

## Meson-Exchange Currents and Quasielastic Antineutrino Cross Sections in the Superscaling Approximation

J. E. Amaro

*Departamento de Física Atómica, Molecular y Nuclear and Instituto Carlos I de Física Teórica y Computacional, Universidad de Granada, 18071 Granada, Spain*

M. B. Barbaro

*Dipartimento di Fisica Teorica, Università di Torino and INFN, Sezione di Torino, Via Pietro Giuria 1, 10125 Torino, Italy*

J. A. Caballero

*Departamento de Física Atómica, Molecular y Nuclear, Universidad de Sevilla, 41080 Sevilla, Spain*

T. W. Donnelly

*Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

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We evaluate quasielastic double-differential antineutrino cross sections obtained in a phenomenological model based on the superscaling behavior of electron scattering data and estimate the contribution of the vector meson-exchange currents in the two-particle–two-hole sector. We show that the impact of meson-exchange currents for charge-changing antineutrino reactions is much larger than in the neutrino case.

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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 in the description of the reaction. Unexpectedly, the cross section turns out to be substantially underestimated by the relativistic Fermi gas (RFG) model, unless an unusually large *ad hoc* value of the axial mass  $M_A \approx 1.35 \text{ GeV}/c^2$  (as compared with the standard value  $M_A \approx 1 \text{ GeV}/c^2$ ) is employed in the dipole parametrization of the nucleon axial form factor. From comparisons with electron scattering data the RFG model is known, however, to be too crude to account for the nuclear dynamics—therefore this result is perhaps more an indication of the incompleteness of the theoretical description of the nuclear many-body problem than an unambiguous indication of a larger axial mass.

At the level of the impulse approximation (IA), a number of more sophisticated descriptions of the nuclear dynamics other than the RFG also underpredict the measured CCQE cross section (see, e.g., [2–7]). Possible explanations of this puzzle have been proposed, based either on multinucleon knockout [3,8] or on particular treatments of final-state interactions through phenomenological optical potentials [9], indicating that contributions beyond the naive starting point play an important role in quasielastic (QE) neutrino reactions.

In [5] the predictions of the superscaling approach (SuSA) model including the two-particle–two-hole sector ( $2p$ - $2h$ ) meson-exchange currents (MEC) model were presented and compared with the MiniBooNE data on muon

neutrino scattering from  $^{12}\text{C}$ . The SuSA approach has been discussed at length in [10–13]: comparisons with inclusive electron scattering data have been made using scaling functions obtained from the *longitudinal* inclusive response which is then employed universally for the QE transverse scaling function (and hence the transverse inclusive QE response) and for the inelastic response (production of  $\pi$ ,  $\Delta$ , deep inelastic scattering, etc.). This representation of the QE and inelastic parts of the inclusive cross section is then added to the  $2p$ - $2h$  MEC contribution obtained in a relativistic model [14,15] to yield the total inclusive cross section. Good agreement is found for comparison of this representation with experiment for a wide range of kinematics. The SuSA approach is then to use exactly the same scaling functions to obtain the QE and  $2p$ - $2h$  MEC contributions for the so-called CCQE cross section, actually the sum of what is called QE in studies of electron scattering plus what is called MEC to distinguish the latter from the contributions that are predominantly due to single-nucleon ejection via one-body operators.

The results of the purely SuSA model, i.e., based on the assumed universality of the scaling function for electromagnetic and weak interactions, for the double-differential, single-differential, and total CCQE neutrino cross sections have been shown to fall below the data for most of the experimental angle and energy bins. The inclusion of  $2p$ - $2h$  MEC in the SuSA approach yields larger cross sections and accordingly better agreement with the data, although theory still lies below the data at larger angles where the cross sections are smaller [5].

In this Letter we apply the same model to antineutrino scattering. The results are shown in Figs. 1–4. In particular, in Fig. 1 antineutrino CCQE cross sections integrated over the  $\bar{\nu}_\mu$  MiniBooNE flux [16] are shown as functions of  $\mu^+$  kinetic energies  $T_\mu$  for angular bins  $\cos\theta_\mu$  ranging from forward to backward angles. For each panel in the figure two curves are shown, the lower in each case (red) being the basic SuSA QE result and the upper (green) being this plus the contributions from  $2p$ - $2h$  MEC in the transverse vector part of the cross section. For comparison, in Fig. 2 the neutrino cross sections versus  $\mu^-$  kinetic energies are shown for the same kinematical conditions, together with the data from [1]. The results here have already been reported in [5,6], although here the full range of kinematics is presented.

