Sivers and Collins effects: from SIDIS and e^+e^- to proton-proton scattering

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RHIC Spin: Next Decade
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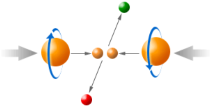


In collaboration with M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia

Polarised Semi Inclusive Deep Inelastic Scattering

Asymmetry in $\gamma^* p$ cm frame of $\ell p^\uparrow \to \ell' h X$

$$A_{UT} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{\frac{1}{2}(d\sigma^\uparrow + d\sigma^\downarrow)}$$

$$d\sigma^\uparrow \equiv \frac{d^6\sigma^{\ell p^\uparrow \to \ell' h X}}{dx_B\, dy\, dz_h\, d^2\mathbf{P}_T\, d\phi_S}$$

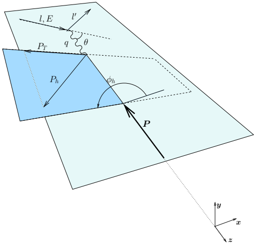
$q = \ell - \ell'$

$Q^2 = -q^2$

$x = \frac{Q^2}{2P\cdot q}$

$y = \frac{Q^2}{sx}$

$z = \frac{P\cdot h}{P\cdot q}$



Contributions at leading twist

$$d\sigma^\uparrow - d\sigma^\downarrow \propto \underbrace{\Delta^N f_{q/p^\uparrow} \otimes d\hat{\sigma} \otimes D_{h/q} \sin(\phi_h - \phi_S)}_{\text{Sivers effect}} +$$

$$+ \underbrace{\Delta_T q \otimes \Delta\hat{\sigma}^\uparrow \otimes \Delta^N D_{h/q^\uparrow} \sin(\phi_h + \phi_S)}_{\text{Collins effect}} +$$

$$+ h_{1T}^\perp \otimes \Delta\hat{\sigma}^\uparrow \otimes \Delta^N D_{h/q^\uparrow} \sin(3\phi_h - \phi_S)$$

Kotzinian 1995;

Mulders, Tangerman 1995;

Bacchetta et al 2007

HERMES and COMPASS experimental data → extraction of TMDs

Sivers effect

The azimuthal asymmetry $A_{UT}^{sin(\phi_h-\phi_S)}$ arises due to Sivers function

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

Sivers 90

Asymmetry $\sim sin(\phi_H-\phi_S)\cdot\ \Delta^N f_{q/p^\uparrow}(x,k_\perp)\otimes\ D_{h/q}(z,p_\perp)$

In the parametrization of the Sivers function of $u, d, \bar{u}, \bar{d}, s, \bar{s}$ we factorize x and $k_\perp$ and use Gaussian $k_\perp$-dependence

$$\Delta^N f_{q/p^\uparrow}(x,k_\perp) = 2\,\mathcal{N}_q(x)\ h(k_\perp)\ f_q(x,k_\perp)\ ,$$

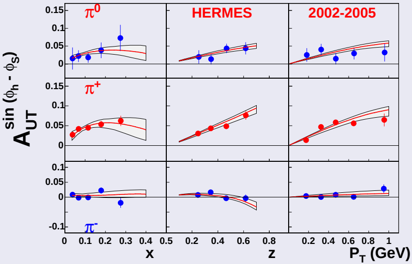
$$\mathcal{N}_q(x)\le 1 \qquad h(k_\perp)\le 1$$

positivity constraint $|\Delta^N f_{q/p^\uparrow}(x,k_\perp)| \le 2f_q(x,k_\perp)$ is fulfilled.
$f_q(x)$ is **GRV98LO**

HERMES and COMPASS DATA

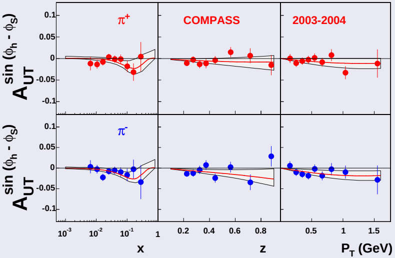
HERMES

$ep \to e\pi X,\ p_{lab} = 27.57$ GeV.



COMPASS

$\mu D \to \mu\pi X,\ p_{lab} = 160$ GeV.

