Constraints on Gluon Sivers Distribution from RHIC Results

M. Anselmino*, U. D’Alesio†, S. Melis§ and F. Murgia†

*Dipartimento di Fisica Teorica, Università di Torino and INFN, Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy
†Dipartimento di Fisica, Università di Cagliari and INFN, Sezione di Cagliari, C.P. 170, I-09042 Monserrato (CA), Italy

Abstract. We consider the recent RHIC data on the transverse single spin asymmetry (SSA) \( A_N \), measured in \( p^↑p \rightarrow \pi^0X \) processes at mid-rapidity by the PHENIX Collaboration. We analyze this experimental information within a hard scattering approach based on a generalized QCD factorization scheme, with unintegrated, transverse momentum dependent (TMD), parton distribution and fragmentation functions. In this kinematical region, only the gluon Sivers effect could give a large contribution to \( A_N \); its vanishing value is thus used to give approximate upper limits on the gluon Sivers function (GSF). Additional constraints from the Burkardt sum rule for the Sivers distributions are also discussed.

Keywords: single spin asymmetries, TMD distributions, Sivers effect

PACS: 12.38.Bx, 13.88.+e, 13.85.Ni, 14.70.Dj

FORMAL APPROACH

Transverse single spin asymmetries can originate, even with a short distance helicity conserving pQCD dynamics, from spin-\( k_⊥ \) correlations in the soft components of the hadronic process \( A^↑B \rightarrow CX \). According to the hard scattering approach to hadronic interactions developed in Refs. [1, 2, 3], based on the assumption of a generalized QCD factorization scheme which involves unintegrated TMD parton distribution and fragmentation functions, the general structure of the cross section for the polarized hadronic process \((A, S_A) + (B, S_B) \rightarrow C + X \) reads (see Ref. [3] for more details)

\[
E_C \frac{d\sigma^{(A, S_A) + (B, S_B) \rightarrow C + X}}{d^3 p_C} = \sum_{a,b,c,d,\{\lambda\}} \int \frac{dx_a dx_b dz}{16\pi^2 x_a x_b z^2 s} d^2 k_{\perp a} d^2 k_{\perp b} d^2 k_{\perp C} \delta(k_{\perp C} : \hat{p}_C) \times J(k_{\perp C}) \rho^{a/A, S_A}_{\lambda_a, \lambda'_a} \hat{f}_{a/A, S_A}(x_a, k_{\perp a}) \rho^{b/B, S_B}_{\lambda'_b, \lambda''_b} \hat{f}_{b/B, S_B}(x_b, k_{\perp b}) \times \hat{M}_{\lambda_c, \lambda_d, \lambda_a, \lambda_b} \hat{M}^*_{\lambda_c', \lambda_d', \lambda_a', \lambda_b'} \delta(\hat{s} + \hat{t} + \hat{u}) \hat{D}^{\lambda_c, \lambda''_c}_{\lambda_c', \lambda''_c'}(z, k_{\perp C}),
\]

where all parton intrinsic motions are fully taken into account, both in the soft, non perturbative components and in the hard, pQCD interactions.

The main features of Eq. (1) are the appearance of several spin and \( k_⊥ \) dependent distribution and fragmentation functions and the non-collinear partonic configuration

---

1 Talk delivered by U. D’Alesio at the “17th International Spin Physics Symposium”, SPIN2006, October 2-7, 2006, Kyoto, Japan.
which lead to many $k_\perp$ dependent phases. In Ref. [3] it was explicitly shown that the only sizeable contributions to the transverse single spin asymmetry $A_N(p^\uparrow p \rightarrow \pi X)$, in the kinematical region of large positive $x_F$ come from the Sivers [4] and, less importantly, from the Collins [5] mechanisms. Moreover, while the quark contribution is totally dominant at large, positive $x_F$ values (for polarized protons moving along the positive $Z$-axis), the gluon contribution may be sizeable in the mid-rapidity and negative $x_F$ regions.

Data in the mid-rapidity region are available from the E704 [6] and PHENIX [7] experiments; the region of negative values of $x_F$ has been covered by the STAR [8] and BRAHMS experiments [9]. In these kinematical regions $A_N(p^\uparrow p \rightarrow \pi X)$ is largely dominated by the Sivers effect [4], all other contributions being almost vanishing, and Eq. (1) gives [1]:

$$\frac{E_\pi d\sigma^\uparrow}{d^3p_\pi} - \frac{E_\pi d\sigma^\downarrow}{d^3p_\pi} \simeq \sum_{a,b,c,d} \int dx_a dx_b dz \frac{d^2k_{\perp a} d^2k_{\perp b} d^3k_{\perp \pi} \delta(k_{\perp \pi} \cdot \hat{p}_x)}{\pi x_a x_b z^2 s} J(k_{\perp \pi})$$

