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Sivers and Collins Single Spin Asymmetries

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Based on PLB 612 (2005) 233, PRD 73 (2006) 014021, PRD 73 (2006) 094023, PRD 73 (2006) 094025.

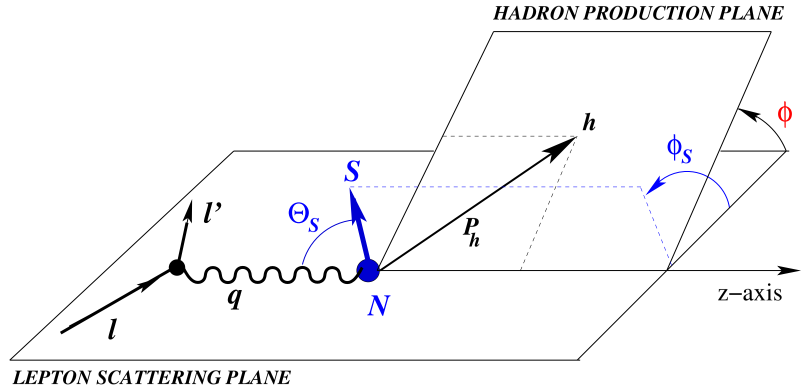
Overview:

- What is Sivers effect?
- Sivers effect in SIDIS & Drell-Yan $\longrightarrow$ testing QCD predictions.
- Sivers effect for kaons — daily impact of new data!
- What is Collins effect?
- Collins effect in SIDIS & e^+e^--annihilation.
- Emerging picture of Collins function & transversity.
- Summary & Conclusions.

SIDIS on transv. polarized target

Expressions in LO $1/Q$ (Kotzinian, Boer, Mulders, ... 90s)

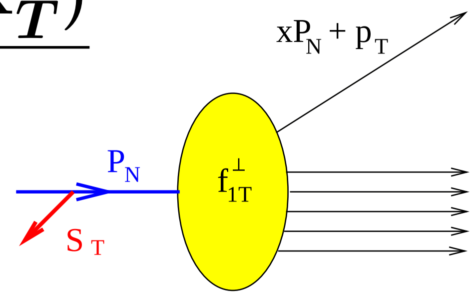
Factorization with k_T (Ji, Ma, Yuan&Collins, Metz 2004)



$$\frac{d^3\sigma_T}{dx\,dz\,d\phi} = \frac{d^3\sigma_{unp}}{dx\,dz\,d\phi}\Big\{1 + S_T\Big[\underbrace{\sin(\phi-\phi_S)\,A_{UT}^{\sin(\phi-\phi_S)}}_{\text{Sivers effect}} + \underbrace{\sin(\phi+\phi_S)\,A_{UT}^{\sin(\phi+\phi_S)}}_{\text{Collins effect}} + \cdots\Big]\Big\}$$

- Sivers function $f_{1T}^{\perp}(x,\mathrm{p}_T^2)$ "twist-2", naively/artificially "T-odd" (Teryaev talk) .
- Left-right asymmetry of PDF.

Sivers SSA: $$A_{UT}^{\sin(\phi-\phi_S)} \propto \frac{f_{1T}^{\perp a}(x,\mathrm{p}_T^2)\otimes D_1^a(z,\mathrm{K}_T^2)}{f_1^a(x)D_1^a(z)}$$



(Sivers 1991, Brodsky, Hwang, Schmidt & Collins 2002)

(Belitsky, Ji, Yuan & Boer, Mulders, Pijlman 2003)

- Remarkable **universality** property $$\boxed{f_{1T}^{\perp}|_{DIS} = -f_{1T}^{\perp}|_{DY}}$$ (Collins 2002).

Of absolute importance to be tested experimentally!

Sivers effect in SIDIS

HERMES	**proton**	**clearly seen**	(PRL94(2005)012002, AIP792(2005)933)
COMPASS	**deuteron**	$\sim$ **0** within error bars	(PRL94(2005)202002)

Questions:

- $A_{UT}^{\sin(\phi-\phi_S)} \propto \frac{f_{1T}^{\perp a}(x,\mathbf{p}_T^2)\otimes D_1^a(z,\mathbf{K}_T^2)}{f_1^a(x)D_1^a(z)}$ $\quad \underbrace{f_1^a(x),\ D_1^a(z)\ \text{known}}_{\text{(e.g. GRV, Kretzer)}} \Rightarrow$ allow to extract $f_{1T}^{\perp}$ **?**

- Are COMPASS and HERMES data compatible **?**

- Possible to test $f_{1T}^{\perp}|_{DIS} = -f_{1T}^{\perp}|_{DY}$**?**

Answers: Yes. Yes. Yes. The problem, however, is K_T-dependence!

Our works
Anselmino et al., PRD 71 (2005) 074006 and 72 (2005) 094007
Vogelsang and Yuan, PRD72 (2005) 054028
See also Anselmino *et al.*, "Comparing extractions of Sivers functions", Como-proceeding, hep-ph/0511017

$A^{P_{h\perp}/M_N \sin(\phi-\phi_S)}$	$A^{\sin(\phi-\phi_S)}$
model-independent, theoretically preferable but officially not recommended for use	experimentally preferable (no acceptance effects), recommended, but model-dependent

Our study of HERMES data (PRL 94 (2005) 012002):

- Neglect soft factors
- Gaussian $f_{1T}^{\perp a}(x,\mathbf{p}_T^2) \equiv f_{1T}^{\perp a}(x)\dfrac{\exp(-\mathbf{p}_T^2/p_{\rm Siv}^2)}{\pi\, p_{\rm Siv}^2}$ & $D_1^a(z,\mathbf{K}_T^2)$ analog $\longrightarrow$

$$A_{UT}^{\sin(\phi-\phi_S)} = -\frac{a_{\rm Gauss}\sum_a e_a^2\, f_{1T}^{\perp(1)a}(x)\, D_1^a(z)}{\sum_b e_b^2\, f_1^b(x)\, D_1^b(z)}$$

with $f_{1T}^{\perp(1)}(x) = \int d^2\mathbf{p}_T\, \frac{\mathbf{p}_T^2}{2M_N^2}\, f_{1T}^{\perp}(x,\mathbf{p}_T^2)$

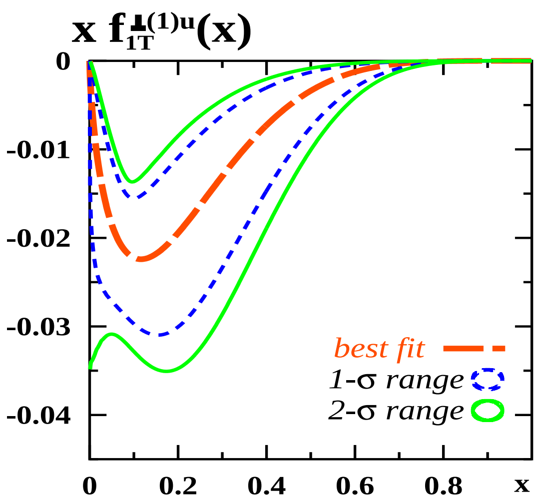
& $0.72 < a_{\rm Gauss} = \frac{\sqrt{\pi}\, M_N}{\sqrt{p_{\rm Siv}^2 + K_{D_1}^2/z^2}} < 0.83$

- $x f_{1T}^{\perp(1)u} = -x f_{1T}^{\perp(1)d} = A x^b (1-x)^5 \overset{\rm fit}{=} -0.18 x^{0.66}(1-x)^5$

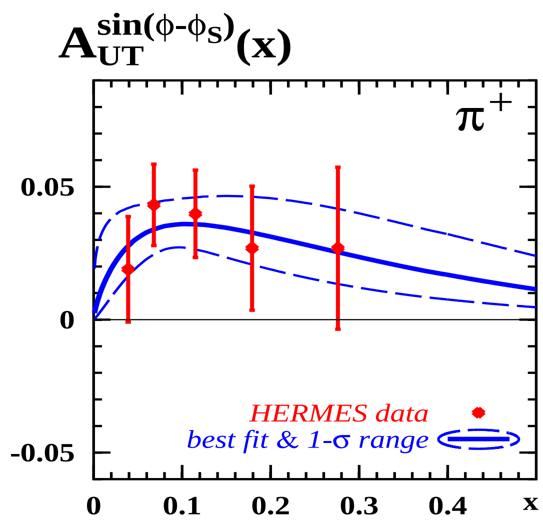
in large-N_c limit (Pobylitsa 2003), and neglect $\bar{q}$, s, ...

