UNIFYING THE MECHANISMS FOR SINGLE SPIN ASYMMETRIES IN HARD PROCESSES

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By studying the single transverse-spin asymmetry at the intermediate transverse momentum region in hard processes, Drell-Yan and SIDIS, we demonstrated that the two mechanisms proposed to explain the large SSAs are unified.

Single transverse-spin asymmetry (SSA) in high energy hadronic scattering has a long history. The size of the observed asymmetries came as a surprise and has posed a challenge for researchers in this field[1]. Two mechanisms have been proposed in QCD to explain the the large size of SSAs: One is the so-called (naive) time-reversal-odd (T-odd) and transverse-momentum dependent (TMD) parton distributions[2]; and the other follows the collinear QCD factorization approach and presents the SSAs in terms of spin-dependent twist-three quark-gluon correlation functions (ETQS mechanism)[3,4].

In our recent publications[5], we demonstrated, at the first time, that these two mechanisms are unified, by studying the SSAs at intermediated transverse momentum in semi-inclusive DIS (SIDIS) and Drell-Yan processes. In both processes, At large $q_\perp \sim Q$, the ETQS mechanism applies, and the resulting SSA is of twist-three nature. At small $q_\perp \ll Q$, a factorization in terms of TMD parton distribution applies [6], involving in case of the SSA the Sivers functions. If $q_\perp$ is much larger than $\Lambda_{\rm QCD}$, the dependence of these functions on transverse momentum may be computed using QCD perturbation theory. At the same time, the result obtained within the ETQS formalism may also be extrapolated into the regime $\Lambda_{\rm QCD} \ll q_\perp \ll Q$, and we demonstrated that the result of this extrapolation is identical to that obtained using the TMD approach [5]. In this sense, we have unified the two mechanisms widely held responsible for the observed SSAs.

In this talk, I will present the result for SIDIS. In single transverse-spin polarized deep inelastic scattering, the relevant leptonic tensor is defined as $L^{\mu\nu}(\ell,q) = 2\left(\ell^\mu\ell'^\nu + \ell^\mu\ell'^\nu - g^{\mu\nu}Q^2/2\right)$, and the hadronic tensor $W^{\mu\nu}$ can be decomposed into $W^{\mu\nu} = \sum_{i=1}^5 V_i^{\mu\nu} W_i$ [7]. In this study, are primarily interested in hadron production in an intermediate transverse momentum region, $\Lambda_{\rm QCD} \ll P_{h\perp} \ll Q$, and we will investigate the limit $P_{h\perp} \ll Q$ of the ETQS result. In that limit, V_1 alone provides the leading behavior, so that all other terms than V_1 will be neglected in the following discussions.

After summing over the contributions from all diagrams, we find the transverse-spin dependent cross section can be written as, in the limit of $\Lambda_{\rm QCD} \ll P_{h\perp} \ll Q$,

$$\frac{d\Delta\sigma(S_\perp)}{dx_B dy dz_h d^2\vec{P}_{h\perp}} = -\frac{4\pi\alpha_{\rm em}^2 S_{ep}}{Q^4}\epsilon^{\alpha\beta}S_\perp^\alpha \frac{z_h P_{h\perp}^\beta}{(\vec{P}_{h\perp}^2)^2}\frac{\alpha_s}{2\pi^2}\int \frac{dxdz}{xz}\hat{q}(z) \times\left\{\delta(\hat{\xi}-1)A + \delta(\xi-1)B\right\} , \quad (1)$$

where

$$A = \frac{1}{2N_C}\left\{\left[x\frac{\partial}{\partial x}T_F(x,x)\right](1+\xi^2) + T_F(x,x-\widehat{x}_g)\frac{1+\xi}{(1-\xi)_+} + T_F(x,x)\frac{(1-\xi)^2(2\xi+1)-2}{(1-\xi)_+}\right\} + C_F T_F(x,x-\widehat{x}_g)\frac{1+\xi}{(1-\xi)_+} , \quad (2)$$

$$B = C_F T_F(x,x)\left[\frac{1+\hat{\xi}^2}{(1-\hat{\xi})_+} + 2\delta(\hat{\xi}-1)\ln\frac{z_h^2 Q^2}{\vec{P}_{h\perp}^2}\right] , \quad (3)$$

with $\widehat{x}_g \equiv (1-\xi)x = x - x_B$.

On the other hand, when $P_{h\perp} \ll Q$, we know that a transverse-momentum-dependent factorization applies [6]. Following this reference, the differential SIDIS cross section may be written as

$$\frac{d\sigma}{dx_B dy dz_h d^2\vec{P}_{h\perp}} = \frac{4\pi\alpha_{\rm em}^2 S_{ep}}{Q^4}(1-y+\frac{y^2}{2})x_B\sin(\phi_h-\phi_S)|S_\perp|F_{UT}^{(1)} , \quad (4)$$

where ϕ_S and ϕ_h are the azimuthal angles of the proton's transverse polarization vector and of the transverse momentum vector of the final-state hadron, respectively. $F_{UT}^{(1)}$ has the following factorized form [6]:

$$F_{UT}^{(1)} = \sum_{q=u,d,s,\dots} e_q^2\int d^2\vec{k}_\perp d^2\vec{p}_\perp d^2\vec{\lambda}_\perp \vec{k}_\perp\cdot\hat{\vec{P}}_{h\perp} q_T(x_B,k_\perp)/M_P \times\hat{q}(z_h,p_\perp)\left(S(\vec{\lambda}_\perp)\right)^{-1} H_{UT}^{(1)}(Q^2)\,\delta^{(2)}\left(z_h\vec{k}_\perp + \vec{p}_\perp + \vec{\lambda}_\perp - \vec{P}_{h\perp}\right) , \quad (5)$$

