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On the $\sin\phi_R$ single longitudinal spin asymmetry in dihadron production in SIDIS

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We study the single longitudinal-spin asymmetry of dihadron production in semi-inclusive deep inelastic scattering process in which the transverse momentum of the final-state hadron pairs is integrated out. In Particular, we investigate origins of the $\sin\phi_R$ azimuthal asymmetry for which we take into account the coupling of the twist-3 distributions h_L and the dihadron framgentation function (DiFF) $H_{1,ot}^{\sphericalangle}$ as well as the coupling of the helicity distribution g_1 and the twist-3 DiFF $\widetilde{G}^{\sphericalangle}$. To this end The unknown twist-3 dihadron fragmentation function $\widetilde{G}^{\sphericalangle}$ is calculated in a spectator model which is successful in describing the dihadron production in unpolarized process. We estimate the $\sin\phi_R$ asymmetry of dihadron production in SIDIS at the kinematics of COMPASS and compare it with the preliminary COMPASS data. Although the asymmetry is dominated by the $h_L H_1^{\sphericalangle}$ term, we find that the contribution from the $g_1\widetilde{G}^{\sphericalangle}$ term should also be taken into account in certain kinematical region.

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1. Introduction

The azimuthal asymmetries in semi-inclusive deep inelastic scattering (SIDIS) process have been recognized as useful tools for these quests. The full description of SIDIS includes a set of parton distribution functions (PDFs) and fragmentation functions (FFs). [1, 2]. The unpolarized DiFFs were introduced in Ref. [3], and their evolution equations have been investigated in Refs. [4, 5, 6]. Particularly, the chiral-odd DiFF $H_1^{\sphericalangle}$ [7, 8, 9] plays an important role in accessing transversity distribution, as it couples with h_1 at the leading-twist level in the collinear factorization. In this work, we study the $\sin\phi_R$ asymmetry by adopting the spectator model results for the distribution functions and fragmentation functions. We not only take into account the coupling $h_L H_1^{\sphericalangle}$, but also investigate the role of the T-odd DiFF $\tilde{G}^{\sphericalangle}$, which encodes the quark-gluon-quark correlation and has not been considered in previous studies.

2. Formalism of the $\sin\phi_R$ asymmetry of dihadron production in SIDIS

As displayed in Fig.1, the process under study is the dihadron production in SIDIS off a longitudinally polarized proton target:

$$\mu(\ell) + p^{\rightarrow}(P) \longrightarrow \mu(\ell') + h^+(P_1) + h^-(P_2) + X, \tag{2.1}$$

where the four-momenta of the incoming and the outgoing leptons are denoted by ℓ and ℓ', P is the momentum of the target with mass M. In this process, the active quark with momentum p is struck by the virtual photon with momentum $q = \ell - \ell'$. The final-state quark with momentum $k = p + q$ then fragments into two final-state hadrons, h^+ and h^-, plus unobserved state X. The momenta of the pair are denoted by P_1, P_2.

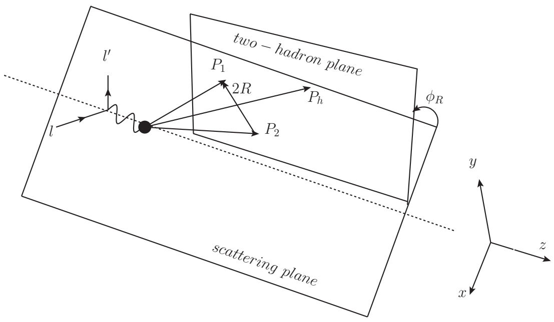

Figure 1: Angle definitions involved in the measurement of the single longitudinal-spin asymmetry in deep-inelastic production of two hadrons in the current region.

The twist-3 DiFF $\widetilde{G}^{\sphericalangle}$ arises from the multiparton correlation during the quark fragmentation, described by the quark-gluon-quark correlator [13, 15]:

$$\begin{aligned}\widetilde{\Delta}_A^{\alpha}(z,k_T,R) = {} & \frac{1}{2z}\sum_X \int \frac{d\xi^+ d^2\xi_T}{(2\pi)^3} e^{ik\cdot\xi} \langle 0| \int_{\pm\infty^+}^{\xi^+} d\eta^+ \mathscr{U}^{\xi_T}_{(\infty^+,\xi^+)} \\ & \times g F_\perp^{-\alpha} \mathscr{U}^{\xi_T}_{(\eta^+,\xi^+)} \psi(\xi) |P_h,R;X\rangle \langle P_h,R;X| \bar{\psi}(0) \mathscr{U}^{0_T}_{(0^+,\infty^+)} \mathscr{U}^{\infty^+}_{(0_T,\xi_T)} |0\rangle \,|_{\eta^+=\xi^+=0,\eta_T=\xi_T} \,.\end{aligned} \tag{2.2}$$

