One-pion production in neutrino-nucleus collisions

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Abstract. We use our model for neutrino pion production on the nucleon to study pion production on a nucleus. The model is conveniently modified to include in-medium corrections and its validity is extended up to 2 GeV neutrino energies by the inclusion of new resonant contributions in the production process. Our results are compared with recent MiniBooNE data measured in mineral oil. Our total cross sections are below data for neutrino energies above ≈ 1 GeV. As with other theoretical calculations, the agreement with data improves if we neglect pion final state interaction. This is also the case for differential cross sections convoluted over the neutrino flux.

Keywords: One-pion production by neutrinos
PACS: 13.15.+g,25.30.Pt

INTRODUCTION

The MiniBooNE Collaboration has recently published one pion production cross sections on mineral oil (CH_2) by $\nu_\mu/\overline{\nu}_\mu$ neutrinos with energies below 2 GeV [1, 2, 3]. These are the first pion production cross sections to be measured since the old bubble chamber experiments carried out at Argonne National Laboratory (ANL) [4, 5] and Brookhaven National Laboratory (BNL) [6]. The latter were measured in deuterium where nuclear effects are small [7, 8]. MiniBooNE data poses an extra problem to theoretical models due to the expected relevance of in-medium modifications and final state interaction (FSI) in carbon. In Ref. [9], the use of a formation time/zone, that reduces the impact of FSI, leads to a good agreement with the shape of different neutral current (*NC*) π^0 production differential cross sections. Charged current (*CC*) single pion production off ^{12}C for neutrino energies up to 1 GeV is analyzed in Ref. [10]. Their results for total cross sections are below MiniBooNE data in the high neutrino energy region ($0.8-1$ GeV) and the agreement improves if FSI is neglected. A different approach valid only in the low Q^2 region is presented in Ref. [11]. There the authors evaluate pion production by neutrinos in the low Q^2 region and for neutrinos in the energy range $0.5\sim 2$ GeV. The model is based on partial conservation of the axial current (PCAC) hypothesis, the conserved vector current (CVC) hypothesis and the use of experimental cross section data at the nucleon level. The agreement found with MiniBooNE data is good for Q^2 values up to 0.2 GeV^2. In Ref. [12] the authors use the Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) model finding that total cross sections measured by MiniBooNE are higher than theoretical ones for neutrino energies above $0.8\sim 0.9$ GeV. As in Ref. [10], the agreement with data for total and different flux averaged differential cross sections is better if pion FSI is neglected. However, as also shown in Ref. [12], the same FSI model applied to pion photoproduction is able to give a fair reproduction of experiment in that case.

In this contribution we address the problem of pion production in a nucleus starting from our pion production model at the nucleon level taken from Refs. [13, 8]. In order to better compare to MiniBooNE data we extend the model up to 2 GeV neutrino energies, well above the Δ resonance region for which it was originally developed. Above the Delta region also the $D_{13}(1520)$ resonance plays a role [14] and in the present calculation we include its contribution. We also take into account in-medium corrections to the production process. Those are Pauli-blocking and Fermi motion and the important corrections that originate from Δ resonance modification inside the nuclear medium. Another issue is pion FSI for which we use a simulation program that follows the work done in Ref. [15] where a general simulation code for inclusive pion nucleus reactions was developed. In some of the channels coherent pion production is also possible and to evaluate its contribution we shall take our results in Ref. [16] that uses the model we derived in Ref. [17].

PION PRODUCTION MODEL

Our full model for one pion production on the nucleon is depicted in Fig. 1. It contains the dominant Δ-pole resonance

