HELCITY FORMALISM AND SPIN ASYMMETRIES IN HADRONIC PROCESSES*

M. ANSELMINO, a M. BOGLIONE, a U. D’ALESIO, b E. LEADER, c S. MELIS, b F. MURGIA b

a Dipartimento di Fisica Teorica, Università di Torino and INFN, Sezione di Torino, V. P. Giuria 1, 10125 Torino, Italy
b Dipartimento di Fisica, Università di Cagliari and INFN, Sezione di Cagliari, C.P. 170, 09042 Monserrato (CA), Italy
c Imperial College London, Prince Consort Road, London SW7 2BW, U.K.

We present a generalized QCD factorization scheme for the high energy inclusive polarized process, \((A, S_A) + (B, S_B) \rightarrow C + X\), including all intrinsic partonic motions. This introduces many non-trivial azimuthal phases and several new spin and \(k_{\perp}\) dependent soft functions. The formal expressions for single and double spin asymmetries are discussed. Numerical results for \(A_N(p^\uparrow p \rightarrow \pi X)\) are presented.

1. Introduction and formalism

Recently\(^1\),\(^2\),\(^3\) we have developed an approach to study (un)polarized cross sections for inclusive particle production in hadronic collisions at high energy and moderately large \(p_T\) and semi-inclusive deeply inelastic scattering (SIDIS).\(^4\) Assuming that factorization is preserved, this approach generalizes the usual Leading Order (LO), collinear perturbative QCD formalism by including spin and intrinsic transverse momentum, \(k_{\perp}\), effects both in the soft contributions (parton distribution (PDF) and fragmentation (FF) functions) and in the elementary processes. Helicity formalism is adopted and exact non collinear kinematics is fully taken into account. Unpolarized cross sections and transverse single spin asymmetries (SSA), with emphasis on the Sivers\(^5\) and Collins\(^6\) effects, were already discussed in Refs. 1, 2. Here we report on the most complete case of unpolarized cross sections and single and double spin asymmetries for the process \((A, S_A) + (B, S_B) \rightarrow C + X\).\(^3\) The cross section for this process can be given as a LO (factorized) convolution of all possible hard elementary QCD processes, \(ab \rightarrow cd\), with soft,

* Talk delivered by F. Murgia at the “International Workshop on Transverse Polarisation Phenomena in Hard Processes”, TRANSVERSITY 2005, September 7-10, 2005, Como, Italy.
leading twist, spin and $k_\perp$ dependent PDF and FF (see Eq. (8) of Ref. 2):

$$\frac{E_C \, d\sigma^{(A,S_A) + (B,S_B) \rightarrow C + X}}{d^3p_C} =$$

$$\sum_{a,b,c,d,\{\lambda\}} \int \frac{dx_a \, dx_b \, dz}{16\pi^2 x_a x_b z^2 s} \, d^2k_{\perp a} \, d^2k_{\perp b} \, d^3k_{\perp C} \, \delta(k_{\perp C} \cdot \hat{p}_C) \, J(k_{\perp C})$$

$$\times \rho_{\lambda_a,\lambda'_a}^{a/A,S_A} \hat{f}_{a/A,S_A}(x_a, k_{\perp a}) \, \rho_{\lambda_b,\lambda'_b}^{b/B,S_B} \hat{f}_{b/B,S_B}(x_b, k_{\perp b})$$

$$\times \hat{M}_{\lambda_a,\lambda'_a;\lambda_b,\lambda'_b} \hat{M}^*_{\lambda'_a,\lambda'_b;\lambda_a,\lambda_b} \delta(\hat{s} + \hat{t} + \hat{u}) \, \hat{D}_{\lambda_a,\lambda'_a}(z, k_{\perp C}) ,$$

where $A, B$ are initial, spin 1/2 hadrons in pure spin states $S_A$ and $S_B$; $C$ is the unpolarized observed hadron; $J(k_{\perp C})$ is a phase-space kinematical factor; $\rho_{\lambda_a,\lambda'_a}^{a/A,S_A} \hat{f}_{a/A,S_A}(x_a, k_{\perp a})$ contains all information on parton $a$ and its polarization state, through its helicity density matrix and the spin and $k_\perp$ dependent PDF (analogously for parton $b$); $\hat{M}_{\lambda_a,\lambda'_a;\lambda_b,\lambda'_b}$ are the LO helicity amplitudes for the elementary process $a b \rightarrow c d$; $\hat{D}_{\lambda_a,\lambda'_a}(z, k_{\perp C})$ is a product of soft helicity fragmentation amplitudes for the $c \rightarrow C + X$ process.