Results:

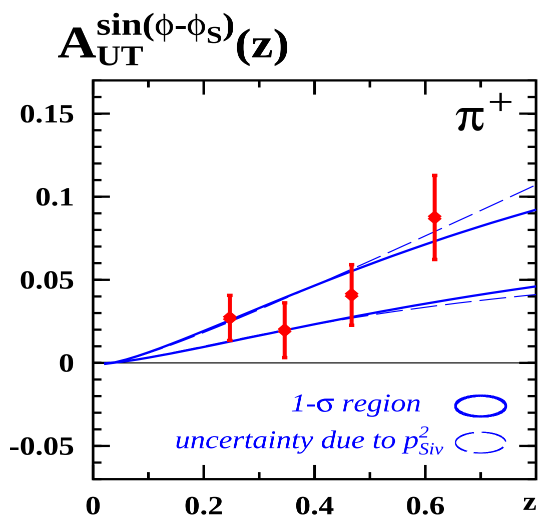
$\chi^2_{/\rm d.o.f.} \sim 0.3$



Sivers function



x-dependence (input)
Good description!



z-dependence (not used)
Cross-check: Ok!

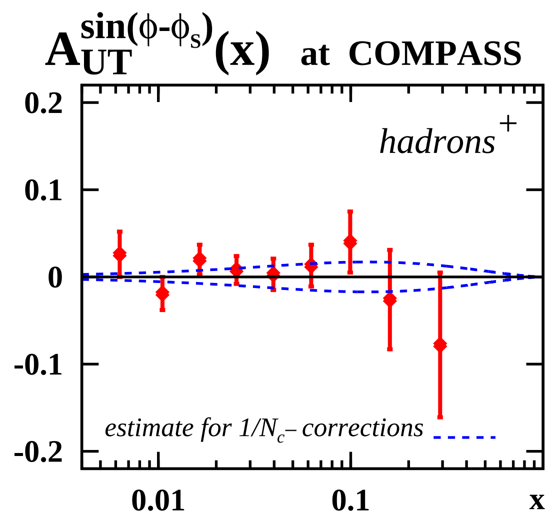
What do we learn?

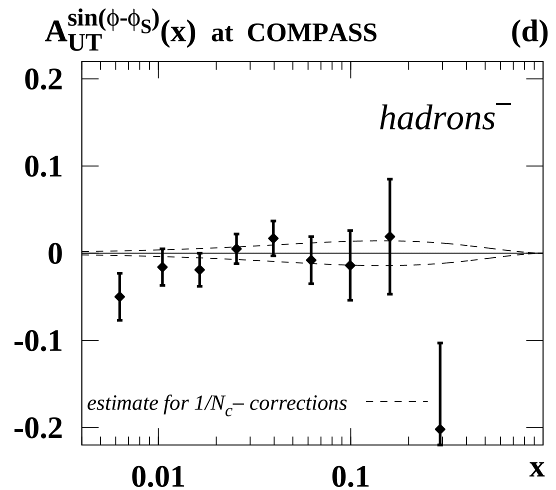
- Good fit to HERMES **possible** with large-N_c $f_{1T}^{\perp u} = -f_{1T}^{\perp d}$
- COMPASS: deuteron target

$$f_{1T}^{\perp u/\text{deut}} \approx \underbrace{f_{1T}^{\perp u} + f_{1T}^{\perp d}}_{1/N_c\text{-correction}} \overset{\text{assume}}{=} \pm\frac{1}{N_c}|f_{1T}^{\perp u} - f_{1T}^{\perp d}| \Rightarrow$$

$1/N_c$ useful for HERMES & COMPASS

. . . at present stage!





- Supports intuitive picture (Burkardt 2002, Lu&Schmidt 2006)

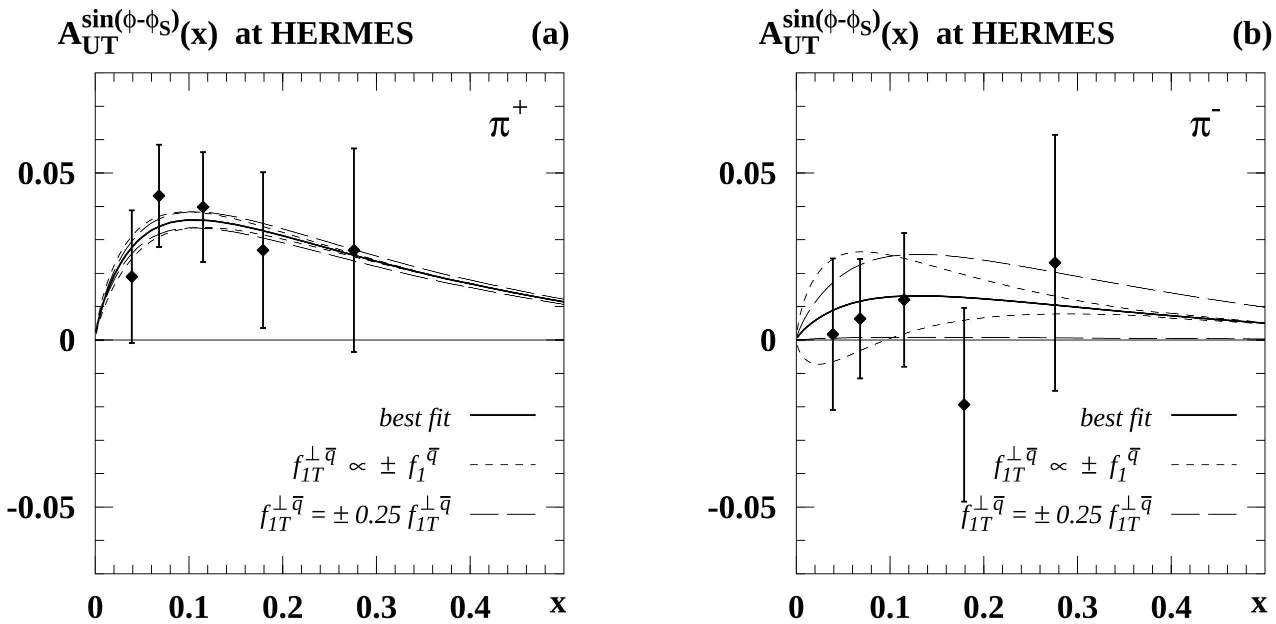
$\int \mathrm{d}x\, f_{1T\,\text{SIDIS}}^{\perp(1)u}(x) \propto -\kappa^u < 0$, $\int \mathrm{d}x\, f_{1T\,\text{SIDIS}}^{\perp(1)d}(x) \propto -\kappa^d > 0$

Suspicion: Maybe large-N_c works *particularly well* for Sivers function since it *works* particularly well for anomalous magnetic moments **???**

Recall: $$\underbrace{|\kappa^u - \kappa^d| \sim 3.706}_{\mathcal{O}(N_c^2)} \gg \underbrace{|\kappa^u + \kappa^d| \sim 0.360}_{\mathcal{O}(N_c)}$$

Sivers-$\bar{q}$

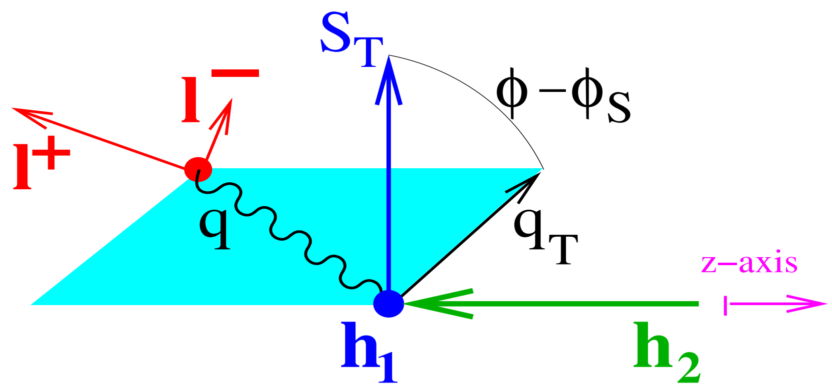
Assume: $f_{1T}^{\perp\bar{q}} = \pm f_{1T}^{\perp q}(x) \begin{cases} 0.25 = \text{const} & \text{model I} \\ \dfrac{f_1^{\bar{q}}(x)}{f_1^{q}(x)} & \text{model II} \end{cases}$ (for illustrative purposes).



