PROCEEDINGS OF SCIENCE

A_N in inclusive lepton-proton collisions

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Some estimates for the transverse single spin asymmetry, A_N, in the inclusive processes $\ell p^\uparrow \to hX$ are compared with new experimental data. The calculations are based on the Sivers and Collins functions as extracted from SIDIS azimuthal asymmetries, within a transverse momentum dependent factorization approach. The values of A_N thus obtained agree in sign and shape with the data. Predictions for future experiments are also given.

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1. Introduction and Formalism

We present a phenomenological analysis of recent HERMES data [1] for the single spin asymmetry (SSA) measured in the inclusive hadron production in lepton proton collisions. This study is based on a previous paper [2], recently extended [3], where we considered the transverse SSAs for the $\ell p^\uparrow \to hX$ process in the $\ell - p$ center of mass (*c.m.*) frame, with a single large P_T final particle.

Such A_N is the exact analogue of the SSAs observed in $p p^\uparrow \to hX$, the well known and large left-right asymmetries (see Ref. [4] and references therein). On the other hand, the process is essentially a semi-inclusive deep inelastic scattering (SIDIS) process, for which, at large Q^2 values (and small P_T in the $\gamma^* - p$ *c.m.* frame), the TMD factorization is proven to hold [5, 6]. Notice that even without the detections of the final lepton, large P_T values imply large values of Q^2.

We computed these SSAs assuming the TMD factorization and using the relevant TMDs (Sivers and Collins functions) as extracted from SIDIS data. A first simplified study of A_N in $\ell p^\uparrow \to hX$ processes was performed in Ref. [7]. The process was also considered in Refs. [8] in the framework of collinear twist-three formalism.

In Ref. [2] (where all details can be found) we considered the process $p^\uparrow \ell \to hX$ in the proton-lepton *c.m.* frame (with the polarized proton moving along the positive Z_{cm} axis) with:

$$A_N = \frac{d\sigma^\uparrow(\boldsymbol{P}_T) - d\sigma^\downarrow(\boldsymbol{P}_T)}{d\sigma^\uparrow(\boldsymbol{P}_T) + d\sigma^\downarrow(\boldsymbol{P}_T)} = \frac{d\sigma^\uparrow(\boldsymbol{P}_T) - d\sigma^\uparrow(-\boldsymbol{P}_T)}{2\,d\sigma^{\rm unp}(\boldsymbol{P}_T)}\,, \tag{1.1}$$

where

$$d\sigma^{\uparrow,\downarrow} \equiv \frac{E_h\, d\sigma^{p^{\uparrow,\downarrow}\ell \to hX}}{d^3\boldsymbol{P}_h} \tag{1.2}$$

is the cross section for the inclusive process $p^{\uparrow,\downarrow}\ell \to hX$ with a transversely polarized proton with spin $\uparrow$ or $\downarrow$ w.r.t. the scattering plane [2]. For a generic transverse polarization along an azimuthal direction ϕ_S in the chosen reference frame, in which the $\uparrow$ direction is given by $\phi_S = \pi/2$, one has:

$$A(\phi_S, S_T) = \boldsymbol{S}_T \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{P}}_T)\, A_N = S_T \sin\phi_S\, A_N\,, \tag{1.3}$$

where $\boldsymbol{p}$ is the proton momentum. Notice that one simply has:

$$A_{TU}^{\sin\phi_S} \equiv \frac{2}{S_T}\, \frac{\int d\phi_S\, [d\sigma(\phi_S) - d\sigma(\phi_S+\pi)]\, \sin\phi_S}{\int d\phi_S\, [d\sigma(\phi_S) + d\sigma(\phi_S+\pi)]} = A_N\,. \tag{1.4}$$