The remaining notation, in particular for kinematical variables, should be obvious. Let us stress here that a formal proof of factorization for the $AB \rightarrow C + X$ process in the non collinear case is still missing; universality and evolution properties of the new spin and $k_\perp$ dependent PDF and FF are not established or well known yet; a consistent account of all higher-twist effects is still missing. In the sequel, we will discuss in more detail the basic ingredients of Eq. (1).

2. Spin and $k_\perp$ dependent PDF and FF (leading twist)

The most general expression for the helicity density matrix of quark $a$ inside hadron $A$ with polarization state $S_A$ is

$$\rho_{\lambda_a,\lambda'_a}^{a/A,S_A} = \frac{1}{2} \left( \frac{1 + P_j^a}{P_j^a} - \frac{i P_j^a}{P_j^a} \right)_{S_A} = \frac{1}{2} \left( \frac{1 + P_j^a}{P_j^a} e^{i\phi_{a,n}} - i P_j^a \right)_{S_A} ,$$

where $P_j^a$ is the $j$-th component of the quark polarization vector in its helicity frame. Introducing soft, nonperturbative helicity amplitudes for the inclusive process $A \rightarrow a + X$, $\hat{F}_{\lambda_a,\lambda'_a;\lambda_A}$, we can write

$$\rho_{\lambda_a,\lambda'_a}^{a/A,S_A} \hat{f}_{a/A,S_A}(x_a, k_{\perp a}) = \sum_{\lambda_A,\lambda'_A} \rho_{\lambda_a,\lambda'_a;\lambda_A}^{A/S_A} \int_{X_A,\lambda_X_A} \hat{F}_{\lambda_a,\lambda'_a;\lambda_A} \hat{F}^{\lambda_a,\lambda'_a;\lambda_A}$$

$$\equiv \sum_{\lambda_A,\lambda'_A} \rho_{\lambda_a,\lambda'_a;\lambda_A}^{A/S_A} \hat{F}_{\lambda_a,\lambda'_a;\lambda_A} ,$$

(3)
where \( \rho^{A,S}_{\lambda_A,\lambda'_A} \) is in turn the helicity density matrix of hadron \( A \)

\[
\rho^{A,S}_{\lambda_A,\lambda'_A} = \frac{1}{2} \left( 1 + P^A_P \frac{P^A_{\perp}}{P^A_X} i P^A_Y - P^A_Z \right) = \frac{1}{2} \left( 1 + P^A_P \frac{P^A_{\perp}}{P^A_X} e^{-i\phi_{SA}} - P^A_L \right),
\]

and \( P^A_P \) is the \( J \)-th component of the hadron polarization vector in its helicity rest frame. The definition of \( \tilde{F}^{\lambda_A,\lambda'_A}_{A,A} \) in terms of the helicity amplitudes \( \tilde{F}^{\lambda_A,\lambda'_A}_{A,A} \) can be deduced from Eq. (3). One can see that, due to rotational invariance and parity properties, the following relations hold:\(^7\)

\[
\tilde{F}^{\lambda_A,\lambda'_A}_{A,A} = \left( \tilde{F}^{\lambda_A,\lambda'_A}_{A,A} \right)^*;
\]

\[
\tilde{F}^{\lambda_A,\lambda'_A}_{A,A}(x_a, k_{\perp}) = \tilde{F}^{\lambda_A,\lambda'_A}_{A,A}(x_a, k_{\perp}) \exp \left[ i (\lambda_A - \lambda'_A) \phi_a \right],
\]

\[
F^{-\lambda_A,-\lambda'_A} = (-1)^{2(S_A-S_a)} (-1)^{(\lambda_A-\lambda_a)} \tilde{F}^{\lambda_A,\lambda'_A}_{A,A}.
\]

