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Hard exclusive electroproduction of pions

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Abstract. We investigate the exclusive electroproduction of π^+ mesons from nucleons. To leading-twist, leading-order α_s accuracy, the corresponding production amplitude can be decomposed into pseudovector and pseudoscalar parts. Both can be expressed in terms of quark double distribution functions of the nucleon. While the pseudovector contribution is connected to ordinary polarized quark distributions, the pseudoscalar part can be related to one-pion t-channel exchange. We observe that the pseudovector part of the production amplitude is important at $x_{\mathrm{Bj}} < 0.1$. On the other hand, for $0.1 < x_{\mathrm{Bj}} < 0.4$, contributions from one-pion exchange dominate.

1 Introduction

Hard exclusive electroproduction of mesons from nucleons has become a field of growing interest. The recent progress in the QCD analysis of such processes is based on a factorization theorem [1] (see also [2–5]) that is valid in the case of longitudinally polarized photons: At large photon virtualities, $Q^2 \gg \Lambda^2_{\mathrm{QCD}}$, the underlying photon–parton subprocesses are dominated by short distances, hence can be calculated perturbatively. On the other hand, all information on the long-distance dynamics of quarks and gluons can be collected in the distribution amplitude of the produced meson and in generalized (skewed [2,6] or double [2]) parton distribution functions of the nucleon. As a consequence, experimental investigations of meson production processes allow one to probe details of the quark–gluon dynamics in nucleons beyond our current knowledge, which has been obtained mainly from inclusive high-energy processes. Ongoing and planned measurements at DESY (HERA [7], HERMES [8]), CERN (COMPASS [9]), and Jefferson Lab [10] are therefore of great interest.

In our previous work [4,11] we have derived the leading-order QCD production amplitudes for neutral pseudoscalar mesons and vector mesons. The corresponding cross sections have been discussed within a specific model [12] for double parton distributions. In this paper we consider hard electroproduction of charged pions. This process generates interest in particular from the fact that it receives significant contributions from two production mechanisms: Either (i) the photon interacts with a quark from the nucleon which, after hard-gluon exchange, combines with a second quark of the target to the final pion, or (ii) the pion is produced from the meson cloud of the nucleon. The latter mechanism is often referred to as the pion-pole contribution. In meson-cloud models of the nucleon, the second mechanism directly involves the electromagnetic form factor $F_\pi(Q^2)$ of the pion (see, e.g., [13] and references therein). Pion electroproduction has therefore often been considered a generic process for determining $F_\pi(Q^2)$ (see, e.g., [14]). However, as discussed in [15], there may be significant uncertainties due to type-(i) contributions. The latter have been modeled in [15] in terms of hard-gluon exchange diagrams, with nonperturbative factors estimated by an overlap of light-cone wave functions with Chernyak–Zhitnitsky-type distribution amplitudes [17].

In this work, we address questions similar to those raised in [15]. The distinctive feature of our approach is a systematic use of perturbative QCD (PQCD) factorization [1,2]. Within a consistent PQCD analysis, all necessary information about the nucleon structure is contained in quark double distributions. The latter are constrained through the behavior of ordinary quark distribution functions, as well as through sum rules and symmetry properties (for a discussion, see [4,16]). In particular, we show that actually both production mechanisms, (i) and (ii), can be formulated in terms of quark double distribution functions of the nucleon; i.e., the existence of the pion-pole contribution fits into the PQCD factorization framework.

After modeling the involved double distribution functions, we calculate the differential cross section of π^+ production in the region of small momentum transfers, $-t < 0.5\ \mathrm{GeV}^2$. We find that both mechanisms, (i) and (ii), contribute significantly. While one-pion exchange domi-

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nates at intermediate values of Bjorken x, the two-quark exchange is relevant mainly at small x_{Bj}.

The paper is organized as follows: In Sect. 2 we present the amplitudes for charged-pion electroproduction. Pseudovector and pseudoscalar parts of the relevant double distribution functions are associated in Sect. 3 and 4 with the perturbative and pion-pole contributions, respectively. Results are presented in Sect. 5. Finally, in Sect. 6, we summarize.

