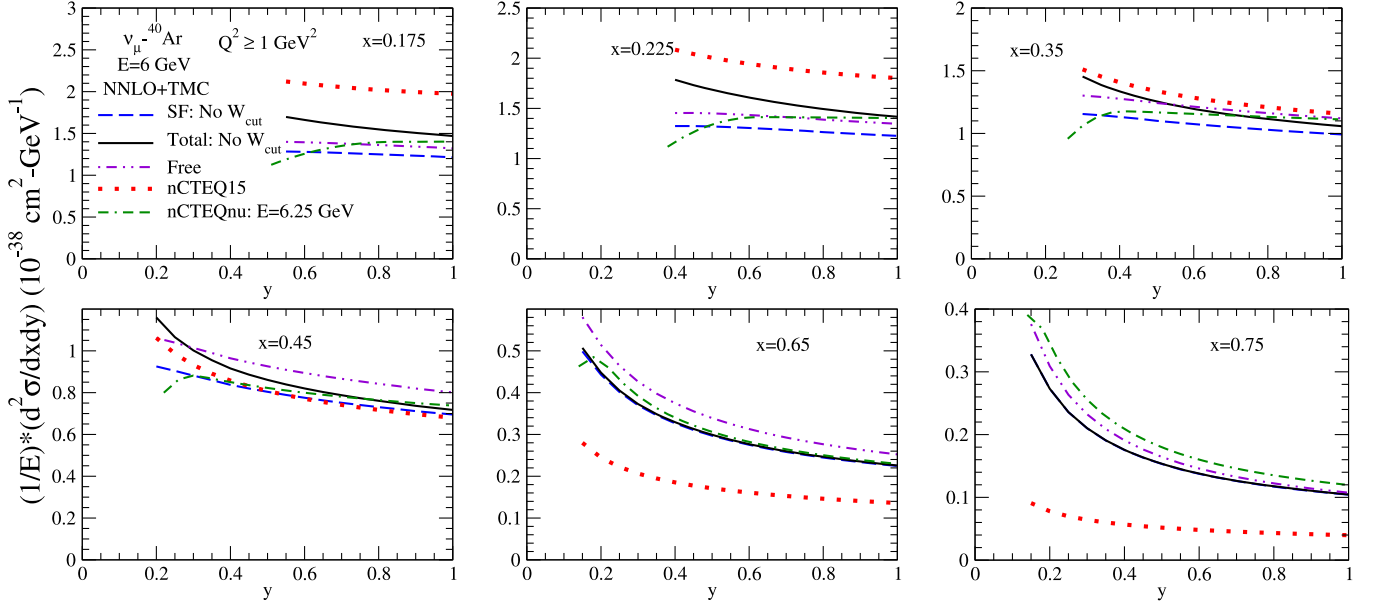


FIG. 6. $\frac{1}{E} \frac{d^2 \sigma}{dx dy}$ as a function of y at $E = 6$ GeV for the charged current $\nu_\mu - {}^{40}\text{Ar}$ DIS process at different values of x . The results are presented for $Q^2 \geq 1 \text{ GeV}^2$, without applying any cut on W . The numerical calculations are performed at NNLO, incorporating the TMC effect, using the spectral function only (dashed lines) and the full model (solid lines). The results are also compared with the phenomenological nuclear PDF parametrizations: nCTEQ15 [27] (dotted lines) and nCTEQnu [28] (double-dash-dotted lines). For comparison, the results for a free nucleon target are also included (double-dot-dashed lines) without applying any cut on W .

at lower values of inelasticity; however, they become smaller with increasing x (> 0.65). The results based on the nCTEQ15 PDFs parametrization [27] are found to be in reasonable agreement with the present calculations only in the region $0.35 \leq x \leq 0.45$, while there is a noticeable

enhancement in the low- x (≤ 0.35) region and reduction in the high- x (> 0.35) region.

In order to ensure a genuine DIS region, a cut on the invariant mass W of the hadronic system is needed. It is expected that imposing a cut on the invariant mass W of the

