

Spin and transverse-momentum dependent fracture function in SIDIS

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Summary. — The recently developed leading twist formalism for spin and transverse-momentum dependent fracture functions is shortly described. We demonstrate that the process of double hadron production in polarized SIDIS—with one spinless hadron produced in the current fragmentation region (CFR) and another in the target fragmentation region (TFR)—would provide access to all 16 leading twist fracture functions. Some particular cases are presented.

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1. – Introduction

So far most SIDIS experiments were studied in the CFR, where an adequate theoretical formalism based on distribution and fragmentation functions has been established (see for example ref. [1]). However, for a full understanding of the hadronization process after the hard lepton-quark scattering, also the factorized approach to SIDIS description in the TFR has to be explored. The corresponding theoretical basis—the fracture functions formalism—was established in ref. [2] for hadron transverse-momentum integrated unpolarized cross-section. Recently this approach was generalized [3] to the spin and transverse-momentum dependent case (STMD).

We use the standard DIS notations and in the $\gamma^* - N$ c.m. frame we define the z -axis along the direction of \mathbf{q} (the virtual photon momentum) and the x -axis along ℓ_T , the lepton transverse momentum. The kinematics of the produced hadron in the TFR is

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defined by the variable $\zeta = P_h^-/P^- \simeq E_h/E$ and its transverse momentum $\mathbf{P}_{h\perp}$ (with magnitude $P_{h\perp}$ and azimuthal angle ϕ_h). The azimuthal angle of the nucleon transverse polarization is denoted as ϕ_S .

The STMD fracture functions \mathcal{M} has a clear probabilistic meaning: it is the conditional probability to produce a hadron h in the TFR when the hard scattering occurs on a quark q from the target nucleon N .

The most general expression of the LO STMD fracture functions for unpolarized ($\mathcal{M}^{[\gamma^-]}$), longitudinally polarized ($\mathcal{M}^{[\gamma^- \gamma_5]}$) and transversely polarized ($\mathcal{M}^{[i \sigma^{i-} \gamma_5]}$) quarks are introduced in the expansion of the leading twist projections as [3, 4]:

$$\begin{aligned}
(1) \quad \mathcal{M}^{[\gamma^-]} &= \hat{u}_1 + \frac{\mathbf{P}_{h\perp} \times \mathbf{S}_\perp}{m_h} \hat{u}_{1T}^h + \frac{\mathbf{k}_\perp \times \mathbf{S}_\perp}{m_N} \hat{u}_{1T}^\perp + \frac{S_\parallel (\mathbf{k}_\perp \times \mathbf{P}_{h\perp})}{m_N m_h} \hat{u}_{1L}^{\perp h} \\
(2) \quad \mathcal{M}^{[\gamma^- \gamma_5]} &= S_\parallel \hat{t}_{1L} + \frac{\mathbf{P}_{h\perp} \cdot \mathbf{S}_\perp}{m_h} \hat{t}_{1T}^h + \frac{\mathbf{k}_\perp \cdot \mathbf{S}_\perp}{m_N} \hat{t}_{1T}^\perp + \frac{\mathbf{k}_\perp \times \mathbf{P}_{h\perp}}{m_N m_h} \hat{t}_1^{\perp h} \\
(3) \quad \mathcal{M}^{[i \sigma^{i-} \gamma_5]} &= S_\perp^i \hat{t}_{1T} + \frac{S_\parallel P_{h\perp}^i}{m_h} \hat{t}_{1L}^h + \frac{S_\parallel k_\perp^i}{m_N} \hat{t}_{1L}^\perp + \frac{(\mathbf{P}_{h\perp} \cdot \mathbf{S}_\perp) P_{h\perp}^i}{m_h^2} \hat{t}_{1T}^{hh} \\
&\quad + \frac{(\mathbf{k}_\perp \cdot \mathbf{S}_\perp) k_\perp^i}{m_N^2} \hat{t}_{1T}^{\perp\perp} + \frac{(\mathbf{k}_\perp \cdot \mathbf{S}_\perp) P_{h\perp}^i - (\mathbf{P}_{h\perp} \cdot \mathbf{S}_\perp) k_\perp^i}{m_N m_h} \hat{t}_{1T}^{\perp h} \\
&\quad + \frac{\epsilon_\perp^{ij} P_{h\perp j}}{m_h} \hat{t}_1^h + \frac{\epsilon_\perp^{ij} k_{\perp j}}{m_N} \hat{t}_1^\perp,
\end{aligned}$$

where \mathbf{k}_\perp is the quark transverse momentum and by the vector product of two-dimensional vectors \mathbf{a} and \mathbf{b} we mean the pseudo-scalar quantity $\mathbf{a} \times \mathbf{b} = \epsilon^{ij} a_i b_j = ab \sin(\phi_b - \phi_a)$. All fracture functions depend on the scalar variables x_B , k_\perp^2 , ζ , $P_{h\perp}^2$ and $\mathbf{k}_\perp \cdot \mathbf{P}_{h\perp}$.

