# Extracting the Sivers function from polarized SIDIS data and making predictions

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

# Outline of this talk

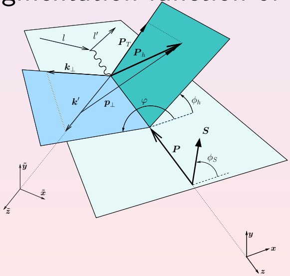
1. Polarized **SIDIS**
   - Sivers Effect
   - Experimental situation
   - The model
2. Results
   - Sivers functions
   - Description of HERMES data
   - Description of COMPASS data
   - Predictions for HERMES
   - Predictions for COMPASS
   - Predictions for JLab
   - Single spin asymmetries in Drell-Yan processes
3. Conclusions

# 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

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

# SIVERS EFFECT

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$$= f_{q/p}(x,k_\perp) - f_{1T}^{\perp q}(x,k_\perp)\,\frac{|\mathbf{k}_\perp|}{m_p}\sin(\varphi-\phi_S)$$

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 $\langle k_\perp^2 \rangle$.

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

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

$$\textit{where} \quad \langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_\perp^2 \rangle$$

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 $\cos(\phi_\mathrm{h})$ (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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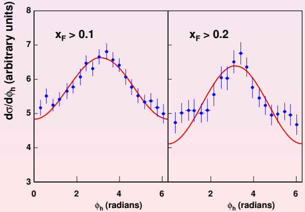
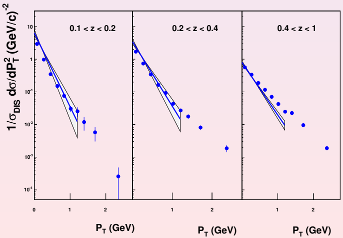
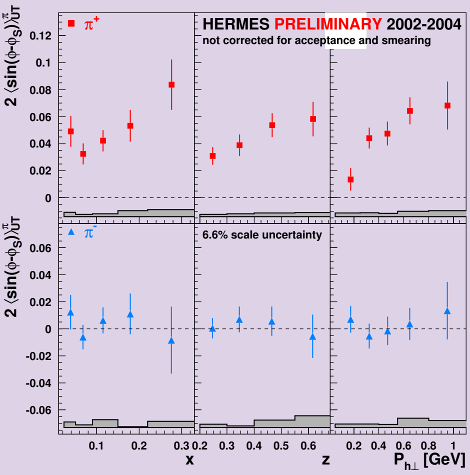
the unpolarised cross section becomes dependent on $\langle p_\perp^2 \rangle$ and $\langle k_\perp^2 \rangle$.



# Experimental situation.

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



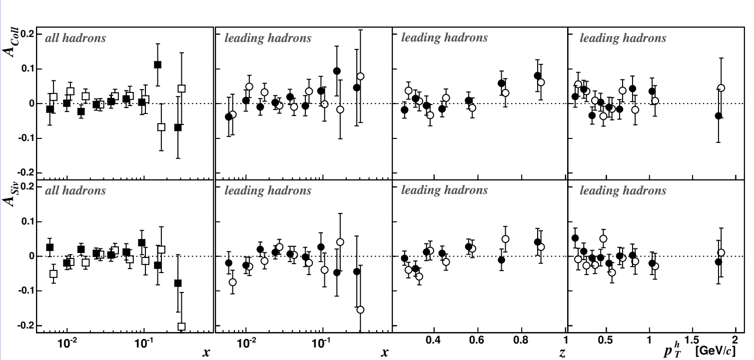

HERMES Collaboration. Hydrogen target. $E_e = 27.57$ GeV.

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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**We use**

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

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

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

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

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

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

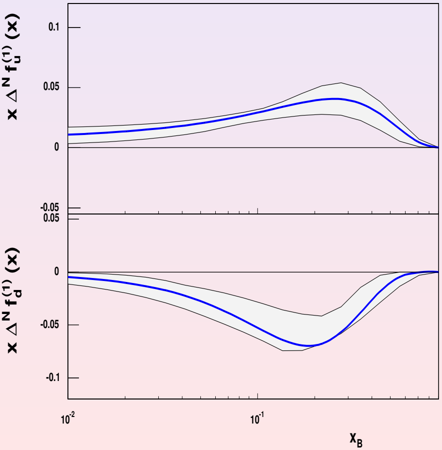
Table: Best values of the parameters of the Sivers functions.

