The Sivers and Collins asymmetries are the most interesting Single Spin Asymmetries in semi-inclusive deeply inelastic scattering with transverse target polarization. In this talk we present our understanding of these phenomena.

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1 Introduction

Single spin asymmetries (SSA) in hard reactions have a long history dating back to the 1970s when significant polarizations of Λ-hyperons in collisions of unpolarized hadrons were observed [1], and to the early 1990s when large asymmetries in $p^\uparrow p \rightarrow \pi X$ or $p^\uparrow \bar{p} \rightarrow \pi X$ were found at FNAL [2]. No fully consistent and satisfactory unifying approach to the theoretical description of these observations has been found so far — see the reviews [3, 4].

Interestingly, the most recently observed SSA phenomena, namely those in semi-inclusive deeply inelastic scattering (SIDIS) seem better under control. This is in particular the case for the transverse target SSA observed at HERMES and COMPASS [5, 6, 7]. On the basis of a generalized factorization approach in which transverse parton momenta are taken into account [8, 9, 10] these “leading twist” asymmetries can be explained [11] in terms of the Sivers [12, 13, 14, 15] or Collins effect [16]. The former describes, loosely speaking, the distribution of unpolarized partons in a transversely polarized proton, the latter describes the fragmentation of transversely polarized partons into unpolarized hadrons. In the transverse target SSA these effects can be distinguished by the different azimuthal angle distribution of the produced hadrons: Sivers effect $\propto \sin(\phi - \phi_S)$, while Collins effect $\propto \sin(\phi + \phi_S)$, where $\phi$ and $\phi_S$ denote respectively the azimuthal angles of the produced hadron and the target polarization vector with respect to the axis defined by the hard virtual photon [11]. Both effects have been subject to intensive phenomenological studies in hadron-hadron-collisions [17, 18, 19, 20, 21] and in SIDIS [22, 23, 24, 25]. For the longitudinal target SSA in SIDIS, which were observed first but are dominated by subleading-twist effects, the situation is less clear and their description (presuming that factorization holds) is more involved.

In this talk our understanding of these phenomena is presented.
2 Sivers effect

The Sivers effect [12] was originally suggested to explain the large single spin asymmetries (SSA) observed in $p^+p \rightarrow \pi X$ (and $\bar{p}^+p \rightarrow \pi X$) at FNAL [2] and recently at higher energies in the RHIC experiment [26]. The effect considers a non-trivial correlation between (the transverse component of) the nucleon spin $S_T$ and intrinsic transverse parton momenta $p_T$ in the nucleon. It is proportional to the “(naively or artificially) T-odd” structure $(S_T \times p_T)P_N$ and quantified in terms of the Sivers function $f_{1T}^\perp(x, p_T^2)$ [27, 11] responsible for the left-right asymmetry in transversely polarized nucleon whose precise definition in QCD was worked out only recently [13, 14, 15].

Our approach to the description of the Sivers effect in SIDIS and Drell-Yan was described in detail on the spin conference in Prague last year [28] (see also [22, 30, 29]), and we will restrict ourselves to review here only the main points.

2.1 Sivers effect in SIDIS

The azimuthal SSA measured by HERMES & COMPASS in the SIDIS process $lp^+ \rightarrow l'hX$ (see Fig. 1) is defined as

$$A_{UT}^{\sin(\phi - \phi_S)} = (-2) a_{\text{Gauss}} \frac{\sum_a e_a^2 x f_{1T}^{\perp(a)}(x) D_1^a(z)}{\sum_a e_a^2 x f_1^a(x) D_1^a(z)}$$

where $N^{\uparrow(\downarrow)}$ are the event counts for the respective transverse target polarization. We assume the distributions of transverse parton and hadron momenta in distribution (DF) and fragmentation function (FF) to be Gaussian with corresponding averaged transverse momenta to be flavour and $x$- or $z$-independent. The experimental data [5, 6] are presented in the form of [30]

$$A_{UT}^{\sin(\phi - \phi_S)} = (-2) a_{\text{Gauss}} \frac{\sum_a e_a^2 x f_{1T}^{\perp(a)}(x) D_1^a(z)}{\sum_a e_a^2 x f_1^a(x) D_1^a(z)}$$

with $a_{\text{Gauss}} = \frac{\sqrt{\pi}}{2} \frac{M_N}{\sqrt{p_{\text{Siv}}^2 + K_{D1}/z^2}}$

and with

$$f_{1T}^{\perp(a)}(x) \equiv \int d^2 p_T \frac{p_T^2}{2M_N^2} f_{1T}^{\perp}(x, p_T^2)$$

