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Azimuthal asymmetry in unpolarized πN Drell–Yan process

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Abstract

Taking into account the effect of final-state interaction, we calculate the non-zero (naïve) T-odd transverse momentum dependent distribution $h_1^{\perp}(x, \mathbf{k}_{\perp}^2)$ of the pion in a quark-spectator-antiquark model with effective pion-quark-antiquark coupling as a dipole form factor. Using the model result we estimate the $\cos 2\phi$ asymmetries in the unpolarized $\pi^- N$ Drell–Yan process which can be expressed as $h_1^{\perp} \times \bar{h}_1^{\perp}$. We find that the resulting $h_{1\pi}^{\perp}(x, \mathbf{k}_{\perp}^2)$ has the advantage to reproduce the asymmetry that agrees with the experimental data measured by NA10 Collaboration. We estimate the $\cos 2\phi$ asymmetries averaged over the kinematics of NA10 experiments for 140, 194 and 286 GeV π^- beam and compare them with relevant experimental data.

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1. Introduction

Recently it is demonstrated that the effect of final-state interaction (FSI) or initial-state interaction (ISI) can lead to significant azimuthal asymmetries in various high energy scattering processes involving hadrons [1,2]. Among these asymmetries, single spin asymmetry (SSA) in semi-inclusive deeply inelastic scattering (SIDIS) [1] and that in Drell–Yan processes [2] from FSI/ISI via the exchange of a gluon, have been explored and are recognized as previously known Sivers effect [3,4]. This effect, formerly thought to be forbidden by the time-reversal property of QCD [5], can be survived from time-reversal invariance due to the presence of the path-ordered exponential (Wilson line) in the gauge-invariant definition of the transverse momentum dependent parton distributions [6–8]. Along this direction some phenomenological studies [9–11] have been carried out on transverse single-spin asymmetries in SIDIS process, which is under investigation by current ex-

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periment [12]. Analogously the exchange of a gluon can also lead to another leading twist (naive) T-odd distribution $h_1^{\perp}(x, \mathbf{k}_{\perp}^2)$: the covariant transversely polarization density of quarks inside an unpolarized hadron. This chiral-odd partner of Sivers effect function, introduced first in Ref. [13] and is referred to as Boer–Mulders function, has been proposed [14] to account for the large $\cos 2\phi$ asymmetries in the unpolarized pion-nucleon Drell–Yan process that were measured more than 10 years ago [15,16]. Recently $h_1^{\perp}(x, \mathbf{k}_{\perp}^2)$ of the proton has been computed in a quark-scalar diquark model [9,17] and also used to analyze the consequent $\cos 2\phi$ azimuthal asymmetries in both unpolarized ep SIDIS process [9] and unpolarized $p\bar{p}$ Drell–Yan process [17], respectively.

The same mechanism producing T-odd distribution functions can be applied to other hadrons such as mesons. In a previous paper [18] we reported that non-zero $h_1^{\perp}$ of the quark inside the pion (denoted as $h_{1\pi}^{\perp}$) can also arise from final-state interaction, by applying a simple quark spectator-antiquark model. Among the phenomenological implications of the function $h_{1\pi}^{\perp}$ is an important result for the $\cos 2\phi$ azimuthal asymmetry in the unpolarized $\pi^- N$ Drell–Yan process [15,16], which can be produced by the product of $h_1^{\perp}$ of the pion and that of the nucleon. Therefore, one can investigate how the theoretical prediction of the asymmetry is comparable with the experimental result, as a test of the theory and the model. In the present Letter, based on $h_{1\pi}^{\perp}$ from our model calculation, we analyze the $\cos 2\phi$ azimuthal asymmetry in the unpolarized $\pi^- N$ Drell–Yan process by considering the kinematical region of NA10 experiments [15]. To obtain the right Q_T dependence of the asymmetry, we recalculate $h_{1\pi}^{\perp}(x, \mathbf{k}_{\perp}^2)$ in a spectator model similar to the model used in Ref. [18]. The difference is that here we treat the effective pion-quark-antiquark coupling g_π as a dipole form factor $g_\pi(k^2)$, in contrary to the treatment in Ref. [18] where we take g_π as a constant. We find that $h_{1\pi}^{\perp}(x, \mathbf{k}_{\perp}^2)$ resulting from the new treatment together with $h_1^{\perp}(x, \mathbf{k}_{\perp}^2)$ for the nucleon in a similar treatment [10] can reproduce the $\cos 2\phi$ asymmetry which agrees with NA10 data. We give the asymmetries predicted by our model averaged over the kinematics of NA10 experiments for 140, 194 and 286 GeV π^- beam and find that the energy dependence of these asymmetries is not strong.

