The role of three-gluon correlation functions in the single spin asymmetry

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Abstract. We study the twist-3 three-gluon contribution to the single spin asymmetry in the light-hadron production in pp collision in the framework of the collinear factorization. We derive the corresponding cross section formula in the leading order with respect to the QCD coupling constant. We also present a numerical calculation of the asymmetry at the RHIC energy, using a model for the three-gluon correlation functions suggested by the asymmetry for the D-meson production at RHIC. We found that the asymmetries for the light-hadron and the jet productions are very useful to constrain the magnitude and form of the correlation functions. Since the three-gluon correlation functions shift the asymmetry for all kinds of hadrons in the same direction, it is unlikely that they become a main source of the asymmetry.

1 Introduction

The origin of the transverse single-spin asymmetry (SSA) $A_N \equiv (\sigma^\uparrow - \sigma^\downarrow)/(\sigma^\uparrow + \sigma^\downarrow)$ for $p^\uparrow p \to hX$ ($h = \pi, K, \eta$, jet) observed by the Relativistic Heavy Ion collider (RHIC) at the Brookhaven National Laboratory (BNL) [1]-[9] is yet to be clarified in terms of the twist-3 mechanism in the framework of the collinear factorization. This process receives, in principle, four types of the twist-3 contributions depending on the type of the twist-3 correlation function participating in the cross section; i.e., (i) twist-3 quark-gluon correlation function in the polarized nucleon [10]-[16], (ii) twist-3 three-gluon correlation function in the polarized nucleon [17]-[22], (iii) twist-3 fragmentation for the final hadron [24]-[27] and (iv) twist-3 quark-gluon correlation function in the initial unpolarized nucleon [28]. The last contribution (iv) was shown to be negligible due to the small partonic hard cross sections [29]. So far most of the analyses of A_N for the light-hadron production has been performed, assuming that the contribution (i) is the sole origin of the asymmetry [14, 30–32]. However, the resulting quark-gluon correlation functions turned out to have a sign opposite to that of the Sivers function obtained from the analyses of SSAs observed in semi-inclusive deep inelastic scattering (SIDIS) [33]. Clearly the other sources, (ii) and (iii), should also play an important role for the asymmetry. More recently the cross section formula for (iii) was derived in [27], and an analysis of A_N for the pion

production at RHIC has been performed including the effects of (i) and (iii), in which the Sivers function and the transversity distribution for the nucleon and the Collins functions for the pion have been fixed using the data of SIDIS and e^+e^--annihilations and the twist-3 fragmentation function has been fitted to reproduce the RHIC A_N data [34]. The analysis has shown that the combination can describe the A_N data consistently with other two processes. To justify this scenario for A_N, it is also important to analyze the role of the above (ii).

In our recent papers, we have derived the contribution of the twist-3 three-gluon correlation functions in the transversely polarized nucleon to the single spin asymmetry for the D-meson productions in SIDIS, $ep^\uparrow \to eDX$ [19, 35], and the pp collision, $p^\uparrow p \to DX$ [21], and the Drell-Yan/direct-photon processes, $p^\uparrow p \to \gamma^{(*)}X$ [22]. Using some models for the three-gluon correlation functions, we also studied its impact on the corresponding asymmetries at the energy of RHIC and the Electron-Ion-Collider (EIC). In a recent paper [23], we have extended these analyses to the light-hadron production in the pp collision. This has completed the corresponding leading order twist-3 cross section for $p^\uparrow p \to hX$ together with the known result for the above contributions (i) and (iii). This talk is a summary of [23].

This paper is organized as follows: After introducing the three-gluon correlation functions in section 2, we present the twist-3 cross section in section 3. In section 4, we study its impact on the SSA in the light-hadron productions at the RHIC energy by using the model in [21, 22]. We will see the three-gluon correlation disturbs the observed patterns of the asymmetry seriously, which indi-

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cates that this process may be used to constrain the magnitude and the form of the three-gluon correlations.

