CCQE, 2p2h excitations and $\nu-$energy reconstruction

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Abstract. We analyze the MiniBooNE muon neutrino CCQE-like $d\sigma/dT_\mu d\cos\theta_\mu$ data using a theoretical model that, among other nuclear effects, includes RPA correlations and 2p2h (multinucleon) mechanisms. These corrections turn out to be essential for the description of the data. We find that MiniBooNE CCQE-like data are fully compatible with former determinations of the nucleon axial mass $M_A \sim 1.05$ GeV. This is in sharp contrast with several previous analysis where anomalously large values of $M_A \sim 1.4$ GeV have been suggested. We also show that because of the the multinucleon mechanism effects, the algorithm used to reconstruct the neutrino energy is not adequate when dealing with quasielastic-like events. Finally, we analyze the MiniBooNE unfolded cross section, and show that it exhibits an excess (deficit) of low (high) energy neutrinos, which is an artifact of the unfolding process that ignores 2p2h mechanisms.

Keywords: quasielastic scattering, nucleon axial mass, neutrino energy reconstruction
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INTRODUCTION

A correct understanding of neutrino-nucleus interactions is crucial to minimize systematic uncertainties in neutrino oscillation experiments [1]. Most of the new generation of neutrino experiments are exploring neutrino-nuclear scattering processes at intermediate energies (≤ 2 GeV), thus experiments like SciBooNE [2] or MiniBooNE [3, 4, 5, 6] have produced good quality data for quasi-elastic scattering and pion production in this neutrino energy region. These new data show interesting deviations from the predictions of present models that have raised doubts in the areas which seemed to be well understood [7, 8]. The list of new puzzles is quite long and seems to be expanding. In this talk, we focus in particular on charged-current quasi-elastic (CCQE) scattering, and we would try to shed some light into three of these puzzles: i) What is the value of the nucleon axial mass? ii) How large is the two-body current contribution that can mimic genuine QE interactions?, and iii) What is the impact of the multinucleon processes on the neutrino energy reconstruction and on the neutrino flux-unfolded cross sections?

CCQE-LIKE SCATTERING

The inclusive cross section for the process $\nu_\ell(k) + A_Z \to \ell^-(k') + X$ is determined by the W gauge boson selfenergy in the nuclear medium [9, 10], and in particular for the different modes in which it can be absorbed. The most relevant ones are: the absorption by one nucleon, or by a pair of correlated nucleons that are exchanging virtual mesons (π, ρ, $\cdots$), or the excitation of a Δ or a higher energy resonance, etc. (see Fig. 1). In most theoretical works QE is used for processes where the gauge boson W is absorbed by just one nucleon, which together with a lepton is emitted (see Fig. 1a). In what follows, we will refer to this contribution as *genuine* QE. However, the recent MiniBooNE CCQE data [3] include events in which only a muon is detected (we will refer to them as QE-like events). This data selection is adopted because ejected nucleons are not detected in that experiment. Thus, the QE-like sample does not include events with pions coming off the nucleus, since they will give rise to additional leptons after their decay (see Fig. 1c). However, this event-sample includes multinucleon events, as those displayed in Fig. 1e, where the gauge boson is absorbed by two interacting nucleons (in the many body language, this amounts to the excitation of a 2p2h nuclear component). On the other hand, other events like real pion production followed by its absorption should be also included in the QE-like sample, though the MiniBooNE analysis Monte Carlo corrects for those. Here, there is a

