Twist-3 Quark-Gluon Correlation Contribution to Single-Transverse Spin Asymmetry for Direct-Photon and Single-Jet Productions in pp Collision

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\textbf{Abstract}—We study the contribution of the collinear twist-3 quark-gluon correlation to the single transverse-spin asymmetry in direct-photon and single-jet productions in \textit{pp} collision. At typical RHIC kinematics we find sizable asymmetries in the forward region of the polarized nucleon while they are almost zero in the backward region. We also find the soft-fermion pole contribution is vanishingly small, suggesting the measurement of these asymmetries provides us with an unique opportunity to determine the net soft-gluon pole function.

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The study of large single transverse-spin asymmetry (SSA) in inclusive reactions has provided us with a range of new insights into the partonic structure of hadrons. When the transverse momentum of the final-state particle $P_T$ is large, the SSA can be described as a twist-3 observable in the framework of the collinear factorization \cite{1–3}. In principle, the relevant twist-3 multiparton correlation effects exist both in the initial-state and the final-state hadrons. In the inclusive hadron production in \textit{pp} collision and semi-inclusive DIS, this coexistence makes it difficult to identify the origin of SSA uniquely. The SSA for direct-photon and single-jet productions play a crucial role since the responsible effect exists only in the initial-state hadrons.

In this report, as a reference for future RHIC experiment, we present our estimate of the SSA in these processes, $A_N^{\gamma,\text{jet}} = \Delta \sigma^{\gamma,\text{jet}} / \sigma^{\gamma,\text{jet}}$, by taking into account the whole twist-3 quark-gluon correlation contribution which are composed of the soft-gluon pole (SGP) and soft-fermion pole (SFP) components. A comparison with forthcoming measurements would shed new light on the net initial-state quark-gluon correlation inside the transversely polarized nucleon.

The relevant single-spin-dependent cross sections are schematically represented as \cite{4–6}

\begin{equation}
\Delta \sigma^{\gamma,\text{jet}} \sim \sum_{a, b} \left( c^a_f(x, x) - x \frac{dG^a_f(x, x)}{dx} f^b(x') \otimes \hat{\sigma}^\text{SGP}_{ab \rightarrow \gamma, \text{jet}} \right. \\
+ \left. \sum_{a, b} (G^a_f(0, x) + \tilde{G}^a_f(0, x)) \otimes f^b(x') \otimes \hat{\sigma}^\text{SFP}_{ab \rightarrow \gamma, \text{jet}} \right),
\end{equation}

where the symbol $\otimes$ denotes the convolution with respect to the partonic momentum fractions.

\{ $G^a_f, \tilde{G}^a_f$ \} is a complete set of the quark-gluon correlation function for flavor $a$, $f^b(x')$ is the unpolarized parton distribution for flavor $b$, and $\hat{\sigma}^\text{SGP, SFP}_{ab \rightarrow \gamma, \text{jet}}$ are the corresponding partonic hard cross sections. The SGP and SFP functions, $G^a_f(x, x)$ and $G^a_f(0, x) + \tilde{G}^a_f(0, x)$, for light-quark flavors ($a = u, d, s, \bar{u}, \bar{d}, \bar{s}$) have been determined by an analysis of RHIC $A_N$ data for the inclusive pion and kaon productions \cite{8}. For the unpolarized parton distribution, we use the GRV98LO parton distribution \cite{9} to keep the consistency with our previous works. The scales in the parton distribution and fragmentation functions are taken as $\mu = P_T$.

Figure 1 shows the calculated $A_N^\gamma$ and $A_N^{\gamma,\text{jet}}$ as a function of Feynman-$x$ ($x_F$) at $\sqrt{S} = 200$ GeV for pseudorapidity $\eta$ and $P_T$, respectively, in comparison with $A_N^{\gamma,\text{iso}}$. From this figure one can see $A_N^\gamma$ is particularly large and drops as a function of $x_F$ in the forward region while $A_N^{\gamma,\text{jet}}$ behaves similarly to $A_N^{\gamma,\text{iso}}$. These behaviors are qualitatively consistent with the previous calculation \cite{10}. One of the important features is that the large asymmetries arise only in the forward region while they are almost zero in the backward region. This observation is interesting especially for the direct-photon process, because the 3-gluon correlation effect, which is another source of SSA, could appear only in the backward region \cite{11}. Namely, the role of

\footnote{For the definition and property of these functions, see \cite{7}.}
the quark-gluon and 3-gluon correlations for $A_N$ is completely separated into the forward and backward regions, respectively, so that the measurement of $A_N$ in whole $x_F$-region could give a clear information for both twist-3 multiparton correlations inside the transversely polarized nucleon.

To see the relative importance of each pole contribution, we show the separation of $A_N$ into the SGP and SFP components in Fig. 2. From this decomposition, one finds the large forward $A_N$ is mostly from the SGP component while the SFP one is vanishingly small in whole $x_F$ region. As shown in [12], in the case of light-hadron production, a sizable SFP contribution to $A_N$ manifests itself at moderate $x_F$ due to the large gluon-to-pion and gluon-to-kaon fragmentation functions of the DSS parametrization [13]. For direct-photon and jet processes, however, due to the absence of the large fragmentation function, the SFP contribution is sufficiently suppressed. This suggests the SSA in these two processes would be golden channels to probe the net SGP component of the quark-gluon correlation function.

In summary, we have estimated the contribution of the twist-3 quark-gluon correlation in the polarized nucleon for the SSA in the direct-photon and the single-jet productions at the typical RHIC kinematics. We have found $A_N$ is particularly large in the forward region of the polarized nucleon while the behavior of $A_N^{\text{jet}}$ is similar to that for $\pi^0$. In both processes, the SGP component gives rise to dominant contribution for the forward SSA while the SFP one is vanishingly small in the whole $x_F$-region. In addition, for the direct-photon process, we have shown there is no competition between the quark-gluon and the 3-gluon correlation contributions. Owing to these features, the measure-

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**Fig. 1.** Comparison of the $x_F$-dependence of $A_N$ for direct-photon, jet and $\pi^0$ at fixed $\eta = 3.3$ (left) and $P_T = 2$ GeV (right), respectively. The center-of-mass energy $\sqrt{S}$ is taken at 200 GeV. The plots are restricted in the region $P_T \geq 1$ GeV.

**Fig. 2.** Separation of $A_N^\gamma$ and $A_N^{\text{jet}}$ in the left panel of Fig. 1 into the SGP and SFP components. Also shown in the right panel is the further separation of the SGP component into the initial-state and final-state interaction contributions.
ment of the forward $A_N^f$ and $A_N^{\text{jet}}$ would provide an unique opportunity for determining the SGP function in global QCD analysis of SSA.

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