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Transverse Single-Spin Asymmetries: Challenges and Recent Progress

A. Metz[1] , D. Pitonyak[2], A. Schäfer[3], M. Schlegel[4] , W. Vogelsang[4], J. Zhou[3]

[1]Department of Physics, SERC, Temple University, Philadelphia, PA 19122, USA

[2]RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973 USA

[3]Institute for Theoretical Physics, Regensburg University, Universitatsstraße 31, 93053 Regensburg, Germany

[4]Institute for Theoretical Physics, Tübingen University, Auf der Morgenstelle 14, 72076, Tübingen, Germany

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**Andreas Metz · Daniel Pitonyak · Andreas Schäfer ·
Marc Schlegel · Werner Vogelsang · Jian Zhou**

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Abstract Transverse single-spin asymmetries are among the most intriguing observables in hadronic physics. Though such asymmetries were already measured for the first time about four decades ago, their origin is still under debate. Here we consider transverse single-spin asymmetries in semi-inclusive lepton-nucleon scattering, in nucleon-nucleon scattering, and in inclusive lepton-nucleon scattering. It is argued that, according to recent work, the single-spin asymmetries for those three processes may be simultaneously described in perturbative QCD, where the re-scattering of the active partons plays a crucial role. A comparison of single-spin asymmetries in different reactions can also shed light on the universality of transverse momentum dependent parton correlation functions. In particular, we discuss what existing data may tell us about the predicted process dependence of the Sivers function.

Keywords single-spin asymmetries · twist-3 collinear factorization · multi-parton correlations · universality of parton correlators

1 Introduction

The first evidence of a nonzero transverse single-spin asymmetry (SSA) in a hard semi-inclusive process was the observed polarization (up to about 30 %) of neutral Λ-hyperons in the process $p\,Be \to \Lambda^\uparrow X$ at FermiLab [1]. This pioneering experiment was followed by many other studies of hyperon polarization, as well as SSA measurements for $p^\uparrow p \to h\,X$ (with h denoting a hadron) (and $p^\uparrow \bar{p} \to h\,X$) at FermiLab and more recently at RHIC. During the last decade, transverse SSAs have also been studied in

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A. Metz
Department of Physics, Temple University, 1925 N. 12th Street, Philadelphia, Pennsylvania 19122, USA
Tel.: +1-215-204-7668
Fax: +1-215-204-5652
E-mail: metza@temple.edu

D. Pitonyak
RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA

A. Schäfer
Institute for Theoretical Physics, Regensburg University, Universitätsstraße 31, 93053 Regensburg, Germany

M. Schlegel
Institute for Theoretical Physics, Tübingen University, Auf der Morgenstelle 14, 72076 Tübingen, Germany

W. Vogelsang
Institute for Theoretical Physics, Tübingen University, Auf der Morgenstelle 14, 72076 Tübingen, Germany

J. Zhou
Institute for Theoretical Physics, Regensburg University, Universitätsstraße 31, 93053 Regensburg, Germany

semi-inclusive deep-inelastic lepton-nucleon scattering (DIS) by HERMES, COMPASS, and at JLab. Moreover, data on SSAs for fully inclusive DIS has been reported very recently.

In general, a nonzero transverse SSA requires the interference between two amplitudes having a different phase. Therefore, at least one of the amplitudes must have an imaginary part. In an early attempt to describe SSAs in perturbative QCD, the imaginary part was generated in a hard partonic interaction [2]. Such a scenario predicts very small SSAs as they are proportional to the strong coupling $\alpha_s = g^2/4\pi$ and, in particular, to the quark mass. Soon afterwards it was pointed out that three-parton correlators may give rise to (significant) transverse SSAs [3]. For example, this applies to the (twist-3) transverse SSA in $p^\uparrow p \to h\,X$, where taking into account three-parton correlations is in fact mandatory for a full QCD description. In this context, the Qiu-Sterman (QS) function [4; 5], which parameterizes a certain quark-gluon-quark correlator for a transversely polarized nucleon, for a long time has been considered the most important entity. Generally, contributions involving three-parton correlators appear as a result of the re-interaction of active partons with the remnants of either the incoming hadrons or of the fragmenting partons. Recent developments have shown that the twist-3 fragmentation contribution could play a very important role for the transverse SSA in $p^\uparrow p \to h\,X$ [6; 7].

