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Comparison of cross section models for neutrino-induced single pion production

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Neutrinos in the energy range from a few hundred MeV to several GeV are relevant for the study of neutrino oscillation by atmospheric neutrino observation and long baseline experiments. In this intermediate energy region, charged-current quasi-elastic scattering (CCQE), single pion production, and deep inelastic scattering coexist with comparable contributions. The T2K experiment has been using CCQE events as the primary data sample to measure neutrino oscillations, whereas single pion production events are used as the signal in the recent analyses. Single pion production is crucial in the NOvA and future DUNE experiment as they measure the neutrino oscillation at higher energy than T2K with the longer baseline. Similarly, single pion production can be a background in proton decay searches at Super-Kamiokande and future experiments, including Hyper-Kamiokande. Therefore, it is important to understand the cross section and kinematics of single pion production to improve the precision of neutrino oscillation parameter measurements and proton decay searches. For this purpose, we evaluated a new model for single pion production, called the dynamical coupled-channels (DCC) model. In this study, we compared it with the Berger-Sehgal model, which is currently used in the NEUT neutrino interaction generator and the cross section measurements from the MiniBooNE experiment.

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1. Cross section models

Neutrino-induced single pion production is simulated using the NEUT neutrino interaction generator[1] in the Super-Kamiokande experiment and the T2K experiment. The interaction mode is determined using the cross section of each mode for the energy of incoming neutrino, and the kinematics of outgoing particles is calculated from the elementary processes of the interaction. NEUT is also able to simulate secondary interactions of hadrons, including the scattering and an absorption, called final state interaction (FSI).

At the energy range of a few hundred MeV to several GeV, charged current quasi-elastic scattering, single pion production and deep inelastic scattering (DIS) coexist. The features of two cross section models for the single pion production, which are compared in this study, are described as follows:

Berger-Sehgal model Berger-Sehgal model[2] calculates cross section for meson producing interactions via the resonance state N^* (e.g., $\nu_l + N \rightarrow l^- + N^*,\ \ N^* \rightarrow N + \pi$) in a way that includes lepton mass effects, as an update of the original Rein-Sehgal model[3], which takes the mass of the charged lepton as zero. 18 different resonance states are taken into account in the range of invariant mass $W < 2\,\mathrm{GeV/c^2}$. This model has been used in various neutrino interaction simulation programs such as NEUT and GENIE. Graczyk-Sobchek form factor[4] is used in this study.

Dynamical coupled-channels model Dynamical coupled-channels (DCC) model[5] is constructed by analyzing the measurements in which pions and other mesons are produced by pion and nucleon scattering, i.e., $\pi + N$, $\gamma + p \rightarrow \pi + N$, $\pi + \pi + N$, $\eta + N$, $K + \Lambda$, $K + \Sigma$ data for $W \leq 2.1\,\mathrm{GeV/c^2}$. One of the features of the DCC model is that it takes into account the coupling of strong interactions associated with resonance states in the energy range of a few hundred MeV to a few GeV (resonance region), where nucleon resonances are produced.

2. Comparisons

Total cross section is calculated as a function of neutrino energy. In addition to the total cross sections, differential cross sections are compared by focusing on three variables that characterize the cross section: neutrino energy (E_ν), four-momentum transfer (Q^2), and hadronic invariant mass (W).

