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New Collinear Twist-3 Analysis of Transverse SSA: Toward a Resolution to the Sign-Mismatch Problem

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Toward a solution for the sign-mismatch problem

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Abstract We present a new collinear twist-3 analysis of the transverse SSA A_N at RHIC. We use the TMD Sivers/Collins function to fix some of the relevant collinear twist-3 functions and perform a fit of the RHIC data with other parameterized twist-3 functions. This allows us to keep the consistency among descriptions in pp collision, SIDIS, and e^+e^- annihilation and thus could provide a unified description of the spin asymmetries in the low- and high-P_T processes. By taking into account the twist-3 fragmentation contribution, we show for the first time this contribution could be the main source of A_N in $pp^\uparrow \to hX$ and its inclusion could provide a solution for the sign-mismatch problem.

Keywords single-spin asymmetries · collinear factorization · twist-3 fragmentation

1 Introduction

The large transverse SSA A_N observed in polarized QCD processes has been a long-standing problem in hadron physics. Since the conventional parton model fails to explain its origin [1], it has turned out they reflect novel quark-gluon substructure of hadrons beyond the collinear parton model.

By now QCD mechanisms leading to such large A_N have been understood in some detail. On one hand, the Sivers/Collins mechanism has been proposed within the TMD factorization [2; 3; 4] and successfully applied to describe the asymmetries in low-P_T SIDIS and e^+e^- annihilation where pQCD works since another hard scale Q is involved [5; 6]. On the other hand, the twist-3 approach within the collinear factorization has been significantly developed in the last decades to explain the origin of A_N in high-P_T processes [7; 8; 9]. In particular, the contribution from twist-3 quark-gluon correlation inside the transversely polarized proton has been widely studied, since this effect was initially thought as the main source of the A_N for light-hadron production in pp collision, $pp^\uparrow \to hX$. Indeed, previous studies

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with the inclusion of this effect obtained a reasonable description of A_N in $pp^\uparrow \to hX$ [10; 11; 12; 13]. However, as will be discussed in section 2, it has been pointed out that this effect cannot be the main source of A_N in $pp^\uparrow \to hX$ since the obtained twist-3 function $T_F(x,x)$ has the opposite sign with the one expected from studies for the Sivers effect in SIDIS [14]. This inconsistency, the so-called "sign-mismatch" problem, has indicated the potential importance of the contribution from twist-3 fragmentation in $pp^\uparrow \to hX$, which has not been taken into account in previous analyses.

In this report, we present a new collinear twist-3 analysis of A_N^π measured at RHIC. By including the twist-3 fragmentation contribution, we show for the first time this contribution could be the main source of A_N in $pp^\uparrow \to hX$ and its inclusion could provide a unified description of the asymmetries in SIDIS, e^+e^-, and pp. This report is a brief summary of our recent work [15].

2 Collinear twist-3 formalism

In principle three types of twist-3 effects contribute to A_N in $pp^\uparrow \to hX$. Their contribution to the polarized cross section is schematically expressed as

$$\begin{aligned} d\sigma(\mathbf{S}_\perp) &= H \otimes f_{a/p^\uparrow(3)} \otimes f_{b/p(2)} \otimes D_{h/c(2)} \\ &+ H' \otimes f_{a/p^\uparrow(2)} \otimes f_{b/p(3)} \otimes D_{h/c(2)} \\ &+ H'' \otimes f_{a/p^\uparrow(2)} \otimes f_{b/p(2)} \otimes D_{h/c(3)}, \end{aligned} \tag{1}$$

where $\otimes$ represents the convolution with respect to the appropriate momentum fractions. $f_{a/p^\uparrow(t)}$ denotes the twist-t parton distribution function (PDF) for parton a in the transversely polarized proton $p^\uparrow$, and similarly for the other PDF $f_{b/p(t)}$ and fragmentation function (FF) $D_{h/c(t)}$ for hadron h in parton c. H, H', and H'' denote the hard cross sections for each twist-3 contribution.