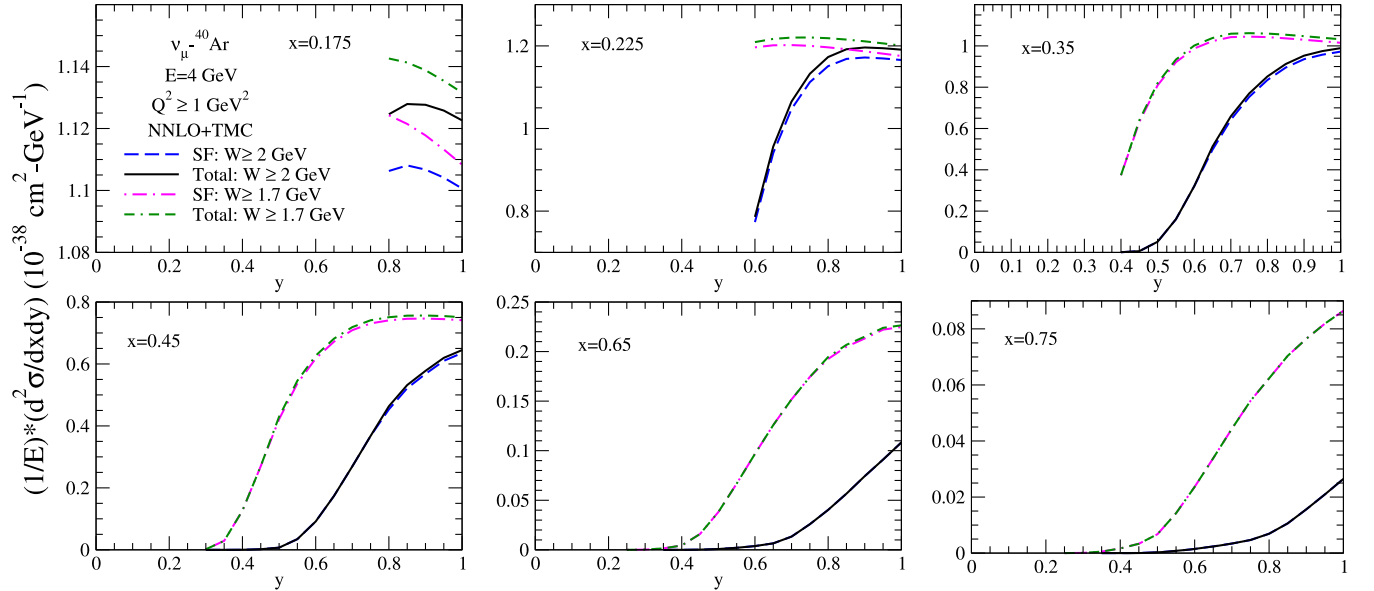


FIG. 7. $\frac{1}{E} \frac{d^2 \sigma}{dx dy}$ as a function of y at $E = 4$ GeV for the charged current $\nu_\mu - {}^{40}\text{Ar}$ DIS process at different values of x . The results are presented for $Q^2 \geq 1 \text{ GeV}^2$, with a cut on W . The numerical calculations are performed at NNLO, incorporating the TMC effect. The results obtained using the spectral function only, with a W cut of 1.7 GeV (2 GeV), are shown by the dash-dotted (dashed) lines. The results obtained using the full model, with a W cut of 1.7 GeV (2 GeV), are shown by the double-dash-dotted (solid) lines.

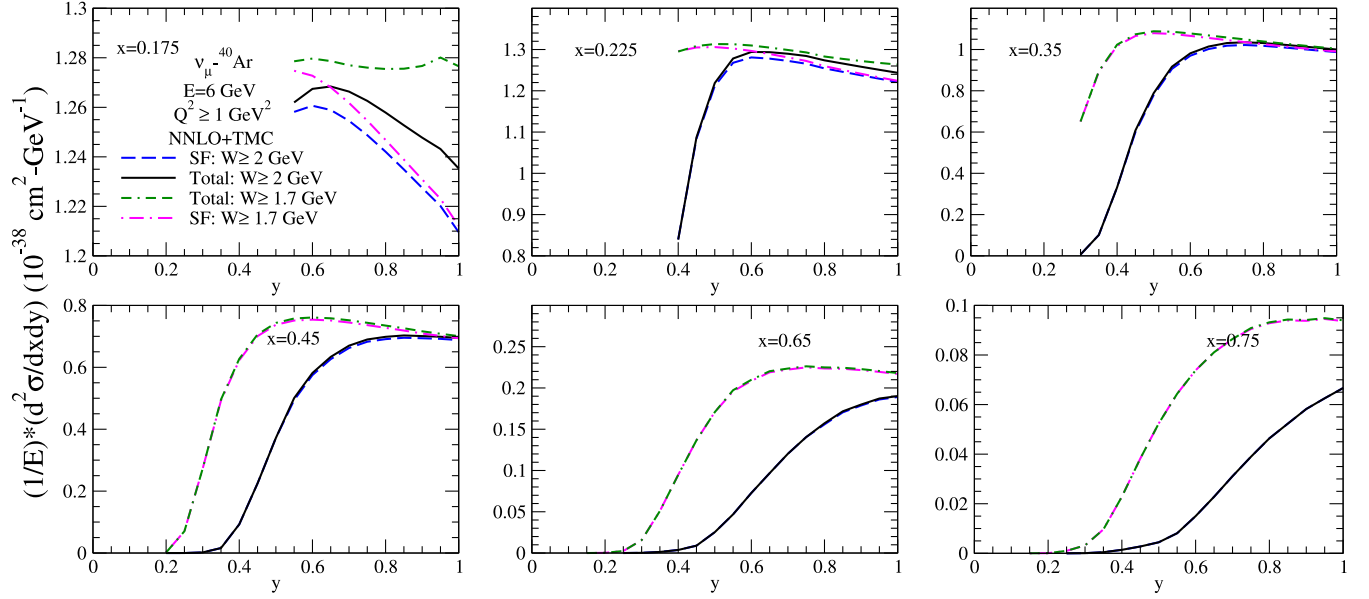


FIG. 8. $\frac{1}{E} \frac{d^2 \sigma}{dx dy}$ as a function of y at $E = 6$ GeV for the charged current $\nu_\mu - {}^{40}\text{Ar}$ DIS process at different values of x . The line styles follow the same convention as in Fig. 7.

hadronic system will reduce the cross section. However, the choice of this W cut must be both judicious and physically well motivated. Such a selection is crucial in weak-interaction-induced deep inelastic scattering, as it enables a clear separation of the deep inelastic scattering region from the inelastic processes dominated by the baryon resonance excitations. The W threshold therefore serves as a key discriminator between the

resonance-dominated region and the onset of genuine DIS, as well as the multiparticle production channels, as discussed in Sec. I. To illustrate the effect of the W cut on the differential cross sections, we present the results in Figs. 7 and 8 for $E = 4$ GeV and $E = 6$ GeV, respectively. The numerical results are shown for different choices of W cuts, namely $W \geq 1.7$ GeV and $W \geq 2$ GeV, since no unique kinematic boundaries are defined in the literature for the

