

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 $x_{Bj} < 0.1$. On the other hand, for $0.1 < x_{Bj} < 0.4$ contributions from one pion exchange dominate.

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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, 3, 4, 5]) valid in the case of longitudinally polarized photons: at large photon virtualities, $Q^2 \gg \Lambda_{\text{QCD}}^2$, the underlying photon-parton sub-processes are dominated by short distances and, 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 to probe details of the quark-gluon dynamics in nucleons beyond our current knowledge 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. Interest in this process arises 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 as a generic process to determine $F_\pi(Q^2)$ (see e.g. [14]). However, as discussed in ref.[15], there may be significant uncertainties due to type (i) contributions. The latter have been modeled in ref.[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 π^+ production cross section in the region of small momentum transfers, $-t < 0.5 \text{ GeV}^2$. We find that both mechanisms, (i) and (ii), contribute significantly. While one pion

exchange dominates at intermediate values of Bjorken- x , perturbative quark exchange is relevant mainly at small x_{Bj} .

The paper is organized as follows: in Sec.2 we present the amplitudes for charged pion electroproduction. Pseudovector and pseudoscalar parts of the relevant double distribution functions are associated in Sec.3 and 4 with the perturbative and pion pole contribution, respectively. Results are presented in Sec.5. Finally 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, $Q^2 = -q^2 \gg \Lambda_{\text{QCD}}^2$, and moderate momentum transfer to the nucleon target, $|t| \lesssim \Lambda_{\text{QCD}}^2$. Using the techniques outlined in refs.[1, 2, 4, 11] gives the following result for the π^+ virtual photoproduction amplitude in leading twist, leading order α_s accuracy:

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

Here the notation $\int d[x, y] \dots = \int_0^1 dx \int_0^{\bar{x}} dy \dots$, 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 with $n \cdot a = a^+ = a^0 + a^3$ 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 $\Phi_\pi(\tau)$ [18, 19]:

$$\langle \pi^+(q') | \bar{\psi}_u(x) \gamma_5 \hat{n} \psi_d(y) | 0 \rangle = -i f_\pi (q' \cdot n) \int_0^1 \Phi_\pi(\tau) e^{iq' \cdot (\tau x + \bar{\tau} y)} d\tau, \tag{2}$$

where quark fields ψ with proper flavor quantum numbers enter.

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:

$$\begin{aligned}
& \langle n(P', S') | \bar{\psi}_d(0) \gamma_5 \hat{n} [0, z] \psi_u(z) | p(P, S) \rangle_{z^2=0} = \\
& \quad \bar{N}(P', S') \gamma_5 \hat{n} N(P, S) \int d[x, y] \left(e^{-ix(P \cdot z) - iy(r \cdot z)} \Delta F^{du} + e^{ix(P \cdot z) - iy(r \cdot z)} \Delta \bar{F}^{du} \right) \\
& \quad - \bar{N}(P', S') \gamma_5 N(P, S) \frac{r \cdot n}{2M} \int d[x, y] \left(e^{-ix(P \cdot z) - iy(r \cdot z)} \Delta K^{du} + e^{ix(P \cdot z) - iy(r \cdot z)} \Delta \bar{K}^{du} \right).
\end{aligned} \tag{3}$$

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 (3) are separated by a light-like distance $z \sim n$. Gauge invariance is guaranteed by the path-ordered exponential

$$[0, z] = \mathcal{P} \exp[-igz_\mu \int_0^1 A^\mu(z\lambda) d\lambda]$$

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}_{π^+} 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 flavor non-diagonal double distribution functions ΔF^{du} with flavor diagonal ones. In particular we use [11]:

$$\langle n | \hat{O}^{du}(z) | p \rangle = \langle p | \hat{O}^{uu}(z) | p \rangle - \langle p | \hat{O}^{dd}(z) | p \rangle, \tag{4}$$

with

$$\hat{O}^{q'q}(z) = \bar{\psi}_q(0) \gamma_5 \hat{n} [0, z] \psi_{q'}(z) \Big|_{z^2=0}. \tag{5}$$