Do not influenced very much!

Have a first idea of $f_{1T}^{\perp q}|_{\text{SIDIS}}$!

Sivers effect in DY $h_1^\uparrow h_2 \to l^+ l^- X$



$$A_{UT}^{\sin(\phi-\phi_S)} = + \frac{a_{\text{Gauss}}^{\text{DY}} \sum_a e_a^2 f_{1T\,\text{DY}}^{\perp(1)a}(x_1) f_1^{\bar{a}}(x_2)}{\sum_a e_a^2 f_1^a(x_1) f_1^{\bar{a}}(x_2)}$$

$$y = \frac{1}{2} \ln(p_1 \cdot q / p_2 \cdot q), \quad x_{1,2} = (Q^2/s)^{1/2} e^{\pm y} \quad , \; a_{\text{Gauss}}^{\text{DY}} = \frac{\sqrt{\pi}}{2} \frac{M_N}{\sqrt{\langle p_T^2 \rangle_{\text{Siv}} + \langle p_T^2 \rangle_{\text{unp}}}}$$

- **PAX at GSI**

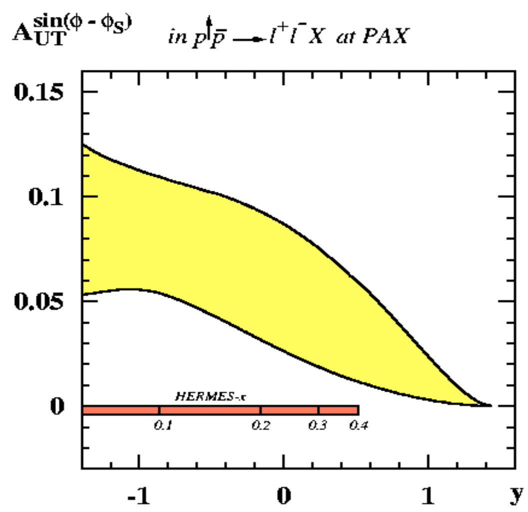
$p^\uparrow \bar{p} \to l^+ l^- X$ (byproduct)

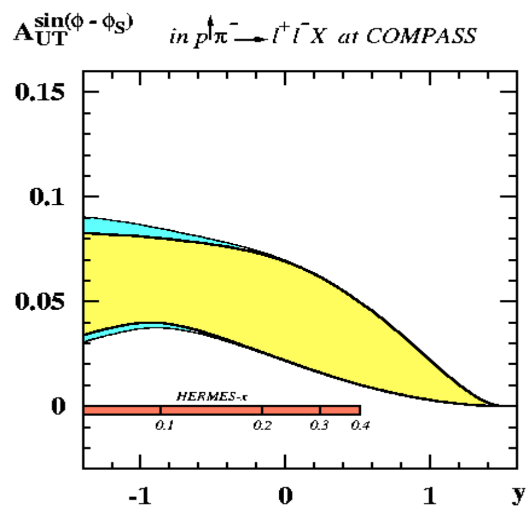
- **COMPASS**

$p^\uparrow \pi^- \to l^+ l^- X$

Annihilations of valence (mainly u & $\bar{u}$) dominate.

$\Rightarrow$ not sensitive to Sivers sea, good!





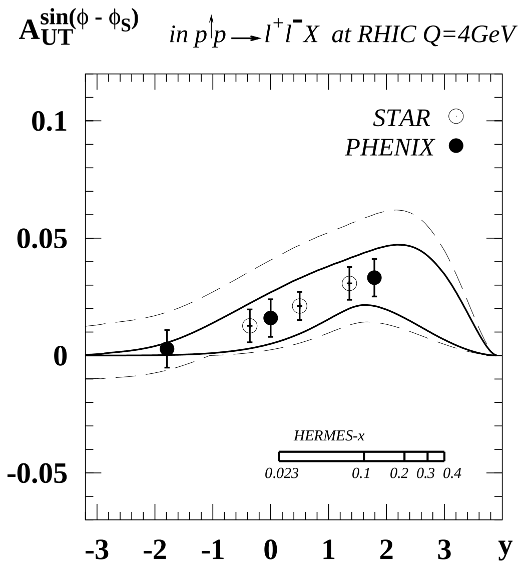
- **RHIC**

$p^{\uparrow}p \;\rightarrow\; l^{+}l^{-}X$

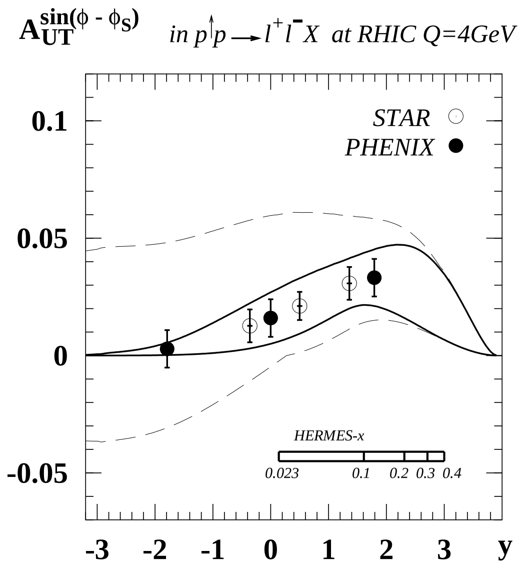
$\boldsymbol{y} > 0$: Can test "change sign" of Sivers-q,

$\boldsymbol{y} < 0$: Can provide information on Sivers-$\bar{q}$.

Error bars $\int \mathrm{d}t\, \mathcal{L} \sim 125\,\mathrm{pb}^{-1}$ realistic till 2012, later RHIC II.



Model I



Model II

$\Longrightarrow$ RHIC, COMPASS & PAX can test change of sign of Sivers-q,
RHIC in addition can provide information on Sivers-$\bar{q}$.

For some while (Como workshop September 2005 — DIS'06 in Tsukuba April 2006) happy with situation: first rough understanding of Sivers in SIDIS, predictions for DY done, wait till 2012.

But then . . .!

Kaon Sivers effect in SIDIS at HERMES

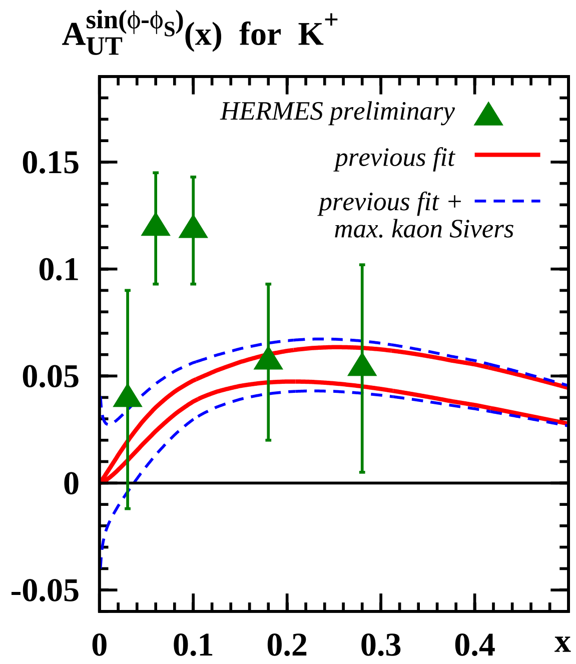
Observation: **(Sivers K^+ SSA) $\approx 2\times$(Sivers π^+ SSA) at small-x.**

How to explain?

