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Single Spin Asymmetry in Inclusive Hadron Production in pp Scattering from Collins Mechanism

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Abstract

We study the Collins mechanism contribution to the single transverse spin asymmetry in inclusive hadron production in pp scattering $p^\uparrow p \to \pi X$ from the leading jet fragmentation. The azimuthal asymmetric distribution of hadron in the jet leads to a single spin asymmetry for the produced hadron in the Lab frame. The effect is evaluated in a transverse momentum dependent model that takes into account the transverse momentum dependence in the fragmentation process. We find the asymmetry is comparable in size to the experimental observation at RHIC at $\sqrt{s} = 200GeV$.

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Single-transverse spin asymmetries (SSA) in hadronic processes have a long history [1, 2]. They are defined as the spin asymmetries when we flip the transverse spin of one of the hadrons involved in the scattering: $A = (d\sigma(S_\perp) - d\sigma(-S_\perp))/(d\sigma(S_\perp) + d\sigma(-S_\perp))$. Recent experimental studies of SSAs in polarized semi-inclusive lepton-nucleon deep inelastic scattering (SIDIS) [3, 4], in hadronic collisions [5–9], and in the relevant e^+e^- annihilation process [10], have renewed the theoretical interest in SSAs and in understanding their roles in hadron structure and Quantum Chromodynamics (QCD). Among the theoretical approaches proposed in the QCD framework, the transverse momentum dependent (TMD) parton distribution approach [11–18] and the twist-3 quark-gluon correlation approach [19, 20] are the most discussed in the last few years, and it has been demonstrated that these two approaches are actually consistent with each other in the overlap regions where both apply [21].

For the SSAs in hadron production, two important contributions have been identified in the literature: one is associated with the so-called Sivers effect [11, 20] from the incoming polarized nucleon; and one with the Collins effect [12] in the fragmentation process for the final state hadron. Both effects shall contribute to the SSA in inclusive hadron production in nucleon-nucleon scattering, for example, in pion production in $p^\uparrow p \to \pi X$. However, how the transverse momentum dependent Sivers and Collins functions contribute to the inclusive hadron production in $p^\uparrow p \to \pi X$ is not clear, because the large $p_\perp$ of the final state hadron has no direct connection with the intrinsic transverse momentum of partons in nucleon or the transverse momentum in the fragmentation process. Therefore, these effects can only be evaluated in a model-dependent way [13, 22]. Meanwhile, for the Sivers effects, the initial and final state interactions are crucial to the nonzero SSA in the hadronic processes [15], which have not yet been implemented in the model calculations [13, 22]. Thus, it is more appropriate to adopt the twist-3 quark-gluon correlation approach for the Sivers contribution in $p^\uparrow p \to \pi X$, which takes into account the initial and final state interaction effects in the formalism [20].

For the Collins effect, a twist-3 extension to the fragmentation process has been formulated in [23]. However, a universality argument for the Collins function [24] would indicate the contributions calculated in [23] vanishes. This universality has also been recently extended to pp collisions [25]. Therefore, to establish a consistent framework for the twist-three quark-gluon correlation contribution in the fragmentation process, we need further theoretical developments. Before that, it is worthwhile to investigate the Collins effects contribution

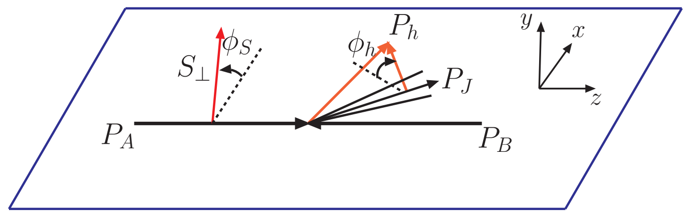

FIG. 1: *Illustration of the kinematics for the azimuthal distribution of hadrons inside a jet in pp scattering.*

to the inclusive hadron's SSA $p^\uparrow p \to \pi X$ by extending the results of [25] and using a transverse momentum dependent model in the quark fragmentation. This is what we will explore in this paper. Earlier works on the Collins contribution can be found in [26–28].