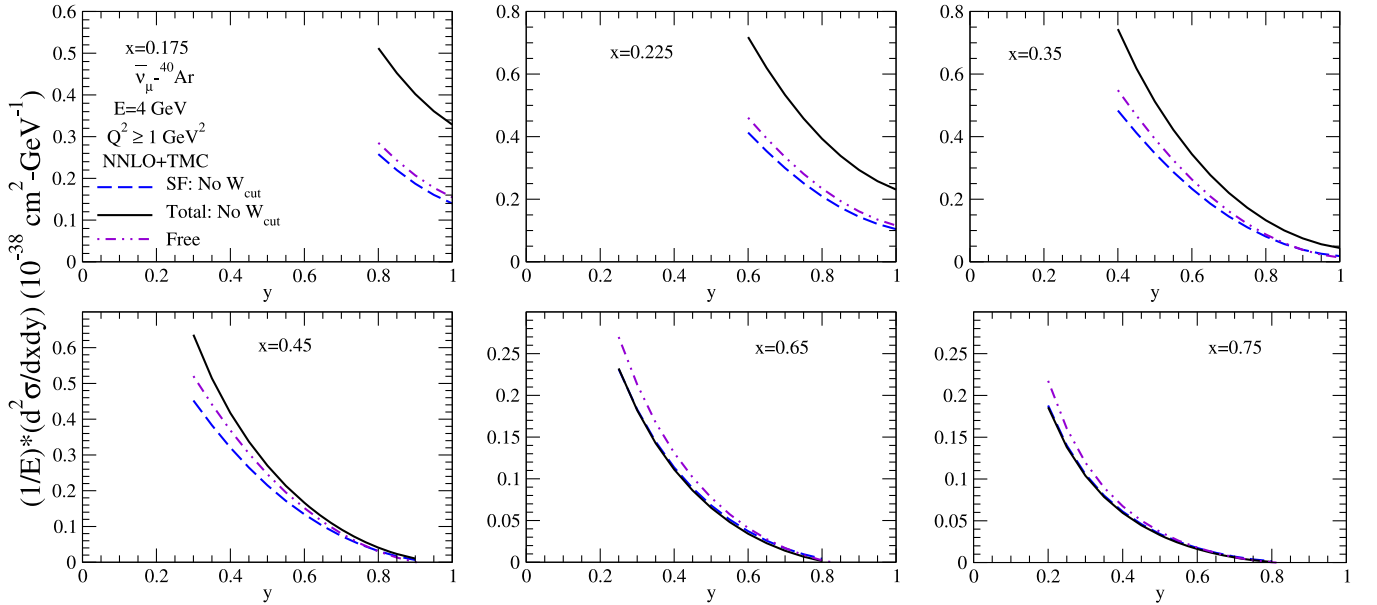


FIG. 9. $\frac{1}{E} \frac{d^2 \sigma}{dx dy}$ as a function of y at $E = 4$ GeV for the charged current $\bar{\nu}_\mu - {}^{40}\text{Ar}$ DIS process at the different values of x . The results are presented for $Q^2 \geq 1 \text{ GeV}^2$, without applying any cut on W . The numerical calculations are performed at NNLO, incorporating the TMC effect, using the spectral function only (dashed lines) and the full model (solid lines). For comparison, results for a free nucleon target are also included (double-dot-dashed lines).

transition region from nucleon resonances to deep inelastic scattering, as discussed earlier in the text. We find that the differential cross sections obtained with a cut on W are significantly suppressed, and this suppression becomes more pronounced with an increasing W cut (i.e., $W \geq 2$ GeV compared to $W \geq 1.7$ GeV). For example, in Fig. 7, when a cut of $W \geq 1.7$ GeV is applied, the suppression is about 24% at $y = 0.6$ and 17% at $y = 0.8$ for $x = 0.225$. However, for $x = 0.45$ the suppression becomes 88% at $y = 0.4$, 30% at $y = 0.6$ and $\sim 9\%$ at $y = 0.8$. The results obtained with a $W \geq 2$ GeV cut are further suppressed by about 26% at $y = 0.6$ and 3% at $y = 0.8$ for $x = 0.225$, while for $x = 0.45$, the suppression is about 10% at $y = 0.4$, 5% at $y = 0.6$, and 35% at $y = 0.8$. It is important to note that the effect of the W cut becomes more pronounced with increasing x , particularly in the low- to intermediate- y region. Furthermore, the application of a cut on the W also leads to a reduction in the mesonic cloud contribution for low to intermediate values of x . As expected, the impact of the W cut decreases with increasing neutrino beam energy. From Fig. 8, it may be observed that at $E = 6$ GeV the difference between the results obtained for $W \geq 1.7$ GeV and $W \geq 2$ GeV is about 68%(85%) at $y = 0.6$ and 20%(38%) at $y = 0.8$ for $x = 0.35(0.45)$.

In Figs. 9 and 10, the results for the $\bar{\nu}_\mu - {}^{40}\text{Ar}$ differential scattering cross sections are presented at beam energies $E = 4$ GeV and $E = 6$ GeV, respectively, without any constraint on the center of mass energy W . The differential cross sections $\frac{1}{E} \frac{d^2\sigma}{dx dy}$, for $\bar{\nu}_\mu - {}^{40}\text{Ar}$ obtained using the SF

only get suppressed due to nuclear structure effects compared to those for the free nucleon target over the entire kinematic region of x and y . The qualitative dependence of the differential cross sections on x and y is similar to that observed in the neutrino case (Figs. 5 and 6); however, there are quantitative differences. The difference between the neutrino- and antineutrino- induced cross sections arises primarily from the nature of contribution from the structure function $F_3^A(x, Q^2)$. In neutrino scattering, $F_3^A(x, Q^2)$ contributes constructively along with the contributions of $F_1^A(x, Q^2)$ and $F_2^A(x, Q^2)$, whereas in the case of antineutrinos it enters with an opposite (negative) sign, as evident from Eq. (21). This sign reversal leads to a distinctly different behavior of the cross sections in the case of the neutrino and antineutrino scattering from nuclei. It is important to emphasize that even for scattering on free nucleon targets, the antineutrino cross section is intrinsically smaller than the neutrino cross section (see Fig. 3), a feature that persists in the presence of nuclear medium effects. For example, the reduction in the cross section due to the effect of the nuclear structure, relative to the free nucleon case, is about 13% at $y = 0.45$ for $0.35 \leq x \leq 0.65$ at $E = 4$ GeV.

