The rôle of Cahn and Sivers effects in Deep Inelastic Scattering

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In collaboration with M. Anselmino, E. Boglione, U. D'Alessio, F. Murgia, and A. Kotzinian

Phys. Rev. **D71** (2005) 074006, hep-ph/0501196

Outline of this talk

Unpolarized SIDIS

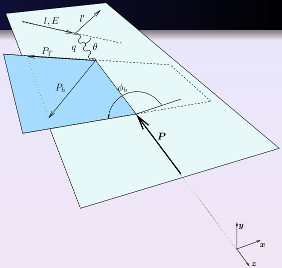
Cross section of SIDIS

$$d\sigma^{lp\to lhX} = \sum_q f_q(x, Q^2) \otimes d\sigma^{lq\to lq} \otimes D_q^h(z, Q^2) \,,$$

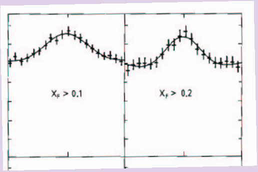
where f_q is the parton q distribution function, D_q^h is the fragmentation function of parton q into a hadron h.
In collinear parton model we have

$$\sigma^{lq\to lq} \propto \hat{s}^2 + \hat{u}^2 \propto 1 + (1-y)^2$$

thus no dependence on azimuthal angle ϕ_h at first order of PT.
The experimental data reveal that
$d\sigma^{lp\to lh^{\pm}X}/d\phi_h \propto \mathrm{A} + \mathrm{B}\cdot\cos(\phi_\mathrm{h}) + \mathrm{D}\cdot\cos(2\phi_\mathrm{h})$



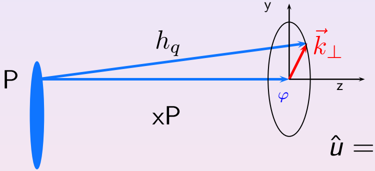
EMC data



M. Arneodo et al (EMC): Measurement of hadron azimuthal distributions, Z. Phys. C 34 (1987) 277

Intrinsic $k_\perp$

Robert Cahn[1] introduced parton intrinsic transverse momentum $k_\perp$, parton momentum $h_q = xP + k_\perp$, where $k_\perp = (0, k_\perp cos(\varphi), k_\perp sin(\varphi), 0)$



$$\hat{s} = sx\left[1 - \frac{2k_\perp}{Q}\sqrt{1-y}\cdot\cos(\varphi)\right] + \mathcal{O}\left(\frac{k_\perp^2}{Q}\right)$$

$$\hat{u} = sx(1-y)\left[1 - \frac{2k_\perp}{Q\sqrt{1-y}}\cdot\cos(\varphi)\right] + \mathcal{O}\left(\frac{k_\perp^2}{Q}\right)$$

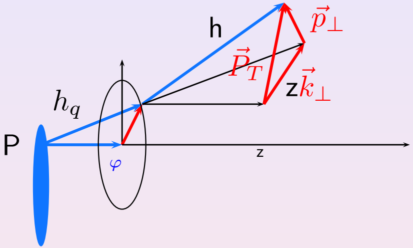
Hence (assuming collinear fragmentation, $\phi_h = \varphi$)

$$\frac{d\sigma_{ep\to ehX}}{d\phi_h} \propto \hat{s}^2 + \hat{u}^2 \propto \mathrm{A} + \mathrm{B}\cdot\cos(\phi_\mathrm{h}) + \mathrm{D}\cdot\cos(2\phi_\mathrm{h})$$

and these modulations of the cross section with azimuthal angle are called **Cahn effect**.

[1] R. Cahn, Phys. Lett. B 78 (1978) 269; Phys. Rev. D 40 (1989) 3107

The situation is more complicated as the produced hadron may also have intrinsic transverse momentum with respect to the fragmenting parton.