Using Eq. (5) one can easily associate the eight functions

\[
F^{++}, \ F^{++}, \ F^{-+}, \ F^{-+}, \ F^{+-}, \ F^{+-}, \ F^{++}, \ F^{+-},
\]

to the eight leading twist, spin and \( k_{\perp} \) dependent PDF: \( F^{++} \pm F^{+-} \) are respectively related to the unpolarized and longitudinally polarized PDF, \( f_a/A \) and \( \Delta_L f_a/A \); \( F^{++} \pm F^{+-} \) are related with the two possible contributions to the transversity PDF; \( F^{++} \pm F^{+-} \) are respectively related to the probability of finding an unpolarized (longitudinally polarized) parton inside a transversely polarized hadron, the Sivers function;\(^5\) \( \Delta^N f_a/A \) (the \( g_{1T} \) PDF); \( F^{++} \pm F^{+-} \) are related to the probability of finding a transversely polarized parton respectively inside an unpolarized hadron (the so-called Boer-Mulders function);\(^8\) \( \Delta^N f_a/A \) and inside a longitudinally polarized hadron, the \( h_{1L} \) PDF. More precisely, the relations are the following:\(^3\)

\[
\hat{f}_{a/A} = \hat{f}_{a/A,S_L} = (F^{++} + F^{+-})
\]

\[
\hat{f}_{a/A,S_T} = \hat{f}_{a/A} + \frac{1}{2} \Delta \hat{f}_{a/S_T} = (F^{++} + F^{+-}) + 2 \text{Im} F^{++} \sin(\phi_{SA} - \phi_a)
\]

\[
P^a_x \hat{f}_{a/A,S_L} = \Delta \hat{f}_{s_x/S_L} = 2 \text{Re} F^{++}
\]

\[
P^a_y \hat{f}_{a/A,S_T} = \Delta \hat{f}_{s_y/S_T} = (F^{++} + F^{+-}) \cos(\phi_{SA} - \phi_a)
\]

\[
P^a_y \hat{f}_{a/A,S_L} = -2 \text{Im} F^{++}
\]

\[
P^a_y \hat{f}_{a/A,S_T} = -2 \text{Im} F^{++} + (F^{++} - F^{-+}) \sin(\phi_{SA} - \phi_a)
\]

\[
P^a_x \hat{f}_{a/A,S_L} = \Delta \hat{f}_{s_x/S_L} = (F^{++} - F^{-+})
\]

\[
P^a_x \hat{f}_{a/A,S_T} = 2 \text{Re} F^{++} \cos(\phi_{SA} - \phi_a),
\]
where $\phi_{S_A}$ and $\phi_a$ are respectively the azimuthal angle of the hadron spin polarization vector and of the parton $a$ transverse momentum, $k_{\perp a}$, in the hadronic c.m. frame. We have also used the notation $\Delta f_{s_i/S_J} = \hat{f}_{s_i}/S_J - \hat{f}_{-s_i}/S_J$. More details and relations with the notation of the Amsterdam group can be found in Ref. 3. Since the helicity density matrix for a massless gluon can be formally written similarly to that of a quark, 

$$\rho^{\lambda_a,\lambda_b}_{S_A} = \frac{1}{2} \left( \frac{1 + P_g^2}{T_1^g + iT_2^g} - P_g^{\circ} e^{-2i\phi} \right) = \frac{1}{2} \left( \frac{1 + P_g^{\circ} e^{-2i\phi}}{1 - P_g^{\circ} e^{-2i\phi}} \right),$$

where $T_1^g$ and $T_2^g$ are related to the degree of linear polarization of the gluon, relations analogous to those shown for quarks hold also for gluons. 

Analogously, introducing soft nonperturbative helicity fragmentation amplitudes for the process $c \rightarrow C + X$, and limiting to the case of unpolarized hadron $C$, properties similar to those shown for PDF in Eq. (5) hold. From these relations one can easily see that, for each parton, only two independent FF survive: the usual unpolarized FF; the well known Collins function for (linearly) polarized gluons, $\Delta N^{+g}_{C/\perp}(z,k_{\perp C})$, and a Collins-like function for (linearly) polarized gluons, $\Delta N^{+g}_{C/T}(z,k_{\perp C})$. 

