The Sivers Function From SIDIS Data

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We study the Sivers effect in transverse single spin asymmetries (SSA) for pion and kaon
production in Semi-Inclusive Deep Inelastic Scattering (SIDIS) processes. We perform
a fit of $A^{\sin(\phi_h - \phi_S)}_{UT}$ taking into account the recent data from HERMES and COMPASS
Collaborations, which allow a new determination of the Sivers distribution functions for
quark and anti-quark with $u$, $d$ and also $s$ flavours. Estimates for forthcoming SIDIS
experiments at COMPASS and JLab are given.

Data on the transverse single spin asymmetry $A^{\sin(\phi_h - \phi_S)}_{UT}$ for polarized SIDIS processes,
$\ell p(S) \rightarrow \ell' h X$, collected by the HERMES [1] and COMPASS [2] Collaborations allowed
us [3, 4] to perform a rather well constrained extraction of the Sivers distribution function
[5, 6] for $u$ and $d$ quarks, assuming a negligibly small Sivers sea. Recently, much higher
statistics data on the $A^{\sin(\phi_h - \phi_S)}_{UT}$ azimuthal asymmetries for SIDIS have become available:
in Ref. [7] the HERMES Collaboration presents neutral pion and charged kaon azimuthal
asymmetries, in addition to higher precision data on charged pion asymmetries; moreover,
Refs. [8, 9] show the COMPASS Collaboration measurements for separated charged pion
and kaon asymmetries, together with some data for $K^0_S$ production.

Here we present the analysis of these new experimental sets of data [10]. They give us a
better understanding of the $u$ and $d$ flavour Sivers distribution functions at low-intermediate
$x$ and, most importantly, a first insight into the sea contributions to the Sivers functions.

The SIDIS transverse single spin asymmetry $A^{\sin(\phi_h - \phi_S)}_{UT}$ is defined as

$$A^{\sin(\phi_h - \phi_S)}_{UT} = 2 \frac{\int d\phi_S d\phi_h [d\sigma^\uparrow - d\sigma^\downarrow] \sin(\phi_h - \phi_S)}{\int d\phi_S d\phi_h [d\sigma^\uparrow + d\sigma^\downarrow]}, \quad (1)$$

where $\phi_S$ and $\phi_h$ are the azimuthal angles identifying the directions of the proton spin $S$
and of the outgoing hadron $h$ in the $\gamma^* p$ c.m. frame, see Fig. 1 of Ref. [10]. Taking into
account intrinsic parton motion, this transverse single spin asymmetry, can be written, at

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order \((k_\perp/Q)\), as:
\[
A^{\sin(\phi_h - \phi_S)}_{UT} = \frac{\sum_q \int d\phi_S d\phi_h d^2k_\perp \Delta^N f_{q/P}^\perp(x,k_\perp) \sin(\varphi - \phi_S) \frac{d\sigma_{\ell q - \ell q}}{dQ^2} D_q^h(z,p_\perp) \sin(\phi_h - \phi_S)}{\sum_q \int d\phi_S d\phi_h d^2k_\perp f_{q/P}(x,k_\perp) \frac{d\sigma_{\ell q - \ell q}}{dQ^2} D_q^h(z,p_\perp)} ,
\]
where \(\varphi\) defines the direction of the incoming (and outgoing) quark transverse momentum, \(k_\perp = k_\perp(\cos \varphi, \sin \varphi, 0)\); \(f_{q/P}(x,k_\perp)\) is the unpolarized \(x\) and \(k_\perp\) dependent parton distribution function (PDF); \(d\sigma_{\ell q - \ell q}/dQ^2\) is the unpolarized cross section for the elementary scattering \(\ell q \to \ell q\); \(D_q^h(z,p_\perp)\) is the fragmentation function describing the hadronization of the final quark \(q\) into the detected hadron \(h\) with a light-cone momentum fraction \(z\) and a transverse momentum \(p_\perp\) with respect to the fragmenting quark; finally, \(\Delta^N f_{q/P}^\perp(x,k_\perp)\) is the Sivers function, parameterized in terms of the unpolarized distribution function as:
\[
\Delta^N f_{q/P}^\perp(x,k_\perp) = 2 N_q(x) h(k_\perp) f_{q/P}(x,k_\perp) ,
\]
with
\[
N_q(x) = N_q x^{\alpha_q}(1 - x)^{\beta_q} \frac{(\alpha_q + \beta_q)(\alpha_q + \beta_q)}{\alpha_q^\alpha_q \beta_q^\beta_q} , \quad h(k_\perp) = \sqrt{2} e^{k_\perp^2/M_1^2} ,
\]
where \(N_q \in [-1, 1]\), \(\alpha_q\), \(\beta_q\) and \(M_1\) (GeV/c) are free parameters to be determined by fitting the experimental data. Notice that \(h(k_\perp) \leq 1\) for any \(k_\perp\) and \(|N_q(x)| \leq 1\) for any \(x\), therefore the positivity bound for the Sivers function is automatically fulfilled. For the unpolarized distribution and fragmentation functions, we adopt the common factorized gaussian form