So far, a lot of efforts have been devoted to study the effects of twist-3 PDFs contained in the first and second terms in Eq. (1). The contribution of the second term is known to be negligible in this process [16; 17] while the first term could lead a sizable contribution to A_N. Thus it was believed that the contribution from the first term was the main source of A_N [10; 11; 12; 13; 18; 19; 20]. Indeed, all previous analyses which took into account the first term accomplished a reasonable description of A_N. However, it has been pointed out that the SGP function $T_F(x,x)$ obtained in such analysis has the sign opposite to the one expected from the relation to the TMD Sivers function,

$$T_F^q(x,x) = -\int d^2\mathbf{p}_\perp \frac{\mathbf{p}_\perp^2}{M} f_{1T}^{\perp q}(x,\mathbf{p}_\perp^2)\big|_{\rm SIDIS}. \tag{2}$$

This "sign-mismatch" puzzle cannot be solved with a more flexible parameterization of the Sivers function [21], so that it has been recognized that the contribution from twist-3 distribution cannot be the main source of A_N in $pp^\uparrow \to hX$. Another evidence of this statement is the fact that within the collinear twist-3 approach one obtains the wrong sign for the neutron A_N in inclusive DIS [22; 23] when using T_F extracted directly from A_N in $pp^\uparrow \to hX$ [24].

At this point, one naturally comes to think about the role of the third term in Eq. (1), namely the contribution from twist-3 fragmentation. Its complete cross section was derived very recently by two of the authors (A.M. and D.P.) and reads [25; 27]

$$\begin{aligned} \frac{P_h^0 d\sigma(\mathbf{S}_\perp)}{d^3\mathbf{P}_h} &= -\frac{2\alpha_s^2 M_h}{S}\epsilon_{\perp,\alpha\beta} S_\perp^\alpha P_{h\perp}^\beta \sum_i \sum_{a,b,c} \int_{z_{min}}^1 \frac{dz}{z^3} \int_{x'_{min}}^1 \frac{dx'}{x'} \frac{1}{x} \frac{1}{x'S+T/z} \frac{1}{-x'\hat{t}-x\hat{u}} h_1^a(x) f_1^b(x') \\ &\times \left\{ \left[\hat{H}^{C/c}(z) - z\frac{d\hat{H}^{C/c}(z)}{dz} \right] S_{\hat{H}}^i + \frac{1}{z} H^{C/c}(z) S_H^i + 2z^2 \int_z^\infty \frac{dz_1}{z_1^2} \frac{1}{\frac{1}{z}-\frac{1}{z_1}} \hat{H}_{FU}^{C/c,\Im}(z,z_1) \frac{1}{\xi} S_{\hat{H}_{FU}}^i \right\} \end{aligned} \tag{3}$$

where i denotes the channel, $x = -x'(U/z)/(x'S+T/z)$, $x'_{min} = -(T/z)/(U/z+S)$, $z_{min} = -(T+U)/S$, and $\xi = (1-z/z_1)$. Here we used the Mandelstam variables $S = (P+P')^2$, $T = (P-P_h)^2$, and $U = (P'-P_h)^2$, which on the partonic level give $\hat{s} = xx'S$, $\hat{t} = xT/z$, and $\hat{u} = x'U/z$. Oftentimes one also uses $x_F = 2P_{hz}/\sqrt{S}$, where P_{hz} is the longitudinal momentum of the hadron, as well as the pseudo-rapidity $\eta = -\ln\tan(\theta/2)$, where θ is the scattering angle. The variables x_F, η are further