$$\times \Delta f_{a/p^\uparrow}(x_a, k_{\perp \pi}) \hat{f}_{b/p}(x_b, k_{\perp b}) \hat{s}^2 \frac{d\hat{\sigma}^{ab \rightarrow cd}}{dt}(x_a, x_b, \hat{s}, \hat{t}, \hat{u}) \delta(\hat{s} + \hat{t} + \hat{u}) \hat{D}_{\pi/c}(z, k_{\perp \pi}),$$

where

$$\Delta f_{a/p^\uparrow}(x_a, k_{\perp \pi}) \equiv f_{a/p^\uparrow}(x_a, k_{\perp \pi}) - f_{a/p^\downarrow}(x_a, k_{\perp \pi}) = \Delta^N f_{a/p^\uparrow}(x_a, k_{\perp \pi}) \cos \phi_a.$$  \hfill (3)

$\Delta^N f_{a/p^\uparrow}(x_a, k_{\perp \pi})$ [or $f_{a/p^\downarrow}(x_a, k_{\perp \pi})$] is referred to as the Sivers distribution function of parton $a$ inside a transversely polarized (along the $Y$-axis) proton (moving along the $Z$-axis). $\phi_a$ is the azimuthal angle of the intrinsic transverse momentum $k_{\perp \pi}$ of parton $a$.

The azimuthal phase factor $\cos \phi_a$ appearing in the numerator of $A_N$, Eqs. (2) and (3), plays a crucial role and deserves a comment. The only other term depending on $\phi_a$ in Eq. (2) is the partonic cross section, in particular via the corresponding Mandelstam variable $\hat{t}$. Therefore while at large positive $x_F$ ($t$-channel dominated) the integration over $\phi_a$ does not necessarily suppress $A_N$, for negative values of $x_F$ ($u$-channel dominated) one is roughly left with the $d^2 k_{\perp \pi} \cos \phi_a$ integration alone, which cancels the potentially large Sivers contribution. As a consequence, one cannot get significant information on the gluon Sivers distribution from the recent STAR and BRAHMS data at negative values of $x_F$. (Notice that at lower values of $\sqrt{s}$ the suppression induced by the $\cos \phi_a$ dependence would be less drastic.)

The same arguments do not apply to inclusive hadronic processes at mid-rapidity and moderately large $p_T$ values, for which data from PHENIX [7] are already available, for neutral pions and charged hadron production. For these processes, the gluon contribution is dominant and the Sivers effect can survive the phase integration. The possibility of accessing the gluon Sivers function has been also investigated in Refs. [10, 11, 12].

Indirect constraints on the GSF could also be obtained from a sum rule for the Sivers distribution recently derived by Burkardt [13]. The Burkardt Sum Rule (BSR) states that the total (integrated over $x$ and $k_{\perp}$) transverse momentum of all partons (quarks, antiquarks and gluons) in a transversely polarized proton must be zero,

$$\langle k_{\perp} \rangle = \sum_a \langle k_{\perp} \rangle_a = \int dx \int d^2 k_{\perp} k_{\perp} \sum_a \Delta \hat{f}_{a/p^\uparrow}(x, k_{\perp}) = 0.$$  \hfill (4)
In the following we shall simply check whether or not the proposed parameterizations of the Sivers functions are compatible with the BSR.

PHENOMENOLOGY

We consider the PHENIX data\cite{7} on $A_N$ for the $p^+ p \rightarrow \pi^0 X$ process at RHIC, at $\sqrt{s} = 200$ GeV, with $p_T$ ranging from 1.0 to 5.0 GeV/c and mid-rapidity values, $|\eta| < 0.35$. In this kinematical regime, at the lowest $p_T$ values, $x_{min}$ can be as small as 0.005. Therefore, partonic channels involving a gluon in the transversely polarized initial proton dominate over those involving a quark. This gluon dominance, together with the (almost) vanishing of all possible contributions to $A_N$ other than the Sivers effect, allows to put upper bounds on the GSF. Due to possible mixing with quark initiated contributions, the same is not true for the E704 data\cite{6} at lower energies and comparable rapidity and $p_T$ ranges.

In Ref.\cite{1} we have shown that reasonable fits to the SSA for the $p^+ p \rightarrow \pi X$ process at large positive $x_F$ can be obtained by using valence-like Sivers functions for $u$ and $d$ quarks, which turn out to have opposite signs. The use of valence-like $u$ and $d$ Sivers functions alone predicts an almost vanishing SSA in the mid-rapidity region, compatible with available data (see Fig. 1(left), for the PHENIX results). Their parameterizations\cite{1,14} are also compatible with the BSR, Eq. (4). Although a large gluon Sivers function would not modify the analysis of the SIDIS, E704 and STAR data at large positive $x_F$, it would strongly affect the description of the mid-rapidity PHENIX data.