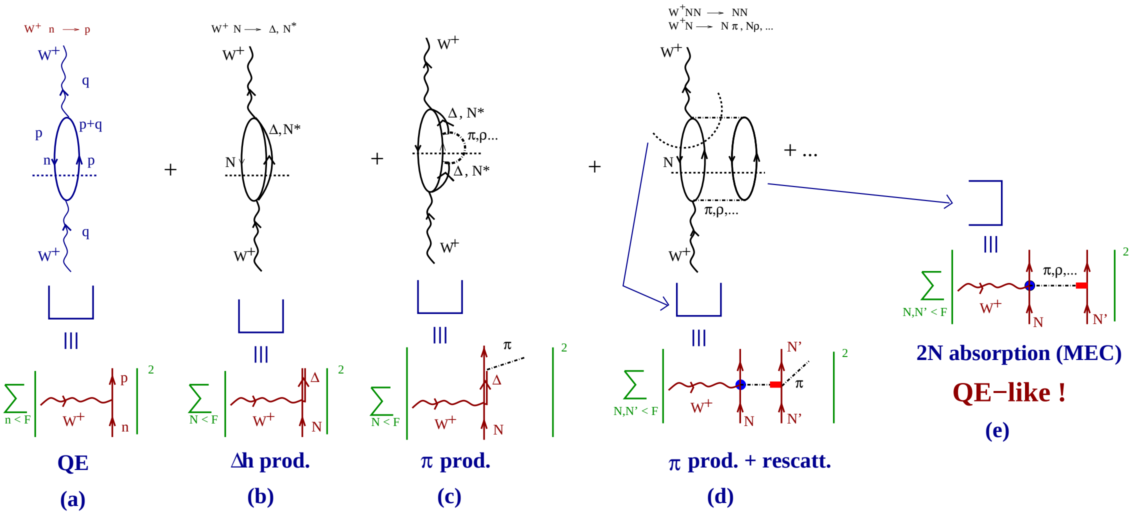

FIGURE 1. Diagrammatic representation of some diagrams contributing to the $W-$selfenergy and their connection with different absorption modes of the gauge boson in the nuclear medium.

subtlety that is worth to comment in some detail. Let us pay attention to processes like the one depicted in the bottom panel of Fig. 1c, but when the pion is off-shell instead of being on the mass-shell. In any of these processes, the virtual pion, that is produced in the first step, will be necessarily absorbed by a second nucleon, and thus the process should be classified/cataloged as a two nucleon W absorption mechanism (Fig. 1e). Hence, events originated by these kind of processes do not contribute to the genuine QE cross section, but they do to the cross section measured in the MiniBooNE experiment.

After this discussion, we draw a first important conclusion: the MiniBooNE CCQE data [3] cannot be directly compared to most of the previous theoretical calculations, in which only the one-body genuine QE contribution was usually considered. This was first pointed out by M. Martini et al. [11, 12]. Indeed, the absolute values of the CCQE cross section reported in [3] are too large as compared to the consensus of theoretical predictions for the genuine QE contribution [13]. Thus, the cross section per nucleon on ^{12}C is clearly larger than for free nucleons, and a fit, using a relativistic Fermi gas model, to the data led to an axial mass, $M_A = 1.35 \pm 0.17$ GeV [3] , much larger than the previous world average (≈ 1.03 GeV). Similar results have been later obtained analyzing MiniBooNE data with more sophisticated treatments of the nuclear effects that work well in the study of electron scattering [14, 15, 16].

In what follows, we present results from a microscopic calculation [9, 10] of the CCQE-like 2D cross section $d\sigma/dT_\mu d\cos\theta_\mu$. There are no free parameters in the description of nuclear effects, since they were fixed in previous studies of photon, electron, and pion interactions with nuclei [17, 18, 19, 20]. We approximate the CCQE-like cross section by the sum of the genuine QE contribution (Fig. 1a) and that induced by 2p2h mechanisms (Fig. 1e), for which the gauge boson is being absorbed by two or more nucleons without producing pions.

The genuine QE contribution was studied in [9] incorporating several nuclear effects. The main one is the medium polarization (RPA), that accounts for the change of the electroweak coupling strengths, from their free nucleon values, due to the presence of strongly interacting nucleons. Indeed, the quenching of axial current is a well-established phenomenon. The RPA re-summation accounts for the medium polarization effects in the 1p1h contribution (Fig. 1(a)) to the W selfenergy by substituting it by a collective response as shown diagrammatically in the left panel of Fig. 2. Evaluating these effects, requires of an in medium baryon-baryon effective force, that within our model includes Δ-hole degrees of freedom, short range correlations and explicit π and ρ meson exchanges in the vector-isovector channel. RPA effects are important, as can be appreciated in Fig. 3. In the left panel, we show results [21] for the genuine QE contribution from our model (labeled as IFIC) for the CC quasielastic $\nu_\mu-{}^{12}$C double differential cross sections convoluted with the MiniBooNE flux. There, we also display results from the model of M. Martini et al. (labeled as Lyon) taken from [22]. The predictions of both groups for this genuine QE contribution, with and without RPA effects, turn out to be in a quite good agreement. We would finally like to remark that the RPA corrections strongly decrease as the neutrino energy increases, while they strongly modify the q^2-differential distributions at low neutrino energies, as can be appreciated in the middle and right panels of Fig. 3, respectively.