- "Only difference" between π^+ and K^+ is $\bar{d} \leftrightarrow \bar{s}$,

$$R = \frac{A(K^+)}{A(\pi^+)} \approx \frac{B(x)+0.35 f_{1T}^{\perp\bar{s}}(x)}{B(x)+0.09 f_{1T}^{\perp\bar{d}}(x)}\,.$$

$$B(x) \approx f_{1T}^{\perp u} + 0.15(f_{1T}^{\perp d} + 4 f_{1T}^{\perp\bar{u}} + f_{1T}^{\perp\bar{d}} + f_{1T}^{\perp s} + f_{1T}^{\perp\bar{s}})$$



- Include previously neglected strange sea Sivers!?
- Let s, $\bar{s}$ Sivers saturate positivity bound?
  (Bacchetta, Boglione, Henneman and Mulders, PRL85(00)712)
- Definitely does not explain factor of 2!
- Reasonable to consider s, $\bar{s}$ but to neglect $\bar{u}$ and $\bar{d}$? No!

Recall: sizeable Sivers-$\bar{q}$ (see models used in DY)
within error bars of $\pi^\pm$ Sivers SSA!

$\Rightarrow$ Consider all of them $f_{1T}^{\perp u}$, $f_{1T}^{\perp d}$, $f_{1T}^{\perp\bar{u}}$, $f_{1T}^{\perp\bar{d}}$, $f_{1T}^{\perp s}$, $f_{1T}^{\perp\bar{s}}$

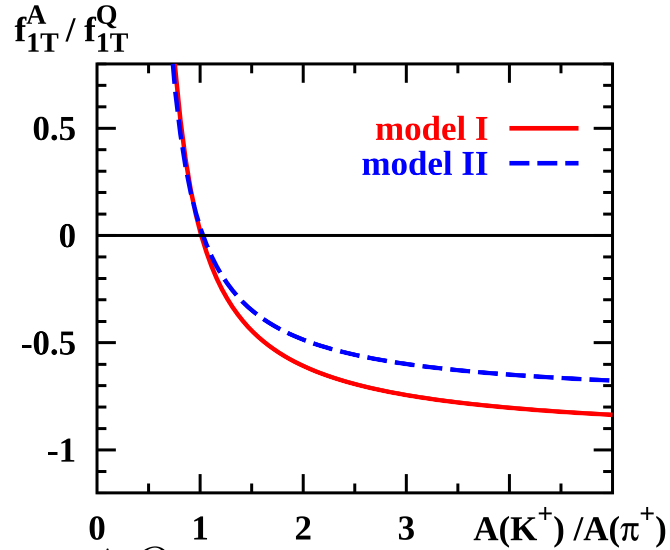
Understand K^+ Sivers effect qualitatively.

Admittedly many free parameters. $\Rightarrow$ Consider models:

- Model I: $f_{1T}^{\perp Q} \equiv f_{1T}^{\perp u} \approx -f_{1T}^{\perp d}$, $f_{1T}^{\perp A} \equiv f_{1T}^{\perp \bar{u}} \approx f_{1T}^{\perp \bar{d}} \approx f_{1T}^{\perp s} \approx -f_{1T}^{\perp \bar{s}}$
- Model II: $f_{1T}^{\perp Q} \equiv f_{1T}^{\perp u} \approx -2 f_{1T}^{\perp d}$ $f_{1T}^{\perp A} \equiv$ same as above

(Q motivated by our works, Anselmino et al. and Vogelsang & Yuan)

At given x, $R = \dfrac{A(K^+)}{A(\pi^+)}$ is function of $\dfrac{f_{1T}^{\perp A}(x)}{f_{1T}^{\perp Q}(x)}$



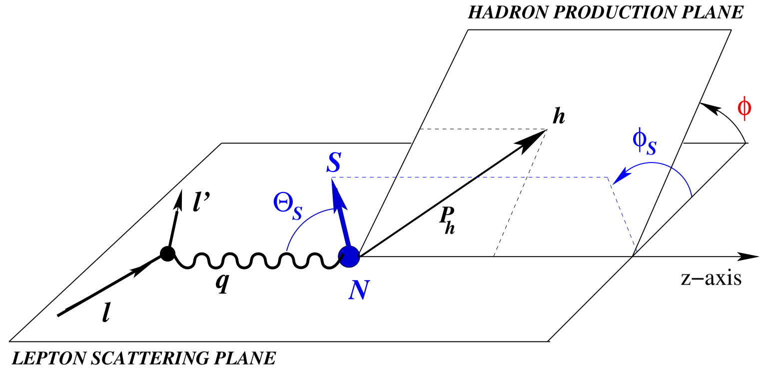
How much Sivers-$\bar{q}$ needed to explain K^+/π^+?

- At large x, $R \approx 1$; thus $f_{1T}^{\perp A}(x) \approx 0$.
- At small x, $R \approx (2-3)$; then $f_{1T}^{\perp A}(x) \approx -(0.5-0.7) f_{1T}^{\perp Q}$. Not unusual in small-$x$ region!

1. K^+ data show importance of Sivers sea quarks.
2. Sizeable R seems compatible with Sivers-$\bar{q}$ of natural size.

Illustrative study to be confirmed by simultaneous fit of $\pi^\pm$ and $K^\pm$ SSAs. First experience (Prokudin talk at Trento-2007.) was not very successful.

Collins effect in SIDIS



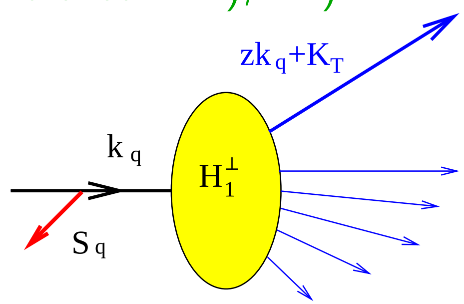
- **SIDIS, transversely polarized target**
- Expressions in LO, $1/Q$ (Kotzinian, Boer, Mulders, . . . 1990s)
- k_T–factorization (Ji, Ma, Yuan&Collins, Metz 2004)

$$\frac{d^3\sigma_{UT}}{dx\,dz\,d\phi} = \frac{d^3\sigma_{\rm unp}}{dx\,dz\,d\phi}\Big\{1 + S_T\Big[\underbrace{\sin(\phi-\phi_S)\,A_{UT}^{\sin(\phi-\phi_S)}}_{\text{Sivers effect}} + \underbrace{\sin(\phi+\phi_S)\,A_{UT}^{\sin(\phi+\phi_S)}}_{\text{Collins effect}} + \cdots\Big]\Big\}$$

$$\Rightarrow \text{Collins SSA :}\quad A_{UT}^{\sin(\phi+\phi_S)} \propto \frac{h_1^a(x,\mathrm{p}_T^2)\otimes H_1^{\perp a}(z,\mathrm{K}_T^2)}{f_1^a(x)D_1^a(z)}$$

- $H_1^{\perp}(z,\mathrm{K}_T^2)$ **"twist-2", chirally odd & "naively T-odd"**

(Collins 1992, Efremov, Mankiewicz, Tornquist 1992 (transversal handedness ≡ interference PFF), . . .)



- Left-right asymmetry in fragmentation process
- **Transversity $h_1^a(x)$, twist-2, chirally odd**

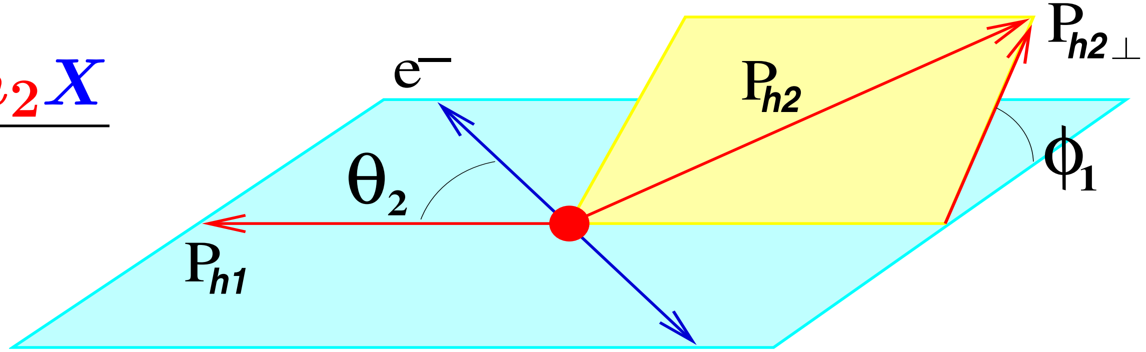
(Ralston&Soper 1979, . . .)