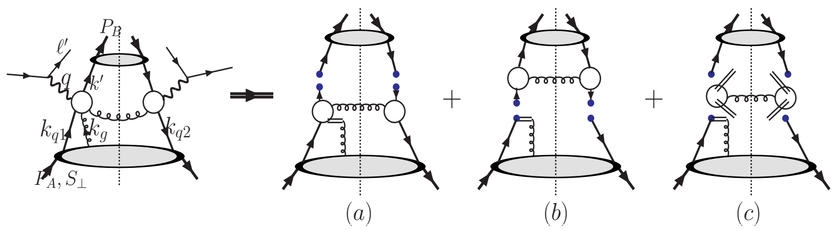

Figure 1. *The factorization arguments for the consistency between the two mechanisms: left is a generic Feynman diagram in the twist-three quark-gluon correlation formalism; and the right is the corresponding TMD factorization form decomposed into different regions, (a) the Sivers function, (b) the fragmentaion function, and (c) the soft factor.*

where $\hat{\vec{P}}_{h\perp}$ is a unit vector in direction of $\vec{P}_{h\perp}$, and $\hat{q}$ and q_T are unpolarized quark fragmentation function and the Sivers TMD quark distribution, respectively. We can compute the various factors in the factorization formulas(5) at large transverse momentum ($P_{h\perp} \gg \Lambda_{\rm QCD}$). The unpolarized quark fragmentation functions is expressed in terms of the $k_\perp$-integrated one,

$$\hat{q}(z_h,p_\perp)=\frac{\alpha_s}{2\pi^2}\frac{1}{\vec{p}_\perp^{\,2}}C_F\int\frac{dz}{z}\hat{q}(z)\left[\frac{1+\hat{\xi}^2}{(1-\hat{\xi})_+}+\delta(\hat{\xi}-1)\left(\ln\frac{\hat{\zeta}^2}{\vec{p}_\perp^2}-1\right)\right] ,$$

where $\hat{q}(z)$ is the integrated quark fragmentation function and $\hat{\xi}=z_h/z$.

Similarly, the Sivers function at large $k_\perp$ can also be calculated perturbatively. Because it is (naively) time-reversal-odd, the only contribution comes from the twist-three quark-gluon correlation function T_F. Carrying out the calculations accordingly, we find [5]

$$q_T(x_B,k_\perp)=\frac{-\alpha_s}{4\pi^2}\frac{2M_P}{(\vec{k}_\perp^2)^2}\int\frac{dx}{x}\left\{A+C_FT_F(x,x)\delta(\xi-1)\left(\ln\frac{x_B^2\zeta^2}{\vec{k}_\perp^2}-1\right)\right\}$$

where A has been defined in Eq. (3) and where $\xi=x_B/x$. The Siver function for the Drell-Yan process can be calculated similarly, which is found to be the same with an opposite sign[5], as expected from its definition[8]. This sign difference comes from the different directions of the gauge links in the two processes: in DIS the gauge link arises from final-state interactions and runs to positive light-cone infinity, while in Drell-Yan it is due to initial-state interactions and goes to $-\infty$.

In order to calculate the explicit $P_{h\perp}$-dependence generated by the TMD factorization, we let one of the transverse momenta $\vec{k}_\perp$, $\vec{p}_\perp$, and $\vec{\lambda}_\perp$ be of the order of $\vec{P}_{h\perp}$ and the others much smaller. When $\vec{\lambda}_\perp$ is large, for example, we neglect $\vec{k}_\perp$ and $\vec{p}_\perp$ in the delta function, and the integrations over these momenta yield either the ordinary quark distribution, or a $k_\perp$ moment of the Sivers function. The latter is related to the twist-three correlation [9]:

$$\int d^2\vec{k}_\perp q(x,k_\perp) = q(x) \ , \qquad \int d^2\vec{k}_\perp \vec{k}_\perp^2 q_T(k_\perp,x)/M_P = -T_F(x,x) \ . \quad (6)$$

In case $\vec{\lambda}_\perp$ is neglected in the delta function, one makes use of the relation [6] $\int d^2\vec{\lambda}_\perp S(\lambda_\perp) = 1$. Substituting the above equations into the factorization formula (5), it is easy to see that we reproduce the twist-three result in Eq. (3). This consistency can also be illustrated from the diagrams in Fig. 1, where we showed a generic twist-three Feynman diagram can be factorized into various factors in the TMD factorization formula (5), according to different momentum region of the radiated gluon: parallel to the polarized proton or the final state observed hadron, or soft.

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