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Single-spin asymmetry $A_{UUT}^{\sin\phi_{S_h}}$ of proton and Λ production in SIDIS at subleading twist

Wenjuan MAO[*†]

School of Physics and Telecommunication Engineering, Zhoukou Normal University, Zhoukou 466001, Henan, China
E-mail: wjmao@seu.edu.cn

Yongliang Yang

School of Physics, Southeast University, Nanjing 211189, China
College of Physics, Qingdao University, Qingdao 266071, China
E-mail: yangyl@seu.edu.cn

Zhun LU

School of Physics, Southeast University, Nanjing 211189, China
E-mail: zhunlu@seu.edu.cn

Bo-Qiang Ma

School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
E-mail: mabq@pku.edu.cn

We investigate the single-spin asymmetry with a $\sin\phi_{S_h}$ modulation for the transversely polarized proton and Λ production in semi-inclusive inelastic scattering process, where ϕ_{S_h} is the azimuthal angle of the transverse spin of the final hadron. Theoretically, the spin asymmetry can be interpreted by the convolution of the twist-3 transverse momentum dependent distributions and twist-2 fragmentation functions. In this work, three different origins in terms of the hH_1 term, the $f^\perp D_{1T}^\perp$ term and the $g^\perp G_{1T}$ term are taken into account simultaneously for this asymmetry. We calculate the twist-3 quark transverse momentum dependent distributions h, $f^\perp$ and $g^\perp$ by using the quark spectator diquark model, and we investigate the role of the fragmentation functions H_1, $D_{1T}^\perp$ and G_{1T} in the $\sin\phi_{S_h}$ asymmetry as well. We also predict the numerical results of the asymmetries for the proton and the Λ production at JLab with a 12 GeV beam and at COMPASS with a 160 GeV beam, separately. From the comparison of the different sources for the asymmetry, we find that, the distribution h and the fragmentation function H_1 give the dominant contribution to the $\sin\phi_{S_h}$ asymmetry for proton production, while the distribution $f^\perp$ might be probed by the convolution with $D_{1T}^\perp$ in the Λ production at JLab 12 GeV.

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1. Introduction

In this work, we extend the phenomenological study of the polarized hadron production in SIDIS at the twist-3 level within the transverse momentum dependent (TMD) framework. We focus on the single spin asymmetry (SSA) with a $\sin\phi_{S_h}$ modulation in the transversely polarized hadron production in SIDIS off an unpolarized nucleon: $\ell + N \longrightarrow \ell' + h^\uparrow + X$, where ϕ_{S_h} is the azimuthal angle of the transverse spin S_{hT} with respect to the lepton plane. Following Ref. [1, 2], there are several contributions to this asymmetry from the convolutions of the twist-2 TMD fragmentation functions with twist-3 TMD distribution functions. We calculate the involved distributions and the fragmentation functions in a spectator diquark model [3, 4]. Using the model results, we investigate the roles of the hH_1, $g^\perp G_{1T}$ and $f^\perp D_{1T}^\perp$ couplings in the SSA $A_{UUT}^{\sin\phi_{S_h}}$ for the transversely polarized proton and the Λ hyperon production in SIDIS at the JLab 12 GeV and at COMPASS.

2. Twist-3 TMD distribution functions in a spectator model

The three involved twist-3 TMD distributions in this work are the T-odd distribution $g^\perp$, the T-even distribution $f^\perp$ and the T-odd distribution h, respectively. We have presented the calculation on the T-odd distribution $g^\perp$ in a spectator model with both the scalar and the axial-vector diquark in Ref. [5, 6]. Therefore, following the same method, we can calculate the other two twist-3 TMD distribution functions h and $f^\perp$ from the quark-quark correlator $\Phi(x, \boldsymbol{p_T}; S)$ via the traces

$$\frac{1}{4}\,\mathrm{Tr}[(\Phi(x,\boldsymbol{p}_T;S) + \Phi(x,\boldsymbol{p}_T;-S))\, i\sigma^{\alpha\beta}\gamma_5] = -\frac{M}{P^+}\varepsilon_T^{\alpha\beta} h, \tag{2.1}$$

$$\frac{1}{4}\,\mathrm{Tr}[(\Phi(x,\boldsymbol{p}_T;S) + \Phi(x,\boldsymbol{p}_T;-S))\, \gamma^{\alpha}] = \frac{p_T^\alpha}{P^+} f^\perp\,. \tag{2.2}$$