The effects from  $2p$ - $2h$  MEC for the antineutrino case are especially striking: for instance, for the first angular bin shown ( $0.8 < \cos\theta_\mu < 0.9$ ) the MEC contribute about 38% to the total cross section at the peak, while for  $0 < \cos\theta_\mu < 0.1$  this rises to about 44% at the peak. In contrast

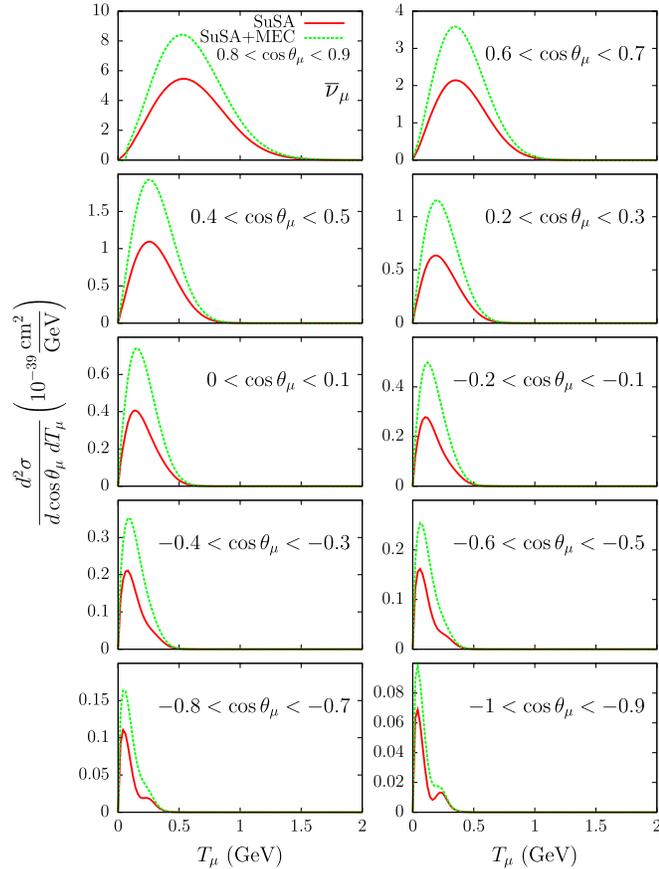


FIG. 1 (color online). Flux-integrated double-differential cross section per target nucleon for the  $\bar{\nu}_\mu$  CCQE process on  $^{12}\text{C}$  displayed versus the  $\mu^+$  kinetic energy  $T_\mu$  for various bins of  $\cos\theta_\mu$ . The lower curves in each panel (red) show the SuSA QE results, while the upper curves (green) show those results plus the contributions from  $2p$ - $2h$  MEC.

(see Fig. 2) the relative percentage coming from MEC is much smaller in the neutrino case. The origin of these differences is clear. For neutrinos one has three basic contributions, namely, from the SuSA QE contributions to the transverse and longitudinal  $V$ - $V$  and transverse  $A$ - $A$  responses together with small contributions from the charge-longitudinal  $A$ - $A$  responses, contributions from  $2p$ - $2h$  MEC (which in leading order only enter in the transverse  $V$ - $V$  sector) and the  $V$ - $A$  interference contribution. For neutrinos the last is constructive and the MEC effects are to be weighed against relatively large QE contributions. However, for antineutrinos the  $V$ - $A$  interference is destructive; accordingly the total QE contribution is significantly reduced for antineutrinos and consequently when the MEC are added they play a much more significant role. To illustrate this point, consider the angular bin  $0.6 < \cos\theta_\mu < 0.7$ : while the neutrino and antineutrino fluxes are different, making the comparisons not quite trivial, if one evaluates the three contributions at the peaks of the cross sections one is led to conclude that the QE contribution without the  $V$ - $A$  interference is about 6.0, the  $V$ - $A$  interference is about 3.9 and the MEC about 1.5 in the units used for the figures. So for neutrinos the total QE

