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 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.

The investigation of nucleon's sub-structure has entered a new era. In past decades an understanding of nucleons in terms of quarks and gluons (partons), the degrees of freedom of Quantum Chromodynamics (QCD), has been successfully established. Progress was achieved in constructing a "one-dimensional" light-cone picture of the nucleon based on the longitudinal motion of partons in fast moving nucleons. In recent years theoretical breakthroughs extended this description in the transverse as well as light-cone momentum space (three dimensions). Transverse-spin dependent observables, such as single transverse spin asymmetries (SSAs) provide firm evidence for a three-dimensional tomography of the nucleon due to a non-trivial correlation between the transverse spin and the parton's transverse momentum, and present unique opportunities to study QCD dynamics, particularly QCD factorization and universality of the parton distributions [1].

Large 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 [3–5]. Two different yet related QCD factorization formalisms have been proposed to describe the asymmetries. One relies on the so-called transverse momentum dependent (TMD) factorization [6, 7], which is valid for the processes with two characteristic scales; for example the photon's virtuality Q and $P_{h\perp}$ of the produced hadron in SIDIS, where $\Lambda_{\rm QCD}^2 \lesssim P_{h\perp}^2 \ll Q^2$. In this formalism transverse spin effects are associated with TMD parton distribution functions and fragmentation functions (PDFs and FFs). Then there is the collinear factorization formalism at next-to-leading power (twist-3) in the hard scale [8, 9]. This approach is valid for processes with only one characteristic hard scale, for instance, the transverse momentum $P_{h\perp}^2 \gg \Lambda_{\rm QCD}^2$ of the produced hadron in proton-proton (pp) 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 $T_{q,F}(x,x)$ [8].

Of central importance in the study of SSAs is the Sivers [10] 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: that is its existence relies on the initial-state and final-state interactions (ISIs and FSIs) between the struck parton and the remnant of the polarized hadron. These interactions depend on the color flow of the specific scattering process considered, thus giving rise to process-dependent Wilson lines in the gauge-invariant definition of the relevant TMD PDFs - in this case so-called Sivers functions $f_{1T}^\perp(x, k_\perp^2)$. The often discussed case is the difference between the FSIs in SIDIS and the ISIs in Drell-Yan (DY) production in pp collisions which leads to an opposite sign in the Sivers function probed in these two processes, indicating that the Sivers function is not universal [11].

On the other hand in the twist-3 collinear factorization approach, the process-dependence of the ISIs and FSIs is absorbed into the short-distance, perturbative cut scattering amplitudes, where the relevant twist-3 three-parton correlation functions are universal. As a result, TMD and collinear twist-3 factorization formalisms are closely related to each other [12]. The relevant functions - the Sivers function and the ETQS twist-3 function are connected through the following relation [13, 14],

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

where the subscript emphasizes that the Sivers function is probed in the SIDIS process. In other words, starting from the Sivers functions extracted from SIDIS, one can derive a functional form for ETQS function $T_{q,F}(x,x)$. In

combination with the calculable short-distance cut scattering amplitudes, one should be able to predict the SSAs of inclusive particle production in pp collisions. However, a recent study [14–16] for inclusive *hadron* production in pp collisions shows that such 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. However, since the SSAs of inclusive hadron production can also receive contributions from the fragmentation process [9], a thorough analysis demands including such contributions.

A new opportunity presents itself however, with a recent inclusive jet measurements performed at the AnDY experiment at RHIC [17]. 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 [14, 18, 19]. This is the main purpose of our paper. We analyze the spin asymmetry for single inclusive jet production in pp collisions collected by the AnDY experiment and the Sivers asymmetry data from SIDIS experiments. We assess whether they are compatible with each other; in other words, whether the jet asymmetry is consistent with our expectation on the process-dependence of the Sivers effect.

