Multinucleon ejection model for two body current neutrino interactions

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A model is proposed to describe nucleons ejected from a nucleus as a result of two body current neutrino interaction. The model can be easily implemented in Monte Carlo neutrino event generators. Various possibilities to measure two body current contribution are discussed. The model can provide a help in identifying genuine charge current quasielastic events and allow for better determination of the systematic error of neutrino energy reconstruction in neutrino oscillation experiments.

I. INTRODUCTION

There is a lot of evidence for a significant multinucleon ejection contribution to the inclusive neutrino charge current (CC) cross section in the 1 GeV energy region [1]. On the experimental side, several recent nuclear target CCQE (CC quasi elastic) cross section measurements reported large value of the axial mass (M_A) in disagreement both with the older deuterium target measurements [2] and also with the electroproduction arguments [3]. A possible explanation for the discrepancy is that some events interpreted as CCQE are in fact due to a different dynamical mechanism which typically leads to multinucleon emission [4]. In fact, in the case of the MiniBooNE (MB) CCQE measurement, nucleons in the final state were not analyzed at all. MB collaboration reported the high statistics 2-dimensional muon inclusive cross section which is likely to contain a large multinucleon ejection contribution and thus provides a challenge for theoretical models [5].

On the theoretical side there are several two-body current computations which support the idea of the significant multinucleon contribution to the CC neutrino scattering. The first was the Marteau model, based on the earlier works of Ericson and Delorme [6]. The model is formulated in the framework of the non-relativistic Fermi Gas in the Local Density Approximation (LDA) approach. It includes the QE and Δ excitation elementary interactions, Random Phase Approximation (RPA are in medium polarization corrections important in the low four-momentum transfer region [7]) effects and Δ self-energy in the nuclear matter [8]. The model was later upgraded by Martini, Ericson, Chanfray and Marteau (MEChM model) and compared to the MB data [4]. It predicts a large np-nh (n particles and n holes; in the Fermi Gas picture ejection of n particles means that there are also n holes left in the Fermi sea) contribution to the CC cross section which can explain the MB CCQE anomalous M_A measurement. With the inclusion of the relativistic corrections the MB 2D differential cross section can be reproduced [9].

Another approach to the multinucleon ejection was proposed by Nieves, Ruiz Simo and Vicente Vacas [10].

The model uses techniques developed for the analysis of the inclusive electron-nucleus cross section in the kinematical region containing both QE and Δ excitation peaks [11]. The model is relativistic and incorporates similar nuclear effects as the MEChM model. In the paper [12] the comparison was done to the MB 2D CCQE data and the best fit axial mass value 1.08 ± 0.03 GeV was obtained.

The third microscopic computation of the multinucleon ejection in electron and neutrino interactions was discussed in a series of papers [13]. There are many similarities but also some differences between the three approaches and detail discussion of them can be found in [14].

Recently, an effective approach to describe multinucleon contribution to the neutrino inclusive cross section was also proposed. The Transverse Enhancement model (TEM) [15] is based on the analysis of the electron-carbon scattering data and parameterizes the multinucleon ejection contribution to the muon inclusive cross section in terms of a modification of the magnetic electromagnetic form factor. The model predicts that the two body current contribution is less important at larger neutrino energies which can reduce a tension between the MB and NOMAD [16] axial mass measurements.

In all the approaches the calculated quantity is the contribution to muon inclusive differential cross section corresponding to multinucleon ejection. This is sufficient if the aim is to reproduce the MB 2D CCQE data. However, any attempt to separate dynamical mechanism leading to the CCQE-like events (defined here as those with no pions in the final state) must be based on a careful investigation of the hadrons in the final state. This introduces a new ingredient to the discussion, the Final State Interactions (FSI) effects. There are always CCQE-like events which are not really CCQE due to FSI effects. The major contribution comes from the pion absorption but there are also events with several nucleons in the final state originating from a primary CCQE interaction with energetic outgoing proton. A further clarification is necessary: in this paper the term *CCQE* will always refer to primary interactions. The basic picture is that of a nucleus as composed from quasi-free nucleons.

In many neutrino oscillation experiments neutrino energy is reconstructed based on the muon information only and it is clear that the two body current contribution can introduce a significant bias and should be considered in

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the evaluation of systematic errors. It is important to develop models of the two body current contribution which can be implemented in neutrino Monte Carlo (MC) event generators [17] and for that one needs predictions for nucleons in the final state. The aim of this paper is to propose a model to provide such an information. The nucleon ejection part of the model is quite universal and can be used together with any model of the double differential muon inclusive cross section for the multinucleon ejection.

The paper is organized in the following way. In Sect. 2 the multinucleon ejection model is introduced. In order to make numerical predictions a model of muon 2D differential cross section is necessary. Two such models are described: a microscopic model inspired by the Marteau approach and the effective TE model. Both models have been implemented in the NuWro MC event generator [18]. In Sect. 3 some predictions from the model are shown and the focus is on demostration of the relevance of the FSI effects. Section 4 contains a discussion of possible ways to measure the two body contribution experimentally and a few final remarks can be found in Sect. 5.

II. THE MODEL

The multinucleon ejection model proposed in this paper is quite general. It needs as an input a muon inclusive differential cross section model and two models used in the numerical computations will be described in II B.

A. Nucleon ejection model

Two basic assumptions of the model is that the energy and momentum are transfered to two (or three) nucleons simultaneously.

