Accessing the distribution of linearly polarized gluons in unpolarized hadrons

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Abstract. Gluons inside unpolarized hadrons can be linearly polarized provided they have a nonzero transverse momentum. The simplest and theoretically safest way to probe this distribution of linearly polarized gluons is through \( \cos^2 \phi \) asymmetries in heavy quark pair or dijet production in electron-hadron collisions. Future Electron-Ion Collider (EIC) or Large Hadron electron Collider (LHeC) experiments are ideally suited for this purpose. Here we estimate the maximum asymmetries for EIC kinematics.

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INTRODUCTION

Linearly polarized gluons in an unpolarized hadron, carrying a light-cone momentum fraction \( x \) and transverse momentum \( p_T \) w.r.t. to the parent’s momentum, are described by the transverse momentum dependent distribution (TMD) \( h_1^{\perp g}(x, p_T^2) \) [1, 2, 3]. Unlike the quark TMD \( h_1^{\perp q} \) of transversely polarized quarks inside an unpolarized hadron (also frequently referred to as Boer-Mulders function) [4], \( h_1^{\perp g} \) is chiral-even and \( T \)-even. This means it does not require initial or final state interactions (ISI/FSI) to be nonzero. Nevertheless, as any TMD, \( h_1^{\perp g} \) can receive contributions from ISI or FSI and therefore can be process dependent, in other words, non-universal, and its extraction can be hampered in nonfactorizing cases.

Thus far no experimental studies of \( h_1^{\perp g} \) have been performed. As recently pointed out, it is possible to obtain an extraction of \( h_1^{\perp g} \) in a simple and theoretically safe manner, since unlike \( h_1^{\perp q} \) it does not need to appear in pairs [3]. Here we will discuss observables that involve only a single \( h_1^{\perp g} \) in semi-inclusive DIS to two heavy quarks or to two jets, which allow for TMD factorization and hence a safe extraction. The corresponding

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AZIMUTHAL ASYMMETRIES

We first consider heavy quark (HQ) production, \( e(\ell) + h(P) \rightarrow e(\ell') + Q(K_1) + \bar{Q}(K_2) + X \), where the four-momenta of the particles are given within brackets, and the heavy quark-antiquark pair in the final state is almost back-to-back in the plane perpendicular to the direction of the exchanged photon and hadron. We look at the heavy quarks created in the photon-gluon fusion process, which can be distinguished kinematically from intrinsic charm production; e.g., from the \( Q\bar{Q} \) invariant mass distribution. The calculation proceeds along the lines explained in Refs. [2, 6]. We obtain for the cross section

\[
\frac{d\sigma}{dy_1 dy_2 dy d\phi dK_{\perp}} = \frac{\alpha^2 \alpha_s}{\pi s M_1^2} \frac{(1 + y_{x_B})}{y^5 x_B} \left( A + B q_T^2 \cos 2\phi \right) \delta(1 - z_1 - z_2). \tag{1}
\]

This expression involves the standard DIS variables: \( Q^2 = -q^2 \), where \( q \) is the momentum of the virtual photon, \( x_B = Q^2 / 2 P \cdot q, y = P \cdot q / P \cdot \ell \) and \( s = (\ell + P)^2 = 2 \ell \cdot P = 2 P \cdot q / y = Q^2 / x_B y \). Furthermore, we have for the HQ transverse momenta \( K_{1\perp}^2 = -K_{2\perp}^2 \) and introduced the rapidities \( y_i \) for the HQ momenta (along photon-target direction). We denote the proton mass with \( M \) and the heavy (anti)quark mass with \( M_Q \). For the partonic subprocess we have \( p + q = K_1 + K_2 \), implying \( z_1 + z_2 = 1 \), where \( z_i = P \cdot K_i / P \cdot q \). We introduced the sum and difference of the HQ transverse momenta, \( K_\perp = (K_{1\perp} - K_{2\perp}) / 2 \) and \( q_T = K_{1\perp} + K_{2\perp} \), considering \( |q_T| \ll |K_\perp| \). In that situation, we can use the approximate HQ transverse momenta \( K_{1\perp} \approx K_\perp \) and \( K_{2\perp} \approx -K_\perp \) denoting \( M_{1\perp}^2 \approx M_{2\perp}^2 = M_Q^2 + K_\perp^2 \). The azimuthal angles of \( q_T \) and \( K_\perp \) are denoted by \( \phi_T \) and \( \phi_\perp \) respectively, and \( \phi \equiv \phi_T - \phi_\perp \). The functions \( A \) and \( B \) depend on \( y, z(\equiv z_2), Q^2 / M_1^2, M_Q^2 / M_1^2, \) and \( q_T^2 \).

