Single spin asymmetries in inclusive hadron production from SIDIS to hadronic collisions: universality and phenomenology

M. Boglione, U. D’Alesio, and F. Murgia

1Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy
2Dipartimento di Fisica, Università di Cagliari, Cittadella Universitaria, I-09042 Monserrato (CA), Italy
3Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, C.P. 170, I-09042 Monserrato (CA), Italy

(Dated: February 2, 2008)

In a perturbative QCD approach, with inclusion of spin and transverse momentum effects, experimental data on azimuthal asymmetries observed in polarized semi-inclusive deeply inelastic scattering and $e^+e^-$ annihilations can be used to determine the Sivers, transversity and Collins soft functions. By using these functions, within the same scheme, we predict $p^1p \rightarrow h + X$ single spin asymmetries in remarkable agreement with RHIC experimental data.

PACS numbers: 13.88.+e, 13.60.Hb, 13.85.Ni

Several azimuthal spin asymmetries have recently been measured in different processes: semi-inclusive deeply inelastic scattering (SIDIS) [1, 2, 3], inclusive particle production from hadronic collisions [4, 5, 6, 7, 8, 9, 10] and from $e^+e^-$ annihilations [11]. Sizable transverse single spin asymmetries (SSAs) and large transverse hyperon polarizations, see e.g. [12], severely challenged the predictions of leading order perturbative QCD (pQCD) obtained in collinear configuration [13], where the constituent partons and the corresponding observed hadrons are assumed to be collinear. Lately, a remarkable success in reproducing SSA experimental data has been achieved in the framework of non-collinear pQCD, by including spin and partonic intrinsic motion effects. This requires the introduction of a new class of transverse momentum dependent (TMD) parton distribution (PDFs) and fragmentation functions (FFs). Phenomenologically, the most relevant are, at leading twist, the Sivers [14, 15] and Boer-Mulders [16] distribution functions and the Collins fragmentation function [17]. In fact, in a factorized pQCD approach, they are responsible for most of the azimuthal spin asymmetries observed in SIDIS and Drell-Yan (DY) processes, and in $e^+e^-$ annihilations. Factorization theorems have been proved for SIDIS and DY processes [18], in the kinematical regime where two well distinct energy scales are present: a large scale - either the photon virtuality or the invariant mass of the leptonic pair, $Q$ - and a low-moderate scale - the transverse momentum, $p_T$, of the observed hadron or of the leptonic pair with respect to the colliding beams - so that $\Lambda_{QCD} \approx p_T \ll Q$.

Although the large SSAs observed in inclusive single particle production in hadronic collisions motivated a huge theoretical effort towards a pQCD treatment of these processes with the inclusion of TMD effects, a proof of factorization for this case is still lacking. Moreover, it has been shown that in a QCD approach the Sivers and Boer-Mulders effects vanish unless initial and final state interactions between the struck parton and the spectators are included [19, 20]. These effects, which can be accounted for by including appropriate color gauge links (Wilson lines) in the invariant definition of the factorized hadronic correlators, can actually be reabsorbed in prefactors associated to the hard partonic cross sections. Notice that these prefactors are different for different processes [21]. These results, while validating the interpretation of the Sivers and Boer-Mulders functions as the basic mechanisms generating SSAs and azimuthal asymmetries, question their universality properties and the whole concept of factorization. In other words, for these processes factorization is broken, but in a known and predictable way (i.e. through the action of the hard scattering prefactors), so that the total polarized and unpolarized cross sections can still be calculated in a scheme where factorization should be understood at best in a generalized, transverse momentum dependent way. Significant progress in this sense has been achieved in the context of inclusive almost back-to-back two-particle (e.g., dijet, photon-jet) production in hadronic collisions [22, 23, 24]. While these results give very useful indications and suggest caution in treating single particle production at large $p_T$, they cannot give definitive statements on this process, where the low energy scale (the intrinsic $k_{\perp}$) is integrated over and unobserved.

