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1 Probing the linear polarization of gluons in unpolarized hadrons at EIC

Daniël Boer[1], *Stanley J. Brodsky*[2], *Piet J. Mulders*[3], *Cristian Pisano*[4]

[1] *Theory Group, KVI, University of Groningen, The Netherlands*
[2] *SLAC National Accelerator Laboratory, Stanford University, USA*
[3] *Department of Physics and Astronomy, Vrije Universiteit Amsterdam, The Netherlands*
[4] *Dipartimento di Fisica, Università di Cagliari, and INFN, Sezione di Cagliari, Italy*

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 TMD distribution of linearly polarized gluons is through $\cos 2\phi$ asymmetries in heavy quark pair or dijet production in electron-hadron collisions. Future EIC or LHeC experiments are ideally suited for this purpose. Here we estimate the maximum asymmetries for EIC kinematics.

Linearly polarized gluons in an unpolarized hadron, carrying a light-cone momentum fraction x and transverse momentum $\boldsymbol{p}_T$ w.r.t. to the parent's momentum, are described by the TMD $h_1^{\perp\, g}(x, \boldsymbol{p}_T^2)$ [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 hadroproduction processes run into the problem of factorization breaking [5, 3].

We first consider heavy quark (HQ) production, $e(\ell)+h(P)\to e(\ell')+Q(K_1)+\bar{Q}(K_2)+X$, 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. The calculation proceeds along the lines explained in Refs. [2, 6]. We obtain for the cross section integrated over the angular distribution of the back-scattered electron $e(\ell')$:

$$\frac{d\sigma}{dy_1\, dy_2\, dy\, dx_B\, d^2\boldsymbol{q}_T\, d^2\boldsymbol{K}_\perp} = \frac{\alpha^2\alpha_s}{\pi s M_\perp^2}\,\frac{(1+yx_B)}{y^5 x_B}\left(A + \frac{\boldsymbol{q}_T^2}{M^2}\, B\, \cos 2\phi\right)\delta(1-z_1-z_2)\,. \quad (1)$$

This expression involves the standard DIS variables: $Q^2 = -q^2$, where q is the momentum of the virtual photon, $x_B = Q^2/2P\cdot q, y = P\cdot q/P\cdot \ell$ 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 $K_{i\perp}^2 = -\boldsymbol{K}_{i\perp}^2$ and introduced the rapidities y_i for the HQ momenta (along photon-target direction). We

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SLAC National Accelerator Laboratory, Menlo Park, CA 94025

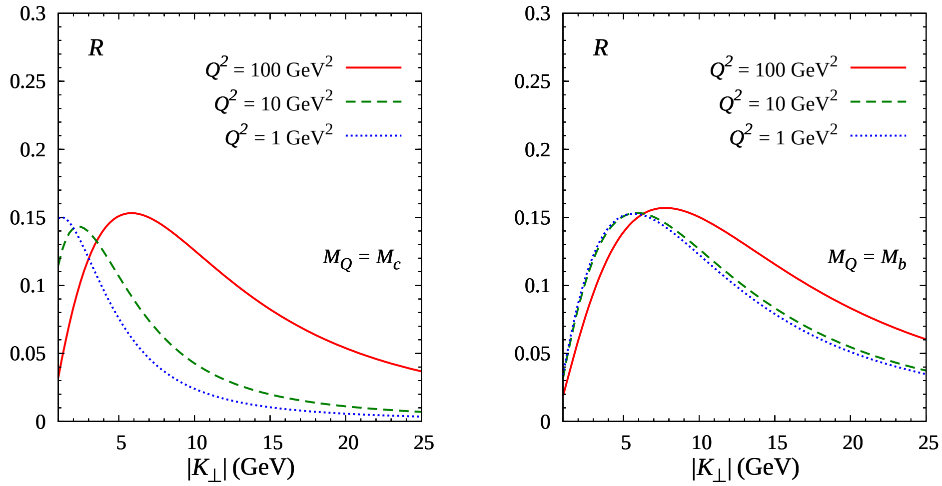

Figure 1: Upper bounds of the asymmetry ratio R in equation (3) as a function of $|\boldsymbol{K}_\perp|$ at different values of Q^2, with $y = 0.01$ and $z = 0.5$.

