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Superscaling Predictions for Neutrino and Antineutrino Cross Sections at MiniBooNE

J.A. Caballero[1], **M.V. Ivanov**[2,3], **J.M. Udias**[2], **A.N. Antonov**[3], **M.B. Barbaro**[4], **E. Moya de Guerra**[2], **J.E. Amaro**[5], **T.W. Donnelly**[6]

[1]Departamento de Física Atómica, Molecular y Nuclear, Universidad de Sevilla, 41080 Sevilla, Spain

[2]Grupo de Física Nuclear, Departamento de Física Atómica, Molecular y Nuclear, Facultad de Ciencias Físicas, Universidad Complutense de Madrid, CEI Moncloa, Madrid E-28040, Spain

[3]Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia 1784, Bulgaria

[4]Dipartimento di Fisica, Università di Torino and INFN, Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy

[5]Departamento de Física Atómica, Molecular y Nuclear and Instituto Carlos I de Física Teorica y Computacional, Universidad de Granada, 18071 Granada, SPAIN

[6]Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Abstract. 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 2p-2h sector. We show that the impact of meson-exchange currents for charge-changing antineutrino reactions is much larger than in the neutrino case. On the other hand, superscaling-based approach predictions to neutrino-induced charged-current charged pion production in the Δ-resonance region are explored under MiniBooNE experimental conditions. The results obtained are compared with the corresponding MiniBooNE experimental data.

1 Introduction

The properties of neutrinos are being studied with increasing interest as these may carry important information about the limits of the Standard Model. In most neutrino experiments, the interactions of the neutrinos occur with nucleons bound in nuclei. The influence of nucleon-nucleon interactions on the response of nuclei to neutrino probes must then be considered. Model predictions for these reactions involve many different effects such as nuclear correlations, interactions in the final state, possible modification of the nucleon properties inside the nuclear medium, that presently cannot be computed in an unambiguous and precise way. One way of avoiding model-dependencies is to use the nuclear response to other leptonic probes, such as electrons, under similar conditions to the neutrino experiments. The extensive analyses of scaling [1–3] and superscaling [4–9] phenomena observed in electron-nucleus scattering lead to the use of the scaling function directly extracted from (e, e') data to predict neutrino (antineutrino)-nucleus cross sections [10], not relying on a particular nuclear structure model. Within the Superscaling Approach (SuSA) a *"superscaling function"* $f(\psi)$ is built by factoring-out the single-nucleon content off the double-differential cross section and plotting the remaining nuclear response versus a scaling variable $\psi(q, \omega)$. Approximate scaling of the first kind, *i.e.*, no explicit dependence of $f(\psi)$ on the momentum transfer q, can be seen at transfer energies below the quasielastic (QE) peak. Scaling of second kind, *i.e.*, no dependence of $f(\psi)$ on the mass number, turns out to be excellent in the same region. When scaling of both first and second types occur, one says that superscaling takes place.

The analyses of the world data on inclusive electron-nucleus scattering [6] confirmed the observation of superscaling and thus justified the extraction of a universal nuclear response to be also used for weak interacting probes. However, while there is a number of theoretical models that exhibit superscaling, such as for instance the relativistic Fermi gas (RFG) [4, 5], the nuclear response departs from the one derived from the experimental data. This showed the necessity to consider more complex dynamical pictures of finite nuclear systems – beyond the RFG – in order to describe the nuclear response at intermediate energies. The model has been applied to neutral current scattering [11] and it has also been extended to the Δ-resonance region [10] where the response of the nuclear system proceeds through excitation of internal nucleonic degrees of freedom. This procedure has been possible due to the large amount of available high-quality data of inelastic electron scattering cross sections on ^{12}C, including also separate information on the longitudinal and transverse responses, the latter containing important contributions introduced by effects beyond the impulse approximation (non-nucleonic).

