Sivers function: SIDIS data, fits and predictions

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based on *Phys. Rev.* **D71** (2005) 074006 and hep-ph/0507181

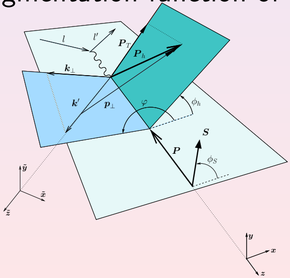
Outline of this talk

Polarized **SIDIS** and Sivers effect

Cross section of polarized **SIDIS**

$$\mathrm{d}\sigma^{lp^\uparrow \to lhX} = \sum_q f_{q/p^\uparrow}(x, \mathbf{k}_\perp, Q^2) \otimes \mathrm{d}\sigma^{lq^\uparrow \to lq^\uparrow} \otimes D^h_{q^\uparrow}(z, \mathbf{p}_\perp, Q^2)$$

where $f_{q/p^\uparrow}$ is the parton q distribution function, $D^h_{q^\uparrow}$ is the fragmentation function of parton q into a hadron h.



An asymmetry is defined as

$$\mathrm{A} = \frac{\mathrm{d}\sigma^{\Uparrow} - \mathrm{d}\sigma^{\Downarrow}}{\mathrm{d}\sigma^{\Uparrow} + \mathrm{d}\sigma^{\Downarrow}}$$

Let us consider a particular case of azimuthal modulations in parton density distribution, the so called **Sivers effect**.

D. Sivers, *Phys. Rev.* **D41** (1990) 83; *Phys. Rev.* **D43** (1991) 261

SIVERS EFFECT

Intrinsic transverse momentum $\mathbf{k}_\perp$ of partons inside the proton plays crucial role in Sivers effect. Unpolarized quark distributions inside a transversely polarized proton may be written as

PDF

$$
\begin{aligned}
f_{q/p^\uparrow}(x,\mathbf{k}_\perp) &= f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\mathbf{S}_T\cdot(\hat{\mathbf{P}}\times\hat{\mathbf{k}}_\perp) \\
&= f_{q/p}(x,k_\perp) - f_{1T}^{\perp q}(x,k_\perp)\,\frac{|\mathbf{k}_\perp|}{m_p}\sin(\varphi-\phi_S)
\end{aligned}
$$

where $\Delta^N f_{q/p^\uparrow}(x,k_\perp)$ is the so called Sivers function which must comply with the following positivity bound

$$
\left|\frac{\Delta^N f_{q/p^\uparrow}(x,k_\perp)}{2 f_{q/p}(x,k_\perp)}\right| \le 1
$$

SIVERS EFFECT

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PDF

$$f_{q/p^\uparrow}(x,\mathbf{k}_\perp) = f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\mathbf{S}_T\cdot(\hat{\mathbf{P}}\times\hat{\mathbf{k}}_\perp)$$
$$= f_{q/p}(x,k_\perp) - f_{1T}^{\perp q}(x,k_\perp)\,\frac{|\mathbf{k}_\perp|}{m_p}\sin(\varphi-\phi_S)$$

The arising SSA has the following form $A_{UT}^{sin(\phi_h-\phi_S)} =$

$$\frac{\sum_q \int d\{\phi_h\phi_S\mathbf{k}_\perp\}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\sin(\varphi-\phi_S)\frac{d\hat\sigma^{\ell q\to\ell q}}{dQ^2}J\frac{z}{z_h}D_q^h(z,\mathbf{p}_\perp)\sin(\phi_h-\phi_S)}{2\pi\sum_q\int d\phi_h\,d^2\mathbf{k}_\perp\;f_q(x,\mathbf{k}_\perp)\,\frac{d\hat\sigma^{\ell q\to\ell q}}{dQ^2}J\frac{z}{z_h}D_q^h(z,\mathbf{p}_\perp)}$$