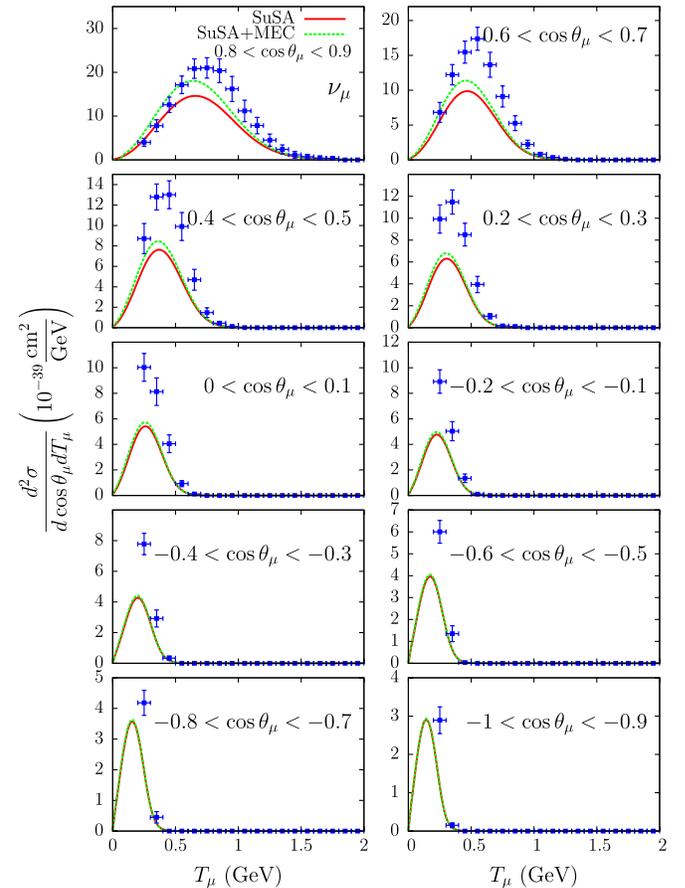


FIG. 2 (color online). As for Fig. 1, but for  $\nu_\mu$  scattering versus  $\mu^-$  kinetic energy  $T_\mu$ . The data are from Ref. [1].

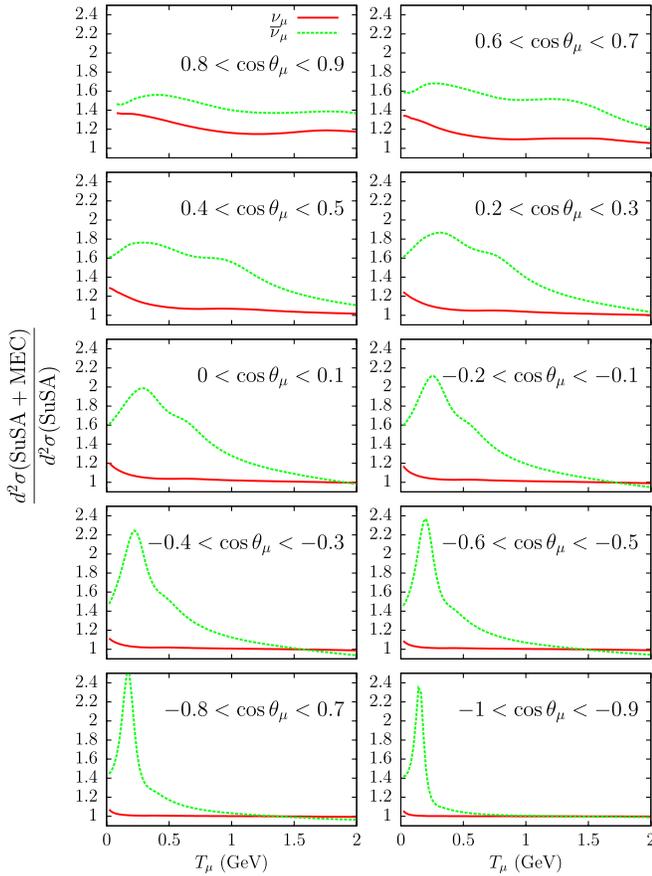


FIG. 3 (color online). Ratio of double-differential cross sections with and without MEC:  $d^2\sigma(\text{SuSA} + \text{MEC})/d^2\sigma(\text{SuSA})$  for neutrino (lower curves, red) and antineutrino (upper curves, green) scattering versus muon kinetic energy  $T_\mu$ .