- **Long. polarized target**: $A_{UL}^{\sin 2\phi} \propto H_1^{\perp}$ at HERMES ~ 0; promising preliminary CLAS data.

Collins effect in $e^+e^- \to h_1 h_2 X$

$h_1 \in$ jet$_1$, $h_2 \in$ jet$_2$

(Boer, Jakob, Mulders, 1997)



e^+e^- rest frame

$$\frac{d^2\sigma^{e^+e^-\to h_1 h_2 X}}{d\phi_1 d\cos\theta_2} = \frac{d^2\sigma_{unp}}{d\phi_1 d\cos\theta_2}\underbrace{\left[1+\cos(2\phi_1)\frac{\sin^2\theta_2}{1+\cos^2\theta_2}C_{\rm Gauss}\frac{\sum_a e_a^2 H_1^{\perp a(1/2)} H_1^{\perp\bar{a}(1/2)}}{\sum_a e_a^2 D_1^a D_1^{\bar{a}}}\right]}_{\equiv A_1}$$

$$C_{\rm Gauss}(z_1,z_2) = \frac{16}{\pi}\frac{z_1 z_2}{z_1^2+z_2^2}, \quad H_1^{\perp(1/2)a}(z) = \int d^2K_T \frac{|K_T|}{2zm_\pi} H_1^{\perp a}(z,K_T) \le \frac{1}{2}D_1^a(z)$$

Same azimuthal dependence comes from radiative and acceptance effects

Trick used at BELLE: $\frac{A_1^U}{A_1^L} \approx 1+\cos(2\phi_1)\; P_1$

Universality: expect the same Collins function in e^+e^- and SIDIS

(Metz 2002, Collins & Metz 2005)

though . . . not yet fully convinced (Amsterdam group)

Available data & Main assumptions

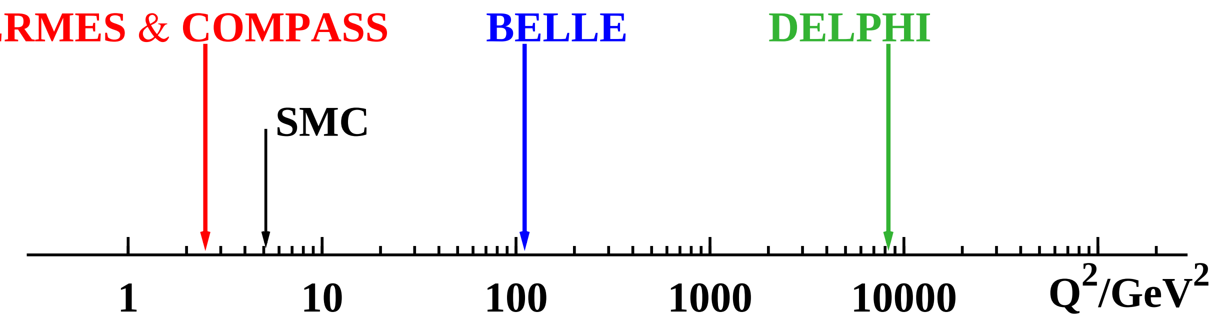
- SIDIS: HERMES (PRL94(2005)012002, hep-ex/0408013 & AIP 792(2005)933, hep-ex/0507013)
- SIDIS: COMPASS (PRL94,202002(2005), NPB765(2007)31)
- e^+e^- BELLE (PRL**96**(2006)232002). Very recently A_1^U/A_1^C was reported (hep-ex/0607014).

also:

- SIDIS: SMC preliminary (Bravar, Nucl.Phys.Proc.Suppl.**79**(1999)520)
- e^+e^- DELPHI preliminary (Efremov,Smirnova,Tkachev, Nucl.Phys.Proc.Suppl.**79**(1999)554)

Question : **Are all these data due to the same Collins effect?**

Problems :



- Different scales.
- Sudakov suppression.
- Soft factors.
- Unknown functions $H_1^{\perp}(z, K_T)$, $h_1^a(x, p_T)$.
- Unknown k_T-dependence.

Way out:

- Neglect soft factors.
- Disregard Sudakov suppression.
- Different scales $\Rightarrow$ **compare** $H_1^{\perp}/D_1$ (presumably less scale-dependent).
- $f_1^a(x)$ from GRV98, $D_1^a(z)$ from Kretzer2000; Kretzer,Leader,Christova2001.
- $h_1^a(x)$ from chiral quark-soliton model (PRD64(2001)034013) — about 20% accuracy.
- $F(x,k_T) = F(x) \cdot G(k_T)$&Gaussian, if $\langle P_{h\perp} \rangle \ll \langle Q \rangle$ ✓& at HERMES ✓
  (D'Alesio&Murgia2004)

$\Rightarrow$ **Basically two unknown** $\langle H_1^{\perp\text{fav}} \rangle$, $\langle H_1^{\perp\text{unf}} \rangle$ can be extracted from π^+, π^- HERMES – modulo uncertainties due to our assumptions.

Emerging picture of Collins function from SIDIS

$$A_{UT}^{\sin(\phi+\phi_S)} = 2\,\frac{\sum_a e_a^2\, x h_1^a(x)\; B_{\rm Gauss} H_1^{\perp(1/2)a}(z)}{\sum_a e_a^2\, x f_1^a(x)\; D_1^a(z)} \qquad B_{\rm Gauss}(z) = \frac{1}{\sqrt{1+z^2\,\langle \mathbf{p}_{h_1}^2\rangle/\langle \mathbf{K}_{H_1}^2\rangle}} \leq 1$$

For pions, two functions :

$$H_1^{\perp\rm fav} = H_1^{\perp u/\pi^+} = H_1^{\perp d/\pi^-} = \dots$$

$$H_1^{\perp\rm unf} = H_1^{\perp u/\pi^-} = H_1^{\perp d/\pi^+} = \dots$$

natural (?) to expect $|H_1^{\perp\rm fav}| \gg |H_1^{\perp\rm unf}|$

Fit HERMES $\Rightarrow$

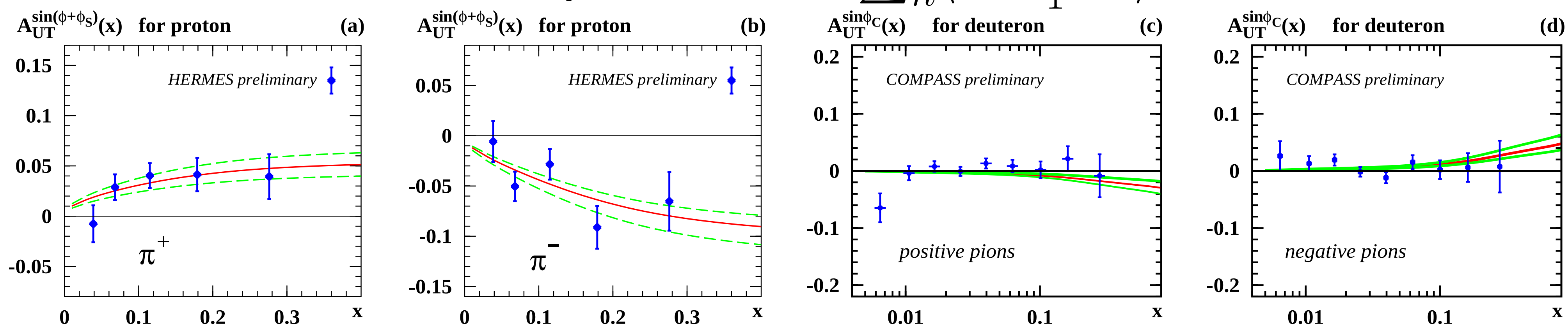
$$\langle B_{\rm Gauss} H_1^{\perp(1/2)\rm fav}\rangle = (3.5 \pm 0.8)\cdot 10^{-2}$$

$$\langle B_{\rm Gauss} H_1^{\perp(1/2)\rm unf}\rangle = -(3.8 \pm 0.7)\cdot 10^{-2}$$

$$H_1^{\perp\rm unf} \approx -H_1^{\perp\rm fav}$$

$\longrightarrow$ string fragmentation (Artru,Czyżewski,Yabuki,ZPhysC73(1997)527)

$\longrightarrow$ Schäfer-Teryaev sum rule $\sum_h \langle z^2 H_1^{\perp(1)}\rangle = 0$ (PRD61(2000)077903)



- Good description of HERMES
- compatible with COMPASS

Emerging picture of transversity from SIDIS

How model dependent is our result?

