Single transverse-spin asymmetry for direct-photon and single-jet productions at RHIC

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Abstract

We study the single transverse-spin asymmetry for the inclusive direct-photon and single-jet productions in the proton-proton collision based on the twist-3 mechanism in the collinear factorization. Taking into account all the effects from the twist-3 quark-gluon correlation functions inside a transversely polarized proton, we present a prediction for the asymmetries at the typical RHIC kinematics. In both processes we find sizable asymmetries in the forward region of the polarized proton while they are almost zero in the backward region. This implies that if one finds a nonzero asymmetries in the backward region in these processes, it should be ascribed wholly to the three-gluon correlations. We also find the soft-gluon pole contribution is dominant and the soft-fermion pole contribution is negligible in the whole Feynman-$x$ region for these asymmetries.
Study of large single transverse-spin asymmetry (SSA) in inclusive reactions has provided us with a range of new insights into the quark-gluon structure of hadrons and has significantly developed the theoretical framework for the application of perturbative QCD to hard processes. (See [1, 2] for a review.) When the transverse momentum of the final-state particle $P_T$ is large enough ($P_T \gg \Lambda_{\text{QCD}}$), the SSA can be described as a twist-3 observable in the framework of the collinear factorization [3, 4, 5, 6]. From this perspective, there have been many works which have explored the effects of twist-3 multiparton correlation functions on SSA [4, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30]. Among variety of observed SSAs, those for the inclusive single-hadron ($\pi$, $K$, $\eta$ etc) production in the pp collision at RHIC [31, 32, 33, 34, 35, 36, 37] are particularly suitable for the analysis based on the twist-3 mechanism, since most data are in the range of $P_T \geq 1$ GeV and, in particular, the next-to-leading order perturbative QCD calculation reproduces the twist-2 unpolarized cross section perfectly well [38]. In fact in the application of this mechanism to the RHIC $A_N$ data, it has been demonstrated that the quark-gluon correlation function in the transversely polarized proton reproduces the characteristic features of the observed asymmetry [10, 21, 22]. This description, however, is based on the assumption that the whole asymmetry comes from the quark-gluon correlation. Other sources of SSAs, such as the twist-3 fragmentation function [19, 20] and the three-gluon correlation function [6, 24, 25, 26], may possibly bring a significant contribution to the asymmetry.

In order to clarify the origin of the observed SSA, it is important to separate each competing effect by measuring SSAs in other processes. For example, the contribution from the twist-3 fragmentation function can be eliminated by studying direct-photon and single-jet production:

$$ p^+ + p \to \left\{ \gamma, \text{jet} \right\} + X. $$

(1)

In these processes, the quark-gluon and the three-gluon correlation functions bring asymmetries through two types of the pole contributions, i.e., soft-gluon-pole (SGP) and the soft-fermion pole (SFP). For the direct-photon process, we have recently derived the contribution of the SFP component of the quark-gluon correlation function to the single-spin dependent cross section at leading-order (LO) perturbative QCD [23]. Combined with the contribution from the SGP component [4, 11, 15] and the three-gluon correlation function [26], the complete LO twist-3 formula is currently available. In principle, for these processes, one can see only the combined effect of the quark-gluon and the three-gluon correlations. For the direct-photon production process, however, it has been shown that the three-gluon correlation function does not give rise to $A_N$ at $x_F > 0$ due to the smallness of the corresponding partonic cross section [26]. Therefore, if a nonzero $A_N^\gamma$ is experimentally

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1 Here we consider the isolated-photon production in which the fragmentation contribution is suppressed by an appropriate isolation cut.

2 The Drell-Yan process is another example in which no fragmentation function contributes. But the hard-pole component of the quark-gluon correlation functions also contributes to the cross section, which makes it difficult to determine the form of each function [11, 23].
observed at $x_F > 0$, it should directly be ascribed to the quark-gluon correlation function in the polarized nucleon. The SSA for the single-jet production also play a similar role in investigating the multiparton correlations, although there is no knowledge on the impact of the three-gluon correlation contribution at this point. Confrontation with future data for the processes (1) is particularly useful to test models for the quark-gluon correlation function in the transversely polarized nucleon [29].

