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How to measure the linear polarization of gluons in unpolarized proton using the heavy-quark pair leptoproduction

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ABSTRACT

We study the azimuthal $\cos\varphi$ and $\cos 2\varphi$ asymmetries in heavy-quark pair leptoproduction, $lN \to l' Q \bar{Q} X$, as probes of linearly polarized gluons inside unpolarized proton, where the azimuth φ is the angle between the lepton scattering plane (l, l') and the heavy quark production plane (N, Q). First, we determine the maximal values for the $\cos\varphi$ and $\cos 2\varphi$ asymmetries allowed by the photon–gluon fusion with unpolarized gluons; these predictions are large, $(\sqrt{3}-1)/2$ and $1/3$, respectively. Then we calculate the contribution of the transverse-momentum dependent gluonic counterpart of the Boer–Mulders function, $h_1^{\perp g}$, describing the linear polarization of gluons inside unpolarized proton. Our analysis shows that the maximum values of the azimuthal distributions depend strongly on the gluon polarization; they vary from 0 to 1 depending on $h_1^{\perp g}$. We conclude that the azimuthal $\cos\varphi$ and $\cos 2\varphi$ asymmetries in heavy-quark pair leptoproduction are predicted to be large and very sensitive to the contribution of linearly polarized gluons. For this reason, future measurements of the azimuthal distributions in charm and bottom production at the proposed EIC and LHeC colliders seem to be very promising for determination of the linear polarization of gluons inside unpolarized proton.

1. Introduction and notation

Search for the polarized quarks and gluons in unpolarized hadrons is of special interest in studies of the spin-orbit couplings of partons and understanding of the proton spin decomposition. The corresponding transverse momentum dependent (TMD) distributions of the transversely polarized quarks, $h_1^{\perp q}(\zeta, \vec{k}_T^2)$, and linearly polarized gluons, $h_1^{\perp g}(\zeta, \vec{k}_T^2)$, in an unpolarized nucleon have been introduced in Refs. [1] and [2]. Contrary to its quark version (i.e. so-called Boer–Mulders function $h_1^{\perp q}$) the TMD density $h_1^{\perp g}$ is T- and chiral-even. For this reason, like the unpolarized TMD gluon density $f_1^g(\zeta, \vec{k}_T^2)$, the function $h_1^{\perp g}$ can directly be probed in certain electroproduction experiments.

Azimuthal correlations in heavy quark pair (and dijet) production in unpolarized electron–proton collisions as probes of the density $h_1^{\perp g}$ have been considered in Refs. [3–5].[1] In leading order (LO) in QCD, the complete angular structure of the pair production cross section has been obtained in terms of seven azimuthal modulations. However, only two of these modulations are really independent; they can be chosen as the $\cos\varphi$ and $\cos 2\varphi$ distributions, where φ is the heavy quark (or anti-quark) azimuthal angle [7].

In the present paper, we provide the QCD predictions for the $\cos\varphi$ and $\cos 2\varphi$ asymmetries in the heavy-quark pair production. Our analysis shows that these azimuthal asymmetries (AAs) are expected to be large in wide kinematic ranges and very sensitive to the function $h_1^{\perp g}(\zeta, \vec{k}_T^2)$. We conclude that the $\cos\varphi$ and $\cos 2\varphi$ distributions could be good probes of the linearly polarized gluons inside unpolarized proton.

In Refs. [3–5], it was proposed to study the linearly polarized gluons in unpolarized nucleon using the heavy-quark pair production in the reaction

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[1] Concerning the opportunities to measure the function $h_1^{\perp g}$ in unpolarized hadron–hadron collisions, see review [6].

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$$l(\ell) + N(P) \to l'(\ell - q) + Q(p_Q) + \bar{Q}(p_{\bar{Q}}) + X(p_X). \tag{1}$$

To describe this process, the following hadron-level variables are used:

$$\begin{aligned} &\bar{S} = 2(\ell \cdot P), && y = \frac{q \cdot P}{\ell \cdot P}, && T_1 = (P - p_Q)^2 - m^2, \\ &Q^2 = -q^2, && x = \frac{Q^2}{2q \cdot P}, && U_1 = (q - p_Q)^2 - m^2, \\ &S = (q + P)^2, && && \\ &z = -\frac{T_1}{2q \cdot P}, && && \end{aligned} \tag{2}$$

where m is the heavy-quark mass.

