Single Transverse-Spin Asymmetry in Open Charm Production in SIDIS

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Abstract. We discuss the single transverse-spin asymmetry (SSA) to be observed in the *D*-meson production with large transverse-momentum in semi-inclusive DIS (SIDIS), $ep^{\uparrow} \to eDX$. This contribution is embodied as a twist-3 mechanism in the collinear factorization, which is induced by purely gluonic correlation inside the transversely-polarized nucleon, in particular, by the three-gluon correlation effects. We derive the first complete formula for the corresponding SSA in the leading-order QCD, revealing the five independent structures with respect to the dependence on the azimuthal angle for the produced *D*-meson. Our result obeys universal structure behind the SSAs in a variety of hard processes. We present the numerical calculations of our SSA formula for the *D*-meson production at the kinematics relevant to a future Electron Ion Collider.

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Charm productions in semi-inclusive DIS (SIDIS), as well as in the pp collision, are known to be associated with the twist-2 gluon distributions in the nucleon, since the $c\bar{c}$-pair creation through the photon-gluon or gluon-gluon fusion is their driving subprocess. Similarly, the twist-3 contributions in the charm productions can be generated by the purely gluonic effects inside the nucleon, in particular, the multi-gluon correlations. Indeed, the observation of the single transverse-spin asymmetry (SSA) in the open charm productions allows us to probe the corresponding twist-3 effects [1, 2, 3, 4, 5].

The corresponding SSA arises as a *naively T-odd* effect in the cross section for the scattering of transversely-polarized nucleon off an unpolarized particle, observing a *D*-meson with momentum P_h in the final state, and this requires, (i) nonzero transverse-momentum $P_{h\perp}$ originating from transverse motion of quark or gluon; (ii) nucleon helicity flip in the cut diagrams for the cross section, corresponding to the transverse polarization; and (iii) interaction beyond Born level to produce the interfering phase between the LHS and the RHS of the cut in those diagrams. In particular, for large $P_{h\perp} \gg \Lambda_{\rm QCD}$ to be dealt with the collinear-factorization framework, (i) should come from perturbative mechanism as the recoil from the hard (unobserved) final-state partons, while nonperturbative effects can participate in the other two, (ii) and (iii), allowing us to obtain observably large SSA. This is realized with the twist-3 multi-gluon correlation functions for the transversely-polarized nucleon [3]. This twist-3 mechanism may be considered as an extension of the corresponding mechanism for the SSA in the pion productions in the SIDIS [6], pp collisions [7], etc., based on the quark-gluon correlations in the nucleon, but it has been clarified [3] that a straightforward extension [1, 2] leads to missing many

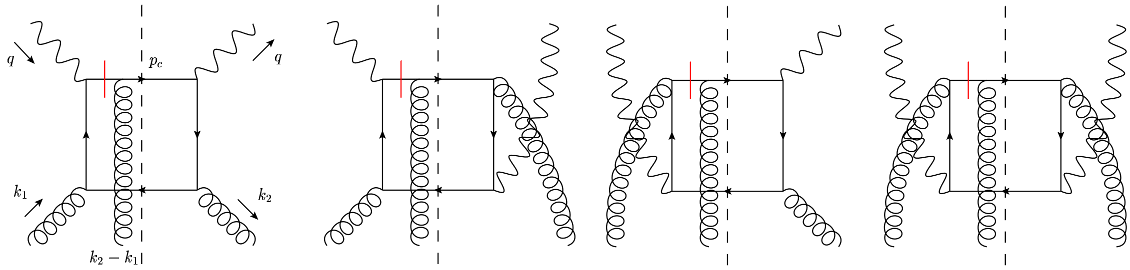

FIGURE 1. Feynman diagrams for partonic subprocess in $ep^{\uparrow} \to eDX$; mirror diagrams also contribute.