Alternatively, a more phenomenological approach to inclusive single particle production in hadronic collisions has been formulated in the context of a generalized parton model, with the inclusion of spin and transverse momentum effects [25, 26]. In this approach factorization is assumed as a reasonable starting point, leading twist TMD distributions keep their partonic interpretation and are therefore expected to be universal and process independent. Although reasonable, these assumptions must undergo phenomenological scrutiny by careful comparison with experimental measurements. In this scheme, one should try to reproduce the available data on SSAs coming from SIDIS, hadronic collisions and $e^+e^-$ annihilations with a single set of universal, TMD distributions. Historically, this approach was first applied to the $p^1p \rightarrow \pi + X$ process, since low energy results were available at $\sqrt{s} = 20$ GeV from the E704 Collabora-
tion. Later on, high energy regimes became available at RHIC \( \sqrt{s} = 200 \) GeV experiments. Recently, the same approach has been independently applied to the Sivers and Collins azimuthal asymmetries measured by the HERMES and COMPASS Collaborations, and to the double hadron azimuthal correlations measured in \( e^+e^- \) annihilations. High quality global fits to all experimental data have allowed the simultaneous determination of the Sivers [27] and transversity distributions and of the Collins fragmentation function [28].

In this paper, for the first time, we investigate the possibility of reproducing unpolarized cross sections and SSAs in proton-proton collisions, by using the Sivers and transversity distribution functions, and the Collins fragmentation function, as determined by fitting SIDIS and \( e^+e^- \) experimental data, without any modification. No fit to \( pp \) collision data will be used nor performed, so that all our results may be considered as genuine predictions.

Let us briefly sketch the basic relations adopted in our approach. For a detailed and complete treatment we refer to the original papers [26, 29]. The invariant differential cross section for the polarized process \( p^+/p \to \pi + X \) can be written as

\[
\frac{E_\pi \, d\sigma_{p^+/p \to \pi + X}}{d^3p_\pi} = \sum_{a,b,c,d,\{\lambda\}} \int \frac{dx_a \, dx_b \, dz}{16\pi^2 x_a x_b z^2 S} \, d^2k_{\perp a} \, d^2k_{\perp b} \, d^3k_{\perp \pi} \, \delta(k_{\perp \pi} \cdot \hat{p}_c) \, J(k_{\perp \pi})
\]

The SSA can be expressed as the ratio \( A_N = (d\sigma^\uparrow \pm d\sigma^\downarrow)/(d\sigma^\uparrow + d\sigma^\downarrow) \). In Ref. [26] it was shown that in the TMD generalized parton model several terms, other than those present in the collinear configuration, contribute to both the numerator and the denominator of \( A_N \). These contributions were neglected in earlier TMD parton models which lacked proper inclusion of spin effects. However, Refs. [26, 29] have shown that for both the E704 and RHIC kinematics, the numerator of the SSA is dominated by the Sivers effect, with a small or negligible contribution from the Collins effect, while the denominator is essentially given by the TMD unpolarized contribution which generalizes the usual collinear one. Therefore, in the case of interest here, Eq. (1) takes the simple form

\[
\frac{E_\pi \, d\sigma_{p^+/p \to \pi + X}}{d^3p_\pi} \sim \sum_{a,b,c,d,\{\lambda\}} \int \frac{dx_a \, dx_b \, dz}{16\pi^2 x_a x_b z^2 S} \, d^2k_{\perp a} \, d^2k_{\perp b} \, d^3k_{\perp \pi} \, \delta(k_{\perp \pi} \cdot \hat{p}_c) \, J(k_{\perp \pi})
\]

\[
\times \left[ f_a/p(x_a, k_{\perp a}) \pm \frac{1}{2} \lambda^N \hat{f}_a/p^\uparrow(x_a, k_{\perp a}) \right] \hat{f}_b/p^\uparrow(x_b, k_{\perp b}) |M_{\lambda_\pi, \lambda_\pi_a, \lambda_\pi_b}|^2 \, \delta(\hat{s} + \hat{t} + \hat{u}) \, D_{\pi/c}(z, k_{\perp \pi})
\]

Notice that the contribution due to the convolution of the transversity distribution with the Collins fragmentation function [28], has actually been included in our calculations. However, this effect is marginal in our results, with the exception of the BRAHMS \( A_N \) of Fig. 2. All other terms are totally negligible in the kinematical configurations considered, as their azimuthal phase factors become very complex and in general, under full \( k_{\perp} \) integrations, wash out the corresponding contributions. Consequently, the dominant terms at numerator and denominator are the Sivers effect and the unpolarized term, which have the simplest azimuthal phases.

