Collins Effect in SIDIS and in $e^+e^-$ Annihilation

A. V. Efremov*, K. Goeke† and P. Schweitzer‡

*Joint Institute for Nuclear Research, Dubna, 141980 Russia. E-mail: efremov@theor.jinr.ru
†Institut für Theoretische Physik II, Ruhr-Universität Bochum, Germany

Abstract. We review the present understanding of the nucleon transversity distribution and Collins fragmentation function, based on Ref.[1], and discuss how Drell-Yan experiments will improve it.

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1. Introduction. The chirally odd transversity distribution function $h_{a1}(x)$ cannot be extracted from data on semi-inclusive deep inelastic scattering (SIDIS) alone. It enters the expression for the Collins single spin asymmetry (SSA) in SIDIS together with the chirally odd and equally unknown Collins fragmentation function [2] (FF) $H_{a1}(z)$

$$A_{UT}^{\sin(\phi + \phi_S)} = 2 \sum_a e_a^2 h_{a1}(x) B_G H_{a1}(z) \sum_a e_a^2 x f_{a1}(x) D_{a1}(z)$$

(1)

However, $H_{a1}(z)$ is accessible in $e^+e^- \rightarrow \bar{q}q \rightarrow 2\text{jets}$ where the quark transverse spin correlation induces a specific azimuthal correlation of two hadrons in opposite jets [5]

$$d\sigma = d\sigma_{\text{unp}} \left[ 1 + \cos(2\phi_1) \frac{\sin^2 \theta}{1 + \cos^2 \theta} C_G \times \sum_a e_a^2 H_{a1}^2(z) D_{a1}^2(z) \right]$$

(2)

where $\phi_1$ is azimuthal angle of hadron 1 around z-axis along hadron 2, and $\theta$ is electron polar angle. Also here we assume the Gauss model and $C_G(z_1, z_2) = \frac{16}{\pi} z_1 z_2 / (z_1^2 + z_2^2)$.

First experimental indications for the Collins effect were obtained from studies of preliminary SMC data on SIDIS [6] and DELPHI data on charged hadron production in $e^+e^-$ annihilations at the $Z^0$-pole [7]. More recently HERMES reported data on the Collins (SSA) in SIDIS from proton target [8, 9] giving the first unambiguous evidence that $H_{a1}^q$ and $h_{a1}^q(x)$ are non-zero, while in the COMPASS experiment [10] the Collins effect from a deuteron target was found compatible with zero within error bars. Finally, last year the BELLE collaboration presented data on sizeable azimuthal correlation in $e^+e^-$ annihilations at a center of mass energy of 60MeV below the $\Upsilon$-resonance [11, 12].

The question which arises is: Are all these data from different SIDIS and $e^+e^-$ experiments compatible, i.e. due to the same effect, namely the Collins effect?

1 We assume a factorized Gaussian dependence on parton and hadron transverse momenta [3] with $B_G(z) = (1 + z^2 \langle p_T^2 \rangle / \langle K_T^2 \rangle)^{-1/2}$ and define $H_{a1}^q(z) \equiv H_{a1}^{(1/2)q}(z) = \int d^2K_T \frac{K_T^2}{2\pi} H_{a1}^q(z, K_T)$ for brevity. The Gaussian widths are assumed flavor and $x$- or $z$-independent. We neglect throughout soft factors [4].
In order to answer this question we extract $H_1^a$ from HERMES [9] and BELLE [11, 12] data, and compare the obtained ratios $H_1^a/D_1^a$ to each other and to other experiments. Such “analyzing powers” might be expected to be weakly scale-dependent, as the experience with other spin observables [13, 14] indicates.

2. Collins effect in SIDIS. In order to extract information on Collins FF from SIDIS a model for the unknown $h_1^a(x)$ is needed. We use predictions from chiral quark-soliton model [15] which provides a good description of unpolarized and helicity distribution [16]. On the basis of Eq. (1), the assumptions in Footnote 1, and the parameterizations [17, 18] for $f_1^a(x)$ and $D_1^a(z)$ at $Q^2 = 2.5\,\text{GeV}^2$, we obtain from the HERMES data [9]:

$$\langle 2B_G H_1^{\text{fav}} \rangle \approx (3.5 \pm 0.8) \, , \quad \langle 2B_G H_1^{\text{unf}} \rangle = - (3.8 \pm 0.7) \, .$$

Here “fav” (“unf”) means favored $u \rightarrow \pi^+, d \rightarrow \pi^-$, etc. (unfavored $u \rightarrow \pi^-$, etc.) fragmentation, and $\langle \ldots \rangle$ denotes average over $z$ within the HERMES cuts $0.2 \leq z \leq 0.7$.

