Single spin asymmetries in $\ell p \rightarrow h + X$ processes

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We study the transverse single spin asymmetry (SSA), $A_N$, for the single inclusive process $\ell p \uparrow \rightarrow h + X$, in a perturbative QCD factorization scheme with inclusion of spin and transverse momentum dependent (TMD) distributions. By adopting the relevant TMDs (Sivers and Collins functions) as extracted from semi-inclusive deep inelastic scattering (SIDIS) and $e^+e^-$ data, predictions for these SSAs are given. A measurement of $A_N$ for this process could then provide a direct test of the validity of the TMD factorization.

1 Introduction

In this contribution [1] we discuss a preliminary study of transverse SSAs in inclusive hadron production in lepton-proton collisions as a tool to test the TMD factorization hypothesis.

Azimuthal and transverse single spin asymmetries, with their behaviour and size, definitely represent a challenge for the QCD factorization theorems and, at the same time, have opened a new way to learn on the spin structure of hadrons. A large amount of data has been analyzed by many experimental collaborations in various inclusive processes (for reviews see, e.g., Ref. [2]): the left-right asymmetries in single polarized proton-proton collisions (from the early E704 to the latest STAR and BRAHMS data), the azimuthal asymmetries in single polarized SIDIS (HERMES and COMPASS) and in hadron-pair production in $e^+e^-$ annihilation (Belle).

Two theoretical approaches have been proposed to describe such phenomena [2]: i) a generalization of the pQCD factorization scheme with inclusion of a new class of spin and TMD distribution and fragmentation functions; ii) a collinear QCD factorization theorem in terms of higher-twist parton correlation functions.

The first approach was initially adopted [3] to explain the early SSAs observed in $pp \rightarrow \pi + X$ and later applied, with success, to predict [4] $A_N$ at much larger energies. An extended and systematic study can be found in Ref. [5]. Presently, the TMD approach is believed to hold for SSAs characterized by the presence of two scales, a large (i.e. $Q^2$) and a small one ($p_T \simeq \Lambda_{\text{QCD}}$), like for the production of small $p_T$ hadrons in SIDIS processes or of small $p_T$ lepton-pairs in Drell-Yan processes [6, 7]. For a detailed and complete classification of all TMDs and their role in azimuthal and SSAs in SIDIS see Ref. [8].

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Based on these results, the first extractions of the Sivers, Collins and transversity functions have been performed [9, 10, 11, 12, 13, 14, 15]. Notice that all these analyses of SIDIS data are carried out in the $\gamma^* - p$ c.m. frame, according to the following TMD factorization formula:

$$d\sigma^{\ell p - \ell' h + X} \sim \sum_q f_{q/p}(x, k_{\perp}; Q^2) \otimes d\sigma_f^{q/q} \otimes D_{h/q}(z, p_{\perp}; Q^2),$$

(1)

where $k_{\perp}$ and $p_{\perp}$ are, respectively, the transverse momentum of the quark in the proton and of the final hadron with respect to the fragmenting quark.

The alternative formalism, the higher-twist approach, has been proved to hold for SSAs where a single hard scale is relevant, like the inclusive production of large $p_T$ hadrons in hadron-hadron collisions [16]. A corresponding and rich phenomenology has been developed in Refs. [17, 18, 19].

In the last years, these two approaches have been shown to be somewhat related and equivalent in the kinematic regime where they both apply [20]. However, a definite proof of the validity of the TMD factorization for SSAs in inclusive particle production in hadron-hadron collisions is still lacking. In this context, we mention that a sort of modified TMD factorization approach has been discussed in the study of dijet production at large $p_T$ in $pp$ collisions by including the proper gauge-links structure in the elementary processes [21, 22, 23].

What we aim at discussing here is then an experimental test of the TMD factorization by considering the SSA in the $\ell p \rightarrow h + X$ process, where a single large $p_T$ final particle is detected [24]. This is the analogue of the left-right asymmetry observed in $pp \rightarrow h + X$.

Differently from SIDIS, we will now perform the analysis in the lepton-proton c.m. frame without the detection of the final lepton, but still requiring a large $Q^2$ regime (see below).

Similar studies, although with different motivations, were presented in Refs. [25, 26, 27].