Hadron transverse momentum $\vec{P}_T = \vec{p}_\perp + z\vec{k}_\perp$, and $\vec{p}_\perp$ is an analog of $\vec{k}_\perp$ but enters in D_h^q.

$$f_q(x, \vec{k}_\perp) \equiv f_q(x, k_\perp^2)\ ,$$
$$D_h^q(z, \vec{p}_\perp) \equiv D_h^q(z, p_\perp^2)\ ,$$

we obtain

$$\frac{d\sigma_{ep\to ehX}}{d\phi_h} \propto \int \mathrm{d}^2 k_\perp \{[1+(1-y)^2] f_q(x, k_\perp^2) D_h^q(z, (\vec{P}_T - z\vec{k}_\perp)^2) -$$
$$-4\sqrt{1-y}(2-y)\frac{k_\perp \cos(\varphi)}{Q} f_q(x, k_\perp^2) D_h^q(z, (\vec{P}_T - z\vec{k}_\perp)^2)\} + \mathcal{O}\left(\frac{k_\perp^2}{Q^2}\right)$$

Let us assume that $k_\perp$ and $p_\perp$ distributions have the following form

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

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

then we can integrate the previous formula and obtain

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

$$\cdot f_q(x) D_h^q(z) \frac{1}{\pi \langle P_T^2 \rangle} e^{-\frac{P_T^2}{\langle P_T^2 \rangle}} ,$$

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

$\langle p_\perp^2 \rangle$ & $\langle k_\perp^2 \rangle$ are essential ingredients for SSA in SIDIS.

One must describe the data on unpolarized SIDIS before describing SSA.

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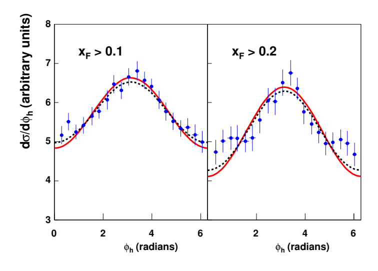
$\langle p_\perp^2\rangle$ & $\langle k_\perp^2\rangle$ are essential ingredients for SSA in SIDIS.
One must describe the data on unpolarized SIDIS before describing SSA.

Cahn Effect

We choose the values for parameters $\langle k_\perp^2 \rangle$ and $\langle p_\perp^2 \rangle$:
$\langle k_\perp^2 \rangle = 0.25$ GeV^2
$\langle p_\perp^2 \rangle = 0.2$ GeV^2
and obtain the following description of angular dependence: ϕ_h dependence was measured by **EMC** at **CERN** in μp and μd scattering at incident beam energies between 100 and 280 GeV.

EMC data



The dashed line corresponds to complete kinematics, the red line up to $\mathcal{O}\left(\frac{k_\perp}{Q}\right)$ terms.

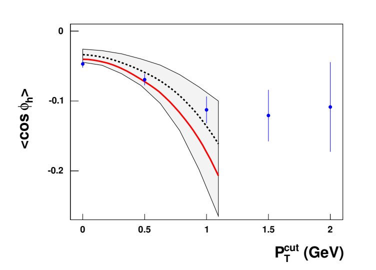
M. Arneodo et al (EMC): Measurement of hadron azimuthal distributions, Z. Phys. C 34 (1987) 277

Cahn Effect

Another feature measured in experiment is

$$\langle\cos(\phi_h)\rangle = \frac{\int \sigma \cos(\phi_h) d\phi_h}{\int \sigma d\phi_h} = \frac{B}{2A}$$

E665 data



The data are from **E665** at Fermilab, $E_{lab} = 490$ GeV. At low P_T^{cut} (σ is integrated on P_T from P_T^{cut} to P_T^{max}) the contribution from nonperturbative intrinsic momentum is dominating, $\gamma^* q \to qg$, $\gamma^* g \to q\bar{q}$ and other perturbative QCD effects dominate at high P_T^{cut}.
The shadowed region corresponds to varying
$\langle k_\perp^2 \rangle$ and $\langle p_\perp^2 \rangle$ by 20%

Cahn Effect

Another feature measured in experiment is

$$\langle\cos(\phi_{\rm h})\rangle = \frac{\int \sigma \cos(\phi_{\rm h}) {\rm d}\phi_{\rm h}}{\int \sigma {\rm d}\phi_{\rm h}} = \frac{\rm B}{\rm 2A}$$