2 Meson Exchange Currents and Quasielastic Neutrino (Antineutrino) Cross Sections

The recent MiniBooNE data on muon neutrino charged-current quasielastic (CCQE) scattering [12] 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 $M_A \simeq 1.35$ GeV/c^2 (as compared with the standard value $M_A \simeq 1$ GeV/c^2) is employed.

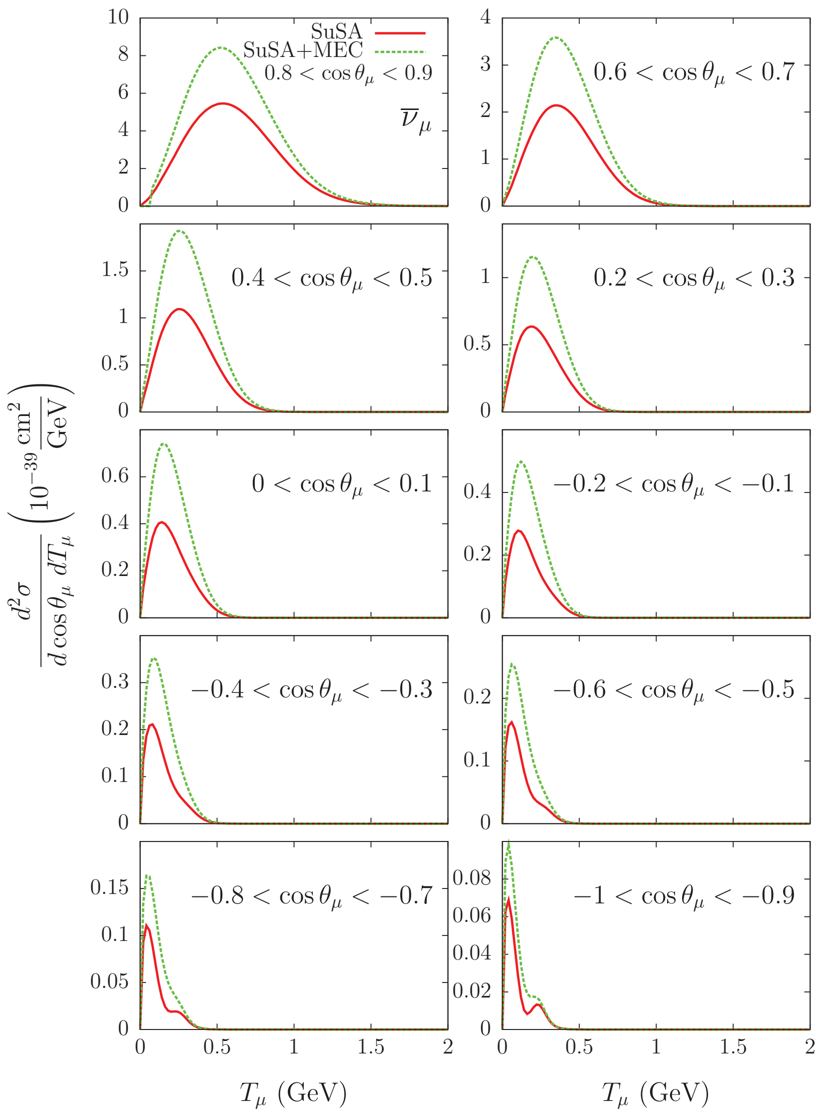

Figure 1. Flux-integrated double-differential cross section per target nucleon for the $\overline{\nu}_\mu$ CCQE process on ^{12}C displayed versus the μ^+ kinetic energy T_μ for various bins of $\cos\theta_\mu$. The lower curves in each panel (red) show the SuSA QE results, while the upper curves (green) show those results plus the contributions from 2p2h MEC.