Thus, the favored and unfavored Collins FFs appear to be of similar magnitude and opposite sign. The string fragmentation picture [19] and Schäfer-Teryaev sum rule [20] provide a qualitative understanding of this behavior. The important role of unfavored FF becomes more evident by considering the analyzing powers

$$\left| \frac{\langle 2B_G H_1^{\text{fav}} \rangle}{\langle D_1^{\text{fav}} \rangle} \right|_{\text{HERMES}} = (7.2 \pm 1.7)\% \, , \quad \left| \frac{\langle 2B_G H_1^{\text{unf}} \rangle}{\langle D_1^{\text{unf}} \rangle} \right|_{\text{HERMES}} = - (14.2 \pm 2.7)\% \, .$$

Fit (3) describes satisfactorily the HERMES proton target data [9] on the Collins SSA (see Figs. 1a, b) and is in agreement with COMPASS deuteron data [10] (Figs. 1c, d).

3. Collins effect in $e^+ e^-$. The specific $\cos 2\phi$ dependence of the cross section (2) could arise also from hard gluon radiation or detector acceptance effects. These effects, being flavor independent, cancel out from the double ratio of $A_1^U$, where both hadrons $h_1 h_2$ are pions of unlike sign, to $A_1^L$, where $h_1 h_2$ are pions of like sign, i.e.

$$\frac{A_1^U}{A_1^L} \approx 1 + \cos(2\phi_1)P_1(z_1, z_2) \, .$$
In order to describe the BELLE data \cite{11} we have chosen the Ansatz and obtained the best fit
\[ H_1^{a}(z) = C_a z D_0^a(z), \quad C_{\text{fav}} = 0.15, \quad C_{\text{unf}} = -0.45, \] (6)
shown in Fig. 2 with 1-\(\sigma\) error band (the errors are correlated). Other Ansätze gave less satisfactory fits.

Notice that azimuthal observables in \(e^+e^-\) annihilation are bilinear in \(H_1^{a}\) and therefore symmetric with respect to the exchange of the signs of \(H_1^{\text{fav}}\) and \(H_1^{\text{unf}}\). Thus in our Ansatz \(P_1(z_1,z_2)\) is symmetric with respect to the exchange \(\text{sign}(C_{\text{fav}}) \leftrightarrow \text{sign}(C_{\text{unf}})\). (And not with respect to \(C_{\text{fav}} \leftrightarrow C_{\text{unf}}\) as incorrectly remarked in \cite{1}.)

The BELLE data \cite{11} unambiguously indicate that \(H_1^{\text{fav}}\) and \(H_1^{\text{unf}}\) have opposite signs, but they cannot tell us which is positive and which is negative. The definite signs in (6) and Fig. 2 are dictated by SIDIS data \cite{9} (and our model \cite{15} with \(h^U(x) > 0\), see Sect.2).

In Fig.3a-d the BELLE data \cite{11} are compared to the theoretical result for \(P_1(z_1,z_2)\) obtained on the basis of the best fit shown in Fig. 2b.

Most interesting recent news are the preliminary BELLE data \cite{12} for the ratio of azimuthal asymmetries of unlike sign pion pairs, \(A_1^U\), to all charged pion pairs, \(A_1^C\). The new observable \(P_C\) is defined analogously to \(P_1\) in Eq. (5) as \(A_1^U / A_1^C \approx (1 + \cos(2\phi) P_C)\).

The fit (6) ideally describes the new experimental points (see Figs. 3a-h)!