The corresponding expressions of h and $f^\perp$ from the scalar component are

$$h(x,\boldsymbol{p}_T^2)_s = -\frac{N_s^2(1-x)^3}{16\pi^3 M}\frac{e_s e_q}{4\pi}\frac{(m+xM)(L_s^2-\boldsymbol{p}_T^2)}{L_s^2(\boldsymbol{p}_T^2+L_s^2)^3}\,, \tag{2.3}$$

$$f^\perp(x,\boldsymbol{p}_T^2)_s = -\frac{N_s^2(1-x)^2}{16\pi^3}\frac{(\boldsymbol{p}_T^2-2mM(1-x)-(1-x^2)M^2+m_s^2)}{(\boldsymbol{p}_T^2+L_s^2)^4}\,, \tag{2.4}$$

and the ones that from the axial-vector diquark component are

$$h(x,\boldsymbol{p}_T^2)_a = 0\,, \tag{2.5}$$

$$f^\perp(x,\boldsymbol{p}_T^2)_a = \frac{N_a^2(1-x)}{16\pi^3}\frac{(x\boldsymbol{p}_T^2+2mM(1-x)^2+(x-1)m^2+(x^3-2x^2+1)M^2-m_a^2)}{L_a^2(\boldsymbol{p}_T^2+L_a^2)^3}\,. \tag{2.6}$$

The detailed calculation of the distributions h and $f^\perp$ has been performed in Ref. [7]. To construct the distributions for the u and d quarks, we adopt the following relation between the flavors and isospins of the diquark $f^u = c_s^2 f^s + c_a^2 f^a$, $f^d = c_{a'}^2 f^{a'}$ [3]. c_s, c_a and $c_{a'}$ are the free parameters of the model, a and a' denote the isoscalar and isovector states of the axial-diquark, respectively.

In Fig. 1, we show the dependence of the distributions $f^\perp$ and h on the flavors, Bjorken x and the active quark transverse momentum $p_T = 0.3$ GeV. As we can see, the distributions $f^{\perp u}$ and $f^{\perp d}$ are in similar sizes in the specified kinematic region ($x = 0.3$ or $p_T = 0.25$ GeV). While

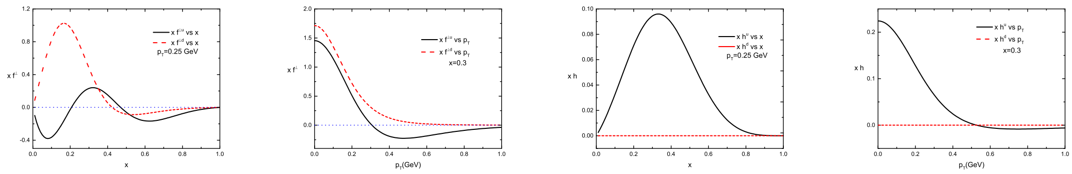

Figure 1: Model results for $xf^{\perp u}(x,p_T^2)$, $xh^u(x,p_T^2)$ (solid line) and $xf^{\perp d}(x,p_T^2)$, $xh^d(x,p_T^2)$ (dashed line).

for the T-odd distribution h, its size is smaller compared to those of the T-even distributions $f^{\perp}$. Particularly, we can verify that h^u vanishes when one integrates out the transverse momentum $\int d^2p_T h^u(x,\boldsymbol{p}_T^2)=0$, which is an expected result from the time-reversal invariance.