terms in the SSA. We shall discuss the leading-order (LO) QCD result for the SSA in the high-$P_{h\perp}$ D-meson production in SIDIS, $e(\ell)+p(p,S_\perp) \to e(\ell')+D(P_h)+X$, controlled by the twist-3 three-gluon correlation functions in the nucleon. We also present a numerical estimate of the corresponding SSA with kinematics of a future Electron Ion Collider (EIC). We use, as usual, the kinematic variables $S_{ep} = (\ell+p)^2$, $q = \ell - \ell'$, $Q^2 = -q^2$, $x_{bj} = Q^2/(2p\cdot q)$, and $z_f = p\cdot P_h/(p\cdot q)$. We work in a frame where the momenta $\vec{q}$ and $\vec{p}$ are collinear, and define $q_T \equiv P_{h\perp}/z_f$ and the azimuthal angles ϕ, Φ_S, and χ of the lepton plane, the spin vector $S_\perp^\mu$, and the D-meson momentum P_h^μ, respectively [3, 4]. We take into account the masses m_c and m_h for the charm quark and the D meson.

In the LO in QCD perturbation theory, the photon-gluon fusion subprocesses of Fig. 1 drive the SSA, where the above-mentioned (i) is provided by the recoil from the hard unobserved $\bar{c}$ quark and the c quark with the momentum p_c fragments into the D-meson in the final state. The short bar on the internal c-quark line indicates that the pole part is to be taken from that propagator, to produce the interfering phase of (iii); we note that these pole contributions from Fig. 1 would cancel the similar contributions from the corresponding mirror diagrams, if the c quark were unobserved in the final state as in the $\bar{D}$-meson production. The external curly lines represent the gluons that are generated from the three-gluon correlations present inside the transversely-polarized nucleon, $\langle pS_\perp|A_\alpha(0)A_\beta(\eta)A_\gamma(\xi)|pS_\perp\rangle$, corresponding to (ii). The diagrams obtained by the permutation of the gluon lines in Fig. 1 also satisfy (i)-(iii), but the Bose statistics of the gluons in the above matrix element guarantees that we need not consider those diagrams separately. Thus, the SSA in the present context can be derived entirely as the contributions of soft-gluon-pole (SGP) type [6], leading to $k_2 - k_1 = 0$, by evaluating the pole part in Fig. 1. The twist-3 nature of those contributions are unraveled by the collinear expansion, as usual. The expansion produces lots of terms, each of which is not gauge invariant. Indeed, many of them vanish or cancel eventually, and the remaining terms can be organized into a gauge-invariant form. This can be demonstrated [3] by sophisticated use of the Ward identities for the contributions of the diagrams in Fig. 1. The resulting factorization formula of the spin-dependent, differential cross section for $ep^{\uparrow} \to eDX$ reads [3, 4] ($[d\omega] \equiv dx_{bj}dQ^2dz_f dq_T^2 d\phi d\chi$, for the differential elements)

$$\frac{d^6\Delta\sigma}{[d\omega]} = \frac{\alpha_{em}^2\alpha_s e_c^2 M_N}{16\pi^2 x_{bj}^2 S_{ep}^2 Q^2}\left(\frac{-\pi}{2}\right)\sum_k \mathscr{A}_k \mathscr{S}_k \int\frac{dx}{x}\int\frac{dz}{z}\delta\left(\frac{q_T^2}{Q^2}-\left(1-\frac{1}{\hat{x}}\right)\left(1-\frac{1}{\hat{z}}\right)+\frac{m_c^2}{\hat{z}^2Q^2}\right)$$

$$\times \sum_{a=c,\bar{c}} D_a(z) \left(\delta_a \left\{ \left[\frac{dO(x,x)}{dx} - \frac{2O(x,x)}{x} \right] \Delta\hat{\sigma}_k^1 + \left[\frac{dO(x,0)}{dx} - \frac{2O(x,0)}{x} \right] \Delta\hat{\sigma}_k^2 \right. \right.$$

$$\left. \left. + \frac{O(x,x)}{x} \Delta\hat{\sigma}_k^3 + \frac{O(x,0)}{x} \Delta\hat{\sigma}_k^4 \right\} + \left\{ O(x,x) \to N(x,x),\ O(x,0) \to -N(x,0) \right\} \right), \tag{1}$$

where $\hat{x} = x_{bj}/x$, $\hat{z} = z_f/z$, and a complete set of twist-3 gluonic correlation functions is defined through the gauge-invariant lightcone correlation of three field-strength tensors [3] ($n^2 = 0$, $p \cdot n = 1$),

