Medium modification of transverse momentum distributions

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A measurement of transverse momenta (P_T) of final-state hadrons in semi-inclusive deep inelastic scattering (SIDIS) $\vec{e}\vec{p} \to e'hX$, for which a hadron is detected in coincidence with the scattered lepton, gives access to the transverse momentum distributions (TMDs) of partons, which are not accessible in inclusive scattering. QCD factorization for SIDIS, established at low transverse momentum in the current-fragmentation region at higher energies [1, 2, 3], provides a rigorous starting point for the study of partonic TMDs from SIDIS data using different spin-dependent and spin-independent observables [4]. The final transverse momentum of the hadron at leading order is defined by the combination $zk_T + p_T$, where k_T and p_T are the transverse momenta of partons involved in distribution and framentation functions respectively.

Azimuthal distributions of final state particles in SIDIS are sensitive to the orbital motion of quarks and play an important role in the study of transverse momentum distributions of quarks in the nucleon. Two fundamental mechanisms have been identified that lead to spin and azimuthal asymmetries in hard processes; the Sivers mechanism [5, 6, 7, 8, 9], which generates an asymmetry in the distribution of quarks due to orbital motion of partons, and the Collins mechanism [8, 10], which generates an asymmetry during the hadronization of quarks.

Measurements of significant azimuthal asymmetries have been reported for pion production in semi-inclusive deep-inelastic scattering by the HERMES and COMPASS Collaborations, as well as the CLAS and Hall-C Collaborations at JLab for different combinations of beam and target polarizations [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21].

TMD distributions at leading tist (see Table 1 left) describe transitions of nucleons with one polarization state to a quark with another polarization state. Similar sets of functions appear in the subleading twist (see Table 2). Corresponding fragmentation functions define fragmentation of partons to hadrons. The diagonal elements of Table 1 left are the momentum, longitudinal and transverse spin distributions of partons and represent well known PDFs related to the leading-twist light-cone wave functions square. Off diagonal elements require non-zero orbital angular momentum and are related to interference between $L = 0$ and $L = 1$ light-cone wave functions [22]. Leading-twist Fragmentation Functions can be analogously decomposed, see Table 1 right.

Both, quark distribution and fragmentation functions modify in the nuclear environment.

N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^{\perp}$
L		$\mathbf{g_{1L}}$	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 , $h_{1T}^{\perp}$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^{\perp}$
L		$\mathbf{G_{1L}}$	G_{1T}
T	$H_1^{\perp}$	$H_{1L}^{\perp}$	H_1 , $H_{1T}^{\perp}$

Table 1: *Left:* Leading twist transverse momentum dependent distribution functions. The U,L,T correspond to unpolarized, longitudinally polarized and transversely polarized nucleons (rows) and quarks (columns) *Right:* Leading twist transverse momentum dependent Fragmentation functions. U,L,T corresponds to polarized quarks (rows) and produced hadrons (columns).

N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h ,e
L	$f_L^{\perp}$	$g_L^{\perp}$	h_L ,e_L
T	f_T , $f_T^{\perp}$	g_T , $g_T^{\perp}$	h_T ,e_T ,$h_T^{\perp}$, $e_T^{\perp}$

Table 2: Twist-3 transverse momentum dependent distribution functions. The U,L,T correspond to unpolarized, longitudinally polarized and transversely polarized nucleons (rows) and quarks (columns)

The gauge-invariant transverse-momentum-dependent quark distribution functions in nuclei can be expressed as a sum of all higher-twist collinear parton matrix elements in terms of a transport operator [23]. Within the framework of a generalized factorization, semi-inclusive deeply inelastic scattering (SIDIS) cross sections can be expressed as a series of products of collinear hard parts and transverse-momentum-dependent (TMD) parton distributions and correlations [23]. The azimuthal asymmetry $\langle \cos\phi \rangle$ of unpolarized SIDIS in the small transverse momentum region will depend on both twist-2 and 3 TMD quark distributions in target nucleons or nuclei. Nuclear broadening of these twist-2 and 3 quark distributions due to final-state multiple scattering in nuclei has been investigated [24] and the nuclear dependence of the azimuthal asymmetry $\langle \cos\phi \rangle$ has been studied. It was shown that the azimuthal asymmetry is suppressed by multiple parton scattering and the transverse momentum dependence of the suppression depends on the relative shape of the twist-2 and 3 quark distributions in the nucleon. Using a Gaussian ansatz for TMD twist-2 and 3 quark distributions in nucleon,

$$f_q^N(x, k_\perp) = \frac{1}{\pi\mu_0^2} f_q^N(x) e^{-k_\perp^2/\mu_0^2}, \tag{1}$$

$$f_{q\perp}^N(x, k_\perp) = \frac{1}{\pi\mu_\perp^2} f_{q\perp}^N(x) e^{-k_\perp^2/\mu_\perp^2}. \tag{2}$$

one can study the nuclear dependence of the azimuthal asymmetry and estimate the smearing effect due to fragmentation. The corresponding TMD distributions in nuclei are,

$$f_q^A(x, k_\perp) \approx \frac{A}{\pi(\mu_0^2 + \Delta_{2F})} f_q^N(x) e^{-k_\perp^2/(\mu_0^2 + \Delta_{2F})}, \tag{3}$$

