Identification of nuclear effects in neutrino and antineutrino interactions on nuclei using generalized final-state correlations

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In the study of neutrino and antineutrino interactions in the GeV regime, kinematic imbalances of the final-state particles have sensitivities to different nuclear effects. Previous ideas based on neutrino quasielastic interactions [Phys. Rev. C94, 015503 (2016), Phys. Rev. C95, 065501 (2017)] are now generalized to antineutrino quasielastic interactions, as well as neutrino and antineutrino pion productions. Measurements of these generalized final-state correlations could provide unique and direct constraints on the nuclear response inherently different for neutrinos and antineutrinos, and therefore delineate effects that could mimic CP violation in neutrino oscillations.

I. INTRODUCTION

It has been well established that good understanding of (anti)neutrino-nucleus cross sections in the GeV regime is necessary for constraining systematic errors in long-baseline oscillation experiments \cite{1,2}. The most important part of this effort is to describe nuclear effects. In the impulse approximation (IA) picture which has solid foundation in the few-GeV neutrino energy region, nuclear effects have impact on target nucleon initial state (Fermi momentum and binding energy) and also through final-state interactions (FSI) on how individual scattering is seen in experimental set-ups. In particular, it is very important to understand well any imprint of nuclear effects on neutrino and antineutrino scattering that could be misunderstood and taken in the data analysis as a manifestation of CP violation.

Besides nuclear effects, the few-GeV energy region is complicated because of the overlap of many reaction channels, physics mechanisms etc. The biggest unknown is the contribution from the two-body current (called here also 2p2h), a subject of many experimental and theoretical studies \cite{3,4}.

Events coming from two-body current mechanism contribute almost entirely to the charged-current (CC) 0\pi category, defined as having one charged lepton and no pion in the final state. They come there together with CC quasielastic (QE) events and also with pion production (RES) followed by absorption inside nucleus.

CC0\pi measurements are very important for experiments like T2K where most of information about the oscillation signal comes from detection of the final-state muons only. However, those measurements are not sufficient to put constraints on the amount of two-body current contributions. It is why there is a growing interest in measurements involving final-state protons. Interpretation of such measurements is challenging as it requires a good control of proton FSI in Monte Carlo (MC) event generators \cite{13}. This will become most exigent in liquid argon (LAr) experiments with a low momentum proton detection threshold \cite{14}. It is known that modeling low-momentum nucleon in-medium cross section is most uncertain \cite{15}. Challenges come together with opportunities and one may hope to learn from proton studies something new about nuclear physics.

Another challenge arising with the era of proton observables is that of the amount of information or how to organize the data. One option is to measure and discuss multidimensional cross section for muon and proton momenta \cite{16}. Another possibility is to look at certain projections defined in such a way that their interpretation is simpler, pointing to particular details of physics mechanisms that are involved.

An intuitive way to look at proton observables is through single-transverse kinematic imbalances (single-TKI) \cite{17}. What is analyzed are only transverse projections of muon and proton momentum vectors on the plane perpendicular to the neutrino direction (known with a good precision). If CCQE interaction occurred on a nucleon at rest and if FSI effects were absent, the sum of the muon and proton momentum projections would vanish. Thus any deviation from zero tells us about nucleon Fermi motion, FSI effects, and also about other interaction mechanisms.

Recently two measurements of single-TKI have been performed by T2K \cite{10} and MINERvA \cite{15} experiments. Their usefulness is immediate. Final-state particle correlations are non-trivial in the presence of nuclear effects: the characteristic imprints from Fermi motion and intranuclear momentum transfer (IMT) (that in our nomenclature includes impact of FSI and 2p2h dynamics) are readily identified in the measured cross sections. The new variable, \textit{transverse boosting angle} \delta_T \textit{(for details, see \cite{17})}, preserves most of the Fermi motion isotropy, and measures the strength of IMT. In the region \delta_T < 90^\circ, both T2K and MINERvA measurements are consistent, showing a common Fermi motion baseline; in the region \delta_T > 90^\circ they differ strongly as \delta_T increases—an intriguing feature pointing to the energy dependence of IMT. In the MINERvA measurement,
δνT also separates model predictions with boosting and dragging effects (“acceleration” vs. “deceleration”) of the FSI [17, 18], and therefore is able to isolate the peculiar elastic component of the GENIE hA FSI model [19].