2 Three-gluon correlation functions in the transversely polarized nucleon

As clarified in [17–19], there are two independent three-gluon correlation functions in the transversely polarized nucleon, $O(x_1, x_2)$ and $N(x_1, x_2)$, which are the Lorentz-scalar functions of the longitudinal momentum fractions x_1 and x_2, defined as

$$
\begin{aligned}
O^{\alpha\beta\gamma}(x_1, x_2) &= -g(i)^3 \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \\
&\quad \times \langle pS_\perp | d_{bca} F_b^{\beta n}(0) F_c^{\gamma n}(\mu n) F_a^{\alpha n}(\lambda n) | pS_\perp \rangle \\
&= 2iM_N \Big[O(x_1, x_2) g^{\alpha\beta} \epsilon^{\gamma pnS_\perp} \\
&\quad + O(x_2, x_2-x_1) g^{\beta\gamma} \epsilon^{\alpha pnS_\perp} \\
&\quad + O(x_1, x_1-x_2) g^{\gamma\alpha} \epsilon^{\beta pnS_\perp} \Big],
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
N^{\alpha\beta\gamma}(x_1, x_2) &= -g(i)^3 \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \\
&\quad \times \langle pS_\perp | if_{bca} F_b^{\beta n}(0) F_c^{\gamma n}(\mu n) F_a^{\alpha n}(\lambda n) | pS_\perp \rangle \\
&= 2iM_N \Big[N(x_1, x_2) g^{\alpha\beta} \epsilon^{\gamma pnS_\perp} \\
&\quad - N(x_2, x_2-x_1) g^{\beta\gamma} \epsilon^{\alpha pnS_\perp} \\
&\quad - N(x_1, x_1-x_2) g^{\gamma\alpha} \epsilon^{\beta pnS_\perp} \Big],
\end{aligned} \tag{2}
$$

where $F_a^{\alpha\beta} \equiv \partial^\alpha A_a^\beta - \partial^\beta A_a^\alpha + g f_{abc} A_b^\alpha A_c^\beta$ is the gluon's field strength, and we used the notation $F_a^{\alpha n} \equiv F_a^{\alpha\beta} n_\beta$ and $\epsilon^{\alpha pnS_\perp} \equiv \epsilon^{\alpha\mu\nu\lambda} p_\mu n_\nu S_{\perp\lambda}$ with the convention $\epsilon_{0123} = 1$. d^{bca} and f^{bca} are the symmetric and anti-symmetric structure constants of the color SU(3) group, and we have suppressed the gauge-link operators which ensure the gauge invariance. p is the nucleon momentum, and $S_\perp$ is the transverse spin vector of the nucleon normalized as $S_\perp^2 = -1$. In the twist-3 accuracy, p can be regarded as light-like ($p^2 = 0$), and n is another lightlike vector satisfying $p \cdot n = 1$. To be specific, we set $p^\mu = (p^+, 0, \mathbf{0}_\perp)$, $n^\mu = (0, n^-, \mathbf{0}_\perp)$, and $S_\perp^\mu = (0, 0, \mathbf{S}_\perp)$. The nucleon mass M_N is introduced to define $O(x_1, x_2)$ and $N(x_1, x_2)$ dimensionless. The decomposition (1) and (2) takes into account all the constraints from hermiticity, invariance under the parity- and time-reversal transformations and the permutation symmetry among the participating three gluon-fields. The functions $O(x_1, x_2)$ and $N(x_1, x_2)$ are real and have the following symmetry properties,

$$
O(x_1, x_2) = O(x_2, x_1), \quad O(x_1, x_2) = O(-x_1, -x_2), \tag{3}
$$

$$
N(x_1, x_2) = N(x_2, x_1), \quad N(x_1, x_2) = -N(-x_1, -x_2). \tag{4}
$$

The functions $N(x_1, x_2)$ and $O(x_1, x_2)$ are, respectively, even and odd under charge conjugation.