We take into account dependence of parton distribution functions and fragmentation functions on intrinsic transverse momenta $k_\perp$ and $p_\perp$:

$$f_q(x, k_\perp^2) = f_q(x)\frac{1}{\pi\langle k_\perp^2\rangle} e^{-\frac{k_\perp^2}{\langle k_\perp^2\rangle}} ,$$

$$D_h^q(z, p_\perp^2) = D_h^q(z)\frac{1}{\pi\langle p_\perp^2\rangle} e^{-\frac{p_\perp^2}{\langle p_\perp^2\rangle}} ,$$

the unpolarised cross section becomes dependent on $\langle p_\perp^2\rangle$ and $\langle k_\perp^2\rangle$.

$$\frac{\mathrm{d}^5\sigma^{ep\to ehX}}{\mathrm{d}x\mathrm{d}y\mathrm{d}z P_T \mathrm{d}P_T \mathrm{d}\phi_h} \propto \{[1+(1-y)^2] - 4\frac{\sqrt{1-y}(2-y)\langle k_\perp^2\rangle z P_T}{(\langle p_\perp^2\rangle + z^2\langle k_\perp^2\rangle)Q}\cos(\phi_\mathrm{h})\} \cdot$$

$$\cdot f_q(x) D_h^q(z)\frac{1}{\pi\langle P_T^2\rangle} e^{-\frac{P_T^2}{\langle P_T^2\rangle}} + \mathcal{O}(k_\perp^2/Q^2) ,$$

where $\langle P_T^2\rangle = \langle p_\perp^2\rangle + z^2\langle k_\perp^2\rangle$

We take into account dependence of parton distribution functions and fragmentation functions on intrinsic transverse momenta $k_\perp$ and $p_\perp$:

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$$D_h^q(z, p_\perp^2) = D_h^q(z) \frac{1}{\pi \langle p_\perp^2 \rangle} e^{-\frac{p_\perp^2}{\langle p_\perp^2 \rangle}},$$

the unpolarised cross section becomes dependent on $\langle p_\perp^2 \rangle$ and $\langle k_\perp^2 \rangle$. Using unpolarised SIDIS data on $\cos(\phi_h)$ (Cahn effect) and P_T^2 dependence we obtain the values

$$\langle k_\perp^2 \rangle = 0.25 \text{ GeV}^2,$$
$$\langle p_\perp^2 \rangle = 0.2 \text{ GeV}^2$$

We take into account dependence of parton distribution functions and fragmentation functions on intrinsic transverse momenta $k_\perp$ and $p_\perp$:

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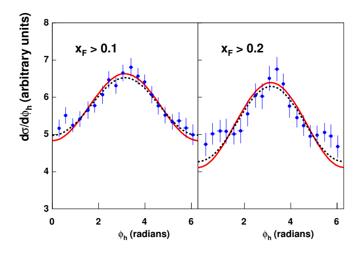
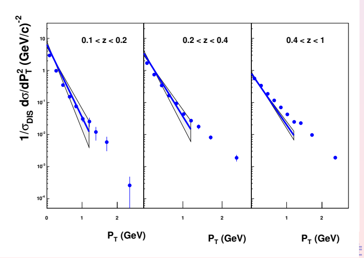
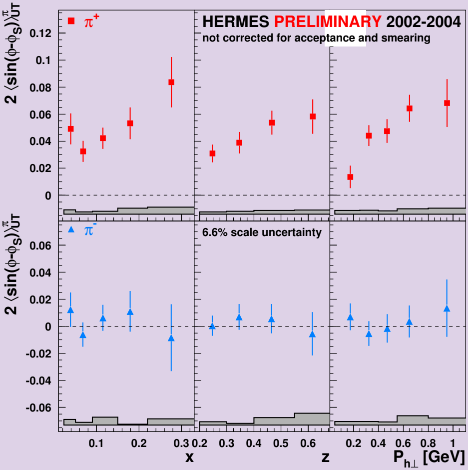
the unpolarised cross section becomes dependent on $\langle p_\perp^2 \rangle$ and $\langle k_\perp^2 \rangle$.





Experimental situation.

