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Indication on the process-dependence of the Sivers effect

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We analyze the spin asymmetry for single inclusive jet production in proton-proton collisions collected by the AnDY experiment and the Sivers asymmetry data from semi-inclusive deep inelastic scattering experiments. In particular, we consider the role color gauge invariance plays in determining the process-dependence of the Sivers effect. We find that after carefully taking into account the initial-state and final-state interactions between the active parton and the remnant of the polarized hadron, the calculated jet spin asymmetry based on the Sivers functions extracted from HERMES and COMPASS experiments is consistent with the AnDY experimental data. This provides a first indication for the process-dependence of the Sivers effect in different processes. We also make predictions for both direct photon and Drell-Yan spin asymmetry, to further test the process-dependence of the Sivers effect in future experiments.

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In these proceedings we present results of Ref. [1] where an indication of the process dependence of the Sivers function was found based on SIDIS data and jet A_N data in pp scattering.

Large single spin asymmetries (SSAs) have been measured in fixed-target and collider mode in single inclusive particle production in nucleon-nucleon scattering experiments [2] and semi-inclusive deep inelastic lepton-nucleon scattering (SIDIS) experiments [3, 4]. Two different yet related QCD factorization formalisms have been proposed to describe the asymmetries. One is the so-called transverse momentum dependent (TMD) factorization [5, 6], which is valid for the processes with two characteristic scales; in SIDIS $\Lambda^2_{\rm QCD} \lesssim P^2_{h\perp} \ll Q^2$. In this formalism transverse spin effects are associated with TMD parton distribution functions and fragmentation functions (PDFs and FFs).

On the other hand is the collinear factorization formalism at next-to-leading power (twist-3) in the hard scale [7, 9]. This approach is valid for processes with only one characteristic hard scale, for instance $P^2_{h\perp} \gg \Lambda^2_{\rm QCD}$ of the produced hadron in proton-proton (pp) collisions collisions. It describes the spin asymmetry in terms of twist-3 three-parton correlation functions. One of the well-known examples is the so-called Efremov-Teryaev-Qiu-Sterman (ETQS) function $T_{q,F}(x,x)$ [7].

Of central importance in the study of SSAs is the Sivers [8] effect which has attracted great attention in recent years. In part this is due to the unique prediction from TMD factorization theorems that the Sivers effect is process-dependent and changes sign in Drell-Yan (DY) production with respect to SIDIS [10]. On the other hand in the twist-3 collinear factorization approach, the process-dependence of the ISIs and FSIs is absorbed into scattering amplitudes and the relevant twist-3 three-parton correlation functions are universal.

The TMD and collinear twist-3 factorization formalisms are closely related to each other [11, 12, 13]

$$T_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}. \tag{1}$$

where the subscript emphasizes that the Sivers function is probed in the SIDIS process. A recent study [13, 14, 15] showed however that for inclusive *hadron* production in pp calculated SSAs are *opposite* to those measured in the experiments. This is known as the "sign mismatch" problem. Whether this finding reflects the inconsistency of our theoretical formalism is a very important question and needs to be explored both theoretically and experimentally.

A new opportunity presents itself however, with a recent inclusive jet measurement performed at the AnDY experiment at RHIC [16]. Since the jet spin asymmetry does not involve fragmentation contributions, this paves the way to precisely test the process-dependence of the Sivers effect in different processes as well as explore the consistency of the TMD and collinear twist-3 factorization formalisms [13, 17, 18].

Let us remind the reader (details can be found in Ref. [1]) that the SIDIS SSA $A_{UT}^{\sin(\phi_h-\phi_s)}$ within the TMD factorization formalism is related to the Sivers function [19]. On the other hand, the single inclusive jet production in transversely-polarized pp collisions, $A(P_A,s_\perp)+B(P_B)\to \mathrm{jet}(P_J)+X$ receives the contribution from $T_{q,F}(x,x)$.