The angular independent part \( A \) is non negative and involves only the unpolarized TMD gluon distribution \( f_1^g \), \( A \equiv e_Q^2 f_1^g \left( x, q_T^2 \right) \cdot g_{e^g \rightarrow eQ\bar{Q}} \geq 0 \). We focus on the magnitude \( B \) of the \( \cos 2\phi \) asymmetry, which is determined by \( h_1^{1g} \). Namely,

\[
B = \frac{1}{M_T^2} e_Q^2 h_1^{1g}(x, q_T^2) \cdot g_{e^g \rightarrow eQ\bar{Q}}, \tag{2}
\]

with

\[
g_{e^g \rightarrow eQ\bar{Q}} = \frac{1}{2} \frac{z(1 - z)}{D^3} \left( 1 - \frac{M_Q^2}{M_\perp^2} \right) a(y) \left\{ [2z(1 - z) b(y) - 1] \frac{Q^2}{M_\perp^2} + 2 \frac{M_Q^2}{M_\perp^2} \right\}, \tag{3}
\]

\[
D \equiv D \left( z, Q^2 / M_1^2 \right) = 1 + z(1 - z) Q^2 / M_1^2, \quad a(y) = 2 - y(2 - y), \quad b(y) = [6 - y(6 - y)] / a(y).
\]

Since \( h_1^{1g} \) is completely unknown, we estimate the maximum asymmetry that is allowed by the bound

\[
|h_1^{1g}(1)(x)| \leq f_1^g(x), \tag{4}
\]
FIGURE 1. Upper bound of $|\langle \cos 2(\phi_T - \phi_\perp) \rangle|$ defined in Eq. (5) as a function of $|K_\perp|$ at different values of $Q^2$, with $y = 0.01$ and $z = 0.5$.

where the superscript (1) denotes the $n = 1$ transverse moment (defined as $f^{(n)}(x) \equiv \int d^2p_T \left( p_T^2/2M^2 \right)^n f(x, p_T^2)$). The function $R$, defined as the upper bound of the absolute value of $\langle \cos 2(\phi_T - \phi_\perp) \rangle$,

$$
|\langle \cos 2(\phi_T - \phi_\perp) \rangle| \equiv \left| \frac{\int d^2q_T \cos 2(\phi_T - \phi_\perp) d\sigma}{\int d^2q_T d\sigma} \right| = \frac{\int d^2q_T q_T^2 |B|}{2 \int d^2q_T^2 A} \leq \frac{|R_{eg\rightarrow eQ\bar{Q}}|}{|B_{eg\rightarrow eQ\bar{Q}}|} \equiv R,
$$

is depicted in Fig. 1 as a function of $|K_\perp|$ (> 1 GeV) at different values of $Q^2$ for charm (left panel) and bottom (right panel) production. We have selected $y = 0.01$, $z = 0.5$, and taken $M_c^2 = 2$ GeV$^2$, $M_b^2 = 25$ GeV$^2$. Such large asymmetries would probably allow an extraction of $h_1^\perp g$ at EIC (or LHeC).

If one keeps the lepton plane angle $\phi_L$, there are other azimuthal dependences, such as $\cos 2(\phi_T - \phi_L)$. The bound on $|\langle \cos 2(\phi_T - \phi_L) \rangle|$, denoted as $R'$, is shown in Fig. 2 in the same kinematic region as in Fig. 1. One can see that $R'$ can be larger than $R$, but only at smaller $|K_\perp|$. $R'$ falls off more rapidly at larger values of $|K_\perp|$ than $R$. We note that it is essential that the individual transverse momenta $K_{i\perp}$ are reconstructed with an accuracy $\delta K_{i\perp}$ better than the magnitude of the sum of the transverse momenta $K_{1\perp} + K_{2\perp} = q_T$. This means one has to satisfy $\delta K_{i\perp} \ll |q_T| \ll |K_\perp|$, which will require a minimum $|K_\perp|$.

The cross section for the process $eh \rightarrow e'J\bar{J}X$ can be calculated in a similar way and is analogous to Eq. (1). In particular, the explicit expression for $B$ can be obtained from the one for HQ production taking $M_Q = 0$, while $A$ now depends also on $x_b$ and receives a contribution from the subprocess $\gamma'q \rightarrow gq$ as well, not just from $\gamma'g \rightarrow q\bar{q}$. Therefore, the maximal asymmetries (not shown) are smaller than for HQ pair production.
**FIGURE 2.** Same as in Fig. 1, but for the upper bound $R'$ of $|\langle \cos 2(\phi_\ell - \phi_T) \rangle|$.

**CONCLUSIONS**

Studies of the azimuthal asymmetry of jet or heavy quark pair production in $e p$ collisions can directly probe $h_{1}^{g}$, the distribution of linearly polarized gluons inside unpolarized hadrons. Breaking of TMD factorization is expected in $p p$ or $p \bar{p}$ collisions, hence a comparison between extractions from these two types of processes would clearly signal the dependence on ISI/FSI. The contribution of $h_{1}^{g}$ to diphoton production has also been studied [7]. Since the proposed measurements are relatively simple (polarized beams are not required), we believe that the experimental determination of $h_{1}^{g}$ and the analysis of its potential process dependence will be feasible in the future.

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