To probe a TMD distribution, the momenta of both heavy quark and anti-quark, $\vec{p}_Q$ and $\vec{p}_{\bar{Q}}$, in the process (1) should be measured (reconstructed). For further analysis, the sum and difference of the transverse heavy quark momenta are introduced,

$$\vec{K}_\perp = \frac{1}{2}\left(\vec{p}_{Q\perp} - \vec{p}_{\bar{Q}\perp}\right), \qquad \vec{q}_T = \vec{p}_{Q\perp} + \vec{p}_{\bar{Q}\perp}, \tag{3}$$

in the plane orthogonal to the direction of the target and the exchanged photon. The azimuthal angles of $\vec{K}_\perp$ and $\vec{q}_T$ (relative to the lepton scattering plane projection, $\phi_l = \phi_{l'} = 0$) are denoted by $\phi_\perp$ and ϕ_T, respectively.

Following Refs. [3–5], we use the approximation when $\vec{q}_T^{\,2} \ll \vec{K}_\perp^2$ and the outgoing heavy quark and anti-quark are almost back-to-back in the transverse plane, see Fig. 1. In this case, the magnitudes of transverse momenta of the heavy quark and anti-quark are practically the same, $\vec{p}_{Q\perp}^{\,2} \simeq \vec{p}_{\bar{Q}\perp}^{\,2} \simeq \vec{K}_\perp^2$.

At LO, $\mathcal{O}(\alpha_{em}\alpha_s)$, the only parton-level subprocess for the reaction (1) is the photon–gluon fusion:

$$\gamma^*(q) + g(k_g) \to Q(p_Q) + \bar{Q}(p_{\bar{Q}}), \tag{4}$$

where

$$k_g^\mu \simeq \zeta P^\mu + k_T^\mu, \qquad \zeta = -\frac{U_1}{y\bar{S} + T_1} = \frac{q \cdot k_g}{q \cdot P}. \tag{5}$$

The corresponding parton-level invariants are:

$$\begin{aligned} &\hat{s} = (q + k_g)^2 \simeq \frac{m^2 + \vec{K}_\perp^2}{z(1-z)}, \\ &t_1 = (k_g - p_Q)^2 - m^2 \simeq \zeta T_1 \simeq -z(\hat{s} + Q^2), \\ &u_1 = U_1 \simeq -(1-z)(\hat{s} + Q^2). \end{aligned} \tag{6}$$

2. Production cross section

Schematically, the contribution of the photon–gluon fusion to the reaction (1) has the following factorized form:

$$\mathrm{d}\sigma \propto L(\ell, q) \otimes \Phi_g(\zeta, k_T) \otimes \left| H_{\gamma^* g \to Q\bar{Q}X}(q, k_g, p_Q, p_{\bar{Q}}) \right|^2, \tag{7}$$

where $L^{\alpha\beta}(\ell, q) = -Q^2 g^{\alpha\beta} + 2(\ell^\alpha \ell'^\beta + \ell^\beta \ell'^\alpha)$ is the leptonic tensor and $H_{\gamma^* g \to Q\bar{Q}X}(q, k_g, p_Q, p_{\bar{Q}})$ is the amplitude for the hard partonic subprocess. The convolutions $\otimes$ stand for the appropriate integration and traces over the color and Dirac indices.

Information about parton densities in unpolarized nucleon is formally encoded in corresponding TMD parton correlators. In particular, the gluon correlator is usually parameterized as [2]

$$\Phi_g^{\mu\nu}(\zeta, k_T) \propto -g_T^{\mu\nu} f_1^g(\zeta, \vec{k}_T^2) + \left(g_T^{\mu\nu} - 2\frac{k_T^\mu k_T^\nu}{k_T^2} \right) \frac{\vec{k}_T^2}{2m_N^2} h_1^{\perp g}(\zeta, \vec{k}_T^2), \tag{8}$$

where m_N is the nucleon mass,

$$g_T^{\mu\nu} = g^{\mu\nu} - \frac{P^\mu n^\nu + P^\nu n^\mu}{P \cdot n}, \qquad n^\mu = \frac{q^\mu + xP^\mu}{P \cdot q}. \tag{9}$$

In Eq. (9), the tensor $-g_T^{\mu\nu}$ is (up to a factor) the density matrix of unpolarized gluons. The TMD distribution $h_1^{\perp g}(\zeta, \vec{k}_T^2)$ describes the contribution of linearly polarized gluons. The degree of their linear polarization is determined by the quantity $r = \frac{\vec{k}_T^2 h_1^{\perp g}}{2m_N^2 f_1^g}$. In particular, the gluons are completely polarized along the $\vec{k}_T$ direction at $r = 1$.[2]