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

$$\begin{aligned}
\mathcal{A}_{\pi^+} = & -i \frac{g^2 C_F f_\pi}{8N_c Q} \frac{\bar{N}(P', S') \gamma_5 \hat{n} N(P, S)}{P \cdot n} \int_0^1 d\tau \frac{\Phi_\pi(\tau)}{\tau \bar{\tau}} \int d[x, y] \left\{ \right. \\
& (e_u - e_d) \left[(\Delta F^{uu} + \Delta \bar{F}^{uu}) - (\Delta F^{dd} + \Delta \bar{F}^{dd}) \right] \left(\frac{\bar{\omega}}{x + 2y + x\bar{\omega} - i\epsilon} + \frac{\bar{\omega}}{x + 2y - x\bar{\omega} - i\epsilon} \right) \\
& \left. - (e_u + e_d) \left[(\Delta F^{uu} - \Delta \bar{F}^{uu}) - (\Delta F^{dd} - \Delta \bar{F}^{dd}) \right] \left(\frac{\bar{\omega}}{x + 2y + x\bar{\omega} - i\epsilon} - \frac{\bar{\omega}}{x + 2y - x\bar{\omega} - i\epsilon} \right) \right\}.
\end{aligned} \tag{6}$$

Here e_u and e_d denote the electromagnetic charges of the up- and down-quarks. Note that \mathcal{A}_{π^+} has a structure similar to the ρ^+ production amplitude derived in [11]: up to

prefactors the ρ^+ amplitude can be obtained from (6) 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 (6) 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 sum rules which relate them to nucleon form factors. Following refs. [20] and [16] we use:

$$\begin{aligned}
 A: \quad \Delta F(x, y; t) &= h(x, y) \Delta q(x) f(t), \\
 B: \quad \Delta F(x, y; t) &= h(x, y) \Delta q(x) \exp \left[\frac{t}{\Lambda^2} \frac{y(1-x-y)}{x(1-x)} \right].
 \end{aligned}
 \tag{7}$$

Here $h(x, y) = 6y(1-x-y)/(1-x)^3$, and $\Delta q(x)$ denotes the corresponding ordinary polarized quark distribution. In numerical calculations presented in this paper we have used Gehrman-Stirling LO set-A parametrizations of polarized quark distributions [21]. Furthermore, we have used the one loop expression for the running coupling constant with $\Lambda_{\text{QCD}} = 200$ MeV. Note that in addition to the above mentioned constraints, the models (7) 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, like in [4], is taken to be equal to the nucleon pseudovector form factor [22]:

$$f(t) = \frac{1}{(1-t/\Lambda^2)^2}.
 \tag{8}$$

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, 20]. 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 $t \approx -0.5$ GeV². Another important feature of model B is, that the small- x behavior of ΔF becomes less and less singular as $|t|$ increases. Such a behavior is expected since, like 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 ref.[20] 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 which makes modeling in this case

more difficult. Nevertheless, some intuition about their magnitude has been obtained from model calculations [23]. 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}_{π^+} 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 (3) 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 [22]:

$$\mathcal{L}_{\pi NN} = \frac{g_{\pi NN}}{2M} (\phi(x) \gamma_\mu \gamma_5 \vec{\tau} \phi(x)) \cdot (\partial^\mu \vec{\varphi}(x)). \quad (9)$$

The nucleon and pion fields are denoted by ϕ and $\vec{\varphi}$, respectively, $\vec{\tau}$ are the common isospin matrices, and $g_{\pi NN}$ is the pion-nucleon coupling constant. Evaluating the matrix element (3) to first order in $g_{\pi NN}$ leads to:

$$\begin{aligned} \langle n(P', S') | \bar{\psi}_d(0) \gamma_5 \hat{n} [0, z] \psi_u(z) | p(P, S) \rangle_{z^2=0} &= \sqrt{2} g_{\pi NN} \bar{N}(P', S') \gamma_5 N(P, S) \\ &\times \int d^4x e^{-ir \cdot x} \langle 0 | T[\bar{\psi}_d(0) \gamma_5 \hat{n} [0, z] \psi_u(z) \phi^+(x)] | 0 \rangle_{z^2=0}, \end{aligned} \quad (10)$$

where $\varphi^+ = \frac{1}{\sqrt{2}}(\varphi_1 + i\varphi_2)$ is the pion field associated with the π^+ meson. The leading-twist contribution to the matrix element (10) arises from the region of phase space where the quark fields are localized near the light-cone, $z^+ \sim 0$. Inserting a full set of intermediate pion states between the pion field and the non-local quark operator gives:

$$\begin{aligned} \langle n(P', S') | \bar{\psi}_d(0) \gamma_5 \hat{n} [0, z] \psi_u(z) | p(P, S) \rangle_{z^2=0} \\ = N(P', S') \gamma_5 N(P, S) \frac{-i\sqrt{2} g_{\pi NN}}{m_\pi^2 - t} \langle 0 | \bar{\psi}_d(0) \gamma_5 \hat{n} [0, z] \psi_u(z) | \pi^+(r) \rangle_{z^2=0}. \end{aligned} \quad (11)$$