Two important transverse SSAs in semi-inclusive DIS (the Sivers effect [8] and the Collins effect [9]) are twist-2 observables. Also those SSAs can be generated by re-scattering of active partons [10]. In QCD factorization in terms of transverse momentum dependent parton distributions (TMDs), the re-scattering effects render the TMDs gauge invariant and imply a process dependence of certain TMDs [11]. While this underlying picture is very appealing from a theoretical point of view, we want to discuss how it compares with existing data. To this end we consider transverse SSAs in semi-inclusive DIS, in processes like $p^\uparrow p \to h\,X$, and in inclusive DIS [12]. Before doing so we briefly review some features of TMDs and of the QS function.

2 TMDs and the Qiu-Sterman function

The Sivers function [8] is generally understood as the source of, e.g., the observed Sivers SSA in semi-inclusive DIS. In order to motivate its definition and its intimate connection to parton re-scattering, it is convenient to first recall the definition of ordinary forward parton distributions (PDFs) of the nucleon. For instance, the unpolarized twist-2 quark distribution f_1^q for a quark flavor q is given by a bilocal correlator according to

$$\frac{1}{2}\int \frac{d\xi^-}{2\pi}\, e^{ik\cdot\xi}\, \big\langle P,S\big|\, \bar\psi^q(0)\,\gamma^+\,\mathcal{W}_{PDF}(0,\xi)\,\psi^q(\xi)\,\big|P,S\big\rangle\Big|_{\xi^+=\xi_T=0} = f_1^q(x)\,, \tag{1}$$

with the two quark fields $\bar\psi^q$ and ψ^q separated along the light cone minus-direction ξ^-. (Here we consider a nucleon with a large light cone plus-momentum.) In (1), P is the 4-momentum of the nucleon, S its spin vector, and k is the 4-momentum of the quark. The PDF f_1^q is merely a function of the longitudinal momentum fraction $x = k^+/P^+$ carried by the quark, where we have suppressed the renormalization scale dependence. The Wilson line $\mathcal{W}_{PDF}$, which renders the definition in (1) color gauge invariant, is generated by the re-interaction of active partons with the remnants of the target through an all order exchange of longitudinally polarized gluons. In the case of DIS, one has final state interactions (FSI) because the re-scattering happens after the hard interaction between the virtual gauge boson and the quark. On the other hand, in the Drell-Yan process, for instance, one is dealing with initial state interactions (ISI). Nevertheless, the Wilson lines in both cases are the same, and the resulting PDFs are universal.

TMDs for unpolarized quarks are defined by generalizing the correlator in (1) such that the quark field ψ^q also depends on the transverse position $\boldsymbol{\xi}_T$,

$$\begin{aligned}&\frac{1}{2}\int \frac{d\xi^-}{2\pi}\,\frac{d^2\boldsymbol{\xi}_T}{(2\pi)^2}\, e^{ik\cdot\xi}\, \big\langle P,S\big|\, \bar\psi^q(0)\,\gamma^+\,\mathcal{W}_{TMD}(0,\xi)\,\psi^q(\xi)\,\big|P,S\big\rangle\Big|_{\xi^+=0}\\ &= f_1^q(x,\mathbf{k}_T^2) - \frac{\mathbf{S}_T\cdot(\hat P\times\mathbf{k}_T)}{M}\, f_{1T}^{\perp q}(x,\mathbf{k}_T^2)\,.\end{aligned} \tag{2}$$