3. Twist-2 TMD fragmentation functions in spectator model

In this section, we will perform the model calculation on the relevant twist-2 TMD polarized fragmentation functions H_1, G_{1T} and $D_{1T}^{\perp}$. Since $D_{1T}^{\perp}$ has been calculated for the Λ hyperon by the same spectator diquark model in Ref. [8], we will focus on the proton fragmentation function $D_1^{p/q}$. The calculation on the left two TMD fragmentation functions H_1 and G_{1T} can be performed from the fragmentation correlation function $\Delta(z,\boldsymbol{k}_T;\boldsymbol{S}_{hT})$ by the traces

$$S_T^{\alpha} H_1(z,\boldsymbol{k}_T^2) = \frac{1}{4}\mathrm{Tr}[(\Delta(z,\boldsymbol{k}_T;\boldsymbol{S}_{hT})-\Delta(z,\boldsymbol{k}_T;-\boldsymbol{S}_{hT}))i\sigma^{\alpha -}\gamma_5], \tag{3.1}$$

$$S_{hL}G_{1L}(z,\boldsymbol{k}_T^2)+\frac{\boldsymbol{k}_T\cdot\boldsymbol{S}_{hT}}{M_h}G_{1T}(z,\boldsymbol{k}_T^2) = \frac{1}{4}\mathrm{Tr}[(\Delta(z,\boldsymbol{k}_T;\boldsymbol{S}_{hT})-\Delta(z,\boldsymbol{k}_T;-\boldsymbol{S}_{hT}))\gamma^{-}\gamma_5]. \tag{3.2}$$

The spin vector of the outgoing hadron S_h has the form $S_h^{\mu}=S_{hL}\frac{(P_h\cdot n_+)n_-^{\mu}-(P_h\cdot n_-)n_+^{\mu}}{M_h}+S_{hT}^{\mu}$.

Assuming the SU(6) spin-flavor symmetry for the final state hadron [9, 10], the relations between quark flavors and diquark types for the proton and the Λ hyperon can be established as

$$D^{\mathrm{u}\to p}=\frac{3}{2}D^{(s)}+\frac{1}{2}D^{(v)},\quad D^{\mathrm{d}\to p}=D^{(v)}, D^{\mathrm{s}\to p}=0 \tag{3.3}$$

$$D^{\mathrm{u}\to\Lambda}=D^{\mathrm{d}\to\Lambda}=\frac{1}{4}D^{(s)}+\frac{3}{4}D^{(v)},\quad D^{\mathrm{s}\to\Lambda}=D^{(s)}. \tag{3.4}$$

Following the method and settings in Ref. [11], the modeling expression of the twist-2 TMD unpolarized fragmentation function D_1 can be obtained as

$$D_1^{(s)}(z,\boldsymbol{k}_T^2)=D_1^{v}(z,\boldsymbol{k}_T^2)=\frac{g_D^2}{2(2\pi)^3}\frac{1}{z^2}e^{\frac{-2k^2}{\Lambda^2}}\frac{(1-z)[z^2k_T^2+(M+zm)^2]}{z^4(k_T^2+L^2)^2}, \tag{3.5}$$

which has already been calculated in Ref. [8]. According to Eq. (3.3) and Eq. (3.5), the unpolarized fragmentation function D_1 for proton satisfies the relation $D_1^{\mathrm{u}\to p}=2D_1^{\mathrm{d}\to p}$, which is consistent with the HKNS parametrization of D_1^p presented in Ref. [12].