The scheme of the procedure to generate nucleon final states is as follows:

- two (or three) nucleons are selected from the Fermi sphere of radius 220 MeV (it is assumed that interaction occurs on carbon)

- four momentum of the hadronic system is calculated by adding four momenta of selected nucleons and the energy and momentum transfered by the interacting neutrino

- the Lorentz boost to the hadronic center of mass system is done

- two (or three) nucleons are selected isotropically in the hadronic center of mass system

- the boost back to the laboratory frame is performed.

Each event is weighted by the muon inclusive differential cross section. The energy balance is done based on the assumptions that inital state nucleons are in the potential well of the depth $V = E_f + 8$ MeV (E_f is the Fermi energy). In the numerical computations:

- the Fermi energy is subtracted from each initial state nucleon

- for each nucleon in the final state (in the LAB frame) its energy is reduced by 8 MeV adjusting the momentum so that it remains on-shell.

The above procedure allows for a smooth distribution of the nucleon momenta in the final state. When the model is implemented in a MC event generator after the initial interection nucleons propagate through a nucleus and are subject to rescatterings. The treatment of energy balance must be consistent with the way in which the cascade model is designed.

The algorithm introduces some correlations between the initial state nucleons: not all the initial configurations give rise to a hadronic system with the center of mass invariant mass larger than $2M$ (or $3M$ for three nucleon ejection; M is nucleon's mass). In the numerical code initial state nucleon configurations are selected until acceptable nucleon momenta are found.

Tests were also done with the fully correlated pairs of nucleons in the initial state in the deuteron-like configuration with opposite three-momenta. It turned out that the results remain virtually unchanged. The most important assumption of the model is that of the isotropic distribution of the final nucleons in the hadronic center of mass frame.

In the Monte Carlo implementation it is assumed that in the CC neutrino reactions $\sim 80\%$ of the final state nucleons are protons and only $\sim 20\%$ are neutrons. For the CC antineutrino reactions the isospin composition of the final state is opposite with $\sim 80\%$ of neutrons and $\sim 20\%$ of protons. Also the authors of the MEChM model claim that in the case of the CC neutrino interactions in the initial state there should be much more proton-neutron than neutron-neutron pairs and as a consequence more proton-proton than proton-neutron pairs in the final state [4].

We note that the above procedure to get nucleons in the final state is similar to the one considered earlier in the paper [23].

B. Muon cross section models

In this subsection two models of muon inclusive cross section models are presented.

1. Microscopic model

The model is based on the Marteau approach [19]. It was developed about 10 years ago and discussed at the
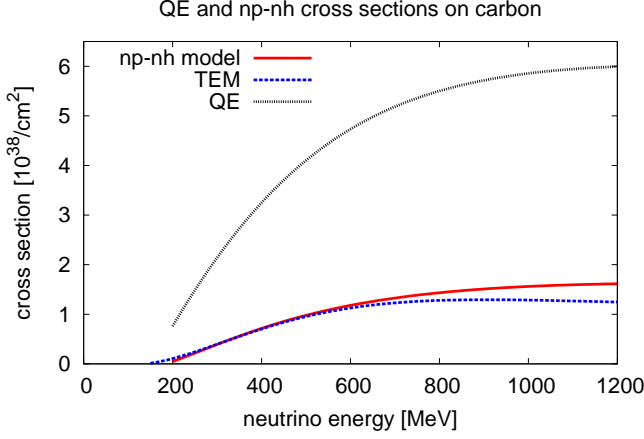
QE and np-nh cross sections on carbon

FIG. 1. (Color online) Predictions for np-nh contribution to the CC scattering on carbon from two models discussed in this paper. For the comparison also QE cross section is shown.

Two body current contributions to dσ/dω, E_ν=750 MeV
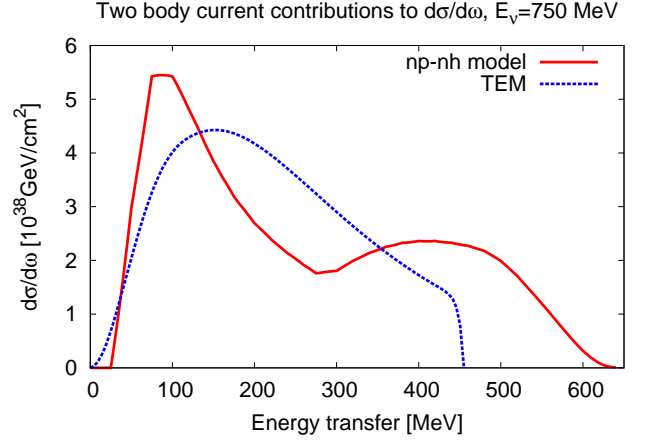
FIG. 2. (Color online) Predictions for the two body current contribution to the CC carbon target differential cross section in energy transfer from two models discussed in this paper.

NuInt02 workshop [20]. The cross section is given as:

$$\frac{d^2\sigma}{dqd\omega} = \frac{G_F \cos^2\theta_C q}{32\pi E_\nu^2} L_{\mu\nu} H^{\mu\nu}, \qquad (1)$$

where E_ν is the neutrino energy, $q^\mu = (\omega, \vec{q})$ is the four-momentum transfer, $q = |\vec{q}|$, $L_{\mu\nu}$ is the leptonic tensor

$$L_{\mu\nu} = 8\left(k'_\mu k_\nu + k_\mu k'_\nu - g_{\mu\nu} k \cdot k' \pm i\epsilon_{\mu\nu\alpha\beta} k'^\alpha k^\beta\right), \quad (2)$$

k and k' are neutrino and charged lepton four-momenta, $\pm$ signs refer to the neutrino and antineutrino cases.