In our model, we assume a transversely polarized quark is produced in hard partonic processes with transverse momentum $P_\perp$ and rapidity y_1. This transversely polarized quark then fragments into a final state hadron with azimuthal asymmetric distribution (relative to the jet) according to the Collins effect [25]. The final state hadron's momentum will naturally be the jet's momentum in a fraction of z_h plus the fragmentation momentum of hadron relative to the jet: P_{hT}. Thus, the azimuthal asymmetry found in [25] will lead to an azimuthal asymmetry of final state hadron in the Lab frame, which is exactly the experimental measurement of the left-right asymmetry A_N. Our approach is a semi-classic picture, in the sense that the quark jet production comes from the hard partonic processes and is calculated from a collinear factorization approach, whereas the fragmentation process takes the TMD effects explicitly. This assumption, of course, will introduce some theoretical uncertainties. However, we argue that our results shall provide a good estimate on how large the Collins effects contribute to the inclusive hadron's SSA in $p^\uparrow p \to \pi X$. It is important to note that, to make reliable predictions for the inclusive process in pp scattering at the transverse momentum region of our interest, we have to take into account the high order perturbative resummation corrections, and the power corrections as well [29].

There have been calculations for the Collins effects contributions to inclusive hadron's SSA $p^\uparrow p \to \pi X$ in the transverse momentum dependent approach similar to our model, where it was claimed that the Collins effect is negligible [28]. However, from our simple picture, we find the contributions are as large as the SSAs observed by the RHIC experiments at $\sqrt{s} = 200GeV$. Let us first recall what has been calculated in [25]. As illustrated in Fig. 1, we studied the process,

$$p(P_A, S_\perp) + p(P_B) \to jet(P_J) + X \to H(P_h) + X \ , \tag{1}$$

where a transversely polarized proton with momentum P_A scatters on another proton with momentum P_B, and produces a jet with momentum P_J (transverse momentum $P_\perp$ and rapidity y_1 in the Lab frame). The three momenta of P_A, P_B and P_J form the so-called reaction plane. Inside the produced jet, the hadrons are distributed around the jet axes. A particular hadron H will carry certain longitudinal momentum fraction z_h of the jet, and its transverse momentum P_{hT} relative to the jet axis will define an azimuthal angle with the reaction plane: ϕ_h, shown in Fig. 1. Thus, the hadron's momentum is defined as $\vec{P}_h = z_h\vec{P}_J + \vec{P}_{hT}$. The relative transverse momentum P_{hT} is orthogonal to the jet's momentum P_J: $\vec{P}_{hT} \cdot \vec{P}_J = 0$. Similarly, we can define the azimuthal angle of the transverse polarization vector of the incident polarized proton: ϕ_S. The Collins effect will contribute to an azimuthal asymmetry for hadron production in term of $\sin(\phi_h - \phi_S)$. The differential cross section can be written as [25]

$$\frac{d\sigma}{dy_1 dy_2 dP_\perp^2 dz d^2P_{hT}} = \frac{d\sigma}{d\mathcal{P}.\mathcal{S}.} = \frac{d\sigma_{UU}}{d\mathcal{P}.\mathcal{S}.} + |S_\perp|\frac{|P_{hT}|}{M_h}\sin(\phi_h - \phi_s)\frac{d\sigma_{TU}}{d\mathcal{P}.\mathcal{S}.} \ , \tag{2}$$

where $d\mathcal{P}.\mathcal{S}. = dy_1 dy_2 dP_\perp^2 dz d^2P_{hT}$ represents the phase space for this process, y_1 and y_2 are rapidities for the jet P_J and the balancing jet, respectively, $P_\perp$ is the jet transverse momentum, and the final observed hadron's kinematic variables z_h and P_{hT} are defined above. $d\sigma_{UU}$ and $d\sigma_{TU}$ are the the spin-averaged and single-transverse-spin dependent cross section terms, respectively. They are defined as [25]

$$\begin{aligned}
\frac{d\sigma_{UU}}{d\mathcal{P}.\mathcal{S}.} &= \sum_{a,b,c} x' f_b(x') x f_a(x) D_c^h(z, P_{hT}) H_{ab\to cd}^{uu} \ , \\
\frac{d\sigma_{TU}}{d\mathcal{P}.\mathcal{S}.} &= \sum_{b,q} x' f_b(x') x \delta q_T(x) \delta\hat{q}(z, P_{hT}) H_{qb\to qb}^{\text{Collins}} \ .
\end{aligned} \tag{3}$$

Here, x and x' are the momentum fractions carried by the parton "a" and"b" from the incident hadrons, respectively. In the above equation, f_a and f_b are the associated parton distributions, $D_q(z_h, P_{hT})$ is the TMD quark fragmentation function, $\delta q_T(x)$ is the quark transversity distribution, and $\delta\hat{q}(z_h, P_{hT})$ the Collins fragmentation function. The hard factors for the spin-averaged cross sections are identical to the differential partonic cross sections: $H_{ab\to cd}^{uu} = d\hat{\sigma}_{ab\to cd}^{uu}/d\hat{t}$, and the spin-dependent hard factors have been calculated in [25].