The inclusion of the mesonic cloud contributions leads to an enhancement in the differential cross sections for $x \leq 0.45$, while the effect is very small for $x > 0.45$. Since $F_3^A(x, Q^2)$ does not receive any mesonic contribution, the modifications to $F_1^A(x, Q^2)$ and $F_2^A(x, Q^2)$ are identical for both neutrino- and antineutrino- induced processes.

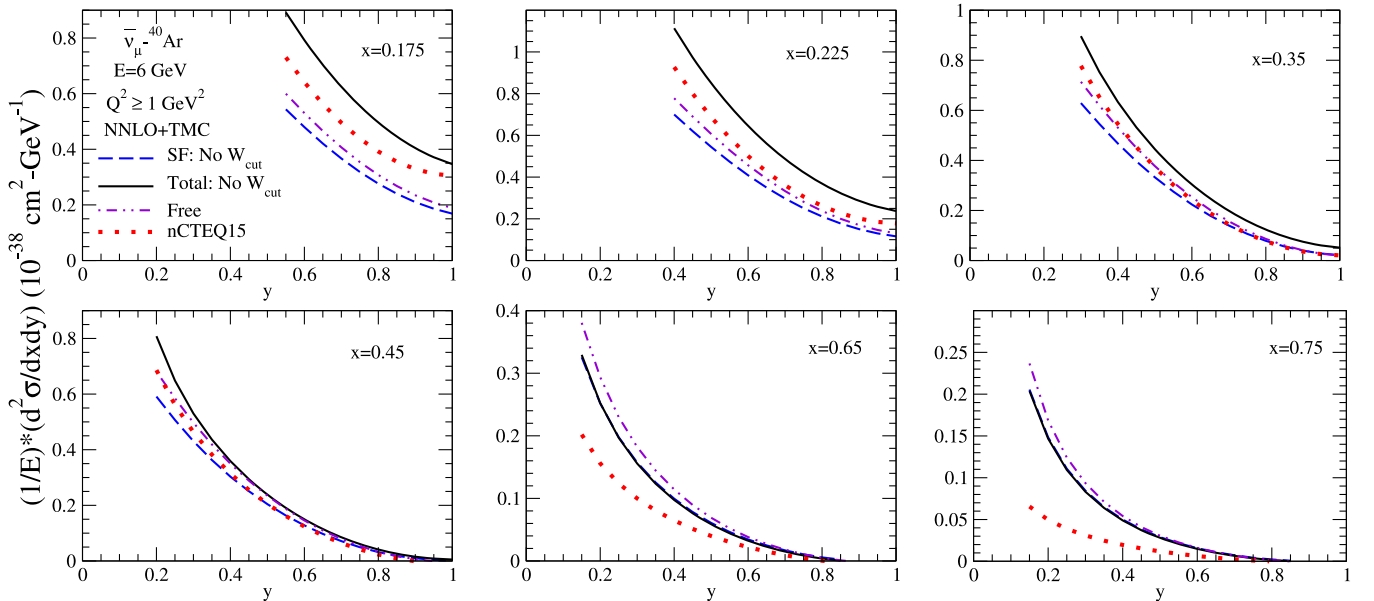


FIG. 10. $\frac{1}{E} \frac{d^2\sigma}{dx dy}$ as a function of y at $E = 6$ GeV for the charged current $\bar{\nu}_\mu - {}^{40}\text{Ar}$ DIS process at the different values of x . The results are presented for $Q^2 \geq 1$ GeV², without applying any cut on W . The numerical calculations are performed at NNLO, incorporating the TMC effect, using the spectral function only (dashed lines) and the full model (solid lines). For comparison, results for a free nucleon target are also included (double-dot-dashed lines). The results are also compared with the phenomenological nuclear PDF parametrization of nCTEQ15 [27] (dotted lines).

