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Abstract. Two relativistic approaches to charged-current quasielastic neutrino-nucleus scattering are illustrated and compared: one is phenomenological and based on the superscaling behavior of electron scattering data and the other relies on the microscopic description of nuclear dynamics in relativistic mean field theory. The role of meson exchange currents in the two-particle two-hole sector is explored. The predictions of the models for differential and total cross sections are presented and compared with the MiniBooNE data.

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The recent MiniBooNE data on muon neutrino charged-current quasielastic (CCQE) scattering [1] have raised an important debate on the role played by both nuclear and nucleonic ingredients entering in the description of the reaction. Unexpectedly, the cross section turns out to be substantially underestimated by the Relativistic Fermi Gas (RFG) prediction, unless an unusually large *ad hoc* value of the axial mass $M_A \simeq 1.35$ GeV/c^2 (as compared to the standard value $M_A \simeq 1$ GeV/c^2) is employed in the dipole parametrization of the nucleon axial form factor. From comparison with electron scattering data the RFG model is known, however, to be too crude to account for the nuclear dynamics: therefore this result should be taken more as an indication of incompleteness of the theoretical description of the nuclear many-body problem rather than as a true indication for a larger axial mass.

At the level of the impulse approximation (IA), a number of much more sophisticated descriptions of the nuclear dynamics other than the RFG also underpredict the measured CCQE cross section (see, e.g., Ref. [2] for a full list of references, that we omit here for loss of space). Possible explanations of this puzzle have been proposed in the literature, based either on multinucleon knockout or on particular treatments of final state interactions through phenomenological optical potentials, indicating that contributions beyond the simple IA play an important role in QE neutrino reactions.

Here we summarize the results of Refs. [3, 4, 5], where the predictions of the following two relativistic models were compared with each other and with the MiniBooNE data:

1. the SuperScaling Approach (SuSA) including 2p2h Meson Exchange Currents (MEC);
2. the Relativistic Mean Field model (RMF).

Both models, although being far more realistic than the RFG, share with it the important property of treating exactly the relativistic aspects of the problem: these cannot be neglected for the kinematics of MiniBooNE, where the neutrino energy reaches values as high as 3 GeV.

The "SuSA" approach [3] is based on the assumed universality of the scaling function for electromagnetic and weak interactions. Analyses of inclusive (e,e') data have demonstrated that at energy transfers below the QE peak superscaling is fulfilled rather well: this means that the reduced cross section is largely independent of the momentum transfer (I-kind scaling) and nuclear target (II-kind scaling), when represented as a function of the appropriate scaling variable. From these analyses a phenomenological scaling function, dramatically different in size and shape from the RFG parabola, has been extracted from the longitudinal QE electron scattering response and used to predict neutrino-nucleus cross sections by multiplying it by the corresponding elementary weak cross sections. The model reproduces by construction the longitudinal electron scattering response at all kinematics and for all nuclei. Its limitations come from the assumptions on which the approach is based, namely: 1) the equality of the longitudinal and transverse

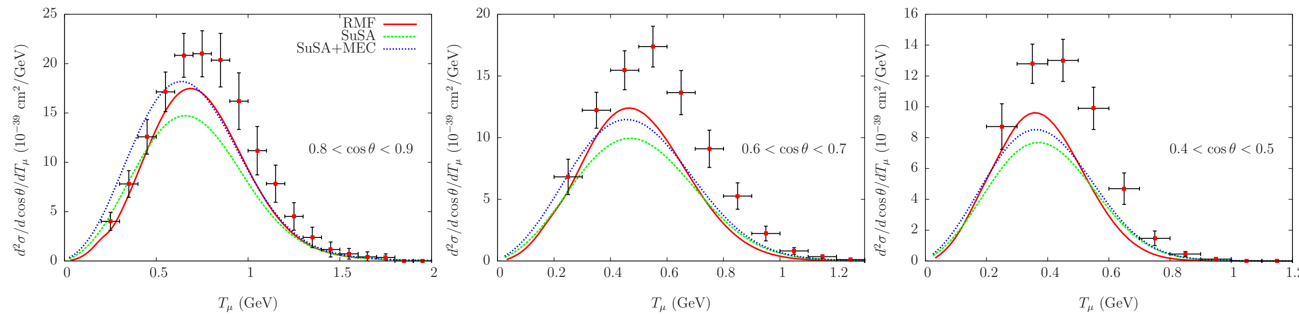

FIGURE 1. Flux-integrated ν_μ-^{12}C CCQE double differential cross section per target nucleon evaluated in the SuSA model with and without inclusion of 2p2h MEC and in the RMF model and displayed versus the muon kinetic energy T_μ for various bins of the muon scattering angle $\cos\theta$. Here and in the following figures the data are from MiniBooNE [1].

