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Azimuthal asymmetry in semi-inclusive deep inelastic scattering off nuclei as probe for $\hat{q}$

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The energy loss parameter $\hat{q}$ is one of the fundamental transport parameters of hadronic matter. Using the twist-4 collinear approach, we show that the $\cos\phi$ azimuthal asymmetry in unpolarized semi-inclusive deeply inelastic scattering off a large nucleus at intermediate transverse momentum is a sensitive observable for its determination. The effect is due to the suppression of the azimuthal asymmetry by final-state multiple scattering.

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I. INTRODUCTION

The detailed understanding of the properties of hot and cold nuclear matter, as described by its transport parameters, is one of the topical problems of QCD, in particular, in connection with high-energy heavy-ion experiments at RHIC and LHC. As deeply inelastic scattering (DIS) is one of the theoretically cleanest processes in QCD, it is tempting to use this probe to determine some of them. We argue that this is indeed possible for the transport parameter $\hat{q}$ if one focuses on transverse–momentum-dependent observables which are especially sensitive to transverse momentum broadening while partons travel through hadronic matter. The transverse momentum broadening effect arises from final-state multiple parton interactions, which are enhanced in nuclear matter. Quite a number of different theoretical approaches have been formulated to describe this phenomenon [1–9] and a variety of precise experimental observations will be needed to decide which of these formulations are incorrect and which are equivalent. One common parameter appearing in all of these approaches is the parton transport parameter $\hat{q}$ which controls parton energy loss or transverse momentum broadening squared per unit of propagation length [1]. Therefore, the calculation and measurement of this transport parameter is an important step toward understanding the intrinsic properties of nuclear matter, both cold and hot.

The multiple parton rescattering in a large nucleus not only leads to energy loss and transverse momentum broadening but also to other nuclear effects, for example, the $\cos\phi$ and $\cos 2\phi$ azimuthal asymmetries of unpolarized semi-inclusive DIS cross sections. In Ref. [10], it was shown that the existence of intrinsic transverse parton momenta in the unpolarized distribution and fragmentation functions can generate such modulations at low transverse momentum. Later, Cahn–effect-based descriptions of azimuthal asymmetries were formulated in terms of twist-2 and twist-3 transverse–momentum-dependent parton distributions (TMDs) [11–14]. At large transverse momentum, such asymmetries result primarily from hard gluon radiation [15] which can be calculated in the framework of collinear factorization. Similar processes are also responsible for the azimuthal angle dependence of Drell-Yan dilepton production [16,17]. In the intermediate transverse momentum region, $\Lambda_{QCD} \ll P_\perp \ll Q$, both, collinear factorization and transverse–momentum-dependent factorization are supposed to apply [18]. Indeed, in this special kinematic region, the match between leading-power TMD factorization and collinear factorization has been made explicit for the $\cos 2\phi$ asymmetry of the Drell-Yan lepton pair angular distribution in [19,20]. In contrast however, it is known already since a while that this equivalence does not extend to subleading power TMD factorization which suffers from severe problems [13,21] and yields results different from that calculated in collinear factorization at intermediate transverse momentum [22].

Azimuthal asymmetries in semi-inclusive deeply inelastic scattering (SIDIS) off nuclei are affected by final-state interactions and thus provide an alternative way to study properties of the nuclear medium. In fact, the nuclear dependence of the angular distribution of Drell-Yan lepton pairs has been calculated both in the small x and intermediate x region, using the collinear twist-4 formalism [23] and the color glass condensate model [24]. Nuclear-dependent azimuthal asymmetries in SIDIS have also been investigated recently based on TMD factorization [25,26]. The central ingredient of the treatment in Ref. [25] is the relation between the nucleon twist-3 TMDs and the nuclear ones. In this paper, we extend that earlier work to a kinematic region of relatively large transverse momenta where the process can be treated within perturbative QCD. To be more specific, we use the collinear twist-4 approach to calculate the nuclear dependence of the $\cos\phi$ azimuthal asymmetry in SIDIS at intermediate transverse momentum $\Lambda_{\rm QCD} \ll P_{J\perp} \ll Q$, where $P_{J\perp}$ is the final-state jet transverse momentum, and Q is the virtual photon momentum. We restrict ourselves to intermediate transverse momentum and the current fragmentation region because here the calculation can be significantly simplified with the help of general power-counting rules valid in light-cone gauge [27,28] as we will demonstrate in the subsequent section. As a result of our explicit calculation, we will show that the nuclear-dependent part of the asymmetry in this specific kinematic region is directly proportional to the parton transverse momentum broadening in a nucleus.