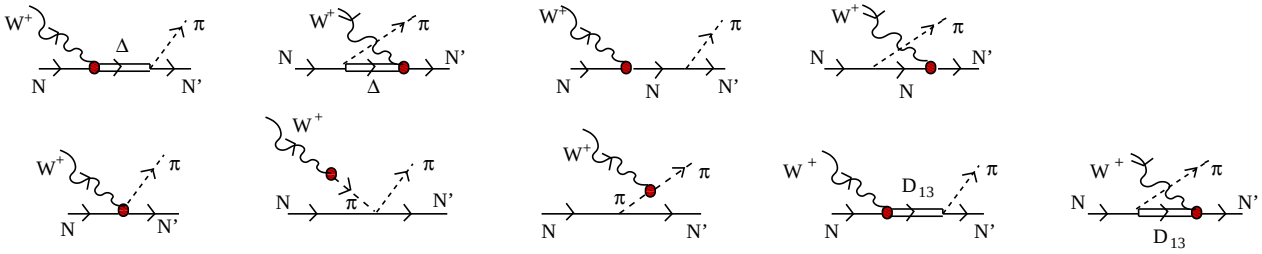

FIGURE 1. Model for the $W^+N \to N'\pi$ reaction. We have Direct and crossed $\Delta(1232)-$ and nucleon pole terms, contact and pion pole contribution, and the pion-in-flight term [13]. In this case we also include direct and crossed D_{13}-pole terms.

term (direct and crossed) and background terms required by chiral symmetry. On top of that we add now the direct and crossed D_{13}-pole terms. The background terms are the leading contributions of a $SU(2)$ nonlinear σ model supplemented with well known form factors in a way that respects both conservation of vector current and the partial conservation of axial current hypotheses. All the details on the Δ and background terms can be found in Refs. [13, 8]. In Ref. [8] we followed the work in Ref. [18] and we made a combined fit of the dominant nucleon-to-Delta axial form factor to ANL and BNL data including both full deuteron effects and flux normalization uncertainties. In Fig. 2 we show the results of that fit compared to experimental data. The axial nucleon-to-Delta form factors obtained in Ref. [8] are the ones we use in the present calculation. As for the D_{13} resonance contribution, all details will be given elsewhere [19]. Note however that as the D_{13} has isospin 1/2 it does not contribute in the $p\pi^+$ channel and thus it does not affect the fit of the axial nucleon to Delta form factors carried out in Ref. [8].

For incoherent production on a nucleus we sum the nucleon cross section over all nucleons in the nucleus. For a charged current (CC) process, using the local density approximation, we arrive for initial pion production (prior to any pion FSI) induced by a neutrino of momentum/energy $|\vec{k}|$ at

$$\frac{d\sigma}{dk 4\pi r^2\, dr\, d\cos\theta_\pi\, dE_\pi} = \Phi(|\vec{k}|) \sum_{N=n,p} 2 \int \frac{d^3p_N}{(2\pi)^3}\, \theta(E_F^N(r) - E_N)\, \theta(E_N + q^0 - E_\pi - E_F^{N'}(r)) \frac{d\hat{\sigma}(\nu N \to l^- N'\pi)}{d\cos\theta_\pi dE_\pi}.$$

with $E_F^N(r) = \sqrt{M^2 + (k_F^N(r))^2}$, being $k_F^N(r) = (3\pi^2\rho_N(r))^{1/3}$ and $\rho_N(r)$ the local Fermi momentum and local density for nucleons of type N. Besides $\Phi(|\vec{k}|)$ is the neutrino flux. $\hat{\sigma}(\nu N \to l^- N'\pi)$ is the cross section at the nucleon level modified by medium effects as discussed below. The above differential cross section is used in a simulation code to generate, at a given point $\vec{r}$ inside the nucleus and by neutrinos of a given energy, pions with a certain energy and momentum direction.

The Δ properties are strongly modified in the nuclear medium [17, 20, 21, 22, 23, 24, 25, 26, 27] and since the direct Δ-pole contribution is the dominant one a more correct treatment is needed for production inside a nucleus. Following

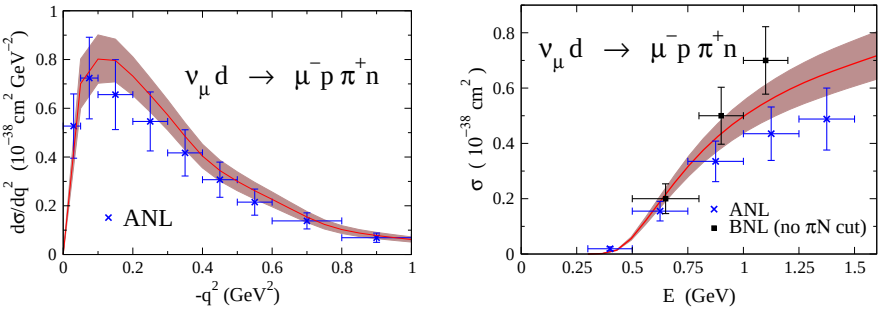

FIGURE 2. Comparison of our model results (solid line) to ANL [5] and BNL [6] experimental data. Theoretical 68% confidence level bands are also shown. Data include a systematic error (20% for ANL and 10% for BNL data) that has been added in quadratures to the statistical published errors. Our theoretical results and ANL data include a $W < 1.4$ GeV cut in the final πN invariant mass.