A refinement of the kinematic imbalance studies was proposed in [20]. The basic observation was that in the IA regime the assumption that the interaction mechanism was CCQE and no FSI occurred allows to resolve the kinematics completely once the final-state muon and proton are measured. The additional piece of information used here comes from the longitudinal components of the final-state muon and proton momenta. The new proposed observable is emulated nucleon momentum pN. Its first measurement was done by MINERvA collaboration [18]. In the data there are three interesting regions in pN. A pronounced peak at pN ∼ 200 MeV/c is, according to MC simulations, dominated overwhelmingly by CCQE events without FSI. Then there is a tail region pN > 400 MeV/c and the intermediate region in between with a lot of structures allowing for detailed studies of interaction mechanisms and FSI effects. The CCQE peak in pN shows the neutron momentum distribution and it may seem surprising that a neutrino measurement with all its limitations allows for a nice visualization of the basic nucleon feature—that of Fermi motion.

Keeping in mind the usefulness of experimental studies of nuclear target reactions with the single-TKI and emulated nucleon momentum observables, we would like to extend this approach to other experimental situations. Several important reactions will be discussed in the same theoretical framework. We will argue that when put together they provide a powerful source of information about reaction mechanisms and nuclear effects.

Processes to be discussed are:

\[ \nu 0\pi N p : \nu A \rightarrow \ell^- p X, \] (1)
\[ \bar{\nu} 0\pi N p : \bar{\nu} A \rightarrow \ell^+ p X, \] (2)
\[ \nu 1\pi N p : \nu A \rightarrow \ell^- p \pi^+ X, \] (3)
\[ \bar{\nu} 1\pi N p : \bar{\nu} A \rightarrow \ell^+ p \pi^- X, \] (4)

where X is a final-state hadronic system consisting of the nuclear remnant with possible additional knocked-out nucleons but without mesons. It is assumed that one charged lepton, one proton, and one charged pion are detected. These include major ν/\bar{\nu} interaction channels at current and future accelerator-based neutrino experiments. The first investigation of the 1π channels [Eqs. (3–4)] using single- and double-TKI [21] was presented in [22].

The goal of this paper is to propose experimental probes for surgical diagnostics in nuclear effects in both neutrino and antineutrino CC interactions. The potential of the new observables will be illustrated by performing numerical simulations using GiBUU and NuWro generators with the MINERvA and T2K beam fluxes. The plan of the paper is as follows. In Sections III IV, we present the signal definitions, the formulae of the generalized final-state correlations, and the simulation details.

In Sections V VI, we discuss the model predictions and the implications.

II. UNDERLYING INTERACTION DYNAMICS

The underlying interaction dynamics of Eqs. (1–4) in IA and neglecting FSI are summarized as follows (to simplify the discussion, we neglect in this section but not in the numerical computations diffractive and higher resonant pion production):

\[ \nu n \rightarrow \ell^- p, \] (5)
not applicable,
\[ \nu p \rightarrow \ell^- \Delta^{++} \rightarrow \ell^- p \pi^+, \] (6)
\[ \bar{\nu} p \rightarrow \ell^+ \Delta^0 \rightarrow \ell^+ p \pi^-. \] (8)

The process in Eq. (2) is forbidden in IA without FSI due to charge imbalance.

In 2p2h dynamics neglecting FSI, additional reaction channels underlying Eqs. (1–2) are:

\[ \nu n N \rightarrow \ell^- p N, \] (9)
\[ \bar{\nu} p p \rightarrow \ell^+ n p, \] (10)

where N stands for either a proton or a neutron. One can see that Eq. (2) becomes possible as a result of 2p2h process. We disregard pion production in 2p2h mechanism about which very little is known.