2 Amplitudes

The calculation of meson electroproduction amplitudes is based on PQCD factorization [1]. It applies to incident longitudinally polarized photons with large space-like momenta, $Q^2 = -q^2 \gg \Lambda^2_{\mathrm{QCD}}$, and to moderate momentum transfer to the nucleon target, $|t| \lesssim \Lambda^2_{\mathrm{QCD}}$. Using the techniques outlined in [1,2,4,11] gives the following result for the π^+ virtual photoproduction amplitude in leading-twist, leading-order α_s accuracy:

$$
\begin{aligned}
\mathcal{A}_{\pi^+} = {} & \mathrm{i}\frac{g^2 C_F}{4N_c}\frac{f_\pi}{Q}\frac{\bar{N}(P',S')\gamma_5\hat{n}N(P,S)}{\bar{P}\cdot n}\int_0^1 \mathrm{d}\tau \frac{\Phi_\pi(\tau)}{\tau\bar{\tau}} \\
& \times \int \mathrm{d}\,[x,y]\Big[(e_d\,\Delta F^{du} - e_u\,\Delta\bar{F}^{du}) \\
& \times \frac{\bar{\omega}}{x+2y+x\bar{\omega}-\mathrm{i}\epsilon} - (e_u\,\Delta F^{du} - e_d\,\Delta\bar{F}^{du}) \\
& \times \frac{\bar{\omega}}{x+2y-x\bar{\omega}-\mathrm{i}\epsilon}\Big] - \mathrm{i}\frac{g^2 C_F}{2N_c}\frac{f_\pi}{Q} \\
& \times \frac{\bar{N}(P',S')\gamma_5 N(P,S)}{2M}\int_0^1 \mathrm{d}\tau\frac{\Phi_\pi(\tau)}{\tau\bar{\tau}}\int \mathrm{d}\,[x,y] \\
& \times \Big[(e_d\,\Delta K^{du} - e_u\,\Delta\bar{K}^{du})\frac{1}{x+2y+x\bar{\omega}-\mathrm{i}\epsilon} \\
& -(e_u\,\Delta K^{du} - e_d\,\Delta\bar{K}^{du})\frac{1}{x+2y-x\bar{\omega}-\mathrm{i}\epsilon}\Big]. \qquad (1)
\end{aligned}
$$

Here the notation $\int \mathrm{d}\,[x,y]\ldots = \int_0^1 \mathrm{d}x \int_0^{\bar{x}} \mathrm{d}y\ \ldots$, with $\bar{x} = 1-x$ is used. $N(P,S)$ and $\bar{N}(P',S')$ are the Dirac spinors of the initial and scattered nucleon, respectively, with the corresponding four-momenta P, P' and spins S, S'. M stands for the nucleon mass. The average nucleon momentum is denoted by $\bar{P} = (P+P')/2$, and the momentum transfer is $r = P - P'$, with $t = r^2$. The produced meson carries the four-momentum q', and $\bar{q} = (q+q')/2$. Furthermore, we have introduced the variable $\bar{\omega} = 2\bar{q}\cdot\bar{P}/(-\bar{q}^2)$. Finally, n is a light-like vector, $n \sim P + x_{\mathrm{N}} q$, where x_{N} is the Nachtmann-x variable [18], normalized such that $n\cdot a = a^+ = a^0 + a^3$ for any vector a, and $\hat{n} = \gamma_\mu n^\mu$.

