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Longitudinal-transverse double-spin asymmetry with a $\cos\phi_S$ modulation in SIDIS

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We study the longitudinal-transverse double-spin asymmetry $A_{LT}^{\cos\phi_S}$ in semi-inclusive DIS for charged and neutral pions production by scattering a longitudinally polarized beam off a transversely polarized proton target. Within the collinear framework, in which the transverse momentum of the final state hadron is integrated out, we predict the asymmetry with a $\cos\phi_S$ modulation for the pion meson productions at the kinematics of CLAS12 and future Electron Ion Collider. There are two contributions to the corresponding asymmetry, one is the convolution of the twist-3 distribution function $g_T(x)$ and the unpolarized fragmentation function $D_1(z)$, the other is the coupling of the transversity distribution function $h_1(x)$ and the collinear twist-3 fragmentation function $\tilde{E}(z)$. Our numerical results show that the $\cos\phi_S$ asymmetry at CLAS12 is sizable, and the fragmentation function $\tilde{E}(z)$ plays an important role in the large-z region. The asymmetries at EIC are much smaller than those at CLAS12 due to the suppression in the large-Q region.

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1. Introduction

Recently, the $\cos\phi_S$ asymmetry in double polarized semi-inclusive deep inelastic scattering (SIDIS) was studied in Ref. [1] via spectator model calculation under the transverse momentum dependent (TMD) framework. In this work, we study the feasibility to access the twist-3 parton distribution functions (PDFs) and fragmentation functions (FFs) [2, 3, 4] via the $\cos\phi_S$ asymmetry in the collinear picture, in which the transverse momentum of the final-state hadron is integrated out (or is not measured). We estimate the $\cos\phi_S$ asymmetry as functions of x and z at kinematics of CLAS12 and the planned Electron Ion Collider (EIC), by considering the contribution from the convolution of the twist-3 PDF $g_T^q(x)$ and the unpolarized FF $D_1^q(z)$, as well the coupling of the transversity $h_1^q(x)$ and the collinear twist-3 chiral-odd FF $\tilde{E}^q(z)$. For the twist-3 PDF $g_T^q(x)$ for u and d quarks, we go beyond the Wandzura-Wilczek approximation [5] by considering the genuine twist-3 contribution [6]. For the FF $\tilde{E}^q(z)$, we adopt an approximate relation between $\tilde{E}(z)$ and $D_1(z)$ motivated by the chiral quark model [7, 8]. Furthermore, we take into account the scale dependences of the PDFs and FFs entering the description of the asymmetry.

2. Formalism on the $\cos\phi_S$ asymmetry in SIDIS at subleading twist

Up to the twist-3 level, focusing on the case where the transverse momentum of the outgoing pion meson is integrated out, the double polarized differential cross section in SIDIS with a longitudinally polarized electron scattering off a transversely polarized target has the form [4]

$$\frac{d^4\sigma}{dxdydzd\phi_S} = \frac{2\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\times\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}(x,z)\,, \tag{2.1}$$

here the collinear counterpart of the original structure function $F_{LT}^{\cos\phi_S}(x,z)$ can be given as [4]

$$\begin{aligned} F_{LT}^{\cos\phi_S}(x,z) &= \int d^2\boldsymbol{P}_{hT} F_{LT}^{\cos\phi_S}(x,z,P_{hT}) \\ &= -x\sum_q e_q^2 \frac{2M}{Q}\left(x g_T^q(x) D_1^q(z) + \frac{M_h}{M} h_1^q(x)\frac{\tilde{E}^q(z)}{z}\right). \end{aligned} \tag{2.2}$$

Since we only consider the case that the longitudinal momentum fraction z of pion is measured, Eq. (2.2) contains the convolution of the twist-3 distribution $g_T^q(x)$ and the twist-2 FF $D_1^q(z)$, as well as that of the twist-3 fragmentation function $\tilde{E}^q(z)$ and the twist-2 PDF $h_1^q(x)$. Thus, the x- and z-dependent $\cos\phi_S$ asymmetry can be defined as

$$A_{LT}^{\cos\phi_s}(x) = \frac{\int dy\int dz \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}(1+\frac{\gamma^2}{2x})\sqrt{2\varepsilon(1-\varepsilon)}F_{LT}^{\cos\phi_s}(x,z)}{\int dy\int dz \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}(1+\frac{\gamma^2}{2x})F_{UU}(x,z)}\,, \tag{2.3}$$

$$A_{LT}^{\cos\phi_s}(z) = \frac{\int dx\int dy \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}(1+\frac{\gamma^2}{2x})\sqrt{2\varepsilon(1-\varepsilon)}F_{LT}^{\cos\phi_s}(x,z)}{\int dx\int dy \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}(1+\frac{\gamma^2}{2x})F_{UU}(x,z)}, \tag{2.4}$$

where F_{UU} is the unpolarized structure function:

$$F_{UU}(x,z) = x\sum_q e_q^2 f_1^q(x) D_1^q(z)\,, \tag{2.5}$$

with $f_1^q(x)$ and $D_1^q(z)$ being the unpolarized PDF and FF, respectively.