When FSI sets in, many new scenarios contributing to reactions in Eqs (1–4) become possible. Most importantly, the pions resulting from primary interactions can be absorbed, and the nucleons can knock-out other nucleons or even pions seen in the final state. Among other channels, Eq. (2) is proposed here for its pure nuclear-effect origin. Its unique feature, as will be shown in following Sections, is the strongly reduced influence from the Fermi motion.

III. GENERALIZED FINAL-STATE CORRELATIONS

The nuclear target processes Eqs. (1–4) can be summarized as:

\[ \nu/\bar{\nu} + A \rightarrow \ell + \bar{N} + X, \] (11)

where \( \bar{N} \) is a proton in Eqs. (1–2) and a pπ pair in Eqs. (3–4). Similarly, in IA the reactions Eq. (11) can be summarized as:

\[ \nu/\bar{\nu} + N \rightarrow \ell + \bar{N}. \] (12)

Accordingly, the definitions of single-TKI given in [17] are generalized so that

\[ \delta \bar{p}_T = \bar{p}_T^\ell + \bar{p}_T^{\bar{N}}, \] (13)
where $\vec{p}_T^l$ and $\vec{p}_T^N$ are the transverse momenta of the lepton and N, respectively. The definition of the transverse boosting angle keeps its original form:

$$\delta\alpha_T \equiv \arccos \frac{-\vec{p}_T^l \cdot \delta \vec{p}_T}{p_T^l \delta p_T}.$$ (14)

Assuming that the target nucleus was at rest and no other particles were knocked out (i.e. X is the nuclear remnant of mass $M_X$), one can resolve kinematics of the process following the steps from Ref. [20]. The result for the longitudinal component of the target nucleon momentum is:

$$p_L = \frac{1}{2} (M_A + k_L^N + p_L^N - E_L - E_N)$$

$$- \frac{\delta p_T^2 + M_X^2}{2(M_A + k_L^N + p_L^N - E_L - E_N)},$$ (15)

where $M_A$ is target nucleus mass, and $k_L^N (p_L^N)$ and $E_L (E_N)$ are the longitudinal momentum and energy of $\ell$ ($N$), respectively.

The emulated nucleon momentum is defined as:

$$p_N \equiv \sqrt{\delta p_T^2 + p_L^2}.$$ (16)

The value of $M_X$ can be expressed in terms of the target nucleus mass $M_A$ and the proton/neutron mean excitation energies $\langle \epsilon \rangle_{p/n}$:

$$M_X = M_A - M_{p/n} + \langle \epsilon \rangle_{p/n},$$ (17)

where $M_{p/n}$ is proton/neutron mass. The values used in this paper are: $\langle \epsilon \rangle_n = 28.7$ MeV and $\langle \epsilon \rangle_p = 26.1$ MeV, see [23], Table 8.

IV. SIMULATIONS

IV.1. NuWro

NuWro [24] is a versatile MC neutrino event generator developed over last 13 years at the Wroclaw University. It provides a complete description of neutrino/antineutrino interactions on arbitrary nucleon/nuclear targets in the energy range from $\sim 100$ MeV to $\sim 1$ TeV. The basic interaction modes on a free-nucleon target are:

- CCQE: see Eq. 5, and its neutral current counterpart,
- RES: covering a region of invariant hadronic mass $W \leq 1.6$ GeV; the dominant RES process is $\Delta(1232)$-resonance excitation as in Eqs. 7–8
- DIS (jargon in the neutrino MC community for shallow and deep inelastic scattering [13]): all the inelastic processes with $W \geq 1.6$ GeV.

In the case of neutrino-nucleus scattering, two new interaction modes are:

- COH: coherent pion production,
- MEC: two-body current processes, called also 2p2h.

Neutrino-nucleus CCQE, RES, DIS, and MEC reactions are modeled as a two-step process; the primary interaction on one or two nucleons is followed by FSI.

NuWro FSI effects are described by custom-made semi-classical intranuclear cascade (INC) model [24]. It includes pion absorption and charge-exchange reactions treated according to the model of Oset et al. [25, 26]. Values of nucleon-nucleon in-medium cross section is based on the computations from Ref. [27].