The hadronic current is:

$$H^{\mu\nu} = H^{\mu\nu}_{NN} + H^{\mu\nu}_{N\Delta} + H^{\mu\nu}_{\Delta N} + H^{\mu\nu}_{\Delta\Delta}, \qquad (3)$$

where $H^{\mu\nu}_{XY}$, $X, Y \in (N, \Delta)$ are expressed in terms of expectation values of spin operators acting in the nucleus Hilbert space, so called nuclear response functions. The model uses quasi elastic form factors to describe the Δ excitation and consistency of the approach was investigated in [21].

More details about the model can be found in [20], see also [6]. The model includes the RPA and Δ in-medium self-energy effects. Recently, the model was upgraded and it now contains the LDA effects. The elementary 2p-2h responses were added following the procedures described in [19]. The model in this paper – like the MEChM model – does not include RPA corrections to the np-nh contribution (the exception are terms describing pionless Δ decays). It was checked that the elementary response functions used in the microscopic model are similar to those used in the MEChM paper, as they are shown in Fig. 3 in [4].

In the Appendix A we collect basic formulas which allow for a comparison with other approaches.

In the microscopic model there is a possibility of two- and three- nucleon ejection. The three nucleon ejection contribution comes from pionless Δ decays i.e. from reactions $N\Delta \to NN$ and $NN\Delta \to NNN$ with N standing for a nucleon [8].

2. Transverse Enhancement Model

In [15] a new approach to describe CCQE scattering on nuclear targets is proposed. The model is easy to implement in MC event generators. It is sufficient to modify the vector magnetic form factor keeping all other ingredients of the CCQE model as in the free nucleon target case.

The authors of [15] proposed for the carbon target a universal transverse enhancement function of Q^2. For the low Q^2 its form is determined by the scaling arguments while for the large Q^2 (> 0.5 GeV^2) it is obtained as a fit to the inclusive electron cross section data from the JUPITER experiment. The prescription to include transverse enhancement contribution in the numerical computations amounts to the replacement:

$$G^{p,n}_M(Q^2) \to \tilde{G}^{p,n}_M(Q^2) = \sqrt{1 + AQ^2 \exp(-\frac{Q^2}{B})}\, G^{p,n}_M(Q^2)$$
$$(4)$$

where $G^{p,n}_M(Q^2)$ are electromagnetic form-factors, $A = 6$ GeV^{-2} and $B = 0.34$ GeV^2.

The most interesting feature of the TEM model is that it offers a possible explanation to the apparent contradiction between low (MB) and high (NOMAD) neutrino energy M_A measurements: for energies up to ~ 700 MeV TEM predicts the cross section to be similar to CCQE with $M_A = 1.3$ GeV. For higher neutrino energies the TEM cross section becomes significantly smaller and at $E_\nu \sim 5$ GeV it corresponds to CCQE with $M_A \sim 1.15$ GeV.

As the TEM prediction for the two body current contribution one takes the difference between the cross sections calculated with the modified and default magnetic form factors:

$$\frac{d^2\sigma^{TEM}}{dqd\omega} = \frac{d^2\sigma^{CCQE}}{dqd\omega}(\tilde{G}^{p,n}_M) - \frac{d^2\sigma^{CCQE}}{dqd\omega}(G^{p,n}_M). \quad (5)$$

In the case of the TE model it is assumed that only two nucleon ejection takes place.

C. Muon CC models comparison

Fig. 1 shows the predictions for the np-nh contribution from both models. It can be seen that they are quite similar in size and only for neutrino energies above 700 MeV the microscopic model predicts larger cross section. For comparison the predictions for the QE cross section (one outgoing nucleon at the interaction point) are shown as well. It follows that in the case of presented models the multinucleon ejection contribution amounts to about 25% of the QE cross section.

Fig. 2 shows the differential cross section for the multinucleon ejection contribution as a function of the energy transfer. It should be stressed that so far no assumptions about the final state nucleons were necessary. It can be seen that the predictions from both models are quite different. In the case of the microscopic model there is a lot of structure coming from various ingredients of the model: contributions from pionless Δ decays, elementary NN and $N\Delta$ 2p-2h responses. Similar structure can be seen also in Fig. 2 in [4]. There are two versions of the MEChM model which differ by elementary 2p-2h response functions. Following the procedures described in [4], by making a fit to the data contained in [22] new responses as functions of the variable $x \equiv Q^2/2M\omega = (q^2 - \omega^2)/2M\omega$ (where M is the nucleon mass) were obtained. However, within the microscopic model of this paper the new responses lead to too rapidly increasing np-nh cross section as a function of neutrino energy and in the rest of this paper the original Marteau responses are used [19].

In the case of the TE model a sharp fall down of the differential cross section at ~ 460 MeV comes from the way in which the model was implemented. We followed the original paper and assumed the target nucleon to be at rest. Pauli blocking effects are introduced by means of a Q^2 depending suppression function. An alternative implementation is to use the Fermi Gas model, but it is not obvious which approach leads to better agreement with the MB 2D CCQE data [24].

