Single-pion production in neutrino interactions

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We study diffractive neutrino-proton and neutrino-nuclear collisions in the framework of the color dipole model and evaluate the single-pion production differential cross-section for the kinematics of the ongoing experiment Minerva at Fermilab [1]

1 Introduction

Due to its V-A form the neutrino-hadron interactions possess a rich structures. However, because of smallness of the cross-sections experimental data have been scarce until recently, mostly being restricted to total cross-sections. With the launch of the new high-statistics experiments like MINERνA at Fermilab [1], the neutrino-hadron interactions can be studied with a better precision and at higher energies than before. The V-A structure of the neutrino-quark amplitudes enables us to study simultaneously $\langle VV\rangle$, $\langle AA\rangle$ and $\langle VA\rangle$ correlators in the same process.

The properties of the vector current have been well studied in interactions of charged leptons and photons with protons and nuclei. For the axial current the situation is more complicated and interesting than for the vector current, especially at small Q^2, because the chiral symmetry breaking generates the near-massless pseudo-goldstone mesons (pions). For this reason the chiral symmetry is vital and should be embedded into any dynamical model used for calculation of the cross section at small Q^2.

In this paper we present the results for diffractive pion production obtained within the color dipole description with axial distribution amplitudes derived in the Instanton Vacuum Model (IVM). Full details of evaluations may be found in our recent papers [2, 3].

2 Results and discussion

Most of the data on neutrino-production of pions on protons have been available so far only at energies close to the resonance region [4]. Data at higher energies are scarce and have rather low statistics [6, 7]. Because the dipole formalism should not be trusted at low energies, we provide predictions for the high energies, which can be accessed in the ongoing experiment Minerva at Fermilab [1, 8].

The Q^2 dependence of the diffractive cross section deserves special attention. It would be very steep at small Q^2, if the pion dominance were real. However, since the pion pole is terminated due to conservation of the lepton current (up to the lepton mass), the Q^2 dependence is controlled by the heavier singularities. In the approximation of an effective singularity at $Q^2 = -M^2$ [9] one should expect the Q^2 dependence to have the dipole form $\propto (Q^2 + M^2)^{-2}$.

The numerical results of the dipole model indeed confirm the dipole-like form of the cross section at small Q^2 with the effective mass $M \approx 0.91$ GeV, which is not far from the mass extracted from data $M \approx 1.1$ GeV [4].