In this paper we use NuWro configuration 17.09. CCQE is described with the local Fermi gas (LFG) model, and the standard vector and axial form factors with the axial mass value of 1.03 GeV. RPA effects are added following Ref. [25]. RES is based on N-$\Delta(1232)$ transition axial form factors found in Ref. [29] by a fit to ANL and BNL pion production data. Nonresonant contribution is added incoherently as explained in Ref. [30]. Nuclear target pion production cross section is reduced due to in-medium self-energy implemented in the approximate way using results of Ref. [31]. Finite $\Delta(1232)$-life-time effects are also included [24] as well as realistic angular distributions of pions resulting from $\Delta(1232)$ decays [32]. DIS is based on inclusive neutrino cross-section computations of Bodek-Yang with hadronization modeled using PYTHIA fragmentation routines. MEC is based on Nieves et al. model [5] with a momentum transfer cut $q \leq 1.2$ GeV/c [6]. As for the MEC hadronic part a model from Ref. [34] is used. It is assumed that in 85% of MEC events the interaction occurs on a proton-neutron pair [32, 33].

IV.2. GiBUU

GiBUU [36, 37] is a theoretical model and also an event generator describing nuclear interactions with nuclei, including photon-, lepton-, hadron-, and nucleus-nucleus reactions, with a consistent treatment of nuclear effects and a sophisticated kinetic hadronic transport framework. In these calculations, both the initial- and final-state hadrons are embedded in a coordinate- and momentum-dependent potential. The 2017 version is used in this study.

The target-nucleon momentum is sampled like in the LFG approach, but due to the nuclear potential the bound nucleon has an effective mass. In this approach, inclusion of RPA correlations are not needed, see [32–40]. The axial mass parameter in the dipole form factor for the quasielastic scattering is set to 1 GeV.

In the pion production kinematic region ($W < 2$ GeV), the vector couplings and transition form factors are determined by the MAID analysis [41]. The axial part for heavier resonances is determined by PCAC arguments and an assumption of a dipole form factor with the axial mass parameter of 1 GeV, whereas for $\Delta(1232)$
the axial part was obtained by a fit to bubble-chamber data \cite{42,43}. The non-resonant contributions (together with the interference one) are added in an incoherent way. Free spectral functions without in-medium corrections are used for the $\Delta$-resonance \cite{44}. GiBUU does not provide predictions for the coherent pion production. Inelastic processes at $W$ above 2 GeV are described as DIS by PYTHIA \cite{45}.

The 2p2h contribution in GiBUU is fully determined by the structure functions $W_1$ and $W_3$. By neglecting the longitudinal part of the response, both structure functions are directly related to the structure functions measured in electron-nucleus scattering \cite{46}. The relative numbers of initial neutron-proton, neutron-neutron, and proton-proton pairs are determined by combinatorics arguments.

After primary interactions, final-state particles are transported on-shell in phase-space volumes where quantum statistical effects like Pauli-Blocking are handled. GiBUU allows for an off-shell transport of hadrons but the results do not change much, and therefore this option is not used in this study. Pion absorption in FSIs are not used in this study. Proton-proton pairs are determined by combinatorics arguments.

FSI effects, it is equal to the target-neutron momentum.

The comparison between NuWro and GiBUU indicates that the initial state is modeled differently. It is clear that with the experimental data it is possible to discriminate between theoretical models, see Refs. \cite{18,50}. For example, the hole spectral function approach \cite{51} as implemented in NuWro provides much better agreement with the data than LFG with RPA corrections, see \cite{18}. For both experiments the shape and position of the peak in the $p_N$ distribution at 150–200 MeV/c: it comes from the neutron Fermi motion.