Using the pion distribution amplitude (2) and comparing with the definition of the pseudoscalar double distribution functions in eq.(3) yields:

$$(\Delta K^{du} + \Delta \bar{K}^{du})(x, y, t \approx 0) = -\frac{2\sqrt{2} f_\pi M g_{\pi NN}}{m_\pi^2 - t} \delta(x) \Phi_\pi(y). \quad (12)$$

As 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:

$$\mathcal{A}_{\pi^+} = -\sqrt{2} g_{\pi NN} \frac{N(P', S') \gamma_5 N(P, S)}{m_\pi^2 - t} \varepsilon_L \cdot (q' + r) F_{\pi^+}(Q^2), \quad (13)$$

where

$$\varepsilon_L = \frac{i}{Q} (q' + r) \quad (14)$$

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

$$F_{\pi^+}(Q^2) = (e_u - e_d) \frac{g^2 C_F f_\pi^2}{2N_c Q^2} \left(\int_0^1 du \frac{\Phi(u)}{u} \right)^2 \quad (15)$$

is the leading QCD contribution to the π^+ electromagnetic form factor at large Q^2 [18, 19].

To twist-2 accuracy, i.e. neglecting terms of order t/Q^2 and m_π^2/Q^2 , the amplitude (13) 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 (12) appears in the production amplitude with a zero coefficient from the difference of two equal quark charges.

To this end 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 an hadronic state should be replaced by the corresponding Regge trajectory. Therefore, at small values of Bjorken- x additional contributions to the pseudoscalar part of the production amplitude \mathcal{A}_{π^+} could occur. Once the pion pole contribution is replaced by reggeized pion (and rho) exchange [24] the relation to the pion electromagnetic form factor seems to be lost (see, however, ref.[25] 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 it contains the dominant contribution at small momentum transfers, i.e. close to the pion pole.

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 $Q^2 = 10 \text{ GeV}^2$. Up to logarithmic corrections the cross section is proportional to $1/Q^6$ as one can infer from eq.(1).

In Fig.1 we show the differential production cross section for the minimal kinematically allowed value of $t = t_{\min} = -x_{\text{Bj}}^2 M^2 / (1 - x_{\text{Bj}})$. We find that the pseudovector contribution (6) dominates at small values of the Bjorken variable x_{Bj} . Its x_{Bj} -dependence reflects the behavior of the relevant forward parton distributions (7). At $x \sim 0.3$ the cross section is governed by the pseudoscalar pion cloud contribution (11).

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 $t = -0.4 \text{ GeV}^2$. 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 $x_{Bj} \lesssim 0.1$. At $x_{Bj} \sim x_{\max}$ the total pion production cross section is about half as large as obtained from the pion cloud contribution alone due to strong interference effects. On the other hand, in model *B* the x_{Bj} -dependence of the pseudovector contribution is similar to the one from the pion cloud. Also, contrary to the previous case, at $x_{Bj} \sim x_{\max}$ 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 a factor 5–10 larger as compared to the π^0 case. At $x_{Bj} \sim 0.3$ 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 ensured for sufficiently large values of Q^2 . Just like 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 the pion form factor in a QCD sum rule related model [26]. Guided by the results of this investigation we expect the dominance of hard gluon exchange for values of Q^2 above 10 GeV².

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 $0 < x_{Bj} < 1$ range. In particular, we have observed that the pseudovector part dominates at small $x_{Bj} < 0.1$. On the other hand, the pion cloud contribution controls the π^+ production at small $t \sim t_{\min}$ and $0.1 < x_{Bj} < 0.4$. At larger values of $|t| \sim 0.4$ GeV² 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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After this paper has been completed, we learned about an independent calculation of π^+ electroproduction which uses skewed parton distributions computed in a chiral quark soliton model [27]. The corresponding results turn out to be quite similar to ours. We thank the authors of [27] for discussions and an exchange of results.