2. Non-zero $h_{1\pi}^{\perp}$ of the pion in spectator model

In this section, we will show how to calculate $h_{1\pi}^{\perp}(x, \mathbf{k}_{\perp}^2)$ in a quark-spectator antiquark model. We follow Ref. [1] to work in Abelian case at first and then generalize the result to QCD. There are pion-quark-antiquark interaction and gluon-spectator antiquark interaction in the model:

$$\mathcal{L}_I = -g_\pi \bar{\psi}\gamma_5\psi\varphi_\pi - e_2\bar{\psi}\gamma^\mu\psi A_\mu + \text{h.c.}, \tag{1}$$

in which g_π is the pion-quark-antiquark effective coupling, and e_2 is the charge of the antiquark. When the intrinsic transverse momentum of the quark is taken into account, as required by T-odd distributions, the quark correlation function of the pion in Feynman gauge (we perform calculation in this gauge) is [7,8]:

$$\begin{aligned}
&\Phi_{\alpha\beta}(x, \mathbf{k}_\perp) \\
&\quad = \int \frac{d\xi^- \, d^2\xi_\perp}{(2\pi)^3} e^{ik\cdot\xi} \langle P_\pi | \bar{\psi}_\beta(0)\mathcal{L}_0(0^-, \infty^-) \\
&\qquad \times \mathcal{L}_\xi^\dagger(\xi^-, \infty^-)\psi_\alpha(\xi) | P_\pi \rangle |_{\xi^+=0},
\end{aligned} \tag{2}$$

where $\mathcal{L}_a(a^-, \infty^-)$ is the path-ordered exponential (Wilson line) accompanied with the quark field which has the form

$$\mathcal{L}_0(0, \infty) = \mathcal{P}\exp\left(-ig\int_{0^-}^{\infty^-} A^+(0, \xi^-, \mathbf{0}_\perp)\, d\xi^-\right), \tag{3}$$

etc. The Wilson line has the importance to make the definition of the distribution/correlation function gauge-invariant. Without the constraint of time-reversal invariance, in leading twist the quark correlation function of the pion can be parameterized into a set of leading twist transverse momentum dependent distribution functions as follows [13,19]

$$\begin{aligned}
&\Phi(x, \mathbf{k}_\perp) \\
&\quad = \frac{1}{2}\left[f_{1\pi}\left(x, \mathbf{k}_\perp^2\right)\not{n} + h_{1\pi}^\perp\left(x, \mathbf{k}_\perp^2\right)\frac{\sigma_{\mu\nu}\mathbf{k}_\perp^\mu n^\nu}{M_\pi}\right],
\end{aligned} \tag{4}$$

where n is the light-like vector with components $(n^+, n^-, \mathbf{n}_\perp) = (1, 0, \mathbf{0}_\perp)$, $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]$ and M_π is the pion mass. Knowing $\Phi_\pi(x, \mathbf{k}_\perp)$, one can obtain these distributions from equations

$$f_{1\pi}\left(x, \mathbf{k}_\perp^2\right) = \text{Tr}\left[\Phi(x, \mathbf{k}_\perp)\gamma^+\right], \tag{5}$$

$$\frac{2h_{1\pi}^\perp(x, \mathbf{k}_\perp^2)\mathbf{k}_\perp^i}{M_\pi} = \text{Tr}\left[\Phi(x, \mathbf{k}_\perp)\sigma^{i+}\right]. \tag{6}$$