3. Helicity amplitudes for the elementary process $ab \rightarrow cd$

Since intrinsic parton motions are fully taken into account in our approach, all soft processes, $A(B) \rightarrow a(b) + X$ and $c \rightarrow C + X$, and the elementary process $ab \rightarrow cd$ take place out of the hadronic production plane (the $XZ_{cm}$ plane). The relation between the elementary helicity amplitudes given in the hadronic c.m. frame, $\hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}$, and those given in the canonical partonic c.m. frame (no azimuthal phases), $\hat{M}^{i}\lambda_c,\lambda_d;\lambda_a,\lambda_b$, has been given in Ref. 2. In summary, 

$$\hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b} = \hat{M}^{i}\lambda_c,\lambda_d;\lambda_a,\lambda_b,$$

$$\times e^{-i[(\lambda_a - \lambda_b)\xi_a - (\lambda_a - \lambda_b)\xi_b]} e^{-i[(\lambda_d - \lambda_a)\xi_d - (\lambda_d - \lambda_a)\xi_c]} e^{i(\lambda_a - \lambda_b)\phi_a},$$

where $\xi_j$, $\tilde{\xi}_j$ ($j = a, b, c, d$), $\phi''$ are phases which depend on the initial kinematical configuration in the hadronic c.m. frame. Parity properties for the canonical helicity amplitudes $\hat{M}^{0}$ are well known, and so are the relations between a given canonical helicity amplitude and those obtained by exchanging the two initial (final) partons. For massless partons there are only three independent helicity amplitudes, $\hat{M}^{0}_{++} = \hat{M}^{0}_{-+} = \hat{M}^{0}_{++} = \hat{M}^{0}_{-+} = \hat{M}^{0}_{++} = \hat{M}^{0}_{-+} = \hat{M}^{0}_{++} = \hat{M}^{0}_{-+}$, where $\varphi_j$ ($j = 1, 2, 3$) are the corresponding phases given in Eq. (9). At LO there are eight
elementary contributions $ab \to cd$ which must be considered separately, since they involve different combinations of PDF and FF in Eq. (1): $q_a q_b \to q_c q_d, g_a g_b \to g_c g_d, q g \to q g, g g \to g g, q q \to g g, g_a q_b \to q g, q q \to g g, g_a g_b \to q q$, $q g \to g c, g d$ (the first contribution includes all quark and antiquark cases).

4. Kernels for the process $A(S_A) + B(S_B) \to C + X$

In the previous sections we have presented all the ingredients required for the evaluation of the convolution integral for the double polarized cross section, Eq. (1). We can then derive the expression of all the physically relevant single and double spin asymmetries for the process $A(S_A) + B(S_B) \to C + X$, and, with appropriate modifications, for other inclusive production processes. Defining kernels as:

$$\Sigma(S_A, S_B)^{ab \to cd} = \sum_{\{\lambda\}} \rho_{a,b} \lambda_a \lambda_b \hat{f}_{a/b} (x_a, k_{\perp}) \rho_{b,c} \lambda_b \lambda_c \hat{f}_{b/c} (x_b, k_{\perp}^b) \times \hat{M}_{\lambda_a; \lambda_b, \xi_a, \xi_b} \hat{M}_{\lambda_b; \lambda_a, \xi_b, \xi_a} \hat{M}_{\lambda_c, \lambda_c; \xi_b, \xi_a} \hat{M}_{\lambda_c, \lambda_c; \xi_b, \xi_a} \hat{M}_{\lambda_c, \lambda_c; \xi_b, \xi_a} \hat{M}_{\lambda_c, \lambda_c; \xi_b, \xi_a}$$

we present here, as an example, the kernel for the $q_a q_b \to q_c q_d$ process:

$$\Sigma(S_A, S_B)^{q_a q_b \to q_c q_d} = \frac{1}{2} \hat{D}_{C/c}(z, k_{\perp}) \hat{f}_{a/S_A} (x_a, k_{\perp}) \hat{f}_{b/S_B} (x_b, k_{\perp})$$

$$\times \left\{ \left( |\hat{M}_1|_1^2 + |\hat{M}_2|_2^2 + |\hat{M}_3|_3^2 \right) + P_x^a P_x^b \left( |\hat{M}_1|^2_1 - |\hat{M}_2|^2_2 - |\hat{M}_3|^2_3 \right) + P_y^a P_y^b \right\}$$

$$\times \left\{ \hat{M}_1^0 \hat{M}_2^0 \left[ (P_x^a P_x^b + P_y^a P_y^b) \cos(\phi_3 - \phi_2) - (P_x^a P_y^b - P_y^a P_x^b) \sin(\phi_3 - \phi_2) \right] + \frac{1}{2} \Delta_N \hat{D}_{C/c}(z, k_{\perp}) \hat{f}_{a/S_A} (x_a, k_{\perp}) \hat{f}_{b/S_B} (x_b, k_{\perp}) \right\}$$

$$+ \hat{M}_1^0 \hat{M}_2^0 \left[ P_x^a \sin(\phi_1 - \phi_2 + \phi_C^H) - P_y^a \cos(\phi_1 - \phi_2 + \phi_C^H) \right]$$

$$\times \hat{M}_3^0 \hat{M}_3^0 \left[ P_y^b \sin(\phi_1 - \phi_3 + \phi_C^H) - P_y^b \cos(\phi_1 - \phi_3 + \phi_C^H) \right],$$

where $\phi_C^H$ is the azimuthal angle of hadron $C$ three-momentum in the helicity frame of parton $c$. A more complete list of kernels for all partonic contributions and more details can be found in Ref. 3.