II. AZIMUTHAL ASYMMETRY IN SIDIS OFF NUCLEUS

The parton model cross section for the unpolarized semi-inclusive DIS process $e(l) + p/A(P) \to e(l') + J(P_J) + X$ takes the general form [13,29],

$$\frac{d\sigma}{dx_B dz dy d^2P_{J\perp}} = \frac{4\pi\alpha_{em}^2 s}{Q^4}\bigg\{\Big(1 - y + \frac{y^2}{2}\Big)F_T + (1-y)F_L + (2-y)\sqrt{1-y}\cos\phi_J F_{\cos\phi_J} + (1-y)\cos(2\phi_J)F_{\cos 2\phi_J}\bigg\} \quad (1)$$

where we use the conventions of Ref. [13]. We define $q = l - l'$ as the virtual photon momentum and its virtuality as $Q^2 = -q^2$, while $x_B = Q^2/2P\cdot q$, $z = P\cdot P_J/P\cdot q$, and $y = P\cdot q/P\cdot l$ are the common DIS variables. The azimuthal angle between the transverse momentum of the outgoing parton $P_{J\perp}$ and the leptonic plane is denoted by ϕ_J. Four structure functions F, depending on x_B, Q^2, z (the fraction of the photon energy carried by the jet) and $P_{J\perp}$, encode the QCD structure of the target and the dynamics of the partonic subprocess. It is convenient to use light-cone coordinates for which $P^\mu = P^+ p^\mu$, $q^\mu = -x_B p^\mu + n^\mu Q^2/(2x_B P^+)$ with $p = (1,0,0,1)/\sqrt{2}$ and $n = (1,0,0,-1)/\sqrt{2}$. At large $P_{J\perp}$, the four functions F can be calculated in collinear twist-2 factorization. As stated above, we restrict ourself to the asymmetry at intermediate transverse momentum $\Lambda_{\rm QCD} \ll P_{J\perp} \ll Q$ in the current fragmentation region where power-counting rules can be applied. In this kinematic region, the power behavior of F_T, F_L, $F_{\cos\phi_J}$, and $F_{\cos 2\phi_J}$ is $1/P_{J\perp}^2$, $1/Q^2$, $1/QP_{J\perp}$, $1/Q^2$, respectively. The $\cos\phi$ asymmetry is determined by the ratio between the functions $F_{UU}^{\cos\phi_J}$ and $F_{UU,T}$, which read [15,22],

$$F_T^{\rm LP} = \frac{1}{P_{J\perp}^2}\frac{\alpha_s C_F}{2\pi^2}\sum_\alpha x_B e_\alpha^2\Big[2\ln\frac{Q^2}{P_{J\perp}^2}\delta(1-z) + \frac{1+z^2}{(1-z)_+}\Big] \times f_1^\alpha(x_B),$$

$$F_{\cos\phi_J}^{\rm LP} = \frac{-1}{zP_{J\perp}Q}\frac{\alpha_s C_F}{2\pi^2}\sum_\alpha x_B e_\alpha^2\Big[2\ln\frac{Q^2}{P_{J\perp}^2}\delta(1-z) + \frac{2z^2}{(1-z)_+}\Big] \times f_1^\alpha(x_B) \quad (2)$$

where $f_1(x)$ is the normal leading-power collinear parton distribution and "LP" denotes the leading-power contribution from $f_1(x)$. The index α runs over flavors of quarks and antiquarks with fractional charge e_α. To extract the nuclear effect we are interested in, one has to go beyond the leading twist treatment and take into account twist-4 contributions.

The machinery of collinear higher-twist factorization was pioneered already in the early 1980s [30], and later frequently applied in hadron spin physics [31] and nuclear physics [3,23,32]. The higher-twist collinear approach has been well established in both the covariant and the light-cone gauge. In order to better classify the contributions according to power-counting rules, we carry our calculation out in the light-cone gauge with retarded boundary conditions. For retarded boundary conditions, certain collinear twist-4 correlators can be directly related to the moment of corresponding TMD distributions.