The long-distance dynamics of the pion in the final state is contained in the decay constant $f_\pi = 133$ MeV and the distribution amplitude $\Phi_\pi(\tau)$ [19,20]:

$$
\begin{aligned}
& \langle \pi^+(q')|\,\bar{\psi}_u(x)\gamma_5\hat{n}\psi_d(y)\,|0\rangle_{(x-y)^2=0} \\
& = -\mathrm{i}f_\pi\,(q'\cdot n)\int_0^1 \Phi_\pi(\tau)\,\mathrm{e}^{\mathrm{i}q'\cdot(\tau x+\bar{\tau}y)}\,\mathrm{d}\tau\,, \qquad (2)
\end{aligned}
$$

where quark fields ψ, with proper flavor quantum numbers, enter. In what follows, we always use the asymptotic expression for the distribution amplitude

$$
\Phi_\pi(\tau) = 6\tau\,(1-\tau)\,. \qquad (3)
$$

The nucleon part of the amplitude (1) is determined by double distribution functions ΔF^{du} and ΔK^{du} which are nondiagonal in flavor. They are defined as matrix elements of a nonlocal quark operator sandwiched between proton and neutron states:

$$
\begin{aligned}
& \langle n(P',S')|\,\bar{\psi}_d(0)\gamma_5\hat{n}\,[0,z]\,\psi_u(z)\,|p(P,S)\rangle_{z^2=0} \\
& = \bar{N}(P',S')\,\gamma_5\hat{n}\,N(P,S)\int \mathrm{d}\,[x,y] \\
& \times \left(\mathrm{e}^{-\mathrm{i}x(P\cdot z)-\mathrm{i}y(r\cdot z)}\Delta F^{du} + \mathrm{e}^{\mathrm{i}x(P\cdot z)-\mathrm{i}\bar{y}(r\cdot z)}\Delta\bar{F}^{du}\right) \\
& -\bar{N}(P',S')\,\gamma_5\,N(P,S)\,\frac{r\cdot n}{2M}\int \mathrm{d}\,[x,y] \\
& \left(\mathrm{e}^{-\mathrm{i}x(P\cdot z)-\mathrm{i}y(r\cdot z)}\Delta K^{du} + \mathrm{e}^{\mathrm{i}x(P\cdot z)-\mathrm{i}\bar{y}(r\cdot z)}\Delta\bar{K}^{du}\right). \quad (4)
\end{aligned}
$$

Here, as in (1), the dependence of the double distribution functions on x, y and t has been suppressed. The up- and down-quark fields in (4) are separated by a light-like distance $z \sim n$. Gauge invariance is guaranteed by the path-ordered exponential

$$
[0,z] = \mathcal{P}\exp\left[-\mathrm{i}gz_\mu\int_0^1 A^\mu(z\lambda)\,d\lambda\right]
$$

which reduces to 1 in axial gauge $n\cdot A = 0$ (g stands for the strong coupling constant, and A^μ denotes the gluon field).

3 Pseudovector contribution

The production amplitude $\mathcal{A}_{\pi^+}$ contains a pseudovector and pseudoscalar contribution proportional to $\bar{N}(P',S')$ $\gamma_5\hat{n}\,N(P,S)$ and $\bar{N}(P',S')\,\gamma_5\,N(P,S)$, respectively. We rewrite the pseudovector part according to isospin relations which connect nondiagonal-flavor double distribution functions ΔF^{du} with diagonal-flavor ones. In particular, we use [11]:

$$
\langle n|\,\hat{O}^{du}(z)\,|p\rangle = \langle p|\,\hat{O}^{uu}(z)\,|p\rangle - \langle p|\,\hat{O}^{dd}(z)\,|p\rangle\,, \qquad (5)
$$

with

$$
\hat{O}^{q\,q'}(z) = \bar{\psi}_q(0)\gamma_5\hat{n}\,[0,z]\,\psi_{q'}(z)\Big|_{z^2=0}. \qquad (6)
$$