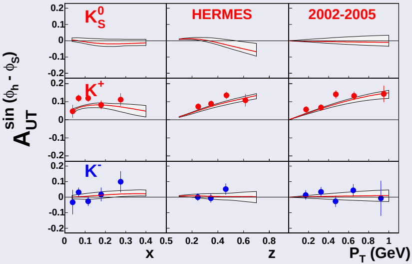


$$lp^{\uparrow} \to l\pi^{+}X \simeq \Delta^{N}u \otimes D_{u/\pi^{+}} > 0$$
$$lp^{\uparrow} \to l\pi^{-}X \simeq 4\Delta^{N}u \otimes D_{u/\pi^{-}} + \Delta^{N}d \otimes D_{d/\pi^{-}} \simeq 0$$
$$lD^{\uparrow} \to l\pi^{+}X \simeq (\Delta^{N}u + \Delta^{N}d) \otimes D_{u/\pi^{+}} \simeq 0$$

HERMES and COMPASS DATA

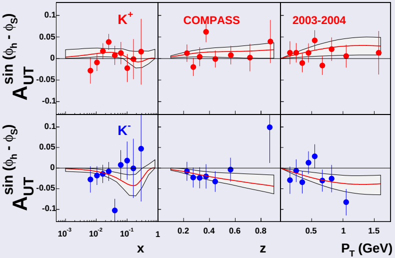
HERMES

$ep \to eKX$, $p_{lab} = 27.57$ GeV.



COMPASS

$\mu D \to \mu KX$, $p_{lab} = 160$ GeV.



Kaon data allow for light antiquark Sivers function extraction.

`M. Anselmino et al Phys.Rev.D79:054010,2009`

Kaon FF

`D. de Florian, R. Sassot, and M. Stratmann Phys. Rev.` **D75** `114010 (2007)`

Kaons vs pions, M. Anselmino et al 09

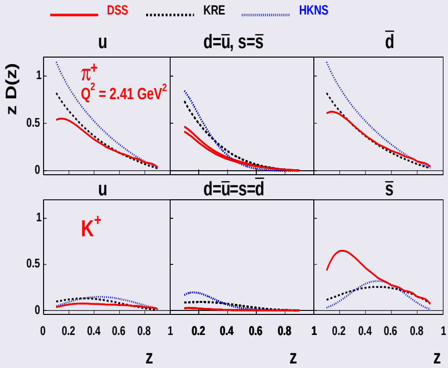
Kaons - pions $s \to d$

Choice of FF set is important especially for Kaon asymmetry.

Kretzer Phys. Rev. D62, 054001 (2000)

DSS D. de Florian, R. Sassot, and M. Stratmann, Phys. Rev. D75, 114010 (2007)

HKNS M. Hirai, S. Kumano, T. H. Nagai, and K. Sudoh, Phys. Rev. D75, 094009 (2007)



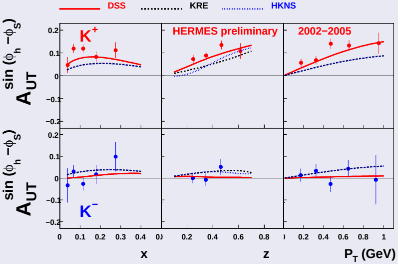
The only set capable of describing HERMES data on K production is DSS.

$K^+(u\bar{s})$, $\pi^+(u\bar{d})$ knowledge of $\bar{s} \to K^+$ FF is very important.

KAON HERMES DATA

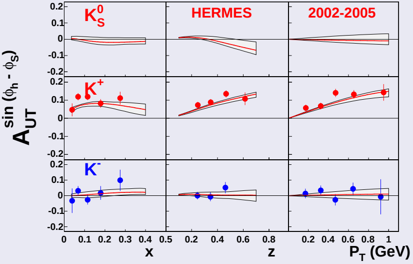
HERMES

$ep \to eKX$, $p_{lab} = 27.57$ GeV.



HERMES

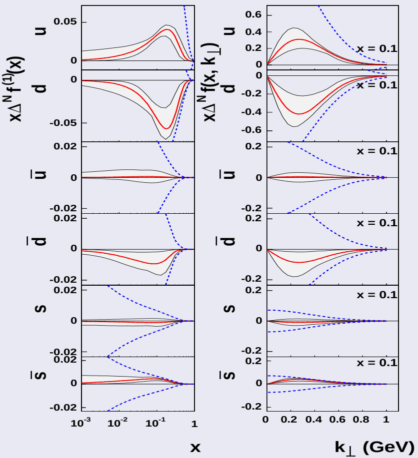
$ep \to eKX$, $p_{lab} = 27.57$ GeV.



Kaon FF de Florian, Sassot, Stratmann 07 (right panel) is compared the Kretzer (dotted lines) and HKNS set (dashed lines) of fragmentation functions (left panel).

Sivers functions

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



Sivers functions for *u*, *d* and *sea* quarks are extracted from HERMES and COMPASS data.
$\Delta^N f_u > 0$, $\Delta^N f_d < 0$, first hints on nonzero sea quark Sivers functions.