Sivers Moments $A_{UT}^{sin(\phi_h-\phi_S)}$



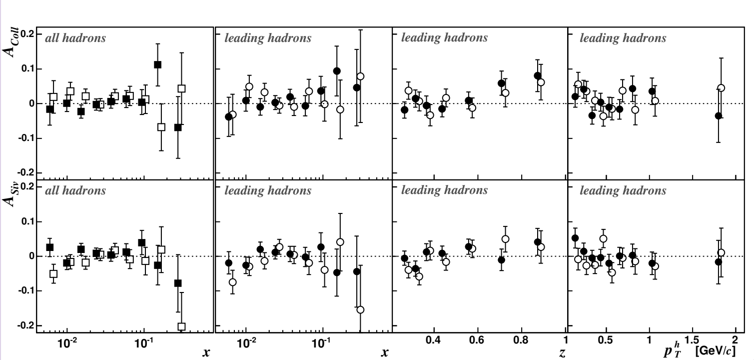
HERMES Collaboration. Hydrogen target. $E_e = 27.57$ GeV.

HERMES Collaboration, M. Diefenthaler, talk delivered at DIS 2005, Madison, Wisconsin (USA), April 27 -- May 1, e-Print Archive: hep-ex/0507013

Experimental situation

COMPASS Collaboration. Deuteron target. $E_\mu = 160$ GeV.

Sivers & Collins Moments



positive (full points) and negative (open points) hadrons

COMPASS Collaboration, *Phys. Rev. Lett.* **94** (2005) 202002

The model for the Sivers function

Let us use the following form for the Sivers functions:

$$\Delta^N f_{q/p^\uparrow}(x, k_\perp) = N_q(x) h(k_\perp) f_{q/p}(x, k_\perp) \ ,$$

Where $f_{q/p}(x)$ is parton q distribution function,

$$N_q(x) = N_q x^{a_q}(1-x)^{b_q} \frac{(a_q+b_q)^{(a_q+b_q)}}{a_q^{a_q} b_q^{b_q}} \ ,$$

$$h(k_\perp) = \sqrt{2e}\,\frac{k_\perp}{M}\, e^{-k_\perp^2/M^2} \text{ or } h(k_\perp) = \frac{2k_\perp M_0}{k_\perp^2 + M_0^2} \ ,$$

where N_q, a_q, b_q and M_0 (GeV/c) are parameters and $q = u, d$.
For the sea quark contributions we assume:

$$\Delta^N f_{q_s/p^\uparrow}(x, k_\perp) = 0$$

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Where $f_{q/p}(x)$ is parton q distribution function,

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We use

$$h(k_\perp) = \frac{2 k_\perp M_0}{k_\perp^2 + M_0^2} \; ,$$

where N_q, a_q, b_q and M_0 (GeV/c) are parameters and $q = u, d$.

$A_{UT}^{sin(\phi_h-\phi_S)}$ approximate result

$$A_{UT}^{\sin(\phi_h-\phi_S)}(x_B, z_h, P_T) \simeq \frac{\Delta\sigma_{\rm siv}}{\sigma_0},$$

$$\Delta\sigma_{\rm siv}(x_B, y, z_h, P_T) = \frac{2\pi\alpha^2}{x_B\, y^2 s} \sum_q e_q^2\, 2\mathcal{N}_q(x_B)\, f_q(x_B)\, D_q^h(z_h)\, \left[1+(1-y)^2\right]$$

$$\cdot\, z_h P_T \frac{\sqrt{2e}\,\widehat{\langle k_\perp^2\rangle}^2}{M\,\widehat{\langle P_T^2\rangle}^2 \langle k_\perp^2\rangle} \exp\left(-\frac{P_T^2}{\widehat{\langle P_T^2\rangle}}\right),$$

$$\sigma_0(x_B, y, z_h, P_T) = 2\pi \frac{2\pi\alpha^2}{x_B\, y^2 s} \sum_q e_q^2\, f_q(x_B)\, D_q^h(z_h)\, \left[1+(1-y)^2\right]$$

$$\cdot\, \frac{1}{\pi\langle P_T^2\rangle} \exp\left(-\frac{P_T^2}{\langle P_T^2\rangle}\right),$$

where

$$\widehat{\langle k_\perp^2\rangle} = \frac{M^2\,\langle k_\perp^2\rangle}{M^2+\langle k_\perp^2\rangle}, \quad \widehat{\langle P_T^2\rangle} = \langle p_\perp^2\rangle + z^2\,\widehat{\langle k_\perp^2\rangle}.$$

