6 April 2000

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 478 (2000) 121–126

Chiral-odd contribution to single-transverse spin asymmetry in hadronic pion production

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Received 4 January 2000; received in revised form 17 February 2000; accepted 18 February 2000
Editor: M. Cvetič

Abstract

A formula for the single transverse spin asymmetry in the large-p_T pion production in the nucleon-nucleon collision is derived. We focus on the chiral-odd contribution where the transversity distribution and the chiral-odd spin-independent twist-3 distribution contributes. This contribution is expected to give rise to a large effect at $x_F \to -1$. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 12.38.-t; 12.38.Bx; 13.85.Ni; 13.88.+e
Keywords: Single transverse spin asymmetry; Twist three; Chiral-odd

Perturbative Quantum Chromodynamics (p-QCD) has been successful in describing numerous spin-averaged hard inclusive processes. In particular, consistent description of accumulated data on the high-p_T production of direct photons, jets and hadrons in the nucleon-nucleon collisions constitutes an important test of p-QCD. (See [1] for a review.) A minimal spin-dependent extension of the high-p_T production is the single transverse spin asymmetry:

$$N'(P', \boldsymbol{S}_\perp) + N(P) \to \pi(P_\pi) + X, \qquad (1)$$

where $\pi(P_\pi)$ is a pion with momentum P_π which has a large transverse momentum $P_{\pi T}$ with respect to the beam axis. (One can similarly consider the asymmetry for the production of a direct photon and a baryon, etc.) Note that the spin vector $(\boldsymbol{S}_\perp)$ of the polarized nucleon has to be orthogonal to the scattering plane. The asymmetry (1) is twist-3 and receives no contribution from the naive parton model. [1] It probes particular quark-gluon correlations in the nucleons and/or the effect of transverse momentum of partons participating the process [2–8]. [2] Although the asymmetry is suppressed by an inverse power of the hard momentum, a large asymmetry has been experimentally observed for the pion and Λ production, in particular, at large x_F [9,10].

In this letter, we derive a QCD formula for the polarized cross section (1). Qiu and Sterman identified a chiral-even contribution which brings a dominant effect at large positive x_F, i.e. forward direction

[1] The asymmetries for the polarized baryon productions, $\boldsymbol{N} + N' \to \boldsymbol{B} + X$ or $N^\uparrow + N' \to B^\uparrow + X$, are twist-2 and are described by the polarized parton distributions [11].

[2] At low $P_{\pi T}$, an approach based on hadronic degrees of freedom may be appropriate [12].

PII: S0370-2693(00)00261-6

with respect to the polarized nucleon beam, and their parametrization for the twist-3 distribution explained the E704 data at $x_F > 0$ [9] reasonably well. Here we intend to present another source of the asymmetry, chiral-odd contribution, which is expected to give a large effect at $x_F \to -1$. This kinematic region is accessible by the ongoing experiment at RHIC.

For later convenience, we recall kinematic variables relevant to the process (1). The differential cross section is a function of the three invariants defined by

$$S = (P + P')^2 \simeq 2P \cdot P',$$
$$T = (P' - P_\pi)^2 \simeq -2P' \cdot P_\pi,$$
$$U = (P - P_\pi)^2 \simeq -2P \cdot P_\pi. \tag{2}$$

The variables

$$x_F = \frac{2P_{\pi\parallel}}{\sqrt{S}} = \frac{T-U}{S},$$
$$x_T = \frac{2P_{\pi T}}{\sqrt{S}} \tag{3}$$

are also used, and are related to T and U as

$$T = -\frac{S}{2}\left[\sqrt{x_F^2 + x_T^2} - x_F\right],$$
$$U = -\frac{S}{2}\left[\sqrt{x_F^2 + x_T^2} + x_F\right]. \tag{4}$$