In terms of diagonal-flavor polarized double distribution functions, the pseudovector part of the amplitude (1) reads:

$$
\begin{aligned}
\mathcal{A}_{\pi^+} = {} & -\mathrm{i}\frac{g^2 C_F}{8N_c}\frac{f_\pi}{Q}\frac{\bar{N}(P',S')\gamma_5\hat{n}N(P,S)}{\bar{P}\cdot n}\int_0^1 \mathrm{d}\tau\frac{\Phi_\pi(\tau)}{\tau\bar{\tau}} \\
& \times \int \mathrm{d}\,[x,y]\Big\{(e_u - e_d)\,\big[(\Delta F^u + \Delta\bar{F}^u)
\end{aligned}
$$

$$
\begin{aligned}
&-(\Delta F^d+\Delta\bar{F}^d)\Big]\left(\frac{\bar{\omega}}{x+2y+x\bar{\omega}-\mathrm{i}\epsilon}+\frac{\bar{\omega}}{x+2y-x\bar{\omega}-\mathrm{i}\epsilon}\right)\\
&-(e_u+e_d)\left[(\Delta F^u-\Delta\bar{F}^u)-(\Delta F^d-\Delta\bar{F}^d)\right]\\
&\times\left(\frac{\bar{\omega}}{x+2y+x\bar{\omega}-\mathrm{i}\epsilon}-\frac{\bar{\omega}}{x+2y-x\bar{\omega}-\mathrm{i}\epsilon}\right)\Bigg\}. \qquad (7)
\end{aligned}
$$

Here e_u and e_d denote the electromagnetic charges of the up and down quarks. Note that $\mathcal{A}_{\pi^+}$ has a structure similar to the ρ^+-production amplitude derived in [11]: Up to prefactors, the ρ^+ amplitude can be obtained from (7) by replacing polarized quark double distribution functions by unpolarized ones, with proper account of their opposite-charge conjugation properties.

In order to obtain a numerical estimate for the pseudovector contribution (7) to π^+-production models for the involved double distributions, ΔF have to be constructed. We are guided here by the appropriate forward limit of double distributions, their symmetry properties, and the sum rules which relate them to nucleon form factors. Following [21] and [16], we use:

$$
\begin{aligned}
&A: \Delta F(x,y;t) = h(x,y)\,\Delta q(x)\,f(t),\\
&B: \Delta F(x,y;t) = h(x,y)\,\Delta q(x)\exp\left[\frac{t}{\Lambda^2}\,\frac{y(1-x-y)}{x(1-x)}\right]. \qquad (8)
\end{aligned}
$$

Here $h(x,y) = 6\,y\,(1-x-y)/(1-x)^3$, and $\Delta q(x)$ denotes the corresponding ordinary polarized quark distribution. In the numerical calculations presented in this paper, we have used Gehrman–Stirling LO set-A parametrizations of polarized quark distributions [22]. Furthermore, we have used the one-loop expression for the running coupling constant with $\Lambda_{\mathrm{QCD}} = 200$ MeV. Note that in addition to the above-mentioned constraints, the models in (8) are consistent with asymptotic solutions of evolution equations for double distributions, and satisfy the symmetries of the latter [4]. The t dependence of double distributions in model A is governed by the form factor $f(t)$, which, as in [4], is taken to be equal to the nucleon pseudovector form factor [23]:

$$
f(t) = \frac{1}{(1-t/\Lambda^2)^2}. \qquad (9)
$$

The exponential dependence of ΔF on the momentum transfer t in model B can be obtained from a simple field-theoretical investigation of double distribution functions outlined in [16,21]. For both models, the scale Λ has been fixed at 1 GeV. With this choice, model B reproduces the nucleon axial form factor up to momentum transfers $t \approx -0.5$ GeV^2. Another important feature of model B is that the small-x behavior of ΔF becomes less and less singular as $|t|$ increases. Such behavior is expected, for as in the case of nucleon form factors, large momentum transfers filter out the minimal contribution to the Fock-space wave function of the target.

