Hard- and soft-fermion-pole contributions to single transverse-spin asymmetry for Drell-Yan process

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Abstract

We study the single transverse-spin asymmetry for the Drell-Yan lepton pair production based on the twist-3 mechanism in the collinear factorization. We calculate all the hard-pole (HP) and the soft-fermion-pole (SFP) contributions to the single-spin-dependent cross section originating from the quark-gluon correlation functions in the transversely polarized nucleon in the leading order with respect to the QCD coupling constant. Combined with the soft-gluon-pole (SGP) contribution, this completes the corresponding twist-3 cross section. In the real photon limit, where all the HP contributions are transformed into the SFP contribution, we find that the SFP partonic hard cross section for the two independent quark-gluon correlation functions coincides in each scattering channel, as in the case of the inclusive light-hadron production. Our result enables one to extract the quark-gluon correlation functions from the forthcoming experiments at several facilities such as RHIC and J-PARC.
Large single transverse-spin asymmetries (SSA) observed in hard inclusive processes have been recognized as a key milestone to probe the internal structure of hadrons beyond the collinear parton model (see [1] for a recent review). On the experimental side, SSA’s in inclusive hadron production in pp collisions [2]-[9] and semi-inclusive deep-inelastic scattering (SIDIS) [10]-[15] have been widely studied in the last decades, and a wealth of SSA data has been reported for the production of a variety of hadrons in a wide kinematical domain. Most of the SSA data in SIDIS is in the region of the small transverse momentum of the final hadron and thus has been analyzed within the framework of the transverse-momentum-dependent factorization [16, 17, 18]. In this framework, correlations between the intrinsic transverse momentum of partons and the spin vector causes SSA and they are classified into the Sivers [19, 20, 21] and Collins [22] effects, which are associated with the initial- and final-state hadrons, respectively. In the SIDIS kinematics, these two effects appear with different dependences on the azimuthal angles and there have been some attempts to extract responsible functions from the analysis of the existing data [23, 24]. On the other hand, for the inclusive single hadron production in pp collision with large transverse momentum, one can analyze the process in the framework of the collinear factorization, in which SSA is described as a leading twist-3 observable originating from multi-parton correlations [25]-[45]. In the twist-3 mechanism, multi-parton correlations are also represented by the twist-3 multi-parton correlation functions in the initial nucleon [25]-[43] and the twist-3 fragmentation functions for the final hadron [44, 45]. For the SSA in the single hadron production in pp collisions, these two effects appear with the same angular dependence and cannot be separated kinematically. Although RHIC $A_N$ data for $p^+p \rightarrow hK$ ($h = \pi, K$) has been well described by assuming solely the effect of the quark-gluon correlation functions in the polarized nucleon [31, 39, 40], relevance of the description is yet to be clarified by a global analysis including the effects of the multi-gluon correlation functions [41, 42, 43] and the twist-3 fragmentation function [44, 45].

The SSA in the Drell-Yan (DY) lepton pair production, $p^+p \rightarrow \gamma^*X \rightarrow \ell^+\ell^-X$, and the direct-photon production, $p^+p \rightarrow \gamma X$, provides us with a unique opportunity to determine the twist-3 quark-gluon correlation functions in the nucleon, since there is no fragmentation ambiguity in the final state. Owing to the naively $T$-odd nature of SSA, it occurs from an interference between the amplitudes which have different complex phases. In the twist-3 mechanism, this phase is supplied as a pole contribution from an internal propagator in the hard part. These poles fix the momentum fraction carried by one of the parton lines emanating from the parent nucleon. Corresponding to the cases in which (i) gluon line becomes soft, (ii) one of the fermion lines becomes soft, and (iii) none of the parton lines becomes soft, those poles are classified, respectively, as the soft-gluon-pole (SGP), the soft-fermion-pole (SFP) and the hard-pole (HP). For the SSA in the DY process, all these poles contribute to the single-spin-dependent cross section. Among them, the contributions from SGP and a part of HP have been calculated in [29, 34], while there has been no calculation for the SFP contribution. Furthermore, some diagrams for the HP contribution were overlooked in the previous calculation. Existence of the new type of diagrams in which a quark-antiquark pair resides in the same side of the final-state cut was recognized earlier in the study of SSA in SIDIS for the SFP contribution [36] and for the HP contributions [38],...
and also in the study on the SFP contribution to $p^*p \to \pi X$ [37]. For the direct photon production, in which HP’s merge into SFP’s, the contribution from those diagrams was not considered in the previous study [25]. Given the unique role of SSA in the DY and the direct-photon processes as stated above, it is necessary and important to have the complete twist-3 section formula for these processes.