According to the QCD factorization theorem, the twist-3 cross section for the pion production (1) can be factorized as [13]

$$\begin{aligned}
&\sigma_{N'^\uparrow + N \to \pi + X} \\
&\quad = \sum_{a,b,c} \big[G_a(x_1', x_2') \\
&\qquad \otimes q_b(x) \otimes \hat{\sigma}_{ab\to c} \otimes D_{c\to\pi}(z) \\
&\qquad + \delta q_a(x') \otimes E_b(x_1, x_2) \\
&\qquad \otimes \hat{\sigma}'_{ab\to c} \otimes D_{c\to\pi}(z) + \delta q_a(x') \otimes q_b(x) \\
&\qquad \otimes \hat{\sigma}''_{ab\to c} \otimes D^{(3)}_{c\to\pi}(z_1, z_2) \big],
\end{aligned} \tag{5}$$

where the functions $G_a(x_1', x_2')$, $E_b(x_1, x_2)$ and $D^{(3)}_{c\to\pi}(z_1, z_2)$ are the twist-3 quantities representing, respectively, the transversely polarized distribution, the unpolarized distribution, and the fragmentation function for the pion, and a, b and c stand for the parton's species. [3]

Other functions in (5) are twist-2; $q_b(x)$ the unpolarized distribution and $\delta q_a(x)$ the transversity distribution, etc. The symbol $\otimes$ denotes convolution. $\hat{\sigma}_{ab\to c}$ etc. represents the partonic cross section for the process $a + b \to c + \mathit{anything}$ which yields large transverse momentum of the parton c.

A systematic QCD analysis for the first term in (5) has been performed in [8]. We shall analyze contribution from the second term in (5) following the method of [8]. [4] To this end we first summerise the twist-2 and twist-3 distributions for completeness. The quark distribution (for flavor a) can be defined by the lightcone Fourier transform of the quark correlation function in the nucleon [14,15]:

$$\begin{aligned}
&\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle PS | \bar{\psi}_j^a(0) \psi_i^a(\lambda n) | PS \rangle \\
&\quad = \tfrac{1}{2}(\not{p})_{ij} q_a(x) + \tfrac{1}{2}(\gamma_5 \not{p})_{ij} (S\cdot n) \Delta q_a(x) \\
&\qquad + \tfrac{1}{2}(\gamma_5 \not{S}_\perp \not{p})_{ij} \delta q_a(x) + \cdots,
\end{aligned} \tag{6}$$

where the spin vector S is normalized as $S^2 = -M^2$ and the two lightlike vectors p and n are introduced by the relation $P = p + M^2 n/2$ and $p \cdot n = 1$. For the nucleon moving in the positive z-direction, the only nonzero components of p and n are $p^+ = P^+$, $n^- = 1/P^+$. Here and below we suppress the gaugelink operators between $\bar{\psi}(0)$ and $\psi(\lambda n)$ which ensures gauge invariance. We write $S = S_\parallel = p - M^2 n/2$ for the longitudinally polarized nucleon and $S = MS_\perp$ for the transversely polarized one. In (6), $q(x)$, $\Delta q(x)$ and $\delta q(x)$ denote, respectively, the unpolarized, longitudinally polarized and transversity distribution, and $+\cdots$ stands for the higher twist distributions.

The twist-3 distributions are characterized by the participation of the explicit gluon fields in the lightcone correlation functions. The complete set of the

[3] We use the primed symbols like x', x_1', x_2', P' for the polarized nucleon, and unprimed ones x, x_1, x_2, P for the unpolarized nucleon. This convention is opposite to [8].

[4] The third term of (5) is also chiral-odd. Analysis of this term is left for future study.