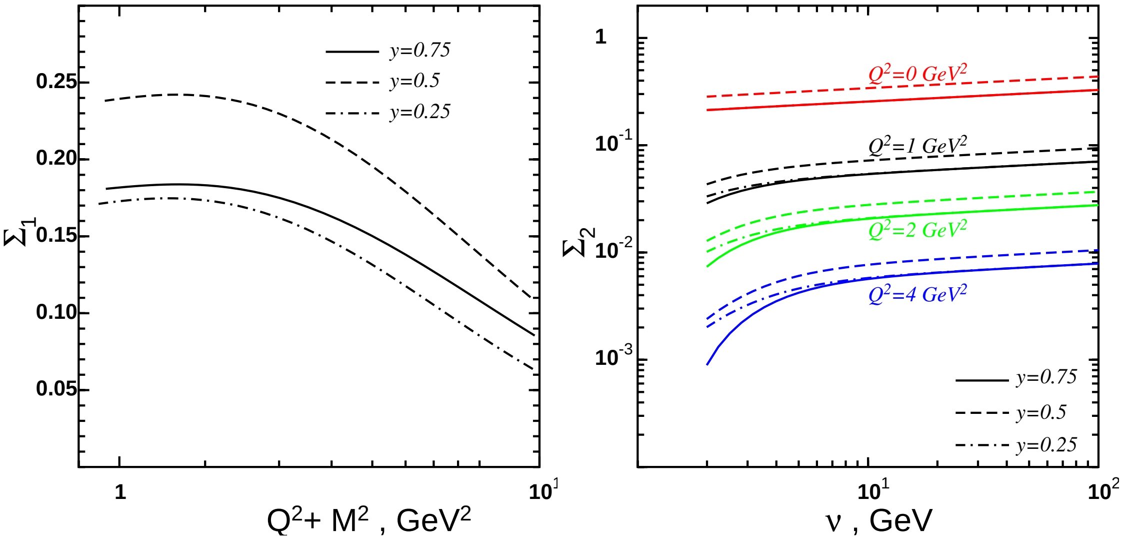

Figure 1: Left: The Q^2-dependence of the cross section of diffractive neutrino-production of pions scaled by factor $(Q^2 + M^2)^2$. Neutrino energy $E_\nu = 20$ GeV, $y = \nu/E_\nu = 0.5$, $\Sigma_1 = (Q^2 + M^2)^2 \nu d^3\sigma/dt\, d\nu\, dQ^2$ [in units $10^{-38} cm^2$]. The mass parameter $M = 0.91$ GeV is adjusted to minimize the variations of the scaled cross section at small Q^2. Right: Forward neutrino-production cross-section of pions as function of ν at several fixed values of y and Q^2, $\Sigma_2 = \nu d^3\sigma/dt\, d\nu\, dQ^2$ [in units $10^{-38} cm^2/GeV^4$].

The forward invariant cross-section of diffractive neutrino-production of pions on protons is depicted in the right pane of the Fig. (1) as function of ν at several fixed values of y and Q^2.

For the nuclei, in the Figure 2 we compare the results for the ratio

$$R^{coh}_{A/N}(\nu, Q^2) = \frac{1}{A} \frac{d^2\sigma_A/d\nu\, dQ^2}{d^2\sigma_N/d\nu\, dQ^2}, \tag{1}$$

is plotted in the Figure 2 by solid curves vs energy ν. These results of the dipole model are compared with the expectations based on the Adler relation [10, 11] shown by dashed lines. Our results significantly underestimate the Adler relation predictions at all energies. At low energies the Adler relation is trivially broken [5, 12] because the longitudinal momentum transfer is large and the amplitudes of pion production on different nucleons are out of coherence. At high energies the lifetime of the intermediate heavy states (a_1 meson, $\rho\pi$, etc.) is long, and absorptive corrections suppress the coherent cross section, leading to a dramatic breakdown of the Adler relation [12].