Look closer: demand extracted $\langle B_{\rm Gauss} H_1^\perp \rangle$ to vary within 1-σ.

Question: How much is $h_1^a(x)$ allowed to vary?

$\Rightarrow$ **Picture:** $\underbrace{h_1^u(x) \text{ within } 30\% \text{ of Soffer bound}}_{\text{supported by lattice QCDSF}}$,

other $h_1^a(x)$ unconstrained.

However, COMPASS data for deuteron limited positivity for $h_1^d(x)$

(Anselmino at al. PRD75(2007)054032, Prokudin talk).

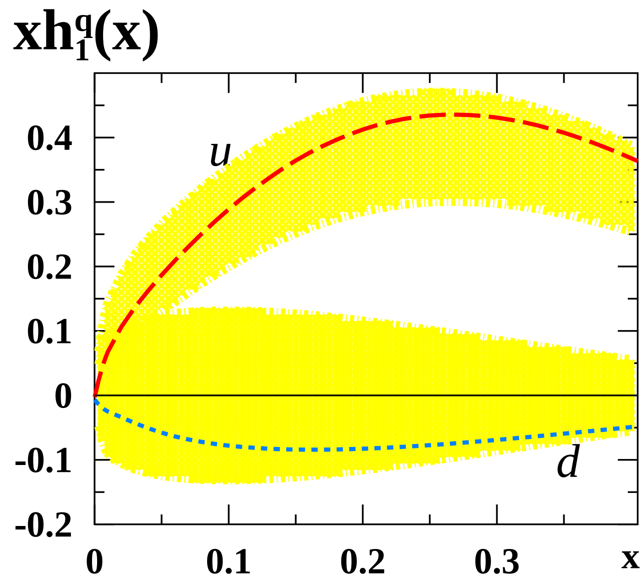
- **Grain of salt: preliminary SMC**

  charged hadrons

  $\langle Q^2 \rangle \sim 5\,\mathrm{GeV}^2, \quad \langle x \rangle \sim 0.08$

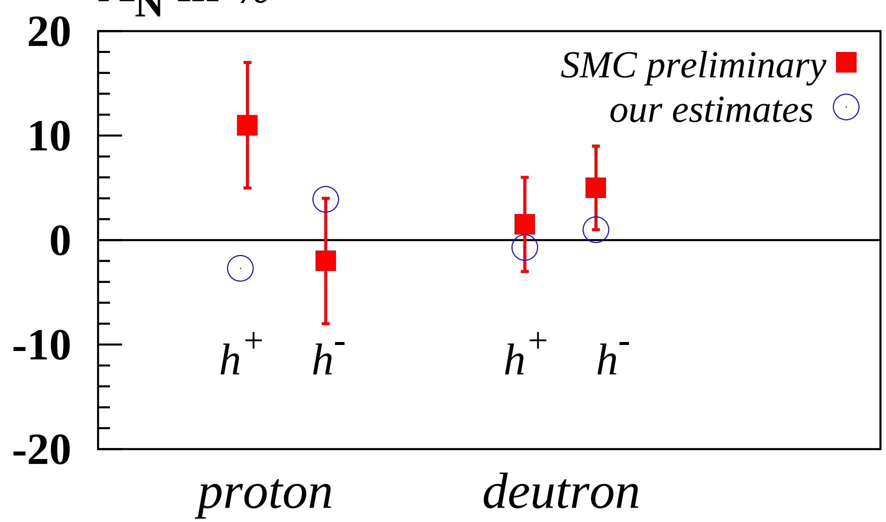
  $\langle z \rangle \sim 0.45$ and $\langle P_{h\perp} \rangle \sim (0.5-0.8)\,\mathrm{GeV}$

Reason to worry? Data are preliminary ...



$h_1^a(x)$ from chiral quark soliton model

A_N in %

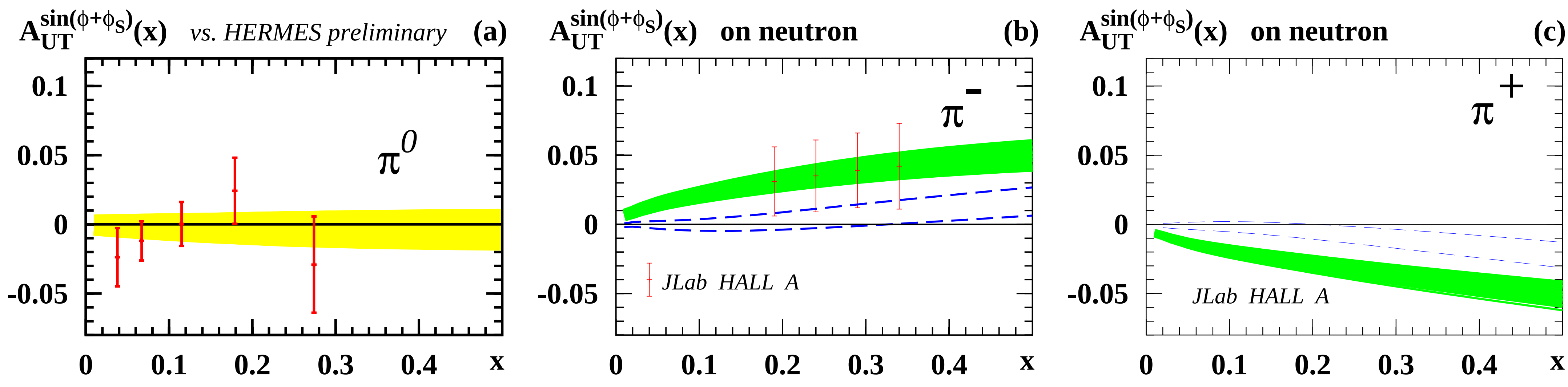


- **Emerging picture of transversity from SIDIS will improve**
  - Data on π^0 & kaons.
  - More data from HERMES proton & deuteron target.
  - More data from COMPASS deuteron & proton target (Anselmino at al.PRD75(2007)054032).
  - Data from CLAS with transv. pol. target.
  - Data from HALL-A, transv. ^{3}He $\approx$ neutron target, $\langle Q^2\rangle \sim 2\,\mathrm{GeV}^2$, $\longrightarrow \boldsymbol{h_1^d(x)}$

    green: $h_1^d(x) < 0$ from chiral quark-soliton model,

    dashed: $h_1^d(x)$ of opposite sign,

    error bars: projections for 24 days of beam time.