4 Pseudoscalar contribution

As explained in [21], the double distributions $\Delta F(x,y;t)$ can be related in the forward limit, $t = 0$, to ordinary polarized quark densities $\Delta q(x)$. Therefore, it is possible to construct plausible models for ΔF, although little is known about their shape from first principles. On the other hand, for the double distributions ΔK, no experimental information on corresponding forward densities is available; this makes modeling in this case more difficult. Nevertheless, some intuition about their magnitude has been obtained from model calculations [25]. Still, contributions of the so-called K-terms to hard exclusive meson production have been neglected so far. In the present case of π^+ production, the situation is different. As we will show, the pseudoscalar piece of the amplitude $\mathcal{A}_{\pi^+}$ can be associated with the virtual photoproduction of pions from the nucleon–pion cloud. Due to the small pion mass, this mechanism is expected to be important, especially at small momentum transfers t.

We are interested in evaluating the contribution to the nucleon matrix element (4) arising from a situation when a quark–antiquark pair with low invariant mass propagates in the t channel, such that it becomes close to a π^+ bound state. To construct the corresponding double distribution function, we introduce an effective Lagrangian describing a pseudovector pion–nucleon interaction [23]:

$$
\mathcal{L}_{\pi NN} = \frac{g_{\pi NN}}{2M}\left(\bar{\phi}(x)\gamma_\mu\gamma_5\vec{\tau}\phi(x)\right)\cdot\left(\partial^\mu\vec{\varphi}(x)\right). \qquad (10)
$$

The nucleon and pion fields are denoted by ϕ and $\vec{\varphi}$, respectively, $\vec{\tau}$ represents common isospin matrices, and $g_{\pi NN}$ is the pion–nucleon coupling constant. Evaluating the matrix element (4) to first order in $g_{\pi NN}$ leads to:

$$
\begin{aligned}
&\langle n(P',S')|\,\bar{\psi}_d(0)\gamma_5\hat{n}\,[0,z]\,\psi_u(z)\,|p(P,S)\rangle_{z^2=0}\\
&= \sqrt{2}g_{\pi NN}\,\bar{N}(P',S')\,\gamma_5\,N(P,S)\int \mathrm{d}^4x\,\mathrm{e}^{-\mathrm{i}r\cdot x}\\
&\quad\times\langle 0|\,T[\bar{\psi}_d(0)\gamma_5\hat{n}\,[0,z]\,\psi_u(z)\,\varphi^+(x)]\,|0\rangle_{z^2=0}\,, \qquad (11)
\end{aligned}
$$

where $\varphi^+ = (1/\sqrt{2})(\varphi_1 + i\,\varphi_2)$ is the pion field associated with the π^+ meson. Note that in the light-cone approach used here, both quark fields (and the gluonic string between them) act at the same light-cone time. Therefore, with respect to light-cone time, the quark operator in (11) can be treated as local. (For an analysis in a covariant framework, see [24].) Saturating the correlator in (11) with a full set of intermediate pion states, quantized at the light-like hypersurface $x^+ = 0$, gives:

$$
\begin{aligned}
&\langle n(P',S')|\,\bar{\psi}_d(0)\gamma_5\hat{n}\,[0,z]\,\psi_u(z)\,|p(P,S)\rangle_{z^2=0}\\
&= N(P',S')\gamma_5 N(P,S)\,\frac{-\mathrm{i}\sqrt{2}g_{\pi NN}}{m_\pi^2-t}\\
&\quad\times\langle 0|\bar{\psi}_d(0)\gamma_5\hat{n}\,[0,z]\,\psi_u(z)|\pi^+(r)\rangle_{z^2=0}. \qquad (12)
\end{aligned}
$$

The notation $|\pi^+(r)\rangle$ is understood as a pion state with a light-cone three-momentum $(r^+, r^\perp)$ as given by the corresponding components of the four-momentum transfer r, while r^- is determined from the on-shell condition. Using the pion distribution amplitude (2) and comparing with the definition of the pseudoscalar double distribution functions in (4), we obtain:

$$\begin{aligned}&\left(\Delta K^{du} + \Delta \bar{K}^{du}\right)(x, y, t \approx 0)\\ &= -\frac{2\sqrt{2} f_\pi M g_{\pi NN}}{m_\pi^2 - t}\,\delta(x)\,\Phi_\pi(y).\end{aligned} \tag{13}$$

Because this contribution can be expressed entirely in terms of ΔK, there is no danger of double counting if we add this term to the contribution arising from a model for ΔF, as discussed in the previous section.