Constraint on Gluon Sivers Function

Burkardt sum rule

$$\sum_a \int dx\, d^2\mathbf{k}_\perp\, \mathbf{k}_\perp\, f_{a/p^\uparrow}(x,\mathbf{k}_\perp) \equiv \sum_a \langle \mathbf{k}_\perp^a \rangle = 0$$

`M. Burkardt Phys.Rev.D69:091501,2004`

$\langle \mathbf{k}_\perp^a \rangle$ is related to the first moment of the Sivers function.

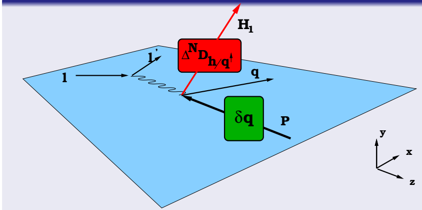
$\langle k_\perp^u \rangle = 96^{+60}_{-28}$ (MeV) $\langle k_\perp^d \rangle = -113^{+45}_{-51}$ (MeV)
The sum rule is almost saturated by u and d quarks at $Q^2 = 2.4$ GeV^2:
$\langle k_\perp^u \rangle + \langle k_\perp^d \rangle = -17^{+37}_{-55}$ (MeV) $\langle k_\perp^{\bar{u}} \rangle + \langle k_\perp^{\bar{d}} \rangle + \langle k_\perp^{s} \rangle + \langle k_\perp^{\bar{s}} \rangle = -14^{+43}_{-66}$ (MeV).

thus leaving little room for the gluon Sivers function
$-10 \le \langle k_\perp^g \rangle \le 48$ (MeV)
Agrees with Anselmino et al 06; Brodsky, Gardner 06

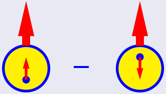
But SIDIS measurements cover restricted region in x: $0.01 \lesssim x \lesssim 0.4$
Still to be investigated...

Collins effect: SIDIS and e^+e^- annihilation

SIDIS $lN \to l' H_1 X$



Collins effect gives rise to azimuthal Single Spin Asymmetry

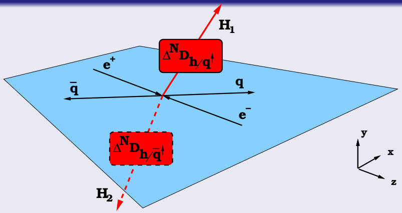


$= \Delta_T q(x, Q^2)$

$= \Delta^N D_{h/q^\uparrow}(z, Q^2)$

J. C. Collins, *Nucl. Phys.* **B396** (1993) 161

$e^+e^- \to H_1 H_2 X$



Collins effect gives rise to azimuthal asymmetry, q and $\bar{q}$ Collins functions are present in the process:

$\Delta^N D_{h/q^\uparrow}(z_1, Q^2)$

$\Delta^N D_{h/\bar{q}^\uparrow}(z_2, Q^2)$

D. Boer, R.Jacob and P. J. Mulders *Nucl. Phys.* **B504** (1997) 345

Collins function and transversity distribution

Model for Collins FF

For $\Delta^N D_{h/q^\uparrow}(z, |p_\perp|) = \frac{2|p_\perp|}{zM_\pi}\, H_1^{\perp q}(z, |p_\perp|)$ we use factorized z and $p_\perp$ and Gaussian dependence on $p_\perp$, $\Delta^N D_{h/q^\uparrow} \propto z^\gamma(1-z)^\delta$, positivity constraint $|\Delta^N D_{h/q^\uparrow}(z, \mathbf{p}_\perp)| \le 2D_{h/q}(z, \mathbf{p}_\perp)$ is fulfilled. $D_{h/q}(z)$ is **DSS**

Model for Transversity distribution

$$\Delta_T q(x, k_\perp) = \frac{1}{2}\,\left[f_{q/p}(x) + \Delta q(x)\right]\,\mathcal{N}_q^T(x)\,\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle_T}}{\pi\langle k_\perp^2\rangle_T},$$

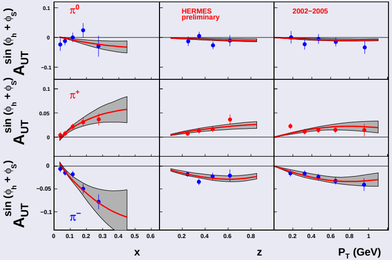
$\Delta_T q(x) \propto x^\alpha(1-x)^\beta$, Soffer bound

$$|\Delta_T q(x)| \le \frac{1}{2}\left[f_{q/p}(x) + \Delta q(x)\right]$$

is fulfilled. $f_q(x)$ is **GRV98LO**, $\Delta q(x)$ is **GSRV98LO**

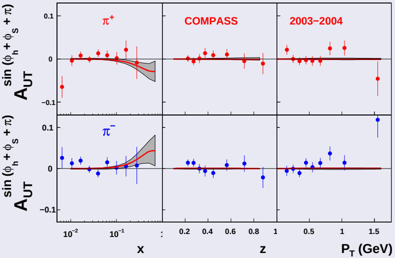
Description of the data

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



$ep \rightarrow e\pi X$, $p_{lab} = 27.57$ GeV.