twist-3 distributions with two quark fields is classified as [4,16,17]

$$\int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \times \langle PS|\bar{\psi}(0)\gamma^\mu g F^{\alpha\beta}(\mu n) n_\beta \psi(\lambda n)|PS\rangle = M p^\mu \epsilon^{\alpha\nu\kappa\lambda} p_\nu n_\kappa S_{\perp\lambda} G_F(x_1,x_2) + \cdots, \tag{7}$$

$$\int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \times \langle PS|\bar{\psi}(0)\gamma^\mu \gamma^5 g F^{\alpha\beta}(\mu n) n_\beta \psi(\lambda n)|PS\rangle = iM p^\mu S_\perp^\alpha \tilde{G}_F(x_1,x_2) + \cdots, \tag{8}$$

$$\begin{aligned}\int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} & e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \\ & \times \langle PS|\bar{\psi}(0)\sigma^{\mu\nu} i\gamma^5 g F^{\alpha\beta}(\mu n) n_\beta \psi(\lambda n)|PS\rangle \\ & = iM(S\cdot n)\{(g^{\mu\alpha}p^\nu - g^{\nu\alpha}p^\mu) \\ & \quad - p^\alpha(n^\mu p^\nu - n^\nu p^\mu)\} H_F(x_1,x_2) \\ & \quad + M(p^\mu \epsilon^{\nu\alpha\beta\lambda} - p^\nu \epsilon^{\mu\alpha\beta\lambda}) \\ & \quad \times p_\lambda n_\beta E_F(x_1,x_2) + \cdots,\end{aligned} \tag{9}$$

where the flavor indices are suppressed for simplicity, and we use the convention for the anti-symmetric tensor as $\epsilon_{0123}=1$. The four functions $G_F(x_1,x_2)$, $\tilde{G}_F(x_1,x_2)$, $E_F(x_1,x_2)$ and $H_F(x_1,x_2)$ are real and have the following symmetry properties due to the time reversal invariance:

$$\begin{aligned} G_F(x_1,x_2) &= G_F(x_2,x_1), \\ \tilde{G}_F(x_1,x_2) &= -\tilde{G}_F(x_2,x_1), \\ E_F(x_1,x_2) &= E_F(x_2,x_1), \\ H_F(x_1,x_2) &= -H_F(x_2,x_1). \end{aligned} \tag{10}$$

Replacement of the gluon field strength $gF^{\alpha\beta}(\mu n)n_\beta$ in the left hand side of (7) -(9) by the covariant derivative $D^\alpha(\mu n)=\partial^\alpha - igA^\alpha(\mu n)$ allows similar decomposition in the right hand side, which defines another complete set of the twist-3 distributions, $G_D(x_1,x_2)$, $\tilde{G}_D(x_1,x_2)$, $E_D(x_1,x_2)$, $H_D(x_1,x_2)$. These four have the symmetry property opposite to those shown in (10). We note that $\{G_F,\tilde{G}_F,E_F,H_F\}$ and $\{G_D,\tilde{G}_D,E_D,H_D\}$ are not independent of each other, but are related by the QCD equation of motion. In deriving the formulas for various cross sections, however, it is convenient to keep both expressions.

In addition to the distribution functions, we need fragmentation functions to describe hadron productions. The quark fragmentation functions for a pion is defined as [14]

$$\sum_X \int \frac{d\lambda}{2\pi} e^{-i\lambda/z} \times \langle 0|\psi_i^c(0)|\pi(P_\pi)X\rangle\langle\pi(P_\pi)X|\bar{\psi}_j^c(\lambda n_\pi)|0\rangle = \frac{1}{z}(\not{p}_\pi)_{ij} D_{c\to\pi}(z) + \cdots, \tag{11}$$

where p_π and n_π are the light-like vector defined from P_π similarly to p and n, and $+\cdots$ denotes higher twist contributions.

With these definitions, one can proceed to calculate the asymmetry (1) for the pion production. The calculation is done in Feynman gauge following [4,8]. Fig. 1 shows typical Feynman diagrams contributing to the asymmetry at twist-3. Usual procedure to analyze the diagrams is the collinear expansion of the parton momenta k_1, k_2 etc connecting the hard scattering part and the nonperturbative hadron matrix elements. (See Fig. 1.) After the collinear expansion, combination of the diagrams gives rise to the gauge invariant twist-3 contributions of the form (5) [8], where the momentum of each parton is expressed by the fractions of the collinear momentum x_1 and x_2 etc with $k_1 = x_1 p$ and $k_2 = x_2 p$ etc. In the chiral-odd contribution (second line of (5)), $E_F(x_1,x_2)$ and $H_F(x_1,x_2)$ appear with the propagator factor

$$\frac{1}{x_1 - x_2 \pm i\varepsilon} = P\frac{1}{x_1-x_2} \mp i\pi\delta(x_1-x_2), \tag{12}$$

as was the case for the chiral-even contribution analysed in [8]. The reality of the cross section forces to take $\delta(x_1-x_2)$ in (12), which keeps only contribution from $E_F(x_1=x, x_2=x)$ (''soft gluon contribution'') due to the symmetry property in (10).