Within a TMD factorization scheme for the process $p\ell \to hX$ with a single large scale (the final hadron transverse momentum P_T in the proton-lepton *c.m.* frame) the main contribution to A_N comes from the Sivers and Collins effects [2]:

$$A_N = \frac{\displaystyle\sum_{q,\{\lambda\}} \int \frac{dx\,dz}{16\pi^2 x z^2 s}\, d^2\boldsymbol{k}_\perp\, d^3\boldsymbol{p}_\perp\, \delta(\boldsymbol{p}_\perp \cdot \hat{\boldsymbol{p}}'_q)\, J(p_\perp)\, \delta(\hat{s}+\hat{t}+\hat{u})\, [\Sigma(\uparrow) - \Sigma(\downarrow)]^{q\ell\to q\ell}}{\displaystyle\sum_{q,\{\lambda\}} \int \frac{dx\,dz}{16\pi^2 x z^2 s}\, d^2\boldsymbol{k}_\perp\, d^3\boldsymbol{p}_\perp\, \delta(\boldsymbol{p}_\perp \cdot \hat{\boldsymbol{p}}'_q)\, J(p_\perp)\, \delta(\hat{s}+\hat{t}+\hat{u})\, [\Sigma(\uparrow) + \Sigma(\downarrow)]^{q\ell\to q\ell}}\,, \tag{1.5}$$

with

$$\begin{aligned}\sum_{\{\lambda\}} [\Sigma(\uparrow) - \Sigma(\downarrow)]^{q\ell\to q\ell} \;=\;& \frac{1}{2}\, \Delta^N f_{q/p^\uparrow}(x,k_\perp) \cos\phi\, \left[|\hat{M}_1^0|^2 + |\hat{M}_2^0|^2\right] D_{h/q}(z,p_\perp) \\ &+\; h_{1q}(x,k_\perp)\, \hat{M}_1^0 \hat{M}_2^0\, \Delta^N D_{h/q^\uparrow}(z,p_\perp)\, \cos(\phi' + \phi_q^h)\end{aligned} \tag{1.6}$$

$$\sum_{\{\lambda\}} [\Sigma(\uparrow)+\Sigma(\downarrow)]^{q\ell\to q\ell} = f_{q/p}(x,k_\perp)\,\left[|\hat{M}_1^0|^2+|\hat{M}_2^0|^2\right] D_{h/q}(z,p_\perp)\,. \tag{1.7}$$

All details can be found in Refs. [2, 3]. Here we simply recall some main features.

- $\boldsymbol{k}_\perp, \boldsymbol{p}_\perp$ are respectively the transverse momenta of the parton in the proton and of the final hadron w.r.t. the direction of the fragmenting parton, with momentum $\boldsymbol{p}'_q$. ϕ is the azimuthal angle of $\boldsymbol{k}_\perp$.

- The first term on the r.h.s. of Eq. (1.6) shows the contribution of the Sivers effect [9, 10],

$$\Delta\hat{f}_{q/p,S}(x,\boldsymbol{k}_\perp) \equiv \Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\boldsymbol{S}_T\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp) = -2\,\frac{k_\perp}{M}\,f_{1T}^{\perp q}(x,k_\perp)\,\boldsymbol{S}_T\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)\,. \tag{1.8}$$

  It couples to the unpolarized elementary interaction ($\propto (|\hat{M}_1^0|^2+|\hat{M}_2^0|^2)$) and the unpolarized fragmentation function $D_{h/q}(z,p_\perp)$; the $\cos\phi$ factor arises from the $\boldsymbol{S}_T\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$ factor.

- The second term on the r.h.s. of Eq. (1.6) represents the contribution to A_N of the unintegrated transversity distribution $h_{1q}(x,k_\perp)$ coupled to the Collins function $\Delta^N D_{h/q^\uparrow}(z,p_\perp)$ [11, 10],

$$\Delta\hat{D}_{h/q^\uparrow}(z,\boldsymbol{p}_\perp) \equiv \Delta^N D_{h/q^\uparrow}(z,p_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}'_q\times\hat{\boldsymbol{p}}_\perp) = \frac{2\,p_\perp}{z\,m_h}H_1^{\perp q}(z,p_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}'_q\times\hat{\boldsymbol{p}}_\perp)\,. \tag{1.9}$$

  This effect couples to the spin transfer elementary interaction ($d\hat{\sigma}^{q^\uparrow\ell\to q^\uparrow\ell}-d\hat{\sigma}^{q^\uparrow\ell\to q^\downarrow\ell}\propto \hat{M}_1^0\hat{M}_2^0$). The factor $\cos(\phi'+\phi_q^h)$ arises from phases in the $\boldsymbol{k}_\perp$-dependent transversity distribution, the Collins function and the elementary polarized interaction.