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

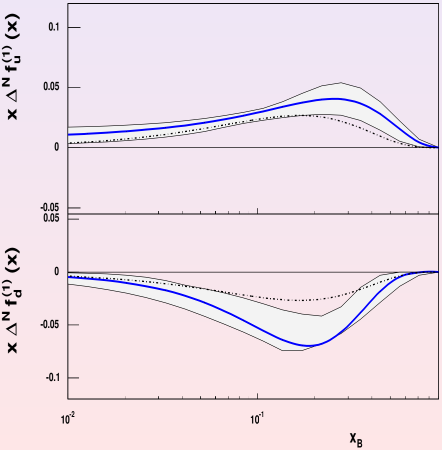
$$\Delta^N f_q^{(1)}(x) \equiv \int d^2\mathbf{k}_\perp \frac{k_\perp}{4m_p}\Delta^N f_{q/p^\uparrow}(x, k_\perp) = -f_{1T}^{\perp(1)q}(x)\,.$$




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

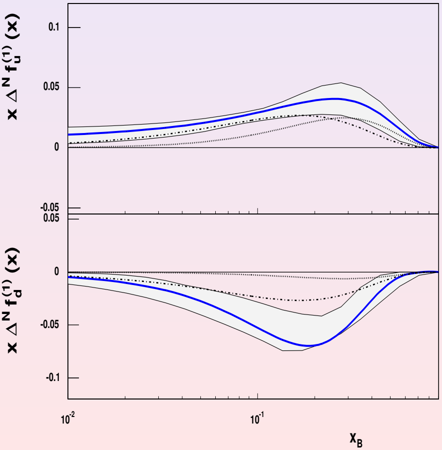
An assumption

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

was made.

# Comparison of Sivers functions

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

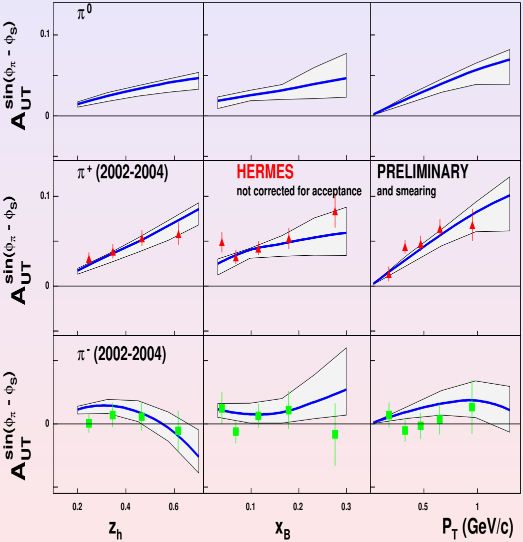



The dotted line show the first $\mathbf{k}_\perp$ moments of the Sivers functions obtained in

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

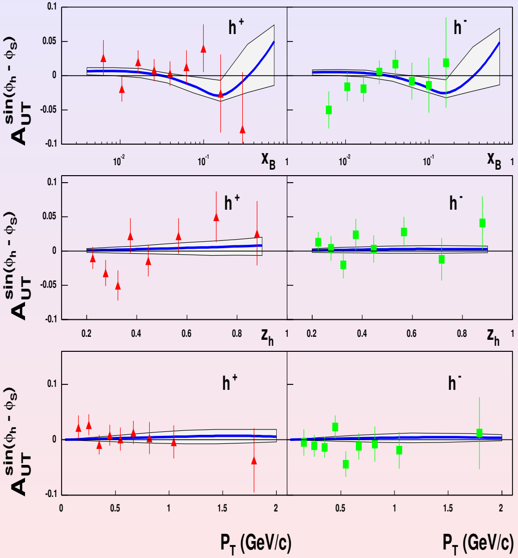
$ep \to e\pi X$

## 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`

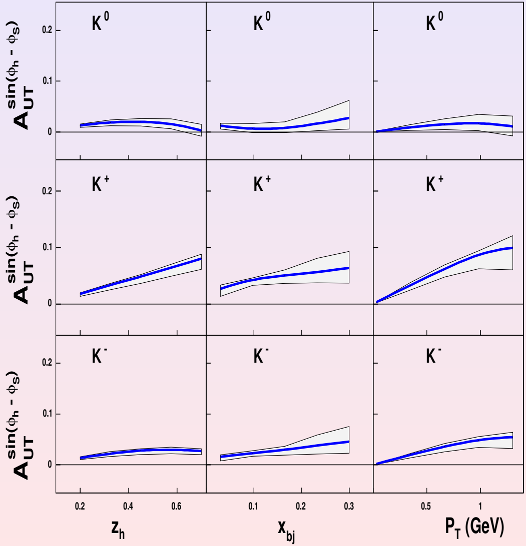
$\mu D \to \mu h^{\pm} X$

## Cuts

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

The blue line corresponds to the result of the fit.