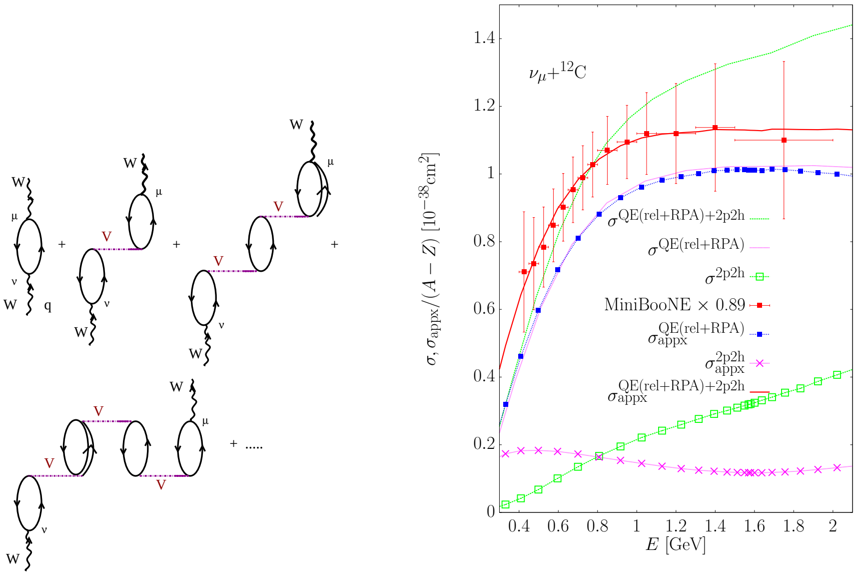

FIGURE 2. Left: Set of irreducible diagrams responsible for the polarization (RPA) effects in the 1p1h contribution to the W self-energy. Right. Theoretical σ and approximate $\sigma_{\rm appx}$ CCQE-like integrated cross sections in carbon as a function of the neutrino energy. Results have been obtained from Refs. [9] and [10] using $M_A \sim 1.05$ GeV. Details can be found in Ref. [23]. The MiniBooNE data [3] and errors (shape) have been re-scaled by a factor 0.89.

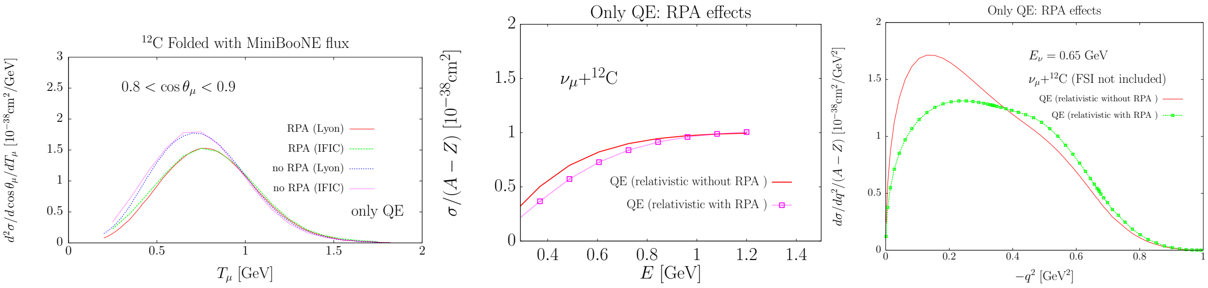

FIGURE 3. Right: MiniBooNE flux-averaged $\nu_\mu - {}^{12}$C double differential cross section per neutron for $0.8 < \cos\theta_\mu < 0.9$ as a function of the muon kinetic energy. The other two plots correspond to different theoretical predictions for muon neutrino CCQE total cross section off ^{12}C as a function of the neutrino energy (middle) and q^2 (right), obtained from the relativistic model of Ref. [9]. In all cases $M_A \sim 1.05$ GeV.

