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Twist-3 approach to single transverse-spin asymmetry

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Summary. — 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 asymmetry in the backward region in these processes, it should be ascribed wholely to the three-gluon correlations.

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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 [1-3]. Since the twist-3 multiparton correlation effects exist both in the initial-state and the final-state hadrons, it is difficult to identify the origin of SSA uniquely in the inclusive hadron production in *pp* collision. 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(1). A comparison with forthcoming measurements would shed new light on the net initial-state quark-gluon correlation inside the transversely polarized nucleon.

(1) This talk is based on our recent paper [4].

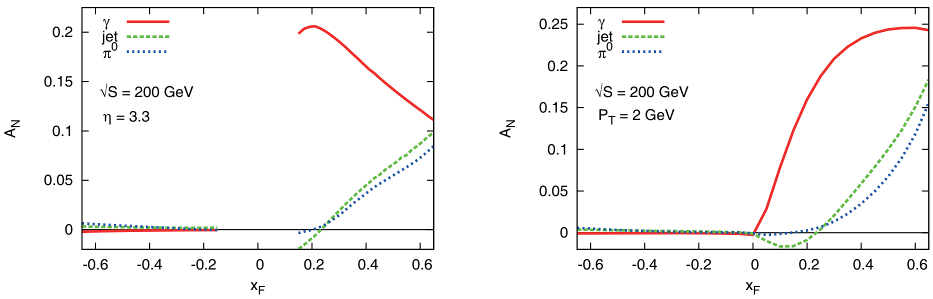

Fig. 1. – Comparison of the x_F-dependence of A_N for direct-photon, jet and π^0 at fixed $\eta = 3.3$ (left) and $P_T = 2\,\mathrm{GeV}$ (right), respectively. The center-of-mass energy $\sqrt{S}$ is taken to be 200 GeV. In the left panel, the plots are restricted in the region $P_T \geq 1\,\mathrm{GeV}$.

The relevant single-spin-dependent cross sections take the form of [5-7]

$$\Delta\sigma^{\gamma,\mathrm{jet}} \sim \sum_{a,b}\left(G_F^a(x,x) - x\frac{\mathrm{d}G_F^a(x,x)}{\mathrm{d}x}\right)\otimes f^b(x')\otimes\hat{\sigma}^{\mathrm{SGP}}_{ab\to\gamma,\mathrm{jet}} + \sum_{a,b}\left(G_F^a(0,x) + \widetilde{G}_F^a(0,x)\right)\otimes f^b(x')\otimes\hat{\sigma}^{\mathrm{SFP}}_{ab\to\gamma,\mathrm{jet}}, \tag{1}$$

where the symbol $\otimes$ denotes the convolution with respect to the partonic momentum fractions. $\{G_F^a, \widetilde{G}_F^a\}$ 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 $\hat{\sigma}^{\mathrm{SGP,SFP}}_{ab\to\gamma,\mathrm{jet}}$ are the corresponding partonic hard cross sections. The SGP and SFP functions, $G_F^a(x,x)$ and $G_F^a(0,x) + \widetilde{G}_F^a(0,x)$, 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 [8]. The scales in the parton distribution and fragmentation functions are taken to be $\mu = P_T$.

Figure 1 shows A_N for the direct-photon and the jet productions as a function of x_F at $\sqrt{S} = 200\,\mathrm{GeV}$ at the pseudorapidity $\eta = 3.3$ and at $P_T = 2\,\mathrm{GeV}$. In the figure we also plot A_N for the π^0 production for comparison. First of all, A_N^γ is significantly larger than $A_N^{\pi^0,\mathrm{jet}}$. 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_N^γ is completely different from $A_N^{\pi^0,\mathrm{jet}}$. As shown in the left panel of fig. 1, for the fixed η, A_N^γ has a peak at small x_F and decreases as x_F increases, while $A_N^{\pi^0,\mathrm{jet}}$ increases in the forward direction. These features at $x_F > 0$ were also observed in the previous analysis of [9]. The similarity between A_N^{jet} and $A_N^{\pi^0}$ in their magnitude and behavior can be easily understood because they have the common partonic subprocesses. 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 has been shown that the three-gluon correlation function does not give rise to nonzero A_N at $x_F > 0$ [10]. Thus the quark-gluon correlation function is the only source for A_N in this region. Accordingly measurement of A_N^γ 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.