The purpose of this Letter is to derive the entire HP and SFP contributions associated with the twist-3 quark-gluon correlation functions to these processes. Combining the result with the known SGP cross section, this will complete the twist-3 cross sections and will enable us to extract more complete and pure information on the quark-gluon correlations from experiments.

We consider the SSA for the DY process

$$p^+(p, S_\perp) + p(p') \to \gamma^*(q) + X,$$

where $\gamma^*$ is the virtual photon with the four momentum $q$ ($q^2 = Q^2$) decaying into a lepton pair in the final state. $p$ and $p'$ are the four momenta of the initial protons which can be regarded as lightlike ($p^2 = p'^2 = 0$) in the twist-3 accuracy, and $S_\perp$ is the spin vector of the transversely polarized proton normalized as $S_\perp^2 = -1$. In the transversely polarized proton there are two independent twist-3 quark-gluon correlation functions, $G_{F,a}(x_1, x_2)$ and $\bar{G}_{F,a}(x_1, x_2)$, for each quark flavor $a$ defined as

$$M_{Fij}^a(x_1, x_2) = \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{\lambda x_1} e^{\mu(x_2-x_1)} \langle pS_\perp | \bar{\psi}_j^a(0) g F^{a\beta}(\mu n) n_\beta \psi_i^a(\lambda n) | pS_\perp \rangle$$

$$= \frac{M_N}{4} (\bar{p})_{ij} e^{\mu n S_\perp} G_{F,a}(x_1, x_2) + i \frac{M_N}{4} (\gamma_5 \bar{p})_{ij} e^{n S_\perp} \bar{G}_{F,a}(x_1, x_2) + \cdots,$$  

(2)

where $\psi_i^a$ is the quark field with spinor index $i$, $F^{a\beta}$ is the gluon’s field strength and the gauge link operators between these fields are suppressed for simplicity. $n$ is another lightlike vector satisfying $p \cdot n = 1$ and $n \cdot S_\perp = 0$, and $e^{\mu n S_\perp} = e^{\epsilon_{\mu\nu\rho\sigma} n_\nu S_{\perp\rho}/2}$ with $\epsilon_{0123} = 1$. $M_N$ is the nucleon mass introduced to define the correlation functions dimensionless and the ellipses represent twist-4 or higher. The QCD coupling constant $g$ follows our convention for the covariant derivative $D^\mu = \partial^\mu - igA^\mu$. The variables $x_1$ and $x_2$ denote the longitudinal momentum fractions of the quarks and the gluon coming out of the transversely polarized proton. We remind the symmetry property $G_{F,a}(x_1, x_2) = G_{F,a}(x_2, x_1)$ and $\bar{G}_{F,a}(x_1, x_2) = -\bar{G}_{F,a}(x_2, x_1)$. (See [32, 33] for the detailed property of $G_F(x_1, x_2)$ and $\bar{G}_F(x_1, x_2)$.) Following our convention in [37], the correlation functions for the anti-quark flavor are related to those for the quark flavor as

$$G_{F,a}(x_1, x_2) = G_{F,a}(-x_2, -x_1), \quad \bar{G}_{F,a}(x_1, x_2) = -\bar{G}_{F,a}(-x_2, -x_1).$$  

(3)

We also remind that the replacement of the field strength by the covariant derivative as $g F^{a\beta}(\mu n) n_\beta \rightarrow D^\alpha(\mu n)$ in (2) defines other twist-3 quark-gluon correlation functions $G_{D,a}(x_1, x_2)$ and $\bar{G}_{D,a}(x_1, x_2)$ in the same decomposition corresponding to $G_{F,a}(x_1, x_2)$ and
Figure 1: Generic diagrams giving rise to the twist-3 single-spin-dependent cross section for the Drell-Yan process originating from the quark-gluon correlation functions in the nucleon (upper blob). Momenta of the parton lines coming out of the polarized nucleon are set to \( k_i = x_i p \) \((i = 1, 2)\). Mirror diagrams also contribute.