Similarly, we can get the model results of the TMD fragmentation functions H_1 and G_{1T} [7]

$$H_1^R(z,\boldsymbol{k}_T^2)=a_R\frac{g_D^2}{2(2\pi)^3}\frac{1}{z^2}e^{\frac{-2k^2}{\Lambda^2}}\frac{(1-z)[(zm+M_h)^2]}{z^4(\boldsymbol{k}_T^2+L_f^2)^2}, \tag{3.6}$$

$$G_{1T}^R(z,\boldsymbol{k}_T^2)=a_R\frac{g_D^2}{(2\pi)^3}\frac{1}{z^2}e^{\frac{-2k^2}{\Lambda^2}}\frac{M_h(zm+M_h)(1-z)}{z^3(\boldsymbol{k}_T^2+L_f^2)^2}, \tag{3.7}$$

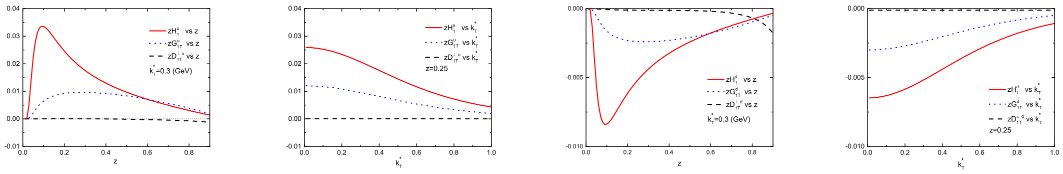

Figure 2: Model results of zH_1^u and zH_1^d (solid line), zG_{1T}^u (dotted line) and zG_{1T}^d, $zD_{1T}^{\perp u}$ and $zD_{1T}^{\perp d}$(dashed line) for the proton.

with $L_f^2 = \frac{1-z}{z^2}M_h^2 + m^2 + \frac{m_D^2 - m^2}{z}$. From Eqs. (3.3), (3.4) and (3.6), (3.7), one can find that for the fragmentation functions H_1 and G_{1T}, both the u and d quark fragmenting to the Λ hyperon will vanish in our model, while the u and d quark fragmenting to the proton will be nonzero. That is, for the Λ production, we only need to consider the contribution from $D_{1T}^{\perp}$.

In Fig. 2, we present our model results of the twist-2 TMD fragmentation functions H_1, G_{1T} and $D_{1T}^{\perp}$ for the u and d quark fragmenting to the proton. As one can see, H_1 and G_{1T} decrease but $D_{1T}^{\perp}$ increases with increasing z; the magnitude of H_1 is lager than that of G_{1T}, while $D_{1T}^{\perp}$ is nonzero only in the large z region. From the view of the flavors, H_1^u and G_{1T}^u are positive in the model, while H_1^d and G_{1T}^d are negative. As for $D_{1T}^{\perp}$, only $D_{1T}^{\perp d}$ becomes sizable at large z.

4. Prediction on the SSA of transversely polarized proton and Λ hyperon in SIDIS

The differential cross section of the process for the transverse polarized hadron in SIDIS off the unpolarized proton is generally expressed as [13]

$$\frac{d\sigma}{dxdydzd\phi d\psi dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}(1+\frac{\gamma^2}{2x})\left\{F_{UUU} + |S_{hT}|\sin\phi_{S_h}\sqrt{2\varepsilon(1+\varepsilon)}F_{UUT}^{\sin\phi_{S_h}} + \cdots\right\}. \tag{4.1}$$

Here F_{UUU} and $F_{\mathrm{UUT}}^{\sin\phi_{S_h}}$ are structure functions that contributes to the $\sin\phi_{S_h}$ azimuthal asymmetry, which $P_{h\perp}$-dependent expression can be defined as

$$A_{UUT}^{\sin\phi_{S_h}}(P_{h\perp}) = \frac{\int dx \int dy \int dz\, \frac{1}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\sqrt{2\varepsilon(1+\varepsilon)}\,F_{UUT}^{\sin\phi_{S_h}}}{\int dx \int dy \int dz\, \frac{1}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)F_{\mathrm{UUU}}}. \tag{4.2}$$

The x-dependent and the z-dependent asymmetries can be given in a similar way.