In order to perform the calculations, we strictly follow Refs. [27, 28] where the azimuthal asymmetries measured by the HERMES and COMPASS Collaborations for semi-inclusive pion and charged hadron production have been used to extract the Sivers function and, via a combined analysis of Belle data on \( e^+e^- \to \pi\pi + X \), the transversity distribution and the Collins fragmentation function. It is important to recall that in SIDIS the Sivers and Collins contributions to the asymmetry can be disentangled by considering suitable moments of the azimuthal distributions of the observed hadrons.

In what follows, we will adopt the same Sivers and transversity distributions and the Collins FF as in Refs. [27, 28]. Our aim is to calculate the SSA for pion and kaon production in polarized \( pp \) collisions, for the RHIC kinematical range. Notice that no fit is performed, we will simply compare our predictions to data on unpolarized cross sections and SSAs from the STAR and BRAHMS Collaborations. All TMD functions have a simple ansatz form in which the \( k_{\perp} \) and lightcone fraction dependences are factorized, with a flavor independent Gaussian shape for the proton transverse distribution.

As in Ref. [27], we adopt the MRST01 PDF set [31] and the Kretzer FF set [32]. Following Ref. [29] we fix the factorization scale to \( \mu = \hat{p}_{cT}/2 \), where \( \hat{p}_{cT} \) is the transverse momentum of the fragmenting parton \( c \) in the partonic c.m. frame. Notice that, although our calculations are performed at lowest order in pQCD, no additional \( K- \)
factors are introduced.

In Fig. 1 panel (a), we show the unpolarized cross section for neutral pion production in $pp$ collisions, at $\sqrt{s} = 200$ GeV and two different average pseudorapidities, $\langle \eta \rangle = 3.3$ and $\langle \eta \rangle = 3.8$, as a function of $E_\pi$. The corresponding SSAs, $A_N(p^1p \rightarrow n^0 + X)$, are plotted in panels (b), (c) and (d) as a function of $x_F$ at fixed rapidity values, (b), and as a function of $p_T$ at different bins in $x_F$, (c) and (d). The curves are our predictions, compared to STAR experimental data \[10, 33\]. In this case the Collins effect is totally negligible.

In Fig. 2 (a) and (b) panels, we compare our predictions to BRAHMS data on unpolarized cross sections for charged pion production \[34\], as a function of $x_F$ bins in $x$. The corresponding SSAs, (a) and (b), and SSAs, (c), to the BRAHMS data for charged kaon production \[21\] are shown together with the Collins contribution alone (thin lines). Therefore, the total contribution obtained by adding the Sivers and the Collins effect (thick lines) is shown together with the Collins contribution alone (thin lines).

Finally, in Fig. 3 we compare our predictions for unpolarized cross sections, (a) and (b), and SSAs, (c), to the BRAHMS data for charged kaon production \[21\]. Notice that for $A_N$ we consider only the Sivers effect as the Collins contribution is small and the unknown kaon Collins functions are still under study.

Let us comment on these results:
1) On the whole, with the exception of low $p_T$ STAR data, our predictions are in remarkably good agreement, both in size and sign, with RHIC data. In particular, there are no evident contradictions that could be interpreted as signals of sizable factorization and universality breaking between SIDIS and $pp$ collisions. We believe this information may be very useful in the context of the recent theoretical developments: in fact, although factorization-breaking terms could in principle be there, it is not easy to infer how sizable and significant their contributions should be for the processes and kinematical configurations where data are presently available.