\[
\tilde{G}_{F,a}(x_1, x_2), \text{ respectively. However, they are not independent, in particular, at } x_1 \neq x_2, \text{ which are relevant to the HP and SFP contributions, they are related by the relation [32],}
\]

\[
G_{D,a}(x_1, x_2) = \frac{G_{F,a}(x_1, x_2)}{x_1 - x_2}, \quad \tilde{G}_{D,a}(x_1, x_2) = \frac{\tilde{G}_{F,a}(x_1, x_2)}{x_1 - x_2}, \quad (x_1 \neq x_2). \tag{4}
\]

Figure 1 shows the generic twist-3 diagrams giving rise to SSA for the DY process. Their mirror diagrams also give the same contribution as those shown in Fig. 1. Following the twist-3 formalism for the contribution of the quark-gluon correlation functions developed in [33] (see also [37]), one can obtain the single-spin-dependent cross section from the HP and SFP as

\[
\frac{d^4 \Delta \sigma^{\text{HP},\text{SFP}}}{dQ^2 dy d^2 q_{\perp}} = \frac{\alpha_{em}^2 \alpha_s}{3 \pi S Q^2} \int \frac{dx'}{x'} \int dx_1 \int dx_2 \frac{1}{x_1 - x_2} \times \text{Tr}[i M_F^\alpha(x_1, x_2) S_{\alpha}^{\text{HP},\text{SFP}}(x_1 p, x_2 p, x' p', q)] f(x'),
\tag{5}
\]

where \( y \) and \( q_{\perp} \) are, respectively, the rapidity and the transverse momentum of the virtual photon, \( S = (p + p')^2 \) is the center of mass energy, \( \alpha_{em} \approx 1/137 \) and \( \alpha_s = g^2/(4\pi) \) are, respectively, the electromagnetic and the strong coupling constants, \( f(x') \) is the unpolarized parton density in the unpolarized proton. \( S_{\alpha}^{\text{HP},\text{SFP}}(x_1 p, x_2 p, x' p', q) \) is the corresponding hard part for the HP and SFP contributions in which parton momenta coming from the polarized nucleon are set to \( k_i = x_i p \) \((i = 1, 2)\). \( \text{Tr}[\cdot \cdot \cdot] \) indicates the trace over spinor and color indices.

Figures 2 and 3 show the two types of diagrams generating HP’s. Those in Fig. 2 were considered for the \( G_F \) contribution in [29]. In these diagrams, the quark propagator with
Figure 2: Feynman diagrams for the HP contribution (HP1) corresponding to Figs. 1 (a) and (b). An extra coherent gluon line coming out of the polarized nucleon attaches to one of the dots numbered as (1), (2) and (3). The propagator with a short bar gives rise to the HP at $x_1 = x_B$.

Figure 3: Feynman diagrams for the HP contribution (HP2) corresponding to Fig. 1 (c). An extra coherent gluon line coming out of the polarized nucleon attaches to one of the dots numbered as (1) and (2). The propagator with a short bar gives rise to the HP at $x_1 = -x_B$.

A short bar carrying the momentum $x_1 p - q$ gives rise to the HP at $x_1 = Q^2 / (2 p \cdot q) \equiv x_B$.

Diagrams in Fig. 3 are the new ones not considered in [29] and have the two quark lines from the polarized nucleon in the same side of the final-state cut. There the quark propagator with a short bar carrying the momentum $x_1 p + q$ gives rise to the HP at $x_1 = -x_B$.

Calculating the diagrams in Figs. 2 and 3, we obtain the HP contribution to the twist-3 cross section as

$$
\frac{d^4 \Delta \sigma_{\text{DY},\text{HP}}}{dQ^2 dy d^2 q_{\perp}} = \frac{\alpha_s \alpha_e}{3\pi N S Q^2} \frac{(\pi) M_N}{2} \int \frac{dx'}{x'} \int \frac{dx}{x} \delta(\hat{s} + \hat{t} + \hat{u} - Q^2)