COMPASS $A_{UT}^{sin(\phi_h+\phi_S+\pi)}$



$\mu D \rightarrow \mu\pi X$, $p_{lab} = 160$ GeV

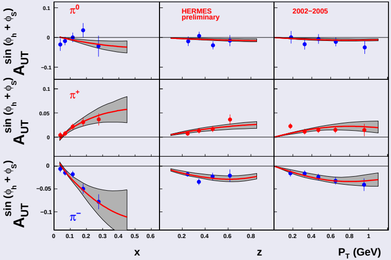
M.Anselmino et al, Nucl.Phys.Proc.Suppl.191:98-107,2009

HERMES, M. Diefenthaler, (2007),arXiv:0706.2242

COMPASS, M. Alekseev et al., (2008), Phys.Lett.B673:127-135,2009

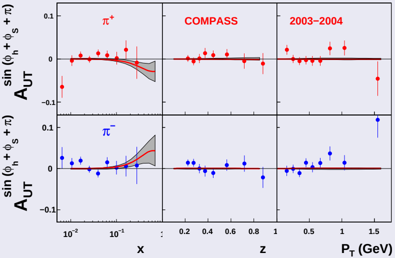
Description of the data

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



$ep \to e\pi X$, $p_{lab} = 27.57$ GeV.

COMPASS $A_{UT}^{sin(\phi_h+\phi_S+\pi)}$



$\mu D \to \mu\pi X$, $p_{lab} = 160$ GeV

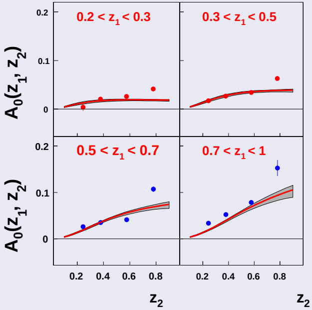
$$lp^\uparrow \to l\pi^+X \simeq \Delta_T u \otimes \Delta^N D_{u/\pi^+} > 0$$

$$lp^\uparrow \to l\pi^-X \simeq \Delta_T u \otimes \Delta^N D_{u/\pi^-} < 0$$

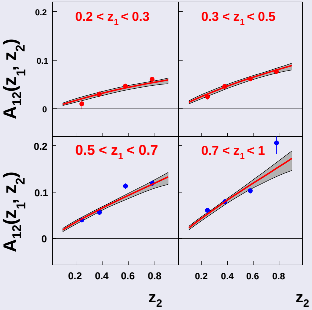
$$lD^\uparrow \to l\pi^+X \simeq (\Delta_T u + \Delta_T d) \otimes \Delta^N D_{u/\pi^+} \simeq 0$$

Description of the data e^+e^-

BELLE $\cos(2\varphi_0)$



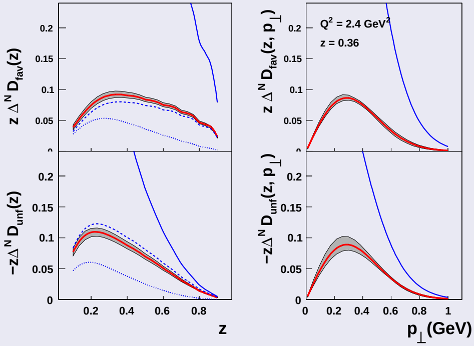
BELLE $\cos(\varphi_1 + \varphi_2)$



$e^+e^- \rightarrow \pi\pi X$, $\sqrt{s} = 10.58$ GeV

`Belle, K. Abe et al., Phys. Rev. Lett. 96 (2006) 232002`

Collins fragmentation function

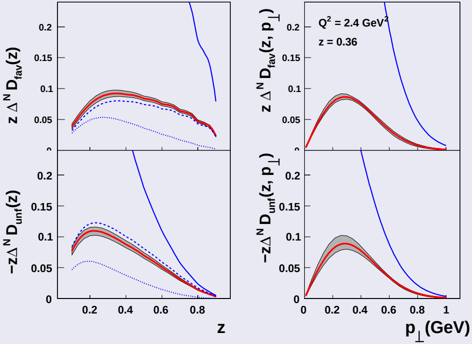


compared to Ref. [1] (dashed line), Ref. [2] (dotted line)

[1] A. V. Efremov, K. Goeke, and P. Schweitzer, Phys. Rev. **D73**, 094025 (2006).

