Single-Spin Asymmetries $A_{UL}^{\sin \phi_h}$ in Semi-Inclusive Pions Production

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The single-spin asymmetry $A_{UL}^{\sin \phi_h}$ of charged and neutral pion production in semi-inclusive deep-inelastic scattering on longitudinally polarized nucleon targets is studied. We particularly consider the effects of the twist-3 transverse-momentum dependent distribution functions $f_L^\perp$ and h_L , which are calculated in two different spectator-diquark models. We estimate the asymmetry for π^+ , π^- and π^0 produced off the proton target at HERMES and compare the results with the HERMES measurements. We also predict the same asymmetric moment for different pions at the kinematics of CLAS 5.5 GeV on a proton target, as well as at COMPASS on a deuteron target for comparison.

Keywords: Single-spin asymmetries; semi-inclusive deep inelastic scattering; transverse-momentum dependent distribution function.

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1. Introduction

As the first unambiguous single-spin phenomenon measured in Semi-inclusive deep-inelastic scattering (SIDIS), the longitudinal target spin asymmetry (LTSA)¹⁻⁴ has attracted a lot of theoretical attentions. Experimentally, the LTSA is usually measured by using the target which is longitudinally polarized with respect to the incoming beam direction, which makes the interpretation of the asymmetry more complicated. This is because in this case the measured asymmetry contains contributions from both the transverse and longitudinal polarization components with respect to the virtual photon direction. The small but non-vanishing transverse polarization component, although suppressed by a factor $1/Q$ compared to the longitudinal component, can contribute to the measured asymmetry through the

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collins⁵ or Sivers⁶ effects, which are leading-twist observables. Apart from the leading-twist effects, there are also competing contributions that originate from the various convolutions of the twist-3 quark distribution functions or fragmentation functions with their twist-2 counterparts, due to the presence of the large longitudinal polarization component.

The purpose of this work is to study the LTSA based upon the contributions from the subleading-twist effects. Although those effects encode important twist-3 dynamics of the nucleon, they have not been fully considered in the previous theoretical analyses. At the twist-3 level, there are four individual contributions⁷ that can give rise to the LTSA. Two of them are from the twist-3 fragmentation functions, while another two are from the twist-3 distribution functions. Here we will focus on the effects of the twist-3 quark distributions, that is, the distributions $f_L^\perp(x, \mathbf{k}_T^2)$ and $h_L(x, \mathbf{k}_T^2)$. The former distribution is a T-odd function and can be viewed as the twist-3 analogy of the Sivers function;⁶ it gives rise to the LTSA through the coupling with the unpolarized fragmentation function D_1 . The latter one is a chiral-odd distribution, and its contribution to the LTSA involves the so called Collins function $H_1^\perp$.⁵ In our study, we will take both the $f_L^\perp D_1$ term⁸ and the $h_L H_1^\perp$ term⁹ into consideration. To quantitatively predict the LTSA in SIDIS contributed by the subleading-twist effect, we will employ spectator-diquark models to calculate the TMD distributions $f_L^\perp$ and h_L for the u and d valence quarks inside the proton.

2. Model Calculation of TMD Distributions $f_L^\perp$ and h_L

The gauge-invariant quark-quark correlator for the longitudinally polarized nucleon can be expressed as

$$\begin{aligned} \Phi^{[+]}(x, \mathbf{k}_T) &= \int \frac{d\xi^- d^2\xi_T}{(2\pi)^3} e^{ik \cdot \xi} \langle PS_L | \bar{\psi}_j(0) \mathcal{L}[0^-, \infty^-] \\ &\quad \times \mathcal{L}[0_T, \xi_T] \mathcal{L}[\infty^-, \xi^-] \psi_i(\xi) | PS_L \rangle. \end{aligned}$$

It can be calculated by the spectator models.^{10–13} Here we consider the contributions of both the scalar diquark and the axial-vector diquark, and use the dipolar form factor for the nucleon-quark-diquark couplings. For comparison, we also adopt two different spectator models to calculate the distributions h_L and $f_L^\perp$: the first one has been developed in Ref. 13, while the second has been adopted in Ref. 11. There are two differences between these two models, one is the option for the propagator of the axial-vector diquark, the other is the relation between the quark flavors under study and the diquark types.