In the following, we will study how the above azimuthal asymmetry contributes to the SSA in inclusive hadron production in pp scattering $p^\uparrow p \to \pi X$, especially at RHIC energy. In order to estimate this contribution, we assume that the hadron production is dominated by the leading jet fragmentation, and the Collins effects discussed above shall lead to a nonzero azimuthal asymmetry in the Lab frame, for example, in term of $\sin(\Phi_h - \Phi_S)$ where Φ_h and Φ_S are the azimuthal angles of the final state hadron and the polarization vector in the Lab frame. Following this assumption, the hadron production follows two steps: jet production and hadron fragmentation. In the fragmentation process, as we mentioned above, the hadron's momentum $\vec{P}_h$ will be

$$\vec{P}_h = z_h \vec{P}_J + \vec{P}_{hT} \ . \tag{4}$$

If we choose the jet transverse momentum direction as $\hat{x}$ direction as we plotted in Fig. 1, the final hadron's momentum can be parameterized as follows,

$$\begin{aligned} P_{hx} &= z_h P_\perp + P_{hT} \cos\phi_h \cos\theta \ , \\ P_{hy} &= P_{hT} \sin\phi_h \ , \\ P_{hz} &= z_h P_{Jz} - P_{hT} \cos\phi_h \sin\theta \ , \end{aligned} \tag{5}$$

where $P_\perp$ is the transverse momentum of the jet in the Lab frame, θ the polar angle between the jet and plus $\hat{z}$ direction (the polarized nucleon momentum direction): $y_1 \approx \eta = -\ln\tan(\theta/2)$, and y_1 and η are the rapidity and pseudorapidity of the hadron, respectively. We can also work out the general results for any azimuthal angle (Φ_J) of the jet in the Lab frame. At RHIC experiment, a sizable single spin asymmetry has been observed in the forward direction, which means $\theta \approx 0$. We further assume that $P_{hT} \ll P_\perp$, so that the rapidity of the hadron will approximately equal to the jet's rapidity. The uncertainties coming from this approximation can be further studied by taking into account the full kinematics in the fragmentation process. With the above kinematics of P_{hx}, P_{hy}, and P_{hz}, we will be able to derive the transverse momentum $P_{h\perp}$ and azimuthal angle Φ_h for the final state hadron in the Lab frame.

By integrating the fragmentation functions over z_h and P_{hT}, we will obtain the differential cross sections and the spin asymmetries depending on the final state hadron's kinematics, y_1 and $\vec{P}_{h\perp}$, where $\vec{P}_{h\perp}$ is hadron's transverse momentum in the Lab frame. Let us first estimate roughly how the above effect contributes to the SSA for pion production in pp scattering

$p^\uparrow p \to \pi X$, especially for the sign. Suppose the incident nucleon A is polarized along the $\hat{y}$ direction, and we assume that π^+ is dominated by the valence u-quark fragmentation in the forward rapidity region. The HERMES data show that the Collins function for u-quark fragmentation into π^+ is negative if the u-quark transversity distribution is positive in the valence region [30]. From the differential cross section Eq. (2), we will find that the π^+ will prefer to be produced with ϕ_h around 0, which will lead to an increase of π^+ production in $+\hat{x}$ direction. That means this contribution will result into a positive left-right (A_N) asymmetry for π^+. Similarly, we find that the contribution to π^- left-right asymmetry is negative, and that for π^0 will be determined by the contributions from both u and d quarks. These estimates are consistent with the experimental trends for the SSAs in pion productions at RHIC [5, 6, 8, 9].

