Pion production in the T2K experiment

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Background: Pion production gives information on the axial form factors of nucleon resonances. It also introduces a noticeable background to quasi-elastic measurements on nuclear targets and thus has a significant impact on precision studies of neutrino oscillation parameters.

Purpose: To clarify neutrino-induced pion production on nucleons and nuclei.

Method: The Giessen Boltzmann–Uehling–Uhlenbeck (GiBUU) model is used for the description of neutrino-nucleus reactions.

Results: Theoretical results for differential cross sections for the T2K neutrino flux at the ND280 detector and integrated cross sections as a function of neutrino energy are given. Two sets of pion production data on elementary targets are used as inputs to obtain limits for pion production in neutrino-nucleus reactions.

Conclusions: Pion production in the T2K ND280 detector can help to narrow down the uncertainties in the elementary pion production cross sections. It can also give valuable information on the nucleon-Δ axial form factor.

I. INTRODUCTION

Pion production in neutrino-nucleus reactions represents one of the main backgrounds to the identification of charged current quasielastic (CC QE) scattering; the latter is used as a tool to reconstruct the neutrino energy. Pions in the final state that go unobserved for some experimental reasons contribute to the background as well as pions produced in the initial reaction that are absorbed in the nucleus (so-called stuck-pion events). Experimentalists are well aware of this latter complication and have subtracted the cross sections for such events from their original data. This is done with the help of event generators such as NUANCE (for MiniBooNE) or GENIE or NEUT (for T2K) that are tuned to experimental pion data obtained in the same experiment. The quality of the measured pion production cross sections as well as the quality of the generators thus directly affect the final QE data. Furthermore, the subtraction of stuck-pion events from the QE-like ones involves the reconstruction of neutrino energies which itself can distort the cross sections [1]. In [2] it has been shown that even in the absence of 2p-2h or deep inelastic scattering (DIS) processes the energy reconstruction is affected by pion events. For example, for Cerenkov type detectors the reconstructed energy exhibit a bump at values lower than the true neutrino energy, this bump being dependent on the pion detection threshold (see Figs. 6 and 7 in [2]).

For experiments in the current era of precise measurements it is, therefore, important to have the pion production well under control. In [3] we have performed a detailed comparison of theoretical calculations, which use state-of-the-art primary pion production models and final state interactions, with the MiniBooNE data [4, 5]. The calculated cross sections are consistently lower than the experimental ones and show a different kinetic energy (or momentum) distributions of pions; both of these features have recently been confirmed by Hernandez et al. [6].

The major source of uncertainty in our theoretical calculations is the elementary pion production cross section used as input. Currently it is only known with at least

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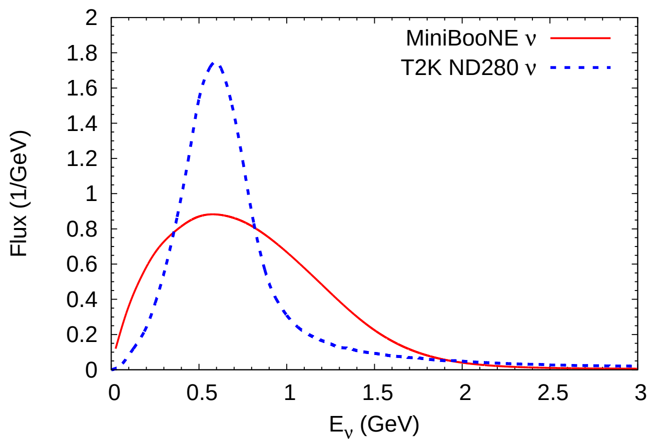

FIG. 1. (Color online) Flux distributions for the experiments MiniBooNE (solid line) and T2K (dashed line), both normalized to 1 when integrated over their full range. The long flat tail of the T2K flux ranging up to 22 GeV is not shown. The distributions are taken from [11] and [12].

a 30% level of uncertainty, which is based on the old bubble-chamber data on proton and deuterium targets. Only the upper boundary of this uncertainty range (BNL data [7] as opposed to those obtained at ANL [8]) comes close to the MiniBooNE data. A definite statement on the validity of the elementary cross sections is, however, not possible since also flux uncertainties could be responsible for the observed disagreement. In addition, also 2p2h1π processes could play a role [3]. A first attempt in this direction has recently been undertaken in Ref. [9].