Not only does this induce in f_1^q a dependence on the transverse quark momentum $\mathbf{k}_T$, but it also gives rise to a correlation between $\mathbf{k}_T$, the direction of the nucleon momentum $\hat P = \mathbf{P}/|\mathbf{P}|$, and the

transverse spin vector of the nucleon $\mathbf{S}_T$. (M is the nucleon mass.) The strength of this correlation is given by the Sivers function $f_{1T}^{\perp q}$ [8; 13]. Based on Eq. (2), one easily sees the connection between $f_{1T}^{\perp}$ and transverse SSAs: the entire expression on the r.h.s. of (2) can be understood as the density of unpolarized quarks in a transversely polarized nucleon. The second term in this expression reverses its sign when the direction of $\mathbf{S}_T$ is reversed, which implies a SSA on the level of the parton density. This can lead to transverse SSAs in a full process, where the contribution of the quark flavor q to the asymmetry is proportional to the ratio $f_{1T}^{\perp q}/f_1^q$. Like in the case of PDFs a Wilson line, generated by parton re-scattering and denoted here by $\mathcal{W}_{TMD}$, ensures the color gauge invariance of the correlator in (2). Neglecting the Wilson line in (2) leads to a vanishing Sivers function [9]. In turn, this implies that measuring $f_{1T}^{\perp}$ allows one to directly explore the role played by parton re-scattering.

Since in semi-inclusive DIS the active parton undergoes FSI while in Drell-Yan one has ISI, the Wilson line $\mathcal{W}_{TMD}$ in (2) runs along different paths for the two processes. Therefore, *a priori*, one has two different definitions of TMDs which, however, can be related by means of time-reversal (and parity), leading to [11]

$$f_{1T}^{\perp}\big|_{DY} = -f_{1T}^{\perp}\big|_{SIDIS}\,, \tag{3}$$

i.e., the Sivers function is not universal but changes sign when going from semi-inclusive DIS to Drell-Yan. The process dependence in (3) follows from TMD factorization and is a direct consequence of the parton re-scattering. As we argue below, there already exists some indication of the process dependence of $f_{1T}^{\perp}$ based on current phenomenology even though the Sivers function has not yet been measured in Drell-Yan.

Also TMD parton fragmentation functions (FFs) can give rise to transverse SSAs where the Collins function $H_1^{\perp}$ [9], describing the fragmentation of a transversely polarized quark into an unpolarized hadron, is the most prominent candidate. Like for PDFs, the operator definitions of FFs contain Wilson lines that are generated by parton re-scattering. If one compares now, e.g., TMD-FFs in semi-inclusive DIS and in $e^+e^- \to h_1 h_2 X$ the respective Wilson lines, *a priori*, are different. Despite this fact it was found that leading twist TMD-FFs in those two processes are not sensitive to the path of the Wilson line and hence are universal [14; 15]. This feature is due to the specific kinematics of the fragmentation process and was confirmed in a number of studies.

Let us finally address the QS function T_F. It is defined through a (light cone) quark-gluon-quark correlator according to [4; 5; 16]

$$\int \frac{d\xi^- d\zeta^-}{4\pi}\, e^{ixP^+\xi^-}\, \langle P,S|\bar{\psi}^q(0)\,\gamma^+\, F_{QCD}^{+i}(\zeta^-)\,\psi^q(\xi^-)|P,S\rangle = -\varepsilon_T^{ij} S_T^j\, T_F^q(x,x)\,, \tag{4}$$

where F_{QCD}^{+i} is a component of the gluon field strength tensor, i and j are transverse indices, and $\varepsilon_T^{ij} \equiv \varepsilon^{-+ij}$. In the correlator in (4), the longitudinal momentum of the gluon is zero, and therefore T_F is also often referred to as soft-gluon-pole matrix element. The model-independent relation [17; 16]

$$g\,T_F(x,x) = -\int d^2\mathbf{k}_T\, \frac{\mathbf{k}_T^2}{M}\, f_{1T}^{\perp}(x,\mathbf{k}_T^2)\Big|_{SIDIS} \tag{5}$$

is very important for the discussion below since it allows one to quantitatively compare transverse SSAs obtained in different processes.