2) Although remarkable, one should not overestimate the significance of our results. First of all, the HERMES and COMPASS data on SIDIS used in the fits of Refs. \[27, 28\] are collected mainly in the region of low-intermediate values of the Bjorken variable $x_B \lesssim 0.3$. Therefore, the fits strictly constrain our parameterization for the Sivers function only in the low $x$ region. Consequently, with these parameterizations we are unable to reproduce the low energy results on the SSA for charged pions at large $x_F$ of the E704 collaboration. Similarly, with the average $k_\perp$’s for PDFs and FFs extracted from SIDIS, we underestimate the corresponding unpolarized cross sections by a factor which cannot simply be attributed to pQCD $K$-factors. Further advances in this direction would require a simultaneous fit of SIDIS and $pp$ data, which would give tighter constraints on the large $x$ behaviour of our parameterizations.

3) In the color gauge invariant TMD approach of Ref. \[21\] gauge links result in numerical prefactors which can be absorbed in generalized parton cross sections. These factors may be different for different processes, therefore breaking factorization. No calculations have been performed within this scheme for the single inclusive particle production in hadronic collisions, but only for the double inclusive case. However, it is possible that in the kinematical configurations considered here, the dominant partonic contributions are those with positive prefactors, close to one. Therefore, our findings cannot be interpreted as contradicting the color gauge invariant approach; rather, they could indicate that in these situations the generalized parton model and the color gauge invariant approach give very similar results. Unambiguously different predictions from the two approaches could instead be found in SSAs in DY process and in photonjet production in $pp$ collisions, see e.g. Refs. \[27, 35, 36\].

4) For the $pp$ case (and for SIDIS at large transverse momentum of the observed hadron, comparable with $Q$) there is a well known alternative approach, the collinear twist-three formalism \[37\]. Ref. \[38\] showed that results comparable or better than those found in a TMD approach can be obtained for SSAs in $pp$ collisions. Let us point out, however, that in Ref. \[38\] all available $pp$ data were included in the fit, while our results can be considered as genuine predictions. Concerning the low energy E704 data, this approach faces similar problems both for SSAs and unpolarized cross sections.

5) The fit of SIDIS data used here was performed before data on Sivers and Collins asymmetries for neutral pions and kaons were made available by the HERMES collaboration. Also COMPASS results on separated pions and kaons became available afterwards. This could partially explain the poorer agreement with kaon production data from BRAHMS. Nevertheless, let us stress that kaon data are much more challenging in SIDIS itself, since they are crucially dependent on the strange and $u$-, $d$-sea quark contributions to the Sivers function. Notice that non-leading contributions in the fragmentation functions are presently known with less accuracy also in the collinear unpolarized case. Some progress in this direction has been recently achieved and a new set of fragmentation functions is available for kaons \[39\] which differ substantially from those adopted in this paper. A detailed study of these effects is beyond the aim of this paper and requires a new fitting procedure and an updated analysis, which will be discussed elsewhere \[40\].

In conclusion, this phenomenological analysis shows that most of the available high energy data on unpolarized cross sections and SSAs for single inclusive particle production in SIDIS and in $pp$ collisions can be well reproduced in the framework of a generalized parton model, with inclusion of spin effects and leading twist TMD distributions, in particular the Sivers function.
Figure 1: Panel (a): Invariant differential cross section for $pp \to \pi^0 + X$ at $\sqrt{s} = 200$ GeV and two pseudorapidity values, $\eta = 3.3$ and $\eta = 3.8$, vs. $E_\pi$. Data are from STAR [33]. Curves are obtained adopting the unpolarized $k_t$-dependent PDFs and FFs of Ref. [30]. Panels (b), (c) and (d): $A_N$ for $pp \to \pi^0 + X$ at $\sqrt{s} = 200$ GeV and two pseudorapidity values, $\eta = 3.3$ and $\eta = 3.7$, vs. $x_F$ (b), and at different $x_F$ values vs. $p_T$, (c) and (d). Data are from STAR [10]. Curves are obtained using the Sivers functions as determined in Ref. [27] by fitting SIDIS data.