related by $x_F = 2P_{h\perp}\sinh(\eta)/\sqrt{S}$, where $P_{h\perp}$ is the transverse momentum of the hadron. The non-perturbative parts in (3) are the transversity h_1, the unpolarized PDF f_1, and the three twist-3 FFs $\hat{H}$, H, and $\hat{H}_{FU}^{\Im}$, with the last one parameterizing the imaginary part of a 3-parton correlator. The definition of those functions and the explicit form of the hard scattering coefficients S^i can be found in [27]. The cross section formula Eq. (3) involves three twist-3 FFs, $\hat{H}$, H and $\hat{H}_{FU}$. Among them, the function $\hat{H}$ is related to the $k_\perp$-moment of the TMD Collins function $H_1^{\perp h/q}$ as

$$\hat{H}^{h/q}(z) = z^2 \int d^2\mathbf{k}_\perp \frac{\mathbf{k}_\perp^2}{2M_h^2} H_1^{\perp h/q}(z, z^2\mathbf{k}_\perp^2). \tag{4}$$

Since the Collins function has been extracted by a simultaneous analysis of data on the asymmetries in e^+e^- and SIDIS [6], one can use that result to fix the function $\hat{H}$ so as to keep consistency with those two processes. We also note the QCD equation of motion reduces the number of independent twist-3 functions [26; 27],

$$H^{h/q}(z) = -2z\hat{H}^{h/q}(z) + 2z^3 \int_z^\infty \frac{dz_1}{z_1^2} \frac{1}{\frac{1}{z} - \frac{1}{z_1}} \hat{H}_{FU}^{h/q,\Im}(z, z_1). \tag{5}$$

All in all, we have only one unknown function $\hat{H}_{FU}^{\Im}$. The main purpose of this study is to perform a fit of the RHIC A_N data with the twist-3 FFs toward a solution of the sign-mismatch problem.

3 Phenomenology of A_N for pion production

We perform a fit of A_N in $pp^\uparrow \to hX$ in the forward region of the polarized proton, which has been studied by the STAR [28; 29; 30], BRAHMS [31], and PHENIX [32] collaborations at RHIC. In this analysis we focus on data at $\sqrt{S} = 200$ GeV for which typically $P_{h\perp} > 1$ GeV. Throughout we use the GRV98 unpolarized PDF [33] and the DSS unpolarized FFs [34]. The SGP contribution is computed by fixing T_F through Eq. (2) with two different inputs for the Sivers function — SV1: $f_{1T}^\perp$ from Ref. [5], obtained from SIDIS data on $A_{\rm SIDIS}^{\rm Siv}$ [35; 36]; and SV2: $f_{1T}^\perp$ from Ref. [37], "constructed" such that, in the TMD approach, the contribution of the Sivers effect to A_N is maximized while maintaining a good description of $A_{\rm SIDIS}^{\rm Siv}$. These two inputs for $f_{1T}^\perp$ are mainly distinct by their quite different large-x behavior. To compute the contribution in (3) we take h_1 and $H_1^\perp$ (which fixes $\hat{H}$ through (4)) from [6]. Then we parameterize the 3-parton FF for the favored component as

$$\frac{\hat{H}_{FU}^{\pi^+/(u,\bar{d}),\Im}(z, z_1)}{D^{\pi^+/(u,\bar{d})}(z) D^{\pi^+/(u,\bar{d})}(z/z_1)} = \frac{N_{\rm fav}}{2I_{\rm fav}J_{\rm fav}} z^{\alpha_{\rm fav}} (z/z_1)^{\alpha'_{\rm fav}} (1-z)^{\beta_{\rm fav}} (1-z/z_1)^{\beta'_{\rm fav}}, \tag{6}$$

with the free parameters $N_{\rm fav}$, $\alpha_{\rm fav}$, $\alpha'_{\rm fav}$, $\beta_{\rm fav}$, $\beta'_{\rm fav}$ and the unpolarized FF D. Note that the allowed range for z and z/z_1 is $[0, 1]$ and that our ansatz satisfies the constraint $\hat{H}_{FU}(z, z) = 0$ [38; 39]. The factors $I_{\rm fav}$ and $J_{\rm fav}$ are introduced so that the 3-parton correlator satisfies $\int_0^1 dz H_{(3)}^{\pi^+/u}(z) = N_{\rm fav}$ at the initial scale, where $H_{(3)}$ represents the entire second term on the r.h.s. of (5)[1].