We use predictions from the QCD limit of a large number of colours $N_c$. In this limit it was proven in a model independent way that [31]

$$f_{1T}^{\perp(a)}(x, p_T^2) = -f_{1T}^{\perp(d)}(x, p_T^2) \text{ modulo } 1/N_c$$

and

$$f_{1T}^{\perp(u)}(x, p_T^2) = -f_{1T}^{\perp(d)}(x, p_T^2) \text{ modulo } 1/N_c$$
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for not too small and not too large $x$ satisfying $xN_c = \mathcal{O}(N_c^0)$. Analog relations hold for the Sivers antiquark distributions.

Imposing the large-$N_c$ relation (4) as an additional constraint, and neglecting effects of antiquarks and heavier flavours, it is shown [30] that the HERMES data [5] can be described by the following 2-parameter ansatz and best fit

$$f^{(1) \perp}_{1T} (x) = -f^{(1) \perp}_{1T} \text{ansatz} \sim A x^b (1 - x)^5 \text{ fit} = -0.17 x^{0.66} (1 - x)^5. \quad (5)$$

The fit and its 1- and 2-$\sigma$ uncertainty due to the statistical error of the data [5] are shown in Fig. 2a. In Fig. 2b and c we compare the Sivers SSA obtained on the basis of our fit (5) to the HERMES data [5].

As an intermediate summary we conclude that the HERMES data [5] are well compatible with the large-$N_c$ predictions (4) for the Sivers function [31] and that the fit (5) satisfies the positivity bounds [32]. Remarkably, the sign of the extracted Sivers function in Eq. (5) agrees with the physical picture discussed in [33].

In our fitting procedure we did not use the HERMES data [5] on the $z$-dependence of the Sivers SSA. These data could have been used as an additional constraint for the integrals of $x f^{(1) \perp}_{1T} (x)$ in the range $0.023 < x < 0.4$, which corresponds to the cuts in the HERMES experiment. This would have helped to improve the significance of the fit, considering that only few $x$-data points are available. Instead, we use these data as a valuable cross check of our approach. As the $z$-shape of the SSA is dictated by the unpolarized fragmentation function $D^{\perp}_1 (z)$ and the $z$-dependence of the Gaussian factor $a_{\text{Gauss}}$ in Eq. (2), this is not only a cross check for the extracted Sivers function, but it also tests the Gauss and the large-$N_c$ ansatz (4) itself. In Fig. 2b we confront our fit result (5) with the $z$-dependent HERMES data on the Sivers SSA [5]. We observe a satisfactory agreement.

In the ansatz (5) we neglected the Sivers distributions for antiquarks and for the strange and heavier quarks. Are these reasonable approximations?

We have explicitly checked that Sivers $\bar{u}$- and $\bar{d}$-distributions play a negligible role for the $\pi^+$ SSA, and give more pronounced effects for the $\pi^-$ SSA. In fact,
we found that even sizeable Sivers $\bar{u}$- and $\bar{d}$-distributions cannot be resolved within the error bars of the present data [5]. Also the neglect of Siver strangeness seems reasonable. We shall, however, come back to this point in the next Section.

Next let us address the $1/N_c$-corrections. In order to have an idea of the effect of these corrections, let us assume that the flavour singlet Sivers distribution is not exactly zero but suppressed by exactly a factor of $1/N_c$ with respect to the flavour non-singlet combination according to Eq. (4). That is,

\[
\left| f_{1T}^{\perp(1)u} + f_{1T}^{\perp(1)d}(x) \right| \pm \frac{1}{N_c} \left( f_{1T}^{\perp(1)u} - f_{1T}^{\perp(1)d}(x) \right),
\]

where we use $f_{1T}^{\perp(1)q}(x)$ from Eq. (5) and set $N_c = 3$.