5. Cross section and SSA for the process $pp \to \pi + X$

The formalism described in the previous sections is very general and can be applied to the calculation of unpolarized cross sections, single and double
spin asymmetries for inclusive particle production in hadronic collisions. As an explicit example, we now discuss the transverse single spin asymmetry for inclusive pion production in proton-proton collisions, \( A_N(pp \rightarrow \pi^+X) = (d\sigma^+ - d\sigma^-)/(d\sigma^+ + d\sigma^-) \), where \( d\sigma^\uparrow \) stands for the cross section of Eq. (1) with \( S_A = \uparrow, S_B = 0 \). We present, limiting ourselves to the case \( q_aq_b \rightarrow q_cq_d \), the combination of kernels appearing in the numerator and denominator of the SSA (dependence on \( x_{a,b}, k_{a,b} \) in PDF and on \( z, k_{\perp C} \) in FF is understood):

\[
\frac{1}{2} \Delta \hat{f}_{a/A^\uparrow} \hat{f}_{b/B} \left[ |\hat{M}_1^0|^2 + |\hat{M}_2^0|^2 + |\hat{M}_3^0|^2 \right] \hat{D}_{C/c} \\
+ 2 \left[ \Delta^- \hat{f}_{s_{a/\uparrow}} (\varphi_3 - \varphi_2) - \Delta \hat{f}_{s_{a/\uparrow}} \sin(\varphi_3 - \varphi_2) \right] \Delta \hat{f}_{s_{b/B}} \hat{M}_2^0 \hat{M}_3^0 \hat{D}_{C/c} \\
+ \left[ \Delta^- \hat{f}_{s_{a/\uparrow}} \cos(\varphi_1 - \varphi_2 + \phi_C^H) - \Delta \hat{f}_{s_{a/\uparrow}} \sin(\varphi_1 - \varphi_2 + \phi_C^H) \right] \\
\times \hat{f}_{b/B} \hat{M}_1^0 \hat{M}_3^0 \Delta^N \hat{D}_{C/c^\uparrow} \\
+ \frac{1}{2} \Delta \hat{f}_{a/A^\uparrow} \Delta \hat{f}_{s_{s_{b/B}}} \cos(\varphi_1 - \varphi_3 + \phi_C^H) \hat{M}_1^0 \hat{M}_3^0 \Delta^N \hat{D}_{C/c^\uparrow},
\]

\[
\frac{1}{2} \Delta \hat{f}_{a/A^\uparrow} \hat{f}_{b/B} \left[ |\hat{M}_1^0|^2 + |\hat{M}_2^0|^2 + |\hat{M}_3^0|^2 \right] \hat{D}_{C/c} \\
+ 2 \Delta \hat{f}_{s_{a/\uparrow}} \hat{f}_{s_{b/B}} \cos(\varphi_3 - \varphi_2) \hat{M}_2^0 \hat{M}_3^0 \hat{D}_{C/c} \\
+ \left[ \hat{f}_{a/A} \Delta \hat{f}_{s_{s_{b/B}}} \cos(\varphi_1 - \varphi_3 + \phi_C^H) \hat{M}_1^0 \hat{M}_3^0 \\
+ \Delta \hat{f}_{s_{a/\uparrow}} \hat{f}_{b/B} \cos(\varphi_1 - \varphi_2 + \phi_C^H) \hat{M}_1^0 \hat{M}_2^0 \right] \Delta^N \hat{D}_{C/c^\uparrow}.
\]