3 Twist-3 cross section for $p^\uparrow p \to hX$ induced by the three-gluon correlation functions

The twist-3 single-spin-dependent cross section for the process $p^\uparrow(p, S_\perp) + p(p') \to h(P_h) + X$ induced by the

three-gluon correlation functions has been obtained in [23] by applying the formalism developed in [19–22]. It reads

$$
E_{P_h} \frac{d^3 \Delta\sigma}{d^3 P_h} = \frac{2\pi M_N \alpha_s^2}{S} \epsilon^{P_h p n S_\perp}
$$

$$
\times \sum_{i,j} \int \frac{dx}{x} \int \frac{dx'}{x'} f_i(x') \int \frac{dz}{z^2} D_j(z) \delta(\hat{s} + \hat{t} + \hat{u}) \frac{1}{z\hat{u}}
$$

$$
\times \Big[\zeta_{ij} \Big(\frac{d}{dx} O(x) - \frac{2O(x)}{x} \Big) \hat{\sigma}_{gi \to j}^{(O)} + \Big(\frac{d}{dx} N(x) - \frac{2N(x)}{x} \Big) \hat{\sigma}_{gi \to j}^{(N)} \Big],
$$

$$
\tag{5}
$$

where the functions $O(x)$ and $N(x)$ are defined as

$$
O(x) \equiv O(x, x) + O(x, 0),
$$

$$
N(x) \equiv N(x, x) - N(x, 0), \tag{6}
$$

and the factor ζ_{ij} is defined so that $\zeta_{ij} = -1$ when i or j is an anti-quark flavor and $\zeta_{ij} = 1$ for other cases. $f_i(x')$ and $D_i(z)$ are, respectively, unpolarized distribution and fragmentation functions for the quark and anti-quark flavors and the gluon ($i = q, \bar{q}, g$). The partonic hard crosss sections $\hat{\sigma}_{gi \to j}^{(O,N)}$ can be written as the sum of the contributions from the initial-state-interaction (ISI) and the final-state-interaction (FSI) diagrams as

$$
\hat{\sigma}_{gi \to j}^{(O,N)} = \hat{\sigma}_{gi \to j}^{(O,N)I} - \frac{\hat{s}}{\hat{t}} \hat{\sigma}_{gi \to j}^{(O,N)F}, \tag{7}
$$

and they are given in terms of the partonic Mandelstam variables, $\hat{s} = (xp + x'p')^2$, $\hat{t} = (xp - p_c)^2$, $\hat{u} = (x'p' - p_c)^2$. The cross sections $\hat{\sigma}_{gi \to j}^{(O,N)I,F}$ are given as follows [23]:

(i) Unpolarized quark distribution channels:

   (a) Quark fragmentation channel:

$$
\hat{\sigma}_{gq \to q}^{(O)I} = -\hat{\sigma}_{gq \to q}^{(N)I} = \frac{\hat{t}(\hat{s}^2 + \hat{t}^2)}{\hat{s}\hat{u}^2} - \frac{1}{N^2} \Big(\frac{\hat{s}}{\hat{t}} + \frac{\hat{t}}{\hat{s}} \Big), \tag{8}
$$

$$
\hat{\sigma}_{gq \to q}^{(O)F} = \hat{\sigma}_{gq \to q}^{(N)F} = -\frac{\hat{s}(\hat{s}^2 + \hat{t}^2)}{\hat{t}\hat{u}^2} + \frac{1}{N^2} \Big(\frac{\hat{s}}{\hat{t}} + \frac{\hat{t}}{\hat{s}} \Big). \tag{9}
$$

   (b) Gluon fragmentation channel:

$$
\hat{\sigma}_{gq \to g}^{(O)I} = -\hat{\sigma}_{gq \to g}^{(N)I}
$$

$$
= \frac{\hat{u}(\hat{s}^2 + \hat{u}^2)}{\hat{s}\hat{t}^2} - \frac{1}{N^2} \Big(\frac{\hat{s}}{\hat{u}} + \frac{\hat{u}}{\hat{s}} \Big), \tag{10}
$$

$$
\hat{\sigma}_{gq \to g}^{(O)F} = \frac{(\hat{s} - \hat{u})(\hat{s}^2 + \hat{u}^2)}{\hat{s}\hat{t}\hat{u}}, \tag{11}
$$

$$
\hat{\sigma}_{gq \to g}^{(N)F} = \frac{(\hat{s}^2 + \hat{u}^2)^2}{\hat{s}\hat{t}^2\hat{u}}, \tag{12}
$$

(ii) Unpolarized gluon distribution channels:

