Transverse single-spin asymmetries

Jian-Wei Qiu[1,2]

[1]Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
[2]C.N. Yang Institute for Theoretical Phyics, Stony Brook University, Stony Brook, NY 11794, USA

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In this talk, I will review the physics behind the measured large transverse single-spin asymmetries (SSAs) of cross sections with large momentum transfers in high energy collisions, and the twist-3 mechanism to generate the SSAs in perturbative QCD. I will also discuss the connection between the twist-3 collinear factorization approach and the transverse momentum dependent factorization approach to SSAs.

1 Introduction

Transverse single-spin asymmetry (SSA), $A_N \equiv (\sigma(s_T) - \sigma(-s_T))/(\sigma(s_T) + \sigma(-s_T))$, is defined as the ratio of the difference and the sum of the cross sections when the spin of one of the identified hadron s_T is flipped. Large SSAs of cross sections with a large momentum transfer in high energy collisions were once thought impossible in QCD [1]. With over 30 years of experimental as well as theoretical efforts, large SSAs are not only possible in QCD, but also carry extremely valuable information on the motion and structure of quarks and gluons inside a transversely polarized hadron. In this talk, I will briefly review our current understanding of the physics that is responsible for generating the measured large SSAs of cross sections with large momentum transfers in high energy collisions.

2 QCD factorization approaches to SSAs

Two complementary QCD-based approaches have been proposed to analyze the physics behind the measured SSAs: the transverse momentum dependent (TMD) factorization approach [2, 3, 4, 5, 6, 7] and the collinear factorization approach [8, 9, 10, 11, 12, 13, 14, 15]. In the TMD factorization approach, the asymmetry was attributed to the spin and transverse momentum correlation between the identified hadron and the active parton, and represented by the TMD parton distribution or fragmentation function. For example, the Sivers effect (Sivers function) [2] represents how hadron spin influences parton's transverse motion inside a transversely polarized hadron, while the Collins effect (Collins function) [3] describes how parton's transverse spin affects the parton's hadronization. On the other hand, in the collinear factorization approach, all active partons' transverse momenta are integrated into the collinear distributions, and the explicit spin-transverse momentum correlation in the TMD approach is now included into the high twist collinear parton distributions or fragmentation functions. The asymmetry in the collinear factorization approach is represented by twist-3 collinear parton distributions or fragmentation functions, which carry the net effect of spin-transverse momentum correlations generated by QCD color Lorentz force [16]. The TMD factorization approach is more suitable for evaluating the SSAs of scattering processes with two very different momentum transfers, $Q_1 \gg Q_2 \gtrsim \Lambda_{\rm QCD}$, where the Q_2 is sensitive to the active parton's transverse momentum, while the collinear factorization approach is more relevant to the SSAs of scattering cross sections with all observed momentum transfers hard and comparable: $Q_i \sim Q \gg \Lambda_{\rm QCD}$. Although the two approaches each have their own kinematic domain of validity, they are consistent with each other in the perturbative regime where they both apply[17, 18].

Both factorization approaches necessarily introduce a factorization scale, $\mu \gg \Lambda_{\rm QCD}$, to separate the calculable short-distance perturbative dynamics from the long-distance nonperturbative physics of the observed cross sections or the asymmetries. Since the physical observables, the cross sections or the asymmetries, are independent of the choice of the factorization scale, the scale dependence of the nonperturbative distributions, either TMD distributions or twist-3 collinear distributions, must match the scale dependence of corresponding perturbative hard parts. That is, the factorization scale dependence of the nonperturbative distributions is perturbatively calculable and is a prediction of QCD perturbation theory when $\mu \gg \Lambda_{\rm QCD}$. For example, the scale dependence of the leading power parton distributions obeys DGLAP evolution equations whose evolution kernels are perturbatively calculable, and has been very successfully tested when the scale varies from a few GeV to the hundreds of GeV. The scale dependence of the Sivers function was recently evaluated [19, 20], while the scale dependence of twist-3 correlation functions and fragmentation functions were derived by several groups [21, 22, 23, 24, 25, 26, 27, 28]. In the rest of this talk, I will concentrate on the discussion of the collinear factorization approach to SSAs.

3 Collinear factorization approach to SSAs

With one large momentum transfer Q, the hard scattering is localized to a distance scale of $1/Q$. Since pulling an extra physically polarized parton from the colliding hadron into the localized collision point is suppressed by a power of $1/Q$, the cross section for a hadron A to scatter off a hadron B can be expanded in a power series in $1/Q$,

$$\sigma_{AB}(Q,\vec{s}) = \sigma_{AB}^{\rm LP}(Q,\vec{s}) + \frac{Q_s}{Q}\,\sigma_{AB}^{\rm NLP}(Q,\vec{s}) + ... \tag{1}$$

$$\approx H_{ab}^{\rm LP}\otimes f_{a/A}\otimes f_{b/B} + \frac{Q_s}{Q}\,H_{ab}^{\rm NLP}\otimes \mathcal{T}_{a/A}\otimes f_{b/B} + ... \tag{2}$$