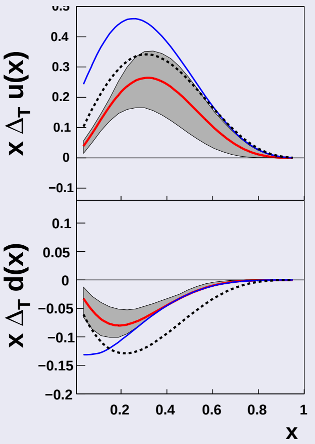
[2] W. Vogelsang and F. Yuan, Phys. Rev. **D72**, 054028 (2005).

Collins fragmentation function



$$\Delta^N D_{fav} = \Delta^N D_{u/\pi^+} > 0$$
$$\Delta^N D_{unfav} = \Delta^N D_{u/\pi^-} < 0$$
$$|\Delta^N D_{fav}| \simeq |\Delta^N D_{unfav}|$$

Transversity vs. helicity



1. Solid red line – transversity distribution

$$\Delta_T q(x)$$

this analysis at $Q^2 = 2.4$ GeV^2.

2. Solid blue line – Soffer bound

$$\frac{q(x) + \Delta q(x)}{2}$$

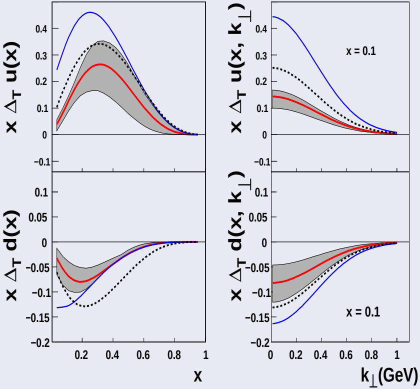
GRV98LO + GRSV98LO

3. Dashed line – helicity distribution

$$\Delta q(x)$$

GRSV98LO

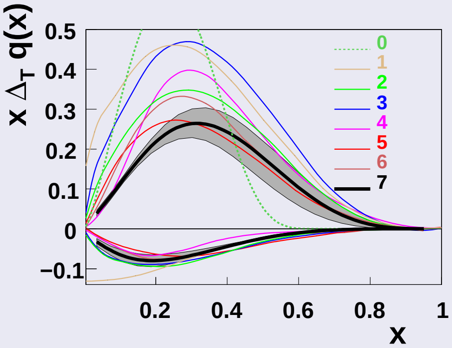
Transversity



- This is the extraction of transversity from new experimental data. PRD75:054032,2007, arXiv:0812.4366
- $\Delta_T u(x) > 0$ and $\Delta_T d(x) < 0$
- $|\Delta_T q(x)| < |\Delta q(x)|$.

Transversity, comparison with models

New extraction is close to most models.

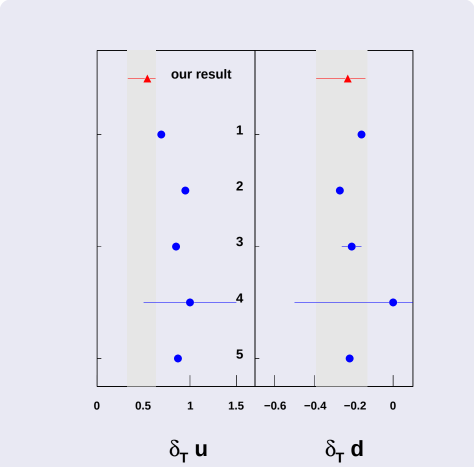


0. Barone, Calarco, Drago PLB 390 287 (97)
1. Soffer et al. PRD 65 (02)
2. Korotkov et al. EPJC 18 (01)
3. Schweitzer et al. PRD 64 (01)
4. Wakamatsu, PLB B653 (07)
5. Pasquini et al., PRD 72 (05)
6. Cloet, Bentz and Thomas PLB 659 (08)
7. This analysis.

Tensor charges

$$\delta q = \int_0^1 dx\,(\Delta_T q - \Delta_T \bar{q}) = \int_0^1 dx\,\Delta_T q$$

$\Delta_T u = 0.54^{+0.09}_{-0.22}$, $\Delta_T d = -0.23^{+0.09}_{-0.16}$ at $Q^2 = 0.8$ GeV^2



1. Quark-diquark model:
   Cloet, Bentz and Thomas
   PLB **659**, 214 (2008), $Q^2 = 0.4$ GeV^2
2. CQSM:
   M. Wakamatsu, PLB **653** (2007) 398.
   $Q^2 = 0.3$ GeV^2
3. Lattice QCD:
   M. Gockeler et al.,
   Phys.Lett.B627:113-123,2005 ,
   $Q^2 = 4$ GeV^2
4. QCD sum rules:
   Han-xin He, Xiang-Dong Ji,
   PRD 52:2960-2963,1995, $Q^2 \sim 1$ GeV^2
5. Constituent quark model:
   B. Pasquini, M. Pincetti, and
   S. Boffi, PRD72(2005)094029 and
   PRD76(2007)034020, $Q^2 \sim 0.8$ GeV^2