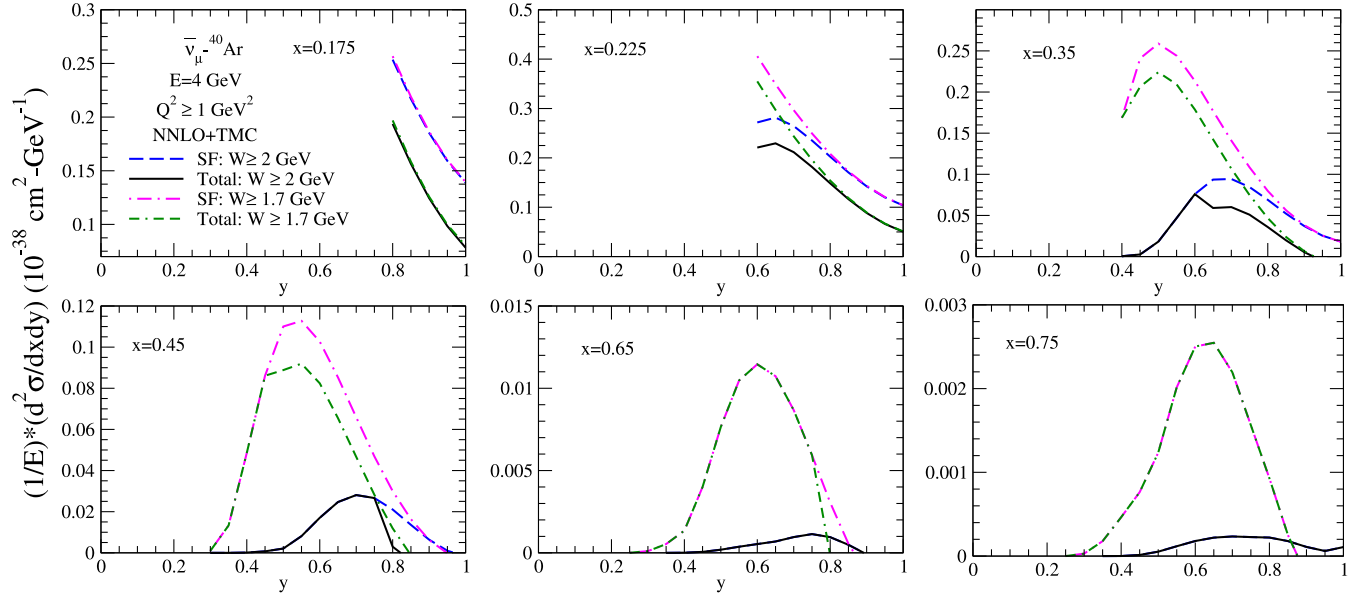


FIG. 11. $\frac{1}{E} \frac{d^2\sigma}{dx dy}$ as a function of y at $E = 4$ GeV for the charged current $\bar{\nu}_\mu - {}^{40}\text{Ar}$ DIS process at different values of x . The line styles follow the same convention as in Fig. 7.

However, because the antineutrino cross section is suppressed due to the negative contribution of $F_3^A(x, Q^2)$, the relative impact of mesonic contributions becomes more pronounced in the antineutrino case. For instance, the enhancement is about 75% at $y = 0.65$ for $x = 0.225$; 50% at $y = 0.45$ and 48% at $y = 0.65$ for $x = 0.35$; and 27% at $y = 0.45$ and 24% at $y = 0.65$ when $x = 0.45$. We find that the net effect of the nuclear medium corrections (“Total”) is to increase the differential cross sections obtained using the full model relative to the case of the free nucleon target for $x \leq 0.45$; for example, this enhancement in the results is about 30%(10%) at $y = 0.5$ and 51% (35%) at $y = 0.8$ for $x = 0.35(0.45)$ and $E = 4$ GeV, while for $x > 0.45$, the effect of the nuclear medium corrections is to decrease the differential cross sections. For example, at $x = 0.65$ and $E = 4$ GeV, this decrease is about 16% at $y = 0.5$ and 38% at $y = 0.8$ from the $\bar{\nu}_\mu - N$ scattering cross sections. It may be noted that the nuclear medium effects in the $\bar{\nu}_\mu - {}^{40}\text{Ar}$ deep inelastic scattering are more pronounced than in the $\nu_\mu - {}^{40}\text{Ar}$ case. The results shown in Fig. 10 for $E = 6$ GeV are compared with those obtained using the nCTEQ15 nuclear PDFs parametrization [27]. We find that our numerical results are larger than the nCTEQ15 results in the entire range of x , while they show reasonable agreement only in the intermediate x region ($0.35 \leq x \leq 0.45$). Hence, further work is needed to better understand nuclear medium effects over the full range of the Bjorken x .

The numerical results for the $\bar{\nu}_\mu - {}^{40}\text{Ar}$ differential cross sections are presented in Figs. 11 and 12 by applying cuts of $W \geq 1.7$ GeV and $W \geq 2$ GeV on the center of mass energy W , which show a suppression of the cross sections

due to a cut on W . The differing impact of the invariant mass cut W_{cut} on the neutrino and antineutrino cross sections can again be traced to the different nature of the contributions of $F_3^A(x, Q^2)$ to the cross section, which enters with a negative sign in the antineutrino case, thereby modifying the sensitivity of the cross section to the imposed kinematic constraint. For example, when a cut of $W \geq 1.7$ GeV is applied, the suppression is about 45–50% at $y = 0.6$ and 56–60% at $y = 0.8$ for $x = 0.225$ and $4 \text{ GeV} \leq E \leq 6 \text{ GeV}$, relative to the results obtained without applying any cut on W . It may be observed that the effect of the W cut is more pronounced in the antineutrino-induced processes than in the neutrino-induced ones. The impact of the W cut on the mesonic contribution is quantitatively smaller than that observed in the ν_μ induced process.

In Figs. 13 and 14, we present the numerical results for $\frac{1}{E} \frac{d\sigma}{dx}$, using Eq. (10), obtained by integrating $\frac{1}{E} \frac{d^2\sigma}{dx dy}$ over the entire range of inelasticity y , i.e., $[0, 1]$. These results are shown in Fig. 13 for ν_μ , and in Fig. 14 for $\bar{\nu}_\mu$ induced reactions on the ${}^{40}\text{Ar}$ target, for the incoming beam energies of $E = 4$ GeV (left panel) and $E = 6$ GeV (right panel).