Using the MINUIT package we fit the fragmentation contribution to data for A_N^π. To facilitate the fit we only keep 7 parameters in $\hat{H}_{FU}^{\pi^+/q,\Im}$ free. We also allow the β-parameters $\beta_u^T = \beta_d^T$ of the transversity to vary within the error range given in [6]. For the SV1 input we have obtained a very good description of A_N for pions as shown in Fig. 1 (χ^2/d.o.f. = 1.03). We emphasize that such a positive outcome is non-trivial if one keeps in mind the constraint in (5) and the need to simultaneously fit data for $A_N^{\pi^0}$ and $A_N^{\pi^\pm}$. For the SV2 input the values of the fit parameters are similar, with an equally successful fit (χ^2/d.o.f. = 1.10).

The obtained twist-3 FFs are shown in Fig. 2 where we plotted the functions $H^{\pi^+/q}$ and $\tilde{H}_{FU}^{\pi^+/q} \equiv \int_z^\infty \frac{dz_1}{z_1^2} \frac{1}{\frac{1}{z}-\frac{1}{z_1}} \frac{1}{\xi} \hat{H}_{FU}^{\pi^+/q,\Im}(z, z_1)$. In either case the favored and disfavored FFs have opposite signs. This

[1] For the details, see [15].

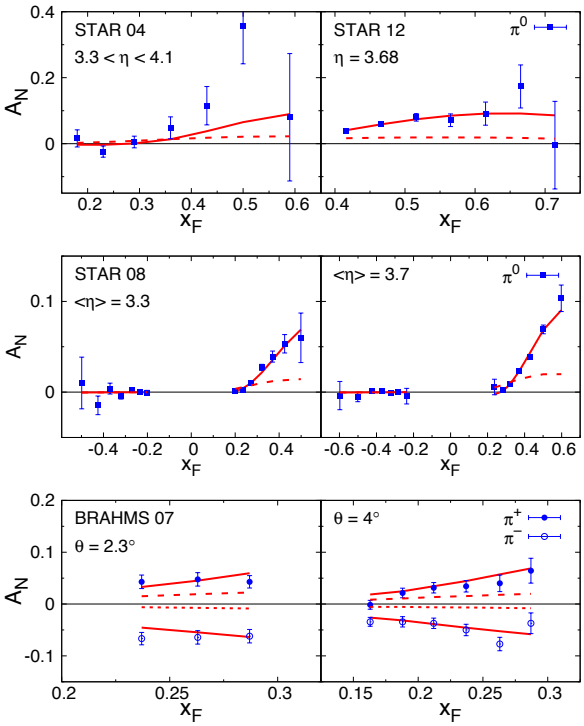

Fig. 1 Results of the fit for $A_N^{\pi^0}$'s at RHIC [28; 29; 30; 31]. The dashed line (dotted line in the case of π^-) means $\hat{H}_{FU}^{\Im}$ switched off.

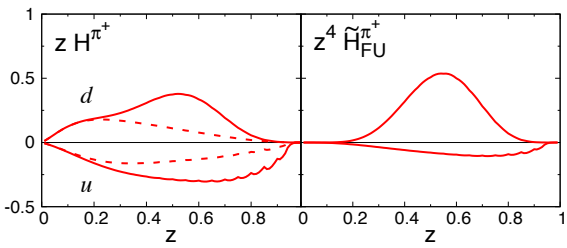

Fig. 2 The twist-3 FFs obtained from the fit. The dashed line means $\hat{H}_{FU}^{\Im}$ switched off.