On a deuteron target, the leading $1/N_c$ prediction gives zero for the SSA, so that the $1/N_c$ corrections are all that remain. Assuming for simplicity that the positive and negative hadrons identified at COMPASS are mainly pions, we obtain in our rough model (6) for $1/N_c$-corrections the results shown in Fig. 3. Clearly, we see that the COMPASS data [6] are compatible with the large-$N_c$ corrections being of a magnitude compatible with our model.

Thus, the reason why our large-$N_c$ approach works here, is due to the fact that current precision of the first experimental data [5,6] is comparable to the theoretical accuracy of the large-$N_c$ relation (4). In future, with increasing precision of the data, it will certainly be necessary to refine the fit ansatz (5) to include $1/N_c$ corrections and antiquarks.

Our fit is in qualitative agreement with extractions of the Sivers function [23, 24, 25] from the same [5] and from the more recent and more precise (but preliminary) HERMES data [7] (see [34] for a detailed comparison).

2.2 Sivers effect for kaons

In the HERMES experiment the RICH detector allows to separate kaons and pions. The outcome of the HERMES experiment is as follows [35]. The Sivers SSA for $K^+$ is about (10-15)% in the region of $x = (0.05 - 0.15)$, i.e. about factor (2-3) larger than the $\pi^+$ SSA. In the region of $x \geq 0.15$ it is (within large error bars) of comparable size as the $\pi^+$ SSA. The $K^-$ Sivers SSA is compatible with zero within large error bars. Can one understand this behaviour?

Let us use the results discussed in Sec 2.1 in order to estimate the Sivers SSA for kaons at HERMES. For $f_1^q(x)$ we use the parameterization [36], for the kaon FF the parameterization [37]. We obtain the results shown as solid lines in Fig. 4.

In our estimate we have neglected the Sivers effect for strange quarks. Could therefore the unknown strangeness Sivers function yield to some surprises and change drastically the picture in Fig. 4 (solid lines)?
Let us assume that the s- and \( \bar{s} \)-Sivers distributions saturate the positivity bound with the unpolarized distributions \( f_1^T(x) = f_1^T \) from (36). Then we obtain the result shown as dashed line in Fig. 4. We observe that corrections due to the strangeness Sivers functions have little impact.

“The only difference” between the SSA for \( \pi^+ \) and \( K^+ \) is the exchange \( d \leftrightarrow s \). For \( R \equiv \frac{A(K^+)/A(\pi^+)}{A(\pi^+)/A(K^+)} \), i.e. the ratio of the \( K^+ \) to \( \pi^+ \) Sivers SSA, one obtains numerically in the HERMES kinematics

\[
R = \frac{A(K^+)}{A(\pi^+)} \approx \frac{B(x) + 0.35 f_{1T}^{+\bar{d}}(x)}{B(x) + 0.09 f_{1T}^{+d}(x)},
\]

\( B(x) \approx f_{1T}^{+u} + 0.15(f_{1T}^{+d} + 4 f_{1T}^{+\bar{d}} + f_{1T}^{+\bar{s}} + f_{1T}^{+s} + f_{1T}^{+\bar{d}}) \),

where we used the parameterizations (36) (37).

How much Sivers-\( \bar{q} \) is needed to explain \( K^+/\pi^+ \)? Just to have a better feeling on that, let us consider two models motivated by our (22) and the works (23) (24) (25):

- Model I: \( f_{1T}^{Q} = f_{1T}^{u} \approx -f_{1T}^{d} \), \( f_{1T}^{A} = f_{1T}^{u} \approx f_{1T}^{d} \approx f_{1T}^{s} \approx -f_{1T}^{d} \)

- Model II: \( f_{1T}^{Q} = f_{1T}^{u} \approx -2f_{1T}^{d} \), \( f_{1T}^{A} \) same as above.