Following the standard procedure, the higher-twist contributions can be systematically isolated by expanding the hard part in the parton intrinsic transverse momentum and including the diagrams with transverse polarized gluon exchange between the struck parton and the target remnant. At twist-4 level, the correlators associated with these two types of contributions are of the form $\langle\bar\psi\partial_\perp\partial_\perp\psi\rangle$, $\langle\bar\psi\partial_\perp A_\perp\psi\rangle$, and $\langle\bar\psi A_\perp A_\perp\psi\rangle$. The general power-counting rule [27,28] states that the diagrams with one additional transversely polarized gluon exchange are suppressed by one additional power of $\Lambda_{\rm QCD}/Q$ in the current fragmentation region where $P_{J\perp} \ll Q$, as long as final-state interactions at $y^- = +\infty$ have been removed by imposing retarded boundary conditions [33]. Therefore, the possible leading powers of the corresponding hard parts convoluted with the correlators $\langle\bar\psi\partial_\perp\partial_\perp\psi\rangle$, $\langle\bar\psi\partial_\perp A_\perp\psi\rangle$, and $\langle\bar\psi A_\perp A_\perp\psi\rangle$ are suppressed by the powers of $\Lambda_{\rm QCD}^2/P_{J\perp}^2$, $\Lambda_{\rm QCD}^2/QP_{J\perp}$, and $\Lambda_{\rm QCD}^2/Q^2$, respectively. The explicit calculation shows that the leading-power contribution from $\langle\bar\psi\partial_\perp\partial_\perp\psi\rangle$ drops out in the azimuthal–angle-dependent cross section such that its subleading part $\Lambda_{\rm QCD}^2/QP_{J\perp}$ generates the nonvanishing $\cos\phi$ asymmetry. The hard part associated with the correlator $\langle\bar\psi\partial_\perp A_\perp\psi\rangle$ contributes to the $\cos\phi$ asymmetry with the same power $\Lambda_{\rm QCD}^2/QP_{J\perp}$. As a result, we can eventually neglect all diagrams with two transversely polarized gluon exchanges and are left with the contributions from the correlators of the first two types.

To be more specific, the following three twist-4 collinear correlators enter the calculation,

$$\begin{aligned} ff_1(x) &= \int \frac{dy^-}{4\pi} e^{ixP^+y^-} \langle P|\bar{\psi}(0)\gamma^+(-i\partial_{\perp\rho})(-i\partial_{\perp\sigma})\psi(y)|P\rangle d^{\rho\sigma}, \\ \varphi_\perp(x) &= \int \frac{dy^-}{4\pi} e^{ixP^+y^-} \langle P|\bar{\psi}(0)\gamma^+(-i\partial_{\perp\rho})D_{\perp\sigma}(y)\psi(y)|P\rangle d^{\rho\sigma}, \\ \tilde{\varphi}_\perp(x) &= \int \frac{dy^-}{4\pi} e^{ixP^+y^-} \langle P|\bar{\psi}(0)\gamma^5\gamma^+(-i\partial_{\perp\rho})D_{\perp\sigma}(y)\psi(y)|P\rangle d^{\rho\sigma} \end{aligned} \tag{3}$$

where $D_\rho = -i\partial_\rho + A_\rho$ and $d^{\rho\sigma} = -g^{\rho\sigma} + (p^\rho n^\sigma + p^\sigma n^\rho)/p\cdot n$. Since the gauge is completely fixed by choosing retarded boundary conditions in the light-cone gauge, all three correlators can be uniquely brought into a gauge-invariant form. The nuclear dependence has been encoded in the above twist-4 matrix elements. It will become evident when we relate them to the relevant moment of the corresponding nuclear TMDs. The perturbative calculation of the hard coefficients associated with these twist-4 correlators is straightforward. The functions F_T and $F_{\cos\phi_J}$ can thus be expressed as convolutions of the hard coefficients and the twist-4 correlators given above. At small transverse momentum $P_{J\perp} \ll Q$, the results take a remarkably simple form,