To see whether the inclusive jet data in pp collisions are consistent with the Sivers asymmetry data in SIDIS processes, we perform a global fit of the SIDIS Sivers asymmetry data collected by the HERMES and COMPASS experiments [3, 4] to extract the Sivers functions. We then derive the

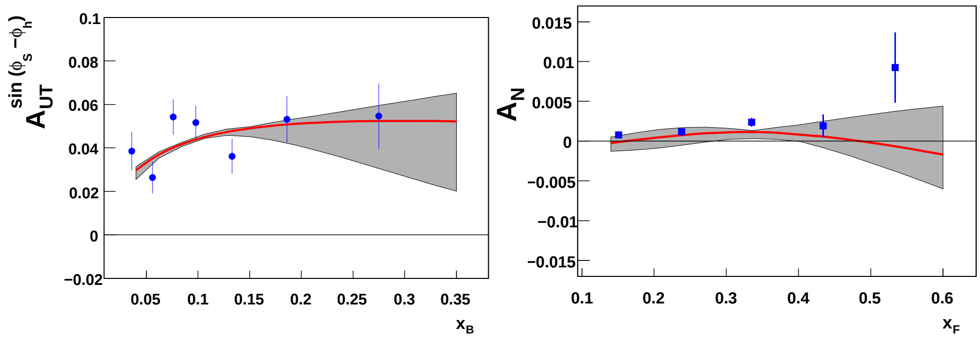

Figure 1: (Left panel) Description of the HERMES [3] data for π^+ production as a function of Bjorken x_B. (Right panel) Description of AnDY data [16] for inclusive jet production at forward rapidity $\langle y \rangle = 3.25$ at $\sqrt{s}$=500 GeV. The solid lines are the central values and the shaded region corresponds to the parameter scan as explained in the text.

functional form for twist-3 ETQS function $T_{q,F}(x,x)$ with the help of Eq. (1) and in turn compute the jet spin asymmetry A_N to be compared with the data collected by AnDY experiment [16].

We adopt the Gaussian forms in Ref. [21] for the spin-averaged PDFs, $f_{q/A}(x,k_\perp^2)$ and FFs $D_{h/q}(z,p_\perp^2)$, with the Gaussian width, $\langle k_\perp^2 \rangle = 0.25$ GeV^2 and $\langle p_\perp^2 \rangle = 0.2$ GeV^2. The quark Sivers function $f_{1T}^{\perp q}(x,k_\perp^2)$ for SIDIS is parameterized as,

$$f_{1T}^{\perp q}(x,k_\perp^2) = -\mathcal{N}_q(x) h(k_\perp) f_{q/A}(x,k_\perp^2), \tag{2}$$

where the $k_\perp$-dependence $h(k_\perp) = \sqrt{2e}\,\frac{M}{M_1}\,e^{-k_\perp^2/M_1^2}$, with M the proton mass, and the x-dependent coefficient $\mathcal{N}_q(x) = N_q x^{\alpha_q}(1-x)^{\beta_q}(\alpha_q+\beta_q)^{\alpha_q+\beta_q}/(\alpha_q{}^{\alpha_q}\beta_q{}^{\beta_q})$.

Fitting the pion data from both HERMES and COMPASS we obtain a very good description of SIDIS data, with $\chi^2/d.o.f. = 1.04$. The resulting set of parameters are presented in Ref. [1]. The biggest uncertainty is on parameters β_{u_v} and β_{d_v}. This happens because SIDIS data covers a rather limited kinematic region in $x \lesssim 0.3$, as seen clearly in the HERMES plot Fig. 1. Note that future measurements of JLab 12 [22] will explore the high-x region in SIDIS.

In order to find the region of allowed values of β_{u_v} and β_{d_v}, we perform the scan procedure, also used in Ref. [23] to study the Collins effect. We produce a grid of values β_{u_v}, $\beta_{d_v} \in [0,4]$ in steps of 0.25 and for each pair of β_{u_v}, β_{d_v} perform a fit of SIDIS data. The resulting sets of parameters corresponding to 289 pairs of β_{u_v}, β_{d_v} give very good description of SIDIS data with $\chi^2/d.o.f \in [1.04, 1.08]$; they are all almost statistically identical. We present a comparison to the SIDIS data in Fig. 1, which gives a very good description of HERMES π^+ data.