$A_{UT}^{sin(\phi_h-\phi_S)}$ approximate result

$$A_{UT}^{\sin(\phi_h-\phi_S)}(x_B, z_h, P_T) \simeq \frac{\Delta\sigma_{\mathrm{siv}}}{\sigma_0} \,,$$

$$\Delta\sigma_{\mathrm{siv}}(x_B, y, z_h, P_T) = \frac{2\pi\alpha^2}{x_B\, y^2 s} \sum_q e_q^2\, 2\mathcal{N}_q(x_B)\, f_q(x_B)\, D_q^h(z_h)\left[1+(1-y)^2\right]$$

$$\cdot\, z_h P_T \frac{\sqrt{2e}\,\widehat{\langle k_\perp^2\rangle}^2}{M\,\widehat{\langle P_T^2\rangle}^2 \langle k_\perp^2\rangle} \exp\left(-\frac{P_T^2}{\widehat{\langle P_T^2\rangle}}\right),$$

$$\sigma_0(x_B, y, z_h, P_T) = 2\pi\frac{2\pi\alpha^2}{x_B\, y^2 s} \sum_q e_q^2\, f_q(x_B)\, D_q^h(z_h)\left[1+(1-y)^2\right]$$

$$\cdot\, \frac{1}{\pi\langle P_T^2\rangle} \exp\left(-\frac{P_T^2}{\langle P_T^2\rangle}\right),$$

$A_{UT}^{\sin(\phi_h-\phi_S)} \propto z_h P_T$ and $A_{UT}^{\sin(\phi_h-\phi_S)} = 0$ when $z_h = 0$ or $P_T = 0$.

Description of $A_{UT}^{sin(\phi_h-\phi_S)}$

$N_u =$	0.33 ± 0.13	$N_d =$	-1.00 ± 0.11
$a_u =$	0.28 ± 0.34	$a_d =$	1.19 ± 0.46
$b_u =$	0.46 ± 2.71	$b_d =$	3.99 ± 4.14
$M_0^2 =$	$0.32 \pm 0.26\ (\mathrm{GeV}/c)^2$	$\chi^2/d.o.f. =$	1.08

Table: Best values of the parameters of the Sivers functions.

Sivers functions are better constrained by current data on $A_{UT}^{sin(\phi_h-\phi_S)}$.

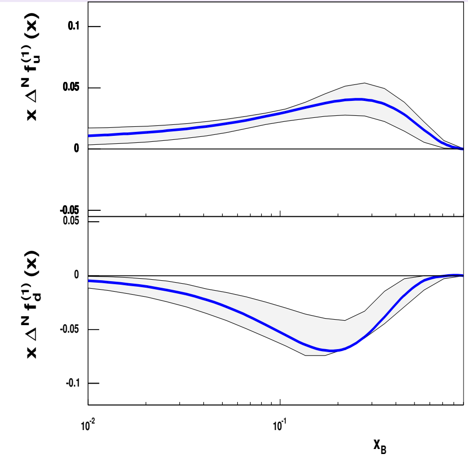
It is interesting to compare the Sivers functions obtained here, with those obtained by fitting the SSA observed by the E704 Collaboration in $p^\uparrow p \to \pi X$ processes:

$$N_u = 0.4, a_u = 3.0, b_u = 0.6$$

$$N_d = -1.0, a_d = 3.0, b_d = 0.5$$

Comparison of Sivers functions

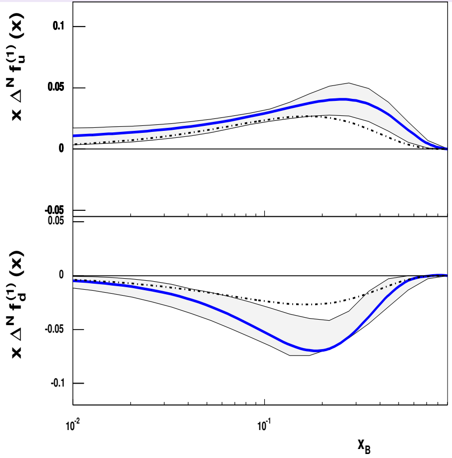
$$\Delta^N f_q^{(1)}(x) \equiv \int d^2 \mathbf{k}_\perp \frac{k_\perp}{4m_p} \Delta^N f_{q/p^\uparrow}(x, k_\perp) = -f_{1T}^{\perp(1)q}(x) \, .$$