$$F_T^{\text{twist-4}} = \frac{1}{P_{J\perp}^2}\frac{\alpha_s C_F}{2\pi^2}\sum_\alpha x_B e_\alpha^2\left\{\left[2\ln\frac{Q^2}{P_{J\perp}^2}\delta(1-z) + \frac{1+z^2}{(1-z)_+}\right] \times f_1^\alpha(x_B) + \frac{z^2(1+z^2)}{(1-z)_+}\frac{1}{P_{J\perp}^2} ff_1^\alpha(x_B)\right\}, \tag{4}$$

$$F_{\cos\phi_J}^{\text{twist-4}} = \frac{-1}{zP_{J\perp}Q}\frac{\alpha_s C_F}{2\pi^2}\sum_\alpha x_B e_\alpha^2\left\{\left[2\ln\frac{Q^2}{P_{J\perp}^2}\delta(1-z) + \frac{2z^2}{(1-z)_+}\right] f_1^\alpha(x_B) + \frac{2z^2(1+z^2)}{(1-z)_+}\frac{1}{P_{J\perp}^2} \times[-\mathrm{Re}\varphi_\perp^\alpha(x_B) + \mathrm{Im}\tilde{\varphi}_\perp^\alpha(x_B)]\right\}. \tag{5}$$

Using the QCD equation of motion, one obtains the relation

$$-\mathrm{Re}\varphi_\perp(x) + \mathrm{Im}\tilde{\varphi}_\perp(x) = xff_\perp(x) \tag{6}$$

where

$$ff_\perp(x) = \int \frac{dy^-}{4\pi} e^{ixP^+y^-} \langle P|\bar{\psi}(0)(-i\not{\partial}_\perp)\psi(y)|P\rangle. \tag{7}$$

One should note that the calculations just discussed apply to SIDIS of both nuclear and nucleon targets. All results have the same form and differ only in that the collinear correlators are taken inside of a nucleus or a nucleon. In this paper, we only focus on the leading nuclear-dependent effect which is proportional to the length of propagation in the nuclear medium and assume $f_1^A = Af_1^N$. The leading nuclear dependence of the azimuthal angle asymmetry is thus generated by the nuclear dependence of the collinear twist-4 correlators, which can be best seen from the following relations between the twist-4 correlators and the moments of TMDs with retarded boundary conditions,

$$ff_1(x) = \int d^2k_\perp k_\perp^2 f_1(x, k_\perp), \tag{8}$$

$$ff_\perp(x) = \int d^2k_\perp k_\perp^2 f_\perp(x, k_\perp) \tag{9}$$

here, $f_1(x)$ and $f_\perp$ are the normal leading-twist TMD quark distribution and twist-3 TMD distribution, respectively. Note that the above relations are only valid for naive definition of TMDs. Their matrix element definitions are given by

$$f_1(x, k_\perp) = \int \frac{dy^- d^2\vec{y}_\perp}{2(2\pi)^3} e^{ix_B P^+y^- + ik_\perp\cdot y_\perp} \times \langle P|\bar{\psi}(0)\gamma^+\mathcal{L}(0,y)\psi(y)|P\rangle, \tag{10}$$

$$f_\perp(x, k_\perp) = \int \frac{dy^- d^2\vec{y}_\perp}{2(2\pi)^3} e^{ix_B P^+y^- + ik_\perp\cdot y_\perp} \times \frac{k_\perp^\rho}{k_\perp^2}\langle P|\bar{\psi}(0)\gamma_{\perp\rho}\mathcal{L}(0,y)\psi(y)|P\rangle. \tag{11}$$

For retarded boundary conditions, the transverse gauge links appearing in the above matrix elements become unity. The nuclear dependence of the TMD distributions $f_1(x, k_\perp)$ and $f_\perp(x, k_\perp)$ have been worked out and given by [25,34]

$$f_1^A(x, k_\perp) \approx \frac{A}{\pi\Delta_{2F}}\int d^2\ell_\perp e^{-(\vec{k}_\perp - \vec{\ell}_\perp)^2/\Delta_{2F}} f_1^N(x, \ell_\perp), \tag{12}$$

$$f_\perp^A(x, k_\perp) \approx \frac{A}{\pi\Delta_{2F}}\int d^2\ell_\perp \frac{(\vec{k}_\perp\cdot\vec{\ell}_\perp)}{\vec{k}_\perp^2} e^{-(\vec{k}_\perp - \vec{\ell}_\perp)^2/\Delta_{2F}} f_\perp^N(x, \ell_\perp) \tag{13}$$