Figure 2: Panels (a) and (b): Invariant differential cross section for $pp \to \pi^\pm + X$ at $\sqrt{s} = 200$ GeV and two pseudorapidity values, $y = 2.95$ and $y = 3.3$, vs. $p_T$. Data are from BRAHMS [34]. Curves are obtained adopting the same choices as in Fig. 1(a). Panels (c) and (d): $A_N$ for $pp \to \pi^\pm + X$ at $\sqrt{s} = 200$ GeV and two different scattering angles, $\theta = 2.3^\circ$ and $\theta = 4^\circ$, vs. $x_F$. Data are from BRAHMS [9]. Thick curves are obtained adding the Sivers effect, as extracted from SIDIS data in Ref. [27], and the Collins effect coupled with the transversity function, as extracted from a global fit of SIDIS and $e^+e^-$ data in Ref. [28]. The thin lines show the Collins effect: notice that its sign is opposite w.r.t. the Sivers contribution.

Figure 3: Panels (a) and (b): Invariant differential cross section for $pp \to K^\pm + X$ at $\sqrt{s} = 200$ GeV and two pseudorapidity values, $y = 2.95$ and $y = 3.3$, vs. $p_T$. Data are from BRAHMS [34]. Curves are obtained adopting the same choices as in Fig. 1(a). Panel (c): $A_N$ for $pp \to K^\pm + X$ at $\sqrt{s} = 200$ GeV and fixed scattering angle, $\theta = 2.3^\circ$, vs. $x_F$. Data are from BRAHMS [9]. Curves are obtained with the Sivers function as determined in Ref. [27] by fitting SIDIS data.
We remark that while SIDIS data on pion and charged hadron production have been used for the fits, it is not so for the pp case, where all our results are genuine predictions. Their agreement with data seems to indicate that the role of possible factorization-breaking terms may be marginal for the processes and kinematical ranges considered here. We believe that this phenomenological information may presently be very useful, given the rapid development of this field of research. Our results indicate that our approach and the pQCD color gauge-link formalism cannot be distinguished on the basis of these processes. One should rather look at Sivers single spin asymmetries in DY processes, in prompt photon collisions. These reactions might also be useful in disentangling our approach from the collinear twist-three formalism.

In future, data at large $x_F(x_B)$ in pp collisions(SIDIS) would be very helpful in further constraining our parameterizations, testing our model more severely. Moreover, new kaon data challenge the phenomenology of SSAs, as they definitely involve the role of sea quark TMD distributions. This issue will be studied in Ref. [40].

Acknowledgments

We thank M. Anselmino and A. Prokudin for useful discussions and J. H. Lee for his help in drawing Figs. 2 and 3. We acknowledge support of the European Community - Research Infrastructure Activity under the FP6 “Structuring the European Research Area” program (HadronPhysics, contract number RI3-CT-2004-506078). M.B. acknowledge partial support by MIUR under cofinanziamento PRIN 2006.