From SIDIS to $P^{\uparrow}P \to \pi X$

- Assuming TMD factorization for $A(S_A)B(S_B) \to HX$ we obtain Anselmino et al Phys.Rev.D73:014020,2006

$$E\frac{d\sigma^{A(S_A)B(S_B)\to H+X}}{d^3P_H} \propto \sum_{i=a,b,c,d}\sum_{\lambda,\lambda'}\int dx_i d^2k_{\perp i}\rho^{a/A,S_A}_{\lambda_a,\lambda'_a} f_{a/A,S_A}(x_a,\mathbf{k}_{\perp a})$$
$$\rho^{b/B,S_B}_{\lambda_b,\lambda'_b} f_{b/B,S_B}(x_b,\mathbf{k}_{\perp b}) M_{\lambda_i} M^*_{\lambda'_i} D_{c/H}(z_c,k_{\perp c})$$

internal x-variables are integrated over.

- Sivers and Collins effects are not separated in $P^{\uparrow}P \to \pi X$:

$$\sigma^{\uparrow}-\sigma^{\downarrow} \propto \underbrace{\Delta^N f_{a/P^{\uparrow}}(x_a,k_{\perp a})\otimes f_{b/P}(x_b,k_{\perp b})\otimes\hat{\sigma}\otimes D_{\pi/c}(z_c,k_{\perp c})}_{Sivers\quad effect} +$$
$$\underbrace{h_{1a}(x_a,k_{\perp a})\otimes f_{b/P}(x_b,k_{\perp b})\otimes\Delta\hat{\sigma}\otimes\Delta^N D_{\pi/c^{\uparrow}}(z_c,k_{\perp c})}_{Collins\quad effect} + \ldots$$

- Integration over internal variables usually cover wide regions of x and z making direct comparison to SIDIS difficult

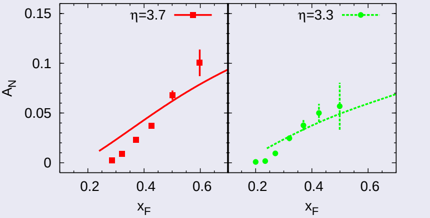
From SIDIS to $P^{\uparrow}P \to \pi X$: Universality

- Collins fragmentation function is universal in SIDIS and PP. Collins and Metz 04, Yuan 09
- The Sivers distribution function is process dependent. SIDIS - DY sign change of the Sivers function. Collins 02
  $\Delta^N f_{q/p^{\uparrow}\,DY} = -\Delta^N f_{q/p^{\uparrow}\,SIDIS}$
- Gauge link dependence can be absorbed into the elementary scattering cross sections in PP scattering. Bacchetta, Bomhof, Mulders, Pijlman, 05; Ratcliffe, Teryaev 08
- Test of these relations is possible in $P^{\uparrow}P \to jet + jet + X$ Boer, Vogelsang 04, in $P^{\uparrow}P \to \gamma + jet + X$ Bacchetta, Bomhof, D'Alesio, Mulders, Murgia 07 or in $P^{\uparrow}P \to W^{\pm} + X$ Kang, Qiu 09
- Gauge links are not present in the Generalized Parton Model Anselmino et al 06
- We try to check numerically consistency between SIDIS data and PP data *assuming the same Sivers, Collins functions and transversity in PP scattering as in SIDIS* using GPM Anselmino et al 06.

From SIDIS to $P^{\uparrow}P \to \pi X$: Maximizing contributions

We maximize Sivers effect at RHIC:
$\Delta^N f_u(x, k_\perp) = 2 f_u(x, k_\perp)$, $\Delta^N f_d(x, k_\perp) = -2 f_d(x, k_\perp)$ (the same signs as in SIDIS)

STAR $\sqrt{s} = 200$ GeV $P^{\uparrow}P \to \pi^0 X$



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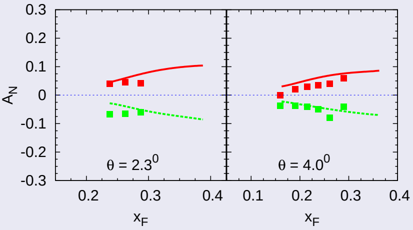
BRAHMS $P^{\uparrow}P \to \pi^{\pm} X$



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From SIDIS to $P^{\uparrow}P \to \pi X$: Maximizing contributions

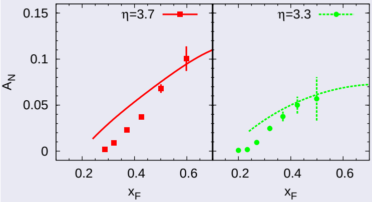
We maximize Collins effect at RHIC:

