The nucleon axial mass and the MiniBooNE CCQE neutrino-nucleus data

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Abstract. We analyze the MiniBooNE CCQE $d\sigma/dT_\mu d\cos\theta_\mu$ data using a theoretical model that has proved to be quite successful in the analysis of nuclear reactions with electron, photon and pion probes. We find that RPA and multinucleon knockout turn out to be essential for the description of the MiniBooNE data. We show these measurements are fully compatible with former determinations of nucleon axial mass M_A, in contrast with several previous analyses, which have suggested an anomalously large value. We find, $M_A = 1.08 \pm 0.03$ GeV. We also argue that the procedure, commonly used to reconstruct the neutrino energy for QE events from the muon angle and energy, could be unreliable for a wide region of the phase space, due to the large importance of multinucleon events.

1. Introduction

The interaction of neutrinos with nuclei at intermediate energies provides relevant information on the axial hadronic currents. The predicted cross sections for charged current (CC) quasielastic (QE) scattering are very similar for most theoretical models, however, they are clearly below the recently published MiniBooNE data [1]. Actually, the cross section per nucleon on ^{12}C is clearly larger than for free nucleons. The discrepancy is large enough to provoke much debate and theoretical attention. Some works try to understand these new data in terms of a larger value of M_A (nucleon axial mass) around 1.3–1.4 GeV [1, 2, 3, 4]. These large values are not only difficult to accommodate theoretically, but are also in conflict with the value for $M_A = 1.03 \pm 0.02$ GeV that is usually quoted as the world average [5, 6].

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). However, in the recent MiniBooNE measurements, QE is related to processes in which only a muon is detected. This latter definition could make sense because ejected nucleons are not detected in that experiment, but includes multinucleon processes (see Fig. 1b) and others like pion production followed by absorption[1]. However, it discards pions coming off the nucleus, since they will give rise to additional leptons after their decay (see Fig. 1c). In any case, their experimental results cannot

[1] Note, MiniBooNE analysis Monte Carlo corrects for those events.

be directly compared to most previous calculations, as it was first pointed out by M. Martini et al. [9, 10], in which only the one-body QE contribution is considered. In this talk, we present

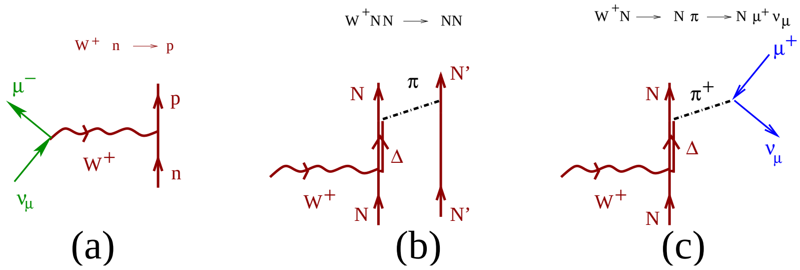

Figure 1. Mechanisms for W absorption inside of a nucleus.

a microscopic calculation of the CCQE-like double differential cross section $\frac{d\sigma}{dT_\mu d\cos\theta_\mu}$ measured by MiniBooNE and we will use these data to extract M_A. We will estimate the CCQE-like cross section by the sum of the theoretical QE (Fig. 1a) cross section and that induced by multinucleon mechanisms, as the one depicted in Fig. 1b, where the gauge boson is being absorbed by two or more nucleons without producing pions.

2. MiniBooNE CCQE-like cross sections and multinucleon mechanisms

First we pay attention to the total cross section and compare our results with the unfolded data of Ref. [1]. Our microscopic model, derived in Refs. [7] and [8], starts from a relativistic local Fermi gas (LFG) picture of the nucleus, which accounts for Pauli blocking and Fermi motion. The QE contribution was studied in [8] incorporating several nuclear effects. The main one is the medium polarization (RPA), including Δ-hole degrees of freedom and explicit π and ρ meson exchanges in the vector-isovector channel of the effective nucleon-nucleon interaction. The model for multinucleon mechanisms (not properly QE but included in the MiniBooNE data [1]) is fully discussed in Ref. [7]. The model includes one, two, and even three-nucleon mechanisms, as well as the excitation of Δ isobars. 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 [11, 12, 13, 14]. This theoretical model has proved to be quite successful in the study of nuclear reactions with photon [11], pion [12, 13] and electron [14] probes.