\times \sum_a \left[ \epsilon_a^2 \left\{ \hat{\sigma}_{V,aa}^{\text{HP1}} G_{F,a}(x_B, x) + \hat{\sigma}_{A,aa}^{\text{HP1}} \tilde{G}_{F,a}(x_B, x) \right\} f_a(x') + \epsilon_a^2 \left\{ \hat{\sigma}_{V,ag}^{\text{HP1}} G_{F,a}(x_B, x) + \hat{\sigma}_{A,ag}^{\text{HP1}} \tilde{G}_{F,a}(x_B, x) \right\} G(x') \right]
$$
where $e_a$ stands for the fraction of the electric charge for the quark flavor $a$, $f_b(x')$ is the unpolarized quark density, and $G(x')$ is the unpolarized gluon density. In (6), the sum for $a$ is over all quark and anti-quark flavors ($a = u, d, s, \bar{u}, d, \bar{s}, ...$), and $\sum_b$ indicates that the sum for $b$ is restricted over the quark flavors when $a$ is a quark and over anti-quark flavors when $a$ is an anti-quark. The partonic hard cross sections are classified by the upper indices $\text{HP1}$ and $\text{HP2}$ corresponding, respectively, to Fig. 2 and Fig. 3. They are the functions of the Mandelstam variables in the parton level, $\hat{s}$ and $\hat{t}$ with a short bar carrying the momentum $x_1 p - x' p'$ (Figs. 4(a) and (b)) and $x_1 p + x' p'$ (Figs. 4(c) and (d)) gives the SFP at $x_1 = 0$. Although diagrams in Fig. 5 also give rise
Figure 4: Feynman diagrams for the SFP contribution corresponding to Figs. 1 (c) and (b). An extra coherent gluon line coming out of the polarized nucleon attaches to one of the dots numbered as (1) and (2). The propagator with a short bar gives rise to the SFP at $x_1 = 0$.

Figure 5: Cancelling pairs of the diagrams for the SFP contribution. An extra coherent gluon line coming out of the polarized nucleon attaches to one of the dots numbered as (1) and (2). Two diagrams in the pair (a) and (b) cancel each other.

to the SFP, they cancels within the pairs (a) and (b). This is because in each pair one diagram is obtained from the other by shifting the position of the cut and the SFP appears with opposite signs [26, 36, 37]. Calculating the diagrams in Fig. 4, one obtains the SFP contribution as

$$
\frac{d^4 \Delta \sigma_{\text{DY}, \text{SFP}}}{dQ^2 dy d^2 \vec{q}_\perp} = \frac{\alpha_{em}^2 \alpha_s}{3 \pi N S Q^2} \frac{(-\pi) M_N}{2} \epsilon^{qms} \int \frac{dx'}{x'} \int dx \frac{1}{x} \delta(\hat{s} + \hat{t} + \hat{u} - Q^2) \\
\times \sum_a \epsilon_a^2 \left[ \left\{ \hat{\sigma}_{V,aa}^{\text{SFP}} G_{F,a}(0, x) + \hat{\sigma}_{A,aa}^{\text{SFP}} \tilde{G}_{F,a}(0, x) \right\} f_a(x') \\
+ \left\{ \hat{\sigma}_{V,ag}^{\text{SFP}} G_{F,a}(0, x) + \hat{\sigma}_{A,ag}^{\text{SFP}} \tilde{G}_{F,a}(0, x) \right\} G(x') \right],
$$

(15)

where the sum for $a$ is over all quark and anti-quark flavors and the partonic hard cross sections are defined as

$$
\hat{\sigma}_{V,aa}^{\text{SFP}} = \frac{2[(\hat{s} - Q^2)^2 + \hat{t} Q^2] \hat{\sigma}_{V,aa}}{N \hat{s} \hat{t} \hat{u}},
$$

(16)
\[ \hat{\sigma}_{A,aa}^{\text{SFP}} = \frac{2[(\hat{s} - Q^2)^2 - \hat{t}Q^2]}{N\hat{s}\hat{t}\hat{u}}, \]  
(17)

\[ \hat{\sigma}_{V,ag}^{\text{SFP}} = \frac{-2[(\hat{s} - Q^2)^2 + \hat{t}Q^2]}{(N^2 - 1)\hat{s}\hat{t}\hat{u}}, \]  
(18)

\[ \hat{\sigma}_{A,ag}^{\text{SFP}} = \frac{-2[(\hat{s} - Q^2)^2 - \hat{t}Q^2]}{(N^2 - 1)\hat{s}\hat{t}\hat{u}}. \]  
(19)

Combination of the above results (6) and (15) and that for the SGP cross section (see, for example, eq.(29) of [34]) gives the complete expression for the leading order (LO) twist-3 single-spin-dependent cross section arising from the quark-gluon correlation functions.