Cross sections of single pion production were measured by the Mini-Booster Neutrino Experiment (MiniBooNE) using muon neutrino energy of around 1 GeV. The results for CC1π^+ ($\nu_\mu + N \rightarrow \mu^- + N + \pi^+$)[6] and CC1$\pi^0$ ($\nu_\mu + n \rightarrow \mu^- + p + \pi^0$)[7] were reported. Figure 1 shows total cross sections as a function of neutrino energy for CC1π^+ and CC1π^0. Error bars in the MiniBooNE data represent systematic uncertainty. The total cross sections calculated by the DCC model are larger than those by the Berger-Sehgal model for neutrino energy $E_\nu < 1.4\,\mathrm{GeV}$ in CC1π^+ channel and $E_\nu < 1.1\,\mathrm{GeV}$ in CC1π^0 channel. Figure 2 shows the measured and predicted differential cross section $\mathrm{d}\sigma/\mathrm{d}Q^2$ which are averaged over the neutrino flux. The differential cross sections in the DCC model are larger at around the peak of $Q^2 \sim 0.2\,\mathrm{GeV^2/c^2}$. The Berger-Sehgal model reproduced the data well in CC1π^+, but there are differences between the models and the data in CC1π^0.

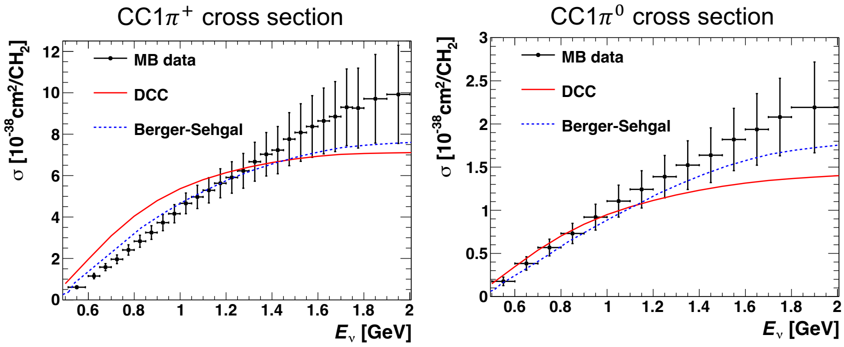

Figure 1: Total cross sections as a function of neutrino energy calculated by cross section models and the MiniBooNE data for CC1π^+ (left)[6] and CC1π^0 (right)[7] channels. The data (black) are compared with the predictions of DCC model (red) and Berger-Sehgal model (blue).

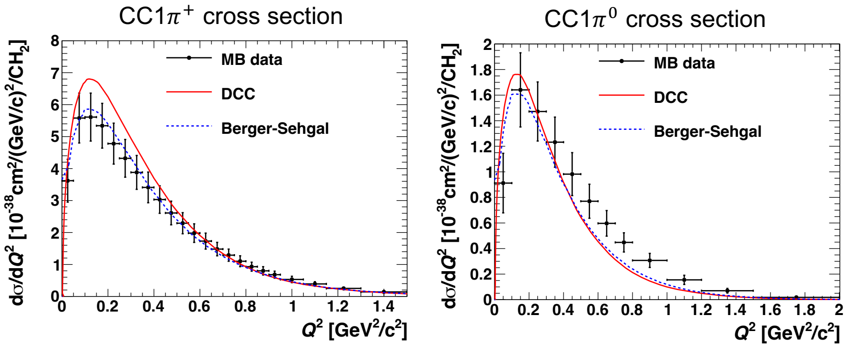

Figure 2: Differential cross section $d\sigma/dQ^2$ calculated by each model and the MiniBooNE data for CC1π^+ (left)[6] and CC1π^0 (right)[7] channels.

In this study, the DCC model was newly implemented in NEUT so that neutrino-induced single pion production can be simulated with it. Single pion production events were generated with the atmospheric neutrino flux at Super-Kamiokande. Left-hand plots of figure 3 show the differential cross section $d\sigma/dQ^2$ per nucleon assuming water target with $E_\nu = 1.0$ GeV, and ratio of DCC to Berger-Sehgal. As Q^2 increases, the ratio gets larger. This leads to the more production of muon with smaller momentum as shown in the right-hand plot of figure 3. The left-hand plot of figure 4 shows the differential cross section $d\sigma/dW$ per nucleon assuming water target with $E_\nu = 1.0$ GeV. The DCC model is larger at $\Delta(1232)$ peak, which results in the production of more pions with smaller momentum as shown in the right-hand plot of figure 4.