The purpose of this Letter is to present a prediction for $A_N$ for the processes (1), using our model for the quark-gluon correlation functions obtained in [21, 22]. There we have performed the fitting of the RHIC $A_N$ data for the $\pi$ and $K$ productions based on the complete twist-3 cross section formula for the quark-gluon correlation functions, and have extracted the SGP and SFP components of those functions. The result reproduced all features of the observed asymmetries including those which were rather unexpected, such as the large $A_N$ for $K^-$ driven by the nonvalence component of the correlation function and the peculiar $P_T$-dependence of the asymmetry, which had not been described by other analyses. In addition, the RHIC-STAR data for the $\eta$-meson agreed with the prediction by the model [22], in which the strange-quark-gluon correlation responsible for $A_N^{K\pm}$ and the strangeness component in the $\eta$-meson fragmentation function play an important role. With these nice features at hand, the prediction of $A_N$ for (1) will be useful as a reference for future experiment. One should keep in mind, however, that our model for the quark-gluon correlation functions was determined by assuming that they are the sole origin for the observed $A_N$ for the light-hadron productions at RHIC. Therefore, if there is a discrepancy between our prediction and a future experiment, it would be a signal for the existence of sizable twist-3 fragmentation or three-gluon correlation functions. We also remind that our SGP function does not agree with what is expected from a naive relation between the SGP function and the moment of the Sivers function (with respect to the transverse momentum $k_\perp$ of the quark) obtained from the analysis of the SSA data of the semi-inclusive deep inelastic scattering [29, 30]. Here we put aside this issue3 and take the view of investigating the prediction of our model which can reproduce all the aspects of the RHIC data for the light-hadron production.

We first recall some basic features of the quark-gluon correlation contribution to the asymmetries for the direct-photon and the single-jet productions. The corresponding single-spin-dependent cross sections for these processes have a common structure as [11, 15, 23]

$$
\Delta\sigma^{\gamma,\text{jet}} \propto \sum_{a,b} \left( G_F^a(x, x) - x \frac{dG_F^a(x, x)}{dx} \right) \otimes f^b(x') \otimes \sigma_{ab\rightarrow\gamma,\text{jet}}^{\text{SGP}}
$$

$$
+ \sum_{a,b} \left( G_F^a(0, x) + \tilde{G}_F^a(0, x) \right) \otimes f^b(x') \otimes \sigma_{ab\rightarrow\gamma,\text{jet}}^{\text{SFP}},
$$

where $G_F^a$ and $\tilde{G}_F^a$ are the quark-gluon correlation functions for a quark or antiquark flavor $a$, $f^b(x')$ is the usual unpolarized parton distribution function for the parton species $b$

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3Clarification of this issue requires the knowledge on the precise $k_\perp$-dependence in the high-$k_\perp$ region as well as the renormalization of the $k_\perp^2$-moment of the Sivers function.
Figure 1: Comparison of the $x_F$-dependence of $A_N$ for the direct-photon, jet and $\pi^0$ productions at the center-of-mass energy $\sqrt{S} = 200$ GeV. The left panel is for the fixed pseudorapidity $\eta = 3.3$, while the right one is for the fixed transverse momentum $P_T = 2$ GeV. In the left panel, the plots are restricted in the region $P_T \geq 1$.

($b=$quark, antiquark or gluon). The symbol $\otimes$ denotes the convolution with respect to the partonic momentum fraction $x$ and $x'$. $\sigma_{ab \rightarrow \gamma, \text{jet}}^{\text{SGP, SFP}}$ represent the corresponding partonic hard cross section for each subprocess and pole. The SGP and SFP functions, $G_F^\gamma(x, x')$ and $G_F^\pi(0, x) + G_F^\pi(0, x')$, for the light-quark flavors ($a = u, d, s, \bar{u}, \bar{d}, \bar{s}$) have been determined by an analysis of the RHIC $A_N$ data for the inclusive pion and kaon productions [21]. For the unpolarized parton distribution $f^b(x')$, we have used the GRV98 LO parton distribution [39]. Throughout this Letter, we choose the scales in the parton distribution and fragmentation functions as $\mu = P_T$ as in the previous studies [21, 22].

Figure 1 shows $A_N$ for the direct-photon and the jet productions as a function of $x_F$ at $\sqrt{S} = 200$ GeV at the pseudorapidity $\eta = 3.3$ and at $P_T = 2$ GeV. In the figure we also plot $A_N$ for the $\pi^0$ production for comparison. First of all, $A_\gamma N$ is significantly larger than $A_{\pi^0, \text{jet}} N$. This is because the color factor for the polarized cross section relative to the unpolarized cross section is much larger for the direct-photon production process than for the others. One also sees that the behavior of $A_\gamma N$ is completely different from $A_{\pi^0, \text{jet}} N$. As shown in the left panel of Fig. 1, for the fixed $\eta$, $A_\gamma N$ has a peak at small $x_F$ and decreases as $x_F$ increases, while $A_{\pi^0, \text{jet}} N$ increases in the forward direction. These features at $x_F > 0$ were also observed in the previous analysis of [29]. The similarity between $A_{\text{jet}}^\gamma N$ and $A_{\pi^0}^N$ in their magnitude and behavior can be easily understood because they have the common partonic subprocesses.