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.*, [13–18]). Possible explanations of this puzzle have been proposed, based either on multinucleon knockout [14, 19]

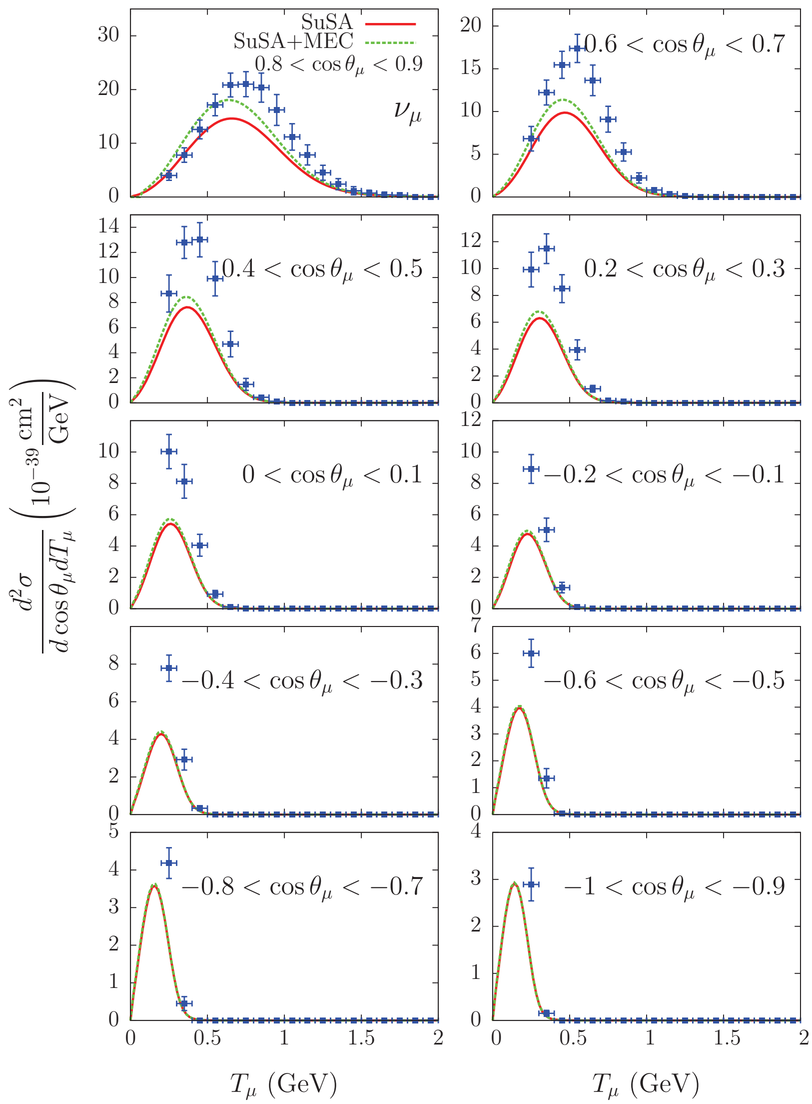

Figure 2. As for Figure 1, but for ν_μ scattering versus μ^- kinetic energy T_μ. The data are from Ref. [12].

or on particular treatments of final-state interactions through phenomenological optical potentials [20], indicating that contributions beyond the naive starting point play an important role in QE neutrino reactions.

In [16] the predictions of SuSA model including 2p-2h Meson-Exchange Currents (MEC) were presented and compared with the MiniBooNE data on muon neutrino scattering from ^{12}C. 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 [16].

In this work we apply the same model to antineutrino scattering. The results are shown in Figures 1-2. In particular, in Figure 1 antineutrino CCQE cross sections integrated over the $\overline{\nu}_\mu$ MiniBooNE flux [21] are shown as functions of μ^+ kinetic energies T_μ 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 Figure 2 the neutrino cross sections versus μ^- kinetic energies are shown for the same kinematical conditions, together with the data from [12].

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 (see Figure 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 VV and transverse AA responses together with small contributions from the charge-longitudinal AA responses, contributions from 2p2h MEC and the VA interference contribution. In leading order the MEC only enter in the transverse VV and in the charge-longitudinal AA sectors. However the latter is extremely small (less than a few %) in the one-body response and therefore we neglect the 2p2h corretions to it. For neutrinos the VA interference is constructive and the MEC effects are to be weighed against relatively large QE contributions. However, for antineutrinos the VA 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.