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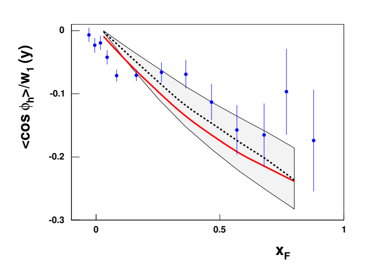
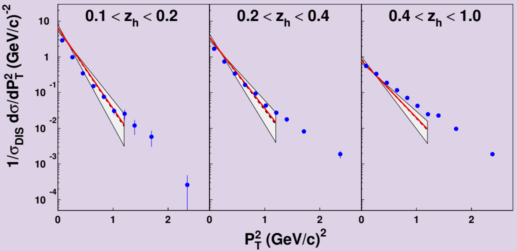


The data are from **EMC** at CERN.
$\langle\cos(\phi_{\rm h})\rangle$ is presented as a function of x_F,
$w_1(y) = \frac{(2-y)\sqrt{1-y}}{1+(1-y)^2}$.
The shadowed region corresponds to varying
$\langle k_\perp^2\rangle$ and $\langle p_\perp^2\rangle$ by 20%

P_T^2 dependence

P_T^2 dependence was measured by **EMC** at **CERN** in μp and μd scattering at incident beam energies between 100 and 280 GeV.

EMC data: J. Ashman et al (EMC) Z. Phys. C 52 (1991) 361-387



At first order
$\langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_\perp^2 \rangle$
The dashed line corresponds to complete kinematics, the red line up to $\mathcal{O}\left(\frac{k_\perp}{Q}\right)$ terms, the shadowed region corresponds to varying $\langle k_\perp^2 \rangle$ and $\langle p_\perp^2 \rangle$ by 20%

We conclude that using the unpolarised data one can fix the values for parameters $\langle k_\perp^2 \rangle$ and $\langle p_\perp^2 \rangle$:
$\langle k_\perp^2 \rangle = 0.25\ \text{GeV}^2$, $\langle p_\perp^2 \rangle = 0.2\ \text{GeV}^2$

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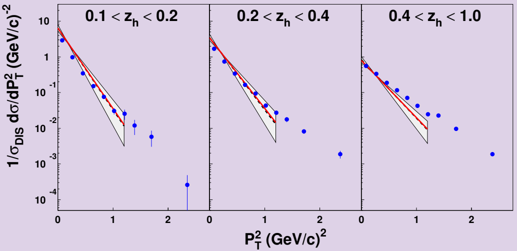

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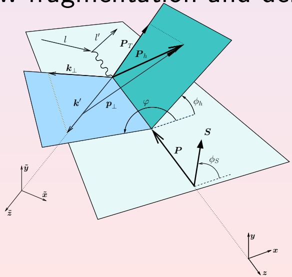
$\langle k_\perp^2 \rangle = 0.25$ GeV^2, $\langle p_\perp^2 \rangle = 0.2$ GeV^2

Polarized **SIDIS** and Sivers effect

Cross section of polarized **SIDIS**

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

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. The structure of cross sections becomes more complicated due to presence of new fragmentation and density functions.



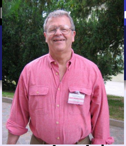
An asymmetry is defined as

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

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

See, for example, A. Kotzinian Nucl. Phys. B 441 (1995) 234-356

SIVERS EFFECT



Unpolarized quark distributions inside a transversely polarized proton may be written as

PDF

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

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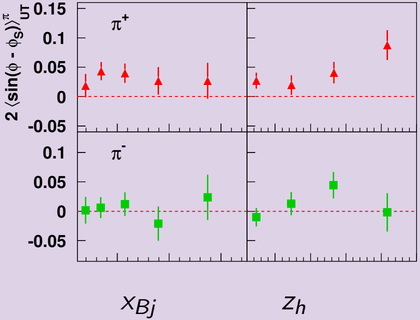
The arising SSA has the following form $A_{UT}^{sin(\phi_h - \phi_S)} =$

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

Experimental situation.