The distributions h_L and $f_L^\perp$ can be extracted by the following traces

$$S_L \frac{M}{P^+} h_L(x, \mathbf{k}_T^2) = \frac{1}{2} \text{Tr}[\Phi^{[+]} i\sigma^{+-} \gamma_5], \quad (1)$$

$$S_L \frac{\epsilon_T^{\alpha\rho} k_{T\rho}}{P^+} f_L^\perp(x, \mathbf{k}_T^2) = -\frac{1}{2} \text{Tr}[\Phi^{[+]} \gamma^\alpha], \quad (2)$$

Fig. 1. The TMD distributions $f_L^\perp$ (left panel) and h_L (right panel) for u and d quarks in Set I.

Fig. 2. The TMD distributions $f_L^\perp$ (left panel) and h_L (right panel) for u and d quarks in Set II.

The detailed calculation and the expressions for the two TMDs can be found in Ref. 14. The numerical results of them as functions of x and k_T are shown in Fig. 1 (calculated from the spectator model in Ref. 13) and Fig. 2 (calculated from the spectator model in Ref. 11). Comparing Fig. 1 with Fig. 2, we can see that the TMD distributions in Set I are very different from those in Set II. In Set I the TMD distributions peak at the small x region, while in Set II they peak at the moderate x region. The k_T -dependence of the TMD distributions shows that the k_T widths for $h_L^q(x, k_T^2)$ and $f_L^{q\perp}(x, k_T^2)$ in Set I is larger than those in Set II, as the sizes of the TMD distributions in Set II decrease very quickly with increasing k_T .

3. Numerical Results for LTSA at HERMES, CLAS and COMPASS

The differential cross section of SIDIS $e(\ell) + p^\rightarrow(P) \rightarrow e'(\ell') + \pi(P_h) + X(P_X)$ under study can be expressed as:⁷

$$\frac{d\sigma}{dx dy dz dP_T^2 d\phi_h} = \frac{2\pi\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \times \left\{ F_{UU} + S_\parallel \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h F_{UL}^{\sin \phi_h} + \dots \right\},$$

where F_{UU} and $F_{UL}^{\sin \phi_h}$ are the spin-averaged and spin-dependent structure functions, respectively. With the structure functions F_{UU} and $F_{UL}^{\sin \phi_h}$, the asymmetry

$A_{UL}^{\sin\phi}$ as a function of P_T therefore can be written as

$$A_{UL}^{\sin\phi_h}(P_T) = \frac{\int dx \int dy \int dz \frac{1}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \sqrt{2\varepsilon(1+\varepsilon)} F_{UL}^{\sin\phi_h}}{\int dx \int dy \int dz \frac{1}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) F_{UU}}. \quad (3)$$

In a similar way, we can define the x -dependent and the z -dependent asymmetries.

In the parton model, based on the tree-level factorization adopted in Ref. 7, F_{UU} and $F_{UL}^{\sin\phi_h}$ can be expressed as the convolutions of twist-2 and twist-3 TMD distribution and fragmentation functions:

$$F_{UU} = \mathcal{C}[f_1 D_1], \quad (4)$$

$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q} \mathcal{C} \left[\frac{\hat{\mathbf{P}}_T \cdot \mathbf{p}_T}{zM_h} \left(x h_L H_1^\perp + \frac{M_h}{M} g_{1L} \frac{\tilde{G}^\perp}{z} \right) + \frac{\hat{\mathbf{P}}_T \cdot \mathbf{k}_T}{M} \left(x f_L^\perp D_1 - \frac{M_h}{M} h_{1L}^\perp \frac{\tilde{H}}{z} \right) \right], \quad (5)$$

where $\hat{\mathbf{P}}_T = \frac{\mathbf{P}_T}{P_T}$ with $P_T = |\mathbf{P}_T|$, and M_h is the mass of the final-state hadron. Eq. (5) shows that, there are four contributions from the convolutions of the twist-3 TMD distribution and fragmentation functions with the twist-2 ones that can contribute to $F_{UL}^{\sin\phi_h}$. We restrict our scope on the $f_L^\perp D_1$ term and the $h_L H_1^\perp$ term in the calculation.