In HERMES paper [1] the lepton moves along the positive Z_{cm} axis. In this reference frame the $\uparrow$ ($\downarrow$) direction is still along the $+Y_{cm}$ ($-Y_{cm}$) axis as in Ref. [2] and only the sign of $x_F=2P_L/\sqrt{s}$ is reversed. More precisely the HERMES azimuthal dependent cross section is defined as [1]:

$$d\sigma = d\sigma_{UU}[1+S_T A_{UT}^{\sin\psi}\sin\psi]\,,\ \text{where}\ \ \sin\psi=\boldsymbol{S}_T\cdot(\hat{\boldsymbol{P}}_T\times\hat{\boldsymbol{k}}) \tag{1.10}$$

coincides with our $\sin\phi_S$ of Eq. (1.3), as $\boldsymbol{p}$ and $\boldsymbol{k}$ (the lepton momentum) are opposite vectors in the lepton-proton *c.m.* frame. Taking into account that "left" and "right" are interchanged in Refs. [2] and [1] (being defined looking downstream along opposite directions, $\boldsymbol{p}$ and $\boldsymbol{k}$) and the definition of x_F, one has:

$$A_{UT}^{\sin\psi}(x_F,P_T) = A_N^{p^\uparrow\ell\to hX}(-x_F,P_T)\,, \tag{1.11}$$

where $A_N^{p^\uparrow\ell\to hX}$ is the SSA in Eq. (1.5) [2], and $A_{UT}^{\sin\psi}$ is the quantity measured by HERMES [1].

2. Results

In the following, adopting the HERMES notation, we show our estimates based on two representative extractions of the Sivers and Collins functions: *i*) the Sivers functions from Ref. [12] (only up and down quarks), together with the first extraction of the transversity and Collins functions of Ref. [13] (SIDIS 1 in the following). In such studies the Kretzer set for the collinear fragmentation functions (FFs) [14] was adopted; *ii*) the Sivers functions from Ref. [15], where also the sea quark contributions were included, together with an updated extraction of the transversity and Collins functions [16] (SIDIS 2 in the following); in these cases we adopted another set for the FFs, namely that one by de Florian, Sassot and Stratmann (DSS) [17].

We consider both the fully inclusive measurements $\ell p \to \pi X$ at large P_T, as well as the sub-sample of data in which also the final lepton is tagged (SIDIS category). In the first case the only large scale is the P_T of the final pion, and for $P_T \simeq 1$ GeV, to avoid the low Q^2 region, one has to look at pion production in the backward proton hemisphere, ($x_F > 0$ in the HERMES conventions). For the tagged-lepton sub-sample data Q^2 is always bigger than 1 GeV^2 and P_T is still defined w.r.t. the lepton-proton direction.

In both cases (inclusive or SIDIS events) the Sivers and Collins effects are not separable.