With models like I and II the ratio of \( K^+ \) to \( \pi^+ \) Sivers SSA is a function of the variable \( \beta = f_{1T}^{Q} / f_{1T}^{A} \) only. Thus, it is possible to invert this relation to have \( \beta \) as a function of the (measured) \( K^+ \) to \( \pi^+ \) Sivers SSA ratio. The exact result of this operation is shown in Fig. 5 which illustrates that one can obtain rather large \( K^+/\pi^+ \) enhancements with still moderate values of \( f_{1T}^{Q} / f_{1T}^{A} \) in the models I and II.

Of course, the models I and II are particular choices. A simultaneous refitting will give us a conclusive answer.

### 2.3 Sivers effect in the Drell-Yan process

A particularly interesting feature of the Sivers function (and other “T-odd” distributions) concerns the universality property. On the basis of time-reversal arguments it was predicted that \( f_{1T}^{Q} \) in SIDIS and DY have opposite sign (we follow the Trento Conventions (38)),

\[
f_{1T}^{Q}(x, p_T^2)_{\text{SIDIS}} = - f_{1T}^{Q}(x, p_T^2)_{\text{DY}}.
\]

The experimental check of Eq. (8) would provide a thorough test of our understanding of the Sivers effect within QCD. In particular, the experimental verification of...
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(8) is a crucial prerequisite for testing the factorization approach to the description of processes containing $p_T$-dependent correlators [8, 9, 10].

On the basis of the first information of the Sivers effect in SIDIS [5, 6] it was shown that the Sivers effect leads to sizeable SSA in $p^+\pi^-\rightarrow l^+l^-X$, which could be performed in the medium or long term, have the advantage of being dominated by annihilation of valence quarks (from $p$) and valence antiquarks (from $\bar{p}$ or $\pi^-$), which yields sizeable counting rates. Moreover, the processes are not very sensitive to the Sivers antiquark distributions, which are not constrained by the present SIDIS data, see [22, 23, 24, 25, 30].

On a shorter term the Sivers effect in DY can be studied in $p^+p \rightarrow l^+l^-X$ at RHIC. In $pp$-collisions inevitably antiquark distributions are involved, and the counting rates are smaller. We have shown, however, that the Sivers SSA in DY can nevertheless be measured at RHIC with an accuracy sufficient to unambiguously test Eq. (8) [29]. We refer to [41, 42, 43, 44, 45, 46, 47] for discussions of further RHIC spin physics prospects, and [48, 49] for early predictions of SSAs in DY.

It remains to be noted that the theoretical understanding of SSA in $p^+p \rightarrow \pi X$, which originally motivated the introduction of the Sivers effect, is more involved and less lucid compared to SIDIS or DY, as here other mechanisms such as the Collins effect [16] and/or dynamical twist-3 effects [50, 51] could generate SSA. Phenomenological studies indicate, however, that in a picture based on $p_T$-dependent correlators the data [2, 26] can be explained in terms of the Sivers effect alone [17, 18, 19] with the other effects playing a less important role [20, 21]. For recent discussions of hadron-hadron collisions with more complicated final states (like, e.g., $p^+p \rightarrow \text{jet}_1\text{jet}_2X$) we refer to Refs. [52].

3 Collins effect

The chirally odd transversity distribution function $h_1^a(x)$ 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 [16] (FF) $H_1^a(z)$ [1]

$$A_{UT}^{\sin(\phi+\phi_S)} = 2 \sum_a e_a^2 x h_1^a(x) B_G H_1^a(z) \sum_a e_a^2 x f_2^a(x) D_1^2(z). \quad (9)$$

However, $H_1^a(z)$ 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

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1) We assume a factorized Gaussian dependence on parton and hadron transverse momenta [53] with $B_G(z) = (1 + z^2 \langle p_{1T}^2 \rangle / \langle K_{2T}^2 \rangle)^{-1/2}$ and define $H_1^a(z) \equiv H_1^{a(1/2)}(z) = \int d^2K_T |H_1^{a(1/2)}(z, K_T)|$ for brevity. The Gaussian widths are assumed flavor and $x$- or $z$-independent. We neglect throughout soft factors [9].
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\[ d\sigma = d\sigma_{\text{unp}} \left[ 1 + \cos(2\phi_1) \frac{\sin^2 \theta}{1 + \cos^2 \theta} C_G \times \frac{\sum_a e_a^2 H_a^1 H_a^0}{\sum_a e_a^2 D_a^1 D_a^0} \right] \]

\[ \equiv A_1 \]

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 \( C_G(z_1, z_2) = \frac{16\pi z_1 z_2}{z_2^2 + z_2^2} \).