Some of the contributions from $E_F(x,x)$ accompany with derivatives of the delta functions like $\delta'(x_1-x_2)$ and $\delta'\left((x'p' + x_1 p - p_\pi/z)^2\right)$. (The latter δ-function comes from the on-shell condition

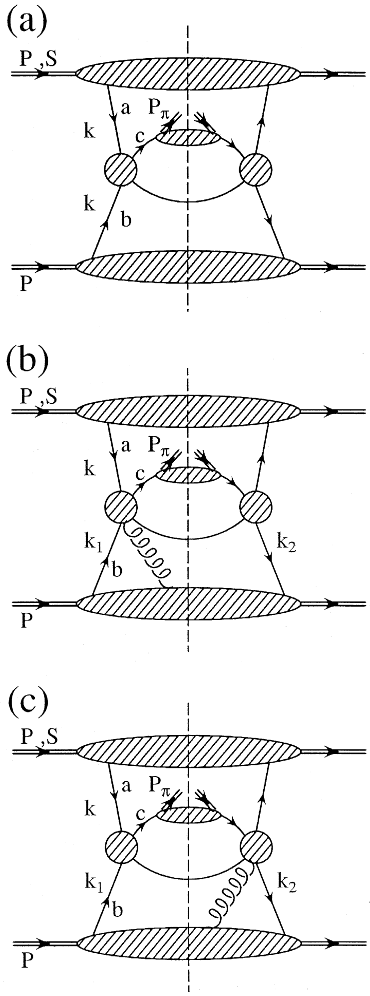

Fig. 1. Schematic representation of the diagrams contributing to the twist-3 cross section (5).

of the spectator parton and p' is the light-like vector defined from P' similarly to p.) These terms lead to $x\frac{\partial}{\partial x}E_F(x,x)$ after integration by parts. At $x_F \to -1$, the process (1) probes the kinematic region with *large* x and *small* x'. In this region, the *valence* component of $E_F(x,x)$ is expected to dominate. Since the valence component of $E_F(x,x)$ is considered to behave as $\sim (1-x)^{\beta}$ $(\beta > 0)$ at large x, one has the relation

$$\left| x\frac{\partial}{\partial x}E_F(x,x)\right| \gg E_F(x,x), \quad \text{as } x \to 1. \qquad (13)$$

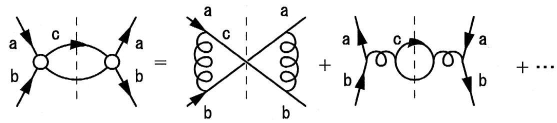

Fig. 2. $2 \to 2$ scattering diagrams contributing to the chiral-odd part of the cross section, i.e. second line of (5).

We thus keep only the terms with $\frac{\partial}{\partial x}E_{Fa}(x,x)$ for the *valence* quark with flavor a (''valence quark-soft gluon'' approximation [8]). On the other hand, $E_D(x_1,x_2)$ and $H_D(x_1,x_2)$ appear with the propagator factor $1/(x_i \pm i\varepsilon)$ $(i=1,2)$ which gives ''soft fermion'' contribution. This contribution, however, does not show up with the derivatives of the delta function. We thus do not include this term in this analysis.