In this situation any independent experiment could clearly help to clarify the situation. Therefore in this brief report we give the results for pion production in the T2K experiment, using the neutrino flux recently published in Ref. [10]. While the peak energy of T2K is similar to that of MiniBooNE (around 600 MeV) the T2K flux distribution is significantly narrower, as shown in Fig. 1. As a consequence, less influence of RPA correlations is expected (because of the smaller weight of lower energies) and, in addition, pion production is expected to be less prevalent (because of the suppression of higher energies) in T2K.

All the results discussed in this paper are obtained within the GiBUU model [13]. All technical details for pion production and an extended discussion of in-medium effects can be found in Ref. [3] devoted to the comparison with the MiniBooNE data, the only difference being the different neutrino flux distribution used here, namely the T2K flux. We stress that there is no tuning of parameters of any kind. The calculations contain QE (with an axial mass of 1 GeV), 2p-2h processes determined with the help of the MiniBooNE data, pion production through resonances and DIS.

For completeness we note here that the present calculations deal only with the incoherent part of the pion production cross section. Coherent pion production from nuclear targets requires phase coherence and can thus not be treated with a transport (or Monte Carlo) description. Generators that contain such contributions use oversimplified descriptions for the coherent pion production cross section (for a discussion see [14]). A calculation that is free of such oversimplifications gives for a ^{12}C target a cross section of about 0.03×10^{-38}cm^2 at the peak T2K energy of 0.6 GeV [15].

II. PION PRODUCTION CROSS SECTIONS

The calculations give a flux-averaged total inclusive cross section of 8.32×10^{-39}cm^2 per nucleon at an average energy of 0.93 GeV. This point fits very nicely into the systematics shown in Fig. 13 in Ref. [16][1]. Our calculated cross section is made up of true quasielastic (QE) scattering (3.68), 2p-2h (0.95), Δ excitation (1.72), higher resonance excitation (0.25), single-pion background (0.44) and DIS (1.29); the numbers in parentheses give the par-

[1] The cross section calculated here is higher than the experimental value of $6.91 \pm 0.13 \pm 0.84 \times 10^{-39}$cm^2 per nucleon at the mean energy of 0.85 GeV [16]. We note that we used the flux taken from [10] and our value of the mean neutrino energy is calculated over the full range of this flux, i.e. up to 22 GeV. This slightly differs from the flux reported in [16, 17] and their energy range up to 10 GeV only.

tial cross sections per nucleon in units of $10^{-39}\mathrm{cm}^2$. At first sight the relatively large DIS contribution is surprising since the T2K flux is peaked at only 0.6 GeV; it has, however, a weak, but long tail all the way up to 22 GeV and the DIS cross section goes linear with energy. From the theoretical side, the pion production cross section is sensitive to the prescription how to describe the transition from resonance-dominated to DIS-dominated physics around invariant masses of about 2 GeV. Here we have used the same prescription (see Ref. [18]) as in our earlier calculations.

The calculated total pion-production cross sections are: 0.65 for $1\pi^-$ production, 1.53 for $1\pi^0$ and 2.53 for $1\pi^+$ (again all per nucleon, in units of $10^{-39}\mathrm{cm}^2$), these numbers can be compared with 5.0 for neutron and 11.2 for proton knock-out. The comparison with the MiniBooNE data in [3] showed that the calculated values, mainly for $1\pi^+$, were in general somewhat too small compared to the data. To facilitate the comparison we, therefore, give in Fig. 2 the integrated single-pion production cross section for ^{12}C target plotted as a function of true neutrino energy. We also show the contributions of the various reaction mechanisms in the lower part of that figure. Fig. 2 shows that pion production through the Δ resonance nearly exhausts the cross section up to a neutrino energy of about 0.8 GeV, with various other components becoming significant above that energy. DIS becomes dominant above about 2 GeV.