We start with the basic formalism for the SIDIS SSA. For hadron production in SIDIS at low transverse momentum $P_{h\perp}$, $e(\ell) + A^\uparrow(P, s_\perp) \rightarrow e(\ell') + h(P_h) + X$, within the TMD factorization formalism, the differential cross section for the Sivers effect reads [20],

$$\frac{d\sigma}{d\,\mathcal{P.S.}} = \sigma_0 \left[F_{UU,T} + \sin(\phi_h - \phi_s) F_{UT,T}^{\sin(\phi_h - \phi_s)} \right], \quad (2)$$

where phase space $d\,\mathcal{P.S.} = dx_B dy d\phi_s dz_h d\phi_h P_{h\perp} dP_{h\perp}$ with the standard SIDIS kinematic variable x_B, y, and z_h. The normalization factor $\sigma_0 = \sigma_0(x_B, y, Q^2)$ and the structure functions $F_{UU,T}$ and $F_{UT,T}^{\sin(\phi_h - \phi_s)}$ are defined in Ref. [15]. The Sivers asymmetry measured in the experiments is defined by $A_{UT}^{\sin(\phi_h - \phi_s)}(x_B, z_h, P_{h\perp}) = \sigma_0(x_B,y,Q^2) F_{UT,T}^{\sin(\phi_h - \phi_s)} / \sigma_0(x_B,y,Q^2) F_{UU,T}$.

On the other hand, the single inclusive jet production in transversely-polarized pp collisions, $A(P_A, s_\perp) + B(P_B) \rightarrow \mathrm{jet}(P_J) + X$, only receives the Sivers type of contributions. Within the collinear factorization formalism, the spin-dependent differential cross section $d\Delta\sigma(s_\perp) = [d\sigma(s_\perp) - d\sigma(-s_\perp)]/2$ can be written as,

$$E_J \frac{d\Delta\sigma(s_\perp)}{d^3 P_J} = \epsilon_{\alpha\beta} s_\perp^\alpha P_{J\perp}^\beta \frac{\alpha_s^2}{s} \sum_{a,b} \int \frac{dx}{x} \frac{dx'}{x'} f_{b/B}(x')$$

$$\times \left[T_{a,F}(x,x) - x \frac{d}{dx} T_{a,F}(x,x) \right]$$

$$\times \frac{1}{\hat{u}} H_{ab\to c}^{\mathrm{Sivers}}(\hat{s}, \hat{t}, \hat{u}) \delta\left(\hat{s} + \hat{t} + \hat{u} \right), \quad (3)$$

where $\sum_{a,b}$ runs over all parton flavors, $f_{b/B}(x')$ is the collinear PDF in the unpolarized proton, and $\hat{s}$, $\hat{t}$, and $\hat{u}$ are the standard partonic Mandelstam variables [15, 21]. $H_{ab\to c}^{\mathrm{Sivers}}$ represent the cut scattering amplitudes for the partonic process $ab \rightarrow cd$ with the expressions given in [16, 21]. It is important to emphasize that in the twist-3 collinear factorization approach, the process-dependence of the ISIs and FSIs, which are determined from the color factors coming from the partonic process cut scattering amplitudes are absorbed into the short-distance perturbative hard-part functions, while the relevant twist-3 three-parton correlation functions $T_{q,F}(x,x)$ are universal or process independent. It is because of this fact that the universal $T_{q,F}(x,x)$ is uniquely related to the Sivers function in SIDIS as in Eq. (1). Thus, the process-dependence of the Sivers effect for jet production is included in $H_{ab\to c}^{\mathrm{Sivers}}$. Now since the SIDIS Sivers asymmetry is only associated with FSIs, while the jet spin asymmetry is associated with both ISIs and FSIs, by comparing the SIDIS measurement and the jet spin asymmetry, we are essentially testing the central role of these ISIs and FSIs, hence the *process dependence* of the Sivers effect. The jet SSA, A_N is computed from the ratio of the spin-dependent to the spin-averaged cross section,

$$A_N = E_J \frac{d\Delta\sigma(s_\perp)}{d^3 P_J} \bigg/ E_J \frac{d\sigma}{d^3 P_J}, \quad (4)$$