The model for multinucleon mechanisms is fully microscopical and it is discussed in detail in [10]. It includes one, two, and even three-nucleon mechanisms, as well as the excitation of Δ isobars. This theoretical model has proved to be quite successful in the study of nuclear reactions with photon [17], pion [18, 19] and electron [20] probes.

Up to neutrino energies around 1 GeV, the predictions of our model obtained with $M_A = 1.05$ GeV compare rather well [10], taking into account experimental and theoretical uncertainties, with the data published by the SciBooNE collaboration for total neutrino inclusive cross sections [2]. On the other hand, the 2p2h contributions allows to describe [21] the CCQE-like flux averaged double differential 2D cross section $d\sigma/dE_\mu d\cos\theta_\mu$ measured by MiniBooNE with values of M_A around 1.03 ± 0.02 GeV that is usually quoted as the world average. This is re-assuring from the theoretical point of view and more satisfactory than the situation envisaged by some other works that described these CCQE-like data in terms of a larger value of M_A of around 1.3–1.4 GeV, as mentioned above. The relative sizes of the genuine QE and 2p2h cross sections in carbon can be appreciated in the right panel of Fig. 2 by looking there at the curves labeled as $\sigma^{\rm QE(rel+RPA)}$ and $\sigma^{\rm 2p2h}$, respectively.

The work of Ref. [22] also include multinucleon mechanisms and find a good description of the 2D MiniBooNE data. Both works also agree on the relevant role played by the 2p2h mechanisms to describe the MiniBooNE data. However, both groups differ considerably in the size (about a factor of two) of the multinucleon effects. There exist indeed some important differences which amount to a more comprehensive inclusion of mechanisms in our scheme and some approximations used in the calculations of [22]. A more detailed discussion on these differences can be found in Refs. [10, 24]. We would also like to point out that the simple phenomenological approach adopted in [25] to account for the 2p2h effects also reinforces the picture that emerges from [21, 22]. Yet, a partial microscopical calculation of the 2p2h contributions to the CCQE cross section has been also presented in Refs. [26] and [27], for neutrino and antineutrino induced reactions, respectively. In these works, the contribution of the vector meson exchange currents in the 2p2h sector is added to the QE neutrino or antineutrino cross section predictions deduced from a phenomenological model based on the super-scaling behavior of electron scattering data. In [28], and for the neutrino case, the SuSA+2p2h results were also compared with those obtained from a relativistic mean field approach. Although, all these schemes do not account for the axial part of the 2p2h effects yet, their results also corroborate that 2p2h meson exchange currents play an important role in both CCQE-like neutrino and antineutrino scattering, and that they may help to resolve the controversy on the nucleon axial mass raised by the recent MiniBooNE data.

A final remark concerns to the importance of 2p2h effects in antineutrino reactions as compared to neutrino ones. In our model the relative importance of the 2p2h channel is somehow larger for antineutrinos [29]. A similar trend, although with a stronger reduction, has been found by Amaro et al. [27] in the SuSA approximation. However, other works like Ref. [30], which reaches agreement with MiniBooNE QE neutrino data by modifying the magnetic form factors of the bound nucleons, and Ref. [12] lead to an enhancement of the effect for antineutrino induced reactions.