With the combination of the spin-dependent structure functions $g_1(x)$ and $g_2(x)$, the related twist-3 distribution function $g_T^q(x)$ can be expressed as [9]:

$$\frac{1}{2}\sum_q e_q^2 g_T^q(x) = g_1(x) + g_2(x)\,, \tag{2.6}$$

where $g_1(x)$ is the leading twist structure function contributed from the helicity PDFs

$$g_1(x) = \frac{1}{2}\sum_q e_q^2 g_1^q(x)\,, \tag{2.7}$$

and $g_2(x)$ is the structure function related to the transverse spin of the target proton. It can be separated into the Wandzura-Wilczek part $g_2^{WW}(x)$ and the genuine twist-3 part $g_2^{\mathrm{tw}-3}(x)$

$$g_2(x) = g_2^{WW}(x) + g_2^{\mathrm{tw}-3}(x)\,. \tag{2.8}$$

If the contribution the higher twist part $g_2^{\mathrm{tw}-3}(x)$ is absent, the structure function $g_2(x)$ is only determined by the structure function $g_1(x)$ with the referred Wandzura-Wilczek approximation [5],

$$g_2 \overset{WW}{\approx} g_2^{WW}(x) = -g_1(x) + \int_x^1 dy \frac{g_1(y)}{y}. \tag{2.9}$$

Particularly, in this work we apply the parameterizations result of $g_2^{\mathrm{tw}-3}(x)$ for proton and neutron in Ref. [6] and consider the isospin symmetry as well as assume that $g_2^{\mathrm{tw}-3}(x)$ is mainly contributed by u and d quarks to obtain the twist-3 PDF $g_T^q(x)$:

$$g_T^u(x) = \int_x^1 dy \frac{g_1^u(y)}{y} + \frac{6}{5}(4g_{2,p}^{\mathrm{tw}-3}(x) - g_{2,n}^{\mathrm{tw}-3}(x)), \tag{2.10}$$

$$g_T^d(x) = \int_x^1 dy \frac{g_1^d(y)}{y} + \frac{6}{5}(4g_{2,n}^{\mathrm{tw}-3}(x) - g_{2,p}^{\mathrm{tw}-3}(x)). \tag{2.11}$$

To estimate the asymmetry $A_{LT}^{\cos\phi_S}$ contributed by $\tilde{E}^q(z)$, we apply the equation of motion relation [3]

$$\frac{E^q(z)}{z} = \frac{\tilde{E}^q(z)}{z} + \frac{m_q}{M_h} D_1^q(z), \tag{2.12}$$

where $E^q(z)$ is the twist-3 FF [10] encoded in the quark-quark correlation during fragmentation, m_q is the current quark mass, and M_h is the mass of final state hadron. The FF $E^q(z)$ can be obtained from the chiral quark model [8]

$$E^q(z) = \frac{m'_q}{M_h}\frac{z}{1-z} D_1^q(z), \tag{2.13}$$

with m'_q being the constituent quark mass. In principle, the current quark mass should be much smaller than the constituent quark mass. As a rough estimate, we assume that values of the two masses are the same for simplicity. Though this assumption may be crude, it will not change the main result as shown in Ref. [11]. Thus, $\tilde{E}^q(z)$ in our estimation can be given as