The x-dependence of the first $\mathbf{k}_\perp$ moment of the extracted Sivers functions for u and d quarks are shown

Comparison of Sivers functions

$$\Delta^N f_q^{(1)}(x) \equiv \int d^2 \mathbf{k}_\perp \frac{k_\perp}{4m_p} \Delta^N f_{q/p^\uparrow}(x, k_\perp) = -f_{1T}^{\perp(1)q}(x) \, .$$



The dot-dashed line show the first $\mathbf{k}_\perp$ moments of the Sivers functions obtained in A.V. Efremov, K. Goeke, S. Menzel, A. Metz and P. Schweitzer, *Phys. Lett.* **B612** (2005) 233

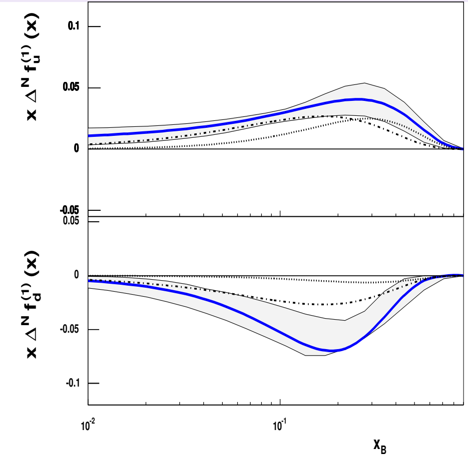
An assumption

$$f_{1T}^{\perp(1)d}(x) = -f_{1T}^{\perp(1)u}(x)$$

was made.

Comparison of Sivers functions

$$\Delta^N f_q^{(1)}(x) \equiv \int d^2\, \mathbf{k}_\perp \frac{k_\perp}{4m_p} \Delta^N f_{q/p^\uparrow}(x, k_\perp) = -f_{1T}^{\perp(1)q}(x)\,.$$

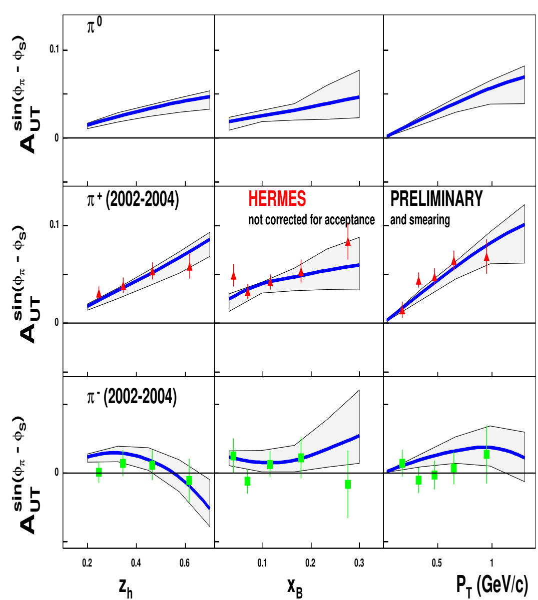


The dotted line show the first $\mathbf{k}_\perp$ moments of the Sivers functions obtained in

F. Yuan, *Phys. Lett.* **B575** (2003) 45

$f_{1T}^{\perp(1)d}(x)$ is negligible.