One can express the t-channel one-pion exchange contribution also in the form:

$$\begin{aligned}\mathcal{A}_{\pi^+} = -\sqrt{2} g_{\pi NN} \frac{N(P', S')\gamma_5 N(P, S)}{m_\pi^2 - t}\,\varepsilon_L \cdot\\ (q' + r)\,F_{\pi^+}(Q^2),\end{aligned} \tag{14}$$

where

$$\varepsilon_L = \frac{\mathrm{i}}{Q}\,(q' + r) \tag{15}$$

stands for the polarization vector of the longitudinally polarized photon, and

$$F_{\pi^+}(Q^2) = (e_u - e_d)\,\frac{g^2 C_F}{2N_c}\,\frac{f_\pi^2}{Q^2}\left(\int_0^1 \mathrm{d}\tau\,\frac{\Phi_\pi(\tau)}{\tau}\right)^2 \tag{16}$$

is the leading QCD contribution to the π^+ electromagnetic form factor at large Q^2 [19,20].

To twist-2 accuracy, i.e., neglecting terms of order t/Q^2 and m_π^2/Q^2, the amplitude (14) is explicitly gauge-invariant. This is guaranteed by the factor $\varepsilon_L \cdot (q' + r)$ which arises from the hard photon–quark interaction. In the one-pion exchange approximation, the difference $\Delta K^{du} - \Delta \bar{K}^{du}$ decouples from the considered production process. Finally, note that in the case of π^0 production, a t-channel exchange contribution similar to (13) appears in the production amplitude, with a zero coefficient from the difference of two equal quark charges.

Some comments regarding one-pion t-channel exchange, as used above, are in order. In general one expects that at large center-of-mass energies, any t-channel exchange of a hadronic state should be replaced by a corresponding Regge trajectory. Therefore, at small values of Bjorken x, additional contributions to the pseudoscalar part of the production amplitude $\mathcal{A}_{\pi^+}$ could occur. Once the pion-pole contribution is replaced by a Reggeized-pion (and -rho) exchange [26], the relation to the pion electromagnetic form factor seems to be lost (see, however, [27] for an attempt to interpret pion electroproduction data in the framework of a Regge exchange model). We restrict ourselves in this work to the simplest model for the pseudoscalar part of the production amplitude, in the hope that this model contains the dominant contribution at small momentum transfers, i.e., close to the pion pole.