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 $M_{i\perp}^2 \approx M_\perp^2 = M_Q^2 + \boldsymbol{K}_\perp^2$. The azimuthal angles of $\boldsymbol{q}_T$ and $\boldsymbol{K}_\perp$ are denoted by ϕ_T and $\phi_\perp$ respectively, and $\phi \equiv \phi_T - \phi_\perp$. The functions A and B depend on $y, z(\equiv\ z_2), Q^2/M_\perp^2, M_Q^2/M_\perp^2$, and $\boldsymbol{q}_T^2$. The angular independent part A involves only the unpolarized TMD gluon distribution f_1^g, while the magnitude B of the $\cos 2\phi$ asymmetry is determined by $h_1^{\perp\,g}$. Since $h_1^{\perp\,g}$ is completely unknown, we estimate the maximum asymmetry that is allowed by the bound [3]

$$|h_1^{\perp\,g(2)}(x)| \leq \frac{\langle p_T^2 \rangle}{2M^2}\, f_1^g(x)\,, \tag{2}$$

where the superscript (2) denotes the $n = 2$ transverse moment (defined as $f^{(n)}(x) \equiv \int d^2\boldsymbol{p}_T\, \left(\boldsymbol{p}_T^2/2M^2\right)^n\, f(x, \boldsymbol{p}_T^2)$). The maximal (absolute) value of the asymmetry ratio

$$R = \left| \frac{\int d^2\boldsymbol{q}_T\, \boldsymbol{q}_T^2\, \cos 2(\phi_T - \phi_\perp)\, d\sigma}{\int d^2\boldsymbol{q}_T\, \boldsymbol{q}_T^2\, d\sigma} \right| = \frac{\int d\boldsymbol{q}_T^2\, \boldsymbol{q}_T^4\, |B|}{2M^2 \int d\boldsymbol{q}_T^2\, \boldsymbol{q}_T^2\, A} \tag{3}$$

is depicted in figure 1 as a function of $|\boldsymbol{K}_\perp|$ (> 1 GeV) at different values of Q^2 for charm (left panel) and bottom (right panel) production, where 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, together with the relative simplicity of the suggested measurement (polarized beams are not required), would probably allow an extraction of $h_1^{\perp\,g}$ at EIC (or LHeC).

If one keeps the lepton plane angle ϕ_ℓ, there are other azimuthal dependences, such as a $\cos 2(\phi_\ell - \phi_T)$. The bound on its asymmetry ratio R' is shown in figure 2 in the same kinematic region as in figure 1. One can see that R' can be larger than R, but only at smaller $|\boldsymbol{K}_\perp|$. R' falls off more rapidly at larger values of $|\boldsymbol{K}_\perp|$ than R. We note that it is essential that the individual transverse momenta $K_{i\perp}$ are reconstructed with an accuracy

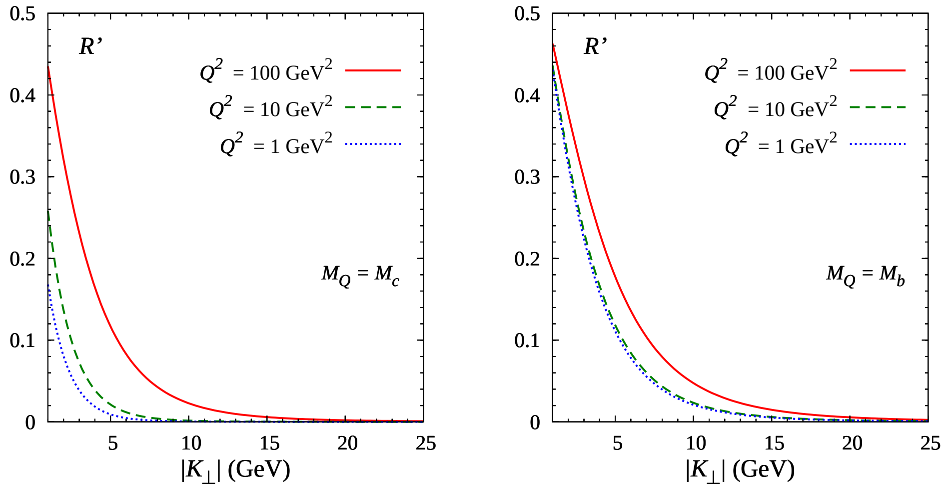

Figure 2: Same as in figure 1, but for the upper bounds of the $\cos 2(\phi_\ell - \phi_T)$ asymmetry.

$\delta K_\perp$ 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 $\delta K_\perp \ll |q_T| \ll |K_\perp|$, which will require a minimum $|K_\perp|$.

The cross section for the process $e\,h \to e'\,\text{jet}\,\text{jet}\,X$ can be calculated in a similar way and is analogous to equation (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 $\gamma^* q \to gq$ as well, not just from $\gamma^* g \to q\bar{q}$. Therefore, the maximal asymmetries (not shown) are smaller than for HQ pair production.

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