$$\mathscr{M}_F^{\alpha\beta\gamma}(x_1,x_2) \equiv -gi^3 \int \frac{d\lambda}{2\pi} \int \frac{d\zeta}{2\pi} e^{i\lambda x_1} e^{i\zeta(x_2-x_1)} \langle pS_\perp | d^{bca} F_b^{\beta n}(0) F_c^{\gamma n}(\zeta n) F_a^{\alpha n}(\lambda n) | pS_\perp \rangle$$

$$= 2iM_N \left[O(x_1,x_2) g^{\alpha\beta} \varepsilon^{\gamma p n S_\perp} + O(-x_2, x_1 - x_2) g^{\beta\gamma} \varepsilon^{\alpha p n S_\perp} + O(x_2 - x_1, -x_1) g^{\gamma\alpha} \varepsilon^{\beta p n S_\perp} \right], \tag{2}$$

and similarly for $N(x_1,x_2)$ with the replacement $d^{bca} \to if^{bca}$, and $D_c(z)$ denotes the usual twist-2 fragmentation function for a c-quark to become the D-meson. The quark-flavor index a can, in principle, be c and $\bar{c}$, with $\delta_c = 1$ and $\delta_{\bar{c}} = -1$, so that the cross section for the $\bar{D}$-meson production $ep^\uparrow \to e\bar{D}X$ can be obtained by a simple replacement of the fragmentation function to that for the $\bar{D}$ meson, $D_a(z) \to \bar{D}_a(z)$. The summation $\sum_k$ implies that the subscript k runs over $1,2,3,4,8,9$, with $\mathscr{A}_1 = 1 + \cosh^2\psi$, $\mathscr{A}_2 = -2$, $\mathscr{A}_3 = -\cos\tilde{\phi}\sinh 2\psi$, $\mathscr{A}_4 = \cos 2\tilde{\phi}\sinh^2\psi$, $\mathscr{A}_8 = -\sin\tilde{\phi}\sinh 2\psi$, and $\mathscr{A}_9 = \sin 2\tilde{\phi}\sinh^2\psi$, where $\cosh\psi \equiv 2x_{bj}S_{ep}/Q^2 - 1$ and $\tilde{\phi} = \phi - \chi$, and $\mathscr{S}_k$ is defined as $\mathscr{S}_k = \sin(\Phi_S - \chi)$ for $k = 1,2,3,4$ and $\mathscr{S}_k = \cos(\Phi_S - \chi)$ for $k = 8,9$. α_{em} is the fine-structure constant, and $e_c = 2/3$ is the electric charge of the c-quark. Partonic hard parts $\Delta\hat{\sigma}_k^i$ depend on m_c as well as other partonic variables; for the explicit formulae of $\Delta\hat{\sigma}_k^i$, we refer the readers to [3]. Note that, instead of evaluating the diagrams in Fig. 1 as above, those results can be obtained using the "master formula" [4], schematically given by

$$\frac{d^6\Delta\sigma}{[d\omega]} \sim -i\pi \int \frac{dx}{x^2} \int \frac{dz}{z} \frac{\partial \mathscr{H}_{\mu\nu}(xp,q,p_c)}{\partial p_{c\perp}^\sigma} \otimes \mathscr{M}_F^{\mu\nu\sigma}(x,x) \otimes D_a(z), \tag{3}$$

where $\mathscr{H}_{\mu\nu}(xp,q,p_c)$ denotes the partonic hard part for the $2 \to 2$ Born subprocess, expressed by the diagrams in Fig. 1 with the soft ($k_2 - k_1 = 0$) gluon line removed. This reveals that $\Delta\hat{\sigma}_k^i$ in (1) are related to the twist-2 hard parts $\mathscr{H}_{\mu\nu}(xp,q,p_c)$, similarly as in the SSA in various processes associated with twist-3 quark-gluon correlation functions.