As we have discussed in [3], the neutrino energy reconstruction works quite well for pion production when it is based on muon-pion kinematics (assuming that 2p2h1π processes play only a minor role). If T2K could collect enough statistics to limit the (reconstructed) energy up to about 0.8 GeV, this would give fairly clean information on the $N\Delta$ coupling. In this energy range the pion production cross section is expected to be at the level of 0.2 - 1.5 $\times 10^{-38}\,\mathrm{cm}^2$ and to be dominated by the production and the following decay of the Δ resonance (see Fig. 2, lower part). Therefore, the absolute value of the cross section will reveal information on the coupling, even

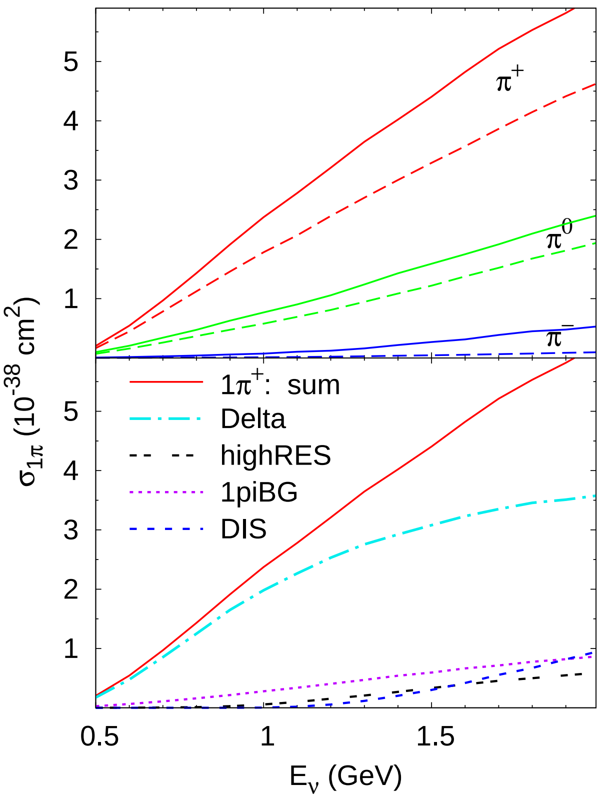

FIG. 2. (Color online) The cross section for single-pion production on ^{12}C as a function of neutrino energy. In the upper part the cross sections are shown for all three charge states for BNL [7] (upper) and ANL [8] (lower) inputs. The solid curves give the results of a calculation with the BNL input, the dashed one that with the ANL input. In the lower part of the figure the contributions from various processes are shown for $1\pi^+$ production. Here the BNL cross sections have been used as elementary input.

when the kinematics of the final pion is modified via final state interactions in a carbon nucleus.

In Fig. 3 we show the pion kinetic energy spectra for all three pion charge states. All the spectra show the well-known shape, with a peak at around $T_\pi = 80$ MeV extending up to about 200 MeV to be followed by a broad shoulder towards higher values of T_π. This shape has also been observed in pion-photoproduction experiments on nuclei [19]. The steep falloff at the right-hand shoulder of the peak is a consequence of pion reabsorption in carbon, which happens mainly through exciting a Δ resonance, followed by a $\Delta N(N) \to NN(N)$ process (see the

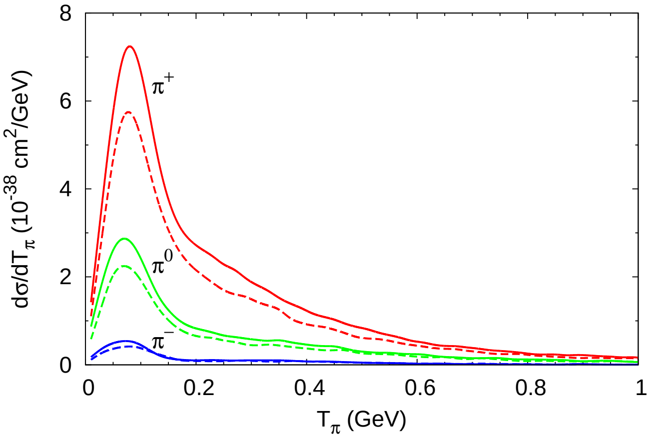

FIG. 3. (Color online) Kinetic energy spectra for pions of indicated charge calculated for the T2K flux [10]. In the pairs of curves the upper, solid curve always gives the results obtained with the BNL input, the lower, dashed one that obtained with the ANL input.