3 Neutrino-Induced Charged-Current Charged Pion Production

The data on neutrino-induced charged-current (CC) charged and neutral pion production cross sections on mineral oil recently released by the MiniBooNE collaboration [22] provides an unprecedented opportunity to carry out a systematic study of double differential cross section of the processes, $\nu_\mu p \to \mu^- p \pi^+$, $\nu_\mu n \to \mu^- n \pi^+$, $\nu_\mu n \to \mu^- p \pi^0$, averaged over the neutrino flux. We present RFG and SuSA predictions for the double-differential cross section for CC neutrino-induced π^+ production on CH_2 averaged over the neutrino flux $\Phi(\epsilon_\nu)$ as a function of the muon kinetic energy T_μ (Figure 3). Each panel corresponds to a bin of $\cos\theta$. In Figure 4 are shown the results obtained by integrating the flux-averaged double-differential cross sections over angle.

The total cross section for π^+ production as a function of the neutrino energy

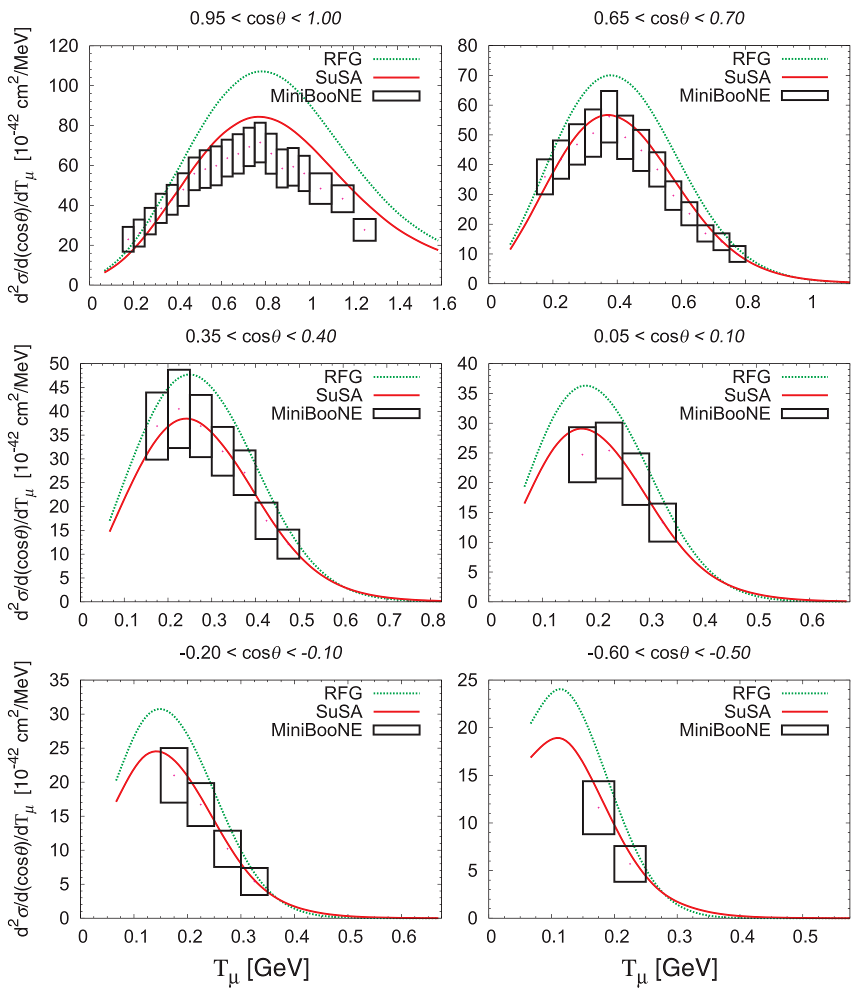

Figure 3. (Color online) The double-differential cross section averaged over the neutrino energy flux as a function of the muon kinetic energy T_μ obtained by SuSA (solid line) and RFG (dotted line) Δ-region scaling functions. In each subfigure the results have been averaged over the corresponding angular bin of $\cos\theta$. The results are compared with the MiniBooNE data [22].