Description of HERMES data



PDF: MRST LO 2001

Phys. Lett. **B531** (2002) 216

FF: Kretzer

Phys. Rev. D62 (2000) 054001

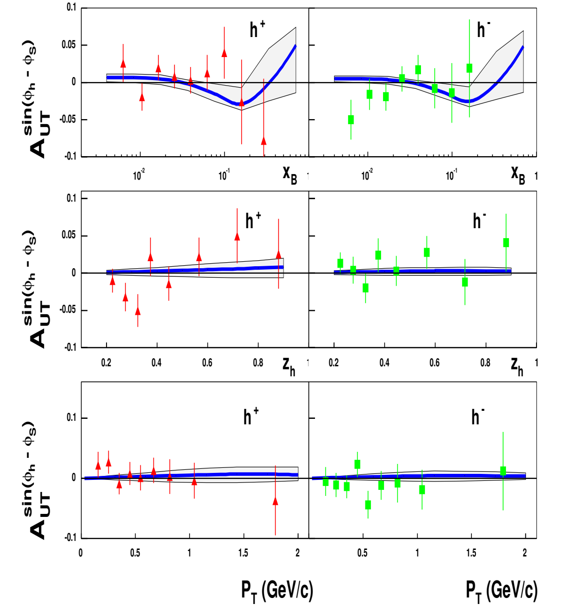
$ep \rightarrow e\pi X$

Cuts

$Q^2 > 1\ \mathrm{GeV}^2$,
$W^2 > 10\ \mathrm{GeV}^2$,
$0.023 < x_B < 0.4$,
$0.2 < z_h < 0.7$,
$0.1 < y < 0.85$,
$P_T > 0.05\ \mathrm{GeV}$

The blue line corresponds to the result of the fit.

Description of COMPASS data



PDF: MRST LO 2001

Eur. Phys. J. C4 (1998) 463

FF: Kretzer

Phys. Rev. D62 (2000) 054001

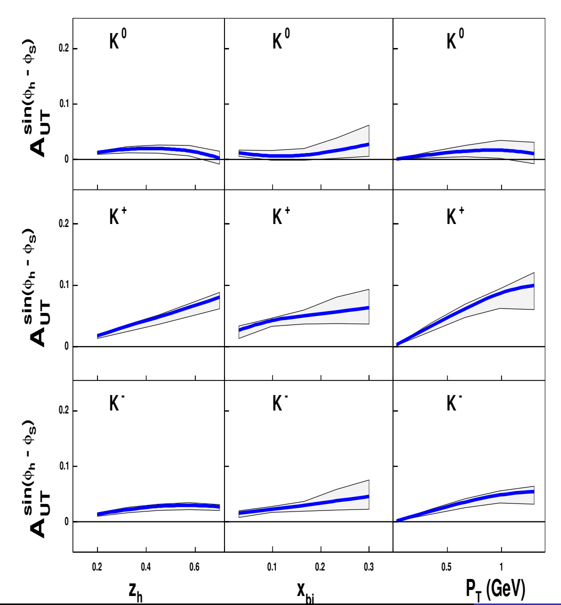
$\mu D \to \mu h^{\pm} X$

Cuts

$Q^2 > 1$ GeV^2,
$W^2 > 25$ GeV^2,
$0 < x_B < 1$,
$0.2 < z_h < 1$,
$0.1 < y < 0.9$,
$P_T > 0.1$ GeV

The blue line corresponds to the result of the fit.

Predictions of $A_{UT}^{sin(\phi_h-\phi_S)}$ at HERMES

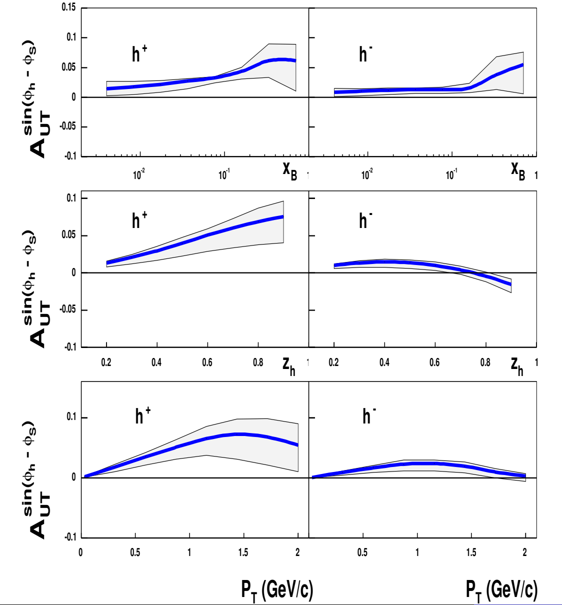


$ep \to e\mathbf{K}X$

All parameters are fixed

Predictions of asymmetry in Kaon production at HERMES.