The hard scattering part $\hat{\sigma}_{ab\to c}$ which appears with $x\frac{\partial}{\partial x}E_F(x,x)$ is obtained from

$$\frac{\partial}{\partial k^{\sigma}_{i\perp}}S(k_1,k_2)|_{k_i=x_ip}$$

where $S(k_1,k_2)$ is the hard part of Fig. 1(b) and (c). The effect of the gluon line entering $\frac{\partial}{\partial k^{\sigma}_{i\perp}}S(k_1,k_2)|_{k_i=x_ip}$ is replaced by $\delta'(x_1-x_2)$ or $\delta(x_1-x_2)$ which occurs from the propagator next to the quark-gluon vertex in $S(k_1,k_2)$, leaving the $2\to 2$ (quark-quark) scattering diagram. Therefore the calculation of $\hat{\sigma}_{ab\to c}$ is reduced to the calculation of $2\to 2$ scattering diagrams. For the chiral-odd contribution, the lowest order contribution to this $2\to 2$ cross section is shown in Fig. 2. Owing to the chiral-odd nature of $\delta q(x)$ and $E_F(x_1,x_2)$, the contribution from the diagrams shown in Fig. 3 vanishes.

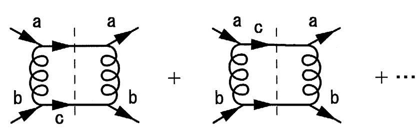

Fig. 3. $2 \to 2$ scattering diagrams not contributing to the chiral-odd part of the cross section.

With the above described procedure, the final result for the differential cross section for (1) is obtained as

$$E_\pi \frac{d^3\Delta\sigma(S_\perp)}{dp_\pi^3}$$
$$= \frac{\pi M\alpha_s^2}{S}\sum_{a,b,c}\int_{z_{\min}}^1 \frac{dz}{z^3}D_{c\to\pi}(z)\int_{x_{\min}}^1 \frac{dx}{x}$$
$$\times \frac{1}{xS+T/z}\int_0^1 \frac{dx'}{x'}\delta\left(x'+\frac{xU/z}{xS+T/z}\right)$$
$$\times \epsilon_{\mu\nu\lambda\sigma}p_\pi^\mu S_\perp^\nu p^\lambda n^\sigma\left(\frac{1}{-\hat{t}}\right)\left[-x\frac{\partial}{\partial x}E_{Fb}(x,x)\right]$$
$$\times \delta q_a(x')\,\delta\hat{\sigma}_{ab\to c}$$
$$+\frac{\pi M\alpha_s^2}{S}\sum_{a,c}\int_{z_{\min}}^1 \frac{dz}{z^3}$$
$$\times D_{c\to\pi}(z)\int_{x'_{\min}}^1 \frac{dx'}{x'}\frac{1}{x'S+U/z}\int_0^1 \frac{dx}{x}\delta$$
$$\times\left(x+\frac{x'T/z}{x'S+U/z}\right)\epsilon_{\mu\nu\lambda\sigma}p_\pi^\mu S_\perp^\nu p^\lambda n^\sigma\left(\frac{1}{-\hat{u}}\right)$$
$$\times\left[-x'\frac{\partial}{\partial x'}G_{Fa}(x',x')\right]$$
$$\times\left[G(x)\,\Delta\hat{\sigma}_{ag\to c}+\sum_b q_b(x)\,\Delta\hat{\sigma}_{ab\to c}\right], \tag{14}$$

where the invariants in the parton level are defined as

$$\hat{s}=(p_a+p_b)^2\simeq(x'P'+xP)^2\simeq xx'S,$$
$$\hat{t}=(p_a-p_c)^2\simeq(x'P'-P_\pi/z)^2\simeq x'T/z,$$
$$\hat{u}=(p_b-p_c)^2\simeq(xP-P_\pi/z)^2\simeq xU/z, \tag{15}$$

and the lower limits for the integration variables are

$$z_{\min}=\frac{-(T+U)}{S}=\sqrt{x_F^2+x_T^2},$$
$$x_{\min}=\frac{-T/z}{S+U/z},\quad x'_{\min}=\frac{-U/z}{S+T/z}. \tag{16}$$