   (a) Quark fragmentation channel:

$$
\hat{\sigma}_{gg \to q}^{(O)I} = \frac{1}{C_F} \frac{(\hat{u} - \hat{t})(\hat{t}^2 + \hat{u}^2)}{2\hat{s}\hat{t}\hat{u}}, \tag{13}
$$

$$
\hat{\sigma}_{gg \to q}^{(N)I} = \frac{1}{C_F} \frac{(\hat{t}^2 + \hat{u}^2)^2}{2\hat{s}^2\hat{t}\hat{u}}, \tag{14}
$$

$$
\hat{\sigma}_{gg \to q}^{(O)F} = \hat{\sigma}_{gg \to q}^{(N)F}
$$

$$
= \Big(-\frac{1}{C_F} \frac{\hat{u}}{2\hat{s}^2\hat{t}} + \frac{1}{N^2 C_F} \frac{1}{2\hat{t}\hat{u}} \Big) (\hat{t}^2 + \hat{u}^2). \tag{15}
$$

(b) Gluon fragmentation channel:

$$\hat{\sigma}_{gg\to g}^{(O)I,F} = 0, \tag{16}$$

$$\hat{\sigma}_{gg\to g}^{(N)I} = \frac{N}{C_F} \frac{2(\hat{t}^2 + \hat{u}^2)(\hat{t}^2 + \hat{t}\hat{u} + \hat{u}^2)^2}{\hat{s}^2 \hat{t}^2 \hat{u}^2}, \tag{17}$$

$$\hat{\sigma}_{gg\to g}^{(N)F} = -\frac{N}{C_F} \frac{2(\hat{t}^2 + 2\hat{t}\hat{u} + 2\hat{u}^2)(\hat{t}^2 + \hat{t}\hat{u} + \hat{u}^2)^2}{\hat{s}^2 \hat{t}^2 \hat{u}^2}. \tag{18}$$

A remarkable feature of (5) is that the partonic hard cross sections for $O(x,x)$ and $O(x,0)$ are identical, and likewise for $N(x,x)$ and $-N(x,0)$. Therefore they contribute to the cross section through the combinations $O(x)$ and $N(x)$ in (6). The same feature was also observed for the twist-3 cross section for the prompt-photon production $p^\uparrow p \to \gamma X$. Note that (13), (14) and (15) are obtained from the result for $p^\uparrow p \to DX$ in [21] by taking the massless limit of the charm-quark mass, $m_c \to 0$. For the processes in which all particles participating in the scattering are massless, three-gluon correlations contribute in the combination of $O(x)$ and $N(x)$. This is in contrast to the case for SIDIS and Drell-Yan processes, where the virtual photon with large Q^2 enters the scattering. The result $\hat{\sigma}_{gg\to g}^{(O)I,F} = 0$ in (16) is due the vanishing color factors.

4 Numerical calculation of the asymmetry at the RHIC energy

To illustrate the effect of the three-gluon correlation functions to A_N for the light-hadron production, we perform here a model calculation of A_N at the RHIC energy. In [21, 22], we employed two models for the three-gluon correlation in the study of A_N in $p^\uparrow p \to DX$ and $p^\uparrow p \to \gamma X$. We use the same models here, i.e,

$$\text{Model 1:} \quad O(x) = N(x) = 0.004\, x\, G(x), \tag{19}$$

$$\text{Model 2:} \quad O(x) = N(x) = 0.001\, \sqrt{x}\, G(x), \tag{20}$$

where $G(x)$ is the twist-2 unpolarized gluon density.[1] The coefficients 0.004 and 0.001 were determined so that the calculated A_N^D does not exceed the RHIC preliminary data for A_N^D [36]. The above model ansatz were motivated to see the effect of the three-gluon correlations in comparison with the gluon density and to see the sensitivity of A_N to the small-x behavior of the functions. We use the unpolarized parton density in [37] and the fragmentation function for the pion in [38]. For the calculation, we set the scale of all the distribution and fragmentation functions at the transverse momentum of the final hadron P_T.