Predictions for COMPASS



PROTON TARGET

$\mu p \to \mu h^{\pm} X$

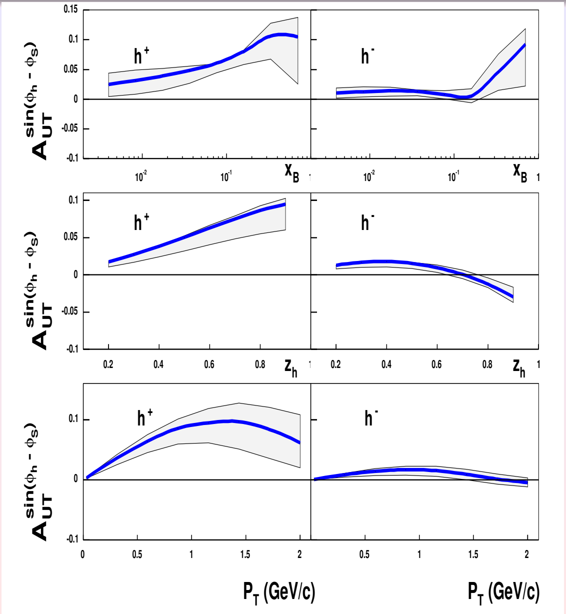
Cuts

$0.2 < z_h < 1$,

$P_T > 0.1$ GeV

Asymmetry is around 5%

Predictions for COMPASS



PROTON TARGET
$\mu p \to \mu h^{\pm} X$

NEW Cuts

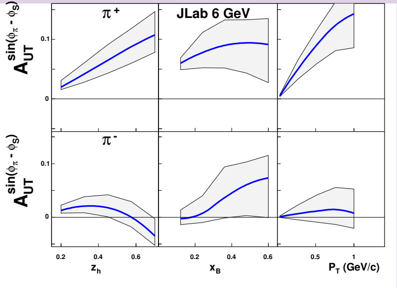
$0.02 < x_B < 1$,
$0.4 < z_h < 1$,
$P_T > 0.2$ GeV

Changed cuts provide higher values of the asymmetry. One should find a compromise between statistic and effect significance.

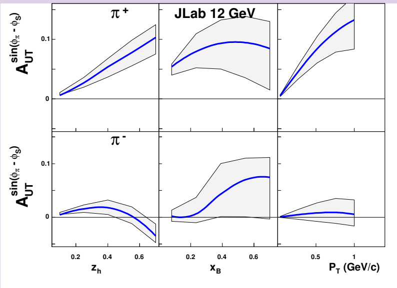
Predictions for JLab

JLab. Hydrogen target.

Sivers $A_{UT}^{sin(\phi_h-\phi_S)}$, 6 GeV



Sivers $A_{UT}^{sin(\phi_h-\phi_S)}$, 12 GeV



High values of asymmetry are expected for π^+ production.
Region of high $x_{Bj} > 0.4$ will be explored giving a possibility to constrain behaviour of Sivers functions.

Single spin asymmetries in Drell-Yan processes

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \,,$$

for Drell-Yan processes, $p^\uparrow \, p \to \ell^+ \, \ell^- \, X$, $p^\uparrow \, \bar{p} \to \ell^+ \, \ell^- \, X$ and $\bar{p}^\uparrow \, p \to \ell^+ \, \ell^- \, X$, where $d\sigma$ stands for

$$\frac{d^4\sigma}{dy \, dM^2 \, d^2\mathbf{q}_T}$$

and y, M^2 and $\mathbf{q}_T$ are respectively the rapidity, the squared invariant mass and the transverse momentum of the lepton pair in the initial nucleon c.m. system.

