Pion production in neutrino-nucleus collisions

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Abstract. We compare our pion production results with recent MiniBooNE data measured in mineral oil. Our total cross sections lie below experimental data for neutrino energies above 1 GeV. Differential cross sections show our model produces too few high energy pions in the forward direction as compared to data. The agreement with experiment improves by artificially removing pion final state interaction.

1. Introduction

In this contribution we present our results [1] for $\nu_\mu/\bar{\nu}_\mu$-induced one pion production cross sections in mineral oil ($CH_2$) for neutrino energies below 2 GeV. These results are compared to the experimental data obtained by the MiniBooNE Collaboration [2 3 4].

Our calculational starting point is the pion production model at the nucleon level of Refs. [5 6], that we have extended from the $\Delta(1232)$ region up to 2 GeV neutrino energies by the inclusion of the $D_{13}(1520)$ resonance. Apart from the $\Delta(1232)$ already present in the model, the $D_{13}(1520)$ resonance gives the most important contribution in that extended energy region [7]. In-medium corrections in the production process include Pauli-blocking, Fermi motion, and the modification of the $\Delta$ resonance properties inside the nuclear medium. Not only the $\Delta$ propagator is modified, but there is also a new pion production contribution (referred to as $C_Q$ in the following) that comes from the changes in the $\Delta$ width in the nuclear environment. For pion final state interaction (FSI) we use a cascade program that follows Ref. [8] where a general simulation code for inclusive pion nucleus reactions was developed. When coherent pion production is possible we evaluate its contribution using the model in Refs. [9 10]. Due to lack of space, here we shall just show the results. For details we refer the reader to Ref [1]. Our results are qualitatively similar to those obtained by other groups [11 12].
2. Results and comparison with MiniBooNE data
We start by showing total cross sections for a given neutrino energy. In the left panel of Fig. 1, we compare with MiniBooNE data our results for $\pi^+$ production in a charged current (CC) process. Our cross sections are below data for neutrino energies above 0.9 GeV. The contribution from the $D_{13}$ resonance only plays a role above $E_\nu = 1.2$ GeV, making some 8% of the total at the highest neutrino energy. The $C_Q$ term contributes for all energies, being around 8% of the total. Similar results are obtained for a final $\pi^0$ (right panel).

![Figure 1](image1)

Figure 1. $1\pi^+$ (left) and $1\pi^0$ (right) total production cross section for $\nu_\mu$ CC interaction in mineral oil. Dashed line: $^{12}$C contribution. Dotted line: $H_2$ contribution. Double-dashed dotted line: Coherent contribution. Solid line: Total contribution. Broken line: Same as solid line but without the $C_Q$ contribution. Dashed-dotted line: Same as solid line but without the contribution from the $D_{13}$. Experimental data taken from Refs. [2] and [3].

![Figure 2](image2)

Figure 2. $1\pi^+$ total production cross section for CC interaction in mineral oil. Solid line: Our full model with $C_5^A(0) = 1$. Dashed line: Full model with $C_5^A(0) = 1.1$. Dashed-dotted line: Full model with $C_5^A(0) = 0.9$. Experimental data taken from Ref. [2].

In Fig. 2 we show the effects in our results of changing the value of the dominant axial nucleon-to-Delta form factor within the uncertainties in its determination in Ref. [6]. A larger value than the central one we use ($C_5^A(0) = 1$) seems to be preferable in the high energy region.

In Fig. 3 we compare results, convoluted with the neutrino flux in Ref. [2], for the differential $\frac{d\sigma}{dT_\pi}$ cross section for CC $1\pi^+$ production by $\nu_\mu$. We disagree with data for $T_\pi$ above 0.15 GeV.
Figure 3. Differential $\frac{d\sigma}{dT_\pi}$ cross section for charged current $1\pi^+$ production by $\nu_\mu$ in mineral oil. Captions as in Fig. 1. We also show in the right panel results without FSI of the final pion (double-dotted dashed line). Data from Ref. [2].

Figure 4. Differential $\frac{d\sigma}{dp_\pi}$ (left panel) and $\frac{d\sigma}{d\cos\theta_\pi}$ (right panel) cross section for CC $1\pi^+$ production by $\nu_\mu$ in mineral oil. Captions as in Figs. 1 and 3. Data from Ref. [3].

The agreement improves if we artificially remove FSI (see right panel). Also in the right panel we show the effects of not including the $C_Q$ or $D_{13}$ contributions. By neglecting the $C_Q$ contribution the cross section decreases by some 10% around the peak at $T_\pi = 0.08$ GeV. The $D_{13}$ plays a very minor role since the neutrino flux peaks at around 600 MeV.

Differential $\frac{d\sigma}{dp_\pi}$ and $\frac{d\sigma}{d\cos\theta_\pi}$ cross sections for CC $1\pi^0$ production by $\nu_\mu$ are shown in Fig. 4. For their evaluation we take the neutrino flux from Ref. [3]. Our model agrees with data for pion momentum below 0.2 GeV/c but it produces too few pions in the momentum region from 0.22 to 0.55 GeV/c. As seen from the angular distribution those missing pions mainly go in the forward direction. The effects of ignoring FSI are also shown in both panels.

In Figs. 5 and 6 we present the results for neutral current (NC) production that we compare with data by the MiniBooNE collaboration [4]. In each case we use the $\nu_\mu/\bar{\nu}_\mu$ fluxes reported in Ref. [4]. Fig. 5 shows the different contributions to the $\frac{d\sigma}{dp_\pi}$ differential cross section. Our results show a depletion in the 0.25 $\sim$ 0.5 GeV/c momentum region though the agreement is better than in the CC case. The results agree with data if one neglects FSI. Looking now at the differential $\frac{d\sigma}{d\cos\theta_\pi}$ cross sections shown in Fig. 6 one can see that our results agree better with data in the antineutrino case where we are within error bars except in the very forward direction. A clear deficit in the forward direction is seen for the reaction with neutrinos but the agreement is better than in the corresponding CC reaction. In both cases, the coherent contribution is shown to be very relevant in the forward direction. Once more, if one artificially
switches off FSI effects we get a good agreement with data.

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 CSD2007-00042, by Generalitat Valenciana under Contract No. PROMETEO/20090090 and by the EU HadronPhysics3 project, Grant Agreement No. 283286.

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