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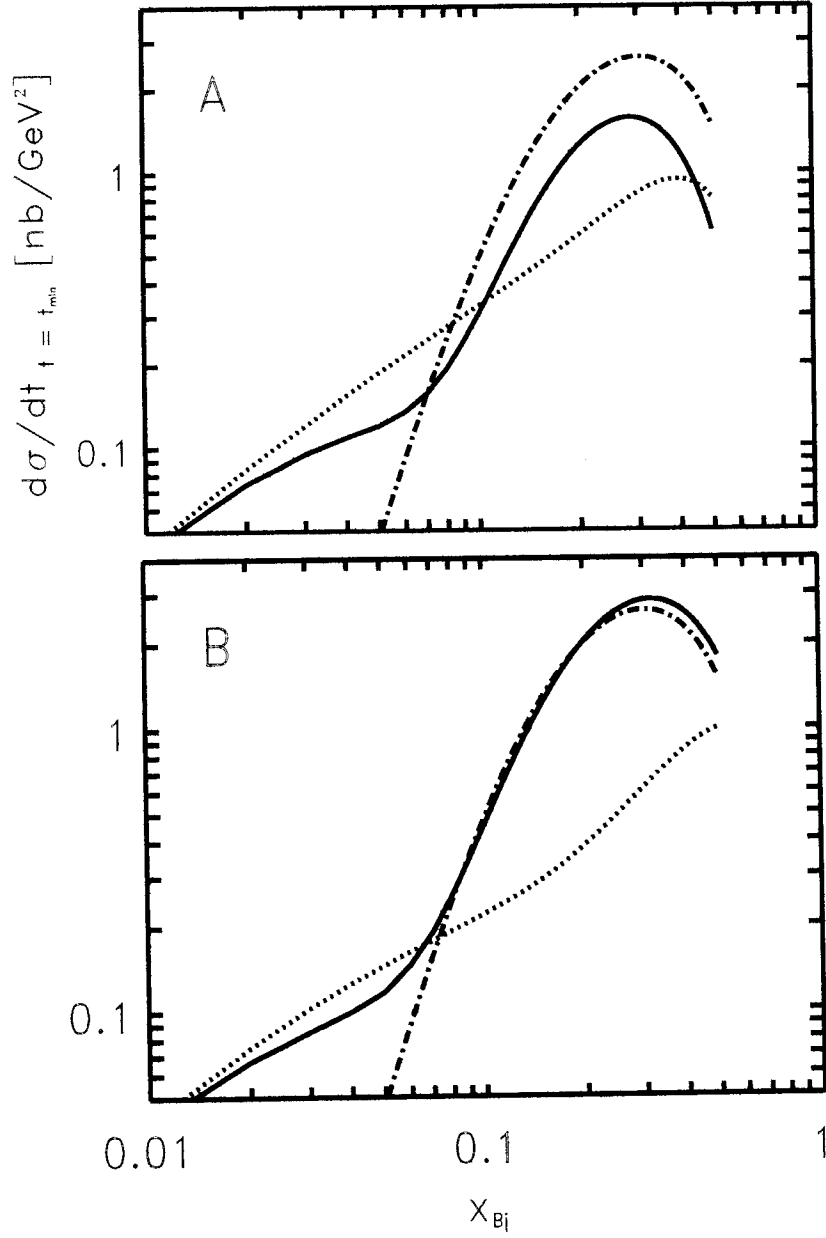


Figure 1: Differential production cross section for exclusive π^+ production through the scattering of longitudinally polarized photons from protons at $t = t_{\min}$ and $Q^2 = 10 \text{ GeV}^2$. The dotted and dot-dashed curves show the pseudovector and pseudoscalar contributions, respectively. The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