In order to see the origin of the different behavior between $A_\gamma N$ and $A_{\text{jet}}^\gamma N$, we first show the decomposition of $A_\gamma N$ and $A_{\text{jet}}^\gamma N$ into the SGP and SFP contributions in Fig. 2. From this decomposition it is clear that for these processes the dominant contribution is from SGP and the effect of SFP is negligible in the whole $x_F$-region. (For the $K^-$ and $\pi^-$ productions, the SFP contribution survive as an important source of SSA in [21].) Therefore the above stated characteristic difference between $A_\gamma N$ and $A_{\text{jet}}^\gamma N$ is due to the difference in
the SGP contribution to those asymmetries. Next we recall that the SGP cross section for $A^\gamma_N$ consists of the initial-state interaction (ISI) and the final-state interaction (FSI) contributions, and the rising behavior of $A^\text{jet}_N$ toward large $x_F$ is mostly due to the latter one (See the right panel of Fig. 2): The partonic hard cross section for the latter accompanies the kinematic factor $\hat{s}/\hat{t}$ compared to the former ($\hat{s}$ and $\hat{t}$ are the Mandelstam variables in the parton level) which enhances the asymmetry in the forward direction combined with the derivative form of the SGP function. Since $A^\gamma_N$ receives the contribution only from the initial-state interaction, it is not enhanced as $A^\text{jet}_N$ in the forward direction. Another reason for the difference resides in the open partonic channels. At moderate $x_F$, the channel $qg \to g$ ($qg \to \gamma$) gives rise to a major contribution to $\Delta\sigma^\text{jet}$ ($\Delta\sigma^\gamma$). At large $x_F$, however, the asymmetry for the jet production is dominated by the channel $qg \to q$, for which no counterpart exist in the direct-photon production. As a consequence, $A^\gamma_N$ has a peak at moderate $x_F$ and decreases as a function of $x_F$ in the forward region. For fixed $P_T$, such behavior is softened as seen from the right panel of Fig. 1 and one finds $A^\gamma_N$ rapidly becomes zero with $x_F \to 0$.

We remind that an experimental observation of this characteristic feature of $A^\gamma_N$ requires a selection of only the direct-photon events. Otherwise the cross section for the prompt-photon production receives a large fragmentation contribution. The polarized cross section for the fragmentation contribution consists of the Sivers and Collins type contributions. A recent model study shows that the Collins type contribution is negligible compared with the Sivers type [41]. Since the Sivers type contribution has the same partonic cross section as for the pion production, the asymmetry for the prompt-photon production which receives a large contamination from the fragmentation photon would become closer to the one for the pion and jet productions [10].

Here we comment on the smallness of the SFP contribution in $A^\gamma_N^\text{jet}$. As shown in [22], in the case of the light-hadron productions, a sizable SFP contribution to $A_N$ appears at mod-
erate $x_F$ mostly through the gluon fragmentation channels owing to the large component of the gluon-to-pion and gluon-to-kaon fragmentation functions in the DSS parametrization combined with the large partonic SFP cross section. For the direct-photon and the jet production processes, however, no such “enhanced” SFP contribution exists because of the absence of the large gluon fragmentation function. Therefore $A_N^{\gamma,\text{jet}}$ are a useful probe for the SGP component of the quark-gluon correlation functions.

As we saw in Fig. 1, for the direct-photon and the jet productions the contribution from the quark-gluon correlation functions is almost zero at $x_F < 0$. This means that if a future experiment finds nonzero asymmetry at $x_F < 0$, it should directly be ascribed to the three-gluon correlation functions in the polarized nucleon. For the direct-photon process, it’s been shown that the three-gluon correlation function does not give rise to nonzero $A_N$ at $x_F > 0$ [26]. Thus the quark-gluon correlation function studied in this Letter is the only source for $A_N$ in this region. Accordingly measurement of $A_N^{\gamma}$ at both $x_F > 0$ and $x_F < 0$ gives an important information on both quark-gluon correlation and the three-gluon correlation in the polarized nucleon.

Next, we explore the $P_T$-dependence of $A_N$, which gives an important test for the twist-3 mechanism for SSA. Shown in Fig. 3 is the $P_T$-dependence of $A_N^{\text{jet}}$ (left panel) and $A_N^{\gamma}$ (right panel) at $\sqrt{S} = 200$ GeV for several rapidity bins in the small $\eta$-region. One sees that $A_N^{\text{jet}}$ is negligible at $0 < P_T < 30$ GeV, while $A_N^{\gamma}$ is clearly finite, especially at $\eta > 0$. For the jet production, the first data on the $P_T$-distribution was recently reported by the STAR collaboration at mid-rapidity for $\sqrt{S} = 200$ GeV [37]. The data for $A_N^{\text{jet}}$ is consistent with zero with a large error bar for $0 < P_T < 30$ GeV, which agrees with the left panel of Fig. 3.