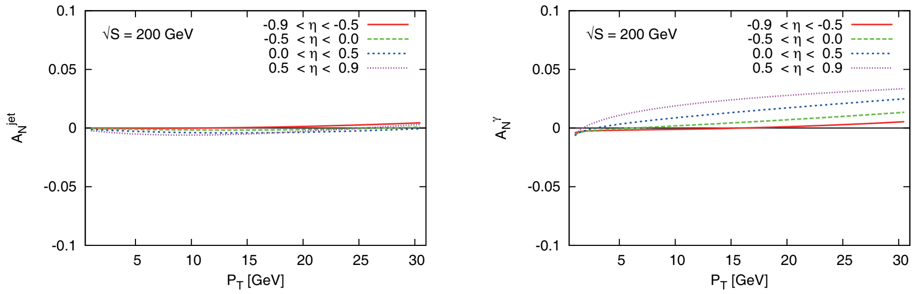

Fig. 2. – P_T-dependence of $A_N^{\rm jet}$ and A_N^{γ} at four different bins of the pseudo-rapidity η corresponding to the RHIC-STAR kinematics in [13].

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. 2 is the P_T-dependence of $A_N^{\rm jet}$ (left panel) and A_N^{γ} (right panel) at $\sqrt{S} = 200\,{\rm GeV}$ for several rapidity bins in the small η-region. One sees that $A_N^{\rm jet}$ is negligible at $0 < P_T < 30\,{\rm GeV}$, while A_N^{γ} 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 $\sqrt{S} = 200\,{\rm GeV}$ [13]. The data for $A_N^{\rm jet}$ is consistent with zero with a large error bar for $0 < P_T < 30\,{\rm GeV}$, which agrees with the left panel of fig. 2.

For the direct-photon production, since our prediction shows finite A_N^{γ} even at relatively small $\eta > 0$, measurement of A_N^{γ} is expected to constrain the quark-gluon correlation function. The P_T-dependence of A_N^{γ} at forward-rapidity is more intriguing. So far, data for the P_T-dependence in the forward region was reported only for the inclusive π^0 production at $\sqrt{S} = 200\,{\rm GeV}$ by the STAR Collaboration [14], where the P_T-distribution has a peak at around a few GeV. In our study [11], 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 [12] 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 $A_N^{\gamma,{\rm jet}}$ approximately follows the power behavior of the twist-3 asymmetry as $A_N^{\gamma,{\rm jet}} \sim O(M_N/P_T)$ at *large* x_F. With this in mind, we show a comparison of the P_T-dependence of A_N

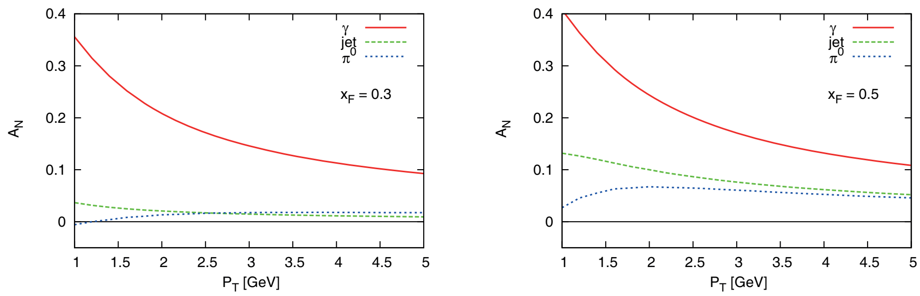

Fig. 3. – Comparison of the P_T-dependence of A_N for the direct-photon, jet, and π^0 productions at $\sqrt{S} = 200\,{\rm GeV}$ for two different values of x_F.

for the direct-photon, jet and π^0 productions at two different values of x_F in fig. 3. As expected, A_N^γ and $A_N^{\rm jet}$ decrease monotonously with increasing P_T unlike the case for π^0. We found, however, that the actual A_N in fig. 3 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.

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_N^γ is significantly larger than $A_N^{\pi^0}$ at moderate $x_F > 0$, while the behavior of $A_N^{\rm jet}$ is similar to $A_N^{\pi^0}$. 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^γ and $A_N^{\rm jet}$ will provide a unique opportunity for clarifying the mechanism of the observed asymmetries.

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