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

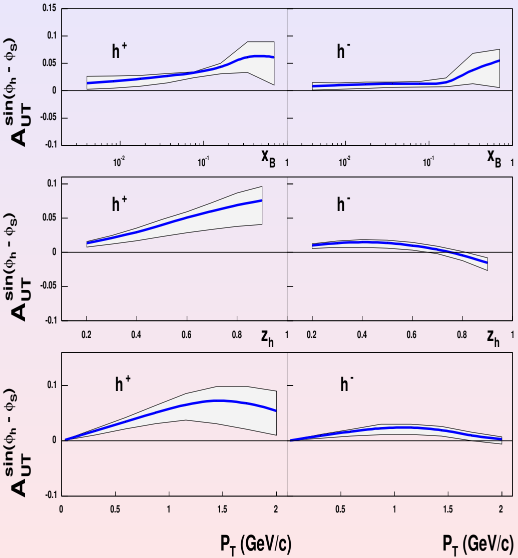



*ep* → *e***K***X*

All parameters are fixed

Predictions of asymmetry in Kaon production at HERMES.

# Predictions for COMPASS




PROTON TARGET

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

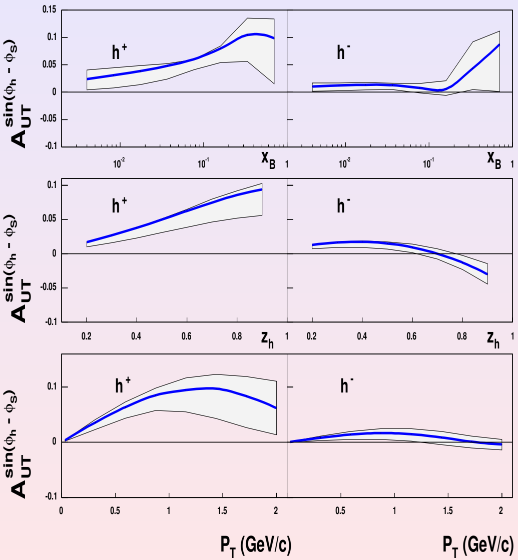
## Cuts

$0.2 < z_h < 1,$

$P_T > 0.1$ GeV

Asymmetry is around 5%

# Predictions for COMPASS




PROTON TARGET

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

**NEW Cuts**

$0.02 < x_{\rm B} < 1$,

$0.4 < z_h < 1$,

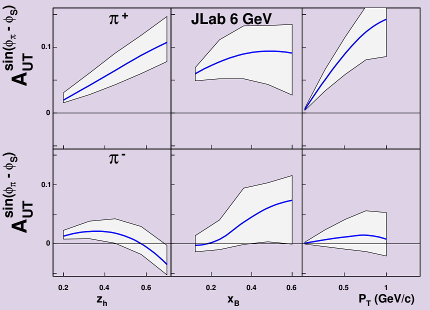
$P_T > 0.2$ GeV

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

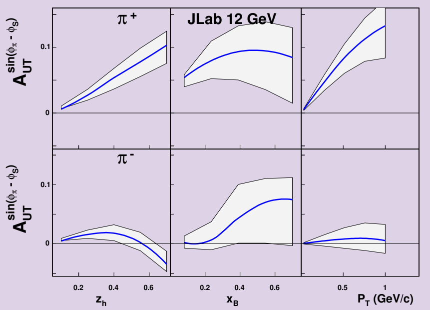
# Predictions for JLab

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 $\pi^+$ 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

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

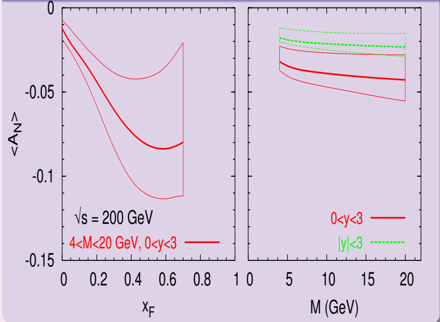
We use the relation

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

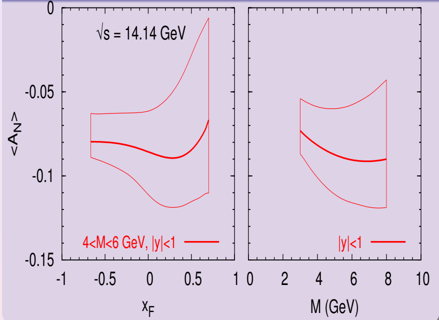
J.C. Collins, *Phys. Lett.* **B536** (2002) 43

# 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 $0 \le q_T \le 1$ 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 $\pi^0$ asymmetries for HERMES experiment are given. $K^+$ and $\pi^0$ 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 $\pi^+$ 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

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