Azimuthal asymmetries as the probe of nuclear matter at EIC

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We study the nuclear dependence of transverse-momentum-dependent (TMD) parton distribution functions (PDFs) and azimuthal asymmetries in semi-inclusive DIS off polarized nuclear targets. Multiple gluon interactions which generate gauge links in the operator definitions of PDFs also induce nuclear effects. The general Gaussian-type broadening effects on TMD PDFs suppress azimuthal asymmetries for eA SIDIS relative to that of eN case, with suppression factors expressed by the jet transport coefficient $\hat{q}$. We study nuclear effects on various azimuthal asymmetries, and calculate the suppression factor with $\hat{q}$ extracted from literature. The numeric results will be helpful for the experimental study of nuclear partonic structure from Semi-inclusive DIS at future EIC.
1. Azimuthal asymmetries of semi-inclusive DIS

Semi-inclusive deeply inelastic scattering (SIDIS) provides a good place to study partonic structure of nucleon/nucleus, especially the transverse-momentum-dependent parton distribution functions (TMD PDFs). Azimuthal asymmetries of semi-inclusive DIS are nice probes to various TMD PDFs involved with different spin and transverse momentum correlations. We have employed collinear expansion [1, 2, 3] to calculate the cross section and azimuthal asymmetries of semi-inclusive DIS [4, 5, 6]. For the process $e^-(l, s_f) + N(p, s) \rightarrow e^-(l') + q(k) + X$, the differential cross section reads,

$$\frac{d\sigma}{dx_Bdyd^2k_\perp} = \frac{2\pi\alpha_{\text{em}}^2 q^2}{Q^2y} (W_{UU} + \lambda_1 W_{LU} + s_1 W_{UT} + \lambda W_{UL} + \lambda_1 \lambda W_{LL} + \lambda_1 s_1 W_{LT}),$$  \hspace{1cm} (1.1)

where $x_B$ the Bjorken variable, $y = \frac{p}{p}\,$ and $Q^2 = -q^2 = -(l-l')^2$. The structure functions $W_{UU}$'s represent contributions from different TMD PDFs with unpolarized, longitudinal-polarized and transversely-polarized beam/target. Each structure function contains contributions from different TMD PDFs. For example,

$$W_{UU} = A(y)f_1(x_B, k_\perp) - \frac{2x_B|\vec k_\perp|}{Q} B(y)f^+(x_B, k_\perp) \cos \phi,$$  \hspace{1cm} (1.2)

$$W_{LU} = -\frac{2x_B|\vec k_\perp|}{Q} D(y)g^+(x_B, k_\perp) \sin \phi,$$  \hspace{1cm} (1.3)

$$W_{UL} = -\frac{2x_B|\vec k_\perp|}{Q} B(y)f_1(x_B, k_\perp) \sin \phi,$$  \hspace{1cm} (1.4)

where $A(y) = 1 + (1-y)^2$, $B(y) = 2(2-y)\sqrt{T-\gamma}$ and $D(y) = 2y\sqrt{T-\gamma}$. For other structure functions see [6]. The TMD PDFs involved has the following operator definitions,

$$f_1(x_B, k_\perp) = \int \frac{dy^-}{4\pi} e^{ip^-y^- - i\vec k_\perp \cdot \vec y^-} \langle N|\bar \psi(0)\gamma^\perp \mathcal{L}'(0;y)\psi(y)|N\rangle,$$  \hspace{1cm} (1.5)

$$f^+(x_B, k_\perp) = \frac{1}{k_\perp^2} \int \frac{p^+dy^-}{4\pi} e^{ip^+y^- - i\vec k_\perp \cdot \vec y^-} \langle N|\bar \psi(0)\gamma_\perp \mathcal{L}'(0;y)\psi(y)|N\rangle,$$  \hspace{1cm} (1.6)

$$f_1^+(x_B, k_\perp) = \frac{1}{k_\perp^2} \int \frac{p^+dy^-}{4\pi} e^{ip^+y^- - i\vec k_\perp \cdot \vec y^-} \langle N,|\bar \psi(0)\epsilon_{\perp i}k_\perp^i \gamma_\perp \mathcal{L}'(0;y)\psi(y)|N,\rangle,$$  \hspace{1cm} (1.7)

$$g^+(x_B, k_\perp) = \frac{1}{k_\perp^2} \int \frac{p^+dy^-}{4\pi} e^{ip^+y^- - i\vec k_\perp \cdot \vec y^-} \langle N,|\bar \psi(0)\epsilon_{\perp i}k_\perp^i \gamma_\perp \mathcal{L}'(0;y)\psi(y)|N,\rangle,$$  \hspace{1cm} (1.8)

where $\mathcal{L}'(0;y)$ is generated by multiple gluon interactions of semi-inclusive DIS, and the existence of $\mathcal{L}'(0;y)$ guarantees the gauge invariance of the operator definitions.