3 Transverse SSAs in different processes

3.1 Semi-inclusive DIS

In semi-inclusive DIS, $\ell\, N \to \ell\, h\, X$, there exist a total of six transverse target SSAs. For low transverse momenta of the final state hadron, where TMD factorization applies, three of those SSAs appear as leading power effects of a 1/Q expansion. ($Q^2 \equiv -q^2$, with q denoting the 4-momentum of the virtual photon.) In the TMD approach, the cross section for $\ell\, N^{\uparrow} \to \ell\, h\, X$ takes the schematic form

$$d\sigma \sim \sin(\phi_h - \phi_S)\, f_{1T}^{\perp} \otimes D_1 + \sin(\phi_h + \phi_S)\, h_1 \otimes H_1^{\perp} + \dots\,, \tag{6}$$

where ϕ_h (ϕ_S) represents the azimuthal angle of the produced hadron (nucleon spin vector). In the Sivers part of the cross section $f_{1T}^{\perp}$ is convoluted with the unpolarized FF D_1, while in the Collins part $H_1^{\perp}$ is convoluted with the nucleon's transversity distribution h_1. The dots in (6) represent one additional leading power term as well as power suppressed contributions.

We begin with discussing the Collins part in (6). A clearly nonzero Collins effect was observed for the first time by the HERMES Collaboration for charged pion production [18]. Subsequent studies at COMPASS, HERMES and JLab confirmed and extended those original findings. First of all, this implies that both the transversity and the Collins function are nonzero. The Collins asymmetry does not necessarily tell us something about parton re-scattering since $H_1^{\perp}$ can be nonzero without this effect [9; 19]. However, one may study the predicted universality of the Collins function because $H_1^{\perp}$ appears also in an azimuthal modulation of the cross section for $e^+e^- \to h_1 h_2 X$ [20; 21]. Data for that observable have been obtained for instance by the Belle Collaboration [22]. A combined analysis of the Collins effect in semi-inclusive DIS and in electron-positron annihilation, assuming universality of $H_1^{\perp}$, gives rise to a transversity which is in reasonable agreement with most model predictions [23]. Therefore, the current phenomenology of the Collins effect is compatible with universality of $H_1^{\perp}$.

Also a nonzero Sivers effect has been observed by HERMES, COMPASS and JLab [18; 24; 25]. The pioneering HERMES measurement [18] could actually be considered as the first experimental evidence of parton re-scattering because, as we discussed above, according to the definition in (2) no re-scattering implies a vanishing Sivers function. At this point one may of course be cautious. For example, it has been speculated that the Sivers function has a source other than the quark re-scattering [26]. Such a scenario would have far-reaching consequences for TMD factorization and also for collinear twist-3 factorization. Note that the latter is fully compatible with the universality property of $f_{1T}^{\perp}$ in (3) [27]. A verification of the process dependence of the Sivers function would provide further evidence for the re-scattering picture. We come back to this point in the discussion below.

3.2 Nucleon-nucleon collisions

Transverse SSAs for $p^{\uparrow}p \to h\,X$ (and $p^{\uparrow}\bar{p} \to h\,X$) have been observed at FermiLab and at RHIC [28; 29; 30]. If the transverse momentum of the produced hadron is sufficiently large such reactions may be treated in perturbative QCD by using collinear factorization. The (transverse) spin-dependent cross section is a twist-3 effect and has the following generic structure which indicates the convolution of hard scattering coefficients with parton correlators,

$$\begin{aligned} d\sigma(\mathbf{S}_T) = H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{C/c(2)} \quad &\to \quad \text{Sivers-type} \\ + H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{C/c(2)} \quad &\to \quad \text{Boer-Mulders-type} \\ + H'' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{C/c(3)} \quad &\to \quad \text{“Collins-type”}\,. \end{aligned} \tag{7}$$

Three terms appear in (7) because the twist-3 effect may either be associated with the transversely polarized nucleon (Sivers-type), or the unpolarized nucleon (Boer-Mulders-type), or the fragmentation process ("Collins-type"). The Sivers-type contribution is related to the re-scattering of the active partons with the remnants of the transversely polarized nucleon [3; 4; 5; 31]. There can be different sources for that part of the cross section, but the soft-gluon-pole contribution related to the QS function T_F is expected to dominate. Assuming that the Sivers-type contribution is the most important effect in (7) — as was often done in the past — one may extract T_F either from the SSAs in nucleon-nucleon collisions or from the Sivers asymmetry in semi-inclusive DIS by exploiting (5). A comparison of such two extractions was performed and gave rise to a striking sign-mismatch [16]. The sign-mismatch apparently implies that the other two terms in (7) should be very important. Since the Boer-Mulders-type contribution has been shown to be small [32], a very large asymmetry has to come from the "Collins-type" contribution. Recently a full result for the twist-3 fragmentation contribution was obtained [6]. Three pieces enter in the calculation: first, transverse parton motion matters, where the relevant fragmentation correlator is a particular transverse momentum moment of the Collins function. One also receives contributions from a collinear quark-quark correlator and from a quark-gluon-quark correlator. (Therefore, in (7) "Collins-type" is put in quotes.) Very recently it has been shown that after including the twist-3 fragmentation contribution one may indeed be able to describe the transverse SSA in proton-proton collisions, where the effects beyond the transverse parton motion play a critical role [7].