\[
f_{q/P}(x,k_\perp) = f_q(x) \frac{1}{\pi \langle k_\perp^2 \rangle} e^{-k_\perp^2/\langle k_\perp^2 \rangle} , \quad D_q^h(z,p_\perp) = D_q^h(z) \frac{1}{\pi \langle p_\perp^2 \rangle} e^{-p_\perp^2/\langle p_\perp^2 \rangle} ,
\]
with \(\langle k_\perp^2 \rangle = 0.25\) (GeV/c)^2 and \(\langle p_\perp^2 \rangle = 0.20\) (GeV/c)^2 fixed by analysing the Cahn effect in unpolarized SIDIS, as in Ref. [3]. The parton distribution functions \(f_q(x)\) and the fragmentation functions \(D_q^h(z)\) also depend on \(Q^2\) via the usual QCD evolution, which will be taken into account, at LO, in all our computations.

Fragmentation functions are a crucial ingredient of our fit. We have considered three different sets: KRE [11], HKNS [12] and DSS [13]. All these sets are basically equivalent as far as pion asymmetries are concerned. However there are important differences in the description of kaon data. In particular the DSS set, contrary to the other two sets, is such that \(D_k^{K^+}(z) \gg D_k^\pi^-(z)\) over the whole \(z\) range. This feature is crucial when studying kaon production processes: first of all, it allows to reproduce kaon multiplicities at HERMES; secondly, it enables us to achieve kaon asymmetries larger than those corresponding to pion production. For these reasons we have chosen the DSS set for our fit. Contrary to the fragmentation sector, the use of different sets of unpolarized distribution functions does not affect our results significantly; here we use the GRV98LO set [14]. As the SIDIS data from HERMES and COMPASS have a limited coverage in \(x\), typically \(x < 0.3 - 0.4\), the experimental asymmetries we are fitting contain very little information on the large \(x\) tail of the Sivers functions. Therefore we assume the same value of \(\beta\) (which is related to the
We have performed a comprehensive analysis of SIDIS data on Sivers azimuthal dependences. It turns out that the data, and in particular the unexpectedly large value of

\[
N_u = 0.35^{+0.08}_{-0.08}
\]

\[
N_d = -0.90^{+0.43}_{-0.10}
\]

\[
\alpha_u = 0.73^{+0.72}_{-0.58}
\]

\[
\alpha_d = 1.08^{+0.82}_{-0.44}
\]

\[
\beta = 3.40_{-2.90}
\]

| Table 1: Best values of the free parameters for the ‘broken sea’ ansatz. The errors are estimated according to the procedure outlined in Appendix A of Ref. [10]. |
|---|---|
| $N_u$ | 0.35$^{+0.08}_{-0.08}$ |
| $N_d$ | -0.90$^{+0.43}_{-0.10}$ |
| $\alpha_u$ | 0.73$^{+0.72}_{-0.58}$ |
| $\alpha_d$ | 1.08$^{+0.82}_{-0.44}$ |
| $\beta$ | 3.40$^{-2.90}$ |

Notice that this choice artificially reduces the width of the uncertainty band at large $x$. Moreover we assume the same $\alpha = \alpha_{sea}$ for all sea quarks. Thus for this so called ‘broken sea’ ansatz fit we then have 11 parameters. The results we obtain for these parameters by fitting simultaneously the four experimental data sets on $A_{UT}^{s}(\phi_{h}-\phi_{s})$, corresponding to pion and kaon production at HERMES [7] and COMPASS [8], are presented in Table I together with the corresponding errors, estimated according to the procedure outlined in Appendix A of Ref. [10].

The fit performed under the ‘broken sea’ ansatz shows a good description of pion and kaon asymmetries. We obtained $\chi^2 = 1.20$ per data point for $K^+$ production at HERMES [7], while for pions we had $\chi^2 = 0.94$ per data point, for a total $\chi^2_{dof} = 1.00$. Our results confirm that $\Delta^N f_{u/p^+} > 0$ and $\Delta^N f_{d/p^+} < 0$ as found in Ref. [4]. Moreover HERMES data on kaon asymmetries cannot be explained without a sea-quark Sivers distribution. In particular we find that $\Delta^N f_{s/p^+} > 0$. Using the Sivers functions determined through our fit, we have given predictions for $A_{UT}^{s}(\phi_{h}-\phi_{s})$ for COMPASS experiment operating with a hydrogen target and at JLab, on proton, neutron and deuteron transversely polarized targets; for details see Ref. [10].

We have performed a comprehensive analysis of SIDIS data on Sivers azimuthal dependences. It turns out that the data, and in particular the unexpectedly large value of

\[
\Delta N_f(x,k_L) = \text{const} \times \exp(i\phi_{h}-\phi_{s})
\]
\( A_{UT}^{\sin(\phi_h-\phi_Z)} \) for \( K^+ \), demand a non vanishing, and large, Sivers distribution for \( \bar{s} \) quarks. The other sea quark (\( \bar{u}, \bar{d}, s \)) contributions are less well determined, although they also seem to be non vanishing.

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