As discussed in \cite{20}, $p_N$ is defined in such a way that, for QE events with knocked-out proton not suffering from FSI effects, it is equal to the target-neutron momentum. This explains the peak in the $p_N$ distribution at 150–200 MeV/c: it comes from the neutron Fermi motion. The comparison between NuWro and GiBUU indicates that the initial state is modeled differently. It is clear that with the experimental data it is possible to discriminate between theoretical models, see Refs. \cite{18,50}. For example, the hole spectral function approach \cite{51} as implemented in NuWro provides much better agreement with the data than LFG with RPA corrections, see \cite{18}. For both experiments the shape and position of the peak in the $p_N$ distribution predicted by NuWro are very similar and the difference is mostly in its height (the T2K peak is higher). Our understanding is that MINERvA has on average more energetic protons which are removed from the Fermi motion peak by stronger FSI to the right tail.

For $\delta_{ETF}$, the non-flatness of the distribution of the QE events indicates the strength of the FSI experienced by

\begin{itemize}
  \item muon
    \begin{itemize}
      \item $\theta_\mu < 20^\circ$
      \item $1.5 \text{ GeV/c} < p_\mu < 10 \text{ GeV/c}$
    \end{itemize}
  \item proton
    \begin{itemize}
      \item $\theta_p < 70^\circ$
      \item $0.45 \text{ GeV/c} < p_p < 1.2 \text{ GeV/c}$
      \item at least one proton satisfies the above criteria and the most energetic one is selected in the analysis
    \end{itemize}
  \item charged pion
    \begin{itemize}
      \item $\theta_\pi < 70^\circ$
      \item $75 \text{ MeV} < T_\pi < 400 \text{ MeV}$
      \item exactly one charged pion satisfies the above criteria
    \end{itemize}
  \item no mesons otherwise,
\end{itemize}

where $p$, $T$, and $\theta$ are the particle momentum, kinetic energy, and angle with respect to the neutrino direction. \textbf{IV.3. MINERvA selection criteria} Predictions are calculated with the NuMI low-energy beam flux \cite{18} on carbon targets with the following particle selection:

\begin{itemize}
  \item muon
    \begin{itemize}
      \item $\theta_\mu < 126.87^\circ$ ($\cos \theta_\mu > -0.6$)
      \item $p_\mu > 0.25 \text{ GeV/c}$
    \end{itemize}
  \item proton
    \begin{itemize}
      \item $\theta_p < 66.42^\circ$ ($\cos \theta_p > 0.4$)
      \item $0.45 \text{ GeV/c} < p_p < 1 \text{ GeV/c}$
      \item at least one proton satisfies the above criteria and the most energetic one is selected in the analysis
    \end{itemize}
  \item charged pion
    \begin{itemize}
      \item $\theta_\pi < 70^\circ$
      \item $75 \text{ MeV} < T_\pi < 400 \text{ MeV}$
      \item exactly one pion satisfying the above criteria
    \end{itemize}
  \item no mesons otherwise.
\end{itemize}

\textbf{IV.4. T2K selection criteria}

Predictions are calculated with the T2K beam flux \cite{49} on carbon targets with the following particle selection:

\begin{itemize}
  \item muon
    \begin{itemize}
      \item $\theta_\mu < 20^\circ$
      \item $1.5 \text{ GeV/c} < p_\mu < 10 \text{ GeV/c}$
    \end{itemize}
  \item proton
    \begin{itemize}
      \item $\theta_p < 70^\circ$
      \item $0.45 \text{ GeV/c} < p_p < 1.2 \text{ GeV/c}$
      \item at least one proton satisfies the above criteria and the most energetic one is selected in the analysis
    \end{itemize}
  \item charged pion
    \begin{itemize}
      \item $\theta_\pi < 70^\circ$
      \item $75 \text{ MeV} < T_\pi < 400 \text{ MeV}$
      \item exactly one charged pion satisfies the above criteria
    \end{itemize}
  \item no mesons otherwise,
\end{itemize}

\textbf{V. RESULTS}
the knocked-out protons. In the bottom panel we see that the fraction of non-QE events gradually increases towards the large $\delta \alpha_T$ direction, and at $\delta \alpha_T = 180^\circ$ the beam-energy dependence becomes maximal.