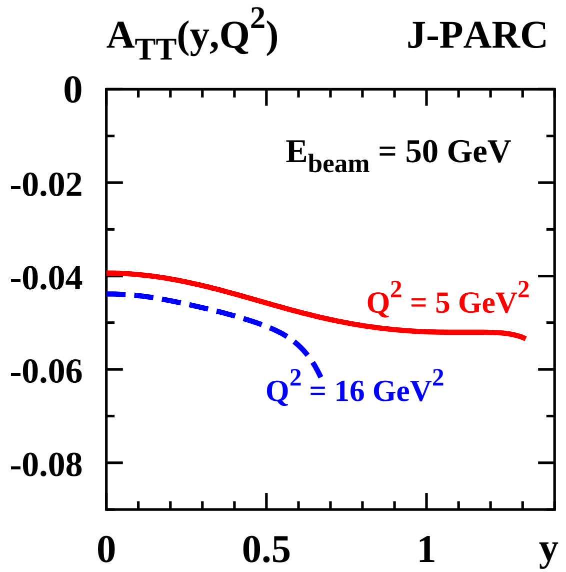
Transversity and Drell-Yan

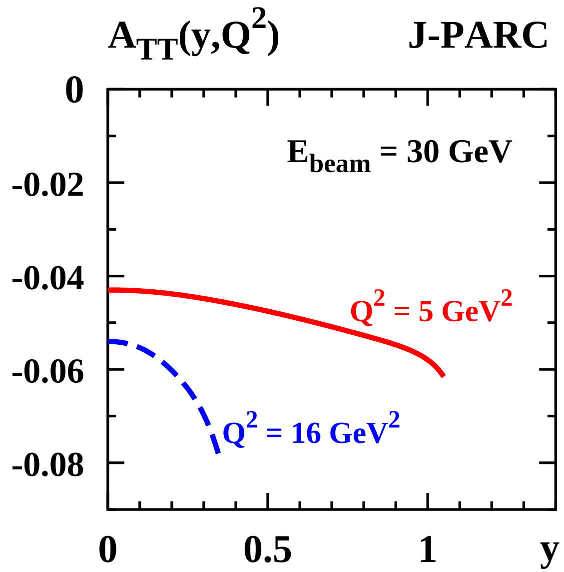
The best and the cleanest way to access transversity h_1

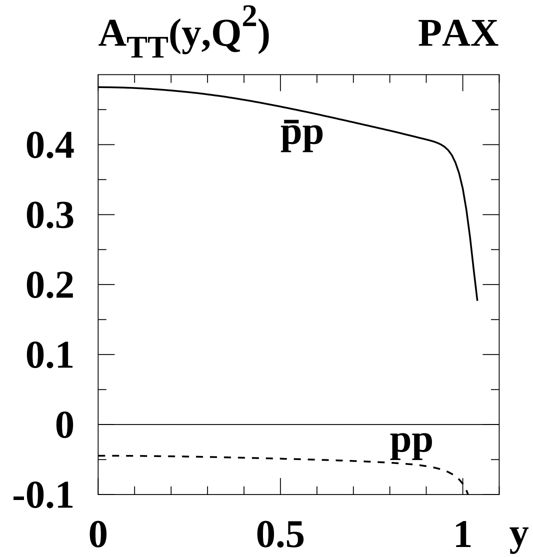
$$A_{TT}(y,Q^2) = \frac{\sum_a e_a^2 h_1^a(x_1,Q^2) h_1^{\bar{a}}(x_2,Q^2)}{\sum_a e_a^2 f_1^a(x_1,Q^2) f_1^{\bar{a}}(x_2,Q^2)}\,, \qquad x_{1/2} = \sqrt{\frac{Q^2}{s}} e^{\pm y}$$

Are planned to be measured at PAX & J-PARC. Our predictions (χQSM):

(A.E.,Goeke, Schweitzer EPJC35:207(04) and work in progress)

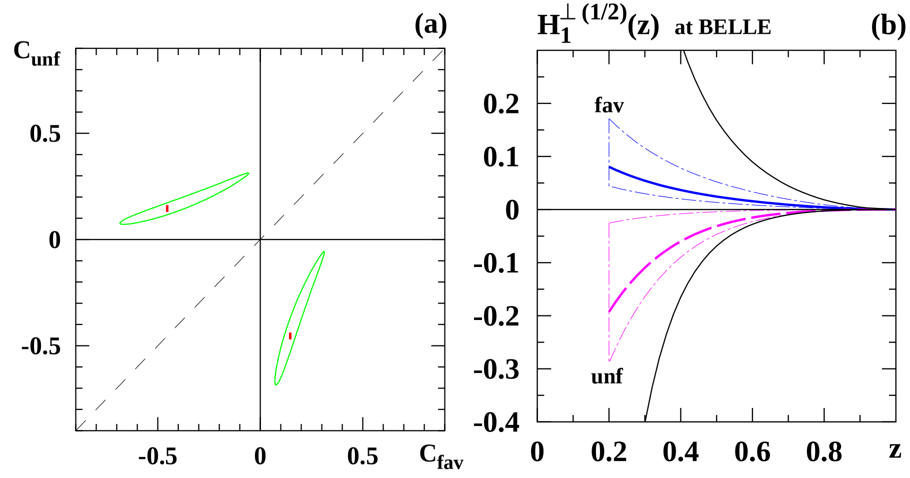






- Rather noticeable effect even for $p_\uparrow p_\uparrow$! (Similar for polarized U-70, Protvino.)
- Mostly sensitive to $h_1^u(x)$.
- Allow discriminate models (e.g. popular guess $h_1^a(x) \approx g_1^a(x)$ would give $A_{TT} \approx 30\%$).

Collins function from e^+e^-



- **BELLE** $e^+e^- \to h_1 h_2 X$ with $h_{1,2} = \pi^\pm$

$$\frac{A_1^U(\phi)}{A_1^L(\phi)} \approx 1 + \cos(2\phi_1)\, \mathbf{P_1}$$

with $\mathbf{P_1}(z_1, z_2) = F(H_1^{\rm fav}, H_1^{\rm unf}, \text{Gauss})$

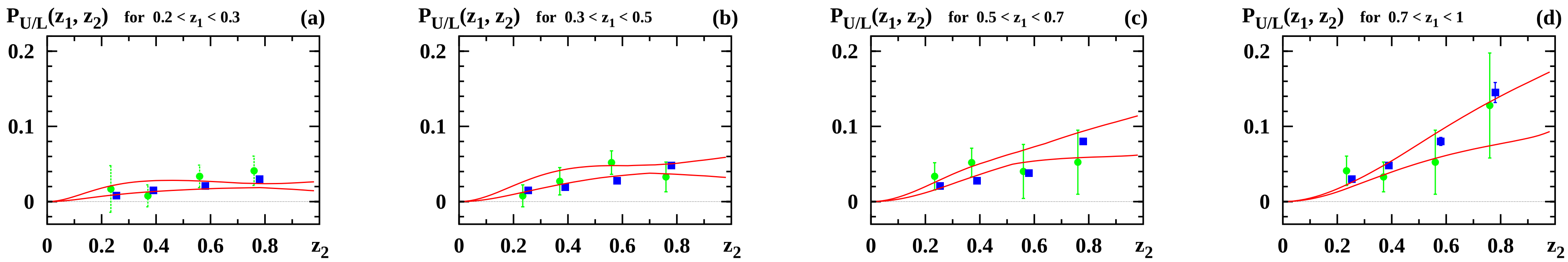
include $s, \bar{s} \to H_1^{\rm unf}$ (fine for D_1)

symmetric $z_1 \leftrightarrow z_2$ or fav $\leftrightarrow$ unf

Best Ansatz $H_1^{\perp(1/2)a} = C_a z D_1^a(z)$, other Ansätze not excluded

Best fit results: $C_{\rm fav} = 0.15, \quad C_{\rm unf} = -0.45$ or vice versa: fav $\leftrightarrow$ unf

sign preferred by HERMES



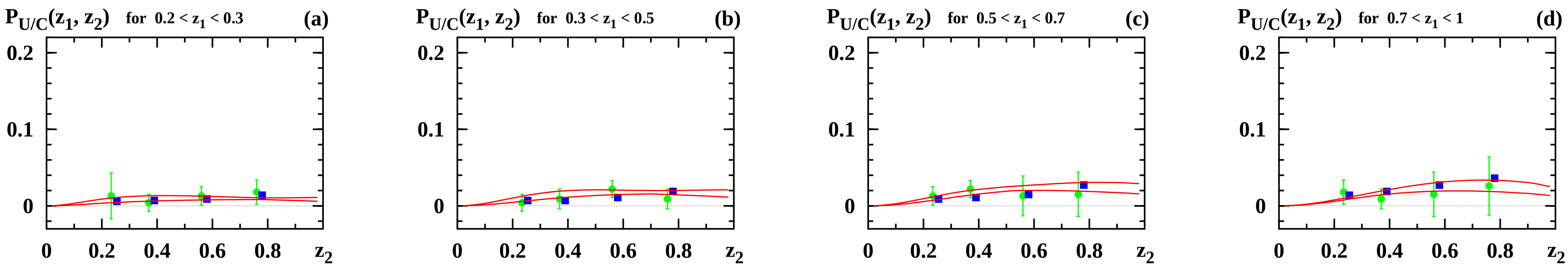
(Blue square - new preliminary data.)