Up to neutrino energies around 1 GeV, the predictions of our model compare rather well, taking into account experimental and theoretical uncertainties, with the recent data published by the SciBooNE collaboration for total neutrino inclusive cross sections [15]. Results are displayed in Fig. 2 taken from Ref. [7]. There, it can also be appreciated how at larger energies, we underestimate the cross section. Indeed, we could observe that some $WNN \to NN\pi$ contributions neglected in our model, become relatively important at these higher energies.

Our predictions [7] for the flux-unfolded muon neutrino's CCQE-like cross section on ^{12}C measured in [1] are depicted in Fig. 3. The first observation is that our QE curve misses the data-points, being our predicted QE cross sections significantly smaller than those reported by the MiniBooNE collaboration. However, when multinucleon knock out contributions are added to the QE prediction of [8], we obtain the solid green line in a better agreement with the MiniBooNE data. In these calculations, M_A is fixed to 1.05 GeV. Thus we confirm the findings of [9, 10] on the crucial role played by the multinucleon mechanisms in the CCQE-like MiniBooNE data, and that when these latter processes are considered, high values of M_A in the 1.3-1.4 GeV range are not needed to describe the data. Our evaluation of these pionless multinucleon emission contributions to the cross section is fully microscopical and it contains terms, which were either not considered or only approximately taken into account in [9].

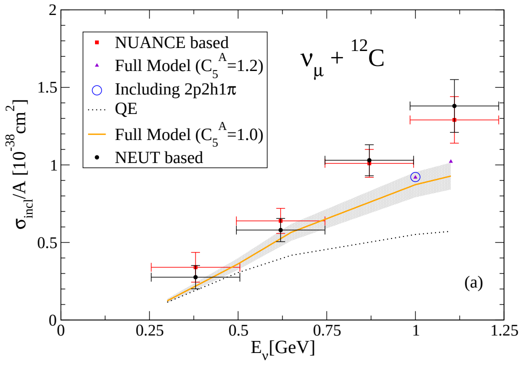

Figure 2. SciBooNE neutrino CC inclusive interaction cross section per nucleon [15], together with the QE and full model (including the theoretical uncertainty band) results of Ref. [7]. See this latter reference for further details.

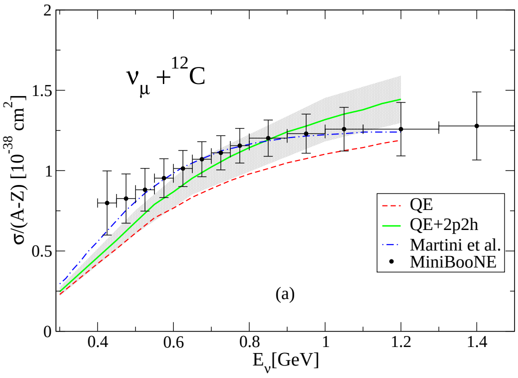

Figure 3. Flux-unfolded MiniBooNE ν_μ CCQE cross section per neutron, together with different theoretical predictions from Ref. [7]. Data points are taken from Ref. [1]. We also show the results (blue dash-dotted line) obtained in Ref. [10].

3. Extracting M_A from MiniBooNE data

The MiniBooNe data include energy and angle distributions as well, and therefore provide a much richer information. Furthermore, the unfolded cross section is not a very clean observable after noticing the importance of multinucleon mechanisms, because the unfolding itself is model dependent and assumes that the events are purely QE. In Fig. 4, we show our results for the MiniBooNE neutrino flux folded CCQE-like $d\sigma/dT_\mu d\cos\theta_\mu$ distribution with $M_A = 1.049$ GeV (value used in our previous works). The full (QE+multinucleon mechanisms) model agrees remarkably well with these data, despite the fact that no parameters have been fitted to data, beyond a global scale, λ.

