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Fragmentation contribution to the transverse single-spin asymmetry in proton–proton collisions

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ABSTRACT

Within the collinear twist-3 framework, we study the single-spin asymmetry (SSA) in collisions between unpolarized protons and transversely polarized protons with focus on the fragmentation term. The fragmentation mechanism must be analyzed in detail in order to unambiguously determine the impact of various contributions to SSAs in hadron production. Such a distinction may also settle the "sign mismatch" between the transverse SSA in proton–proton collisions and the Sivers effect in semi-inclusive deep inelastic scattering. We calculate terms involving quark–quark and quark–gluon–quark correlators, which is an important step in such an investigation.

1. Introduction

Beginning in the late 1970s, calculations of transverse SSAs in inclusive hadron production within the naïve collinear parton model demonstrated that such asymmetries should be on the order of $\alpha_s m_q / P_{h\perp}$, where m_q is the mass of the quark, and $P_{h\perp}$ is the transverse momentum of the detected hadron [1,2]. These predictions contradict the large SSAs seen in experiments [3–9]. However, the use of collinear twist-3 multi-parton correlators established a framework, valid when $\Lambda_{QCD} \ll P_{h\perp}$, that could potentially handle these observables [10–13]. Various processes have been analyzed over the last two decades using this methodology — see [12–25] for some specific examples. (We also mention that other mechanisms have been proposed to explain large SSAs [26–29].) Furthermore, the collinear twist-3 formalism has been used to describe the double-spin observable A_{LT} in different reactions with one large scale [30–37].

In particular, much attention has been given to the transverse target SSA for inclusive single hadron production in proton–proton collisions. This observable was initially believed to be dominated by soft-gluon-pole (SGP) contributions on the side of the transversely polarized proton [13,15], which involves the Efremov–Teryaev–Qiu–Sterman (ETQS) function $T_F(x,x)$. However, a recent fit of $T_F(x,x)$ to $p^{\uparrow} p \to \pi X$ SSA data based on this assumption [15] has led to the so-called "sign mismatch" crisis [38] involving the ETQS function and the transverse momentum dependent (TMD) Sivers function extracted from semi-inclusive deep inelastic scattering (SIDIS) [39] — see also the discussion in [22]. A conceivable resolution could be that SFPs and/or tri-gluon correlations in the proton provide a significant effect. However, even when one calculates the former [17] and includes them in a fit of $T_F(x,x)$ [20], that function has the same sign as the one extracted in Ref. [15]. Also, tri-gluon correlations seem to only be important for processes dominated by gluon–gluon or photon–gluon fusion (e.g., asymmetries in J/ψ production), and for pion production will probably only be relevant in the small and negative x_F regions [40,41]. Therefore, neither SFPs nor tri-gluon correlations seem likely to settle the sign mismatch issue. In addition, chiral-odd collinear twist-3 functions on the side of the unpolarized proton were shown to give insignificant contributions [42], and, therefore, cannot help us with this matter. Other possible explanations, like nodes in x or $k_\perp$ in the Sivers function, have also been explored [38,43], but also seem unable to resolve the crisis. One important term that remains is the fragmentation mechanism, which could at the very least give a piece comparable to the SGP contributions — see [44–46] and references therein — and may be able to account for the sign mismatch.

Actually, the fragmentation contribution has a counterpart in the TMD factorization approach known as the Collins mechanism [47]. This causes azimuthal modulations in the cross section for processes like SIDIS and (almost back-to-back) di-hadron production from electron–positron annihilation. These effects have been measured in both processes [48–52], which has allowed for an extraction of the Collins function [53–55]. In addition, both the collinear twist-3 and TMD approaches to SSAs from fragmentation in SIDIS have been shown to agree in an intermediate momentum region where both formalisms are valid [56]. The TMD Collins mechanism has also been used to describe the fragmentation piece

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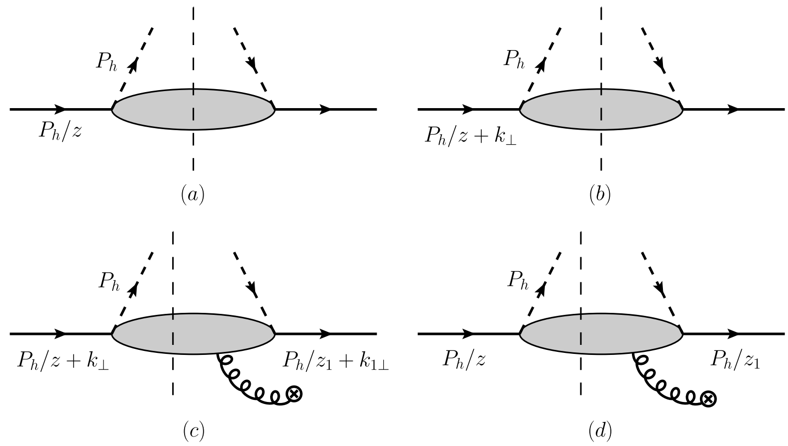

Fig. 1. Feynman diagrams for the twist-3 matrix elements that give contributions to $D_{C/c(3)}$. See the text for more details.

of the SSA in $p^\uparrow p \to \pi X$ [45,46], although a rigorous proof has not been put forth that such a framework can be applied to a process with one large scale.