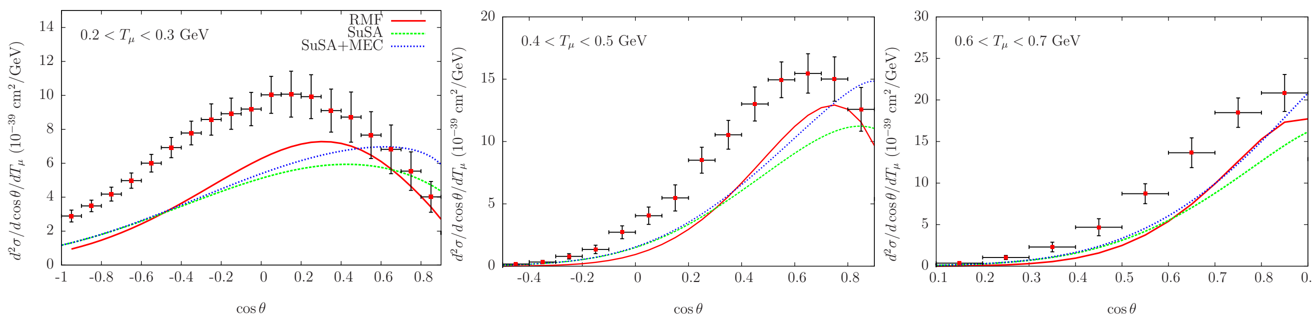

FIGURE 2. Same as Fig. 1, but now displayed versus the scattering angle $\cos\theta$ for various bins of T_μ.

scaling functions (0-kind scaling), a property violated by the L/T separated data, which show a transverse scaling function typically larger than the longitudinal one; 2) the equality of the scaling functions in different isospin channels (III-kind scaling), which allows to use the longitudinal electron scattering data (having both isoscalar and isovector components) to predict the purely isovector CC neutrino cross section.

The results of the SuSA model for the double differential, single differential and total CCQE neutrino cross sections are shown in Figs. 1-3, where they appear to fall below the data for most of the angle and energy bins. Note that we do not compare with the most forward angles ($0.9 < \cos\theta < 1$) since for such kinematics roughly 1/2 of the cross section has been proved [4] to arise from very low excitation energies (<50 MeV), where the cross section is dominated by collective excitations and any approach based on IA is bound to fail.

To go beyond the SuSA approach one must take into account superscaling violations, which occurr mainly in the transverse channel at energies above the QE peak and are associated to non-impulsive effects, like inelastic scattering and meson-exchange currents. The latter are two-body currents carried by a virtual meson exchanged between two bound nucleons and can excite both 1p1h and 2p2h states. In the 1p1h sector, studies of electromagnetic (e,e') process have shown that the MEC, when combined with the corresponding correlations, which are needed to preserve gauge invariance, give a small contribution to the QE cross section and can be neglected in first approximation. On the other hand in the 2p2h sector the MEC are known to give a significant positive contribution to the (e,e') cross section at high energy transfers, leading to a partial filling of the "dip" between the QE and Δ-resonance peaks. This region is relevant for the MiniBooNE experiment, where "QE" events (namely with no real pions in the final state) can involve transferred energies far beyond the QE peak, due to the large energy range spanned by the neutrino flux.

In the results presented in Figs. 1-3 we have used a fully relativistic model, developed for use in electron scattering studies, where all the MEC many-body diagrams containing two pionic lines that contribute to the electromagnetic 2p2h transverse response are taken into account. In order to apply the model to neutrino scattering, we observe that in lowest order the 2p2h sector is not directly reachable for the axial-vector matrix elements. Hence at this order the MEC affect only the transverse polar vector response. As shown in Figs. 1-3, the inclusion of 2p2h MEC in the SuSA approach yields larger cross sections and accordingly better agreement with the data, but theory still lies below the data at larger angles where the cross sections are smaller. It should be noted, however, that the present approach still lacks

