Diffractive neutrino-production of pions in the color dipole model

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Abstract. In this paper we studied the neutrino-proton collisions in the framework of the color dipole model and evaluated the single-pion production cross-section $\nu d\sigma/dtdQ^2d\nu$ in the kinematics of the ongoing Minerva experiment [1].

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INTRODUCTION

Due to its V-A shape the neutrino-hadron interactions possess a very rich structure. However, because of the smallness of the cross-sections until recently the experimental data have been scarce, mostly being limited to the total cross-sections. With the launch of the new high-statistics experiments like MINERνA at Fermilab [1], now the neutrino-hadron interactions may be studied with a better precision. The V-A structure of the neutrino-quark vertices 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 the processes of deep inelastic scattering (DIS) of leptons on protons and nuclei, deeply virtual Compton scattering (DVCS), real Compton scattering (RCS), and vector meson production.

For the axial current the situation is more complicated, 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 which is used for calculation of the cross section at small Q^2.

In the dipole representation, chiral properties are important in evaluation of the distribution amplitudes (DA) of the axial current and pion. Recently, we used the DA of the vector current calculated in the Instanton Vacuum Model (IVM) for the evaluation of several processes [2–5]. In this paper in a similar fashion we use the DAs of the axial current and pion evaluated in the framework of IVM. Since the IVM has a built-in spontaneous chiral symmetry breaking, the $\bar{q}q$ DAs of axial current and pion should automatically satisfy PCAC, and in the small-Q^2 limit reproduce the Adler relation [6, 7].

DIFFRACTIVE PRODUCTION OF PIONS

The cross section of diffractive neutrino-production of a pion on a proton, $\nu p \to l\pi p$, has the form,

$$\nu \frac{d^3\sigma_{\nu p\to\mu\pi p}}{d\nu dt dQ^2} = \frac{G_F^2\, L_{\mu\nu}\left(W_\mu^A\right)^* W_\nu^A}{32\pi^3 m_N^2 E_\nu^2 \sqrt{1+Q^2/\nu^2}}, \tag{1}$$

where E_ν is the energy of the neutrino; ν is the energy of the heavy boson W, or Z, in the target rest frame; m_N is the nucleon mass; $L_{\mu\nu}$ is the lepton tensor; and W_μ^A is the amplitude of pion production by the axial current on the proton target. In the color dipole model this amplitude has the form

$$W_\mu^A\left(s,\Delta,Q^2\right) = \int_0^1 d\beta_1 d\beta_2 d^2r_1 d^2r_2 \bar{\Psi}^\pi\left(\beta_2,\vec{r}_2\right)\mathscr{A}^d\left(\beta_1,\vec{r}_1;\beta_2,\vec{r}_2;\Delta\right)\Psi_\mu^A\left(\beta_1,\vec{r}_1\right) \tag{2}$$

where $\bar{\Psi}^\pi$ and, Ψ_μ^A are the distribution amplitudes (DAs) of the pion and axial current respectively, and $\mathscr{A}^d(\ldots)$ is the dipole scattering amplitude. The axial current DA Ψ_μ^A contains a pion pole, whose contribution to the amplitude is proportional to q_μ, because the pion is spinless. This factor terminates the pion pole because of conservation of the lepton current.

The amplitude $\mathscr{A}^d\left(\beta_1,\vec{r}_1;\beta_2,\vec{r}_2;\Delta\right)$ in (2) is a universal function dependent only on the target but not on the initial and final states. For evaluations we used a parameterization of the amplitude $\mathscr{A}^d\left(\beta_1,\vec{r}_1;\beta_2,\vec{r}_2;\Delta\right)$ discussed in detail in [2, 8–10]. In addition to the axial current contribution, in (2) there should be the contribution of the vector current. This contribution involves a poorly known helicity flip dipole amplitude $\tilde{\mathscr{A}}_d$, which vanishes at high energies as $1/\nu$. Besides, at small Q^2, the vector current contribution is suppressed by a factor Q^2.

NUMERICAL RESULTS

Most of the data on neutrino-production of pions on protons have been available so far only at energies close to the resonance region [11]. Data at higher energies are scarce and have rather low statistics [12, 13]. Because the dipole formalism should not be trusted at low energies, we provide predictions for the energy range of the ongoing experiment Minerva at Fermilab [1, 14].

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, the Q^2 dependence is controlled by heavier singularities. In the approximation of an effective singularity at $Q^2 = -M^2$ [15] one should expect the dipole form $\propto (Q^2+M^2)^{-2}$. Within the dispersion approach the effective mass scale M is expected to be of the order of $1\,\mathrm{GeV}$ [11, 15, 16]. Within the dipole description the Q^2 dependence is controlled by the the IVM mass scale, which is of the order of 700 MeV.