In Fig. 2 results for the $\nu \bar{\nu} \pi Np$ selection are shown in the same format as in Fig. 1. This channel only includes QE events with charge-exchange nucleon FSI; therefore compared to the $\nu \pi Np$ channel the dominant Fermi motion peak is absent, and the rise of $\delta \alpha_T$ is much steeper. An interesting observation with this selection is that the GiBUU and NuWro overall predictions are very similar in shape and normalization, and yet this agreement turns out to be accidental since individual contributions from interaction modes are quite different. This is illustrated with the 2p2h contributions shown separately.

$\nu \pi Np$ and $\nu \bar{\nu} \pi Np$ contain complementary information about FSI and 2p2h mechanisms. For the $\nu \pi Np$ selection, QE FSI events are those with quasielastic proton rescattering. In the $\nu \bar{\nu} \pi Np$ selection, nucleon charge-exchange FSI is needed for the QE mechanism; 2p2h contribution comes either from proton-proton initial pairs without FSI or from proton-neutron pairs with charge-exchange FSI. NuWro assumes a much bigger fraction of initial proton-neutron pairs than GiBUU. We see that the two channels are sensitive to different details of the nucleon FSI and 2p2h mechanisms, and therefore a combined analysis of both channels would help to reveal the full picture of these dynamics.

The channels $\nu \pi Np$ and $\nu \bar{\nu} \pi Np$ (Figs. 3–4) are dominated by RES+DIS contributions. The variable $p_N$ is defined in such a way that, for events with $\Delta(1232)$ excitation decaying into a charged pion and a proton but not suffering from FSI effects, it is equal to the initial-nucleon momentum. This time the target nucleon is a proton and the difference between $\nu \pi Np$ and $\nu \bar{\nu} \pi Np$ is in the charge of the final-state pion. In both cases, a clear Fermi motion peak is predicted by GiBUU and NuWro, but again with different shapes. This peak provides the most direct constraint on the Fermi motion of the initial-state proton, which has not been yet directly studied in neutrino interactions. The overall amount of RES+DIS events without FSI is similar in both models, as demonstrated by the cross section at $\delta \alpha_T \rightarrow 0$. And yet, the $\delta \alpha_T$ rising trend indicates the different FSI strength in the two models. Also, by comparing the rising trend of $\delta \alpha_T$ between the two channels, one can conclude that in both models the $\nu \pi Np$ channel suffers stronger FSI, making a higher tail in $p_N$.

The calculations show that, in the kinematic regions of $\nu \pi Np$ and $\nu \bar{\nu} \pi Np$ probed by MINERvA and T2K experiments, the shape of $p_N$ and $\delta \alpha_T$ would depend only weakly on the neutrino energy. This is a very strong statement to be verified by experiments. We checked that the selection cuts on the final-state pions impose a restriction on $W$, with larger values being more strongly suppressed.

![Graphs showing GiBUU and NuWro predictions for the $\nu \bar{\nu} \pi Np$ selection.](image)

**FIG. 1.** GiBUU and NuWro predictions for the $\nu \bar{\nu} \pi Np$ selection. Differential cross sections in $p_N$ and $\delta \alpha_T$ respectively are compared between the two generators (upper two panels) and between MINERvA and T2K using NuWro (lower two panels). The corresponding QE components are shown.
FIG. 2. Model comparisons for $\bar{\nu}\pi Np$ in the same layout as in Fig. 1. The comparisons between MINERvA and T2K in the lower two panels are shown in shape. The 2p2h components are shown.

FIG. 3. Model comparisons for $\nu\pi Np$ in the same layout as in Fig. 2. The RES+DIS components are shown.
VI. DISCUSSION AND OUTLOOK

The next-generation long-baseline neutrino oscillation experiments DUNE and Hyper-Kamiokande aim to measure CP violation based on a comparison of the neutrino and antineutrino oscillation patterns. In order to achieve this goal a very good control of nuclear effects in (anti)nuetrino scattering is necessary. In particular, it is very important to control nuclear effects that are inherently distinct for neutrino and antineutrino scattering. The proposed generalized final-state correlations among the charged lepton and hadrons are minimally affected by nucleon-level phenomena and the beam flux [17]. They directly reveal details of the nuclear effects and allow to test theoretical models.