From Fig. 13, we observe that the differential cross sections for $\nu_\mu - {}^{40}\text{Ar}$ peak in the intermediate region of x , when no cut is applied on the center of mass of energy W . The differential cross sections decrease with increasing x due to nuclear structure effects. The results obtained using the spectral function only (dashed line) are suppressed relative to those for the free nucleon case. Quantitatively, this suppression is about 10% at $x = 0.3$, 12% at $x = 0.6$, and about 6% at $x = 0.8$ for $E = 4$ GeV, when no cut is applied on W ; for $E = 6$ GeV, it ranges from 5–13% for

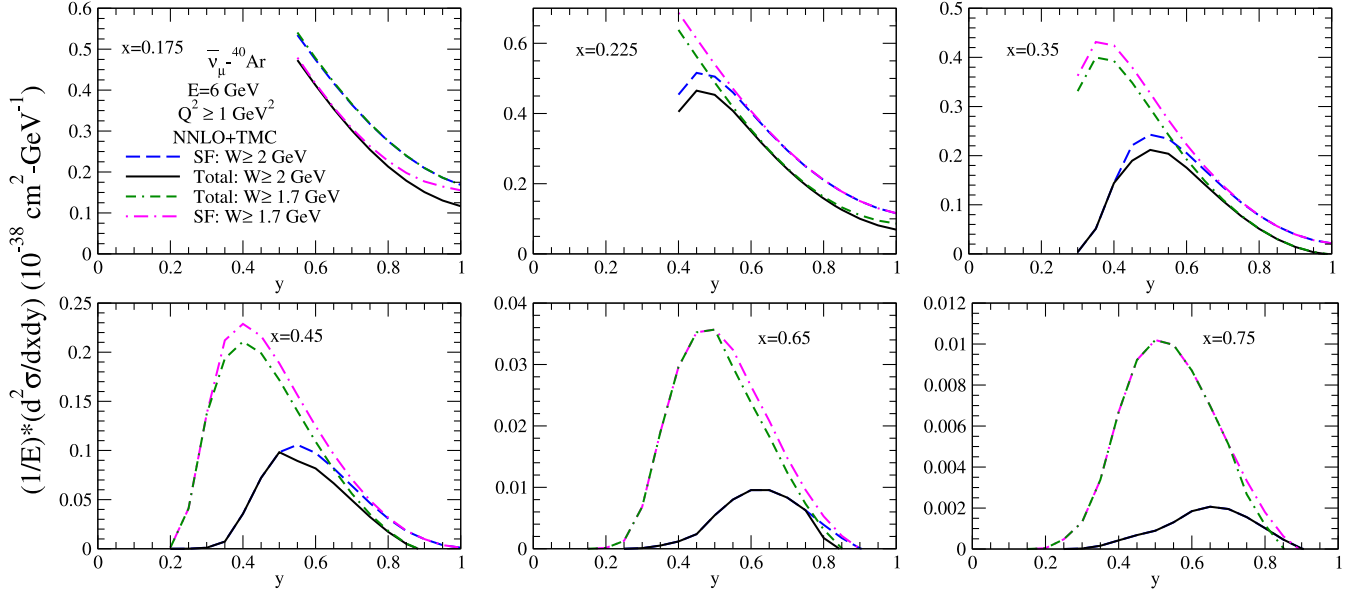


FIG. 12. $\frac{1}{E} \frac{d^2 \sigma}{dx dy}$ as a function of y at $E = 6$ GeV for the charged current $\bar{\nu}_\mu - {}^{40}\text{Ar}$ DIS process at different values of x . The line styles follow the same convention as in Fig. 7.

$0.3 \leq x \leq 0.8$. Furthermore, an enhancement is observed when the mesonic contributions are included in the low-to-intermediate x (≤ 0.5) region; for example, it is about 10–12% at $x = 0.3$, 4–5% at $x = 0.4$ and about 1% at $x = 0.5$ for

$4 \leq E \leq 6$ GeV, in the absence of any W cut. We find that, due to the inclusion of the nuclear medium effects, there is an enhancement in the differential cross section obtained using the full model in the region $x \leq 0.3$ relative to the