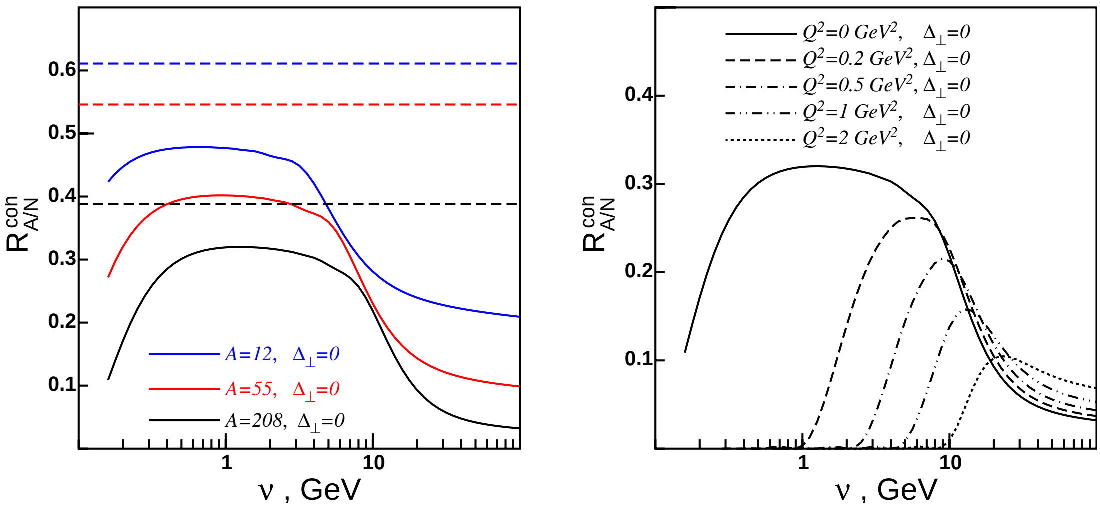

Figure 2: ν-dependence of the ratio of the coherent forward neutrino-pion production cross-sections on nuclear and proton targets. *Left:* ν-dependence of the ratio for different nuclei at $Q^2 = 0$. Solid curves correspond to the color dipole model, dashed lines show the predictions of the Adler relation. *Right:* ν-dependence of the nuclear ratio vs Q^2 for lead ($A = 208$).

There is, however, a wide energy interval from few hundreds MeV up to about 10 GeV, where the Adler relation was expected to be valid [12]. Now we see that even at these energies the Adler relation is broken. To understand why this happens notice that an effective two-channel model used in [12] assumed dominance of two states in the dispersion relation for the axial current, the pion and an effective axial vector pole a with the mass of the order of 1GeV. The condition of validity of the Adler relation was shortness of the coherence length related to the mass of the a-state compared to the nuclear size,

$$l_c^a = \frac{2\nu}{Q^2 + m_a^2} \ll R_A. \tag{2}$$

In contrast to this simple model, the invariant mass of a $\bar{q}q$ dipole is not fixed, $m_{\bar{q}q}^2 = (m_q^2 + k_T^2)/\alpha(1-\alpha)$, where α is the fractional light-cone momentum of the quark. Correspondingly, the related coherence length, $l_c^{\bar{q}q}$ is distributed over a wide mass range, and while the center of the distribution and large masses lead to a short $l_c^{\bar{q}q}$, the low-mass tail of this distribution results in a long $l_c^{\bar{q}q} \gg R_A$. For this reason the absorption corrections suppress the cross section, even at moderate energies.

In Fig. 3 the ratio of the incoherent nuclear-to-nucleon cross-sections

$$R^{inc}_{A/N}(t, \nu, Q^2) = \frac{d\sigma_{\nu A \to l\pi A^*}/dtd\nu dQ^2}{A\, d\sigma_{\nu N \to l\pi N}/dtd\nu dQ^2}, \tag{3}$$

is plotted versus energy ν. As was discussed in [2, 12] the energy dependence of the incoherent cross-section is controlled only by the coherence length l_c^a, related to the heavy axial states, so there are only two regimes: $l_c^a \leq R_A$ and $l_c^a > R_A$. Our numerical calculations confirm such a behavior.

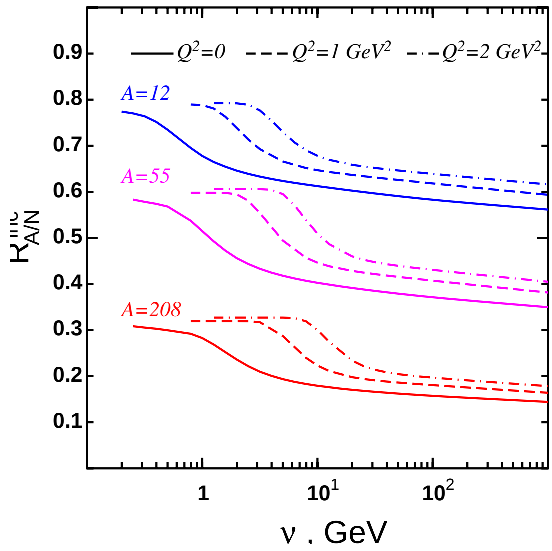

Figure 3: ν-dependence of the ratio of the incoherent forward pion neutrino-production cross-sections on nuclear and proton targets at different virtualities Q^2.

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