III. RESULTS

Figures 3 – 8 show predictions from both models implemented in the NuWro MC event generator. All of them are for protons only because in the experimental analysis neutrons are usually not detected. In Section III we focus on the impact of FSI effects on the results.
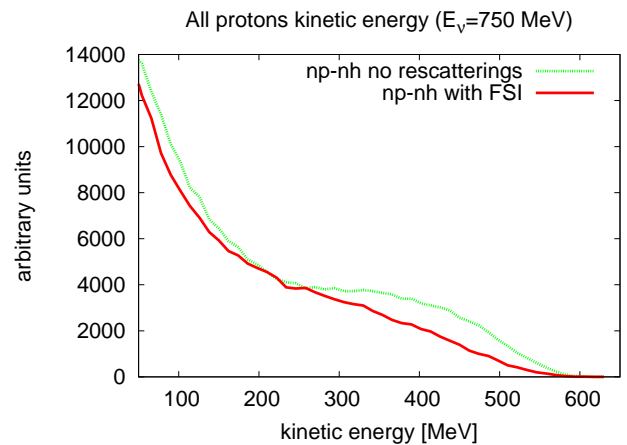

FIG. 3. (Color online) Total kinetic energy of the final state protons coming from two body current interactions as modeled by the microscopic model implemented in NuWro. Predictions from the model with and without nucleon rescatterings are compared. Neutrino energy is 750 MeV.
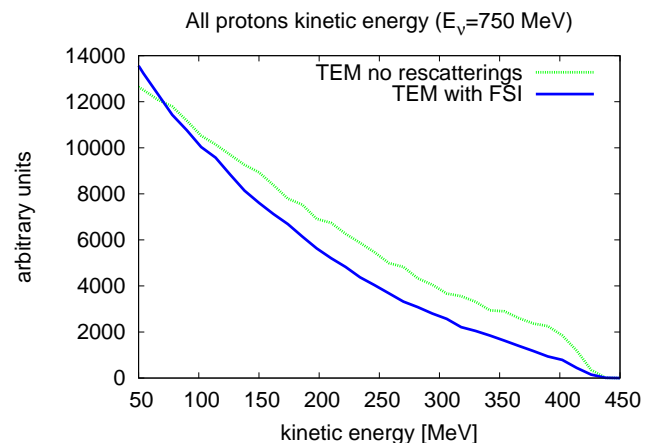

FIG. 4. (Color online) The same as in Fig. 3 but for the TE model.

A. Total kinetic energy

Figs 3 and 4 show the kinetic energy of all the protons in the final state. It is seen that due to rescatterings protons loose a fraction of their kinetic energy. According to the NuWro FSI model it can happen that there are no protons in the final state.

B. Nucleon momenta

Figs 5 – 8 show the distributions of the momenta of highest energy and second highest energy protons in the final state. Again, it is seen that because of reinteractions protons becomes less energetic. One can make a rough estimate that on average their momenta are reduced by
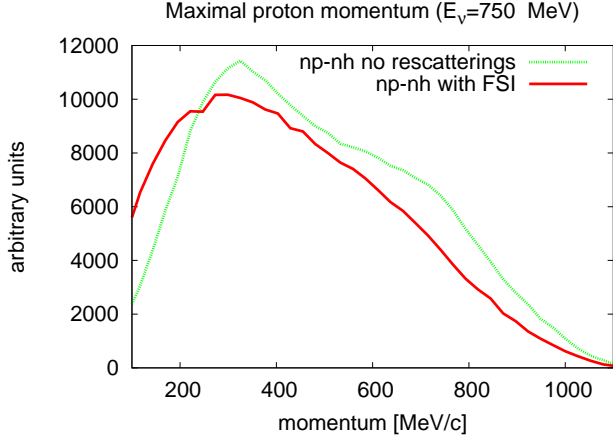
FIG. 5. (Color online) Momentum of most energetic final state protons coming from two body current interactions as modeled by the microscopic model implemented in NuWro. Predictions from the model with and without nucleon rescatterings are compared. Neutrino energy is 750 MeV.
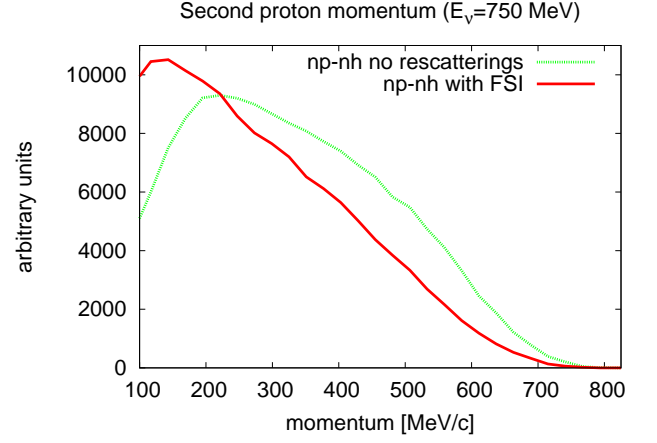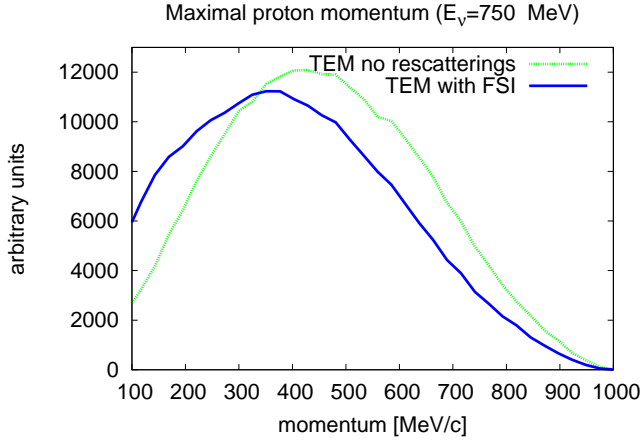

FIG. 7. (Color online) Momentum of second energetic final state protons coming from two body current interactions as modeled by the microscopic model implemented in NuWro. Predictions from the model with and without nucleon rescatterings are compared. Neutrino energy is 750 MeV.