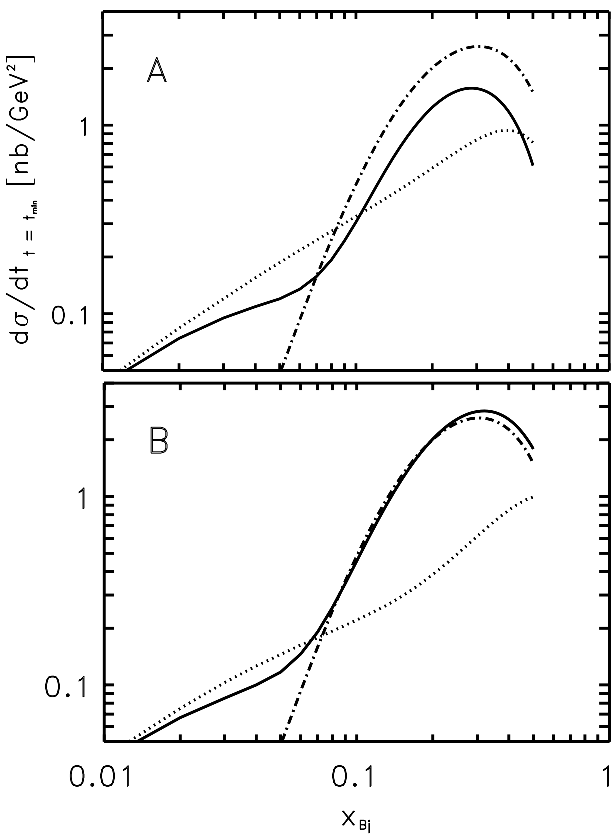

Fig. 1a,b. Differential production cross section for exclusive π^+ production through the scattering of longitudinally polarized photons from protons at $t = t_{\min}$ and $Q^2 = 10$ GeV^2. The dotted and dot-dashed curves show the pseudovector and pseudoscalar contributions, respectively. The upper figure corresponds to model A, the lower one to model B

5 Results

In Figs. 1 and 2 we present results for the cross section of exclusive π^+ production in the scattering of longitudinally polarized photons from nucleons at $Q^2 = 10$ GeV^2. Up to logarithmic corrections, the cross section is proportional to $1/Q^6$, as one can infer from (1).

In Fig. 1, we show the differential production cross section for the minimal kinematically allowed value of $t = t_{\min} = -x_{\mathrm{Bj}}^2 M^2/(1 - x_{\mathrm{Bj}})$. We find that the pseudovector contribution (7) dominates at small values of the Bjorken variable x_{Bj}. Its x_{Bj} dependence reflects the behavior of the relevant forward parton distributions (8). At $x \sim 0.3$, the cross section is governed by the pseudoscalar pion-cloud contribution (12).

While models A and B give qualitatively similar cross sections at small momentum transfers, they start to differ for increasing $|t|$. This is illustrated in Fig. 2, where we present results for the differential production cross section taken at $t = -0.4$ GeV^2. The maximum value of Bjorken x is determined by the condition $|t| \geq |t_{\min}|$. For model A, the pseudovector contribution decreases slowly with decreasing x_{Bj}, and dominates the cross section at $x_{\mathrm{Bj}} \lesssim$

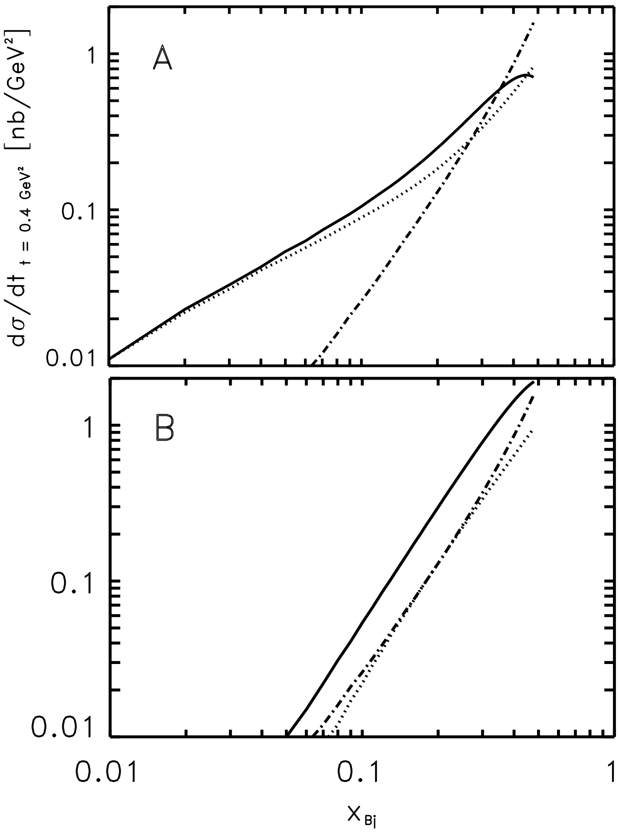

Fig. 2a,b. Differential production cross section for exclusive π^+ production through the scattering of longitudinally polarized photons from protons at $t = -0.4$ GeV^2 and $Q^2 = 10$ GeV^2. The dotted and dot-dashed curves show the pseudovector and pseudoscalar contributions, respectively. The upper figure corresponds to model A, the lower one to model B

0.1. At $x_{\rm Bj} \sim x_{\max}$ the total pion-production cross section is about half as large as that obtained from the pion-cloud contribution alone, due to strong interference effects. On the other hand, in model B, the $x_{\rm Bj}$ dependence of the pseudovector contribution is similar to the one from the pion cloud. Also, contrary to the previous case, at $x_{\rm Bj} \sim x_{\max}$, the production cross section is about 20% larger than obtained from the pion cloud alone.