In what follows (see Ref.\cite{15} for details) we therefore try to understand what is the maximum value of $|\Delta N_g/p^+ (x, k_{\perp})|/2\hat{f}_{g/p} (x, k_{\perp})$ allowed by the PHENIX data; our results are summarized in Fig. 1 (left panel for the SSA and right panel for the GSF):

• The thin, solid line in Fig. 1(left), results from computing $A_N$ using only the valence-like $u$ and $d$ Sivers functions of Ref.\cite{1}.
• The dot-dashed curve in Fig. 1(left) has been obtained by saturating (in magnitude) the GSF to the natural positivity bound [see Eq. (3)]

$$|\Delta N_g/p^+ (x, k_{\perp})| = -2\hat{f}_{g/p} (x, k_{\perp}) \quad (5)$$

The sea-quark Sivers functions are again assumed to vanish. This choice leads to a SSA definitely in contradiction with data and to a strong violation of the BSR.

• The thick, solid curve in Fig. 1(left) has been obtained still assuming that there is no sea-quark Sivers contribution, and looking for a parameterization of $\Delta N_g/p^+$ yielding values of $A_N$ falling, approximately, within one-sigma deviation below the lowest $p_T$ data. The corresponding $x$-dependent part of the GSF, normalized to its positivity bound, $|\Delta N_{f_g/p^+} (x)|/2\hat{f}_{g/p} (x)$, is shown as the solid curve in Fig. 1(right). It leads, within the $x$ range covered by the data, to a strong violation of the BSR.

• We finally consider the inclusion of all sea-quarks ($u_s, \bar{u}_s, d_s, \bar{d}_s, s, \bar{s}$) contributions by using a non-vanishing positive Sivers function which saturates the positivity bound [that is, $\Delta N_{q_s/p^+} (x, k_{\perp}) \equiv 2\hat{f}_{q_s/p} (x, k_{\perp})$]. These contributions could then cancel the negative contribution to $A_N$ of a possibly large GSF. We then look for the largest negative GSF which, together with a positive maximized sea-quark contribution, leads again to the
SSA represented by the thick, solid line of Fig. 1(left). This curve results now as the sum of the (maximized) sea and valence quark contribution (dotted curve) and that of the new GSF (dashed curve), which is plotted as the dashed curve in Fig. 1(right). It is the largest (overmaximized) gluon Sivers function compatible with PHENIX data. Within the $x$ range covered by the data, the (over)maximized sea-quark Sivers distributions give a positive contribution which strongly suppresses the negative contribution of the GSF, so that in this scenario the BSR is satisfied within a 10% level of accuracy.

Summarizing, our analysis shows that the PHENIX data on $A_N(p^+p \rightarrow \pi^0 X)$ allow to put significant quantitative bounds on the magnitude of the GSF. Similar conclusions have been recently reached by studying the Sivers effect in SIDIS off a deuteron target [16].

REFERENCES

1. U. D’Alesio and F. Murgia, Phys. Rev. D70, 074009 (2004).
2. M. Anselmino, M. Boglione, U. D’Alesio, E. Leader and F. Murgia, Phys. Rev. D71, 014002 (2005).
3. M. Anselmino, M. Boglione, U. D’Alesio, E. Leader, S. Melis and F. Murgia, Phys. Rev. D73, 014020 (2006).
4. D.W. Sivers, Phys. Rev. D41, 83 (1990); D43, 261 (1991).
5. J.C. Collins, Nucl. Phys. B396, 61 (1993).
6. D.L. Adams et al. (FNAL-E704 Collaboration), Phys. Rev. D53, 4747 (1996).
7. S.S. Adler et al. (PHENIX Collaboration), Phys. Rev. Lett. 95, 202001 (2005).
8. C.A. Gagliardi (for the STAR Collaboration), hep-ex/0607003.
9. F. Videbaek (for the BRAHMS Collaboration), nucl-ex/0601008.
10. M. Anselmino, M. Boglione, U. D’Alesio, E. Leader and F. Murgia, Phys. Rev. D70, 074025 (2004).
11. D. Boer and W. Vogelsang, Phys. Rev. D69, 094025 (2004).
12. I. Schmidt, J. Soffer and J.J. Yang, Phys. Lett. B612, 258 (2005).
13. M. Burkardt, Phys. Rev. D69, 057501 (2004); D69, 091501 (2004).
14. M. Anselmino, M. Boglione, U. D’Alesio, A. Kotzinian, F. Murgia and A. Prokudin, Phys. Rev. D71, 074006 (2005); D72, 094007 (2005).
15. M. Anselmino, U. D’Alesio, S. Melis and F. Murgia, Phys. Rev. D74, 094011 (2006).
16. S.J. Brodsky and S. Gardner, hep-ph/0608219.