$h_1(x,k_\perp) = \frac{1}{2}(f_u(x,k_\perp) + \Delta u(x,k_\perp))$,

$h_1(x,k_\perp) = -\frac{1}{2}(f_d(x,k_\perp) + \Delta d(x,k_\perp))$ (the same signs as in SIDIS)

$\Delta^N D_{fav}(z,p_\perp) = 2D_{fav}(z,p_\perp)$, $\Delta^N D_{unfav}(z,p_\perp) = -2D_{unfav}(z,p_\perp)$

STAR $\sqrt{s} = 200$ GeV $P^{\uparrow}P \to \pi^0 X$



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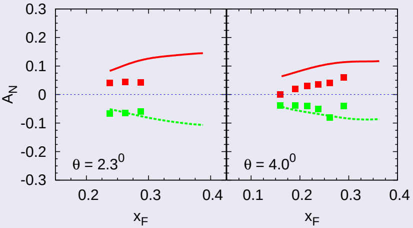
BRAHMS $P^{\uparrow}P \to \pi^{\pm} X$



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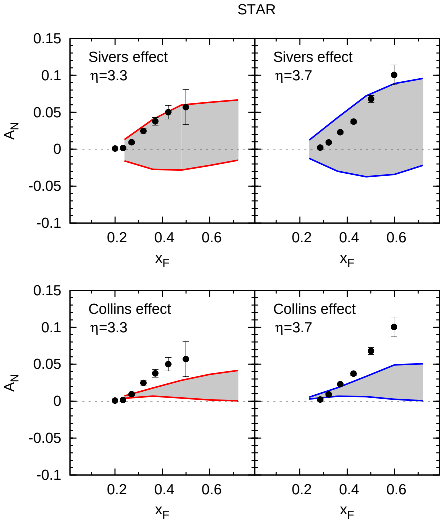
From SIDIS to $P^{\uparrow}P \to \pi X$: Scan of the parameters

- When maximized Collins and Sivers efects can reproduce the *PP* data. How information from SIDIS reflects on *PP*?
- SIDIS data cover limited range $x \lesssim 0.4$
- Sivers function $\Delta^N f_{q/p^{\uparrow}} \propto x^{\alpha}(1-x)^{\beta}$, $\beta = 3.5^{+4.9}_{-2.9}$,
- Transversity $h_1 \propto x^{\alpha}(1-x)^{\beta}$ $\beta = 0.84 \pm 2.3$
- β is always chosen to be the same for u and d quarks.
- Scan at large-x

  In order to saparate u and d quark β and fix high-x behaviour of the distributions we perform a scan over a grid of ${\beta_u}^i \in [0,4]$ and ${\beta_d}^i \in [0,4]$ (in steps of 0.5), and re-run the SIDIS fit. We then select out only $\{{\beta_u}^i, {\beta_d}^j\}$ that correspond to a SIDIS fit with χ^2/dof not larger than about 20% from the minimum original value.

From SIDIS to $P^{\uparrow}P \to \pi X$: Results

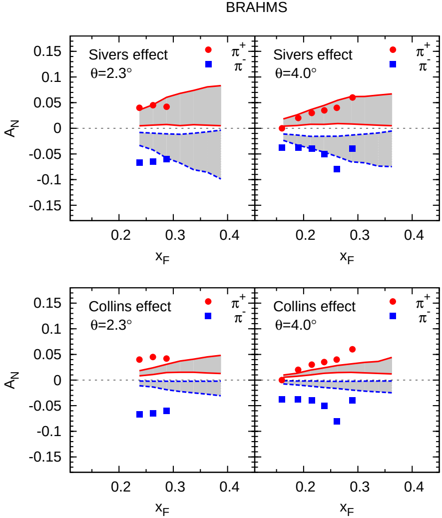
Sivers and Collins effects at STAR $\sqrt{s} = 200$ GeV. $P^{\uparrow}P \to \pi^0 X$



- The shaded bands are obtained by scanning over the β parameters
- Sivers effect contribution is bigger than Collins effect
- Sum of two effects can describe the data

From SIDIS to $P^{\uparrow}P \rightarrow \pi X$: Results

Sivers and Collins effects at BRAHMS $\sqrt{s} = 200$ GeV. $P^{\uparrow}P \rightarrow \pi^{\pm}X$



- The shaded bands are obtained by scanning over the β parameters
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CONCLUSIONS

- Extraction of transversity, Sivers function and Collins FF from HERMES, COMPASS and BELLE data is presented.
- When maximized Collins and Sivers efects can reproduce the $P^{\uparrow}P$ data.
- Assuming factorization and the same Sivers functions in $P^{\uparrow}P$ scattering as in SIDIS the data on single spin asymmetries A_N can be explained by the sum of Sivers and Collins contributions. There is no conclusive evidence from these data on process dependence of the Sivers function.
- Important test of process dependence of the Sivers functions will be A_N in DY, A_N in $P^{\uparrow}P \rightarrow \gamma + jet + X$ and A_N in $P^{\uparrow}P \rightarrow W^{\pm} + X$.

