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# Role of the twist-3 gluon effect on the single transverse-spin asymmetry in the semi-inclusive $J/\psi$ production

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The understanding of the gluon Sivers effect is a challenging problem of future experiments on the nucleon structure. The single transverse-spin asymmetries(SSAs) in heavy quarkonium productions have been recently studied as ideal observables to investigate the gluon Sivers effect within TMD factorization framework. We here show our first study on the SSA in $J/\psi$ production within the collinear twist-3 framework combined with NRQCD framework for the description of the hadronization mechanism of $J/\psi$. Our result shows that the $J/\psi$ SSA is an ideal observable to pin down the $C$-even type twist-3 gluon distribution that has a direct relationship with the gluon Sivers TMD function. We also perform some numerical simulations of the $J/\psi$ SSA for the kinematics accessible at the future electron-ion-collider(EIC) experiment. If we only take into account the color-singlet contribution, all the nonperturbative effects except the $C$-even twist-3 gluon distribution are canceled, which means the $J/\psi$ SSA allows us to directly investigate the gluon Sivers effect at the future EIC.

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## 1. Introduction

The next-generation electron-ion collider(EIC) experiment focuses on the understanding of 3-dimensional structure of the nucleon as one of the main goals. In particular, the Sivers effect caused by the transversely polarized proton has drawn attention in the community for the past couple of decades. Although the quark Sivers effect has been well understood, the gluon Sivers effect is leaving a lot of room for research. The single transverse-spin asymmetries(SSAs) in heavy quarkonium productions have been recently studied as ideal observables to investigate the gluon Sivers effect within the transverse-momentum-dependent(TMD) factorization[1]. However, the study based on another framework, the collinear twist-3 factorization, is required for a comprehensive analysis of the data from the future EIC experiment. We here show our first study on the SSA in $J/\psi$ production within the collinear twist-3 framework combined with NRQCD framework for the description of the hadronization mechanism of $J/\psi$.

## 2. Calculation of the SSA in $J/\psi$ production in SIDIS

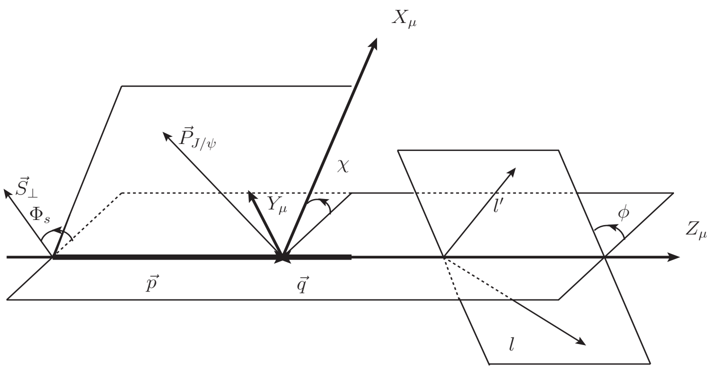


**Figure 1:** Schematic illustration of the scattering in the hadron frame.

We calculate the SSA in $J/\psi$ production in SIDIS,

$$e(\ell) + p^{\uparrow}(p, S_\perp) \to e(\ell') + J/\psi(P_{J/\psi}) + X, \tag{1}$$

in the hadron frame[2]. It is convenient to use the following Lorentz invariant variables to express cross section formulas in SIDIS.

$$S_{ep} = (p+\ell)^2, \quad Q^2 = -q^2 = -(\ell-\ell')^2, \quad x_B = \frac{Q^2}{2p\cdot q}, \quad z_f = \frac{p\cdot P_{J/\psi}}{p\cdot q}. \tag{2}$$