Figure 1 shows the x_F-dependence of the three-gluon contribution to A_N for the $\pi^{\pm,0}$ and jet productions in the pp-collision at the RHIC energy $\sqrt{S}$ = 200 GeV and P_T = 2 GeV. We plotted the contribution from $O(x)$ and $N(x)$ separately to see each effect on A_N. At $x_F > 0$, $N(x)$ gives rise to the large asymmetry and the effect of $O(x)$ is negligible for both models. The origin of the large asymmetry from $N(x)$ is the partonic cross section (18): At large $x_F > 0$, where $-T \ll S \sim -U$, large-x and small-x' region

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[1]In this rough estimate the three-gluon contribution to the asymmetry, we set the scale dependence of the three-gluon correlation to be the same as the twist-2 gluon density.
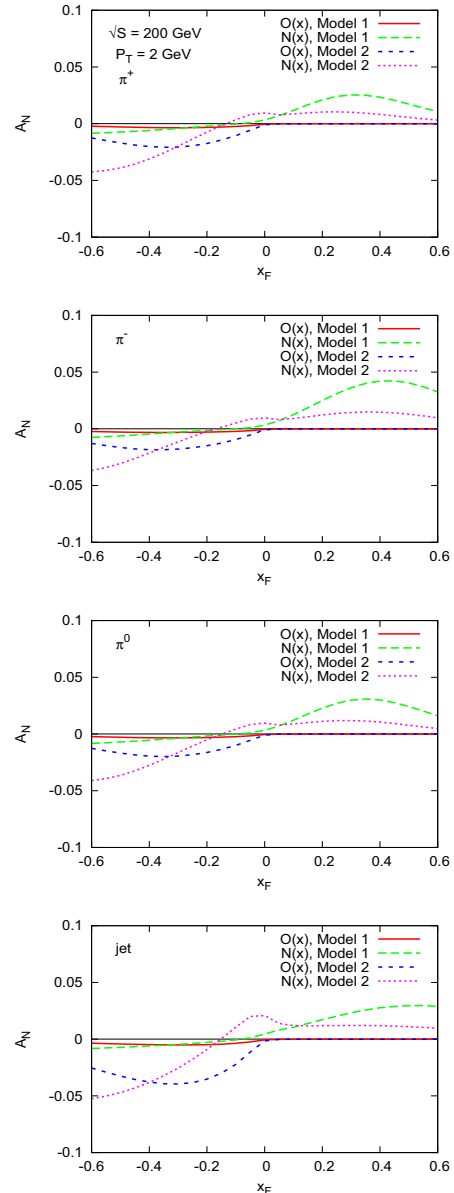

Figure 1. x_F-dependence of the three-gluon contribution to A_N for $p^\uparrow p \to \{\pi^{\pm,0}, \text{jet}\}X$ at $\sqrt{S}$ = 200 GeV and P_T = 2 GeV. The contribution from $O(x)$ and $N(x)$ are plotted separately for models 1 and 2.

is probed, and thus the unpolarized gluon density brings main contribution. While the partonic cross sections in the quark fragmentation channel (13)-(15) are tiny, those in the gluon fragmentation channel (17) and (18) for $N(x)$ are large, in particular, the latter contribution is enhanced by the kinematic factor $\hat{s}/\hat{t}$ in (7) for the FSI.

At $x_F < 0$, in particular, $x_F \to -1$ where $-U \ll S \sim -T$, the region of small-x and large-x' is relevant. Thus the model 1 gives rise to only small asymmetry for both $O(x)$ and $N(x)$ due to their mild behavior at small-x. On the other hand, the model 2 gives the large asymmetry for the two functions. This is due to the large partonic cross section (8) and (9) in the unpolarized quark distribution
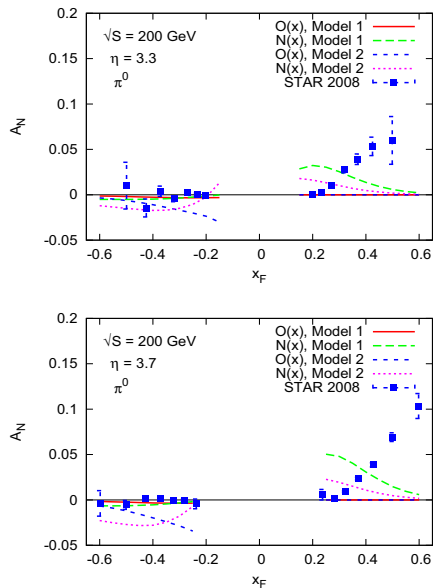
Figure 2. x_F-dependence of the three-gluon contribution to A_N for $p^\uparrow p \to \pi^0 X$ at $\sqrt{S}$ = 200 GeV and P_T = 3.3 and 3.7 in comparison to the RHIC-STAR data [3]. The contribution from $O(x)$ and $N(x)$ are plotted separately for models 1 and 2.