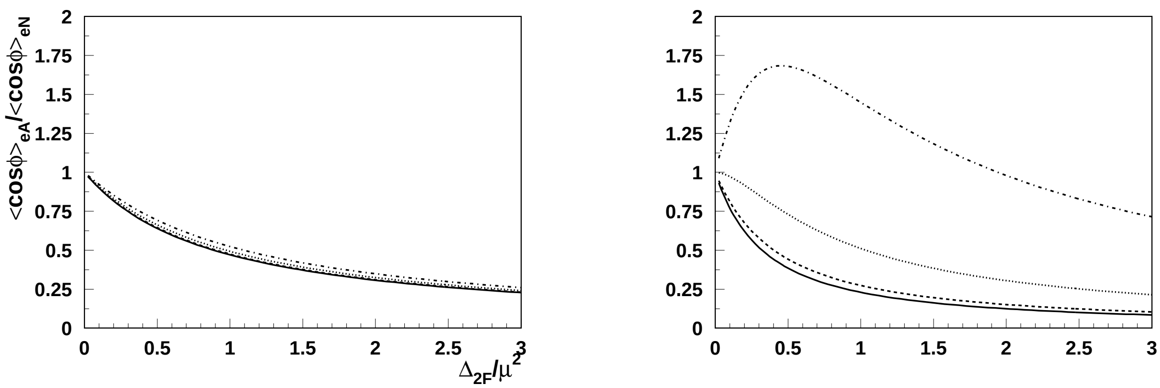

Figure 1: (color online) Ratio $\langle\cos\phi\rangle_{eA}/\langle\cos\phi\rangle_{eN}$ as a function of Δ_{2F} for different $k_\perp$ and the relative width $\mu_\perp^2/\mu_0^2$ of twist-3 and 2 TMD quark distributions.

$$f_{q\perp}^A(x,k_\perp) \approx \frac{A\mu_\perp^2}{\pi(\mu_\perp^2+\Delta_{2F})^2} f_{q\perp}^N(x) e^{-k_\perp^2/(\mu_\perp^2+\Delta_{2F})}. \tag{4}$$

One can then calculate the azimuthal asymmetry for SIDIS off both nucleon

$$\langle\cos\phi\rangle_{eN} = -\frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2}\frac{\mu_0^2}{\mu_\perp^2}\frac{|\vec{k}_\perp|}{Q}\frac{x_B f_{q\perp}^N(x_B)}{f_q^N(x_B)}\exp\Big\{-\frac{\mu_0^2-\mu_\perp^2}{\mu_0^2\mu_\perp^2}k_\perp^2\Big\}, \tag{5}$$

and nuclear targets

$$\langle\cos\phi\rangle_{eA} = -\frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2}\frac{\mu_\perp^2(\mu_0^2+\Delta_{2F})}{(\mu_\perp^2+\Delta_{2F})^2}\frac{|\vec{k}_\perp|}{Q}\frac{x_B f_{q\perp}^N(x)}{f_q^N(x)}\exp\Big\{-\frac{\mu_0^2-\mu_\perp^2}{(\mu_0^2+\Delta_{2F})(\mu_\perp^2+\Delta_{2F})}k_\perp^2\Big\}. \tag{6}$$

The nuclear modification factor for the azimuthal asymmetry is then,

$$\frac{\langle\cos\phi\rangle_{eA}}{\langle\cos\phi\rangle_{eN}} = \frac{\mu_\perp^4(\mu_0^2+\Delta_{2F})}{\mu_0^2(\mu_\perp^2+\Delta_{2F})^2}\exp\Big\{\frac{(\mu_0^2-\mu_\perp^2)\Delta_{2F}(\mu_0^2+\mu_\perp^2+\Delta_{2F})}{\mu_0^2\mu_\perp^2(\mu_0^2+\Delta_{2F})(\mu_\perp^2+\Delta_{2F})}\vec{k}_\perp^2\Big\}. \tag{7}$$

The azimuthal asymmetry $\langle\cos\phi\rangle_{eA}$ in deep inelastic eA scattering is suppressed compared to that in eN scattering and the suppression is inversely proportional to the total transverse momentum broadening Δ_{2F}. In case $\mu_\perp^2 \approx \mu_0^2$ the ratio simplifies (ex. in bag model $\mu_\perp/\mu_0 = 0.94$[25]) ;

$$\frac{\langle\cos\varphi\rangle_{eA}}{\langle\cos\varphi\rangle_{eN}} = \frac{\mu_\perp^2}{\mu_\perp^2+\Delta_{2F}}. \tag{8}$$

and the suppression is practically independent of the transverse momentum $k_\perp$ (see Fig.1). In more general case, the twist-2 and twist-3 TMD quark distributions might have different widths $\mu_\perp^2 \neq \mu_0^2$. The nuclear modification factor for the azimuthal asymmetry will then have non-trivial $k_\perp$ dependence. Fig.1 shows the nuclear modification factors for the azimuthal asymmetry when $\mu_\perp^2/\mu_0^2 = 2$ and 0.5, respectively, as functions of Δ_{2F}/μ_0^2, at different transverse momentum $k_\perp$. In the case $\mu_\perp^2 > \mu_0^2$, the azimuthal asymmetry is suppressed and the suppression increases with the transverse momentum $k_\perp$. In case $\mu_\perp^2 < \mu_0^2$, the suppression decreases with increasing $k_\perp$ and the azimuthal asymmetry could be enhanced for large enough transverse momentum $k_\perp$. Therefore, the nuclear modification of the azimuthal asymmetry and its transverse momentum dependence is a very sensitive probe of the twist-2 and twist-3 TMD quark distribution functions.

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