Quantitatively, we can perform our calculations for the spin asymmetries at RHIC energy. With the above kinematics, we can write down the differential cross section for inclusive hadron production $pp \to \pi X$ coming from the leading jet fragmentation, depending on the final state hadron's kinematics,

$$\begin{aligned} \frac{d\sigma^{uu}}{dy_1 d^2P_{h\perp}} &= \int dy_2 dP_\perp^2 \frac{1}{\pi} d\Phi_J dz_h \Theta(P_\perp - \mathbf{k}_0)\Theta(\Lambda - P_{hT}) \\ &\quad \times x f_a(x) x' f_b(x') D_c(z_h, P_{hT}) H^{uu} , \end{aligned} \tag{6}$$

where the jet's transverse momentum $\vec{P}_\perp$ is integrated out, and also the associated azimuthal angle Φ_J. From the rotation invariance of the above expression, the differential cross section will be azimuthal symmetric for the final state hadron. Thus, it will not depend on the azimuthal angle Φ_h. In the above equation, we have imposed two cuts for the momenta $P_\perp$ and P_{hT}. The minimum value for $P_\perp$ is necessary to guarantee that the fragmentation is coming from the leading jet production, whereas a cut on P_{hT} is needed to ensure that we will not get into un-physical region in the fragmentation process. Theoretical uncertainties can be further studied by varying these two parameters. Similarly the spin dependent cross section can be written as

$$\begin{aligned} \frac{d\Delta\sigma^{UT}(S_\perp)}{dy_1 d^2P_{h\perp}} &= \int dy_2 k_\perp dP_\perp \frac{1}{\pi} d\Phi_J dz_h \Theta(P_\perp - \mathbf{k}_0)\Theta(\Lambda - P_{hT}) \\ &\quad \times \frac{|P_{hT}|}{M_h} \sin(\phi_h - \Phi_S + \Phi_J) x \delta q_T(x) x' f_b(x') \delta\hat{q}(z_h, P_{hT}) H^{\rm Collins}_{qb\to qb} , \end{aligned} \tag{7}$$

where Φ_S is the azimuthal angle of the transverse polarization vector $S_\perp$ in the Lab frame, and its relative angle to the jet defined in Fig. 1 ϕ_S can be written as $\phi_s = \Phi_S - \Phi_J$.

Following above, we further define Φ_h as the azimuthal angle of the produced hadron in the Lab frame, which is different from the above ϕ_h. From these differential cross sections, the left-right asymmetry A_N is calculated as

$$A_N = \frac{\langle 2\sin(\Phi_S - \Phi_h) d\Delta\sigma^{UT}\rangle}{\langle d\sigma^{uu}\rangle} \ . \tag{8}$$

In the numerical simulations, we use simple Gaussian parameterizations for the TMD fragmentation functions,

$$\begin{aligned} D_c(z_h, P_{hT}) &= \frac{1}{\pi\langle p_\perp^2\rangle} e^{-P_{hT}^2/\langle p_\perp^2\rangle} D_c(z_h) \ , \\ \delta\hat{q}(z_h, P_{hT}) &= \frac{2M_h}{(\pi\langle p_\perp^2\rangle)^{3/2}} e^{-P_{hT}^2/\langle p_\perp^2\rangle} \delta\hat{q}^{(1/2)}(z_h) \ , \end{aligned} \tag{9}$$

where $D_c(z_h)$ is the integrated fragmentation function, and $\delta\hat{q}^{(1/2)}$ the so-called half-moment of the Collins function. The above parameterizations have been chosen to give the right normalization for the two fragmentation functions. In the following numerical calculations, we choose the parameters $\langle p_\perp^2\rangle = 0.2GeV^2$, $\Lambda = 1GeV$, and $\mathbf{k}_0 = 1GeV$.

The half-moment of the Collins functions $\delta\hat{q}^{(1/2)}(z_h)$ have been determined from the HERMES data by assuming some functional form dependence on z_h [30–32]. In [30], they are parameterized as $\delta\hat{q}^{(1/2)} = Cz_h(1-z_h)D_c(z_h)$ for the favored and unfavored ones. These parameterizations have to be updated, because the di-hadron production in e^+e^- annihilation from BELLE experiments showed a strong increase of the asymmetry with z_h [10]. To be consistent with this observation, we re-parameterize the Collins functions as follows [31],

$$\begin{aligned} \delta\hat{q}_{fav.}^{\pi(1/2)}(z_h) &= C_f' z_h D_u^{\pi^+}(z_h) \ , \\ \delta\hat{q}_{unfav.}^{\pi(1/2)}(z_h) &= C_u' z_h D_d^{\pi^+}(z_h) \ . \end{aligned} \tag{10}$$

With the new parameters modified from [30]: $C_f' = 0.61C_f$ and $C_u' = 0.65C_u$, we will be able to reproduce the Collins asymmetries for $\pi^\pm$ from HERMES, assuming the quark transversity distributions follow the parameterizations in [33].