### 2 TMD approach to $\ell p \rightarrow h + X$

We consider the process $p^\uparrow \ell \rightarrow h + X$, with $p$ moving along the positive $Z$-axis in the $p - \ell$ c.m. frame, the final hadron produced in the $X - Z$ plane and $\uparrow$ direction along $+Y$ (Fig. 1). We assume the same TMD factorization scheme as for the process $p^\uparrow p \rightarrow h + X$ and compute $A_N = (d\sigma^\uparrow - d\sigma^\downarrow)/(d\sigma^\uparrow + d\sigma^\downarrow)$. The numerator of this SSA reads

$$d\sigma^\uparrow - d\sigma^\downarrow \sim \sum_q \left\{ \Delta^N f_{q/p} \cos \phi_q \otimes d\hat{\sigma} \otimes D_{h/q} \right. \left. + h_{1}^{q/p} \otimes d\Delta \otimes \Delta^N D_{h/q} \cos \phi_C + h_{11}^{q/p} \otimes d\Delta \otimes \Delta^N D_{h/q} \cos(\phi_C - 2\phi_q) \right\},$$

(2)

where the $q\ell \rightarrow q\ell$ elementary cross sections are given by

$$d\sigma \propto e_q^2 \frac{\hat{s}^2 + \hat{t}^2}{2\hat{t}^2} \quad d\Delta \otimes \frac{\hat{s} \hat{u}}{\hat{t}^2},$$

(3)

with $\hat{s}, \hat{t}, \hat{u}$ the Mandelstam invariants and $\phi_C \equiv \phi_h^H + \phi_q$, with $\phi_q(\phi_q')$ the azimuthal angle of the initial (fragmenting) quark in the c.m. frame and $\phi_h^H$ the hadron azimuthal angle.
in the outgoing-quark helicity frame. Notice that the result shown in Eq. (2) can be also obtained as a particular case of the \((A, S_A) + (B, S_B) \rightarrow C + X\) process [5]. In equation (2) we recognize the contributions from the Sivers function [28, 29] (first line)

\[
\hat{f}_{q/p}\uparrow(x, k_\perp) - \hat{f}_{q/p}\downarrow(x, k_\perp) \equiv \Delta Nf_{q/p}\uparrow(x, k_\perp) S \cdot (\hat{p} \times \hat{k}_\perp),
\]

(4)

where the mixed product in our configuration gives the \(\cos \phi_q\) dependence in Eq. (2), and from the Collins function [30] (second line)

\[
\hat{D}_{h/q}\uparrow(z, p_\perp) - \hat{D}_{h/q}\downarrow(z, p_\perp) \equiv \Delta N\hat{D}_{h/q}\uparrow(z, p_\perp) s_q \cdot (\hat{p}_q \times \hat{p}_\perp),
\]

(5)

coupled with \(h_1\) (the TMD transversity distribution) and \(h_{1T}\); in this case the azimuthal dependences in Eq. (2) arise from the phases entering the TMD distributions, the elementary scattering and the Collins function.

Before presenting our results we want to comment on some aspects peculiar for this process. First of all, as in SIDIS, we have a single partonic subprocess and only the \(t\)-channel contribution (much simpler than the \(pp \rightarrow h + X\) case). However, without the detection of the final lepton one is not able to reconstruct the lepton plane and then to access separately the Sivers and the Collins effect (as usually done for SIDIS). On the other hand in the backward region (w.r.t. the proton direction) \(|\hat{u}|\) becomes smaller and so does the spin transfer \(\Delta \hat{\sigma}/\hat{\sigma}\) (see Eq. (3)) implying a strong dynamical suppression of the Collins effect. At the same time, this does not affect the Sivers contribution since, contrary to what happens in \(pp \rightarrow h + X\), no \(\bar{u}\)-channel is active. [Remember also that the \(t\) variable strongly depends on \(\phi_q\) (the azimuthal dependence of the Sivers effect, see Eq. (2))].