Within the collinear twist-3 approach, attempts have been made to formulate the fragmentation term in the SSA for inclusive pion production from proton–proton collisions [57]. However, further work determined the contribution considered in Ref. [57] vanishes due to a universality argument [58–62]. Recent calculations have rectified the situation, and the so-called derivative term was computed for the first time in Ref. [44]. In the current work, we derive not only this term but also the non-derivative term as well as contributions involving quark–gluon–quark (qgq) correlators. In addition, we briefly comment on the implications of this and future studies on the resolution of the "sign mismatch" puzzle as well as the overall understanding of SSAs in proton–proton collisions.

The Letter is organized as follows: in Section 2 we review the collinear twist-3 formalism, and, in particular, discuss the relevant unpolarized fragmentation functions (FFs). In Section 3 we present the result for the fragmentation contribution to the single-spin dependent cross section in $p^\uparrow p \to hX$ and give a few details of the calculation. We conclude the Letter in Section 4.

2. Collinear twist-3 formalism and unpolarized FFs

To start, let us make explicit the process under consideration, namely,

$$A(P, \vec{S}_\perp) + B\big(P'\big) \to C(P_h) + X, \tag{1}$$

where the 4-momenta and polarizations of the incoming protons A, B and outgoing hadron C are indicated. The Mandelstam variables for the process are defined as $S = (P + P')^2$, $T = (P - P_h)^2$, and $U = (P' - P_h)^2$, which on the partonic level give $\hat{s} = xx'S$, $\hat{t} = xT/z$, and $\hat{u} = x'U/z$. The longitudinal momentum fraction x (x') is associated with partons in the transversely polarized (unpolarized) proton. In analogy to the usually defined lightcone vectors $n = (0^+, 1^-, 0_\perp)$ and $\bar{n} = (1^+, 0^-, 0_\perp)$, we also have $n_h \sim P_h$ and $\bar{n}_h \sim (P_h^0, -\vec{P}_h)$ (with $n_h \cdot \bar{n}_h = 1$) as lightcone vectors associated with the outgoing hadron's direction of motion [44]. Such vectors allow us to perform the appropriate twist expansion of the fragmentation correlator in the context of this process. We also note that $\epsilon_\perp^{\mu\nu} = \epsilon^{\rho\sigma\mu\nu}\bar{n}_\rho n_\sigma$ with $\epsilon_\perp^{12} = 1$. We perform the calculation of the transverse SSA in the proton–proton cm-frame, with the transversely polarized proton moving along the positive z-axis.

The first non-vanishing contribution to the spin-dependent cross section is given by terms of twist-3 accuracy and reads

$$\begin{aligned} d\sigma(\vec{P}_{h\perp}, \vec{S}_\perp) = {} & H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{C/c(2)} \\ & + H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{C/c(2)} \\ & + H'' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{C/c(3)}, \end{aligned} \tag{2}$$

where a sum over partonic channels and parton flavors in each channel is understood. In Eq. (2), $f_{a/A(t)}$ ($f_{b/B(t)}$) denotes the distribution function associated with parton a (b) in proton A (B), while $D_{C/c(t)}$ represents the fragmentation function associated with hadron C in parton c. The twist of the functions is indicated by t. The factors H, H', and H'' give the hard parts corresponding to each term, while the symbol $\otimes$ denotes convolutions in the appropriate momentum fractions. As mentioned, the first term in (2) has been analyzed previously in the literature [13,15–17]. Likewise, the second term, which involves chiral-odd twist-3 unpolarized distributions, has also been studied and was shown to be negligible because of the smallness of the hard scattering coefficients [42]. The focus of this work will be on the third term in Eq. (2) involving collinear twist-3 FFs. Therefore, for the situation we consider, $f_{a/A(2)} = h_1^a$ and $f_{b/B(2)} = f_1^b$, where h_1 and f_1 are the standard twist-2 transversity distribution function and unpolarized distribution function, respectively. We then must determine what contributions are possible for $D_{C/c(3)}$.

For a detailed discussion of collinear twist-3 parton distribution functions (PDFs) see, e.g., [19]; the same formalism can be generalized to the fragmentation case. Here we consider the situation where the outgoing hadron has a large minus-component of momentum. The twist-3 matrix elements that we must consider are given by the diagrams in Fig. 1. (Note that tri-gluon correlators are only relevant for fragmentation into a transversely polarized hadron.) In the lightcone ($A^- = 0$) gauge, these graphs lead to the three matrix elements

$$\langle\psi|\rangle\langle|\bar{\psi}\rangle, \ \langle\partial_\perp\psi|\rangle\langle|\bar{\psi}\rangle, \ \langle A_\perp\psi|\rangle\langle|\bar{\psi}\rangle, \tag{3}$$

which result from Figs. 1(a), (b), and (d), respectively. The symbol $|\rangle\langle|$ represents the intermediate $|P_h; X\rangle\langle P_h; X|$ in the fragmentation correlators. We do not have to consider Fig. 1(c) because one does not need to simultaneously take into account $k_\perp$ expansion and $A_\perp$ gluon attachments (which would give rise to twist-4 contributions).

Now that we have determined the relevant twist-3 matrix elements, we must parameterize them in terms of twist-3 FFs that will eventually be involved in our final result. We will follow the work of Ref. [63] in defining these FFs and the relations between them. We first focus on the qgq matrix element $\langle A_\perp\psi|\rangle\langle|\bar{\psi}\rangle$. One notices that this matrix element is not gauge invariant. In analogy to the qgq distribution correlators, this can be resolved in two