All momenta and the spin vector of the polarized proton are given in this frame as

$$\begin{aligned} p &= \Big(\frac{Q}{2x_B}, 0, 0, \frac{Q}{2x_B}\Big), \quad q = \Big(0,0,0,-Q\Big), \quad S_\perp = (0, \cos\Phi_S, \sin\Phi_S, 0), \\ P_{J/\psi} &= \frac{z_f Q}{2}\Big(1 + \frac{P_T^2}{Q^2} + \frac{m_{J/\psi}^2}{z_f^2 Q^2}, \frac{2P_T}{Q}\cos\chi, \frac{2P_T}{Q}\sin\chi, -1 + \frac{P_T^2}{Q^2} + \frac{m_{J/\psi}^2}{z_f^2 Q^2}\Big), \end{aligned} \tag{3}$$

where $P_T = |P^{\perp}_{J/\psi}|/z_f$ and $m_{J/\psi}$ is the mass of $J/\psi$. Using these variables, the unpolarized cross section formula is given by

$$\frac{d^6\sigma}{dx_B dQ^2 dz_f dP_T^2 d\phi d\chi} = \frac{\alpha_{em}^2\alpha_s^2 e_c^2}{4\pi S_{ep}^2 x_B^2 Q^2}\Big(\mathcal{N}\langle O^{J/\psi}(^3S_1^{[1]})\rangle\Big)$$
$$\times \sum_{i=1,\cdots,4,8,9} \mathcal{A}_i(\phi-\chi)\int_0^1 \frac{dx}{x} G(x)\,\hat{\sigma}_i \times \delta\Big[\frac{P_T^2}{Q^2} - \Big(1-\frac{1}{\hat{x}}+\frac{m_{J/\psi}^2}{z_f Q^2}\Big)\Big(1-\frac{1}{z_f}\Big)\Big], \tag{4}$$

where $\hat{x} = x_B/x$, $\alpha_{em}$ and $\alpha_s$ are respectively the QED and the QCD coupling constants, $e_c$ is the electric charge of the charm quark, $G(x)$ is the unpolarized gluon distribution and $\mathcal{N}\langle O^{J/\psi}(^3S_1^{[1]})\rangle$ is the long distance matrix element(LDME) defined in NRQCD framework[3] with its normalization constant $\mathcal{N}$. The hard cross sections $\hat{\sigma}_i$ are listed in the appendix in [2]. The azimuthal dependences are given by

$$\mathcal{A}_1(\varphi) = \frac{4}{y^2}(1-y+\frac{y^2}{2}),\quad \mathcal{A}_2(\varphi) = -2,\quad \mathcal{A}_3(\varphi) = -\frac{4}{y^2}(2-y)\sqrt{1-y}\cos\varphi,$$
$$\mathcal{A}_4(\varphi) = \frac{4}{y^2}(1-y)\cos2\varphi,\quad \mathcal{A}_8(\varphi) = -\frac{4}{y^2}(2-y)\sqrt{1-y}\sin\varphi,\quad \mathcal{A}_9(\varphi) = \frac{4}{y^2}(1-y)\sin2\varphi, \tag{5}$$

where $y = \dfrac{Q^2}{x_B S_{ep}}$. The polarized cross section is given by

$$\frac{d^6\Delta\sigma}{dx_B dQ^2 dz_f dP_T^2 d\phi d\chi} = \frac{\alpha_{em}^2\alpha_s^2 e_c^2(2\pi M_N)}{4\pi S_{ep}^2 x_B^2 Q^2}\Big(\mathcal{N}\langle O^{J/\psi}(^3S_1^{[1]})\rangle\Big)\sum_{i=1,\cdots,4,8,9}\mathcal{A}_i(\phi-\chi)$$
$$\times \mathcal{S}_i(\Phi_S-\chi)\int\frac{dx}{x^2}\delta\Big[\frac{P_T^2}{Q^2} - \Big(1-\frac{1}{\hat{x}}+\frac{m_{J/\psi}^2}{z_f Q^2}\Big)\Big(1-\frac{1}{z_f}\Big)\Big]\Big[N(x,x)\sigma_i^{N1} + N(x,0)\sigma_i^{N2}$$
$$+N(x,Ax)\sigma_i^{N3} + N(x,(1-A)x)\sigma_i^{N4} + N(Ax,-(1-A)x)\sigma_i^{N5}\Big], \tag{6}$$

where $M_N$ is the nucleon mass, $\mathcal{S}_i(\Phi_S-\chi) = \sin(\Phi_S-\chi)(i=1,2,3,4),\ \cos(\Phi_S-\chi)(i=8,9)$. All the hard cross sections are shown in the appendix in [2]. The definition of the $C$-even type twist-3 gluon distribution function $N(x_1,x_2)$ is found in [2]. LDME is exactly canceled between the unpolarized cross section (4) and the polarized cross section (6) in the ratio. Thus we can expect that the SSA in the $J/\psi$ production is an ideal observable to investigate the $C$-even twist-3 gluon distribution function $N(x_1,x_2)$.