Straightforward evaluation yields that at small Q^2 the Q^2-dependence indeed has a dipole-like form with an effective mass $M \approx 0.91$ GeV. In order to get rid of this trivial dependence, in the left pane of the Fig. 1, we plot the forward diffractive neutrino cross section scaled by the factor $(Q^2 + M^2)^2$. As we can see, the scaled cross section is constant up to rather large $Q^2 \sim 3\,\mathrm{GeV}^2$, but substantially deviates from the dipole form at larger Q^2.

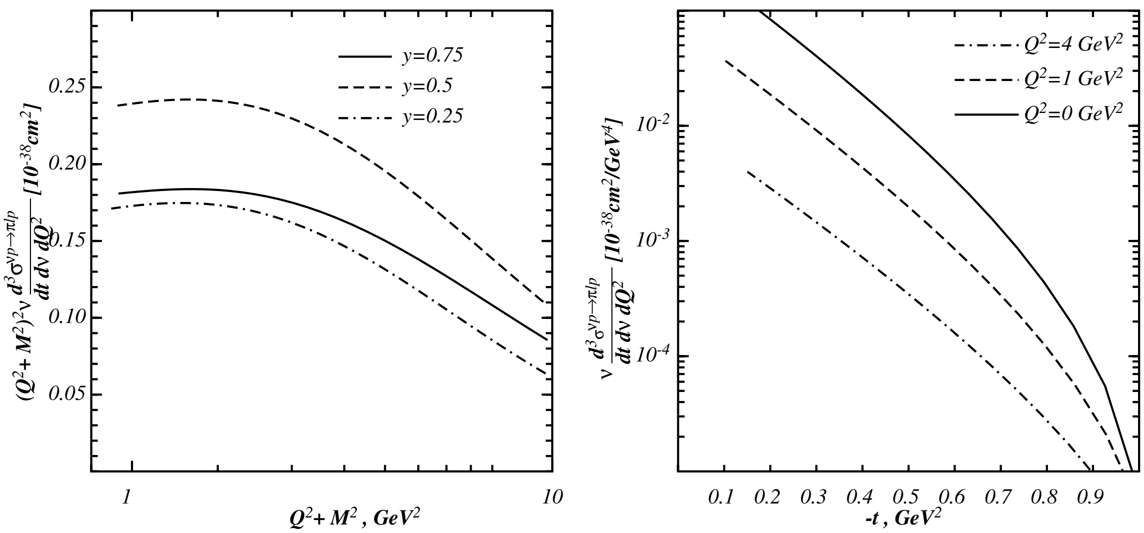

FIGURE 1. Left: The Q^2-dependence of the cross section of diffractive neutrino-production of pions scaled by factor $(Q^2 + M^2)^2$ at neutrino energy $\nu = 10$ GeV and $y = \nu/E_\nu = 0.5$. The mass parameter $M = 0.91\,\mathrm{GeV}$ is adjusted to minimize the variations of the scaled cross section at small Q^2. Right: The t-dependence of the cross section of diffractive neutrino-production of pions at different Q^2 for neutrino energy $E_\nu = 20$ GeV and $y = 0.5$.

The t-dependence of the cross section is controlled by the employed model for impact parameter dependence of the dipole amplitude. The results for t-dependence of the invariant cross-section are shown in the right pane of the Fig. 1.

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

Experimental data for neutrino-production cross section are usually presented as function of neutrino energy E_ν integrated over ν. Unfortunately, in this form one cannot separate physics of low and high energies, and the cross-section gets a substantial contribution from small ν region, e.g. s-channel resonances. This contribution is constant at any high neutrino energy E_ν, and its magnitude is comparable with the diffractive part.

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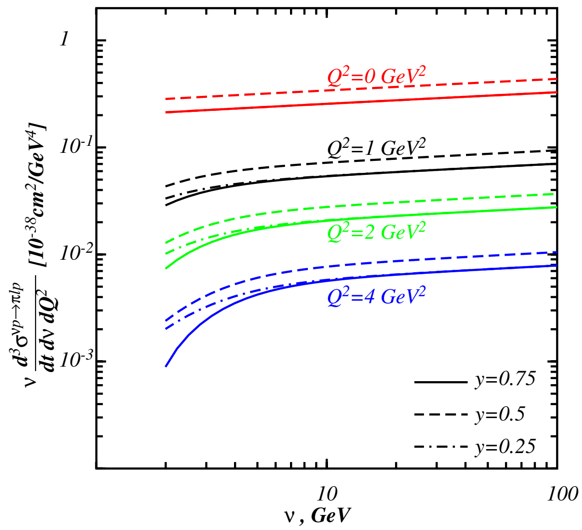

FIGURE 2. [Color online] Forward neutrino-production cross-section of pions as function of ν at several fixed values of y and Q^2.

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