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THANK YOU!

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

We use HERMES and COMPASS data sets on $A_{UT}^{sin(\phi_h+\phi_S)}$ and BELLE data in the fitting procedure.
Favored and unfavored fragmentation functions are defined as follows:

$$D^{fav}(z) \equiv D^{u\to\pi^+}(z) = D^{d\to\pi^-}(z) = D^{\bar{u}\to\pi^-}(z) = D^{\bar{d}\to\pi^+}(z)$$
$$D^{unfav}(z) \equiv D^{u\to\pi^-}(z) = D^{d\to\pi^+}(z) = D^{\bar{u}\to\pi^+}(z) = D^{\bar{d}\to\pi^-}(z)$$

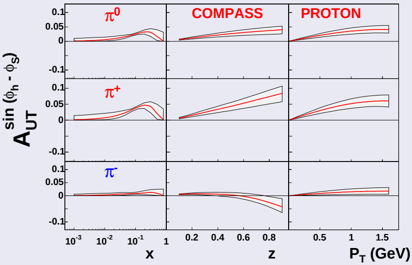
For simplicity we assume that Collins FFs have universal z behaviour and transversity for u and d quarks have universal x behaviour:

$$\alpha_u = \alpha_d \equiv \alpha, \beta_u = \beta_d \equiv \beta$$
$$\gamma_{fav} = \gamma_{unfav} \equiv \gamma, \delta_{fav} = \delta_{unfav} \equiv \delta$$

PREDICTIONS

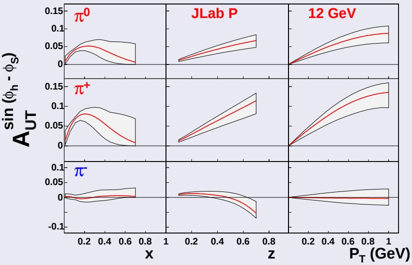
COMPASS on PROTON

$\mu p \to \mu \pi X$, $p_{lab} = 160$ GeV.



JLAB12

$ep \to e\pi X$, $p_{lab} = 12$ GeV.



JLab can improve our knowledge of Sivers function in high x region. COMPASS operating on proton target is expected to measure 5% asymmetry for h^+.

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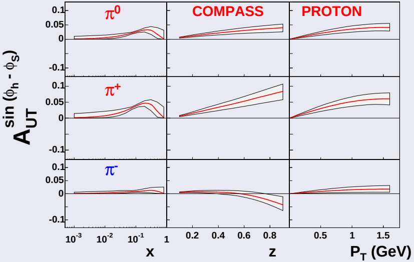
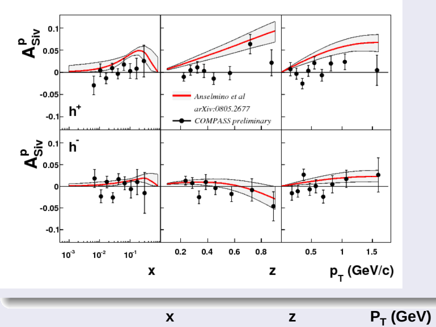


Comparison with preliminary COMPASS data arXiv:0808.0086

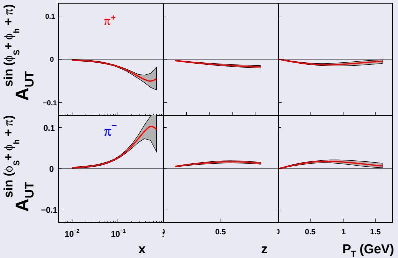


COMPASS data on proton target need to be explained as predictions are not supported by the preliminary data.

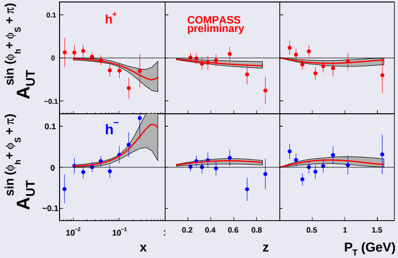
Description of the data

Predictions for COMPASS operating on PROTON target

COMPASS $A_{UT}^{sin(\phi_h+\phi_S+\pi)}$



COMPASS $A_{UT}^{sin(\phi_h+\phi_S+\pi)}$



`Comparison with preliminary COMPASS data arXiv:0808.0086`

`M.Anselmino et al, Nucl.Phys.Proc.Suppl.191:98-107,2009`