## 3. Numerical calculation for the SSA in the $J/\psi$ production

We perform numerical simulations of the $J/\psi$ SSA for the kinematics accessible at the future EIC experiment. The cross sections (4) and (6) can be expanded in terms of five structure functions $\mathcal{F}_i$ $(i=1,2,\cdots 5)$ as

$$\frac{d^6\sigma}{dx_B dQ^2 dz_f dP_T^2 d\phi d\chi} = \sigma_1^{\rm U} + \sigma_2^{\rm U}\cos\phi_h + \sigma_3^{\rm U}\cos2\phi_h. \tag{7}$$
$$\frac{d^6\Delta\sigma}{dx_B dQ^2 dz_f dP_T^2 d\phi d\chi} = \sin(\phi_h-\phi_S)(\mathcal{F}_1+\mathcal{F}_2\cos\phi_h+\mathcal{F}_3\cos2\phi_h)$$
$$+\cos(\phi_h-\phi_S)(\mathcal{F}_4\sin\phi_h+\mathcal{F}_5\sin2\phi_h), \tag{8}$$

where the azimuthal dependences are defined by

$$\phi_h = \phi - \chi, \qquad \phi_h - \phi_S = \Phi_S - \chi. \tag{9}$$

We calculate five normalized structure functions [4],

$$\frac{\mathcal{F}_1}{\sigma_1^{\mathrm{U}}}, \quad \frac{\mathcal{F}_2}{2\sigma_1^{\mathrm{U}}}, \quad \frac{\mathcal{F}_3}{2\sigma_1^{\mathrm{U}}}, \quad \frac{\mathcal{F}_4}{2\sigma_1^{\mathrm{U}}}, \quad \frac{\mathcal{F}_5}{2\sigma_1^{\mathrm{U}}}. \tag{10}$$

The $C$-even function $N(x_1, x_2)$ has not been well constrained by experiment so far. We use the following simple models used in [5].

$$\text{model1}: \quad 0.002xG(x), \qquad \text{model 2}: \quad 0.0005\sqrt{x}G(x). \tag{11}$$

Each structure function depends on five types of $C$-even functions $\{N(x,x),\ N(x,0),\ N(x,Ax),\ N(x,(1-A)x),\ N(Ax,-(1-A)x)\}$. We separately plot the contributions from those five functions by substituting one of the models into each function. We perform our simulations with typical EIC kinematic valuables [6]: $\sqrt{S_{ep}} = 45$ GeV, $Q^2 = 10$ GeV$^2$, $x_B = 0.005$, $P^{\perp}_{J/\psi} = 2$ GeV. Fig. 2 and 3 respectively show our simulations with the model 1 and 2 for the five structure functions. We find that the magnitudes of the contributions are uniformly increased in the model 2 compared to the model 1. This reflects the fact that the model 2 is more singular with respect to $x$ and, therefore, it is enhanced at the small value of $x_B$. Future investigations in a wide range of the Bjorken variable at the EIC will provide rich information about the little-known twist-3 gluon distribution function.