Ref. [23], we modify the Δ propagator in the Δ-pole term as

$$\frac{1}{p_\Delta^2 - M_\Delta^2 + iM_\Delta\Gamma_\Delta} \to \frac{1}{\sqrt{s}+M_\Delta}\,\frac{1}{\sqrt{s}-M_\Delta+i(\Gamma_\Delta^{\rm Pauli}/2-{\rm Im}\Sigma_\Delta)},$$

with $s = p_\Delta^2$, $\Gamma_\Delta^{\rm Pauli}$ the free Δ width corrected by Pauli blocking of the final nucleon, for which we take the expression in Eq.(15) of Ref. [27], and ${\rm Im}\Sigma_\Delta$ the imaginary part of the Δ self-energy in the medium. The evaluation of Σ_Δ is done in Ref. [21] where the imaginary part is parameterized as

$$-{\rm Im}\Sigma_\Delta = C_Q\left(\frac{\rho}{\rho_0}\right)^\alpha + C_{A_2}\left(\frac{\rho}{\rho_0}\right)^\beta + C_{A_3}\left(\frac{\rho}{\rho_0}\right)^\gamma,$$

with $\rho_0 = 0.17\,{\rm fm}^{-3}$. The terms in C_{A_2} and C_{A_3} are related to the two-body absorption $WNN \to NN$ and three-body absorption $WNNN \to NNN$ channels respectively. On the other hand the C_Q term gives rise to a new $WN \to N\pi$ contribution inside the nuclear medium and thus it has to be taken into account beyond its role in modifying the Δ propagator. This new contribution has to be added incoherently and we implement it in a approximate way by taking as amplitude square for this process the amplitude square of the direct Δ-pole contribution multiplied by $\frac{C_Q(\rho/\rho_0)^\alpha}{\Gamma_\Delta/2}$. When coherent production on ^{12}C is possible we evaluate its contribution using our model in Ref. [17] but with the nucleon-to-Delta form factors as extracted in Ref [8].

As already mentioned, to evaluate FSI effects we follow Ref. [15] and we take into account *P*- and *S*-wave pion absorption, and *P*-wave quasielastic scattering on a single nucleon. The *P*- wave interaction is mediated by the Δ resonance excitation. The different contributions to the imaginary part of its self-energy account for pion two- and three-nucleon absorption and quasielastic processes. The probabilities for the different processes are evaluated in nuclear matter as a function of the density and then the local density approximation prescription is used for its use in finite nuclei. After a quasielastic event, pions change momentum and may change its electric charge. The probability for charge exchange and the final momentum distribution after a quasielastic interaction are given in Ref. [15]. That information is used in the simulation program to generate the pion resulting from such a collision. Besides, in between collisions we assume the pions propagate in straight lines. All the details can be found in Ref. [15].

RESULTS AND COMPARISON WITH MINIBOONE DATA

Here we show part of the results we have obtained. A more complete discussion of the relevance of the different contributions will be given in Ref. [19]. In the left panel of Fig. 3 we compare our results for π^+ production in a *CC* process with MiniBooNE data. We take into account the contribution on ^{12}C and the two hydrogens. There is also a small coherent contribution on ^{12}C. Our total result is below data for neutrino energies above 0.9 GeV. The agreement improves if we do not take into account FSI of the pion. A similar result (see right panel of Fig. 3) is obtained for a final π^0.