is like for $H_1^\perp$ where such reversed signs are actually "preferred" by the Schäfer-Teryaev (ST) sum rule $\sum_h \sum_{S_h} \int_0^1 dz\, z\, M_h \hat{H}^{h/q}(z) = 0$ [40; 41]. Note that the ST sum rule, in combination with (5), implies a constraint on a certain linear combination of $H^{h/q}$ and (an integral of) $\hat{H}_{FU}^{h/q,\Im}$. In view of that, reversed signs between favored and disfavored FFs like in Fig. 2 are actually beneficial. Also depicted in Fig. 2 is $H^{\pi^+/q}$ when $\hat{H}_{FU}^{\pi^+/q,\Im}$ is switched off. As shown in Fig. 1, in such a scenario, i.e., by turning off the 3-parton FF, it is difficult to describe the data for A_N even if we take into account the large-x uncertainty of the transversity. According to Fig. 3, the $\hat{H}$ term (including its derivative) contributes only very little to A_N. Also the contribution of $T_F(x,x)$ is small, except for the SV2 input at large x_F, where its contribution is opposite to the data because of the sign-mismatch. Clearly A_N is governed by the H-term. This result can mainly be traced back to the hard scattering coefficients: e.g., for the dominant $qg \to qg$ channel one has $S_H \sim \frac{1}{\hat{t}^3}$, but $S_{\hat{H}} \sim \frac{1}{\hat{t}^2}$ in the forward region where $\hat{t}$ is small [27]. Finally, figure 4 shows the $P_{h\perp}$-dependence of A_N for $\sqrt{s} = 500$ GeV. Preliminary data from STAR, extending to almost $P_{h\perp} = 10$ GeV, shows that A_N is rather flat [42]. Our twist-3 prediction agrees with such trend as observed in the previous study [13], and also the magnitude of A_N is in line with the data.

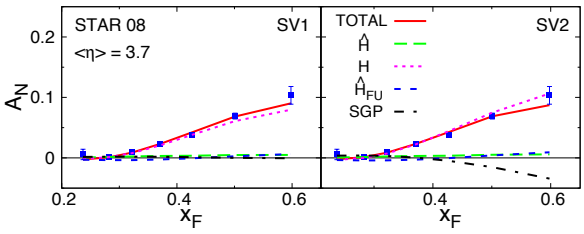

Fig. 3 Individual contributions to $A_N^{\pi^0}$ (data from [29]) for SV1 and SV2 inputs.

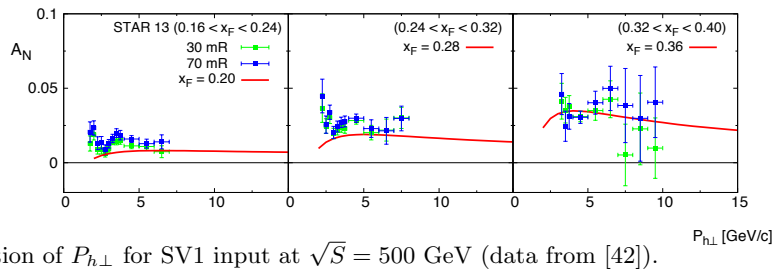

Fig. 4 A_N as function of $P_{h\perp}$ for SV1 input at $\sqrt{S} = 500$ GeV (data from [42]).

4 Summary

We have presented a new collinear twist-3 analysis of the RHIC A_N^π data. In this analysis we have kept the consistency with the Sivers/Collins effects by using the Sivers/Collins functions extracted from low-P_T SIDIS and e^+e^- to fix the relevant collinear twist-3 functions. We have shown for the first time the fragmentation contribution could be the main source of A_N^π and its inclusion could provide a solution for the "sign-mismatch" problem.

Although a first unified description of the asymmetries has been accomplished, much work is left to be done for a complete elucidation of the origin of A_N. First, in this work, we didn't include the contribution from the 3-gluon correlation and part of the quark-gluon correlation inside the transversely polarized proton. In principle, information on these functions could be extracted from other cleaner processes such as direct-photon or jet productions in pp collision. In addition, the twist-3 FFs should be constrained from A_N in other processes like ep collision [43; 44]. Future RHIC and EIC experiments would provide great opportunities to determine these functions.

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