For the direct-photon production, since our prediction shows finite $A_N^{\gamma}$ even at relatively small $\eta > 0$, measurement of $A_N^{\gamma}$ is expected to constrain the quark-gluon correlation function. The $P_T$-dependence of $A_N^{\gamma}$ at forward-rapidity is more intriguing. So far, data for the $P_T$-dependence in the forward region was reported only for the inclusive $\pi^0$ production.
Figure 4: Comparison of the $P_T$-dependence of $A_N$ for the direct-photon, jet, and $\pi^0$ productions at $\sqrt{S} = 200$ GeV for two different values of $x_F$.

at $\sqrt{S} = 200$ GeV by the STAR collaboration \cite{33}, where the $P_T$-distribution has a peak at around a few GeV. In our study \cite{22}, such peculiar behavior of the $P_T$-dependence has been reproduced owing to the large contributions from the gluon-fragmentation channel to the polarized and the unpolarized cross sections with opposite signs, both of which decrease quite fast as $P_T$ increases because of the fast evolution of the DSS fragmentation function in the $P_T \sim$ a few GeV region. Owing to the absence of the fragmentation function and the close relationship for the partonic cross sections between the unpolarized and the SGP cross sections, we expect that $A_N^{\gamma,\text{jet}}$ approximately follows the power behavior of the twist-3 asymmetry as $A_N^{\gamma,\text{jet}} \sim O(M_N/P_T)$ at large $x_F$. With this in mind, we show a comparison of the $P_T$-dependence of $A_N$ for the direct-photon, jet and $\pi^0$ productions at two different values of $x_F$ in Fig. 4. As expected, $A_N^{\gamma}$ and $A_N^{\text{jet}}$ decrease monotonously with increasing $P_T$ unlike the case for $\pi^0$. We found, however, that the actual $A_N$ in Fig. 4 does not decrease as fast as $1/P_T$ at large $P_T$, which is due to the different functional forms of the SGP function and the unpolarized parton density as well as the $P_T$-dependent phase space integral in the convolution. Comparison of these features with a future measurement of the $P_T$-dependence of these asymmetries in the forward region will shed new light on its validity.

Finally, to see the energy dependence of SSA, we show $A_N$ at higher energy, $\sqrt{S} = 500$ GeV, in Fig. 5. From these plots, one finds the behavior of the asymmetry at $\sqrt{S} = 500$ GeV is very similar to that at $\sqrt{S} = 200$ GeV shown in Fig. 1, although the size of the asymmetry becomes approximately one-half of that for $\sqrt{S} = 200$ GeV. As in the case at $\sqrt{S} = 200$ GeV, the dominant contribution is from the SGP component in the whole $x_F$-region. Recently RHIC-$A_N$DY collaboration reported a data for $A_N^{\text{jet}}$ in the forward region at $\sqrt{S} = 500$ GeV \cite{43}. It shows a positive $A_N^{\text{jet}}$ as shown in Fig. 5, but the magnitude is smaller. The difference in the magnitude may be ascribed to the fact that our quark-gluon

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\footnote{In this connection, we recall that the analysis in \cite{21} adopted a simplified scale-dependence for the quark-gluon correlation functions. Use of the correct scale-dependence for those functions \cite{42} may change this additional weak $P_T$-dependence.}
correlation was determined so that it saturates the whole asymmetry for the light-hadron production. More data is needed to clarify the origin of the asymmetry.

In summary, we have presented a prediction for the SSA in the inclusive direct-photon and single-jet productions for the typical RHIC kinematics, using the quark-gluon correlation function determined in our previous analysis of the light-hadron production. We have found $A^\gamma_N$ is significantly larger than $A^{\pi^0}_N$ at moderate $x_F > 0$, while the behavior of $A^{\text{jet}}_N$ is similar to $A^{\pi^0}_N$. In both processes, the SGP contribution dominates the asymmetry, while the SFP contribution is negligible in the whole $x_F$-region. For the direct-photon process, we have shown that the asymmetries at $x_F > 0$ and $x_F < 0$ are, respectively, caused solely by the quark-gluon correlation function and the three-gluon correlation function. These features of $A_N^\gamma$ and $A_N^{\text{jet}}$ will provide a unique opportunity for clarifying the mechanism of the observed asymmetries.

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