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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.

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1. Azimuthal asymmetris 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 with defferent 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 $e^-(l,s_l)+N(p,s)\to e^-(l')+q(k)+X$, the differential cross section reads,

$$\frac{d\sigma}{dx_B dy d^2k_\perp}=\frac{2\pi\alpha_{\rm em}^2 e_q^2}{Q^2 y}\left(W_{UU}+\lambda_l W_{LU}+s_\perp W_{UT}+\lambda W_{UL}+\lambda_l\lambda W_{LL}+\lambda_l s_\perp W_{LT}\right), \tag{1.1}$$

where x_B the Bjorken variable, $y=\frac{p\cdot q}{p\cdot k}$ and $Q^2=-q^2=-(l-l')^2$. The structure functions $W_{s_l s}$'s represent contributions in different polarization cases with U,L,T standing for unpolarized, longitudinal-polarized and transversely-polarized beam/target. Each structure function contain contributions from different TMD PDFs. For example,

$$W_{UU}=A(y)f_1(x_B,k_\perp)-\frac{2x_B|\vec{k}_\perp|}{Q}B(y)f^\perp(x,k_\perp)\cos\phi, \tag{1.2}$$

$$W_{LU}=-\frac{2x_B|\vec{k}_\perp|}{Q}D(y)g^\perp(x_B,k_\perp)\sin\phi, \tag{1.3}$$

$$W_{UL}=-\frac{2x_B|\vec{k}_\perp|}{Q}B(y)f_L^\perp(x_B,k_\perp)\sin\phi, \tag{1.4}$$

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

$$f_1(x,k_\perp)=\int\frac{dy^-}{4\pi}e^{ixp^+y^- -i\vec{k}_\perp\cdot\vec{y}_\perp}\langle N|\bar\psi(0)\gamma^+\mathscr{L}(0;y)\psi(y)|N\rangle, \tag{1.5}$$

$$f^\perp(x,k_\perp)=\frac{1}{k_\perp^2}\int\frac{p^+dy^-}{4\pi}e^{ixp^+y^- -i\vec{k}_\perp\cdot\vec{y}_\perp}\langle N|\bar\psi(0)\not{k}_\perp\mathscr{L}(0;y)\psi(y)|N\rangle, \tag{1.6}$$

$$f_L^\perp(x,k_\perp)=\frac{1}{k_\perp^2}\int\frac{p^+dy^-}{4\pi}e^{ixp^+y^- -i\vec{k}_\perp\cdot\vec{y}_\perp}\langle N,+|\bar\psi(0)\varepsilon_{\perp ij}k_\perp^i\gamma_\perp^j\mathscr{L}(0;y)\psi(y)|N,+\rangle, \tag{1.7}$$

$$g^\perp(x,k_\perp)=\frac{1}{k_\perp^2}\int\frac{p^+dy^-}{4\pi}e^{ixp^+y^- -i\vec{k}_\perp\cdot\vec{y}_\perp}\langle N,+|\bar\psi(0)\varepsilon_{\perp ij}k_\perp^i\gamma_\perp^j\gamma_5\mathscr{L}(0;y)\psi(y)|N,+\rangle, \tag{1.8}$$

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

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

$$\langle\sin\phi\rangle_{LU}=-\lambda_l\frac{|\vec{k}_\perp|}{Q}\frac{D(y)}{A(y)}\frac{x_B g^\perp(x_B,k_\perp)}{f_1(x_B,k_\perp)}, \tag{1.9}$$

$$\langle\sin\phi\rangle_{UL}=-\lambda\frac{|\vec{k}_\perp|}{Q}\frac{B(y)}{A(y)}\frac{x_B f_L^\perp(x_B,k_\perp)}{f_1(x_B,k_\perp)}, \tag{1.10}$$

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By measuring these azimuthal asymmetries we can study various corresponding TMD PDFs. The factor $|\vec{k}_\perp|/Q$ shows that above 2 asymmetries come from twist-3 contributions. Above formulae work equally well for both nucleon and nucleus target.