Finally, by making a replacement \( \alpha_{em}/(3\pi Q^2) \to \delta(Q^2) \) in the Drell-Yan cross section, one obtains the cross section formula for the direct photon production (DP). Since \( x_B \) becomes 0 in this limit, all HP’s in the DY process transform into SFP’s. Consequently, we obtain the SFP contribution for the direct photon production as

\[ E_\gamma \frac{d^3 \Delta \sigma_{\text{DP,SFP}}}{d^3 \vec{q}} = \frac{\alpha_{em}\alpha_s}{2} \frac{(-\pi) M_N}{N S} \epsilon_{qpmS_\perp} \int \frac{dx'}{x'} \int \frac{dx}{x} \delta(\hat{s} + \hat{t} + \hat{u}) \]

\[ \times \sum a \left[ \sum b e_a e_b \hat{\sigma}_{ab}^{\text{SFP}} \left\{ G_{F,a}(0, x) + \tilde{G}_{F,a}(0, x) \right\} f_b(x') \right. \]

\[ + \sum b e_a e_b \hat{\sigma}_{ab}^{\text{SFP}} \left\{ G_{F,a}(0, x) + \tilde{G}_{F,a}(0, x) \right\} f_b(x') \]

\[ + \epsilon_a^2 \hat{\sigma}_{ag}^{\text{SFP}} \left\{ G_{F,a}(0, x) + \tilde{G}_{F,a}(0, x) \right\} G(x'), \]  
(20)

where the meaning of \( \sum_{a,b} \) is the same as in (6) and the partonic hard cross sections are given by

\[ \hat{\sigma}_{ab}^{\text{SFP}} = \frac{2(\hat{s}^2 + \hat{u}^2)}{t^2\hat{u}} + \frac{2\hat{s}(\hat{u} - \hat{s})}{Nt\hat{u}^2} \delta_{ab}, \]  
(21)

\[ \hat{\sigma}_{ab}^{\text{SFP}} = -\frac{2(\hat{s}^2 + \hat{u}^2)}{t^2\hat{u}} + \left[ \frac{2N\hat{s}}{\hat{u}^2} + \frac{2(\hat{u}^2 + \hat{s}\hat{t})}{N\hat{s}\hat{u}} \right] \delta_{ab}, \]  
(22)

\[ \hat{\sigma}_{ag}^{\text{SFP}} = \frac{2[N^2\hat{t}\hat{u} - \hat{s}(\hat{s} - \hat{t})]}{(N^2 - 1)\hat{s}\hat{t}\hat{u}}. \]  
(23)

In the limit \( Q^2 \to 0 \), the hard cross sections for \( G_F \) and \( \tilde{G}_F \) coincide in each scattering channel, and thus the SFP functions appear in the combination of \( G_F(0, x) + \tilde{G}_F(0, x) \), which was also observed in the SFP contribution to SSA in the light hadron production \( p^\uparrow p \to \pi X \) [37]. Although we do not understand the reason for this simplification, it seems to occur when particles participating in the scattering are all massless. This property reduces
the number of independent functions contributing to SSA and serves greatly for the global analysis of SSA. We mention that the sum of the result for the SFP cross section in (20) and the result for the SGP cross section (eq.(30) of [34]) gives the complete LO twist-3 cross section for the direct-photon production, $p^\uparrow p \rightarrow \gamma X$, arising from the quark-gluon correlation functions.

To summarize, we have derived all the HP and SFP contributions to the twist-3 single-spin-dependent cross section for the DY lepton-pair production and the direct-photon production originating from the quark-gluon correlation functions in the transversely polarized nucleon in the LO QCD. In the direct photon limit, the HP’s are transformed into the SFP’s, and we have observed that $G_F$ and $\tilde{G}_F$ have the common SFP hard cross sections in all channels, as in the case of the twist-3 cross section for $p^\uparrow p \rightarrow \pi X$. Combined with the existing result for the SGP cross section for these processes, this completes the whole twist-3 cross section associated with the quark-gluon correlation functions. Forthcoming measurement of the SSA for these two processes at RHIC, J-PARC, etc, provides us with a valuable opportunity to determine these functions.

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