The LO predictions for the azimuth dependent cross section of the reaction (1) are presented in Ref. [4] as follows:

$$\begin{aligned} &\frac{\mathrm{d}^7\sigma}{\mathrm{d}y\,\mathrm{d}x\,\mathrm{d}z\,\mathrm{d}^2\vec{K}_\perp \mathrm{d}^2\vec{q}_T} \\ &\quad = \mathcal{N}\Big\{ A_0 + A_1\cos\phi_\perp + A_2\cos 2\phi_\perp \\ &\qquad + \vec{q}_T^{\,2}\Big[B_0\cos 2(\phi_\perp - \phi_T) + B_1\cos(\phi_\perp - 2\phi_T) \\ &\qquad + B_1'\cos(3\phi_\perp - 2\phi_T) + B_2\cos 2\phi_T + B_2'\cos 2(2\phi_\perp - \phi_T)\Big]\Big\}, \end{aligned} \tag{10}$$

where $\mathcal{N}$ is a normalization factor, $\phi_\perp$ and ϕ_T denote the azimuthal angles of $\vec{K}_\perp$ and $\vec{q}_T$, respectively. The quantities A_i $(i = 0, 1, 2)$ are determined by the unpolarized TMD gluon distribution, $A_i \sim f_1^g$, while B_i $(i = 0, 1, 2)$ and $B'_{1,2}$ depend on the linearly polarized gluon density, $B_i^{(\prime)} \sim h_1^{\perp g}$.

We have recalculated the cross section for the reaction (1) and our results for A_i, B_i and $B_{1,2}^{(\prime)}$ do coincide with the corresponding ones presented in Ref. [4].[3] We have also observed that the expression (10) can be simplified essentially in the adopted approximation when $\vec{q}_T^{\,2} \ll \vec{K}_\perp^2$ and the outgoing heavy quark and anti-quark are almost back-to-back in the transverse plane [7].

To simplify Eq. (10), it is useful to introduce the sum and difference of magnitudes of the heavy quark transverse momenta,

$$\begin{aligned} &K = \frac{1}{2}\left(|\vec{p}_{Q\perp}| + |\vec{p}_{\bar{Q}\perp}|\right), && \vec{K}_\perp^2 = \frac{1}{4}(\Delta K)^2\sin^2\frac{\alpha}{2} + K^2\cos^2\frac{\alpha}{2}, \\ &\Delta K = |\vec{p}_{Q\perp}| - |\vec{p}_{\bar{Q}\perp}|, && \vec{q}_T^{\,2} = (\Delta K)^2\cos^2\frac{\alpha}{2} + 4K^2\sin^2\frac{\alpha}{2}, \end{aligned} \tag{11}$$

where $\alpha = \pi - (\varphi_Q - \varphi_{\bar{Q}})$ and φ_Q $(\varphi_{\bar{Q}})$ is the azimuth of the detected quark (anti-quark), see Fig. 1.

Note first that, at LO in α_s, the quantity ΔK is determined by the gluon transverse momentum in the target, i.e. $\Delta K \le |\vec{k}_T| \sim \Lambda_{\rm QCD}$ because $\vec{q}_T = \vec{k}_T$. Then remember that sizable values for the AAs are expected at $K \sim |\vec{p}_{Q\perp}| \gtrsim m$. In this kinematics (i.e. for $\Delta K/K \sim \Lambda_{\rm QCD}/m \ll 1$), the following relations between the azimuthal angles hold:

$$\begin{aligned} &\phi_\perp \simeq \frac{\varphi_Q + \varphi_{\bar{Q}}}{2} + \frac{\pi}{2} = \varphi_Q + \frac{\alpha}{2}, && \alpha = \pi - (\varphi_Q - \varphi_{\bar{Q}}), \\ &\phi_T \simeq \frac{\varphi_Q + \varphi_{\bar{Q}}}{2} = \varphi_Q + \frac{\alpha - \pi}{2}, && \phi_T \simeq \phi_\perp - \frac{\pi}{2}. \end{aligned} \tag{12}$$

Corrections to the approximate Eqs. (12) are of the order of $\mathcal{O}(\Delta K/K)$. Note also that $\Delta K/K \ll 1$ implies $|\vec{q}_T| \ll |\vec{K}_\perp|$ for $|\varphi_Q - \varphi_{\bar{Q}}| \sim \pi$ and vice versa.

[2] The TMD densities under consideration have to satisfy the positivity bound [2]: $\frac{\vec{k}_T^2}{2m_N^2}|h_1^{\perp g}(\zeta, \vec{k}_T^2)| \le f_1(\zeta, \vec{k}_T^2)$.

[3] The only exception is an evident misprint in Eq. (25) in Ref. [4]. Note also a typo in Eq. (19): instead of $\mathrm{d}y_i = \frac{\mathrm{d}z_i}{z_1 z_2}$ should be $\mathrm{d}y_i = \frac{\mathrm{d}z_i}{z_i}$.

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