Figure 3. P_T-dependence of the three-gluon contribution to A_N for $p^\uparrow p \to \pi^0 X$ at $\sqrt{S}$ = 200 GeV and x_F = 0 in comparison to the RHIC-PHENIX data [8]. The contribution from $O(x)$ and $N(x)$ are plotted separately for models 1 and 2.

three-gluon correlation function, and thus we need a complete analysis including all these effects to draw a definite conclusion.

Figure 3 shows the calculated $A_N^{\pi^0}$ in the midrapidity region ($|\eta| < 0.35$) at $\sqrt{S}$ = 200 GeV in comparison with the RHIC-PHENIX data [8]. Both models give tiny asymmetry due to the small partonic cross sections, so the form of the three-gluon correlation functions is not much constrained by the data in this region.

5 Summary

In this paper we have studied the three-gluon contribution to SSA for the light hadron production in the pp collision, $p^\uparrow p \to hX$. We have derived the corresponding LO twist-3 cross section. Together with the result for the contribution from the quark-gluon correlation and the twist-3 fragmentation functions, this has completed the twist-3 cross section for this process. We have also presented a numerical calculation of the asymmetry at the RHIC energy based on our previous models and have shown that this process could bring a useful constraint on the upper bound of the three-gluon correlation functions.

Acknowledgments

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channel with the quark fragmentation, and a steeply rising behavior in the three-gluon correlations at small-x, which is even more enhanced by the derivative. For $O(x)$, there is a partial cancelation between the ISI and FSI due to the relative signs between (8) and (9), while for $N(x)$ these cross sections contribute constructively. This leads to different behavior of the asymmetry between $N(x)$ and $O(x)$.

Here we note that the three-gluon correlation functions shift the A_N for $\pi^{\pm,0}$ in the same direction, while the observed asymmetries are approximately $A_N^{\pi^+} \simeq -A_N^{\pi^-}$ at $x_F > 0$. This indicates that the three-gluon correlation functions, in particular $N(x)$, cannot be a main source of the A_N for the pion.

Recently, AnDY collaboration at RHIC [9] presented a first A_N data for the jet production, which shows A_N^{jet} is slightly negative at $x_F < 0$. Since only the three-gluon correlation function can cause nonzero asymmetry at $x_F < 0$, the data may be useful to constrain $N(x)$ and $O(x)$.

Figure 2 shows the three-gluon contribution to $A_N^{\pi^0}$ in comparison to the RHIC-STAR data [3] at $\sqrt{S}$ = 200 GeV and the pseudorapidity η = 3.3 and 3.7. One sees that the contribution from $N(x)$ is much larger than the data at small $x_F > 0$ for the two models, and therefore it is unlikely that the magnitude of $N(x)$ is as large as these models in the large-x region. At $x_F < 0$, the contribution of the model 1 is zero and is consistent with data for both $N(x)$ and $O(x)$, while the model 2 for the two functions is far from the data points. This means the three-gluon correlations should behave more mildly than the model 2 in the small-x region. We note, however, that the observed asymmetry results from the combination of the quark-gluon correlation function, twist-3 fragmentation function and the
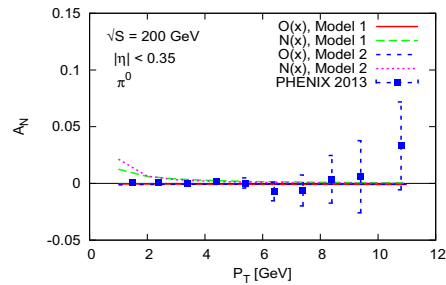
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