In water Cherenkov detectors one looks mainly at CCQE events and it is critical to analyze the oscillation signal with a model describing precisely the distributions of the charged-lepton kinetic energy and angle. Recent studies [1, 2, 23] have shown the effects of the initial states in measuring the oscillation parameters. In the $\delta_{CP}$ measurements where charged-lepton kinematics are used to infer the neutrino energy, understanding of the underlying neutron and proton Fermi motion is particularly important. A direct measurement of proton Fermi motion in the $\nu_1\pi N p$ and $\bar{\nu}_1\pi N p$ channels using $p_N$ could provide valuable knowledge of the response of the constituent proton to the different electroweak probes mediated by $W^{\pm}$-bosons, which could mimic CP violation in neutrino oscillations.

It would be interesting to use the proposed observables in LAr experiments. Argon is a heavier nuclear target which makes nucleon FSI effects stronger. On the other hand, in LAr detectors lower-momentum knocked-out protons with weaker FSI effects are also reconstructed. In the recent measurement of electron scattering on an argon target [52], the Fermi motion peaks from carbon and argon are shown to have different shapes. While Fermi motion of the constituent nucleons in argon nuclei can be inferred with electron scattering, it can be determined in situ in neutrino interactions by measuring $p_N$ in the $\nu_0\pi N p$, $\nu_1\pi N p$, and $\bar{\nu}_1\pi N p$ channels, the response to the axial current elicited.

As is suggested by the MINERvA $\nu_0\pi N p$ measurement [18], state-of-the-art generators fail in the transition region of $p_N$ between the Fermi motion peak and the region that is dominated by FSI and 2p2h. Without the Fermi motion peak in the $\bar{\nu}_0\pi N p$ channel, the source of this model deficit could be determined. More importantly, as [18] suggests that this intermediate region is where the MINERvA empirical 2p2h enhancement [53, 54] is strongest, one might suspect that the deficit could be related to the modeling of 2p2h. In the $\bar{\nu}_0\pi N p$ channel, the ambiguity caused by the Fermi motion tail in constraining 2p2h models is removed, potentially allowing a better understanding of this complicated mechanism. As such, the interplay of several dynamical mechanisms: the initial state, QE, RES, and 2p2h inter-

FIG. 4. Model comparisons for $\bar{\nu}_1\pi N p$ in the same layout as in Fig. 3.
actions, nucleon and pion FSIs, could be resolved.

Apart from nuclear-effect measurements, by selecting the Fermi motion peak in the $p_N$ distribution one can select a high-purity sample of genuine QE and RES events that do not experience FSIs in the $0\pi$ [Eq. (1)] and $1\pi$ [Eqs. (3-4)] channels, respectively. In such samples the neutrino energy can be precisely reconstructed, as was first illustrated for the QE events in [21].

The generalized final-state correlations focus on kinematics imbalances in exclusive reactions, which can be complemented by calorimetric inclusive measurements around the vertex region $^{53, 54}$. For example, a better $p_N$ peak measurement could be achieved by imposing a cut on the vertex energy, so that events other than non-FSI QE/RES are removed from the $0\pi/1\pi$ channel(s).

Finally, the selection of three charged particles required in channels $\nu\pi N p$ and $\bar{\nu}\pi N p$ has important experimental implications. As was first proposed and discussed in [21, 55], neutrino/antineutrino scattering is the only allowed exclusive production mechanism of three charged particles from lepton interactions on free protons. This gives the possibility to extract, on an event-by-event basis, neutrino/antineutrino-hydrogen interactions from compound targets that contain hydrogen atoms. In addition to the double-TKI [21], single-TKI (imbalance between the charged lepton and hadrons) and $p_N$ in principle could also provide separation power between interactions on hydrogen and heavier nuclei when the detector responses are optimized.

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