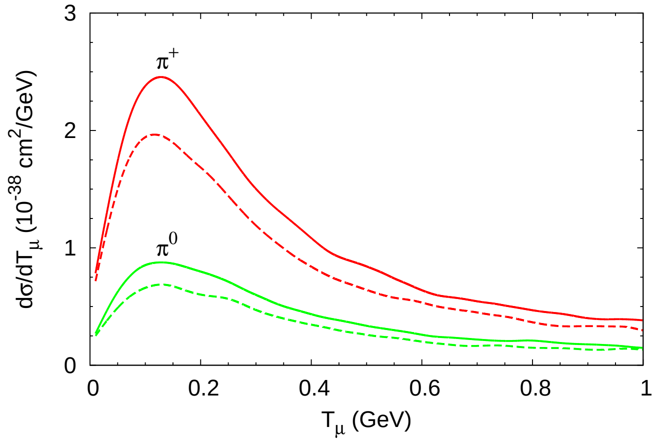

FIG. 4. (color online) Cross sections for $1\pi^+$ and $1\pi^0$ production as a function of the outgoing muon kinetic energy. Solid and dashed curves are as in Fig. 3.

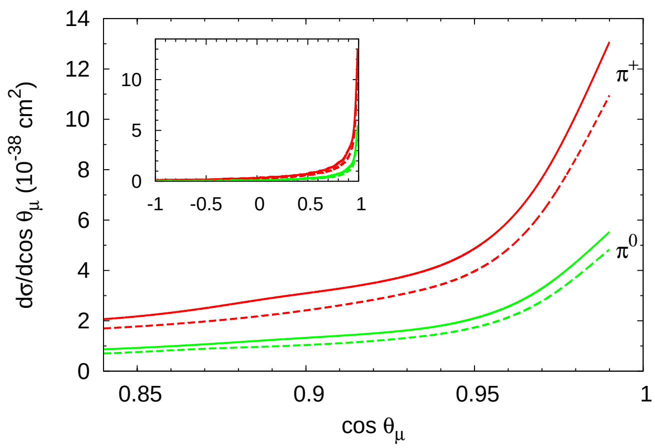

FIG. 5. (color online) Cross sections for $1\pi^+$ and $1\pi^0$ production as a function of the outgoing muon angle. The angular range is restricted to that relevant for the ND280 detector. The inset shows the angular distribution over the full angular range. Solid and dashed curves are as in Fig. 3.

discussion in [3]). It is independent of the production process and should thus be there also in the neutrino-induced pion production on nuclei. Astonishingly, this shape is not seen in the pion spectra obtained by MiniBooNE [4, 5]; it has been suggested that this could be due to a bias in the experimental analysis [20]. The high-energy tails of the pion spectra are mainly caused by pions that were produced by DIS, which starts at neutrino energy about 1 GeV (see fig. 2, lower part). Mostly these high-energy pions cascade down into the Δ region, the remainder making up the tail [18].

In Fig. 4 we show the differential cross sections for single-pion production as a function of the outgoing muon kinetic energy. Similar to the results for MiniBooNE, the cross section peaks at a rather low energy of about 0.15 GeV with a rather flat, long tail towards higher muon kinetic energies. The peak location is roughly determined by the peak energy of the incoming neutrino beam (≈ 0.6 GeV), the Δ excitation energy (≈ 0.3 GeV) and its recoil energy and the muon mass (≈ 0.1 GeV).

Finally, in Fig. 5, we show the angular distribution of the outgoing muons with respect to the neutrino beam direction. The distribution is strongly forward peaked. The T2K ND280 tracking detector, which is mainly sensitive to forward angles, should thus see most of the muons.

The main uncertainty inherent in all these calculations is – besides flux uncertainties – the limited knowledge about the elementary pion production cross sections and, correspondingly, the $N\Delta$ axial coupling. It will, therefore, be interesting to see the experimental results from T2K. A simultaneous comparison of theory with both the

MiniBooNE and the T2K data may help to disentangle the effects of flux and elementary pion production cross section.

III. CONCLUSIONS

Pion production in neutrino-nucleus reactions represents a major background process to quasielastic scattering and thus influences the neutrino energy reconstruction. As a consequence it distorts the oscillation signal. For precision studies of oscillation parameters, such as mixing angles and mass-differences, in the long baseline experiments it is thus important to understand this process in quite some detail. In addition, such experiments could give useful information on the $N\Delta$ axial coupling and form factors which are still largely unknown [21]. Data from the T2K experiment have the potential – when analyzed together with the MiniBooNE data – to answer the question of the correct elementary cross sections for pion production. If limited to reconstructed energies up to 0.8 GeV they can give valuable information to hadron physics. Of course, this would be even more so if elementary targets, such as H or D, could be employed to eliminate any distorting effects of final state interactions. Until such data become available only calculations with reliable and well-tested nuclear physics based generators can be used to analyze the data.

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