Finally, we compare in Fig. 3 to the leading-twist production cross section for π^0 mesons which has been investigated in [4]. At $t = t_{\min}$, the pseudovector contribution to π^+ production is about 5–10 times larger as compared to the π^0 case. At $x_{\rm Bj} \sim 0.3$, large contributions from the pion cloud, which are absent in π^0 production, add further to the cross section ratio.

It should be emphasized that the dominance of the hard-gluon exchange processes considered in this paper can only be confirmed for sufficiently large values of Q^2. Just as in the case of the pion form factor, competing contributions are provided by soft mechanisms which, in this case, correspond to the nonperturbative overlap of three hadronic wave functions. The interplay of soft and hard interaction mechanisms has been studied recently for

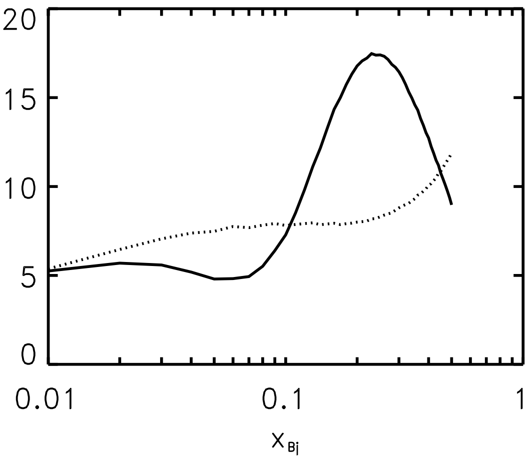

Fig. 3. Ratio of the differential production cross sections for exclusive π^+ and π^0 production, through the scattering of longitudinally polarized photons, from protons at $t = t_{\min}$ and $Q^2 = 10$ GeV^2 for model A. The dotted curve corresponds to the pseudovector contribution alone

the pion form factor in a QCD sum rule-related model [28]. Guided by the results of this investigation, we expect the dominance of hard-gluon exchange for values of Q^2 above 10 GeV^2.

6 Summary

We have discussed the hard exclusive electroproduction of π^+ mesons from nucleons. For longitudinally polarized photons one can express the corresponding photoproduction amplitude to leading-twist, leading-order α_s accuracy in terms of quark double distribution functions of the nucleon. We find that the amplitude receives contributions from pseudovector and pseudoscalar pieces. The pseudovector contribution is determined by quark double distributions with well-known properties in the forward limit, as given by ordinary polarized quark distribution functions. However, for the pseudoscalar part, such information is not available; in this work it has been modeled in terms of an interaction of the virtual photon with the nucleon pion cloud. As a consequence, the related double distribution is determined by the pion distribution amplitude. The corresponding contribution to the pion production amplitude turns out to be proportional to the pion form factor.

We have found that both pseudovector and pseudoscalar terms should be included if one considers the whole $0 < x_{\rm Bj} < 1$ range. In particular, we have observed that the pseudovector part dominates at small $x_{\rm Bj} < 0.1$. On the other hand, the pion-cloud contribution controls the π^+ production at small $t \sim t_{\min}$ and $0.1 < x_{\rm Bj} < 0.4$. At larger values of $|t| \sim 0.4$ GeV^2, the relative weight of pseudoscalar and pseudovector contributions has been found to be sensitive to details of the relevant double distribution functions. Further investigations of double distribution functions, as well as experimental data on exclusive meson production, are certainly needed.

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