NEUTRINO ENERGY RECONSTRUCTION AND THE SHAPE OF THE CCQE-LIKE TOTAL CROSS SECTION

The relevance of the multinucleon mechanisms has some unwanted consequences. Obviously, the neutrino energy reconstruction, based on the QE kinematics is not so reliable [23, 31, 32, 33] and that implies larger systematic uncertainties in the neutrino oscillation experiments analysis. In general, the energy of the neutrino that has originated an event is unknown, and it is common to define a reconstructed neutrino energy $E_{\rm rec}$, obtained from the measured angle (θ_ℓ) and three-momentum ($\vec{p}_\ell$) of the outgoing charged lepton ℓ, as

$$E_{\rm rec} = \frac{ME_\ell - m_\ell^2/2}{M - E_\ell + |\vec{p}_\ell|\cos\theta_\ell} \tag{1}$$

which will correspond to the energy of a neutrino that emits a lepton, of mass m_ℓ and energy, and a gauge boson W that is being absorbed by a nucleon of mass M at rest. The usual reconstruction procedure assumes that we are dealing with a genuine quasielastic event on a nucleon at rest.

Each event contributing to the flux averaged double differential cross section $d\sigma/dE_\ell d\cos\theta_\ell$ defines unambiguously a value of $E_{\rm rec}$. The actual ("true") energy, E, of the neutrino that has produced the event will not be exactly $E_{\rm rec}$. Actually, for each $E_{\rm rec}$, there exists a distribution of true neutrino energies that could give rise to events whose muon kinematics would lead to the given value of $E_{\rm rec}$. In the case of genuine QE events, this distribution is sufficiently peaked around the true neutrino energy to make the algorithm in Eq. (1) accurate enough to study the neutrino oscillation phenomenon [34] or to extract neutrino flux unfolded CCQE cross sections from data (assuming that the neutrino flux spectrum is known) [23, 31].

However, and due to the large importance of the 2p2h events, in the case of CCQE-like events, there are appear a long tail in the distribution of true energies associated to each $E_{\rm rec}$ that makes unreliable the use of Eq. (1). The effects of the inclusion of multinucleon processes on the energy reconstruction have been investigated within our model in [23], finding results in a qualitative agreement with those described in [31]. In [23], it is also studied in detail the ^{12}C unfolded neutrino CCQE-like cross section published in [3]. Indeed, it is shown there, that it is not a very clean observable, because the unfolding procedure itself is model dependent and assumes that the events are purely QE. Moreover, it is also shown the MiniBooNE published cross section differs from the real one $\sigma(E)$. This is illustrated in the right panel of Fig. 2, where different predictions from our model, together with the CCQE-like MiniBooNE data are depicted. The theoretical results are obtained from the relativistic models of Refs. [9] and [10], for the genuine QE and multinucleon contributions, respectively. In al cases M_A is set to 1.05 GeV. First, we see that the theoretical prediction $\sigma^{\rm QE+2p2h}$ does not correctly reproduce the neutrino-energy shape of the published data. The 2p2h contributions clearly improve the description of the data, which are totally missed by the QE prediction. Though the model provides a reasonable description, we observe a sizable excess of low energy neutrinos in the data. The unfolding procedure (see Ref. [23] for some details) does not appreciably distort the genuine QE events, and as can be appreciated in the right panel of Fig. 2, $\sigma_{\text{appx}}(E)$ is an excellent approximation to the real $\sigma(E)$ cross section in that case. However, the situation is drastically different for the 2p2h contribution. It turns out that $\sigma^{\text{2p2h}}_{\text{appx}}(E)$ (result obtained after the unfolding procedure) is a poor estimate of the actual multinucleon mechanism contribution $\sigma^{\text{2p2h}}(E)$. We also observe in Fig. 2 that the MiniBooNE CCQE-like data compare rather well with the σ_{appx}, quantity obtained after implementing the unfolding procedure presumably carried out in [3], but that however, appreciably differs from the actual cross section σ. Therefore, we conclude the MiniBooNE unfolded cross section exhibits an excess (deficit) of low (high) energy neutrinos, which is an artifact of the unfolding process that ignores multinucleon mechanisms.

Similar conclusions are achieved in [29], where the recent MiniBooNE antineutrino CCQE-like data [6] were discussed within our framework. We show first that the model of Refs. [9, 10], that includes RPA and 2p2h effects, satisfactorily describes the 2D data, and second that similar limitations related to the energy reconstruction and the unfolding procedure, when 2p2h effects are ignored, appear also for antineutrino CCQE processes.

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