With cross section for semi-inclusive DIS, we can obtain various azimuthal asymmetries. For example,

$$\langle \sin \phi \rangle_{LU} = \frac{\lambda_1}{Q} \frac{|\vec k_\perp|}{A(y)} \frac{B(y)x_B f_1^+(x_B, k_\perp)}{f_1(x_B, k_\perp)},$$  \hspace{1cm} (1.9)

$$\langle \sin \phi \rangle_{UL} = \frac{\lambda_1}{Q} \frac{|\vec k_\perp|}{A(y)} \frac{B(y)x_B f_1(x_B, k_\perp)}{f_1(x_B, k_\perp)},$$  \hspace{1cm} (1.10)
By measuring these azimuthal asymmetries we can study various corresponding TMD PDFs. The factor $\frac{1}{Q}$ shows that above 2 asymmetries come from twist-3 contributions. Above formulae work equally well for both nucleon and nucleus target.

2. Nuclear dependences

The TMD PDFs contain the information of multiple gluon interactions between the struck quark and the remnant of the target. Gauge link can be naturally derived by this method with correct direction to $\pm \infty$ for SIDIS and $-\infty$ for Drell-Yan. Multiple gluon interactions also lead to nuclear $k_T$—broadening of TMD quark distributions. For a loosely bounded large nucleus, the quark-quark correlation matrix, 

$$\Phi^A(x, k_\perp) \equiv \int \frac{d^4y}{(2\pi)^3} e^{i p \cdot y} e^{-\vec{k}_\perp \cdot \vec{y}} \langle A|\bar{\psi}(0)\Gamma\alpha\mathcal{L}(0; y)\psi(y)|A\rangle,$$  

(2.1)

has a Gaussian broadening with respect to nucleon [7, 8],

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

(2.2)

where $\Delta_{2F} = \int d\xi_1^N f_{q_f}(\xi_1^N)$ is just a line integral of the quark transport coefficient of the nucleus medium. We can extract the nuclear broadening of nuclear TMD PDFs [9], for example,

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

(2.3)

$$k_1^2 g_1^A(x, k_\perp) \approx \frac{A}{\pi\Delta_{2F}} \int d^2\ell_\perp e^{-\vec{k}_\perp \cdot \vec{\ell}_\perp}/\Delta_{2F} (k_\perp \cdot \ell_\perp) g_1^N(x, \ell_\perp),$$  

(2.4)

$$k_1^2 f_1^A(x, k_\perp) \approx \frac{2F_A}{\pi\Delta_{2F}} \int d^2\ell_\perp e^{-\vec{k}_\perp \cdot \vec{\ell}_\perp}/\Delta_{2F} (k_\perp \cdot \ell_\perp) f_1^N(x, \ell_\perp).$$  

(2.5)

To estimate the numerical size we take Gaussian ansatz for $k_T$—distribution for and take identical width $\alpha$ for all TMD PDFs. The ratio of the azimuthal asymmetries of the nucleus/nucleon involved semi-inclusive DIS are thus given by,

$$\frac{\langle \cos \phi \rangle^A_{UL}}{\langle \cos \phi \rangle^A_{UL}} \approx \frac{\alpha}{\alpha + \Delta_{2F}};$$  

(2.6)

$$\frac{\langle \cos \phi \rangle^A_{UL}}{\langle \cos \phi \rangle^N_{UL}} \approx \frac{2F_A}{A} \frac{\alpha}{\alpha + \Delta_{2F}};$$  

(2.7)

The factor $f_s = \frac{\alpha}{\alpha + \Delta_{2F}}$ is key to the nuclear suppression, and we estimate its value by adopting $\alpha$ and $\hat{q}$ values from literature [10, 11, 12]. The explicit dependence on $A$ is given by [9],

$$f_s \approx \frac{1}{1 + 0.114 A^{1/3}}.$$  

(2.8)

The plot of this formula and fit to $k_T$—broadening are shown in the following figure.
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Figure 1: Nuclear $k_T$–broadening (upper panel) and nuclear suppression factor $f_s$ for azimuthal asymmetries [9].

3. Conclusion

We employ collinear expansion to study the azimuthal asymmetries and their nuclear dependences for semi-inclusive DIS. The Gaussian broadening effects generally suppress the asymmetries, and the suppression factor can be quantitatively estimated with reliable input for $k_T$ width and jet transport coefficient from literature. Azimuthal asymmetries show good potential as a new probe of the properties of nuclear medium. This will be a nice topic on future electron-ion collider (EIC).

References