Reexpressing as $\phi - \chi = \tilde{\phi} = \phi_h$, $\Phi_S - \chi = \phi_h - \phi_S$ in the above-mentioned explicit forms of $\mathscr{A}_k$ and $\mathscr{S}_k$, where ϕ_h and ϕ_S represent the azimuthal angles of the hadron plane and the nucleon's spin vector $\vec{S}_\perp$, respectively, measured from the *lepton plane*, one may express (1) as the superposition of five sine modulations,

$$\frac{d^6\Delta\sigma}{[d\omega]} = f_1 \sin(\phi_h - \phi_S) + f_2 \sin(2\phi_h - \phi_S) + f_3 \sin\phi_S + f_4 \sin(3\phi_h - \phi_S) + f_5 \sin(\phi_h + \phi_S), \tag{4}$$

with the corresponding structure functions $f_1, f_2, \ldots, f_5$, similarly as the twist-3 SSA for $ep^\uparrow \to e\pi X$, generated from the quark-gluon correlation functions [8].

As an illustration, we evaluate the SSA for the D^0 production, $ep^\uparrow \to eD^0X$, using (1), (4). In particular, we present $F_1 \equiv f_1/\sigma_1^U$ with the kinematics relevant to a future

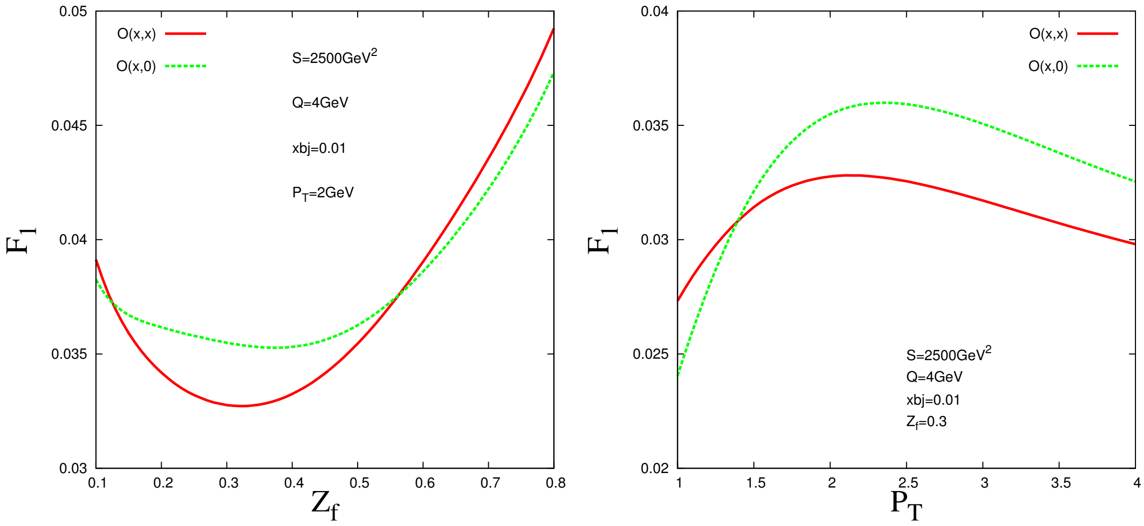

FIGURE 2. The SSA as a function of (a) z_f and (b) $P_T \equiv P_{h\perp}$ at EIC kinematics with $S_{ep} = 2500$ GeV^2.

EIC in Fig. 2, where σ_1^U denotes the twist-2 unpolarized cross section for $ep \to eD^0X$, $d^6\sigma^{\text{unpol}}/[d\omega]$, averaged and integrated over the azimuthal angles ϕ_h and χ, respectively. The solid and dashed curves show the contributions generated by the three-gluon correlation functions of (2), assuming $O(x,x) = O(x,0) = 0.005xG(x)$ [5] (see also [1, 2]) with the unpolarized gluon-density distribution $G(x)$ for the nucleon and using CTEQ6L parton distributions and KKKS fragmentation functions [9] with the scale $\mu^2 = Q^2 + m_c^2 + z_f^2 q_T^2$. The results demonstrate good chance to access multi-gluon effects at EIC. The detailed numerical studies, including those for the asymmetries generated by the other structures $f_2, \ldots, f_5$ in (4), will be presented elsewhere.

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