where the spin-averaged differential cross section $E_J \frac{d\sigma}{d^3 P_J}$ in the denominator is defined in Ref. [15].
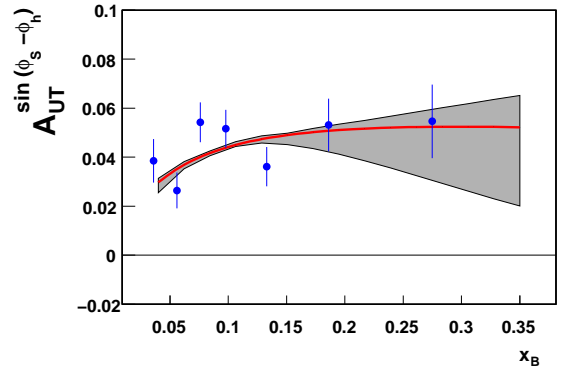

FIG. 1. Description of the HERMES [3] data for π^+ production as a function of Bjorken x_B. The solid lines are the central values from Table I and the shaded region corresponds to the parameter scan as explained in the text.

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 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 from Eq. (4) to

be compared with the data collected by AnDY experiment [17].

We adopt the Gaussian forms in Ref. [22] for the spin-averaged PDFs, $f_{a/A}(x, k_\perp^2)$ and FFs $D_{h/a}(z, p_T^2)$, with the Gaussian width, $\langle k_\perp^2 \rangle = 0.25$ GeV^2 and $\langle p_T^2 \rangle = 0.2$ GeV^2. The quark Sivers function $f_{1T}^{\perp q}(x, k_\perp^2)$ for SIDIS is parameterized as,

$$f_{1T}^{\perp q}(x, k_\perp^2) = -\mathcal{N}_q(x) h(k_\perp) f_{q/A}(x, k_\perp^2), \qquad (5)$$

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 $\mathcal{N}_q(x) = N_q x^{\alpha_q}(1-x)^{\beta_q}(\alpha_q + \beta_q)^{\alpha_q+\beta_q}/(\alpha_q^{\alpha_q}\beta_q^{\beta_q})$. For the purpose of our fit, we use GRV98LO for the spin-averaged collinear PDFs [24] and DSS parametrization for collinear FFs [25]. During the fit we enforce positivity bounds [23] on Sivers functions of quarks and antiquarks. Thus, we will present our results separately as parametrizations for "valence" Sivers functions (u_v and d_v) and "sea" Sivers functions ($\bar{u}$ and $\bar{d}$) in the end. We emphasize that in order to explore the uncertainty in Sivers function in the high-x region, we allow β_{u_v} and β_{d_v} to vary independently as compared with the fit in Ref. [22].

TABLE I. Best values of the free parameters for the Sivers function from fit to SIDIS data [3, 4] on $A_{UT}^{\sin(\phi_h - \phi_s)}$.

$\chi^2/d.o.f. = 1.04$	
$\alpha_{u_v} = 0.05^{+0.2}_{-0.05}$	$\alpha_{d_v} = 0.76^{+0.20}_{-0.20}$
$\beta_{u_v} = 0.78^{+2.35}_{-0.77}$	$\beta_{d_v} = 2.09^{+1.20}_{-0.90}$
$N_{u_v} = 0.34^{+0.04}_{-0.04}$	$N_{d_v} = -1^{+0.42}_{-0}$
$\alpha_{sea} = 0$ fixed	$\beta_{sea} = 0$ fixed
$N_{\bar{u}} = 0.003^{+0.05}_{-0.05}$	$N_{\bar{d}} = -0.15^{+0.08}_{-0.09}$
$M_1^2 = 0.45^{+0.53}_{-0.22}$ (GeV/c)^2	

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 Table I together with the corresponding errors. As one can see, 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 [26] will explore the high-x region in SIDIS which is very important for jet A_N as far as integration over x is performed in Eq. (3).