Good description!

•Important most recent news from BELLE

New double ratio is measured (hep-ex/0607014 and DIS-2007)

$$\frac{A_1^U(\phi)}{A_1^C(\phi)} \approx 1 + \cos(2\phi_1)\ \mathbf{P_c}$$



Excellent confirmation of our picture of Collins effect!

Faith in our first understanding of Collins effect strengthened.
New (preliminary) data, will provide valuable constraints and improve the fits after officially released.

- **DELPHI preliminary**

$e^+e^- \to Z_0 \to h_1 h_2 X$, $\quad h_{1,2} =$ charged hadrons

$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\phi_1} = P_0 \left(1 + \cos(2\phi_1)\, P_2\right), \quad P_2 = \tilde{F}(H_1^{\rm fav} + H_1^{\rm unf})$$

with $P_{2,\mathrm{DELPHI}} = -(0.26 \pm 0.18)\% \pm$ unknown systematics.

- Different scales! Assume $\frac{H_1^\perp}{D_1}\Big|_{\text{one scale}} \approx \frac{H_1^\perp}{D_1}\Big|_{\text{another scale}}$
- $H_1^{\perp c}, H_1^{\perp b}$? Since $m_c, m_b \ll M_Z$: **Maybe unfavoured? Maybe zero?**
- Charged hadrons $= \pi^\pm, K^\pm, \ldots$ with $\lim\limits_{m_\pi \to 0} \frac{H_1^{\perp(1/2)a/\pi}}{D_1^{a/\pi}} = \lim\limits_{m_K \to 0} \frac{H_1^{\perp(1/2)a/K}}{D_1^{a/K}}$

$\Rightarrow$ $P_{2,\text{ estimate}} \approx -(0.06\ \ldots\ 0.29)\%$

$\Rightarrow$ **Preliminary DELPHI seems not incompatible with BELLE!**

Intermediate STATUS :

SIDIS: HERMES & COMPASS compatible
e^+e^-: BELLE & DELPHI not incompatible
$\Rightarrow$ **What about HERMES vs. BELLE?**

• HERMES vs. BELLE

I. $$\frac{\langle 2B_{\rm Gauss} H_1^{\perp(1/2){\rm fav}}\rangle}{\langle D_1^{\rm fav}\rangle}\Big|_{\rm HERMES} = (7.2 \pm 1.7)\% \quad \text{vs.} \quad \frac{\langle 2H_1^{\perp(1/2){\rm fav}}\rangle}{\langle D_1^{\rm fav}\rangle}\Big|_{\rm BELLE} = (5.3\ \ldots\ 20.4)\%$$

$$\frac{\langle 2B_{\rm Gauss} H_1^{\perp(1/2){\rm unf}}\rangle}{\langle D_1^{\rm unf}\rangle}\Big|_{\rm HERMES} = -(14.2 \pm 2.7)\% \quad \text{vs.} \quad \frac{\langle 2H_1^{\perp(1/2){\rm unf}}\rangle}{\langle D_1^{\rm unf}\rangle}\Big|_{\rm BELLE} = -(3.7\ \ldots\ 41.4)\%\,.$$

Central values of HERMES systematically lower then of BELLE.

Evolution? But:

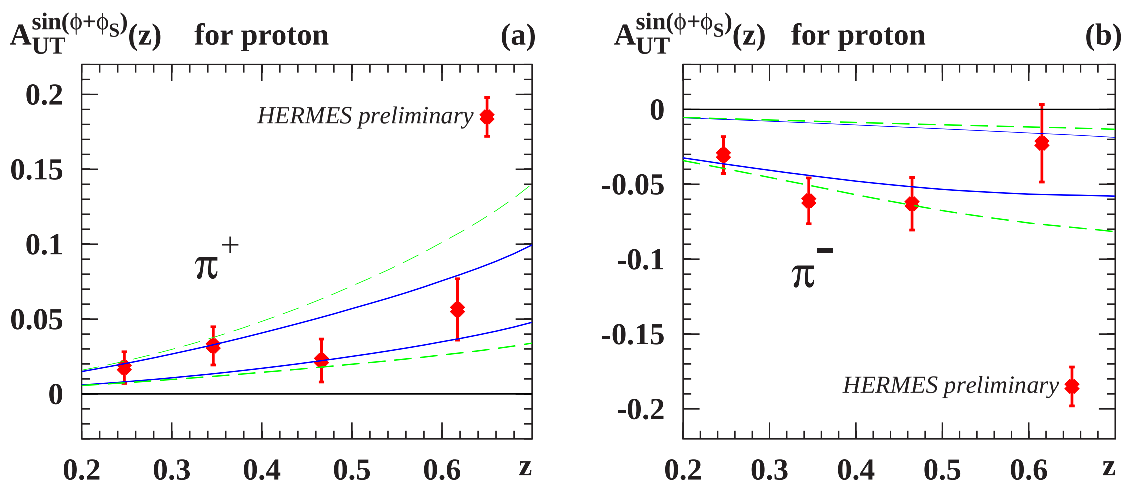
1. $\Uparrow$ $B_{\rm Gauss} < 1$ **2.** $\Uparrow$ Errors correlated!

II. ***z*-dependence at HERMES from BELLE fit for $H_1^\perp(z)$.**

Solid lines – 1σ-range.

Dashed line – unknown Gaussian widths

$$1 \lesssim \frac{\langle \mathbf{p}_{h_1}^2\rangle}{\langle \mathbf{K}_{H_1}^2\rangle} \lesssim 4\,.$$



$\Rightarrow$ **BELLE & HERMES compatible!**

Summary & Conclusions

- HERMES & COMPASS: first data on Sivers effect $\longrightarrow$ first insights.
- SIDIS data from HERMES & COMPASS compatible.
- At present stage large-N_c predictions useful constraint & compatible with data; picture by M. Burkardt $f_{1T}^{\perp q} \sim -\kappa^q$ seems to work.
- Situation improving due to new data from HERMES, COMPASS & JLAB. New impact due to kaons $\rightarrow$ Sivers-$\bar{q}$.
- First understanding $\rightarrow$ Drell–Yan SSA observable at RHIC, COMPASS, PAX. Experimental test of $\boxed{f_{1T}^{\perp}|_{DIS} = -f_{1T}^{\perp}|_{DY}}$ possible.
- Lots of work: e.g. what about SSA in $p^{\uparrow}p \rightarrow \pi X$? (Sivers, Anselmino et al.).

- Collins effect: try of first “global” analysis of data. In good agreement with later global fit (Anselmino at al. PRD75(2007)054032, Prokudin talk)
- e^+e^- **BELLE** consistent with SIDIS **HERMES** & **COMPASS**, preliminary DELPHI consistent with those, preliminary SMC not.
- Emerging picture: $H_1^{\perp u} \approx -H_1^{\perp d}$, possible explanations: string fragmentation, Schäfer–Teryaev sum rule.
- $h_1^u > 0$ and within $30\,\%$ of Soffer bound in agreement with lattice.
- Other $h_1^a(x)$ less known, soon to be improved: HERMES, COMPASS, JLAB & BELLE.
- Use emerging picture to understand other interesting data, e.g. CLAS & HERMES $A_{UL}^{\sin 2\phi}$ or twist-3 $A_{UL}^{\sin\phi}$ and $A_{LU}^{\sin\phi}$ $\longrightarrow$ applications (to be done).
- Encouraging **progress!** (in spite of many forced theoretical uncertainties: soft factor, scale dependence, transverse momenta,...). However, **optimism!** New & more precise data coming in, improved analysis necessary.

Thank you!