$$\tilde{E}^q(z) = \frac{m'_q}{M_h}\frac{z^2}{1-z} D_1^q(z)\,, \tag{2.14}$$

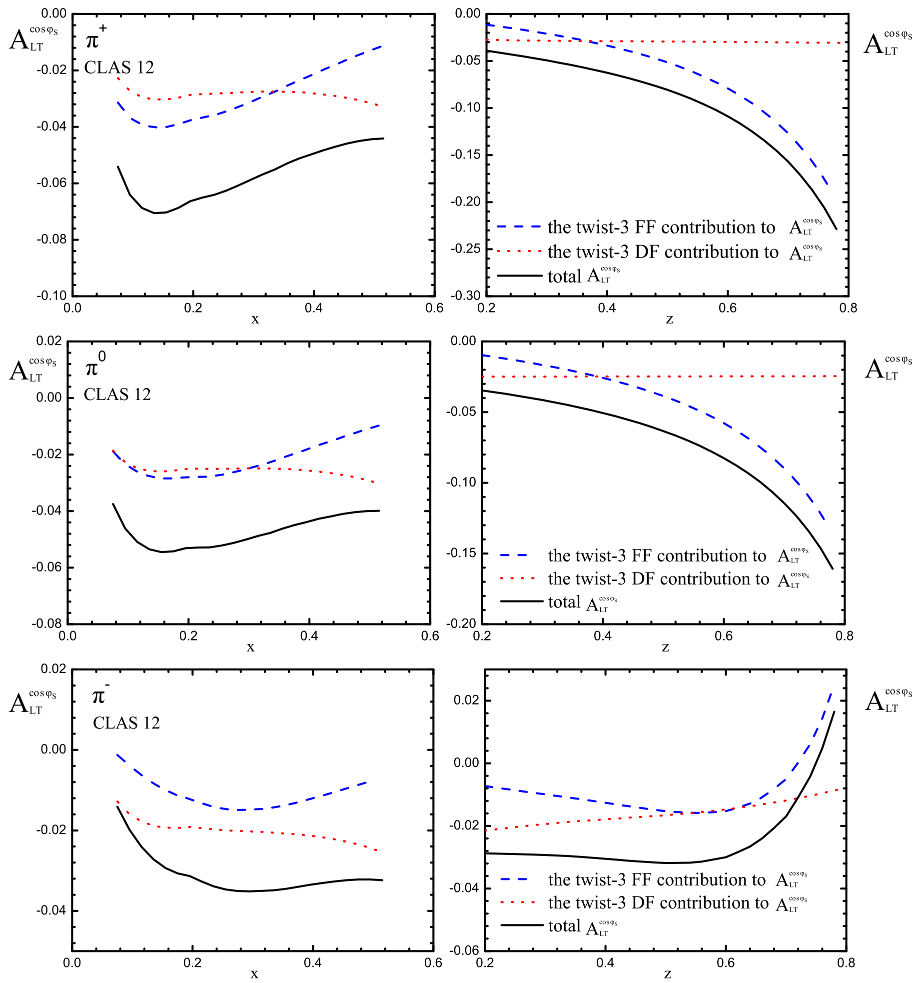

Figure 1: The asymmetry$A_{LT}^{\cos\phi_S}$ of π^+, π^0 and π^- production in SIDIS at CLAS12.

following the choice in Ref. [8], the quark mass $m_q' \approx M/3$. For the unpolarized FF $D_1^q(z)$, we choose the LO set of the DSS parametrization [12].

For the referred PDFs, we adopt the GRSV2000 LO parametrization [13] for the helicity $g_1^q(x)$, and apply the GRV98 leading-order (LO) parametrization [14] for the unpolarized PDF $f_1^q(x)$ to be in consistence with the choices in Ref. [15]. As for the transversity $h_1(x)$ in Eq. (2.2), we adopt the standard parametrization from Ref. [15] (at the initial scale $Q^2 = 2.41$ GeV^2):

$$h_1^q(x) = \frac{1}{2}\mathcal{N}_q^T(x)[f_1^q(x) + g_1^q(x)]\,, \tag{2.15}$$

with

$$\mathcal{N}_q^T(x) = N_q^T x^\alpha (1-x)^\beta \frac{(\alpha+\beta)^{\alpha+\beta}}{\alpha^\alpha \beta^\beta}. \tag{2.16}$$

3. Numerical Estimate

In this section, we perform the numerical calculation to obtain an estimate of the $\cos\phi_S$ asymmetry by taking into account the kinematical configurations at CLAS12 and EIC.