The first term in (14) is the chiral-odd contribution derived here. The partonic cross section $\delta\hat{\sigma}_{ab\to c}$ in this term is obtained from the diagrams in Fig. 2 as

$$\delta\hat{\sigma}_{ab\to c}=\left\{\frac{10}{27}+\frac{1}{27}\left(1+\frac{\hat{t}}{\hat{u}}\right)\right\}\delta_{ab}\delta_{bc},$$
$$\delta\hat{\sigma}_{\bar{a}b\to c}=-\left\{\frac{1}{9}+\frac{7}{9}\left(1+\frac{\hat{t}}{\hat{u}}\right)\right\}\frac{\hat{t}\hat{u}}{\hat{s}^2}\delta_{\bar{a}b},$$
$$\delta\hat{\sigma}_{\bar{a}b\to\bar{c}}=-\left\{\frac{1}{9}+\frac{2}{9}\left(1+\frac{\hat{t}}{\hat{u}}\right)\right\}\frac{\hat{t}\hat{u}}{\hat{s}^2}\delta_{\bar{a}b}. \tag{17}$$

In this contribution, the summation of b is over u- and d- valence quarks in the unpolarized proton, a and c over u, d, $\bar{u}$, $\bar{d}$, s, $\bar{s}$ etc. The second term in (14) is the chiral-even contribution derived in [8] with the unpolarized gluon distribution $G(x)$ and the partonic cross section $\Delta\hat{\sigma}_{ag\to c}$ and $\Delta\hat{\sigma}_{ab\to c}$ shown in the same reference. We have included this term in our notation for completeness.

The chiral-odd contribution derived here yet include unknown function $\delta q_a(x)$ and $E_{Fa}(x,x)$. The information on the former is expected to be obtained from other twist-2 processes like semi-inclusive DIS $(\ell+N^\uparrow\to\ell'+B^\uparrow+X)$ [18], polarized baryon production $(N'+N^\uparrow\to B^\uparrow+X)$ [11], and the polarized Drell–Yan $(N^\uparrow+N^{\uparrow\prime}\to\ell^+\ell^-+X)$ [15,19] etc. To get a crude estimate for the latter, we recall those two functions are given from (6) and (9) as

$$\delta q_a(x)=\frac{i}{2}\epsilon_{S_\perp\sigma pn}\int\frac{d\lambda}{2\pi}e^{i\lambda x}$$
$$\times\langle PS|\bar{\psi}^a(0)\not{n}\gamma_\perp^\sigma\psi^a(\lambda n)|PS\rangle, \tag{18}$$
$$E_{Fa}(x,x)=\frac{-i}{2M}\int\frac{d\lambda}{2\pi}e^{i\lambda x}\langle P|\bar{\psi}^a(0)\not{n}\gamma_{\perp\sigma}$$
$$\times\left\{\int\frac{d\mu}{2\pi}gF^{\sigma\beta}(\mu n)n_\beta\right\}\psi^a(\lambda n)|P\rangle, \tag{19}$$

where $\epsilon_{S_\perp\sigma pn}\equiv\epsilon_{\mu\sigma\nu\lambda}S_\perp^\mu p^\nu n^\lambda$. One notices the similarity between (18) and (19) except that (19) contains the gluon field whose momentum is zero. This motivates us to introduce a model for $E_{Fa}(x,x)$ as

$$E_{Fa}(x,x) = K_a \delta q_a(x) \qquad (20)$$

with K_a some dimensionless parameter. This procedure was actually taken by [8]: Qiu and Sterman set

$$G_{Fa}(x,x) = K'_a q_a(x) \qquad (21)$$

inspired by the forms of the two functions

$$q_a(x) = \tfrac{1}{2}\int \frac{d\lambda}{2\pi} \mathrm{e}^{i\lambda x}\langle P|\bar{\psi}^a(0) \not{n} \psi^a(\lambda n)|P\rangle, \qquad (22)$$

$$G_{Fa}(x,x) = \frac{1}{M}\epsilon_{S_\perp \sigma p n}\int \frac{d\lambda}{2\pi}\mathrm{e}^{i\lambda x}\langle PS|\bar{\psi}^a(0)\not{n} \times \left\{\int \frac{d\mu}{2\pi} gF^{\sigma\beta}(\mu n) n_\beta\right\}\psi^a(\lambda n)|PS\rangle. \qquad (23)$$