where Q_s^2 represents a characteristic scale of the power corrections. The leading power contribution to the cross section can be factorized into a convolution of a localized and perturbatively calculable hard part $H_{ab}^{\rm LP}$ from the collision between partons a and b, and the universal twist-2 collinear parton distribution functions (PDFs), $f_{a/A}$ (and $f_{b/B}$), to find a parton of flavor a (and b) from the colliding hadron A (and B), as indicated in Eq. (2), and does not contribute to the SSA [1]. The leading contribution to SSAs in QCD collinear factorization approach comes from the quantum interference between a partonic scattering amplitude with one active parton and that with an active two-parton composite state [8, 9]. Such a quantum interference can be represented by the universal twist-3 quark-gluon correlation functions, and whose contribution is effectively the first power correction to the spin-dependent cross section and can be perturbatively factorized as in Eq. (2) [29]. Although the power correction to the cross section is formally suppressed by a power of $1/Q$, its contribution to SSAs could be significant in a certain part of the phase space, such as forward region of the polarized hadron from the derivative of the correlation functions, $\frac{d}{dx}\mathcal{T}_{a/h}(x,x)$, which is a natural feature of twist-3 contributions[9]. The predictive power of the approach relies on the universality and our knowledge of the twist-3 correlation functions and fragmentation functions.

For SSAs of single particle inclusive cross section: $A(p_A, s_\perp) + B(p_B) \to h(p) + X$, there could be three potential sources of contributions [10],

$$\begin{aligned} A_N &\propto \sigma_{AB\to h}(Q, s_\perp) - \sigma_{AB\to h}(Q, -s_\perp) \\ &\propto \mathcal{T}^{(3)}_{a/A}(s_\perp) \otimes f_{b/B} \otimes \mathcal{H}^{(S)}_{ab\to c} \otimes D_{h/c} \\ &+ \delta q_{a/A}(s_\perp) \otimes \left[\mathcal{T}^{(\sigma)(3)}_{b/B} \otimes \mathcal{H}^{(BM)}_{ab\to c} \otimes D_{h/c} + f_{b/B} \otimes \mathcal{H}^{(C)}_{ab\to c} \otimes \mathcal{D}^{(3)}_{h/c}\right] \end{aligned} \tag{3}$$

where $\mathcal{T}^{(3)}_{a/A}$ and $\mathcal{T}^{(\sigma)(3)}_{b/B}$ are twist-3 quark-gluon correlation functions of a transversely polarized hadron and that of an unpolarized hadron, respectively, and $\mathcal{D}^{(3)}_{h/c}$ are twist-3 quark-gluon fragmentation functions. The $\mathcal{T}^{(3)}_{a/A}$ take care of the hadron spin flip of the first term, while the twist-2 quark transversity distributions $\delta q_{a/A}(s_\perp)$ take care of the hadron spin flip of the second and the third term. The superscripts, S, BM and C, of partonic hard parts indicate that the first, second, and third term corresponds to, respectively, the sources of SSAs for Sivers, Boer-Mulders, and Collins contribution in the TMD factorization approach.

The first term in Eq. (3) and the twist-3 quark-gluon correlation functions have been systematically studied and compared with data on SSAs, while limited effort has been devoted to the second and third term. With the potential sign conflict between the twist-3 quark-gluon correlation function directly extracted from data on SSAs in hadronic collisions and those indirectly derived from the moments of measured Sivers functions [30], it is very important to investigate the contributions to the SSAs from the second and third term in Eq. (3).

4 Evolution of twist-3 correlation functions

Much of the predictive power of perturbative QCD calculation relies on the factorization and the universality of non-perturbative distributions. An immediate consequence of the QCD factorization formalism for physical observables is that the factorization scale dependence of these universal non-perturbative distributions is also universal and perturbatively calculable, and is a prediction of perturbative QCD dynamics.

A complete and close set of evolution equations for the twist-3 quark-gluon and gluon-gluon correlation functions of a transversely polarized hadron, which are relevant to SSAs, was derived in terms of Feynman diagram approach [21], as well as in terms of the ultra-violet (UV) renormalization of composite operators defining the correlation functions [24]. Leading order evolution kernels for the correlation functions, relevant to the so-called gluonic pole contributions [9], were derived by several groups [21, 22, 23, 24, 26]. An apparent discrepancy between the Feynman diagram approach and that based on the UV renormalization was recently resolved [25, 27]. Leading order kernels for the distributions, relevant to the fermionic pole contribution [9], were recently derived [26].

In addition, the leading order flavor non-singlet evolution kernels for the twist-3 quark-gluon correlation function $\mathcal{T}^{(\sigma)}_{q,F}$ of a unpolarized hadron were derived [22, 27]. Leading order evolution kernels for twist-3 fragmentation functions are also available [28].

5 Summary

The collinear QCD factorization approach to the phenomena of SSAs of cross sections with one large momentum transfer has been well-developed in last thirty years. With the systematic derivation of evolution equations and kernels, the QCD description of the SSAs in terms of the collinear factorization approach is now much more mature. With more future data from RHIC spin program, the SSAs could provide new quantitatively tests of QCD dynamics that could not be explored by measurements of spin-averaged cross sections.

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