result is about 9.9, while the total QE result for antineutrinos is about 2.1. Clearly the MEC contribution of 1.5 in these units has a much greater impact for antineutrinos than for neutrinos. Indeed, measurements of both reactions would likely provide a stringent test of the modeling of the  $2p$ - $2h$  MEC. Moreover, given measurements using different nuclear targets, where one expects the relative contributions from QE scattering and MEC to differ in going from nucleus to nucleus, one would have an additional way to probe the two types of response. To make these observations more quantitative, in Fig. 3 the ratios with and without MEC are shown for the 10 panels used in Figs. 1 and 2, illustrating the much larger role of MEC in the antineutrino case. Note that the small second peak that shows up at larger scattering angles (most apparent in Fig. 1) is due to the destructive contribution of the  $V$ - $A$  interference contribution. Since the  $V$ - $V$  +  $A$ - $A$  and  $V$ - $A$  contributions peak at different values of  $T_\mu$  their having opposite signs leads to an oscillatory result.

Note that in all of the figures discussed above we do not compare with the most forward angles ( $0.9 < \cos\theta_\mu < 1$ ), since for such kinematics roughly 1/2 of the cross section

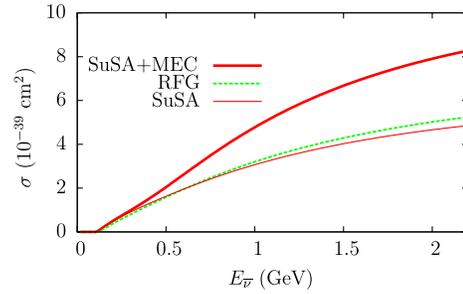


FIG. 4 (color online). Total cross section displayed versus antineutrino energy  $E_{\bar{\nu}_\mu}$  for the pure SuSA model, the SuSA model plus MEC and the pure RFG model.

arises 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. This has been proven [5] for neutrinos and is even more so for the MiniBooNE antineutrino case, where the contribution of low excitation energies persists also at higher scattering angles. This is due to the fact that the mean energy of the antineutrino flux at MiniBooNE is  $\langle E_{\bar{\nu}_\mu} \rangle \simeq 0.66$  GeV, lower than the neutrino one  $\langle E_{\nu_\mu} \rangle \simeq 0.79$  GeV. Specifically, for the lowest angular bin cutting out the contributions from the first 50 MeV reduces the cross section by about 40%, for the next bin ( $0.8 < \cos\theta_\mu < 0.9$ ) the reduction is about 18%, and for larger angles the reduction remains in the range 12%–21%, reaching a minimum for  $0.4 < \cos\theta_\mu < 0.5$ , but rising again when going towards  $180^\circ$ .

Finally, for completeness, in Fig. 4 we give the total cross section for antineutrino scattering (see also [17]). Similar results for neutrinos using the present analysis were discussed in [6]. While the SuSA and RFG QE results are rather similar, it is obvious that the effect of MEC on the total cross section is very large. For instance, at  $E_{\bar{\nu}_\mu} = 1(2)$  GeV this amounts to a 60% (70)% increase. One warning should be repeated here: what is displayed is  $\sigma$  versus  $E_{\bar{\nu}_\mu}$ , which can be done theoretically, whereas what in experimental studies is called  $E_{\bar{\nu}_\mu}^{\text{QE}}$  is something different. The latter is an effective energy obtained by assuming a model for where the peak in the differential cross section occurs.

In summary, we have employed the superscaling analysis together with MEC in a study of antineutrino cross sections. The effects of MEC in the double-differential cross sections are seen to be very important, in fact, relative to the QE contribution, significantly larger than for neutrinos. Work is in progress to explore what happens when other models such as relativistic mean field theory are employed.

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