The second term of (14) with the assumption (21) for $G_F(x',x')$ gives reasonably good fit to the E704 data at $x_F > 0$. Comparison of (18), (19), (22) and (23) would suggest to set the parameter K_a in (20) as $K_a = K'_a$. The direct measurement of δq and E_F would, of course, be prefered.

At large negative x_F, the twist-3 three-gluon distribution coupled with the unpolarized valence quark distribution may bring large effect in the first term of (5) [20]. This contribution, however, does not receive enhancement by the derivative (cf. Eq. (13)). For comparison with experiment, more complete analysis including this term would be necessary.

To summerise, we have derived a chiral-odd contribution to the single transverse spin asymmetry in the pion production, using ‘‘valence quark-soft gluon’’ approximation. This term may give rise to a sizable effect at large negative x_F, as was the case for the chiral-even contribution which gives dominant effect at large positive x_F.

References

[1] J.F. Owens, Rev. Mod. Phys. 59 (1987) 465; R.D. Field, Applications of Perturbative QCD, Addison-Wesley, 1989.
[2] A.V. Efremov, O.V. Teryaev, Sov. J. Nucl. Phys. 36 (1982) 140; Phys. Lett. B 150 (1985) 383.
[3] D. Sivers, Phys. Rev. D 41 (1990) 83; Phys. Rev. D 43 (1991) 261.
[4] J. Qiu, G. Sterman, Phys. Rev. Lett. 67 (1991) 2264; Nucl. Phys. B 378 (1992) 52.
[5] J.C. Collins, Nucl. Phys. B 396 (1993) 161.
[6] M. Anselmino, M. Boglione, F. Murgia, Phys. Lett. B 362 (1995) 164; Phys. Rev. D 60 (1999) 054027.
[7] X. Artru, J. Czyzewski, H. Yabuki, Z. Phys. C 73 (1997) 527.
[8] J. Qiu, G. Sterman, Phys. Rev. D 59 (1999) 014004.
[9] D.L. Adams et al., Phys. Lett. B 261 (1991) 201; B 264 (1991) 462; A. Bravar et al., Phys. Rev. Lett. 77 (1996) 2626.
[10] A. Bravar et al., Phys. Rev. Lett. 75 (1995) 3073.
[11] M. Stratmann, W. Vogelsang, Phys. Lett. B 295 (1992) 277; D. de Florian, M. Stratmann, W. Vogelsang, Phys. Rev. Lett. 81 (1998) 530; D. de Florian, J. Soffer, M. Stratmann, W. Vogelsang, Phys. Lett. B 439 (1998) 176.
[12] C. Boros, Phys. Rev. D 59 (1999) 051501.
[13] J.C. Collins, D.E. Soper, G. Sterman, in: A.H. Mueller (Ed.), Perturbative Quantum Chromodynamics, World Scientific, Singapore, 1989, p. 1.; J. Qiu, G. Sterman, Nucl. Phys. B 353 (1991) 137.
[14] J.C. Collins, D.E. Soper, Nucl. Phys. B 194 (1982) 445.
[15] R.L. Jaffe, X. Ji, Nucl. Phys. B 375 (1992) 527.
[16] D. Boer, P.J. Mulders, O.V. Teryaev, Phys. Rev. D 57 (1998) 3057.
[17] J. Kodaira, K. Tanaka, Prog. Theor. Phys. 101 (1999) 191.
[18] X. Ji, Phys. Rev. D 49 (1994) 114.
[19] J.P. Ralston, D.E. Soper, Nucl. Phys. B 152 (1979) 109; X. Artru, M. Mekhfi, Z. Phys. C 45 (1990) 669.
[20] X. Ji, Phys. Lett. B 289 (1992) 137.