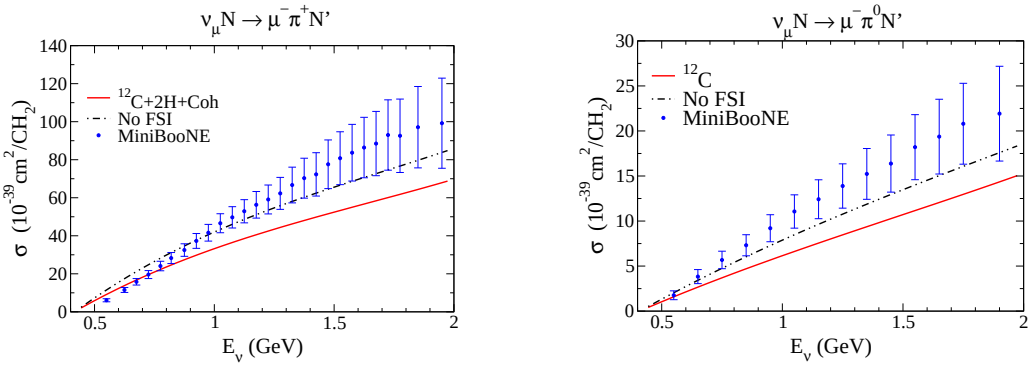

FIGURE 3. 1π total production cross section for ν_μ *CC* interaction in mineral oil. Left Panel: results for a final π^+. Right panel: Results for a final π^0. Solid line: Total contribution. Double-dotted dashed line: Model prediction without FSI of the outgoing pion. Experimental data taken from Ref. [1].

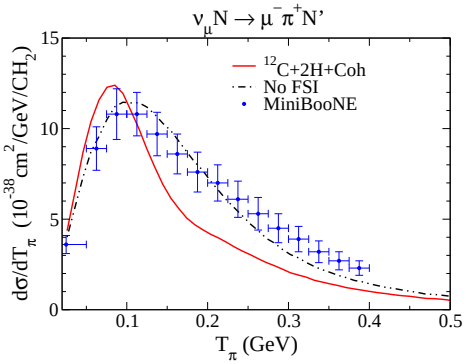

FIGURE 4. Differential $\frac{d\sigma}{dT_\pi}$ cross section for charged current $1\pi^+$ production by ν_μ in mineral oil. Captions as in Fig. 3. Data from Ref. [1].

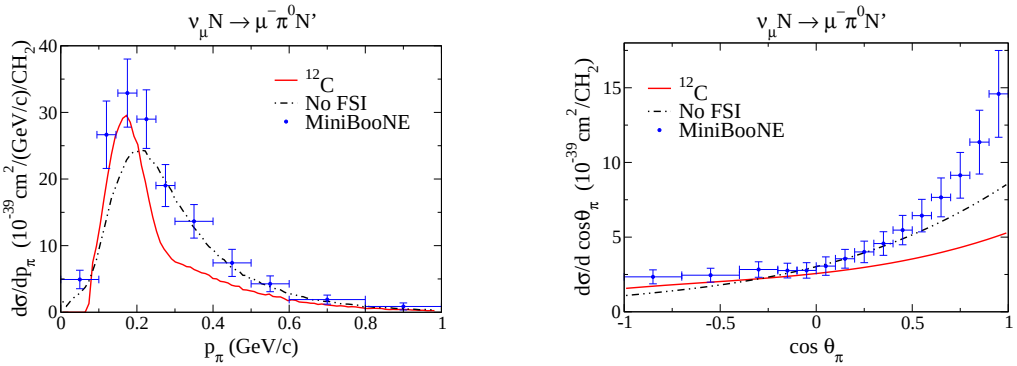

FIGURE 5. Differential $\frac{d\sigma}{dp_\pi}$ (left panel) and $\frac{d\sigma}{d\cos\theta_\pi}$ (right panel) cross section for *CC* $1\pi^0$ production by ν_μ in mineral oil. Captions as in Fig. 3. Data from Ref. [2].

In Fig. 4 we compare the differential $\frac{d\sigma}{dT_\pi}$ cross section for *CC* $1\pi^+$ production by ν_μ. We have taken into account the neutrino flux in Ref. [1] to produce our results. We underestimate data for T_π above 0.15 GeV. This is an effect of FSI of the final pion which above those kinetic energies accounts for a sizable pion absorption driven by the $\Delta(1232)$. Neglecting FSI we get a good agreement with data.