Here, $F_\perp^{-\alpha}$ is the field strength tensor of the gluon. After integrating out $\vec{k}_T$, one obtains

$$\widetilde{\Delta}_A^\alpha(z,\cos\theta,M_h^2,\phi_R) = \frac{z^2|\vec{R}|}{8M_h}\int d^2\vec{k}_T\,\widetilde{\Delta}_A^\alpha(z,k_T,R). \tag{2.3}$$

The DiFF $\widetilde{G}^\sphericalangle$ thus can be extracted from $\widetilde{\Delta}_A^\alpha(z,k_T,R)$ by the trace

$$\frac{\varepsilon_T^{\alpha\beta}R_{T\beta}}{z}\widetilde{G}^\sphericalangle(z,\cos\theta,M_h^2) = 4\pi\mathrm{Tr}[\widetilde{\Delta}_A^\alpha(z,\cos\theta,M_h^2,\phi_R)\gamma^-\gamma_5]. \tag{2.4}$$

As shown in Ref. [17], we can expand the twist-3 DiFF $\widetilde{G}^\sphericalangle$ up to the p-wave level as

$$\widetilde{G}^\sphericalangle(z,\cos\theta,M_h^2) = \widetilde{G}_{ot}^\sphericalangle(z,M_h^2) + \widetilde{G}_{lt}^\sphericalangle(z,M_h^2)\cos\theta. \tag{2.5}$$

Here, $\widetilde{G}_{ot}^\sphericalangle$ originates from the interference of s and p waves, and $\widetilde{G}_{lt}^\sphericalangle$ comes from the interference of two p waves with different polarization. The $\sin\phi_R$ asymmetry of dihadron production in the single longitudinally polarized SIDIS may be expressed as [14],

$$A_{UL}^{\sin\phi_R}(x,z,M_h^2) = -\frac{\sum_a e_a^2\frac{|\vec{R}|}{Q}\left[\frac{|M|}{M_h}xh_L^a(x)H_{1,ot}^{\sphericalangle,a}(z,M_h^2) + \frac{1}{z}g_1(x)\widetilde{G}_{ot}^\sphericalangle(z,M_h^2)\right]}{\sum_a e_a^2 f_1^a(x)D_{1,oo}^a(z,M_h^2)}. \tag{2.6}$$

Following the COMPASS convention, the depolarization factors are not included in the numerator and denominator.

3. Model calculation of $\widetilde{G}_{ot}^\sphericalangle$

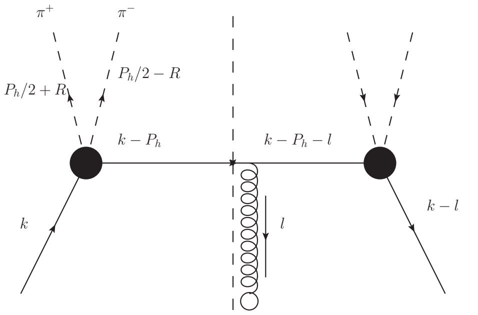

Figure 2: Diagrammatic representation of the correlation function $\widetilde{\Delta}_A^\alpha$ in the spectator model.

In the following, we present the calculation of unknown DiFF $\widetilde{G}_{ot}^\sphericalangle$ in the same spectator model. The corresponding diagram for the calculation in the spectator model is shown in Fig. 2. The left hand side of Fig. 2 corresponds to the quark-hadron vertex $\langle P_h;X|\bar{\psi}(0)|0\rangle$, while the right hand side corresponds to the vertex containing gluon rescattering $\langle 0|igF_\perp^{-\alpha}(\eta^+)\psi(\xi^+)|P_h;X\rangle$. Therefore, the s and p wave contributions to the quark-gluon-quark correlator for dihardon fragmentation in the spectator model can be written as

$$\widetilde{\Delta}_A^\alpha(k,P_h,R) = i\frac{C_F\alpha_s}{2(2\pi)^2(1-z)P_h^-}\frac{1}{k^2-m^2}\int\frac{d^4l}{(2\pi)^4}(l^-g_T^{\alpha\mu} - l_T^\alpha g^{-\mu})$$