It is also well known that the \(\ell p \rightarrow h + X\) process is dominated by quasi-real photon-exchange with low \(p_T\) hadrons in the final state. However, for the validity of the adopted perturbative QCD factorization scheme the elementary scattering must be governed by a large momentum transfer, let us say \(Q^2 > 1\) GeV\(^2\). This is trivially guaranteed in the usual collinear configuration by requiring a moderate-large \(p_T\) for the final hadron (\(p_T \geq 1\) GeV). We have checked that, by including \(k_\perp\) effects in the kinematics, the safe region \((Q^2 > 1\) GeV\(^2\)) corresponds to a minimum \(p_T\) value of the order of 1.5 GeV. More precisely, for such value one has to restrict to the backward region \((x_F = 2p_L/\sqrt{s} < 0)\), while, at larger values, like \(p_T = 2.5\) GeV, we can explore the full \(x_F\) range, remaining in the large \(Q^2\) regime. These are the values considered in our estimates.

A word of caution has still to be added. In our calculation we do not include any hard gluon emission which could give a large \(p_T\) hadron even in the low \(Q^2\) regime. This would lead to a two-jet event and might be experimentally excluded by requiring the absence of any hadron activity in the opposite hemisphere w.r.t. the detected hadron.

3 Results

We show our estimates for two different kinematic setups related to the ongoing HERMES \((p_{\text{Lab}} = 27.5\) GeV) and COMPASS \((p_{\text{Lab}} = 160\) GeV) experiments and focus on pion production. By numerical calculation we have checked that the (maximized) contribution to \(A_N\) coming from \(h_{1T}\) (see Eq. (2)) is totally negligible, as well as the analogous contribution to the unpolarized cross section involving the Boer-Mulders function. In our estimates we will adopt the present information on the relevant TMDs (Sivers, Collins and transversity
functions) as extracted in the latest analyses of SIDIS and $e^+e^-$ data [14, 15]. We will show separately the contribution to $A_N$ from the Sivers or the Collins effect alone.

In Figure 2 (left and central panels) we present our estimates for the Sivers contribution to $A_N$ at HERMES kinematics for two values of $p_T$. As discussed above, for $p_T = 1.5$ GeV only the backward region can be considered. For charged pion production at $p_T = 1.5$ GeV we also show the statistical uncertainty bands from the fits. The largest $A_N$ values obtained correspond to the $x$ region (in the polarized proton) where the Sivers functions, for up and down quarks, reach their maxima. Notice that while for positive $x_F$, the minimum of $x$ (in the polarized proton) is given, roughly, by $x_F$, for negative $x_F$ the minimum of $x$ is controlled by the ratio $p_T/\sqrt{s}$, with $z$ always bigger than $|x_F|$. It is interesting to note the sizable $A_N$ for $\pi^-$ production (larger than the corresponding $A_{UT}$ in SIDIS) due to the dominance of the down-quark contribution with a small contamination from the up quark.

For $p_T = 1.5$ GeV the Collins effect (not shown), involving $h_1$, is negligible, while it reaches at most 1-2% at the largest $|x_F|$ values for $p_T = 2.5$ GeV (Fig. 2, right panel).

In Figure 3 we show the analogous results for COMPASS kinematics. Again at $p_T = 1.5$ GeV only the Sivers effect gives a sizable contribution (left panel), while the Collins effect (not shown) is compatible with zero. At $p_T = 2.5$ GeV the Sivers effect (central panel) dominates only in the backward region, while in the forward region the Collins effect (right panel) becomes sizable.

Notice, however, that for $x_F > 0.3$ we are probing the Sivers and the transversity functions in a region ($x > 0.3$) where they are not constrained by present SIDIS data.
For larger energy values, e.g. $\sqrt{s} = 100$ GeV, like those reachable at the proposed EIC experiments and at the same $p_T$ values as above, we obtain negligible contributions to the SSAs from both the Sivers and the Collins effect. This is due to the low $x$ region explored and the corresponding sea-quark dominance.

Conclusions

We have presented a preliminary phenomenological study of SSAs in $\ell p \to h + X$ within a TMD factorization scheme. This process presents interesting aspects somewhat in between the SIDIS case (for which the factorization is generally accepted) and the $pp \to h + X$ case (where it is assumed). In this sense it could represent a clear test of the TMD factorization hypothesis. By adopting the parameterizations so far extracted from SIDIS data, sizable SSAs ($\approx 5 - 10\%$) can be obtained, mainly due to the Sivers effect and, to a lesser extent, to the Collins effect.

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