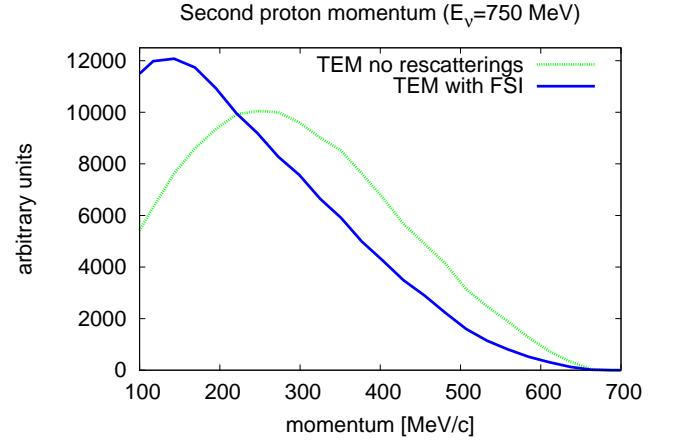FIG. 6. (Color online) The same as in Fig. 5 but for the TE model.

FIG. 8. (Color online) The same as in Fig. 7 but for the TE model.

C. Energy reconstruction

Fig. 11 shows the distribution of reconstructed energy E_{rec}^{QE} obtained within the microscopic model. The true neutrino energy is always 750 MeV. E_{rec}^{QE} is defined based on the information infered from the final muon only, assuming that the interaction is CCQE and the target nucleon is at rest:

$$E_{rec}^{QE} = \frac{2ME_\mu - m^2}{2(M - E_\mu + \sqrt{E_\mu^2 - m^2}\cos\theta_\mu)} \quad (6)$$

where E_μ is muon energy, m is muon mass, and θ_μ is an angle between neutrino and muon three momenta.

The presence of the two body current contribution introduces an important bias and it can be seen that on average the true neutrino energy is larger by $\sim 150 -$

~ 100 MeV/c.

An interesting feature of the distribution of second energetic protons is that the rescatterings make smaller the fraction of events in which there is at most one proton in the final state.

The distributions seen in Figs 7 and 8 are important because they allow for an estimate of the probability that there is a pair of reconstructed protons in the final state. It is interesting that at the neutrino energy of only 750 MeV the second nucleon can be quite energetic.

Figs 9 – 10 show two-dimensional distributions: highest energy versus second highest energy protons for both models. One can see that because the range of energy transfers for the TEM is smaller also the phase space covered by pairs of protons is reduced.
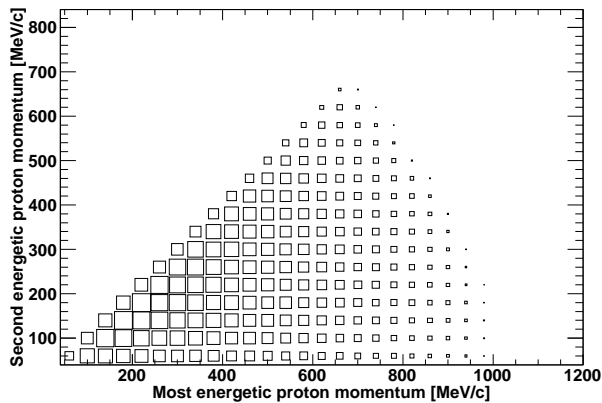
FIG. 9. Two dimensional distribution of proton momenta: highest energy wrt to second highest energy protons. Muon neutrino energy is 750 MeV, simulations are done for the TE model.
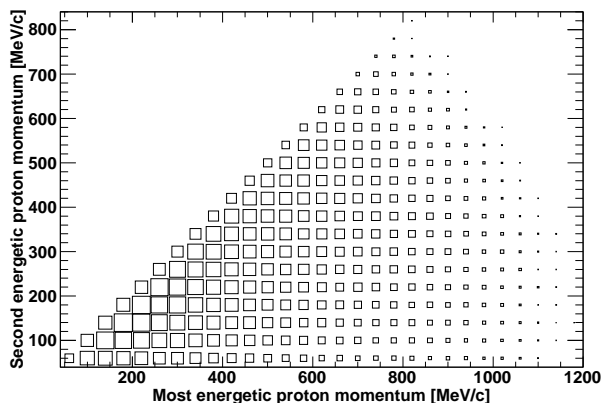

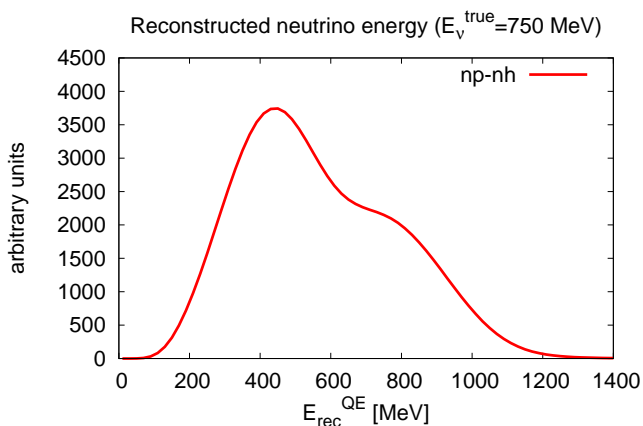FIG. 10. The same as in Fig. 9 but for the microscopic model.