• Fully inclusive case

Only one HERMES data bin covers moderately large P_T values, with $1 \lesssim P_T \lesssim 2.2$ GeV, and $\langle P_T \rangle \simeq$ 1-1.1 GeV. In Fig. 1 we show the results for π^+ (first and second panel) and π^- (third and fourth panel) production coming from SIDIS 1 and SIDIS 2 sets, for the Sivers (dotted blue lines) and Collins (dashed green lines) effects separately, together with their sum (solid red lines) and the envelope of the statistical error bands (shaded area): *i*) here the Collins effect is almost zero, as the partonic spin transfer in the backward proton hemisphere is dynamically suppressed [2], and the azimuthal phase (in the second term on the r.h.s. of Eq. (1.6)) oscillates strongly; *ii*) the Sivers effect does not suffer from any dynamical or azimuthal phase suppression. Indeed, in contrast to $pp \to \pi X$ processes in $\ell p \to \pi X$ only one partonic channel is at work and, for such moderate Q^2 values, the Sivers phase (ϕ) in the first term on the r.h.s. of Eq. (1.6) is still effective in the elementary interaction; *iii*) at this moderate c.m. energy, even in the backward hemisphere of the polarized proton, one probes its valence region, where the extracted Sivers functions are sizeable and well constrained; *iv*) in the backward proton hemisphere at large P_T, Q^2 is predominantly larger than 1 GeV^2 and we can neglect any contribution from quasi-real photo-production.

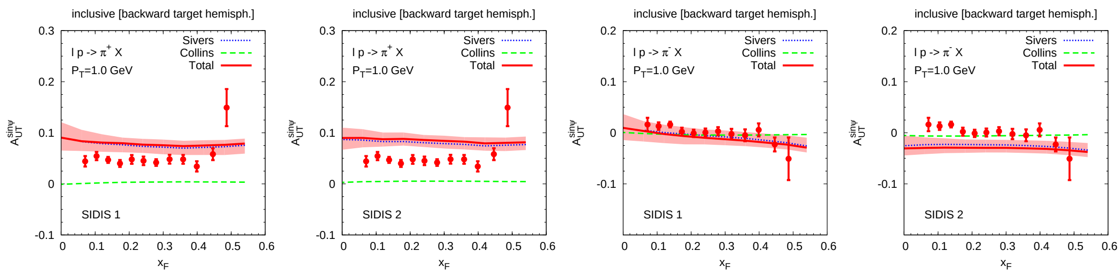

Figure 1: Theoretical estimates for $A_{UT}^{\sin\psi}$ vs. x_F at $P_T = 1$ GeV for inclusive π^+ (first and second panel) and π^- (third and fourth panel) production in $\ell p^\uparrow \to \pi X$ processes, computed according to Eqs. (1.11) and (1.5)–(1.7) of the text and compared with the HERMES data [1]. See the legend and text for details.

• Tagged or semi-inclusive category

We consider also the HERMES sub-sample data where the final lepton is tagged [1] with $Q^2 > 1$ GeV^2, $W^2 > 10$ GeV^2, $0.023 < x_B < 0.4$, $0.1 < y < 0.95$ and $0.2 < z_h < 0.7$ (standard SIDIS variables). We keep focusing only on the large P_T region, namely $P_T > 1$ GeV.

We show our estimates compared with HERMES data in Fig. 2, for positive and negative pion production as a function of P_T at fixed $x_F = 0.2$. Again, we show the contributions from the Sivers (dotted blue line) and Collins (dashed green line) effects separately and added together (solid red

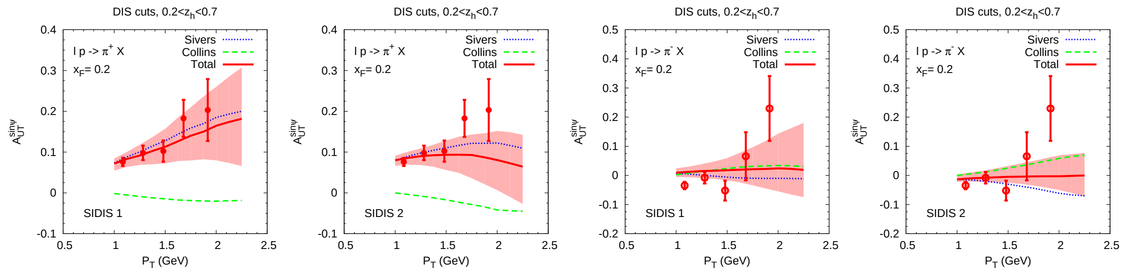

Figure 2: Theoretical estimates for $A_{UT}^{\sin\psi}$ vs. P_T at $x_F = 0.2$ for inclusive π^+ (first and second panel) and π^- (third and fourth panel) production for the lepton tagged events in $\ell\, p^{\uparrow} \to \pi X$ process, computed according to Eqs. (1.11) and (1.5)–(1.7) and compared with the HERMES data [1].

