Understanding the role of Cahn and Sivers effects in Deep Inelastic Scattering[1]

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Abstract. The role of intrinsic $k_\perp$ in semi-inclusive Deep Inelastic Scattering (SIDIS) processes ($\ell p \to \ell h X$) is studied with exact kinematics within QCD parton model at leading order; the dependence of the unpolarized cross section on the azimuthal angle between the leptonic and the hadron production planes (Cahn effect) is compared with data and used to estimate the average values of $k_\perp$ both in quark distribution and fragmentation functions. The resulting picture is applied to the description of the weighted single spin asymmetry $A_{UT}^{\sin(\phi_\pi-\phi_S)}$ recently measured by the HERMES collaboration at DESY; this allows to extract parameters for the quark Sivers functions. The extracted Sivers functions give predictions for the COMPASS measurement of $A_{UT}^{\sin(\phi_\pi-\phi_S)}$ in agreement with recent data, while their contribution to HERMES $A_{UL}^{\sin\phi_\pi}$ is computed and found to be small. Predictions for $A_{UT}^{\sin(\phi_K-\phi_S)}$ for kaon production at HERMES are also given.

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The role of intrinsic $k_\perp$ is known to be important in unpolarized SIDIS processes [1] and becomes crucial for the explanation of many single spin effects recently observed and still under active investigation in several ongoing experiments; spin and $k_\perp$ dependences can couple in parton distribution and fragmentation functions, giving origin to unexpected effects in polarization observables. One such example is the azimuthal asymmetry observed in the scattering of unpolarized leptons off polarized protons [2], [3] and deuterons [4].

A recent analysis of Single Spin Asymmetries (SSA) in $p^\uparrow p \to \pi X$ processes, with a separate study of the Sivers and the Collins contributions, has been performed respectively in Refs. [5] and [6], with the conclusion that the Sivers [7] mechanism alone can explain the data [8], while the Collins [9] mechanism is strongly suppressed.

We considered [11] the role of parton intrinsic motion in SIDIS processes within the QCD parton model at leading order. The average values of $k_\perp$ for quarks inside protons,

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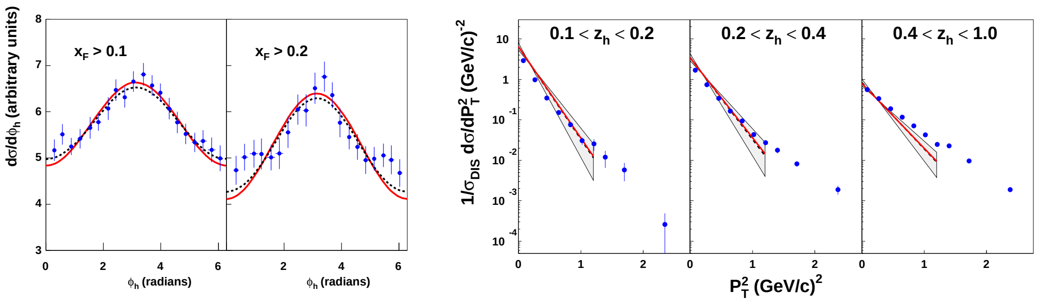

FIGURE 1. Description of the ϕ_h and P_T dependence of the cross section.

and $p_\perp$ for final hadrons inside the fragmenting quark jet, are fixed by comparison with data [10] on the dependence of the unpolarized cross section on the azimuthal angle between the leptonic and the hadronic planes and on P_T.

Within the factorization scheme, assuming an independent fragmentation process, the SIDIS cross section for the production of a hadron h in the current fragmentation region with the inclusion of all intrinsic motions can be written as [11]

$$\frac{d^5\sigma^{\ell p\to\ell hX}}{dx_B\,dQ^2\,dz_h\,d^2\mathbf{P}_T} = \sum_q e_q^2 \int d^2\mathbf{k}_\perp\; f_q(x,k_\perp)\,\frac{2\pi\alpha^2}{x_B^2 s^2}\,\frac{\hat{s}^2+\hat{u}^2}{Q^4} \times D_q^h(z,p_\perp)\,\frac{z}{z_h}\,\frac{x_B}{x}\left(1+\frac{x_B^2}{x^2}\frac{k_\perp^2}{Q^2}\right)^{-1}. \tag{1}$$

It is instructive, and often quite accurate, to consider the above equation in the much simpler limit in which only terms of $O(k_\perp/Q)$ are retained. In such a case $x \simeq x_B, z \simeq z_h$ and $\mathbf{p}_\perp \simeq \mathbf{P}_T - z_h\mathbf{k}_\perp$. In what follows we assume, both for parton densities and fragmentation functions, a factorized Gaussian $k_\perp$ and $p_\perp$ dependence.