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

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

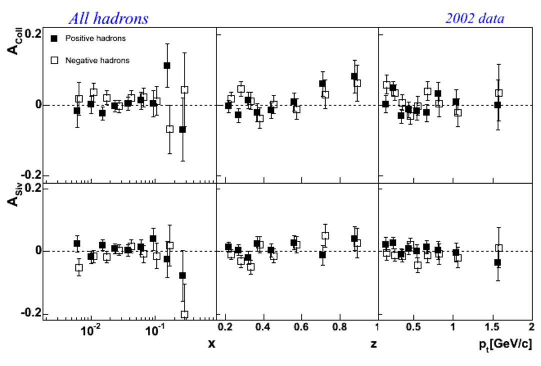


HERMES Collaboration, A. Airapetian *et al.*, *Phys. Rev. Lett.* **94** (2005) 012002, e-Print Archive: hep-ex/0408013

Experimental situation

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

Sivers & Collins Moments



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

COMPASS Collaboration, P. Pagano, talk delivered at the SPIN2004 Symposium, Trieste, Italy, October 10-16, 2004, e-Print Archive: hep-ex/0501035

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,

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

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

where N_q, a_q, b_q and M (GeV$/c$) are parameters and $q = u_v, d_v, u_s, d_s, \bar{u}, \bar{d}$. For the sea quark contributions we assume:

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

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

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

$$\Delta\sigma_{\rm siv}(x_B, y, z_h, P_T) = \frac{2\pi\alpha^2}{x_B\, y^2 s} \sum_q e_q^2\, 2\mathcal{N}_q(x_B)\, f_q(x_B)\, D_q^h(z_h) \left[1+(1-y)^2\right] \cdot z_h P_T \frac{\sqrt{2e}\,\widehat{\langle k_\perp^2\rangle}^2}{M\,\widehat{\langle P_T^2\rangle}^2 \langle k_\perp^2\rangle} \exp\left(-\frac{P_T^2}{\widehat{\langle P_T^2\rangle}}\right),$$

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

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

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

$N_{u_v} =$	0.39 ± 0.39	$N_{d_v} =$	-1.0 ± 1.6
$a_{u_v} =$	0.001 ± 0.950	$a_{d_v} =$	1 ± 1
$b_{u_v} =$	3.5 ± 4.2	$b_{d_v} =$	4.9 ± 4
$N_{\bar{u}} =$	0.98 ± 1.82	$N_{\bar{d}} =$	-1.0 ± 1.9
$a_{\bar{u}} =$	0.78 ± 0.64	$a_{\bar{d}} =$	0.003 ± 3.3
$b_{\bar{u}} =$	0.74 ± 1.32	$b_{\bar{d}} =$	0.01 ± 4.9
$M^2 =$	$0.44 \pm 0.89\ (\mathrm{GeV}/c)^2$	$\chi^2/d.o.f =$	0.89

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

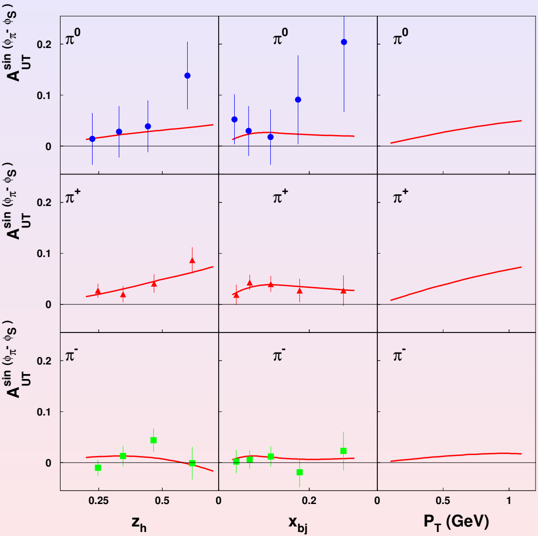
Sivers functions are not well constrained by current data on $A_{UT}^{\sin(\phi_h-\phi_S)}$.