In Fig. 2, we show the numerical estimates from our model calculations of the Collins mechanism contributions to the SSA in π^0 production in pp scattering $p^\uparrow p \to \pi^0 X$ at RHIC at $\sqrt{s} = 200GeV$: left panel as function of $P_{h\perp}$ for $x_F > 0.4$ and all rapidity; the right panel as functions of x_F for two different rapidities: $y = 3.3,\ 3.7$, respectively. Similar results are also obtained for the charged pions. The decrease of the SSA as $P_{h\perp}$ decreases is due to the fact that, in our model, the leading jet fragmentation contribution does not dominate the cross section and the asymmetry at low $P_{h\perp}$ region. Numerically, this decrease comes from a lower cut for the jet transverse momentum $P_\perp > \mathbf{k}_0$ in our formalism Eqs. (6,7). We can further introduce a soft mechanism, which is responsible for the cross section and spin asymmetry in this region. For example, the soft contribution to the spin-average cross section can be parameterized as an exponential function $d\sigma^{uu(s)} \propto e^{-P_{h\perp}/T}$, and we assume it contributes similarly in amount as our leading jet fragmentation at about $1GeV$. The soft mechanism contribution to the SSA can be roughly parameterized as a linear function of $P_{h\perp}$: $A_N^{(s)} = aP_{h\perp}$, since it has to vanish at $P_{h\perp} = 0$. As a simple illustration, we plot the new A_N as dashed curve in the left panel of Fig. 2 when we take into account the soft contribution with a reasonable guess for the parameters: $T \approx 0.14GeV$ and $a \approx 0.06GeV^{-1}$. This new curve shows a deep at the interplay between soft and hard regions. We note that this result could be an artifact of our model. The newest STAR data seem to suggest a similar behavior [6], which may hint that the soft mechanism is important in this region. On the other hand, in the moderate and large transverse momentum region, in general, the spin asymmetry A_N decreases as $P_{h\perp}$ increases, as can be seen from our results in Fig. 2, where we find little influence from the soft contribution.

These plots show that the Collins contributions to the SSA in inclusive hadron production in pp scattering $p^\uparrow p \to \pi X$ are not negligible, rather comparable in size to what we observed at RHIC for charged and neutral pions [5, 6, 8, 9]. However, we will not intend to compare them with the real data on these SSAs, for which we have to take into account the Sivers contributions as well [20].

In conclusion, in this paper, we have studied the Collins mechanism contribution to the inclusive hadron's SSA in pp scattering $p^\uparrow p \to \pi X$ at RHIC in a model where the hadron production comes from the leading jet fragmentation with transverse momentum dependence. These contributions depend on the quark transversity distributions and the Collins fragmentation functions. Contrary to the previous calculations [28], we found that their contributions to the SSA for inclusive π^0 production at RHIC is the same size as the experimental measurement. The discrepancy between [28] and this paper needs further investigations. Our results shall also stimulate more theoretical developments toward a fully understanding for the longstanding SSA phenomena in hadronic processes.

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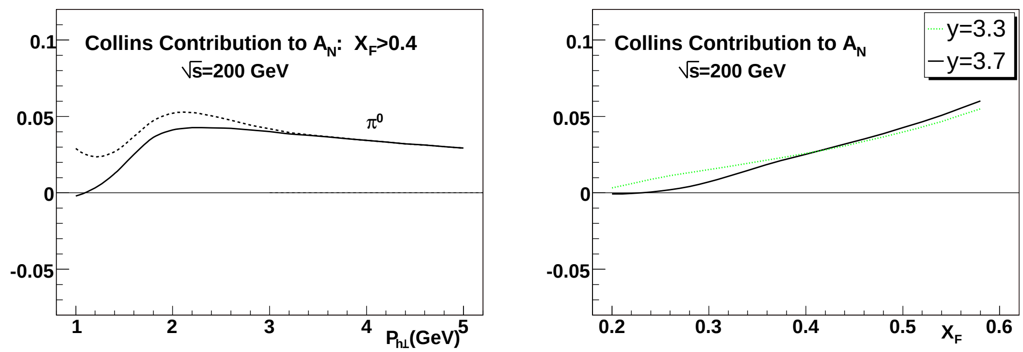

FIG. 2: *Model predictions for the Collins contribution to the SSA in* π^0 *production at RHIC at* $\sqrt{s} = 200GeV$*: left panel as function of* $P_\perp$ *for* $x_F > 0.4$ *and all rapidity; right panel as function of* x_F *for two different rapidity bins,* $y = 3.3,\ 3.7$*, respectively.*

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