In this way the $\mathbf{k}_\perp$ integration in Eq. (1) can be performed analytically, leading to the result, valid up to $O(k_\perp/Q)$:

$$\frac{d^5\sigma^{\ell p\to\ell hX}}{dx_B\,dQ^2\,dz_h\,d^2\mathbf{P}_T} \simeq \sum_q \frac{2\pi\alpha^2 e_q^2}{Q^4}\,f_q(x_B)\,D_q^h(z_h)\Big[1+(1-y)^2 - 4\,\frac{(2-y)\sqrt{1-y}\,\langle k_\perp^2\rangle\,z_h P_T}{\langle P_T^2\rangle\,Q}\,\cos\phi_h\Big]\,\frac{1}{\pi\langle P_T^2\rangle}\,e^{-P_T^2/\langle P_T^2\rangle}\,, \tag{2}$$

where $\langle P_T^2\rangle = \langle p_\perp^2\rangle + z_h^2\langle k_\perp^2\rangle$. The term proportional to $\cos\phi_h$ describes the Cahn effect [1].

By fitting the data [10] on unpolarized SIDIS we obtain the following values of the parameters: $\langle k_\perp^2\rangle = 0.25\ (\mathrm{GeV/c})^2$, $\langle p_\perp^2\rangle = 0.20\ (\mathrm{GeV/c})^2$. The results are shown in Fig. 1.

Such values are then used to compute the SSA for $\ell\, p^\uparrow \to \ell\, h X$ processes. We considered the Sivers mechanism [7] alone. The unpolarized quark (and gluon) distributions inside a transversely polarized proton can be written as:

$$f_{q/p^\uparrow}(x,\mathbf{k}_\perp) = f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\mathbf{S}\cdot(\hat{\mathbf{P}}\times\hat{\mathbf{k}}_\perp)\,, \qquad (3)$$

where $\mathbf{P}$ and $\mathbf{S}$ are respectively the proton momentum and transverse polarization vector, and $\mathbf{k}_\perp$ is the parton transverse momentum; transverse refers to the proton flight direction. Eq. (3) leads to non vanishing SSA, which can be calculated by substituting $f_{q/p}$ by $f_{q/p^\uparrow}$ in Eq. (1).

We parameterize, for each light quark flavour $q = u_v, d_v, u_s, d_s, \bar{u}\bar{d}$, the Sivers function in the following factorized form: $\Delta^N f_{q/p^\uparrow}(x,k_\perp) = 2\,\mathcal{N}_q(x)\,h(k_\perp)\,f_{q/p}(x,k_\perp)$, where $\mathcal{N}_q(x) = N_q x^{a_q}(1-x)^{b_q}\frac{(a_q+b_q)^{(a_q+b_q)}}{a_q^{a_q}b_q^{b_q}}$, $h(k_\perp) = \sqrt{2e}\,\frac{k_\perp}{M'}\,e^{-k_\perp^2/M'^2}$.

Our fit [11] to the HERMES data on $A_{UT}^{\sin(\phi_\pi-\phi_S)}$ [3] is presented in the left panel of Fig. 2.

Having fixed all the parameters we can check the consistency of the model by computing $A_{UT}^{\sin(\phi_\pi-\phi_S)}$ for charged hadron production in COMPASS experiment [4]; our results are given in the right panel of Fig. 2, showing a very good agreement with the data.