We now calculate the jet asymmetry A_N and the resulting shaded region for jet A_N as a function of Feynman x_F the scaled jet longitudinal momentum is shown in Fig. 1. We note that the jet data are inside the shaded region, which demonstrates that SIDIS Sivers data and jet A_N data are statistically compatible with each other. We conclude that this is the first indication for the process-dependence of the Sivers effect.

The very small size of the jet asymmetry is largely due to a cancellation between u and d quark Sivers functions, which have opposite signs. More definite tests of the process dependence and consistency of TMD and collinear twist-3 formalism will come from Drell-Yan and direct photon measurements.

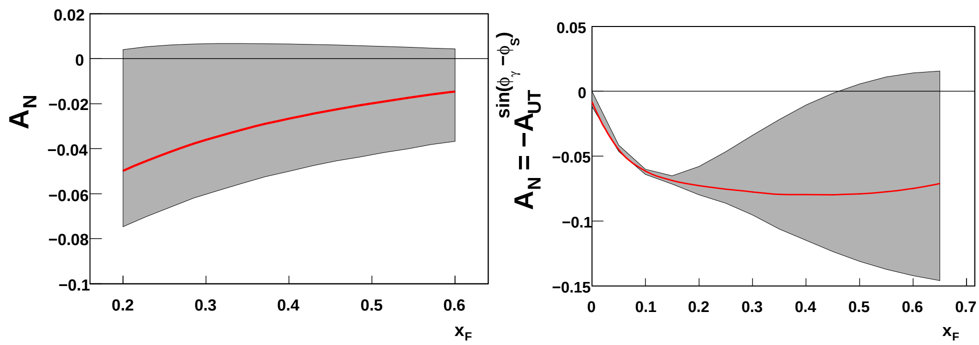

Figure 2: (Left panel) Prediction of direct photon A_N in pp collisions at rapidity $y = 3.5$ at $\sqrt{s}$=200 GeV. (Right panel) Prediction for Sivers asymmetry $A_N \equiv -A_{UT}^{\sin(\phi_\gamma - \phi_S)}$ for DY lepton pair production at $\sqrt{s} = 500$ GeV, for the invariant mass $4 < Q < 8$ GeV and transverse momentum $0 < q_\perp < 1$ GeV.

In this respect DY production is the ideal process to explore process dependence; while direct photon production (though experimentally challenging [25]) can be used to study the consistency of the factorization formalisms. First we make a prediction for the spin asymmetry A_N for direct photon production at RHIC kinematics in Fig. 2. Since u and d quark Sivers functions are now weighted with their electric charge squared, which compensates the cancellation between them, we found that the direct photon A_N has much larger size $\sim 5\%$, and it is negative [26] due to the nature of ISIs associated with the Sivers effect for direct photon production.

Now, using the TMD factorization formalism [29], we compute the DY spin asymmetry $A_N \equiv -A_{UT}^{\sin(\phi_\gamma - \phi_S)}$ at center-of-mass energy $\sqrt{s} = 500$ GeV . Due to the same reason, the asymmetry is large $\sim 8\%$ and negative [24] (see Fig. 2) and at small and intermediate x_F region, the behavior is very similar to that in [29].

In summary, we have analyzed the SSA for inclusive jet production in pp collisions collected by the AnDY experiment and the Sivers asymmetry data from SIDIS experiments. Our result provides a first indication for the process-dependence of the Sivers effect and further demonstrates consistency between the TMD and collinear twist-3 factorization formalisms. However, due to the large uncertainty of the current data from AnDY in the large x_F region, and the small size of the jet spin asymmetry, our result cannot provide conclusive confirmation for process-dependence. Thus we also propose direct photon spin asymmetry along with DY measurements to test the process dependence of the Sivers effect.

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