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:

$$N_u = 0.40, a_u = 3.0, b_u = 0.6$$

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

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



PDF: MRST LO 2001

Eur. Phys. J. C4 (1998) 463

FF: Kretzer

Phys. Rev. D62 (2000) 054001

$ep \to e\pi X$

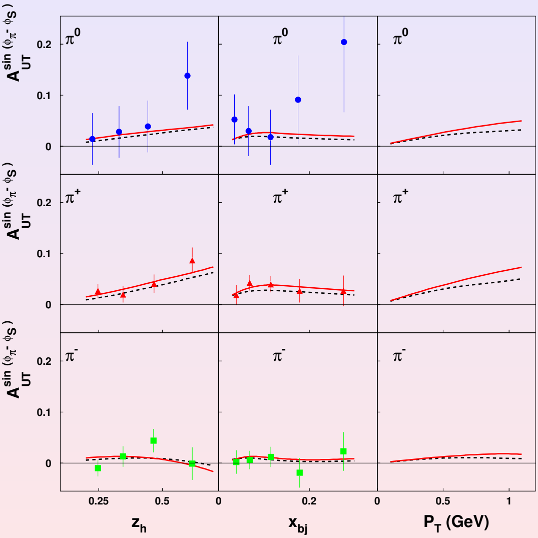
Cuts

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

The red line corresponds to the result of the fit.

A. Airapetian *et al.*, *Phys. Rev. Lett.* **94** (2005) 012002, Eprint number: hep-ex/0408013

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

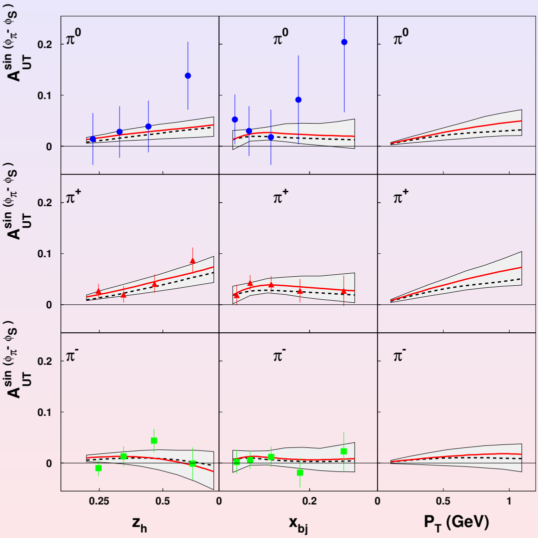


The red line corresponds to the result of the fit.

The dashed line corresponds to complete kinematics.

The shadowed region corresponds to 1 σ deviation at 90% CL.

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



The red line corresponds to the result of the fit.

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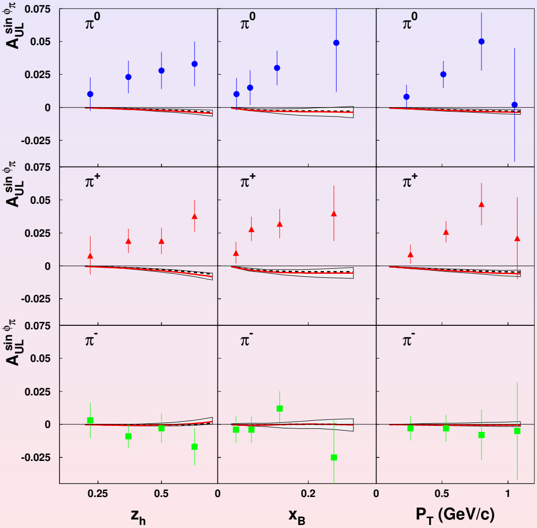
Contribution to $A_{UL}^{sin(\phi_h)}$