To perform the estimate, we adopt a more phenomenological approach by using the factorization at the tree-level [14] to give the expression for the structure function $F_{UUT}^{\sin\phi_{S_h}}$:

$$F_{UUT}^{\sin\phi_{S_h}} \approx \frac{2M}{Q}\mathscr{I}[-xhH_1 + \frac{\boldsymbol{k_T}\cdot\boldsymbol{p_T}}{2MM_h}(-xf^{\perp}D_{1T}^{\perp} - xg^{\perp}G_{1T})]. \tag{4.3}$$

where we introduce the convolution integral

$$\mathscr{I}[\omega f D] = x\sum_q e_q^2 \int d^2\boldsymbol{p}_T \int d^2\boldsymbol{k}_T \delta^2(\boldsymbol{p}_T - \frac{\boldsymbol{P}_{h\perp}}{z} - \boldsymbol{k}_T)w(\boldsymbol{p}_T,\boldsymbol{k}_T)f^q(x,\boldsymbol{p}_T^2)D^q(z,\boldsymbol{k}_T^2), \tag{4.4}$$

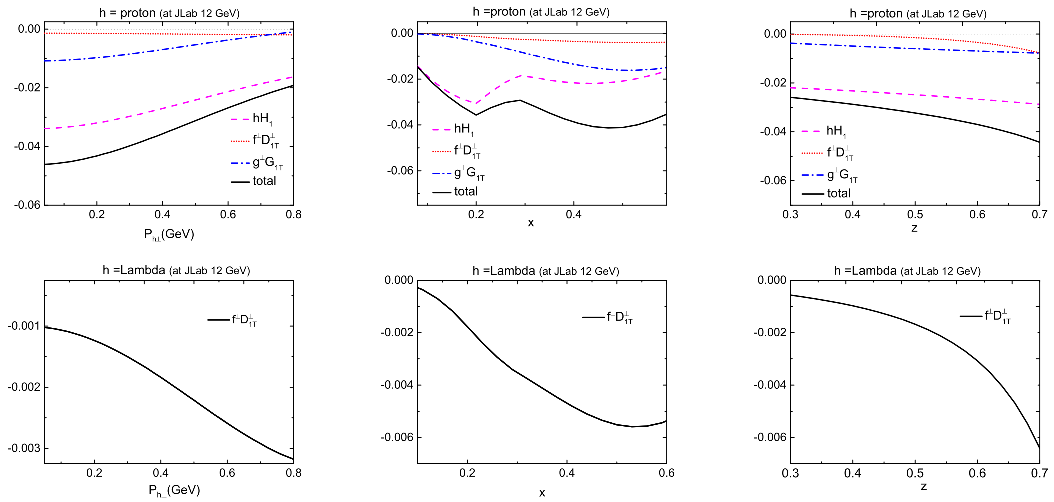

Figure 3: Predictions on the asymmetry $A_{\mathrm{UUT}}^{\sin\phi_{S_h}}$ for proton and Λ in SIDIS at JLab 12 GeV.

and the Wandzur-Wilczek approximation [15] to ignore the contribution from the twist-3 TMD fragmentation functions $\tilde{D}_T$, $\tilde{H}_T^{\perp}$ and $\tilde{H}_T$ to $F_{UUT}^{\sin\phi_{S_h}}$.

Considering the following constraints on the transverse momenta of the initial quarks [16]

$$\begin{cases} \boldsymbol{p}_T^2 \leq (2-x)(1-x)Q^2, & \text{for } \ 0 < x < 1; \\ \boldsymbol{p}_T^2 \leq \frac{x(1-x)}{(1-2x)^2}\,Q^2, & \text{for } \ x < 0.5; \end{cases} \tag{4.5}$$

and the kinematical cuts adopted at JLab 12 GeV

$$0.1 < x < 0.6, \ \ 0.3 < z < 0.7, \ \ Q^2 > 1\mathrm{GeV}^2, \ \ W^2 > 4\,\mathrm{GeV}^2, P_{h\perp} > 0.05\,\mathrm{GeV}, \tag{4.6}$$

we estimate the SSA $A_{UUT}^{\sin\phi_{S_h}}$ of proton and Λ hyperon production in SIDIS. The numerical results are shown in Fig. 3. For proton production, the magnitude of the asymmetry $A_{\mathrm{UUT}}^{\sin\phi_{S_h}}$ is sizable and negative, and the size is around 4% at the kinematics of JLab. While for the Λ hyperon production, the size is smaller than 1%, since it gets contribution only from the $f^{\perp}D_{1T}^{\perp}$ term in our model.