FIG. 11. (Color online) Reconstructed neutrino energy for two body current interactions of $E_\nu = 750$ MeV muon neutrino.

200 MeV than E_{rec}^{QE}.

The TEM uses the QE kinematics and it is not suitable to study the bias in energy reconstruction.

IV. DISCUSSION

A. A role of energy transfer

The predictions from both models implemented in NuWro are quite similar in shape and the only major difference between them is that in microscopic model protons are on average more energetic. This can be understood as a consequence of different shapes of muon differential cross sections in energy transfer. In fact, this energy (a fraction of) is seen as the kinetic energy of ejected protons. From the point of view of the multi-nucleon ejection model, the most important features of muon CC two body current contribution to the differential cross section are: (i) the integrated size, and (ii) the distribution of events in the energy transfer.

B. How to see two body current events

In the 1 GeV energy region (e.g. as it is in the T2K experiment) two body current events are almost all CCQE-like. The probability to produce pions due to FSI effects is negligible. It follows that in the experimental analysis it is important to develop an effective veto on pions.

There seem to be two promising observables which contain an information about the two body current contribution. The first one are pairs of protons in the final state both with momenta above some threshold value. The second one is the integrated kinetic energy of charged hadrons in the final state. In fact, if the typical neutrinos energies are about or below 1 GeV most of the protons will most likely remain not reconstructed and they will only contribute to the vertex activity.

All the computations discussed below are done for the 750 MeV muon neutrinos. They can give an idea about the size of effect to be expected e.g. in the T2K experiment. The computations are done for the models as implemented in NuWro with all the FSI effects being included.

1. Proton pairs

Tables I and II show predicted number of proton pairs with both momenta above various threshold values. The signal is defined as exactly two protons above: 300, 400 and 500 MeV/c. It is assumed that in the samples of events there are no π^0 (π^0 is either reconstructed or at least one energetic photon resulting from its decay is detected). As for $\pi^\pm$ it is assumed that they can be identified if their momenta are above either 0 (i.e. all of them are detected and the sample of events contains no $\pi^\pm$),

$\pi^{\pm}$ cut $[\frac{MeV}{c}]\downarrow$ ‖ proton cut $[\frac{MeV}{c}] \rightarrow$		300	400	500
0	signal	5457	2271	651
	background	13780	7961	2267
200	signal	5465	2271	651
	background	16112	8691	2349

TABLE I. Predicted number of proton pairs with both momenta above various threshold values and two threshold values of the $\pi^{\pm}$ momentum. Simulations were done for 750MeV muon neutrinos. The number of generated events is $2.5 \cdot 10^{5}$. TE model NuWro implementation was used to produce signal events.

$\pi^{\pm}$ cut $[\frac{MeV}{c}]\downarrow$ ‖ proton cut $[\frac{MeV}{c}] \rightarrow$		300	400	500
0	signal	7185	4201	1805
	background	13774	7928	2311
200	signal	7231	4201	1805
	background	16158	8577	2388

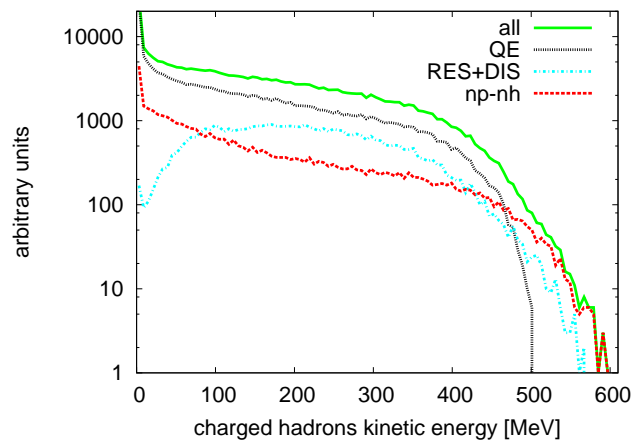TABLE II. The same as in TABLE I but for the NuWro implementation of the microscopic model.

FIG. 12. (Color online) The distribution of hadronic kinetic energy for the events with cuts as described in the text. Simulations were done with 750 MeV muon neutrinos using NuWro implementation of the microscopic model. The number of generated events is $2.5 \cdot 10^{5}$. Contributions from CCQE, RES+DIS and np-nh events are also shown separately.

or 200 MeV/c. In each situation the numbers of signal and background events are shown separately. The background events are those with exactly two protons satisfying the selection criteria but originating from other dynamical mechanisms. The total number of generated CC events is $2.5 \cdot 10^{5}$. In the case of microscopic model for multinucleon ejection the sample of events contains: 59.4% QE and 15.2% two body current events. Remaining are mostly single pion production events. For the TEM the composition of the sample of events is similar. The background for the two proton signal comes mainly from the real pion production and its subsequent absorption. NuWro implementation of the absorption contains only two body mechanism, and the size of the background can be overestimated [26].

We notice that there are noticable differences in the predictions for the number of the signal events from two analyzed model and they show an interesting pattern. In the case of pairs of protons both with momenta above 500 MeV/c the difference is by a factor of 3 while for protons with momenta above 400 MeV/c and 300 MeV/c the differences are only $\sim 80\%$ and $\sim 30\%$. For larger proton momenta the pattern can be explained by the fact that probability of large energy transfer is in the case of microscopic model much bigger. For lower proton momenta the most important becomes the fact that overall cross sections for multinucleon ejection are in both models quite similar.

The numbers of background events are slightly different in both cases. They were generated in two separate simulations and also the cross sections for multinucleon ejection are slightly different.