$$\frac{(\not{k}-\not{l}+m)(F^{s\star}e^{-\frac{k^2}{\Lambda_s^2}}+F^{p\star}e^{-\frac{k^2}{\Lambda_p^2}}\not{R})(\not{k}-\not{P}_h-\not{l}+m_s)\gamma_\mu(\not{k}-\not{P}_h+m_s)(F^s e^{-\frac{k^2}{\Lambda_s^2}}+F^p e^{-\frac{k^2}{\Lambda_p^2}}\not{R})(\not{k}+m)}{(-l^-\pm i\varepsilon)((k-l)^2-m^2-i\varepsilon)((k-P_h-l)^2-m_s^2-i\varepsilon)(l^2-i\varepsilon)}, \tag{3.1}$$

where m and m_s are the masses of the quark and the spectator, and where the factor $(l^- g_T^{\alpha\mu} - l_T^\alpha g^{-\mu})$ comes from the Feynman rule corresponding to the gluon field strength tensor, as denoted by the open circle in Fig. 2. where Λ_s and Λ_p are the z-dependent Λ-cutoffs having the form [17]

$$\Lambda_{s,p} = \alpha_{s,p} z^{\beta_{s,p}}(1-z)^{\gamma_{s,p}}, \tag{3.2}$$

and $2/\Lambda_{sp}^2 = 1/\Lambda_s^2 + 1/\Lambda_p^2$. The on-shell condition of the spectator gives the relation between k^2 and the trasnverse momentum $\vec{k}_T$

$$k^2 = \frac{z}{1-z}|\vec{k}_T|^2 + \frac{M_s^2}{1-z} + \frac{M_h^2}{z}. \tag{3.3}$$

Thus, the final result for $\widetilde{G}_{ot}^{\sphericalangle}(z, M_h^2)$ has the form

$$\widetilde{G}_{ot}^{\sphericalangle}(z,M_h^2) = \frac{\alpha_s C_F z^2|\vec{R}|}{8(2\pi)^4(1-z)M_h}\frac{1}{k^2-m^2}\int d|\vec{k}_T|^2 e^{-\frac{2k^2}{\Lambda_{sp}^2}}\Big\{\mathrm{Im}(F^{s*}F^p)C + \mathrm{Re}(F^{s*}F^p)(k^2-m^2)m_s\big[(A+zB)-I_2\big]\Big\}. \tag{3.4}$$

Here, the coefficients C give

$$C = \int_0^1 dx\int_0^{1-x} dy \frac{-2m[(x+y)k\cdot p - yM_h^2] + m(k^2-m^2)}{x(1-x)k^2 + 2k\cdot(k-P_h)xy + m^2 x + m_s^2 y + y(y-1)(k-P_h)^2}, \tag{3.5}$$

where we can see that once $m = 0$, so the $\mathrm{Im}(F^{s*}F^p)C$ term will disappears, it has no effect on the results. and the coefficients A and B come from the decomposition of the integral [15],

$$\int d^4l \frac{l^\mu\,\delta(l^2)\,\delta((k-l)^2-m^2)}{(k-P_h-l)^2-m_s^2} = A k^\mu + B P_h^\mu, \tag{3.6}$$

and have the expressions

$$A = \frac{I_1}{\lambda(M_h, m_s)}\left(2k^2\left(k^2-m_s^2-M_h^2\right)\frac{I_2}{\pi} + \left(k^2+M_h^2-m_s^2\right)\right), \tag{3.7}$$

$$B = -\frac{2k^2}{\lambda(M_h,m_s)} I_1\left(1 + \frac{k^2+m_s^2-M_h^2}{\pi} I_2\right). \tag{3.8}$$

The functions I_i appearing in the above equations are defined as [16].

4. Numerical estimate

In the following, we numerically estimate the $\sin\phi_R$ azimuthal asymmetry in the dihadron production off a longitudinally polarized proton by considering both the $h_L H_{1,ot}^{\sphericalangle,a}$ term and the $g_1 \widetilde{G}_{ot}^{\sphericalangle}$

term. Using Eq. (2.6), we can obtain the expressions of the x-dependent, z-dependent and M_h-dependent $\sin\phi_R$ asymmetry as follows

$$A_{UL}^{\sin\phi_R}(x) = -\frac{\int dz \int dM_h 2M_h \frac{|\vec{R}|}{Q}[\frac{|M|}{M_h}(4h_L^u(x)+h_L^d(x))xH_{1,ot}^{\sphericalangle}(z,M_h^2)+\frac{1}{z}(4g_1^u(x)+g_1^d(x))\widetilde{G}_{ot}^{\sphericalangle}(z,M_h^2)]}{\int dz \int dM_h 2M_h(4f_1^u(x)+f_1^d(x))D_{1,oo}(z,M_h^2)}, \tag{4.1}$$