First experimental indications for the Collins effect were obtained from studies of preliminary SMC data on SIDIS \([55]\) and DELPHI data on charged hadron production in \( e^+e^- \) annihilations at the \( Z^0 \)-pole \([56]\). More recently HERMES reported data on the Collins (SSA) in SIDIS from proton target \([5, 7]\) giving the first unambiguous evidence that \( H_a^1 \) and \( h_a^1(x) \) are non-zero, while in the COMPASS experiment \([6]\) 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 60 MeV below the \( \Upsilon \)-resonance \([57, 58]\).

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?

In order to answer this question we extract \( H_a^1 \) from HERMES \([7]\) and BELLE \([57, 58]\) data, and compare the obtained ratios \( H_a^1/D_a^1 \) 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 \([59, 60]\) indicates.

### 3.1 Collins effect in SIDIS

In order to extract information on Collins FF from SIDIS a model for the unknown \( h_a^1(x) \) is needed. We use predictions from chiral quark-soliton model \([61]\) which provides a good description of unpolarized and helicity distribution \([62]\). On the basis of Eq. (9), the assumptions in Footnote 1, and the parameterizations \([36, 37]\) for \( f_a^1(x) \) and \( D_a^1(z) \) at \( \langle Q^2 \rangle = 2.5 \text{ GeV}^2 \), we obtain from the HERMES data \([7]\):

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

(11)

Here “fav” (“unf”) means favored \( u \to \pi^+ \) etc. (unfavored \( u \to \pi^- \), 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 \([63]\) and Schäfer-Teryaev sum rule \([64]\) provide a qualitative understanding of this behavior. The important role of unfavored FF becomes more evident by considering the analyzing powers

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

(12)

Fit (11) describes the HERMES proton target data \([7]\) on the Collins SSA (see Figs. 6a, b) and is in agreement with COMPASS deuteron data \([6]\) (Figs. 6c, d).
3.2 Collins effect in $e^+e^-$

The specific $\cos 2\phi$ dependence of the cross section \[ \frac{A_U^T}{A_T^U} \approx 1 + \cos(2\phi_1)P_1(z_1, z_2) \quad \text{(13)} \]

In order to describe the BELLE data \[ \text{we have chosen the Ansatz and obtained the best fit} \]

\[ H_1^a(z) = C_a z \, D_1^a(z), \quad C_{\text{fav}} = 0.15, \quad C_{\text{unf}} = -0.45, \quad \text{(14)} \]

shown in Fig. 7 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 $H_1^{\text{unf}}$.

\[ P_1(z_1, z_2) = \frac{1}{2} (z_1 + z_2) \quad \text{and} \quad P_1(z_1, z_2) = \frac{1}{2} (z_1 - z_2) \]

Fig. 8. a-d: $P_1(z_1, z_2)$ as defined in Eq. \[ \text{for fixed } z_1\text{-bins as function of } z_2 \text{ vs. BELLE data \[ \text{reported in \[58\].} \]}

The observable $P_2(z_1, z_2)$ defined analogously, see text, vs. preliminary BELLE data reported in \[58\].
Thus in our Ansatz $P_1(z_1, z_2)$ is symmetric with respect to the exchange sign($C_{\text{fav}}$) $\leftrightarrow$ sign($C_{\text{unf}}$). (And not with respect to $C_{\text{fav}}$ $\leftrightarrow$ $C_{\text{unf}}$ as incorrectly remarked in [65].)

The BELLE data [57] 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 (14) and Fig. 7 are dictated by SIDIS data [7] (and our model [61] with $h_{1}^{u}(x) > 0$, see Sect. 3.1).

In Fig. 8a-d the BELLE data [57] are compared to the theoretical result for $P_1(z_1, z_2)$ obtained on the basis of the best fit shown in Fig. 7.

Most interesting recent news are the preliminary BELLE data [58] 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. (13) as $A_{1}^{U}/A_{1}^{C} \approx (1 + \cos(2\phi) P_{C})$. The fit (14) ideally describes the new experimental points (see Figs. 8a-h)!