We also estimate this same asymmetry for proton and Λ at COMPASS with the kinematics [17]

$$\begin{aligned} &0.004 < x < 0.7, \ \ 0.1 < y < 0.9, \ \ z > 0.2, \ \ Q^2 > 1\,\mathrm{GeV}^2, \\ &P_{h\perp} > 0.1\,\mathrm{GeV}, \ \ W > 5\,\mathrm{GeV}, \ \ E_h > 1.5\,\mathrm{GeV}. \end{aligned} \tag{4.7}$$

The responding asymmetries $A_{\mathrm{UUT}}^{\sin\phi_{S_h}}$ for proton and Λ hyperon are shown in Fig. 4. Interestingly, the size of the hH_1 contribution at COMPASS is clearly smaller than that of JLab. This is because the twist-3 effect is suppressed by a factor of $1/Q$, while Q at COMPASS is larger than that at JLab.

5. conclusion

In this work, we predicted the contributions from three twist-3 terms to the SSA $A_{UUT}^{\sin\phi_{S_h}}$ in the transversely polarized proton as well as Λ production in SIDIS at the kinematics of JLab 12

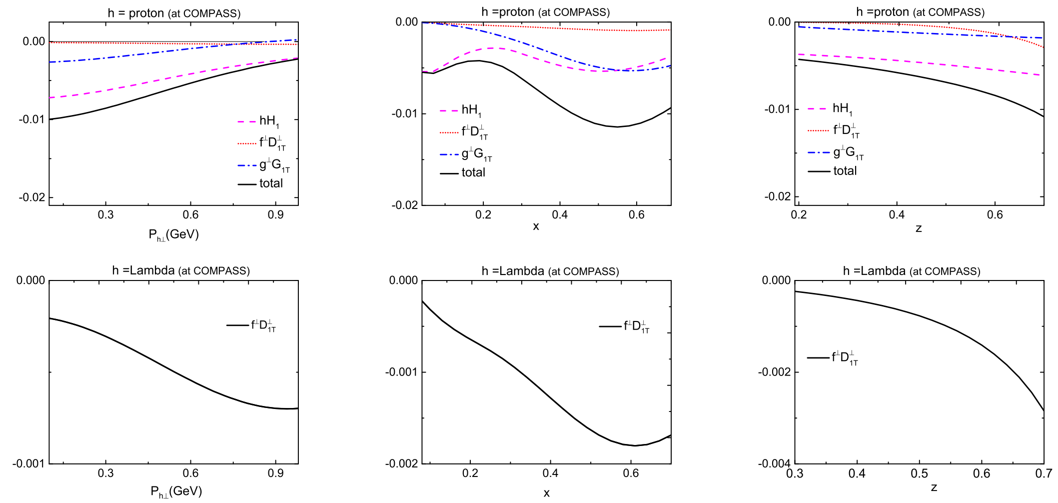

Figure 4: Predictions on the asymmetry $A_{\rm UUT}^{\sin\phi_{S_h}}$ for proton and Λ in SIDIS at COMPASS.

GeV and COMPASS. The estimated contributions to the asymmetry for the proton is sizable and negative. Specifically, the magnitude is around 4% at JLab 12 GeV, but about 1% at COMPASS. The $\sin\phi_{S_h}$ asymmetry from the $f^{\perp}D_{1T}^{\perp}$ term for the Λ hyperon production is much smaller.

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