Single spin asymmetries in Drell-Yan processes

Single spin asymmetry can only originate from the Sivers function and is given by

M. Anselmino, U. D'Alesio and F. Murgia, *Phys. Rev.* **D67** (2003) 074010

$$\frac{\sum_q e_q^2 \int d^2\mathbf{k}_{\perp q}\, d^2\mathbf{k}_{\perp \bar{q}}\, \delta^2(\mathbf{k}_{\perp q} + \mathbf{k}_{\perp \bar{q}} - \mathbf{q}_T)\, \Delta^N f_{q/p^\uparrow}(x_q, \mathbf{k}_{\perp q})\, f_{\bar{q}/p}(x_{\bar{q}}, \mathbf{k}_{\perp \bar{q}})}{2\sum_q e_q^2 \int d^2\mathbf{k}_{\perp q}\, d^2\mathbf{k}_{\perp \bar{q}}\, \delta^2(\mathbf{k}_{\perp q} + \mathbf{k}_{\perp \bar{q}} - \mathbf{q}_T)\, f_{q/p}(x_q, \mathbf{k}_{\perp q})\, f_{\bar{q}/p}(x_{\bar{q}}, \mathbf{k}_{\perp \bar{q}})},$$

where $q = u, \bar{u}, d, \bar{d}, s, \bar{s}$ and

$$x_q = \frac{M}{\sqrt{s}}\, e^y \qquad x_{\bar{q}} = \frac{M}{\sqrt{s}}\, e^{-y}.$$

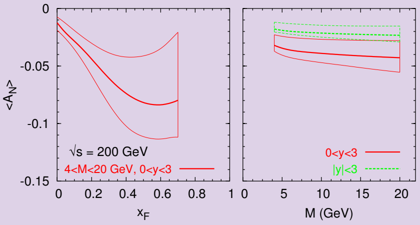
We use the relation

$$\Delta^N f_{q/p^\uparrow}(x, k_\perp)_{D-Y} = -\Delta^N f_{q/p^\uparrow}(x, k_\perp)_{SIDIS}$$

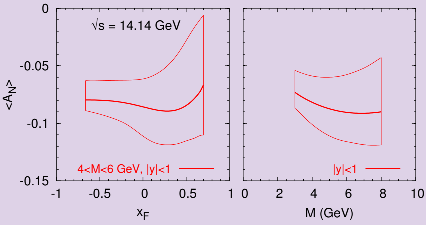
J.C. Collins, *Phys. Lett.* **B536** (2002) 43

Predictions for RHIC and GSI

RHIC, $p^{\uparrow}\, p \to \ell^+\, \ell^-\, X$, 200 GeV



GSI, $p^{\uparrow}\, \bar{p} \to \ell^+\, \ell^-\, X$, 14.14 GeV



A_N is plotted as a function of x_F and M. The lepton pair transverse momentum has been integrated in the range $0 \leq q_T \leq 1$ GeV.

CONCLUSIONS

- Estimates of the Sivers functions for u and d quarks have been obtained. These turn out to be definitely different from zero.
- Prediction for Kaon and π^0 asymmetries for HERMES experiment are given. K^+ and π^0 asymmetries are expected to be sizable.
- A sizeable asymmetry should be measured by COMPASS collaboration once a transversely polarized hydrogen target measurement is done.
- Large values of $A_{UT}^{\sin(\phi_h-\phi_S)}$ are expected at JLab, both in the 6 and 12 GeV operational modes, for π^+ inclusive production.
- QCD relation $\Delta^N f_{q/p^\uparrow}(x,k_\perp)_{D-Y} = -\Delta^N f_{q/p^\uparrow}(x,k_\perp)_{SIDIS}$ was used to compute the single spin asymmetries in Drell-Yan processes. The predicted A_N could be measured at RHIC in $p\,p$ collisions and at the proposed PAX experiment at GSI, in $p\,\bar{p}$ interactions. It would provide a clear test of basic QCD properties.

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CONCLUSIONS

- Estimates of the Sivers functions for u and d quarks have been obtained. These turn out to be definitely different from zero.
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THANK YOU!

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