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. [27] 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. Using these 289 sets of parameters we draw

the shaded corridor in all the plots. It is important to realize that this corridor corresponds to almost the same description of SIDIS data.
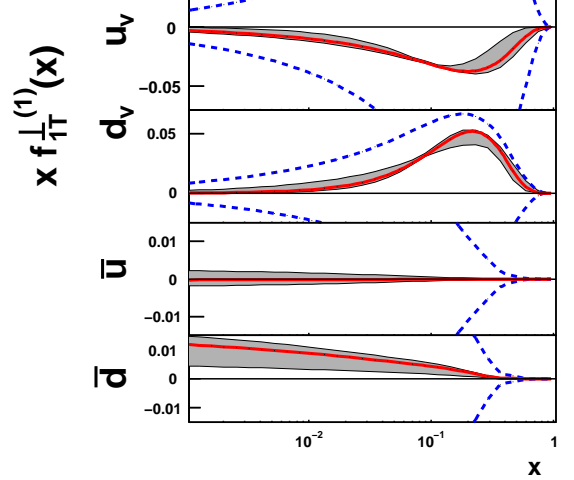

FIG. 2. The first $k_\perp$-moment of the quark Sivers functions as a function of x, here $f_{1T}^{\perp q(1)}(x) = -T_{q,F}(x,x)/2M$. Dashed lines correspond to positivity bounds, while the solid lines and the shaded region are the same as in Fig. 1.

We present a comparison to the SIDIS data in Fig. 1, which gives a very good description of HERMES π^+ data. For π^0, π^- asymmetries and z_h and $P_{h\perp}$ dependencies (and COMPASS data), the description is similar. In Fig. 2 we show the first $k_\perp$-moment of the extracted quark Sivers functions versus x.
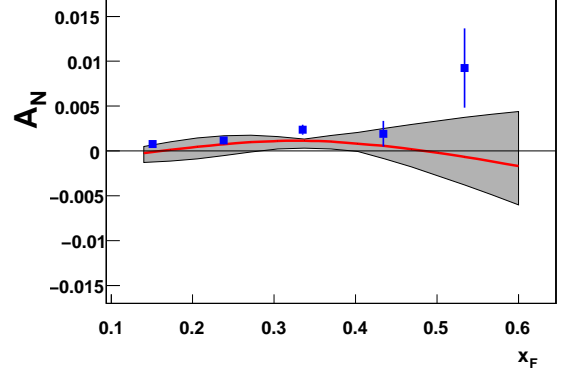

FIG. 3. Description of AnDY data [17] for inclusive jet production at forward rapidity $\langle y \rangle = 3.25$ and center-of-mass energy $\sqrt{s} = 500$ GeV. Shaded region corresponds to the parameter scan.

We now assess whether the recently measured jet spin asymmetry from the AnDY experiment is compatible with the SIDIS Sivers asymmetry data; in other words, whether the jet asymmetry is consistent with our expectation on the process-dependence of the Sivers effect. To this end, we calculate the jet asymmetry A_N from Eq. (4) with our 289 equally-good sets of parameters. The result-
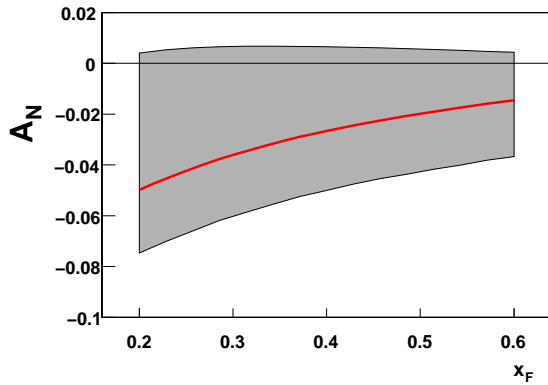
FIG. 4. Prediction of direct photon A_N in pp collisions at rapidity $y = 3.5$ and center-of-mass energy $\sqrt{s}$=200 GeV.

ing shaded region for jet A_N as a function of Feynman $x_F \equiv 2P_{Jz}/\sqrt{s}$ (P_{Jz} the jet longitudinal momentum) is shown in Fig. 3. 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 and that there exists a set of Sivers functions which can describe them simultaneously [28]. Although we cannot claim that our analysis proves the process-dependence of the Sivers effect (the role of ISIs and FSIs) due to the large uncertainty and the very small size of the jet asymmetry data, at the very least such a process-dependence is not in disagreement with the existing experimental data. Thus, we conclude that this is the first indication for the process-dependence of the Sivers effect.