line) with the overall uncertainty bands (shaded area). Some comments follow: *i*) the Collins effect (dashed green lines) is only partially suppressed. The difference between the SIDIS 1 and the SIDIS 2 sets (a factor around 2-3) comes from the different behaviour of the quark transversity functions at moderately large x; *ii*) the Sivers effect (dotted blue lines) for π^+ production (1st and 2nd panel) is sizeable for both sets. On the other hand for π^- production the SIDIS 1 set (3rd panel) gives almost zero due to the strong cancellation between the unsuppressed Sivers up quark distribution coupled to the non-leading FF, with the more suppressed down quark distribution. For the SIDIS 2 set (4th panel), the same large x behaviour of the up and down quark implies no cancellation.

The results expected for JLab 12 at $P_T \simeq 1$ GeV are similar to those observed at HERMES [3].

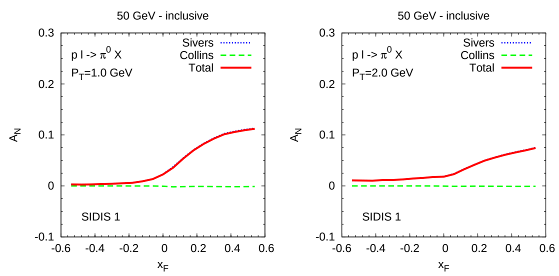

Figure 3: A_N vs. x_F at $\sqrt{s} \simeq 50$ GeV, $P_T = 1$ GeV (left panel) and $P_T = 2$ GeV (right panel) for $p^{\uparrow}\ell \to \pi^0 X$ (here a forward production w.r.t. the proton direction corresponds to $x_F > 0$).

Another interesting aspect is that at larger energies in a TMD scheme this process manifests some of the features of the SSAs in $p\,p \to \pi X$ [18, 4]. Switching now to the configuration where the polarized proton moves along Z_{cm}, i.e. with $x_F > 0$ in the forward hemisphere of $p^{\uparrow}$, in Fig. 3 we show some estimates of A_N for π^0 production at $\sqrt{s} = 50$ GeV adopting the SIDIS 1 set (able to reproduces the behaviour of A_N in $p^{\uparrow}p \to \pi X$ processes [19]). One can observe the following: *i*) the Collins effect in the backward region is totally negligible due to a strong suppression coming from the azimuthal phase integration. In the forward region both sets give tiny values; *ii*) the Sivers effect is sizeable and increasing with x_F for positive values of x_F, while negligible in the negative x_F region. Even if there is only one partonic channel, the weak dependence on the azimuthal phase of the elementary interaction at the large Q^2 values reached at these energies implies a strong suppression at $x_F < 0$. Notice that this behaviour is similar to that observed at various energies in A_N in $p^{\uparrow}p \to hX$ processes, being negligible at negative x_F and increasing with positive values of x_F; *iii*) when one exploits the relation between the Qiu-Sterman function and the Sivers function the twist-3 approach for A_N in $\ell\, p^{\uparrow} \to \text{jet} + X$ [20] gives results similar, in sign and size, to those obtained in a TMD approach [2]. However, the twist-3 collinear scheme, using the SIDIS Sivers functions, leads to values of A_N in $pp \to \pi X$ collisions opposite to those measured [21]. A recent analysis of A_N in pp scattering in the twist-3 formalism [22] aiming at solving this problem introduces new large effects in the fragmentation. It is not clear how much these same effects would change the value of A_N in ℓp processes when going from jet to π^0 production; *iv*) the measurements of SSAs at such large energies, possible at a future Electron-Ion-Collider (EIC) [23] would be an invaluable tool to test the TMD factorization and discriminate among different approaches.

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