$$A_{UL}^{\sin\phi_R}(z) = -\frac{\int dx \int dM_h 2M_h \frac{|\vec{R}|}{Q}[\frac{|M|}{M_h}(4h_L^u(x)+h_L^d(x))xH_{1,ot}^{\sphericalangle}(z,M_h^2)+\frac{1}{z}(4g_1^u(x)+g_1^d(x))\widetilde{G}_{ot}^{\sphericalangle}(z,M_h^2)]}{\int dx \int dM_h 2M_h(4f_1^u(x)+f_1^d(x))D_{1,oo}(z,M_h^2)}, \tag{4.2}$$

$$A_{UL}^{\sin\phi_R}(M_h) = -\frac{\int dx \int dz \frac{|\vec{R}|}{Q}[\frac{|M|}{M_h}(4h_L^u(x)+h_L^d(x))xH_{1,ot}^{\sphericalangle}(z,M_h^2)+\frac{1}{z}(4g_1^u(x)+g_1^d(x))\widetilde{G}_{ot}^{\sphericalangle}(z,M_h^2)]}{\int dx \int dz(4f_1^u(x)+f_1^d(x))D_{1,oo}(z,M_h^2)}. \tag{4.3}$$

For the other DiFFs $H_{1,ot}^{\sphericalangle,a}(z,M_h^2)$ and $D_{1,oo}(z,M_h^2)$ needed in the calculation, we apply the same spectator model results from Ref. [17]. For the twist-3 distribution h_L, we choose the result in Ref. [18], as for the twist-2 PDFs f_1 and g_1, we adopt the results calculated from the same model [19] for consistency. To compare estimate the $\sin\phi_R$ asymmetry in SIDIS at COMPASS, we adopt the following kinematical cuts [14]

$$\begin{aligned} &0.003 < x < 0.4, \quad 0.1 < y < 0.9, \quad 0.2 < z < 0.9, \\ &0.3\text{GeV} < M_h < 1.6\text{GeV}, \quad Q^2 > 1\text{GeV}^2, \quad W > 5\text{GeV}. \end{aligned} \tag{4.4}$$

In Fig. 3, we plot the $\sin\phi_R$ asymmetry in dihadron production off the longitudinally polarized

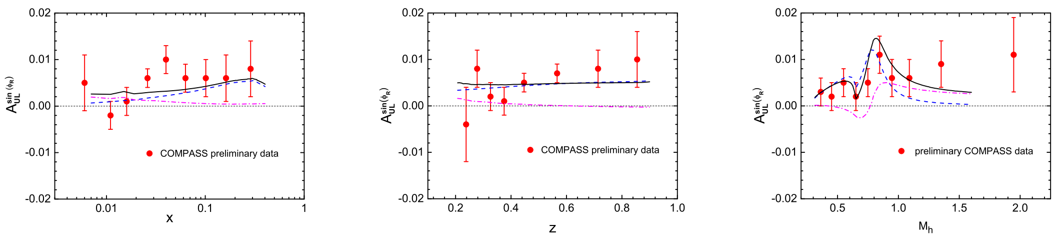

Figure 3: The $\sin\phi_R$ azimuthal asymmetry in dihadron production off the longitudinally polarized proton as functions of x (left panel), z (central panel) and M_h (right panel) at COMPASS. The full circles show the COMPASS preliminary data [14] for comparison. The dashed curves denote the contribution from the $h_L H_{1,ot}^{\sphericalangle}$ term, the dashed-dotted curves represent the contribution from the $g_1 \widetilde{G}^{\sphericalangle}$ term, and the solid lines display the sum of two contributions.

proton at the kinematics of COMPASS. The x-, z- and M_h-dependent asymmetries are depicted in the left panel, central, and right panels of the figure. We find that in the large x region and in the small M_h region, the contribution from the $h_L H_{1,ot}^{\sphericalangle,a}$ term dominates the asymmetry. The $g_1 \widetilde{G}^{\sphericalangle}$ becomes important in the small x region and large M_h region. Combining the contributions from the two terms, our calculation agrees with the COMPASS preliminary data on the $\sin\phi_R$ asymmetry.

5. Conclusion

In this work, we have studied the single longitudinal-spin asymmetry with a $\sin\phi_R$ modulation of dihadron production in SIDIS. We found that the contribution to $\widetilde{G}_{ot}^{\triangleleft}$ comes from the interference of the s and p waves. Using the numerical results of the DiFFs, we estimated the $\sin\phi_R$ asymmetry and compared it with the COMPASS measurement. Our calculation shows that the $h_L\,H_{1,ot}^{\triangleleft}$ term dominates in the most of the kinematical region. However, the inclusion of the $g_1\,G_{ot}^{\triangleleft}$ contribution yields a better description of the COMPASS data, especially in the large M_h region.

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