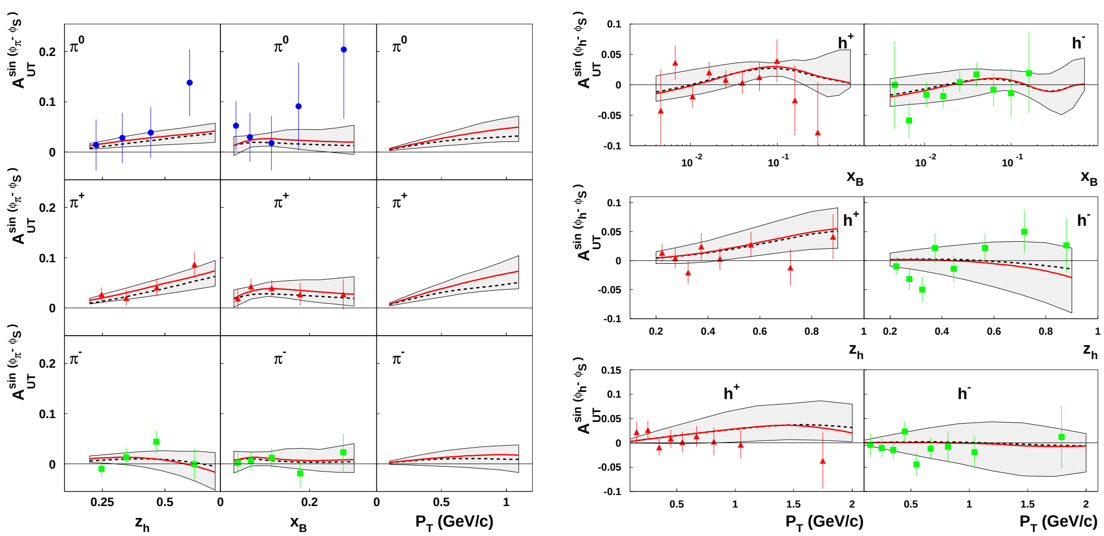

FIGURE 2. HERMES [3] (left) and COMPASS [4] (right) data on $A_{UT}^{\sin(\phi_\pi-\phi_S)}$ for scattering off a transversely polarized proton (deuterium) target and pion (hadron) production. The curves are the results of our fit to the HERMES data and description of the COMPASS data , with exact kinematics (dashed line) or keeping only terms up to $O(k_\perp/Q)$ (solid bold line). The shadowed region corresponds to the theoretical uncertainty due to the parameter errors.

We also compute $A_{UT}^{\sin(\phi_K-\phi_S)}$ for kaon production, which could be measured by HERMES. Our results are given in the right panel of Fig. 3.

Finally, we consider the HERMES data on $A_{UL}^{\sin\phi_\pi}$ obtained in the semi-inclusive electro-production of pions on a longitudinally polarized hydrogen target [2]. We have computed the Sivers contribution to this quantity again with our set of Sivers functions,

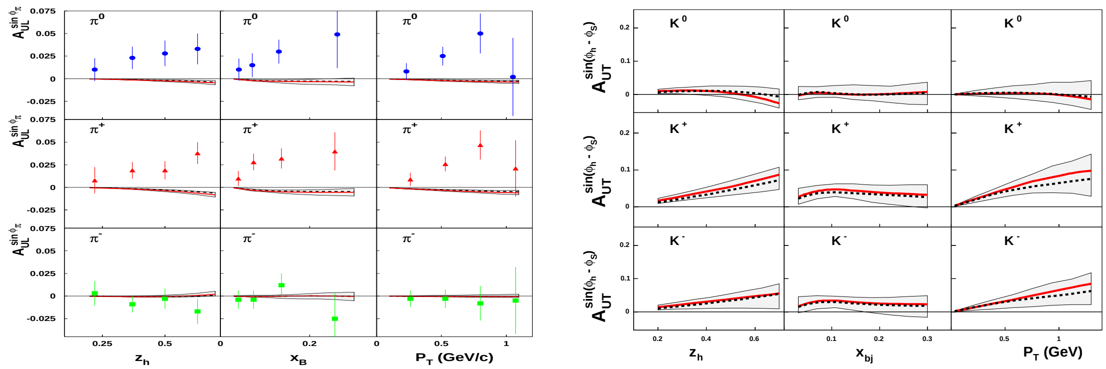

FIGURE 3. HERMES data on $A_{UL}^{\sin(\phi_\pi)}$ [2] for scattering off a longitudinally polarized proton target and pion production (left) and predictions of $A_{UT}^{\sin(\phi_K-\phi_S)}$ for kaon production at HERMES (right).

and compared with data (see left panel of Fig. 3). Notice that no agreement should be necessarily expected, as $A_{UL}^{\sin\phi_\pi}$ can be originated also (even dominantly) from the Collins mechanisms or higher-twist terms.

The HERMES data [3] clearly show a non zero Sivers effect; by a comparison with these data estimates of the Sivers functions for *u* and *d* (both valence and sea) quarks have been obtained. These functions not only describe well the HERMES data, but are also in agreement with COMPASS preliminary data [4].

A phenomenological study of SSA and azimuthal dependences, within a factorization scheme with unintegrated parton distribution and fragmentation functions, is now possible. SIDIS processes with measurements of the Cahn effect, and the various SSA $A_{UL}^{\sin\phi_h}$, $A_{UT}^{\sin(\phi_h-\phi_S)}$ and $A_{UT}^{\sin(\phi_h+\phi_S)}$ provide a rich ground to be further explored, both theoretically and experimentally.

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