4. BELLE vs. HERMES. In order to compare Collins effect in SIDIS at HERMES \cite{8, 9} and in \(e^+e^-\) annihilation at BELLE \cite{11} we consider the ratios \(H_1^{\text{fav}} / D_0^a\) which might be less scale dependent. The BELLE fit in Fig. 2 yields in the HERMES \(z\)-range:
\[
\left| \frac{\langle 2H_1^{\text{fav}} \rangle}{\langle D_0^{\text{fav}} \rangle} \right|_{\text{BELLE}} = (5.3 \cdots 20.4)\%, \quad \left| \frac{\langle 2H_1^{\text{unf}} \rangle}{\langle D_0^{\text{unf}} \rangle} \right|_{\text{BELLE}} = -(3.7 \cdots 41.4)\% . \quad (7)
\]

Comparing the above numbers (the errors are correlated!) to the result in Eq. (4) we see that the effects at HERMES and at BELLE are compatible. The central values of

![FIGURE 2. Collins FF \(H_1^a(z)\) needed to explain BELLE data \cite{11}.](image)

![FIGURE 3. a-d: \(P_1(z_1,z_2)\) as defined in Eq. 5 for fixed \(z_2\)-bins as function of \(z_1\) vs. BELLE data \cite{11}. e-h: The observable \(P_C(z_1,z_2)\) defined analogously, see text, vs. preliminary BELLE data reported in \cite{12}.](image)
the BELLE analyzing powers seem to be systematically larger but this could partly be attributed to evolution effects and to the factor $B_G < 1$ in Eq. (4).

By assuming a weak scale-dependence also for the $z$-dependent ratios

$$\frac{H^u_1(z)}{D^u_1(z)}_{\text{BELLE}} \approx \frac{H^u_1(z)}{D^u_1(z)}_{\text{HERMES}}$$

and considering the 1-$\sigma$ uncertainty of the BELLE fit in Fig. 2 and the sensitivity to unknown Gaussian widths of $H^u_1(z)$ and $h^u_1(x)$, c.f. Footnote 1 and Ref. [1], one obtains also a satisfactory description of the $z$-dependence of the SIDIS HERMES data [9], see Fig. 4.

These observations allow — within the accuracy of the first data and the uncertainties of our study — to draw the conclusion that it is, in fact, the same Collins effect at work in SIDIS [8, 9, 10] and in $e^+e^-$-annihilation [11, 12]. Estimates indicate that the early preliminary DELPHI result [7] is compatible with these findings, see [1] for details.

5. Drell-Yan process. The double-spin asymmetry observable in Drell-Yan (DY) lepton-pair production in proton-proton ($pp$) collisions is given in LO by

$$A_{TT}(x_F) = \frac{\sum_a e_a^2 h^u_1(x_1) h^\pi_1(x_2)}{\sum_a e_a^2 f^u_1(x_1) f^\pi_1(x_2)}$$

where $x_F = x_1 - x_2$ and $x_1x_2 = \frac{Q^2}{s}$. In the kinematics of RHIC $A_{TT}$ is small and difficult to measure [21].

In the J-PARC experiment with $E_{\text{beam}} = 50$GeV $A_{TT}$ would reach $-5\%$ in the model [15], see Fig. 5, and could be measured [23]. The situation is similarly promising in proposed U70-experiment [24].

Finally, in the PAX-experiment proposed at GSI [25] in polarized $\bar{p}p$ collisions one may expect $A_{TT} \sim (30 \cdots 50)\%$ [26]. There $A_{TT} \approx h^u_1(x_1) h^\pi_1(x_2)$ to a good approximation, due to $u$-quark ($\bar{u}$-quark) dominance in the proton (anti-proton) [26].

6. Conclusions. We studied the presently available data on the Collins effect. Within the uncertainties of our study we find that the SIDIS data from HERMES [8, 9] and COMPASS [10] on the Collins SSA from different targets are in agreement with each other and with BELLE data on azimuthal correlations in $e^+e^-$-annihilations [11].

The following picture emerges: favored and unfavored Collins FFs appear to be of comparable magnitude but have opposite signs, and $h^u_1(x)$ seems close to saturating the Soffer bound while the other $h^\pi_1(x)$ are presently unconstrained [1].

These findings are in agreement with the most recent BELLE data [12] and with independent theoretical studies [27].

Further data from SIDIS (COMPASS, JLAB [28], HERMES) and $e^+e^-$ colliders (BELLE) will help to refine and improve this first picture.
The understanding of the novel functions $h_1^A(x)$ and $H_1^A(z)$ emerging from SIDIS and $e^+e^-$-annihilations, however, will be completed and critically reviewed only due to future data on double transverse spin asymmetries in the Drell-Yan process. Experiments are in progress or planned at RHIC, J-PARC, COMPASS, U70 and PAX at GSI.

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