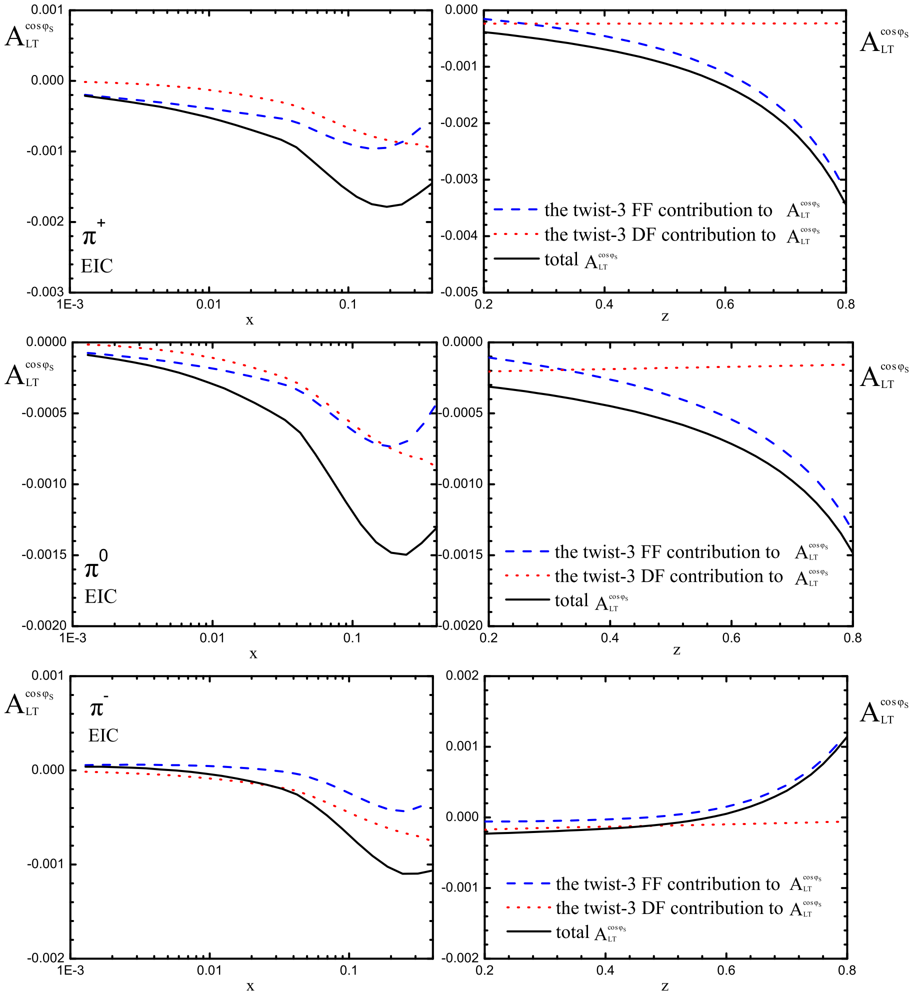

Figure 2: Similar to Fig.1, but at EIC for $\sqrt{s} = 45\,\text{GeV}$.

The kinematical configuration used to calculate the $\cos\phi_S$ asymmetry at CLAS12 is [16],

$$\begin{aligned} &0.072 < x < 0.532, \quad 0.2 < z < 0.8, E_e = 11 \text{ GeV}, \\ &W^2 > \ 4 \text{ GeV}^2, \quad 1 < Q^2 < 6.3 \text{ GeV}^2, \end{aligned} \tag{3.1}$$

where W is the invariant mass of the photon-nucleon system $W^2 = (P+q)^2 \approx \frac{1-x}{x} Q^2$. In the upper, central and lower panels of Fig. 1, we show the x-dependent and z-dependent $\cos\phi_S$ asymmetries at CLAS12 for π^+, π^0 and π^-, respectively. We find the $\cos\phi_S$ asymmetries for both the charged and neutral pions are sizable at CLAS12, about several percent. The size of the asymmetries for π^+ and π^0 is larger than the size of the asymmetry for π^- production. Therefore, it is feasible to measure the $\cos\phi_S$ asymmetry through the CLAS12 experiments, in the case the transverse momentum of the final hadron is not measured.

To calculate the $\cos\phi_S$ asymmetry at EIC, we adopt the following kinematical cuts [16]

$$\begin{aligned} &Q^2 > 1\text{GeV}^2, \quad 0.001 < x < 0.4, \quad 0.01 < y < 0.95, \\ &0.2 < z < 0.8, \quad \sqrt{s} = 45 \text{ GeV}, \quad W > 5 \text{ GeV}. \end{aligned} \tag{3.2}$$

In Fig. 2, we plot $A_{LT}^{\cos\phi_S}$ of charged and neutral pions vs x and z at EIC, similar to the format in Fig. 1. Although the sign and the shape of the asymmetries for different pion productoin at EIC are similar to those at CLAS12, it is found that the $\cos\phi_S$ asymmetry at the kinematical configuration of EIC is much smaller (less than 0.3%). This is because the asymmetry we study is at the twist-3 level, at which the effect will be suppressed by $1/Q$, and the averaged Q value at EIC is much higher than that at CLAS12.

4. Conclusion

In this work, we have studied the $\cos\phi_S$ asymmetry in double polarized SIDIS at CLAS12 and EIC within the collinear framework. The numerical prediction shows that the asymmetries for the charged and neutral pions are all sizable at CLAS12, about several percent. In contrast, the asymmetries at EIC are much smaller due to the suppression in the large-Q region. Although for the x-dependent asymmetry the size of the contribution from $\tilde{E}^q(z)$ is comparable to that from $g_T^q(x)$, we find that the asymmetry in the large-z region is completely dominated by the convolution of $h_1^q(x)$ and $\tilde{E}^q(z)$. Therefore, it might be promising to access the unknown twist-3 FF $\tilde{E}^q(z)$ via the measurement of the $\cos\phi_S$ asymmetry of pion production in SIDIS with the collinear picture.

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