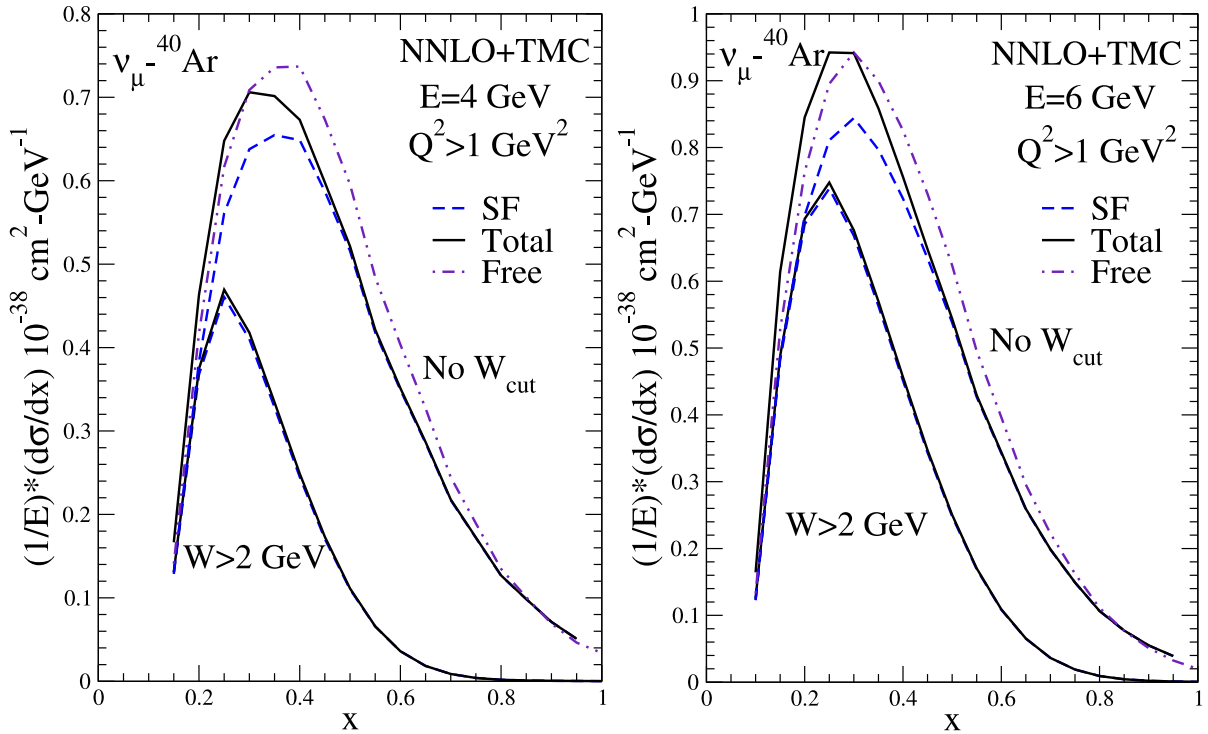


FIG. 13. $\frac{1}{E} \frac{d\sigma}{dx}$ as a function of x for $\nu_\mu - {}^{40}\text{Ar}$ DIS. The upper curves correspond to the results without a cut on W , while the lower curves include a cut of $W \geq 2$ GeV. The calculations are performed at NNLO with the TMC effect for $E = 4$ GeV (left panel) and $E = 6$ GeV (right panel). Results are shown using the SF only (dashed lines) and the full model (Total: solid lines). For comparison, results for a free nucleon target are also included (double-dot-dashed lines).

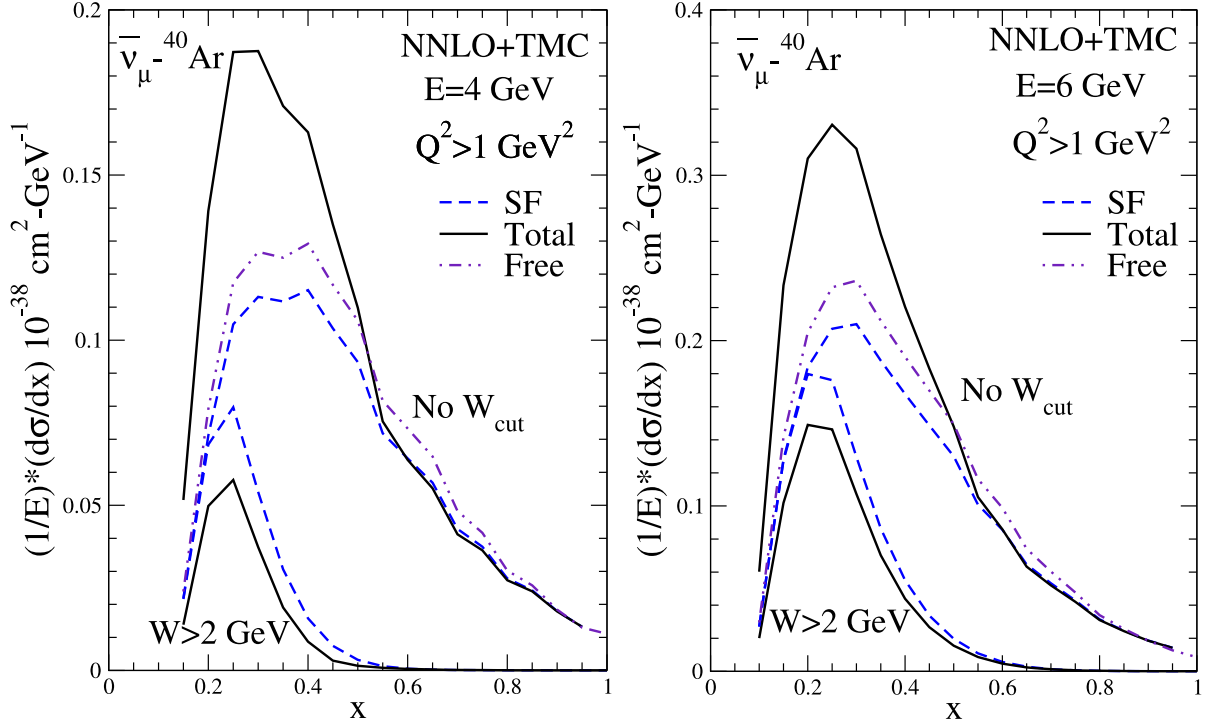


FIG. 14. $\frac{1}{E} \frac{d\sigma}{dx}$ as a function of x for $\bar{\nu}_\mu - {}^{40}\text{Ar}$ DIS. The upper curves correspond to the results without a cut on W , while the lower curves include a cut of $W \geq 2$ GeV. The calculations are performed at NNLO with the TMC effect for $E = 4$ GeV (left panel) and $E = 6$ GeV (right panel). Results are shown using the SF only (dashed lines) and the full model (Total: solid lines). For comparison, results for a free nucleon target are also included (double-dot-dashed lines).

$\nu_\mu - N$ DIS cross sections for $4 \text{ GeV} \leq E \leq 6 \text{ GeV}$; for example, this enhancement is about 16–18% at $x = 0.15$ and 4–5% at $x = 0.25$, while for $x > 0.3$, there is a reduction of about 8–9% at $x = 0.4$, 12–14% for $0.5 \leq x \leq 0.6$ and 4–6% at $x = 0.8$ in the energy region $4 \text{ GeV} \leq E \leq 6 \text{ GeV}$.

We find that the numerical results for the $\bar{\nu}_\mu - {}^{40}\text{Ar}$ DIS process (Fig. 14) follow a similar x dependence to that observed in the $\nu_\mu - {}^{40}\text{Ar}$ DIS process (Fig. 13). In the case of the $\bar{\nu}_\mu - {}^{40}\text{Ar}$ DIS cross sections, we observe that the impact of the nuclear medium effects is to enhance the differential cross sections obtained using the full model for $x \leq 0.55$ relative to the free nucleon case. For example, at $x = 0.2$, this enhancement is about 75% (50%), which becomes 48% (34%) at $x = 0.3$ and to 4% (1%) at $x = 0.5$ for $E = 4(6)$ GeV. However, for $x > 0.55$, these effects lead to a reduction in the differential cross sections, amounting to about 9–14% in the energy region $4 \text{ GeV} \leq E \leq 6 \text{ GeV}$.