3. Conclusions

Two cross section models for neutrino-induced single pion production, the DCC model and the Berger-Sehgal model, are compared in terms of total and differential cross section. Momentum of outgoing muon and pion was compared by implementing the DCC model into the NEUT neutrino event generator. As a result of the comparison, total cross section in DCC is found to be smaller than that in Berger-Sehgal at low resonance region in muon neutrino-induced single pion production. The momentum of outgoing muon and pion tends to be smaller with DCC due to the different Q^2 and W dependence of the differential cross sections in CC1π^+ channel.

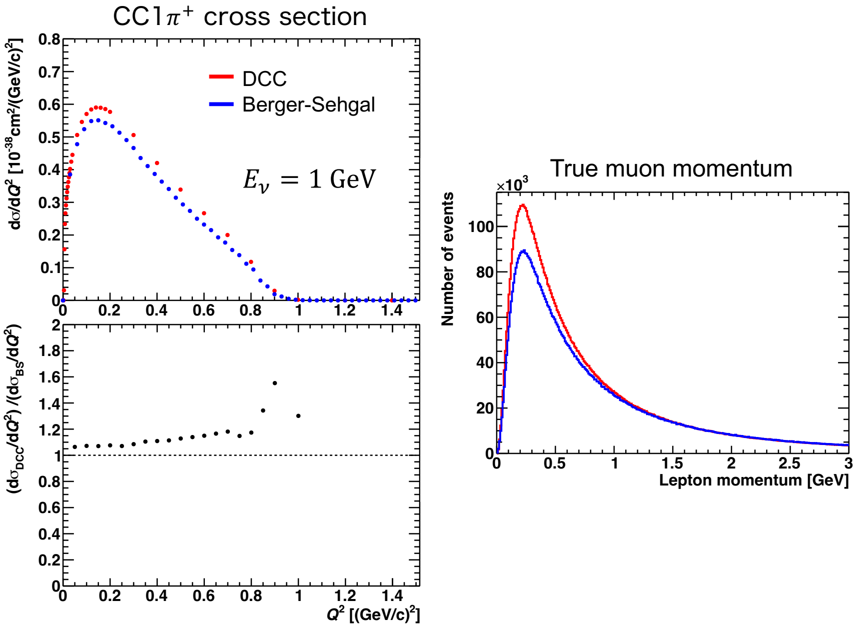

Figure 3: Differential cross section $d\sigma/dQ^2$ per nucleon assuming water target with $E_\nu = 1.0\,\mathrm{GeV}$ (left top), ratio of DCC to Berger-Sehgal (left bottom) and outgoing muon momentum (right).

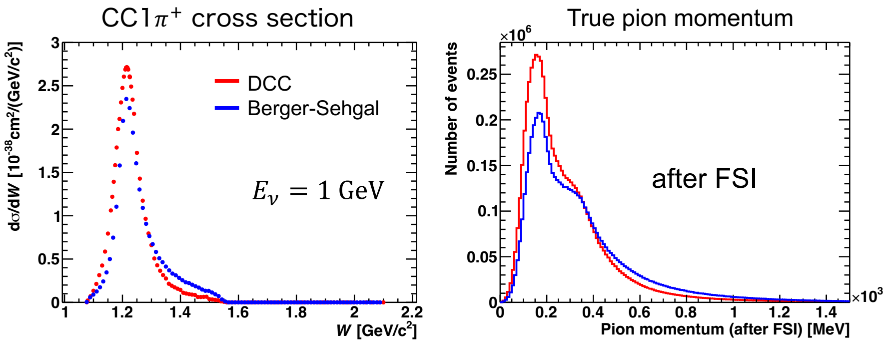

Figure 4: Differential cross section $d\sigma/dW$ per nucleon assuming water target with $E_\nu = 1.0\,\mathrm{GeV}$ (left) and outgoing pion momentum (right).

Acknowledgments

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