There are four terms contributing to the numerator of the SSA, Eq.(12): the Sivers contribution (2nd line); the transversity\( \otimes \)Boer-Mulders contribution (3rd line); the transversity\( \otimes \)Collins contribution (4th and 5th lines); the Sivers\( \otimes \)Boer-Mulders\( \otimes \)Collins contribution (last line). Similarly, there are three terms contributing to the denominator of the SSA, Eq.(13): the usual term involving only unpolarized quantities (2nd line); the Boer-Mulders\( \otimes \)Boer-Mulders contribution (3rd line); the Boer-Mulders\( \otimes \)Collins contribution (last two lines). Similar considerations apply to all other partonic contributions. Whenever gluons are involved, functions analogous to the transversity, Boer-Mulders, Collins functions for quarks, but describing linearly polarized gluons appear, see Ref. 3. Let us now present some numerical results on unpolarized cross sections and SSA for the \( pp \rightarrow \pi + X \) process. Our aim here is basically that of showing the (maximized) possible
contributions of all terms appearing in Eqs. (12), (13), which involve several unknown or poorly known functions. To this end we saturate known positivity bounds for the Collins and Sivers functions, replacing all other $k_\perp$ dependent polarized PDF with the corresponding unpolarized ones (keeping trace of azimuthal phases); we sum all possible contributions with the same sign; for all PDF we assume an $x$ and flavour independent gaussian shape vs. $k_\perp$, taking $\langle k_\perp \rangle = 0.8$ GeV/c, while for FF $\langle k_{\perp,C}(z) \rangle$ is taken as in Ref. 1; for the unpolarized, $k_\perp$-integrated PDF and FF, we take respectively the MRST01 and the KKP sets. See Ref. 1 for all other details on numerical calculations. In Fig. 1 (left) we show the maximized contributions to the unpolarized differential cross section for the $pp \rightarrow \pi^0 + X$ process for the kinematical regime of the E704 data on SSA. The usual contribution clearly dominates, the other two being suppressed by the azimuthal phases. In Fig. 1 (right) we show the contributions to SSA, $A_N(p^+p \rightarrow \pi^+ + X)$, in the same kinematical regime (including the negative $x_F$ region). Full $k_\perp$ treatment and azimuthal phases considerably suppress the Collins effect; the same is not true for Sivers contribution. In Fig. 2 (left) we plot $A_N(p^+p \rightarrow \pi^0 + X)$ for the kinematical regime of the STAR experiment at RHIC. In Fig. 2 (right) we show $A_N(p^+\bar{p} \rightarrow \pi^+ + X)$, in the kinematical regime of the proposed PAX experiment at GSI. These last results are particularly interesting for the gluon Sivers function. Many other
Figure 2. (Maximized) contributions to: (left) $A_N(p^+p \rightarrow \pi^0 + X)$ for STAR kinematics (at $x_F < 0$ all contributions are vanishingly small); (right) $A_N(p^\uparrow\bar{p} \rightarrow \pi^+ + X)$ for PAX kinematics; lines are as in Fig 1.

applications of our formalism are possible and some of them are under investigation, like the study of the double longitudinal asymmetry, $A_{LL}$; for pion production; the transverse $\Lambda$ polarization in unpolarized hadronic reactions; the study of the Collins effect in polarized SIDIS; the Drell-Yan process; inclusive particle production in pion-proton collisions and so on. Hopefully, this thorough phenomenological analysis of present and forthcoming experimental results on spin asymmetries will help in clarifying the role of spin effects in high energy hadronic reactions.

References
1. U. D’Alesio and F. Murgia, Phys. Rev. D70 (2004) 074009
2. M. Anselmino, M. Boglione, U. D’Alesio, E. Leader and F. Murgia, Phys. Rev. D71 (2005) 014002
3. M. Anselmino, M. Boglione, U. D’Alesio, E. Leader, S. Melis and F. Murgia, hep-ph/0509035
4. M. Anselmino, M. Boglione, U. D’Alesio, A. Kotzinian, F. Murgia and A. Prokudin, Phys. Rev. D71 (2005) 074006; Phys. Rev. D72 (2005) 094007
5. D. Sivers, Phys. Rev. D41 (1990) 83; D43 (1991) 261
6. J.C. Collins, Nucl. Phys. B396 (1993) 161
7. E. Leader, Spin in Particle Physics, Cambridge University Press, 2001
8. D. Boer and P.J. Mulders, Phys. Rev. D57 (1998) 5780
9. A.D. Martin, R.G. Roberts, W.J. Stirling and R.S. Thorne, Phys. Lett. B531 (2002) 216
10. B.A. Kniehl, G. Kramer, and B. Pötter, Nucl. Phys. B582 (2000) 514