along with the MiniBooNE data are displayed in Figure 5. Poorer agreement with data than for the flux-averaged cross sections presented in Figures 3–4 is clearly observed. The data seems to follow a more linear dependence with the energy up to 2 GeV than the theory. However, before drawing definite conclusions, one has to consider that the unfolding procedure used to extract the data of Figure 5 is to some extent model dependent. Thus these data are less direct

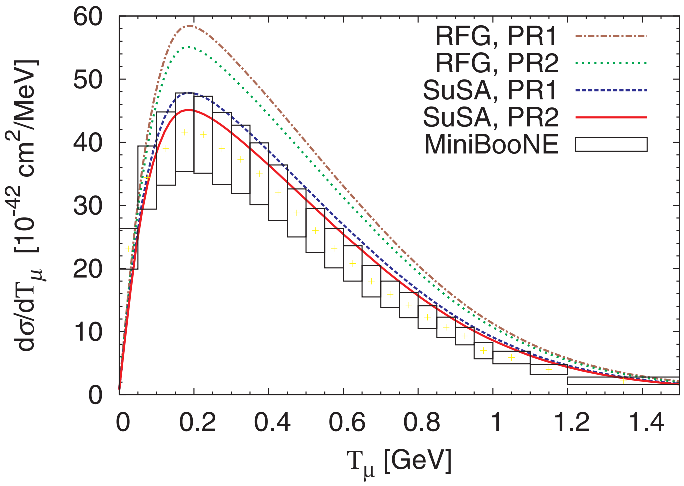

Figure 4. The $d\sigma/dT_\mu$ results obtained by integrating the flux-averaged double-differential cross sections over $\cos\theta$ are compared with the MiniBooNE data [22]. For vector and axial form-factors two parameterizations, "PR1" [23] and "PR2" [24], are used.

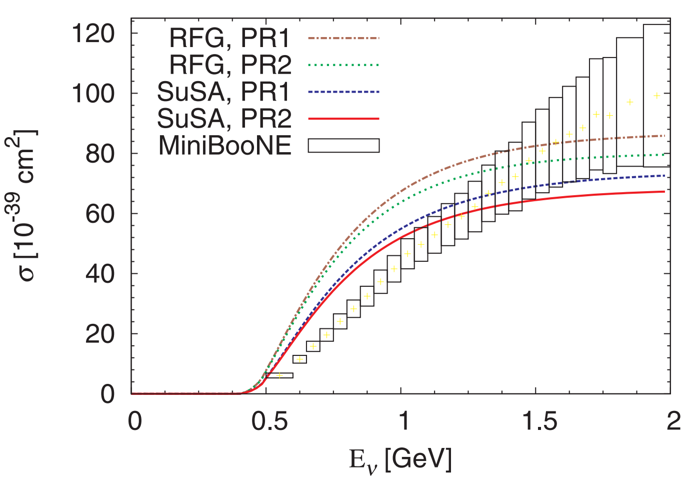

Figure 5. The total cross section for π^+ production are compared with the MiniBooNE data [22]. For vector and axial form-factors two parameterizations, "PR1" [23] and "PR2" [24], are used.

and we consider the comparison with the data of Figures 3–4 to be of more significance.

Summarizing, we show that SuSA predictions are in good agreement with the MiniBooNE experimental data for pionic cross-section in the case of the flux averaged data, while some disagreement remains in the comparison to unfolded neutrino energy data. Notice that the accordance between SuSA and data here is better than the one for the non-pionic case, where the model was found to under-predict the data unless meson exchange currents were explicitly included [17]. We conclude that the SuSA approach for the Δ-region and its extension to neutrino processes may be very useful to predict highly-model-independent cross sections for neutrino-induced CC π^+ production.

Acknowledgements

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