### 3.3 BELLE vs. HERMES

In order to compare Collins effect in SIDIS at HERMES [5, 7] and in $e^{+}e^{-}$-annihilation at BELLE [57] we consider the ratios $H_{1}^{A}/D_{1}^{A}$ which might be less scale dependent. The BELLE fit in Fig. 7 yields in the HERMES $z$-range:

\[\left\langle \frac{2H_{1}^{\text{fav}}}{D_{1}^{\text{fav}}} \right\rangle_{\text{BELLE}} = (5.3 \cdots 20.4)\%, \quad \left\langle \frac{2H_{1}^{\text{unf}}}{D_{1}^{\text{unf}}} \right\rangle_{\text{BELLE}} = -(3.7 \cdots 41.4)\% .\]

Comparing the above numbers (the errors are correlated!) to the result in Eq. (12) we see that the effects at HERMES and at BELLE are compatible. The central values of 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. (12).

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

\[\left\{ \frac{H_{1}^{A}(z)}{D_{1}^{A}(z)} \right\}_{\text{BELLE}} \approx \left\{ \frac{H_{1}^{A}(z)}{D_{1}^{A}(z)} \right\}_{\text{HERMES}} \]

and considering the 1-$\sigma$ uncertainty of the BELLE fit in Fig. 7 and the sensitivity to unknown Gaussian widths of $H_{1}^{A}(z)$ and $h_{1}^{u}(x)$, c.f. Footnote 1 and Ref. [65], one obtains also a satisfactory description of the $z$-dependence of the SIDIS HERMES data [7], see Fig. 9.

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 [5, 7, 6] and in $e^{+}e^{-}$-annihilation [57, 58].
that the early preliminary DELPHI result \[56\] is compatible with these findings, see \[65\] for details.

### 3.4 Transversity in 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

\[
A_{TT}(x_F) = \frac{\sum_a e_a^2 h_{1T}^a(x_1) h_{\bar{a}}(x_2)}{\sum_a e_a^2 f_1^a(x_1) f_1^\bar{a}(x_2)} \tag{17}
\]

where \(x_F = x_1 - x_2\) and \(x_1 x_2 = \frac{Q^2}{s}\). In the kinematics of RHIC \(A_{TT}\) is small and difficult to measure \[41\].

In the J-PARC experiment with \(E_{\text{beam}} = 50\) GeV \(A_{TT}\) would reach \(-5\%\) in the model \[61\], see Fig. 10 and could be measured \[67\].

The situation is similarly promising in proposed U70-experiment \[68\].

Finally, in the PAX-experiment proposed at GSI \[39\] in polarized \(\bar{p}p\) collisions one may expect \(A_{TT} \sim (30 \cdots 50)\%\) \[69\].

\(A_{TT}\) \(\propto h_{u}^1(x_1) h_{\bar{a}}^1(x_2)\) to a good approximation, due to \(u\)-quark (\(\bar{u}\)-quark) dominance in the proton (anti-proton) \[69\].

### 4 Conclusions

Within the uncertainties of our study we find that the SIDIS data from HERMES \[5, 7\] and COMPASS \[6\] on the Sivers and Collins SSA from different targets are in agreement with each other and with BELLE data on azimuthal correlations in \(e^+e^-\)-annihilations \[57\].

At the present stage large-\(N_c\) predictions give useful constraints and are compatible with data.

Data on kaon production provide new interesting information on sea Sivers-\(\bar{q}\). For the Collins FF 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 \(h_{a}^1(x)\) are presently unconstrained \[65\].

These findings are in agreement with old DELPHI \[56\] and with the most recent BELLE data \[58\] and with independent theoretical studies \[25\]. Further data from SIDIS (COMPASS, JLAB \[70\], HERMES) and \(e^+e^-\) colliders (BELLE) will help to refine and improve this first picture.

The understanding of the novel functions \(f_{\perp}^{1-a}\), \(h_{q}^1\) and \(H_{q}^1(z)\) emerging from SIDIS and \(e^+e^-\)-annihilations, however, will be completed only thanks 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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