The inclusion of this scale λ takes into account the global normalization uncertainty of around 10% acknowledged in [1]. Details can be found in [16]. Though the consistency of MiniBooNE data with standard values of M_A has been established now, one could still go further and use our full model to fit the data letting M_A to be a free parameter. We get $M_A = 1.08 \pm 0.03$ GeV and $\lambda = 0.92 \pm 0.03$ with a strong correlation between both parameters. The inclusion of multinucleon mechanisms and RPA is essential to obtain axial masses consistent with the world average. This can be appreciated in Fig. 5, where one can see that RPA strongly decreases the cross section at low energies, while multinucleon mechanisms accumulate their contribution at low muon energies and compensate that depletion. Therefore, the final picture is that of a delicate balance between a dominant single nucleon scattering, corrected by collective effects, and other mechanisms that involve directly two or more nucleons. Both effects can be mimicked by using a large M_A value (LFG entry in Table 1). We also see that the proportion of multinucleon events contributing to the QE-like signal is quite large for low muon energies and thus, the algorithm used to reconstruct the neutrino energy is badly suited for this region. This could

Table 1. Fit results for various models.

LFG	$\lambda = 0.96 \pm 0.03$	$M_A = 1.32 \pm 0.03$ GeV	$\chi^2/\#$ bins = 33/137
Full	$\lambda = 0.92 \pm 0.03$	$M_A = 1.08 \pm 0.03$ GeV	$\chi^2/\#$ bins = 50/137

have consequences in the determination of the oscillation parameters.

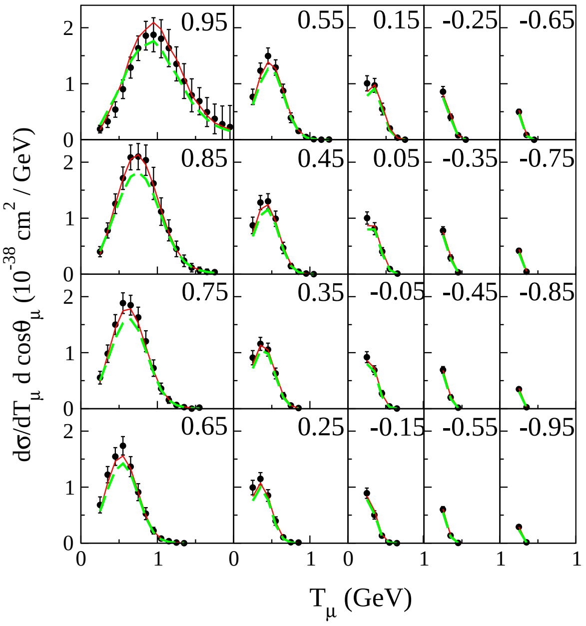

Figure 4. $d\sigma/dT_\mu d(\cos\theta_\mu)$ for different angular bins (labeled by its cosinus central value). Experimental points are taken from Ref. [1]. Green-dashed line (no fit) is the full model prediction (including multinucleon mechanisms and RPA) of Ref. [7] and calculated with $M_A = 1.049$ GeV. Red-solid line is best fit ($M_A = 1.32$ GeV) for the model without RPA and without multinucleon mechanisms.

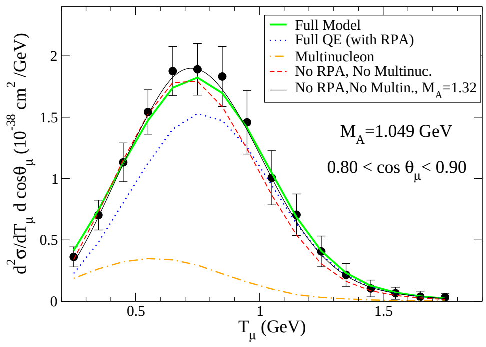

Figure 5. Muon angle and energy distribution for the $0.80 < \cos\theta_\mu < 0.90$ bin. Data from Ref. [1] and calculation with $M_A = 1.32$ GeV are multiplied by 0.9. In the other curves a value of $M_A = 1.049$ GeV was used.

Acknowledgments

This research was supported by DGI and FEDER funds, under contracts FIS2008-01143/FIS, FIS2006-03438 and CSD2007-00042, by Generalitat Valenciana contract PROMETEO/2009/0090 and by the EU HadronPhysics2 project, grant agreement n. 227431.

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