The following kinematics are adopted to estimate the SSAs $A_{UL}^{\sin\phi_h}$ for charged and neutral pion production at HERMES¹

$$0.023 < x < 0.4, \quad 0.1 < y < 0.85, \quad 0.2 < z < 0.7 \\ W^2 > 10 \text{ GeV}^2, \quad Q^2 > \text{GeV}^2, \quad 4 \text{ GeV} < P_\pi < 13.8 \text{ GeV},$$

at CLAS¹⁵

$$0.1 < x < 0.6, \quad 0.4 < z < 0.7, \quad Q^2 > 1 \text{ GeV}^2, \\ P_T > 0.05 \text{ GeV}, \quad W^2 > 4 \text{ GeV}^2,$$

and at COMPASS¹⁶

$$0.004 < x < 0.7, \quad y > 0.1, \quad 0.2 < z < 0.9, \\ x_F > 0, \quad Q^2 > 1 \text{ GeV}^2, \quad 0.1 \text{ GeV} < P_T < 1 \text{ GeV}, \\ 5 \text{ GeV} < W < 18 \text{ GeV}.$$

In the left, central, and right panels of Figs. 3, 4 and 5, we show the results of the LTSAs at HERMES, CLAS, and COMPASS for π^+ , π^- , and π^0 , respectively. In the case of HERMES and CLAS, we calculate the asymmetry $A_{UL}^{\sin\phi_h}$ of charged and neutron pions produced off a proton target, while at COMPASS we predict the same asymmetry produced off a deuteron target. The thick and thin curves are corresponding to the asymmetries calculated from the TMD distributions in Set I and

Fig. 3. The asymmetry $A_{UL}^{\sin \phi_h}$ at HERMES for π^+ (left panel), π^- (central panel) and π^0 (right panel) as functions of x and z . The thick lines and the thin lines are calculated from the Set 1 and Set 2 TMD PDFs, respectively. The solid lines represent the total asymmetries, while the dashed lines shows the asymmetries from the $f_L^\perp D_1$ term, the difference between them gives the asymmetries from the $h_L H_1^\perp$ term.

Fig. 4. The asymmetry $A_{UL}^{\sin \phi_h}$ for π^+ , π^- and π^0 vs x , z and P_T at CLAS 5.5 GeV

Fig. 5. The asymmetry $A_{UL}^{\sin \phi_h}$ for π^+ , π^- and π^0 at COMPASS

Set II. The dashed and solid curves stand for the asymmetries contributed by the $f_L^\perp D_1$ term and the total contribution of the $f_L^\perp D_1$ and $h_L H_1^\perp$ terms, respectively. In the case of π^+ , π^- production at HERMES, we compare our results with the HERMES data,¹ and find that results calculated from both sets of TMD distributions are consistent with HERMES data, especially for the asymmetries calculated from the Set I distributions. In the case of π^0 production, the contribution from the $f_L^\perp D_1$ term dominates that from the $h_L H_1^\perp$ term, especially in the x -dependent asymmetry. This is very different from the case of charged pions, for which the contributions from the $f_L^\perp D_1$ term and the $h_L H_1^\perp$ term are comparable. This tendency is also found in the results at CLAS, where all three pions the asymmetries are sizable and could be measured, although there is sizable contribution from the $h_L H_1^\perp$ term at the high z region. We again find the similar result for the asymmetry of π^0 produced off a deuteron target at COMPASS, therefore it would be feasible to

extract the flavor dependence of $f_L^\perp$ by combining the asymmetries for π^0 using a deuteron target together with a proton target.

4. Summary

We studied the subleading-twist effect on the azimuthal asymmetry $A_{UL}^{\sin\phi_h}$ of pions produced in SIDIS with longitudinal polarized nucleon targets. Two different sets of twist-3 distribution functions $f_L^\perp$ and h_L were employed to analyze the asymmetries at HERMES, CLAS, and COMPASS, simultaneously. Comparing our results with the HERMES data, we find that the signs of the asymmetries for π^+ and π^- agree with the HERMES measurements, and both the $f_L^\perp D_1$ and $h_L H_1^\perp$ terms give substantial contributions to $A_{UL}^{\sin\phi_h}$. The results also show that the $f_L^\perp D_1$ term dominates in the asymmetry for π^0 , especially at HERMES and COMPASS where the beam energies are higher. Thus the measurements of $A_{UL}^{\sin\phi_h}$ for π^0 on the proton target, as well as on the deuteron target, will provide great opportunity to access $f_L^\perp$, including its flavor separation. Also, future CLAS measurements on $A_{UL}^{\sin\phi_h}$ for charged and neutral pions may be used to clarify the role of twist-3 TMD distribution functions in the longitudinal target spin asymmetry.

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