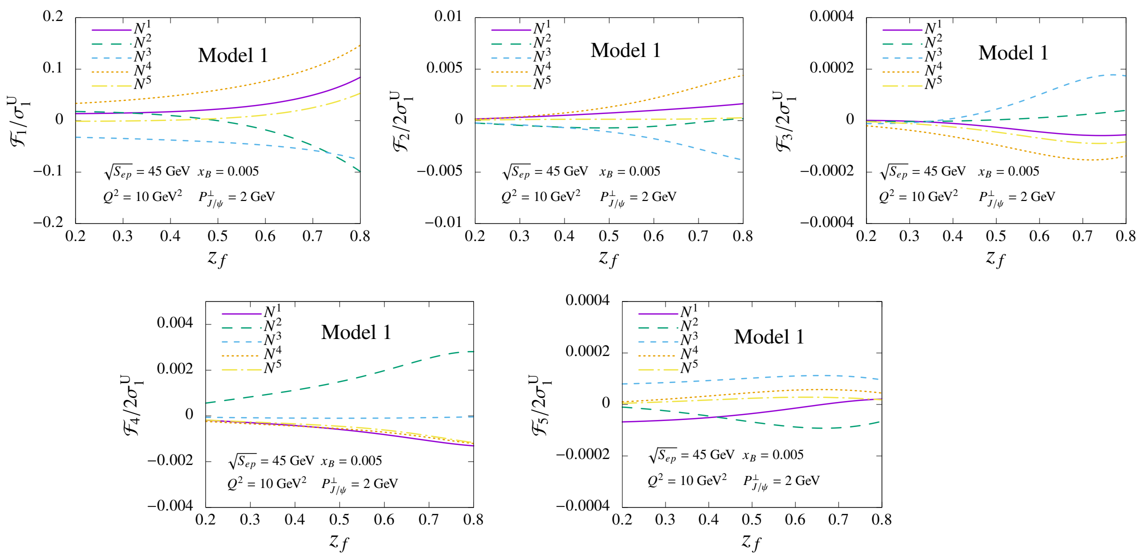


**Figure 2:** Numerical calculations for the normalized structure functions in (10). $N^{1,2,3,4,5}$ respectively show the contributions from the five functions $N(x,x)$, $N(x,0)$, $N(x,Ax)$, $N(x,(1-A)x)$, $N(Ax,-(1-A)x)$ with the model 1 function in (11).

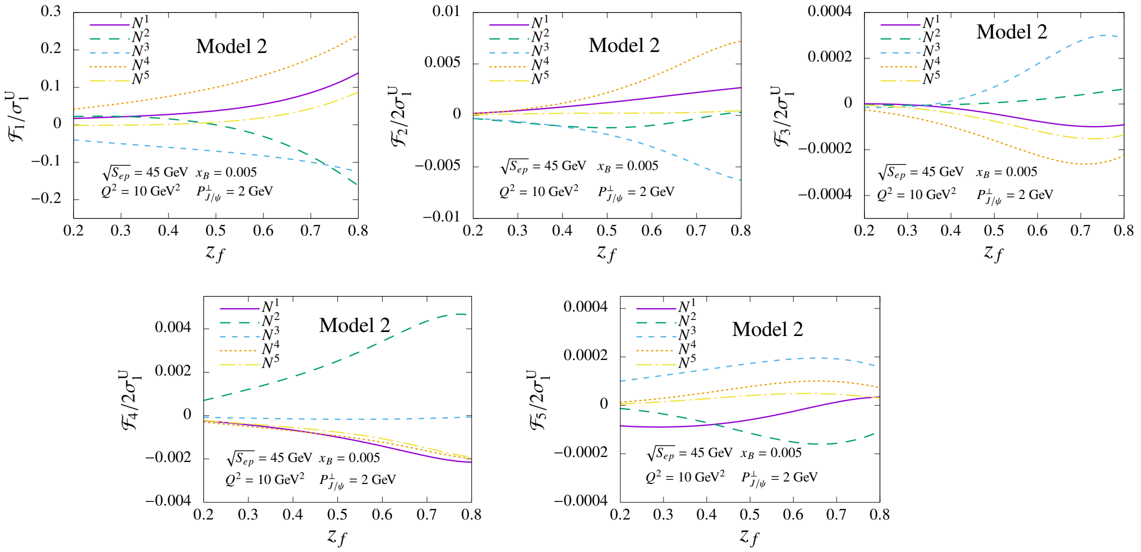


**Figure 3:** Numerical calculations for the normalized structure functions with the model 2 function in (11).

## Acknowledgements

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