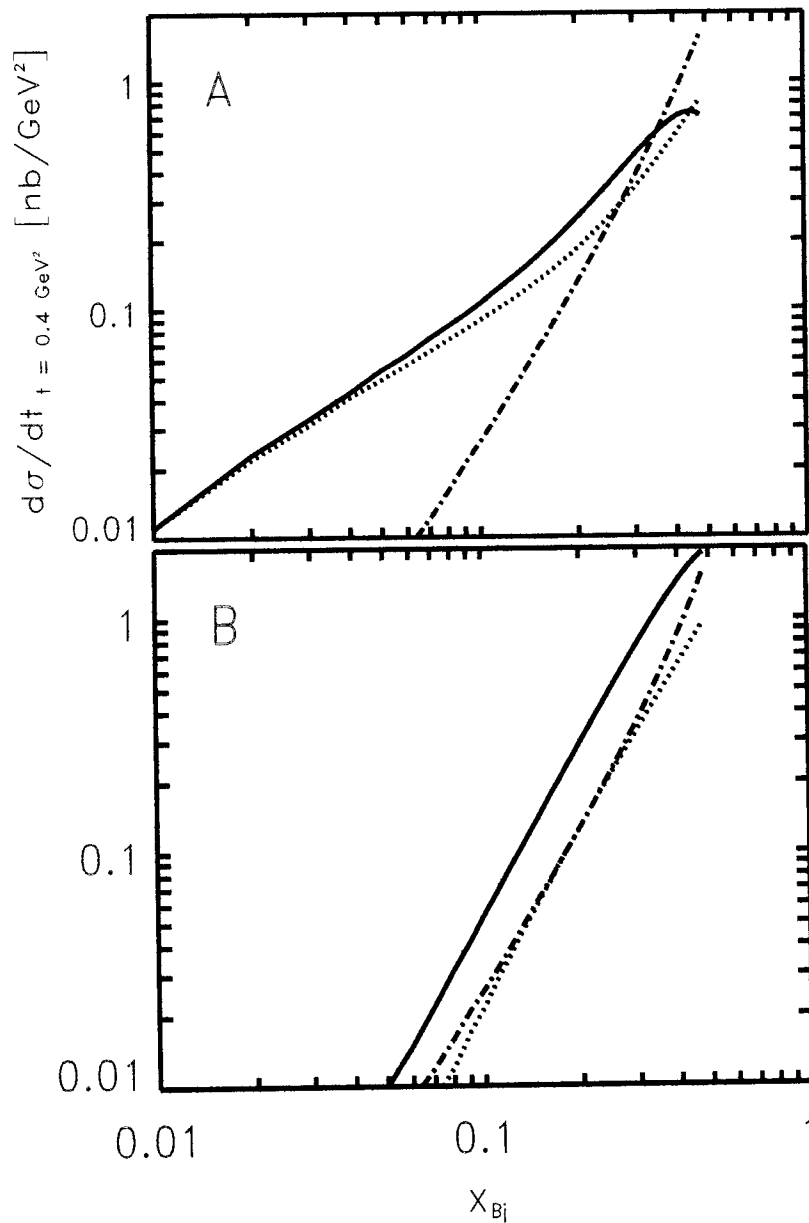


Figure 2: Differential production cross section for exclusive π^+ production through the scattering of longitudinally polarized photons from protons at $t = -0.4 \text{ GeV}^2$ and $Q^2 = 10 \text{ GeV}^2$. The dotted and dot-dashed curves show the pseudovector and pseudoscalar contributions, respectively.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

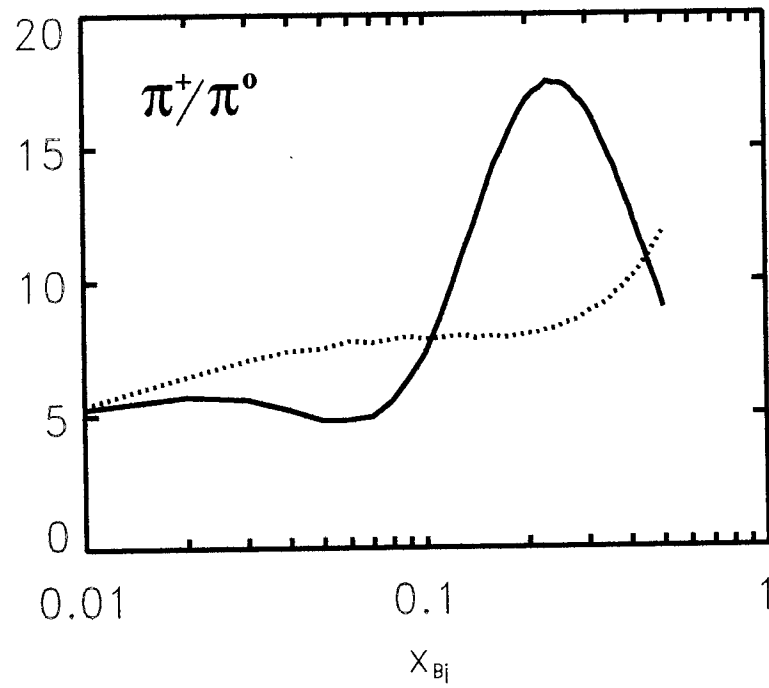


Figure 3: Ratio of the differential production cross sections for exclusive π^+ and π^0 production through the scattering of longitudinally polarized photons from protons at $t = t_{\min}$ and $Q^2 = 10 \text{ GeV}^2$ for model A. The dotted curve corresponds to the pseudovector contribution alone.