The single hadron production in the TFR of SIDIS does not provide access to all fracture functions.

2. – Double hadron leptoproduction (DSIDIS)

In order to have access to all fracture functions one has to “measure” the scattered quark transverse polarization, for example exploiting the Collins effect [5]—the azimuthal correlation of the fragmenting quark transverse polarization, \mathbf{s}'_T , with the produced hadron transverse momentum, \mathbf{p}_\perp :

$$(4) \quad D(z, \mathbf{p}_\perp) = D_1(z, p_\perp^2) + \frac{\mathbf{p}_\perp \times \mathbf{s}'_T}{m_h} H_1^\perp(z, p_\perp^2),$$

where $\mathbf{s}'_T = D_{nn}(y) \mathbf{s}_T$ and $\phi_{s'} = \pi - \phi_s$ with $D_{nn}(y) = [2(1-y)]/[1+(1-y)^2]$.

Let us consider a double hadron production process (DSIDIS)

$$(5) \quad l(\ell) + N(P) \rightarrow l(\ell') + h_1(P_1) + h_2(P_2) + X$$

with (unpolarized) hadron 1 produced in the CFR ($x_{F1} > 0$) and hadron 2 in the TFR ($x_{F2} < 0$), see fig. 1. For hadron h_1 we will use the ordinary scaled variable $z_1 = P_1^+/k'^+ \simeq P \cdot P_1 / P \cdot q$ and its transverse momentum $\mathbf{P}_{1\perp}$ (with magnitude $P_{1\perp}$ and azimuthal angle ϕ_1) and for hadron h_2 the variables $\zeta_2 = P_2^-/P^- \simeq E_2/E$ and $\mathbf{P}_{2\perp}$ ($P_{2\perp}$ and ϕ_2).

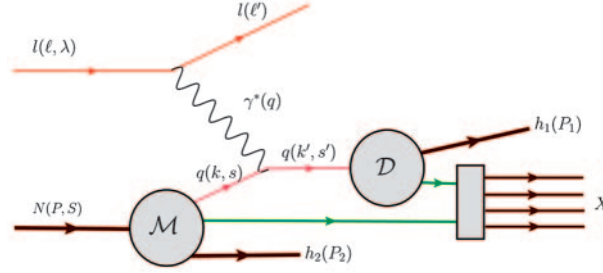


Fig. 1. – DSIDIS description in factorized approach at LO.

The LO expression for the DSIDIS cross-section includes all fracture functions:

$$(6) \quad \frac{d\sigma^{l(\ell, \lambda) + N(P, S) \rightarrow l(\ell') + h_1(P_1) + h_2(P_2) + X}}{dx dy dz_1 d\zeta_2 d^2\mathbf{P}_{1\perp} d^2\mathbf{P}_{2\perp} d\phi_S} = \frac{\alpha^2 x_B}{Q^4 y} [1 + (1 - y)^2] \\ \times \left(\mathcal{M}_{h_2}^{[\gamma^-]} \otimes D_{1q}^{h_1} + \lambda D_{ll}(y) \mathcal{M}_{h_2}^{[\gamma^- \gamma_5]} \otimes D_q^{h_1} + \mathcal{M}_{h_2}^{[i\sigma^{i-} \gamma_5]} \otimes \frac{\mathbf{p}_\perp \times \mathbf{s}'_T}{m_{h_1}} H_{1q}^{\perp h_1} \right) = \\ \frac{\alpha^2 x_B}{Q^4 y} [1 + (1 - y)^2] \\ \times \left(\sigma_{UU} + S_{\parallel} \sigma_{UL} + S_{\perp} \sigma_{UT} + \lambda D_{ll} \sigma_{LU} + \lambda S_{\parallel} D_{ll} \sigma_{LL} + \lambda S_{\perp} D_{ll} \sigma_{LT} \right),$$

where $D_{ll}(y) = y(2 - y)/1 + (1 - y)^2$.