[1] A. Airapetian et al. (HERMES), Phys. Rev. Lett. 94, 012002 (2005), hep-ex/0408013.
[2] V. Y. Alexakhin et al. (COMPASS), Phys. Rev. Lett. 94, 202002 (2005), hep-ex/0503002.
[3] E. S. Ageev et al. (COMPASS), Nucl. Phys. B 765, 31 (2007), hep-ex/0610068.
[4] D. L. Adams et al. (E704), Phys. Lett. B 264, 462 (1991).
[5] D. L. Adams et al. (E704), Phys. Rev. D 53, 4747 (1996).
[6] A. Bravar et al. (E704), Phys. Rev. Lett. 77, 2266 (1996).
[7] J. Adams et al. (STAR), Phys. Rev. Lett. 92, 171801 (2004), hep-ex/0310058.
[8] S. S. Adler et al. (PHENIX), Phys. Rev. Lett. 95, 202001 (2005), hep-ex/0507073.
[9] J. H. Lee and F. Videbaek (BRAHMS), AIP Conf. Proc. 915, 533 (2007).
[10] L. Nogach (STAR), AIP Conf. Proc. 915, 543 (2007), hep-ex/0612030.
[11] K. Abe et al. (Belle), Phys. Rev. Lett. 96, 232002 (2006), hep-ex/0507063.
[12] K. J. Heller (1997), Spin96 Proceedings, World Scientific, Singapore, p. 23.
[13] G. L. Kane, J. Pumplin, and W. Repko, Phys. Rev. Lett. 41, 1689 (1978).
[14] D. W. Sivers, Phys. Rev. D 41, 83 (1990).
[15] D. W. Sivers, Phys. Rev. D 43, 261 (1991).
[16] D. Boer and P. J. Mulders, Phys. Rev. D 57, 5780 (1998), hep-ph/9711485.
[17] J. C. Collins, Nucl. Phys. B 396, 161 (1993), hep-ph/9208213.
[18] X.-d. Ji, J.-P. Ma, and F. Yuan, Phys. Lett. B 597, 299 (2004), hep-ph/0405085.
[19] S. J. Brodsky, D. S. Hwang, and I. Schmidt, Phys. Lett. B 530, 99 (2002), hep-ph/0201296.
[20] J. C. Collins, Phys. Lett. B 536, 43 (2002), hep-ph/0204004.
[21] C. J. Bomhof, P. J. Mulders, and F. Pijlman, Eur. Phys. J. C 47, 147 (2006), hep-ph/0601171.
[22] W. Vogelsang and F. Yuan, Phys. Rev. D 76, 094013 (2007), arXiv:0708.4398 [hep-ph].
[23] J. Collins (2007), arXiv:0708.4410 [hep-ph].
[24] C. J. Bomhof and P. J. Mulders (2007), arXiv:0709.1390 [hep-ph].
[25] M. Anselmino, M. Boglione, and F. Murgia, Phys. Lett. B 362, 164 (1995), hep-ph/9502920.
[26] M. Anselmino et al., Phys. Rev. D 73, 014020 (2006), hep-ph/0509035.
[27] M. Anselmino et al., Phys. Rev. D 72, 094007 (2005), hep-ph/0507181.
[28] M. Anselmino et al., Phys. Rev. D 75, 054032 (2007), hep-ph/0701006.
[29] U. D’Alesio and F. Murgia, Phys. Rev. D 70, 074009 (2004), hep-ph/0408092.
[30] M. Anselmino et al., Phys. Rev. D 71, 074006 (2005), hep-ph/0501196.
[31] A. D. Martin, R. G. Roberts, W. J. Stirling, and R. S. Thorne, Phys. Lett. B 531, 216 (2002), hep-ph/0201127.
[32] S. Kretzer, Phys. Rev. D 62, 054001 (2000), hep-ph/0003177.
[33] J. Adams et al. (STAR), Phys. Rev. Lett. 97, 152302 (2006), nucl-ex/0602011.
[34] I. Arsene et al. (BRAHMS), Phys. Rev. Lett. 98, 252001 (2007), hep-ex/0701041.
[35] A. V. Efremov, K. Goke, S. Menzel, A. Metz, and P. Schweitzer, Phys. Lett. B 612, 233 (2005), hep-ph/0412353.
[36] A. Bacchetta, C. Bomhof, U. D’Alesio, P. J. Mulders, and F. Murgia, Phys. Rev. Lett. 99, 212002 (2007), hep-ph/0703153.
[37] J.-w. Qiu and G. Sterman, Phys. Rev. D 59, 014004 (1998), hep-ph/9806356.
[38] C. Kouvaris, J.-W. Qiu, W. Vogelsang, and F. Yuan, Phys. Rev. D 74, 114013 (2006), hep-ph/0609238.
[39] D. de Florian, R. Sassot, and M. Stratmann, Phys. Rev. D 75, 114010 (2007), hep-ph/0703242.
[40] M. Anselmino et al. (2008), in progress.