As far as the jet is concerned, since it is produced through strong interaction initiated processes, in contrast to direct photon, SIDIS, or DY, 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, an observation from the SIDIS fit and also from the prediction based on large-N_c QCD [29]) which are neither weighted by the quark electric charges squared nor coupled to fragmentation functions. In order to carry out a more definitive test on the process-dependence of the Sivers function, and simultaneously explore the consistency of the TMD and collinear twist-3 factorization formalisms, it is advantageous to study hadronic processes that have larger spin asymmetries. In this respect DY production is the ideal process to explore process dependence, provided that the effects of TMD evolution are completely understood; while direct photon production (though experimentally challenging [30]) 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, $y = 3.5$ and $\sqrt{s} = 200$ GeV, in Fig. 4. Since u and d quark Sivers functions are now weighted with their electric charge squared, which compensates the cancella-

tion between them, we found that the direct photon A_N has much larger size $\sim 5\%$, and it is negative [31] due to the nature of ISIs associated with the Sivers effect for direct photon production.

Now, using the TMD factorization formalism [33, 34], we compute the DY spin asymmetry A_N at center-of-mass energy $\sqrt{s} = 500$ GeV, for invariant mass $4 < Q < 8$ GeV and transverse momentum $0 < q_\perp < 1$ GeV. Due to the same reason, the asymmetry is larger $\sim 8\%$ and negative [35] (see Fig. 5). At small and intermediate x_F region, the behavior is very similar to those in [33, 34]. The large x_F behavior is different though it has a similar uncertainty band.
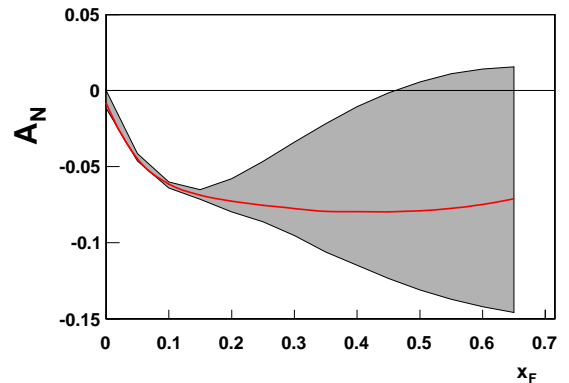

FIG. 5. Prediction for Sivers asymmetry A_N for DY lepton pair production at $\sqrt{s} = 500$ GeV, for the invariant mass $4 < Q < 8$ GeV and transverse momentum $0 < q_\perp < 1$ GeV. Note our A_N is related to the weighted asymmetry defined in Ref. [33] as $A_N = -A_{UT}^{\sin(\phi_\gamma - \phi_S)}$.

In summary, we have analyzed the SSA for inclusive jet production in pp collisions collected by AnDY experiment and the Sivers asymmetry data from SIDIS experiments. We study the effect of ISIs and FSIs between the active parton and the remnant of the hadron on the process-dependence of the Sivers effect for both processes. After carefully taking into account all ISIs and FSIs in the inclusive jet production, we find that the calculated jet spin asymmetry based on the Sivers function extracted from SIDIS experiments are consistent with the AnDY experimental data. 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 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. They are complementary to each other, DY production is the ideal process to explore process dependence, provided that the effects of TMD evolution are completely understood; while direct photon production can be used to study the con-

sistency of the factorization formalisms. We make predictions for these asymmetries at RHIC kinematics, and encourage RHIC to undertake both measurements.

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