The numbers shown in Tables I and II suggest that in order to separate the signal from the background it is enough to have the precision in the background estima-
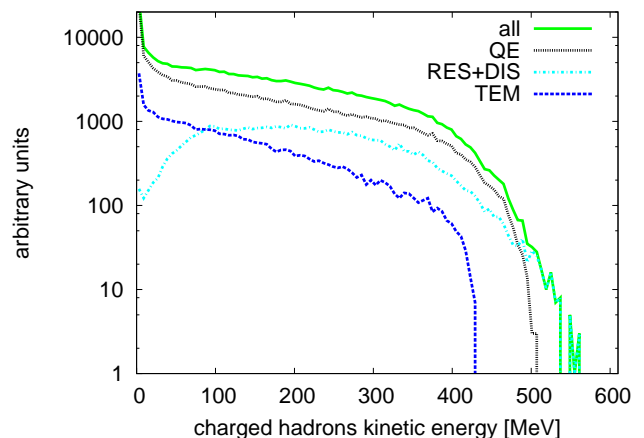

FIG. 13. (Color online) The same as in Fig. 12 but for the TE model.

tion on the level of 50%, which seems to be realistic goal to achieve.

We conclude that counting of proton pairs can provide an experimental proof of existence of the multinucleon ejection contribution and also a tool to discriminate between various models. However, it is necessary to have large samples of event because the probability to have a signal pair of protons with both momenta above 500 MeV/c is only $0.26 - 0.72\%$.
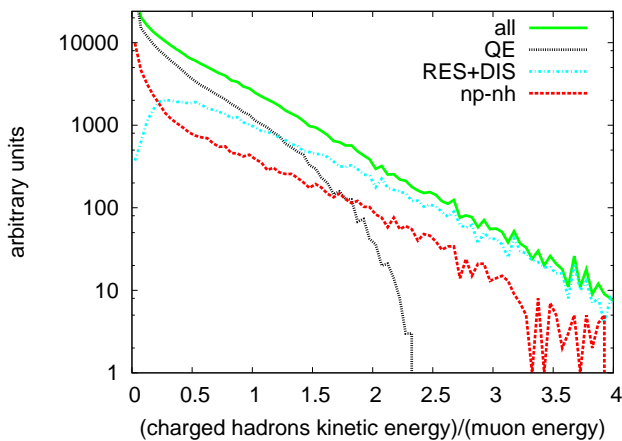
FIG. 14. (Color online) The distribution of hadronic kinetic energy normalized by the muon energy (see Eq. 7) for the events with cuts as described in the text. Simulations were done with 750 MeV muon neutrinos using NuWro implementation of the microscopic model. The number of generated events is $2.5 \cdot 10^5$. Contributions from CCQE, RES+DIS and np-nh events are also shown separately.
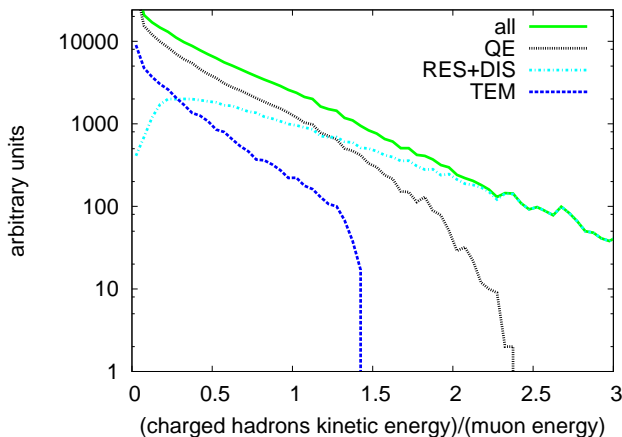

FIG. 15. (Color online) The same as in Fig. 14 but for the TE model.

2. Integrated energy of charged hadrons

For the overall charged hadron kinetic energy two observables can be considered:

$$\sum_j T_j, \qquad \text{and} \qquad \frac{\sum_j T_j}{E_\mu}. \qquad (7)$$

where j runs over charged hadrons in the final state and E_μ is the muon energy. All the protons contribute to the observables defined above, independent on how large their momenta are. Also in this case one must introduce some assumptions about the pions. In the plots shown in Figs 12 – 15 in the signal events there are no π^0 and no $\pi^\pm$ with momenta above 200 MeV/c. In the figures con-

tributions from CCQE, RES+DIS and two body current mechanism are also shown separately. In the neutrino MC nomenclature RES refers to the resonance region and DIS to more inelastic events but for the purpose of this study they are combined together. All three contributions are different in shape. This is clearly seen in the case of RES+DIS. The shape of the multinucleon ejection contribution depend on the underlying muon cross section model and on the FSI effects. It is important to remember that in the distributions shown in Figs 12 and 14 also reconstructed protons are included.

In the actual experimental analysis the directly observable quantity is the reconstructed energy. However, using neutrino MC generator one can make predictions for the shape of the distribution of the reconstructed energy and compare to the data. It can happen that both measured and predicted shapes do not match and that the inclusion of the contribution from the two body current mechanism one gets much better data/MC agreement.

V. FINAL REMARKS

The aim of this paper was to discuss the phenomenological consequences of the two body current contribution to the neutrino CC muon inclusive cross section. In order to estimate the size of effect for the hadron observables the multinucleon ejection model was proposed which can be easily implemented in neutrino MC event generators. Using the model some observables which contain an information about two body current dynamics were discussed.

It is important that the multinucleon ejection model proposed in the Section II A can be used together with any model providing predictions for the two body contribution to the CC inclusive neutrino-nucleus cross section.