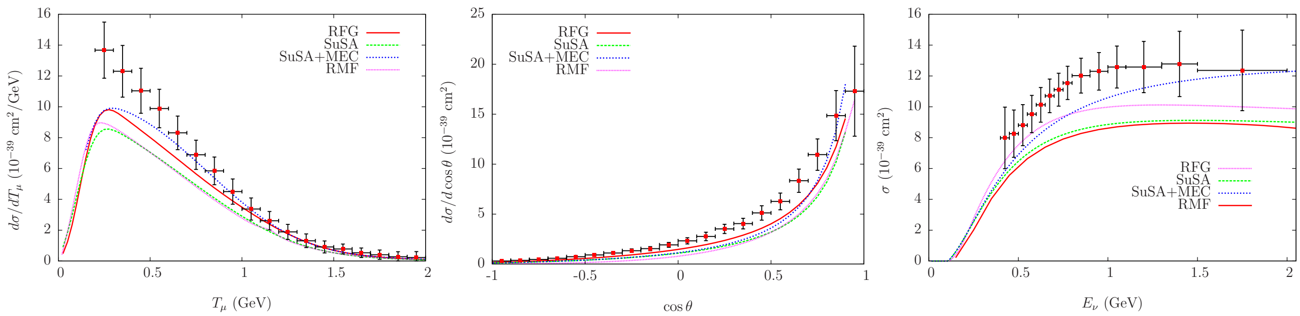

FIGURE 3. Flux-averaged ν_μ-^{12}C CCQE cross section integrated over the scattering angle and displayed versus the muon kinetic energy (left panel), integrated over the muon kinetic energy and displayed versus scattering angle (center panel), integrated over the muon kinetic energy and scattering angle and displayed versus the unfolded neutrino energy (right panel). Beyond the models described in the text, the RFG result is also shown for comparison.

the contributions from the correlation diagrams associated with the MEC which are required by gauge invariance; these might improve the agreement with the data, as suggested by recent results for inclusive electron scattering [6].

Before drawing definitive conclusions on the anomalous axial mass, it is important to explore alternative approaches that have been shown to be successful in describing inclusive QE (e,e') processes. This is the case for the RMF model, where a fully relativistic description (kinematics and dynamics) of the process is incorporated, and final state interactions are taken into account by using the same relativistic scalar and vector energy-independent potentials considered in the description of the initial bound states. The RMF model applied to inclusive QE (e,e') processes has been shown to describe the scaling behaviour and, in contrast with most other nuclear models, to give rise to a superscaling function with a significant asymmetry, in complete accord with data. Moreover, contrary to SuSA, where scaling of the zeroth kind is assumed, the RMF model provides longitudinal and transverse scaling functions which differ by typically 20%, the T one being larger. When applied to the description of CCQE neutrino-nucleus cross sections, the 0-kind scaling violation introduced by the RMF approach, as well as the different isospin character shown by the electromagnetic and weak nucleon form factors, can lead to significant discrepancies between the results provided by SuSA and RMF approaches. This is illustrated in Figs. 1, 2 and 3, where the differences between the SuSA and RMF predictions are especially visible in the double differential cross sections (Figs. 1 and 2), which are better described by the RMF model, and tend instead to be washed out by the integration (Fig. 3).

Summarizing, we have applied two relativistic models, SuSA and RMF, both able to describe with good accuracy the longitudinal (e,e') data, to CCQE neutrino scattering, finding that both underestimate the MiniBooNE cross sections: although the RMF does better than SuSA in reproducing the shape of the double differential cross sections, the two approaches provide almost identical results for the single-differential and total cross sections. Although our scope here is not to extract a value for the axial mass of the nucleon, but rather to understand which nuclear effects are effectively accounted for by a large axial cutoff parameter, let us mention that a best fit of the RMF and SuSA results to the MiniBooNE experimental cross section gives an effective axial mass $M_A^{\rm eff} \simeq 1.5$ GeV/c^2 and values in the range $1.35 < M_A^{\rm eff} < 1.65$ GeV/c^2 yield results compatible with the MiniBooNE data within the experimental errors.

The inclusion of 2p2h MEC contributions in the SuSA approach increases both the differential and the integrated cross sections and thus seems to improve the agreement with the data, suggesting that the data can be explained without the need for a large nucleon axial mass. However, in the present scheme, more refined calculations taking care of correlation currents and MEC effects in the axial-vector channel should be performed before final conclusions can be drawn. We refer the reader to Refs. [3, 4, 5] for further details and results.

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