Moreover, upon comparing the results in Figs. 13 and 14, it is observed that the differential cross sections for the $\bar{\nu}_\mu - {}^{40}\text{Ar}$ DIS process are significantly smaller than those for the $\nu_\mu - {}^{40}\text{Ar}$ DIS case. Quantitatively, the $\frac{1}{E} \frac{d\sigma}{dx}$ results obtained using the spectral function only, are suppressed by about 80%–82% at $E = 4$ GeV and by 74%–77% at $E = 6$ GeV for $0.2 \leq x \leq 0.5$, relative to the corresponding neutrino-argon scattering cross sections.

From Fig. 13, it may also be noticed that when a cut of $W \geq 2$ GeV is applied, the effect of the mesonic contribution becomes negligible. Furthermore, the peak of the differential cross sections shifts toward lower values of x upon applying the W cut, and the cross section is further suppressed in the entire x region relative to the case without a cut on W . From Fig. 14, it is important to note that the mesonic cloud contribution remains significant even after applying a cut of $W \geq 2$ GeV, unlike in the neutrino induced case. Moreover, the suppression in the neutrino (antineutrino) induced deep inelastic differential scattering cross sections obtained with the full model (“Total”) due to the application of the $W \geq 2$ GeV cut is about 27%(70%) at $x = 0.25$ and 63%(94%) at $x = 0.4$ for $E = 4$ GeV, which reduces to 21%(56%) and $\sim 40\%(80\%)$, respectively, at $E = 6$ GeV. Hence, the number of expected antineutrino events in the kinematic region corresponding to safe DIS, i.e., $W \geq 2$ GeV and $Q^2 \geq 1 \text{ GeV}^2$, is significantly suppressed compared to the case without a W cut. This behavior indicates that, in the high- x region corresponding to lower values of the center of mass energy, the contribution from the nucleon resonance region becomes important. Consequently, the applicability of the deep inelastic scattering formalism in the transition region ($W \leq 2$ GeV) may be inadequate, as it could lead to the double counting of neutrino events and introduce additional uncertainties in the determination of the scattering cross sections.

IV. SUMMARY AND CONCLUSION

In this work, we have studied ν_μ and $\bar{\nu}_\mu$ interactions on the ^{40}Ar target in the energy region of a few GeV. The numerical results have been presented for the differential scattering cross sections off the free nucleon as well as off the argon nuclear target in the kinematic region of $Q^2 \geq 1 \text{ GeV}^2$ without and with different cuts on the center of mass energy W . We summarize our findings below.

- (1) The nuclear medium effects on the differential cross sections for the $\nu_\mu - ^{40}\text{Ar}$ and $\bar{\nu}_\mu - ^{40}\text{Ar}$ DIS processes, arising from the inclusion of spectral functions that incorporate the Fermi motion, the binding energy, and the nucleon correlations, lead to a clear suppression of the cross sections. Importantly, this reduction is strongly kinematics dependent and is not uniform across the entire range of Bjorken x and inelasticity y , highlighting the nontrivial role of the nuclear dynamics in shaping the observed behavior.
- (2) The effect of the mesonic contributions is found to play a decisive role in enhancing the cross sections, particularly in the intermediate region of x , relative to the results obtained with only the nuclear structure effects. This enhancement can be as large as 14–20% at $x = 0.35$ and $y = 0.5$, and remains at a comparable level of about 7–10% at $x = 0.45$ and $y = 0.5$ for the ν_μ -induced scattering on the ^{40}Ar target in the energy region $4 \text{ GeV} \leq E \leq 6 \text{ GeV}$. In the case of the antineutrino induced processes, a similarly significant enhancement of 38–48% and 16–25% is observed over the same kinematic region of x and y , underscoring the crucial impact of the mesonic degrees of freedom.
- (3) The effects of the shadowing and the antishadowing corrections are found to be negligibly small in the considered kinematic range of x and y , indicating that their overall impact on the differential cross sections is minimal.
- (4) The nuclear medium effects are found to be significantly more pronounced in the antineutrino-induced processes than in the neutrino-induced processes off the argon nucleus.
- (5) The imposition of a cut on the center of mass energy is found to significantly suppress the cross section in the considered kinematic region of x and y for $4 \leq E \leq 6 \text{ GeV}$. Notably, this suppression becomes increasingly pronounced with increasing x , while it systematically weakens with increasing beam energy.
- (6) The reduction in the $\bar{\nu}_\mu - ^{40}\text{Ar}$ differential cross sections due to the imposition of a cut on the center of mass energy is found to be significantly more substantial than that observed for the $\nu_\mu - ^{40}\text{Ar}$ differential cross sections, underscoring a stronger sensitivity of the antineutrino-induced processes to this kinematic constraint.

To conclude, the nuclear medium effects are found to play a crucial and non-negligible role in the kinematic regime relevant to the DUNE and SBND energies. These effects should be understood with good precision for the current and future generation of (anti)neutrino experiments targeting high precision oscillation measurements. Furthermore, a deeper and more systematic investigation of the nuclear medium effects is imperative, particularly in the Q^2 region where perturbative QCD remains reliably applicable. Such studies are essential for achieving a comprehensive and quantitatively better understanding of the deep inelastic lepton-nucleus scattering.

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DATA AVAILABILITY

The data that support the findings of this article are available on request to the authors.

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