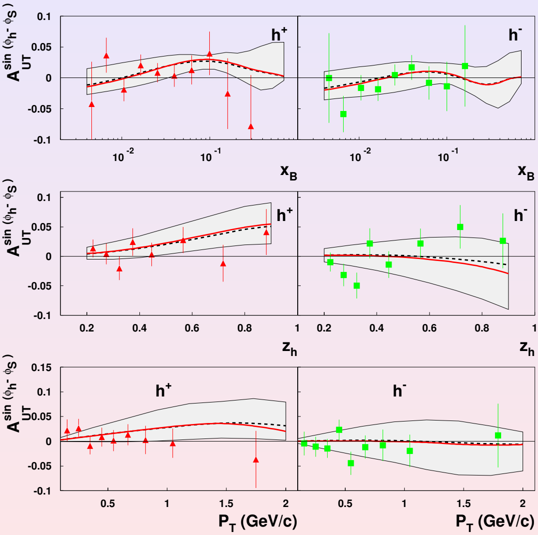
$ep \to e\pi X$

All parameters are fixed

Hermes data on $A_{UL}^{sin(\phi_h)}$. The dashed line corresponds to complete kinematics, the red line up to $\mathcal{O}\left(\frac{k_\perp}{Q}\right)$ terms

HERMES Collaboration, A. Airapetian et al., Phys. Rev. Lett. 84 (2000) 4047; Phys. Rev. D64 (2001) 097101

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



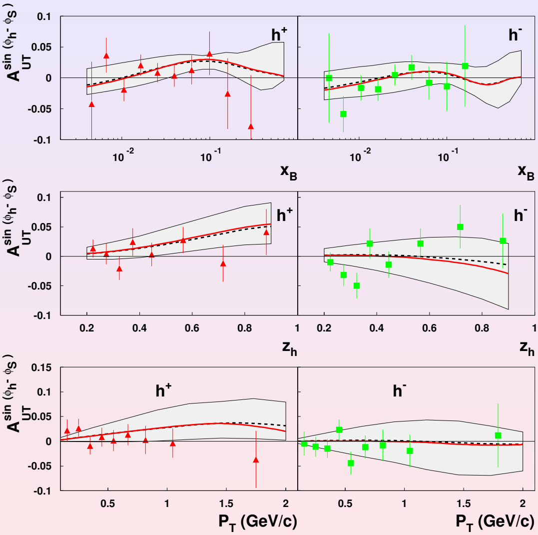
$\mu D \to \mu h^{\pm} X$

All parameters are fixed

COMPASS Collaboration, preliminary data, e-Print Archive: hep-ex/0501035

COMPASS data are compatible with HERMES data

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



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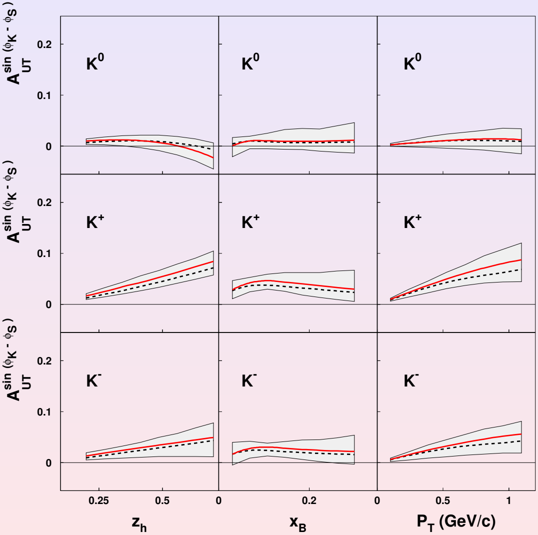
COMPASS Collaboration, preliminary data, e-Print Archive: hep-ex/0501035

COMPASS data are compatible with HERMES data

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



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

All parameters are fixed

Predictions of asymmetry in Kaon production at HERMES. The dashed line corresponds to complete kinematics, the red line up to $\mathcal{O}\left(\frac{k_\perp}{Q}\right)$ terms.

CONCLUSIONS & PLANS

- It is shown that the model with intrinsic $k_\perp$ is capable of reproducing the unpolarized SIDIS data.
- Estimates of the Sivers functions for u and d (both valence and sea) quarks have been obtained.
- Sivers functions are not well constrained by current data on $A_{UT}^{sin(\phi_h-\phi_S)}$.
- $A_{UL}^{sin(\phi_h)}$ is not due to Sivers effect only.
- COMPASS data on $A_{UT}^{sin(\phi_h-\phi_S)}$ are compatible with HERMES data.
- Combined analysis of current and future HERMES and COMPASS data can significantly improve constraints on Sivers functions.

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THANK YOU!