2. Nulcear 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 wth correct direction to $+\infty$ 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,

$$\Phi^A_\alpha(x,k_\perp) \equiv \int \frac{p^+dy^-d^2y_\perp}{(2\pi)^3} e^{ixp^+y^- - i\vec{k}_\perp\cdot\vec{y}_\perp} \langle A|\bar{\psi}(0)\Gamma_\alpha \mathscr{L}(0;y)\psi(y)|A\rangle, \tag{2.1}$$

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

$$\Phi^A_\alpha(x,k_\perp) \approx \frac{A}{\pi\Delta_{2F}} \int d^2\ell_\perp e^{-(\vec{k}_\perp-\vec{\ell}_\perp)^2/\Delta_{2F}} \Phi^N_\alpha(x,\ell_\perp), \tag{2.2}$$

where $\Delta_{2F} = \int d\xi^-_N \hat{q}_F(\xi^-_N)$ 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,

$$f^A_1(x,k_\perp) \approx \frac{A}{\pi\Delta_{2F}} \int d^2\ell_\perp e^{-(\vec{k}_\perp-\vec{\ell}_\perp)^2/\Delta_{2F}} f^N_1(x,\ell_\perp), \tag{2.3}$$

$$k^2_\perp g^{\perp A}(x,k_\perp) \approx \frac{A}{\pi\Delta_{2F}} \int d^2\ell_\perp e^{-(\vec{k}_\perp-\vec{\ell}_\perp)^2/\Delta_{2F}} (k_\perp\cdot\ell_\perp) g^{\perp N}(x,\ell_\perp), \tag{2.4}$$

$$k^2_\perp f^{\perp A}_L(x,k_\perp) \approx \frac{2J_A}{\pi\Delta_{2F}} \int d^2\ell_\perp e^{-(\vec{k}_\perp-\vec{\ell}_\perp)^2/\Delta_{2F}} (k_\perp\cdot\ell_\perp) f^{\perp N}_L(x,\ell_\perp), \tag{2.5}$$

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

$$\frac{\langle\cos\phi\rangle^{eA}_{LU}}{\langle\cos\phi\rangle^{eN}_{LU}} \approx \frac{\alpha}{\alpha+\Delta_{2F}}, \tag{2.6}$$

$$\frac{\langle\cos\phi\rangle^{eA}_{UL}}{\langle\cos\phi\rangle^{eN}_{UL}} \approx \frac{2J_A}{A}\frac{\alpha}{\alpha+\Delta_{2F}}, \tag{2.7}$$

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

$$f_s \approx \frac{1}{1+0.114A^{1/3}}. \tag{2.8}$$

The plot of this formula and fit to k_T-broadening are shown in the following figure.

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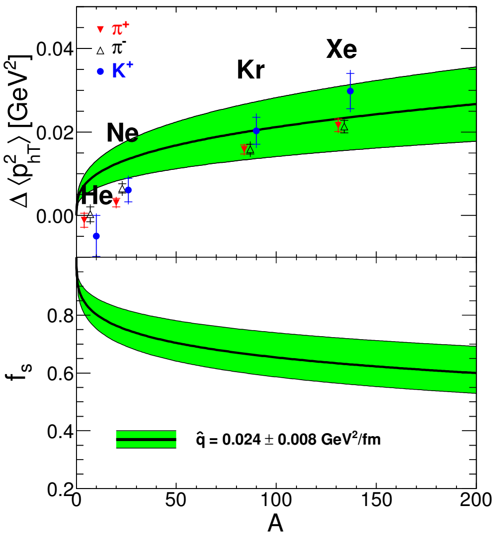

Figure 1: Nuclear k_T-broadening (upper panel) and nuclear suppression factor f_s for azimuthal asymmetries [9].

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).

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