3. – Examples of unintegrated cross-sections: beam spin asymmetry

We show here explicit expressions only for σ_{UU} and $\sigma_{LU}^{(1)}$

$$(7) \quad \sigma_{UU} = F_0^{\hat{u} \cdot D_1} - D_{nn} \left[\frac{P_{1\perp}^2}{m_1 m_N} F_{kp1}^{\hat{t}^\perp \cdot H_1^\perp} \cos(2\phi_1) + \frac{P_{1\perp} P_{2\perp}}{m_1 m_2} F_{p1}^{\hat{t}^h \cdot H_1^\perp} \cos(\phi_1 + \phi_2) \right. \\ \left. + \left(\frac{P_{2\perp}^2}{m_1 m_N} F_{kp2}^{\hat{t}^\perp \cdot H_1^\perp} + \frac{P_{2\perp}^2}{m_1 m_2} F_{p2}^{\hat{t}^h \cdot H_1^\perp} \right) \cos(2\phi_2) \right].$$

$$(8) \quad \sigma_{LU} = -\frac{P_{1\perp} P_{2\perp}}{m_2 m_N} F_{k1}^{\hat{t}^h \cdot D_1} \sin(\phi_1 - \phi_2),$$

where the structure functions F_{\dots} are specific convolutions [6, 7] of fracture and fragmentation functions depending on x , z_1 , ζ_2 , $P_{1\perp}^2$, $P_{2\perp}^2$, $\mathbf{P}_{1\perp} \cdot \mathbf{P}_{2\perp}$.

We notice the presence of terms similar to the Boer-Mulders term appearing in the usual CFR of SIDIS. What is new in DSIDIS is the LO beam spin SSA, absent in the CFR of SIDIS. We further notice that the DSIDIS structure functions may depend in principle on the relative azimuthal angle of the two hadrons, due to presence of the last term among their arguments: $\mathbf{P}_{1\perp} \cdot \mathbf{P}_{2\perp} = P_{1\perp} P_{2\perp} \cos(\Delta\phi)$ with $\Delta\phi = \phi_1 - \phi_2$. This term arise from $\mathbf{k}_\perp \cdot \mathbf{P}_\perp$ correlations in STMD fracture functions and can generate a long range correlation between hadrons produced in CFR and TFR. In practice it is convenient to chose as independent azimuthal angles $\Delta\phi$ and ϕ_2 .

(¹) Expressions for other terms are available in [6].

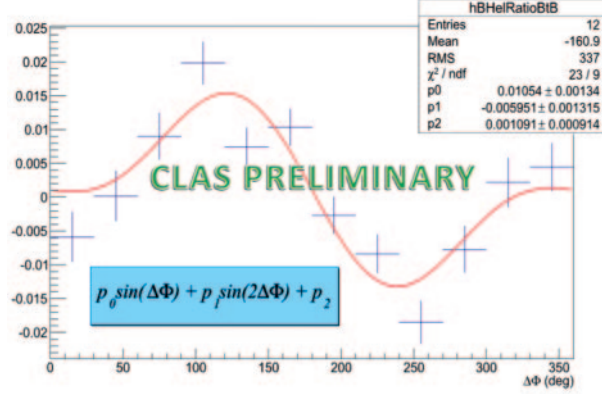


Fig. 2. – The preliminary results for A_{LU} asymmetry from CLAS experiment at JLab.

Let us finally consider the beam spin asymmetry defined as

$$(9) \quad A_{LU}(x, z_1, \zeta_2, P_{1\perp}^2, P_{2\perp}^2, \Delta\phi) = \frac{\int d\phi_2 \sigma_{LU}}{\int d\phi_2 \sigma_{UU}} = \frac{-\frac{P_{1\perp} P_{2\perp}}{m_2 m_N} F_{k1}^{\hat{i}^{\perp h} \cdot D_1} \sin(\Delta\phi)}{F_0^{\hat{u} \cdot D_1}}.$$

If one keeps only the linear terms of the corresponding fracture function expansion in series of $\mathbf{P}_{1\perp} \cdot \mathbf{P}_{2\perp}$ one obtains the following azimuthal dependence of DSIDIS beam spin asymmetry:

$$(10) \quad A_{LU}(x, z_1, \zeta_2, P_{1\perp}^2, P_{2\perp}^2) = a_1 \sin(\Delta\phi) + a_2 \sin(2\Delta\phi)$$

with the amplitudes a_1, a_2 independent of azimuthal angles.

In fig. 2 we present the first preliminary results [8] for A_{LU} asymmetry from CLAS experiment at JLab with π^+ produced in CFR and π^- —in TFR. The nonzero effect were observed!

We stress that the ideal opportunities to test the predictions of the present approach to DSIDIS, would be the future JLab 12 upgrade, in progress, and the EIC facilities, in the planning phase.

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