Identification of the two body current experimental signal can only be possible based on a careful data/MC comparison. For that it is essential to have a reliable model of FSI effects. It is also central to have a good description of the nucleon final states arising after pion absorption.

One should also keep in mind that on the theoretical side there is a lot of uncertainty how large the two body current contribution is expected to be. A careful comparison of the predictions from the models described in the Introduction for the MiniBooNE flux averaged contribution in the region $\cos\theta_\mu \in (0.8, 0.9)$ (see Fig. 6 in [9] , Fig. 3 in [12] and Fig. 4 in [25]) reveals that they differ by a factor of two.

All the microscopic models discussed in this paper are based on the Local Fermi Gas model and the arguments of the paper [27] indicate that in order to evaluate the two body current contribution it is necessary to use more realistic model of the nucleus ground state. For the multinucleon ejection model this would also mean that one should include more correlations between initial state nucleons.

During the work on the upgraded version of this paper an article on the similar subject was published by

Lalakulich et al [28].

Appendix A: Some formulas from the microscopic model used in this paper

The components of the hadronic tensor are expressed as:

$$H^{\mu\nu} = H^{\mu\nu}_{NN} + H^{\mu\nu}_{N\Delta} + H^{\mu\nu}_{\Delta N} + H^{\mu\nu}_{\Delta\Delta}. \quad (A1)$$

For example,

$$H^{00}_{XY} = \sqrt{\frac{M_X + \sqrt{M_X^2 + q^2}}{2M_X}} \sqrt{\frac{M_Y + \sqrt{M_Y^2 + q^2}}{2M_Y}}$$

$$\left(\alpha^0_{0X} \alpha^0_{0Y} R^c_{XY} + \beta^0_{0X} \beta^0_{0Y} R^l_{XY}\right), \quad (A2)$$

$$\alpha^0_{0X} = F_1(\omega, q) - F_2(\omega, q) \frac{q^2}{2M(M_X + E_q^X)}$$

$$\beta^0_{0X} = \frac{q}{M_X + E_q^X}\left(G_A(\omega, q) - \frac{\omega}{2M} G_p(\omega, q)\right). \quad (A3)$$

F_1, F_2, G_A and G_p are standard form factor in the weak nucleon-nucleon transition matrix element.

In the case of free Fermi gas:

$$R_{N\Delta} = R_{\Delta N} = 0,$$

$$R^{c,l,t}_{NN}(\omega, q) = \mathrm{Im}(\Pi^0_{NN})(\omega, q), \quad (A4)$$

$$R^{l,t}_{\Delta\Delta}(\omega, q) = \mathrm{Im}(\Pi^0_{\Delta\Delta})(\omega, q), \quad (A5)$$

$$\mathrm{Im}(\Pi^0_{NN})(\omega, q) = -\frac{M^2}{2\pi^2}$$

$$\int d^3p \frac{\delta(\omega + E^N_{\vec{p}} - E^N_{\vec{p}+\vec{q}})}{E^N_{\vec{p}} E^N_{\vec{p}+\vec{q}}} \Theta(k_F - |\vec{p}|)\Theta(|\vec{p} + \vec{q}| - k_F) =$$

$$= -\frac{M^2}{\pi q}(E_1 - E_2)\Theta(E_1 - E_2), \quad (A6)$$

where $E_1 = E_F$, $E_2 = max(-\frac{\omega}{2}, E_F - \omega, \frac{q}{2}\sqrt{1 + \frac{4M^2}{Q^2}})$.

$$\mathrm{Im}(\Pi^0_{\Delta\Delta})(\omega, q) = -\frac{4M_\Delta^2}{9\pi^3}\int d^3p \frac{\Gamma_\Delta\Theta(k_F - |\vec{p}|)}{(s - M_\Delta^2)^2 + M_\Delta^2\Gamma_\Delta^2}. \quad (A7)$$

$s = (p + q)^2$.

In the nuclear matter Γ_Δ is modified because of Pauli blocking effect which we introduce as a multiplicative factor P_B and also by the Δ self energy:

$$\Gamma_\Delta \to P_B \cdot \Gamma_\Delta - 2\,\mathrm{Im}(\Sigma).$$

Our parameterization of $\mathrm{Im}(\Sigma)$ is based on [8]:

$$\mathrm{Im}(\Sigma) = \mathrm{Im}(\Sigma^{N\pi}) + \mathrm{Im}(\Sigma^{NN}) + \mathrm{Im}(\Sigma^{NNN})$$

where the last two terms correspond to pionless Δ decays with an emission of two and three nucleons. We converted the information contained in [8] to the kinematical situation of the lepton scattering using the procedure described in [20]. Because $\mathrm{Im}(\Sigma)$ depends strongly on the nuclear density it was evaluated (and tabularized) in the Local Density Approximation using the density profile of the carbon nucleus:

$$\mathrm{Im}(\Pi^0_{\Delta\Delta})_{LDA}(\omega, q) =$$

$$-\frac{4M_\Delta^2}{9\pi^3}\int d^3r \rho(\vec{r}) \int d^3p \frac{\Gamma_\Delta(\vec{r})\Theta(k_F - |\vec{p}|)}{(s - M_\Delta^2)^2 + M_\Delta^2\Gamma_\Delta^2(\vec{r})}. \quad (A8)$$

For the real part of the Δ self energy the parametrization

$$M_\Delta \to M_\Delta + 40MeV\frac{\rho}{\rho_0}$$

was used.

Details about the RPA computations can be found in [20].

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