In Fig.5 we show ν_μ differential $\frac{d\sigma}{dp_\pi}$ and $\frac{d\sigma}{d\cos\theta_\pi}$ cross sections for *CC* $1\pi^0$ production. For that we use the neutrino flux reported in Ref. [2] that extends from 2 GeV down to 0.5 GeV neutrino energy. Our results for $\frac{d\sigma}{dp_\pi}$ evaluated without FSI on the final pion agree better with data for pion momentum above 0.2 GeV/c. As a result of FSI, the agreement improves below 0.2 GeV/c, but our model produces too few pions in the momentum region from 0.22 to 0.55 GeV/c. The angular distribution shows those missing pions mainly go in the forward direction.

In Fig. 6 we show results for *NC* production induced by neutrinos that we compare with data by the MiniBooNE Collaboration in Ref. [3]. We use the ν_μ flux reported by MiniBooNE. Our results for $\frac{d\sigma}{dp_\pi}$ without FSI agree nicely with data, while our full model results show a depletion in the $0.25 \sim 0.5$ GeV/c momentum region. The agreement with data is nevertheless better than in the *CC* case. The differential $\frac{d\sigma}{d\cos\theta_\pi}$ cross section is shown in the right panel of Fig. 6. Once again our results without FSI interaction of the final pion show a good agreement with experimental measurements. As for our full results, a clear deficit is seen in the forward direction but the agreement, as it was the case for the $\frac{d\sigma}{dp_\pi}$ differential cross section, is better than in the corresponding *CC* reaction. We obtain similar results for *NC* production induced by antineutrinos, see Ref. [19].

Our results both for *CC* and *NC* processes are in good agreement with the calculations in Refs. [10, 12]. As it is the case there, we also find a better agreement with data if FSI is ignored. The introduction of a formation time/zone, as done in Ref. [9], for pion production and its later interactions in the medium will decrease the effect of FSI and the agreement with data will improve. On the other hand, in Ref. [12] it is shown that the same FSI model applied to pion photoproduction on a nucleus is able to give a fair reproduction of experimental data. In Ref. [19] we also show that

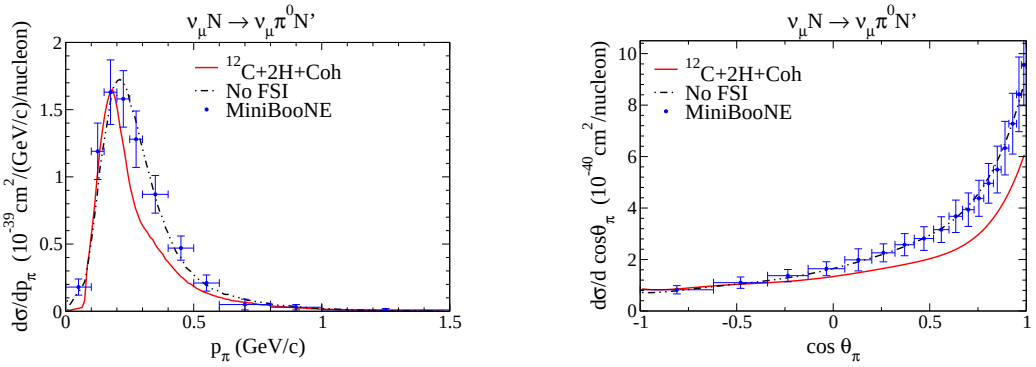

FIGURE 6. Differential $\frac{d\sigma}{dp_\pi}$ (left panel) and $\frac{d\sigma}{d\cos\theta_\pi}$ (right panel) cross sections per nucleon for *NC* $1\pi^0$ production by ν_μ in mineral oil. Captions as in Fig. 3. Data from Ref. [3].

our FSI model gives a fair reproduction of pion photoproduction in nuclei so that it is not clear to us what are the cause for disagreement in the neutrino induced reactions.

ACKNOWLEDGMENTS

This research was supported by the Spanish Ministerio de Economía y Competitividad and European FEDER funds under Contracts Nos. FPA2010- 21750-C02-02, FIS2011-28853-C02-01, FIS2011-28853-C02-02, and the Spanish Consolider-Ingenio 2010 Programme CPAN (CSD2007-00042), by Generalitat Valenciana under Contract No. PROMETEO/20090090 and by the EU HadronPhysics3 project, Grant Agreement No. 283286.

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