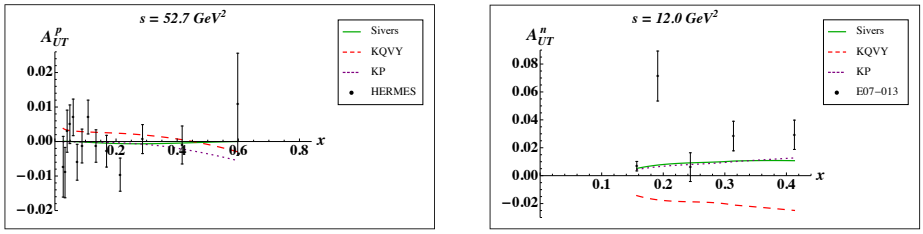

Fig. 1 Left panel: proton target SSA in DIS for three inputs for T_F [39; 31; 40]. The data are results from the HERMES Collaboration [34]. Right panel: neutron target SSA for three inputs for T_F. The data are results from Hall-A at Jefferson Lab [35]. (See text for more details.)

3.3 Inclusive DIS

For fully inclusive DIS, $\ell N \to \ell X$, one can also define a transverse target SSA. This asymmetry vanishes in the one-photon-exchange approximation [33], which implies a small SSA since it would be proportional to the fine structure constant α_{em}. The HERMES Collaboration measured the SSA for a proton target with the result being compatible with zero [34]. Moreover, by using a polarized ^{3}He-target, data for a neutron were obtained in Hall-A at Jefferson Lab [35], providing the first finite transverse SSA in DIS on the (few) percent level. Two-photon-exchange can generate a nonzero SSA. The two photons may couple to the same quark inside the nucleon [36; 37]. The complete calculation for this case is very difficult, and only recently a full result was derived [38]. On the other hand, the two photons can also couple to different quarks in the nucleon [12]. In the following we only consider that contribution which most likely numerically dominates. The required analytical calculation is very similar to the treatment of the transverse SSA in nucleon-nucleon scattering discussed in the previous subsection. In particular, one is sensitive to parton re-scattering (here ISI and FSI of the lepton) — the same physics that underlies the predicted process dependence of the Sivers function [12]. The result of the calculation depends on a quark-photon-quark correlator which has a (model-dependent) relation with the QS function T_F [12]. That connection not only allows us to make predictions for the SSA in DIS but also to relate that observable to other SSAs. Our numerical results, based on three different inputs for T_F, are shown in Fig. 1. The main findings can be discussed by looking at the Sivers-input (T_F obtained from the Sivers function using (5), where $f_{1T}^{\perp}$ was extracted from semi-inclusive DIS [39]) and the KQVY-input (T_F obtained from SSAs in nucleon-nucleon collisions [31]). The Sivers-input gives a perfect result for the proton SSA and a reasonable result for the neutron SSA. Therefore, one can simultaneously describe the Sivers effect in semi-inclusive DIS and the transverse SSA in DIS. This supports the underlying re-scattering picture and can be understood as the first indication of the process dependence of the Sivers function. (The process dependence of $f_{1T}^{\perp}$ was also discussed recently in connection with new RHIC data on $p^{\uparrow}p \to \text{jet}\, X$ [41; 42].) For the KQVY-input one finds, in particular, the wrong sign compared to the neutron data. This indicates that the observed SSAs in nucleon-nucleon collisions are indeed not mainly caused by the Sivers mechanism, but may rather get the main contribution from (twist-3) parton fragmentation as discussed above and argued in [7].

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