where $\Delta_{2F} = \int d\xi^- \hat{q}(\xi)$ with the quark energy loss transport coefficient $\hat{q}$, which controls parton energy loss in a cold nuclear medium and transverse momentum broadening squared per unit of propagation length. The superscripts "A" and "N" denote the nuclear and nucleon TMDs, respectively. Using the relations between nucleon TMDs and nuclear TMDs, we find

$$\int k_\perp^2 f_\perp^A(x, k_\perp) d^2k_\perp - A \int k_\perp^2 f_\perp^N(x, k_\perp) d^2k_\perp = 0, \quad (14)$$

$$\int k_\perp^2 f_1^A(x,k_\perp) d^2k_\perp - A \int k_\perp^2 f_1^N(x,k_\perp) d^2k_\perp = A f_1^N(x) \Delta_{2F} \quad (15)$$

where $f_1^N(x)$ is the ordinary integrated parton distribution function of the nucleon. From the above two identities, we can conclude that the difference of the $\cos\phi_J$ azimuthal asymmetries is proportional to the amount of transverse momentum broadening. More precisely, when $z \neq 1$, one has

$$\begin{aligned} &\langle \cos\phi_J \rangle_{eA} - \langle \cos\phi_J \rangle_{eA} \\ &= \frac{(2-y)\sqrt{1-y}}{1-y+y^2/2} \left(\frac{F_{\cos\phi_J}^{\text{twist-4}}}{F_T^{\text{twist-4}}} \bigg|_{eA} - \frac{F_{\cos\phi_J}^{\text{twist-4}}}{F_T^{\text{twist-4}}} \bigg|_{eN} \right) \\ &\approx \frac{(2-y)\sqrt{1-y}}{1-y+y^2/2} \frac{2z^3}{1+z^2} \frac{\Delta_{2F}}{P_{J\perp} Q}. \end{aligned} \quad (16)$$

In the second step, we have assumed $f_1^A = A f_1^N$ and neglect all terms suppressed by powers of $\Lambda_{\rm QCD}/P_{J\perp}$. This is the main result of this paper, which is valid at intermediate transverse momentum $\Lambda_{\rm QCD} \ll P_{J\perp} \ll Q$. Equation (16) provides a direct handle to extract the crucial parameter $\hat{q}$ from measurements of the azimuthal asymmetry in nuclei and nucleons.

Let us stress at this point that azimuthal asymmetries are not the only quantities which are sensitive to $\hat{q}$. Basically all quantities which depend on transverse momentum are affected by $k_\perp$ broadening in nuclear matter. However, in practice the relationship between $\hat{q}$ and observables will be substantially affected by many corrections: the finite size of nuclei, inhomogenities in density and other fluctuations, differences in the string breaking mechanisms in hadronization between pA and pp collisions, etc. Therefore, one will need as many different observables as possible to correct for such effects and to extract $\hat{q}$ reliably. In this contribution, we argue that azimuthal asymmetries form an additional class of such signals. In fact, it might be an especially interesting one (though probably also one which is hard to measure) because we expect that $\cos\phi$ asymmetries are rather insensitive to the potential differences in transverse momentum modifications induced by string breaking in nuclear and hadron systems.

III. SUMMARY

In summary, we calculated the $\cos\phi$ azimuthal asymmetry in semi-inclusive DIS off a nuclear target within the collinear twist-4 approach. At intermediate transverse momentum, the nuclear dependence of the azimuthal asymmetry is linked to the $k_\perp^2$-moment of the two relevant quark TMD distributions. The difference between nucleon TMDs and nuclear TMDs is generated by final-state interactions, such that the difference in the azimuthal asymmetries is sensitive to their strength. To be more specific, the difference between the $\cos\phi$ azimuthal asymmetries in SIDIS off nucleons and nuclei is proportional to the transverse momentum broadening in the latter. Therefore, it provides an alternative way to pin down the transport parameter $\hat{q}$ by measuring the nuclear dependence of the asymmetry at intermediate transverse momentum.

The approach we developed in this paper can be extended to study the nuclear dependence of azimuthal asymmetries in other processes, such as direct photon production in SIDIS off nuclei and Drell-Yan lepton pair production in high-energy pA scattering.

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