Workshop on "Transverse momentum, spin, and position distributions of partons in hadrons", Trento, 11. – 15. June 2007

Spin asymmetries in semi-inclusive DIS & Drell–Yan process

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in collaboration with

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based on PRD 73 (2006) 094023, PRD 73 (2006) 014021, PLB 612 (2005) 233, recent proceedings

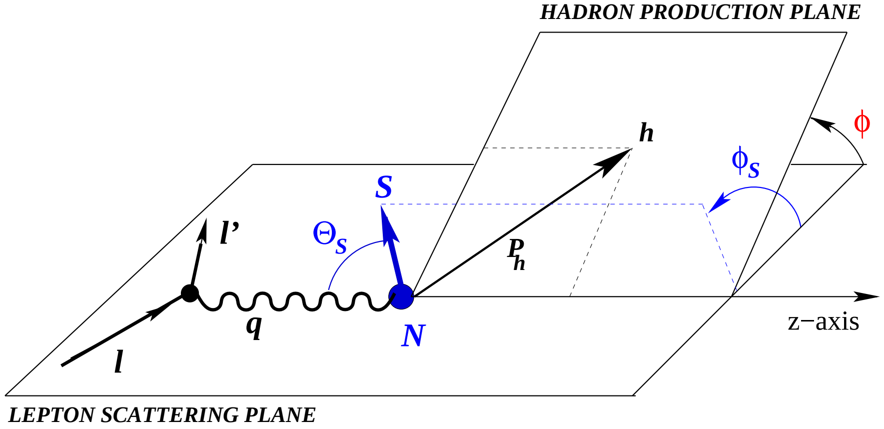
Overview:

- What is Sivers effect?
- Sivers effect in SIDIS
- Sivers effect in Drell-Yan $\longrightarrow$ crucial test!!!
- New data, new developments
- What we learn from emerging first picture of Sivers effect
- Summary

SIDIS $lN \to l'hX$ on transv. polarized target

expressions in LO $1/Q$ Boer, Mulders, ... 1990s
factorization with k_T Ji, Ma, Yuan & Collins, Metz 2004

see recent review:
Bacchetta, Diehl, Goeke, Metz, Mulders, Schlegel, JHEP (2007)



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

today: Alexei Prokudin, PS

$$+\underbrace{\sin(\phi+\phi_S)\,A_{UT}^{\sin(\phi+\phi_S)}}_{\text{Collins effect}}$$

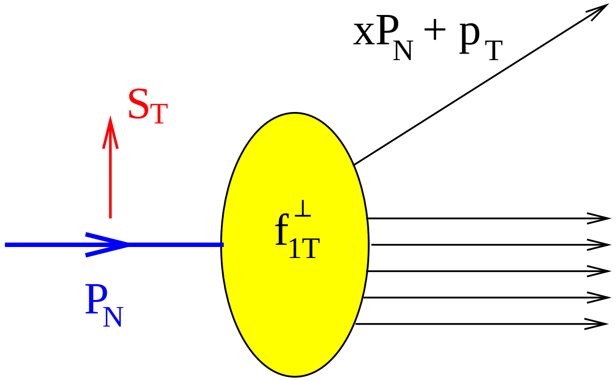
thursday: Boglione, Efremov

yesterday: data on Sivers, Collins, beyond

$$+\underbrace{\cdots\cdots\cdots\cdots}_{\text{beyond Sivers+Collins}}\Big]\Big\}$$

thursday: Aram Kotzinian

Properties of Sivers function $f_{1T}^{\perp q}(x, p_T)$



- introduced to explain SSA in $p^{\uparrow}p \to \pi X$ Sivers 1991 (some [not all] people nervous about factorization)
- **it exists!** Brodsky, Hwang, Schmidt & Collins 2002
- "twist-2" (= not power supressed)
- "T-odd"
- **universality** Collins 2002 $$f_{1T}^{\perp}|_{DIS} = -f_{1T}^{\perp}|_{DY}$$
- flavour dependence $f_{1T}^{\perp u} = -f_{1T}^{\perp d}$ modulo $1/N_c$ corrections Pobylitsa 2003 (★)
- intuitive, model-dependent relation to GPDs: $\int \mathrm{d}x\, f_{1T\,\mathrm{DIS}}^{\perp(1)q}(x) \propto -\kappa^q \begin{cases} < 0 & \text{for } q = u, \\ > 0 & \text{for } q = d. \end{cases}$ Burkardt 2002
- models Brodsky, Hwang, Schmidt & Gamberg et al. & Bacchetta, Schäfer, Yang & Lu, Ma & Yuan & D'Alessio et al.

Sivers effect in SIDIS

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

$\underbrace{f_1^a(x),\ D_1^a(z)\ \text{known}}_{\text{e.g. GRV, Kretzer}} \Rightarrow$ extract $f_{1T}^{\perp}$ **!!**

- **target dependence:**

  proton **effect $\neq 0$**
  deuteron **effect ~ 0**
  } Are COMPASS and HERMES data compatible **?** **Yes!**

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

Subject to intensive & independent studies:

our works PRD 73 (2006) 094023, PRD 73 (2006) 014021, PLB 612 (2005) 233.
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

in the following **our study** of Sivers in SIDIS cf. talks by Alexei Prokudin, Werner Vogelsang

“historical” flashback:

Athens, 6–7 Oct. 2003, *“Transversity Workshop”*,
talk by N. C. Makins on behalf of HERMES Coll.

two preliminary data sets on Sivers (and Collins) effect:

$$A_{UT}^{P_{h\perp}/M_{\rm N}\,\sin(\phi-\phi_S)}$$

$$= \frac{\int \mathrm{d}\phi\; P_{h\perp}/M_N \sin(\phi-\phi_S)(N^{\uparrow}-N^{\downarrow})}{\int \mathrm{d}\phi\; \frac{1}{2}(N^{\uparrow}+N^{\downarrow})}$$

$$= (-2)\frac{\sum_a e_a^2 f_{1T}^{\perp(1)a}(x) D_1^a(z)}{\sum_a e_a^2 f_1^a(x) D_1^a(z)}$$

here $f_{1T}^{\perp(1)a}(x) \equiv \int \mathrm{d}^2\mathbf{p}_T \frac{\mathbf{p}_T^2}{2M_N^2}\, f_{1T}^{\perp a}(x,\mathbf{p}_T)$

model-independent, theoretically preferable
(when soft-factors neglected, which we do)
presently: not only still preliminary
but also officially not recommended for use
Acta Phys. Polon. B36, 209 (2005)

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

$$= \frac{\int \mathrm{d}\phi\; \sin(\phi-\phi_S)(N^{\uparrow}-N^{\downarrow})}{\int \mathrm{d}\phi\; \frac{1}{2}(N^{\uparrow}+N^{\downarrow})}$$

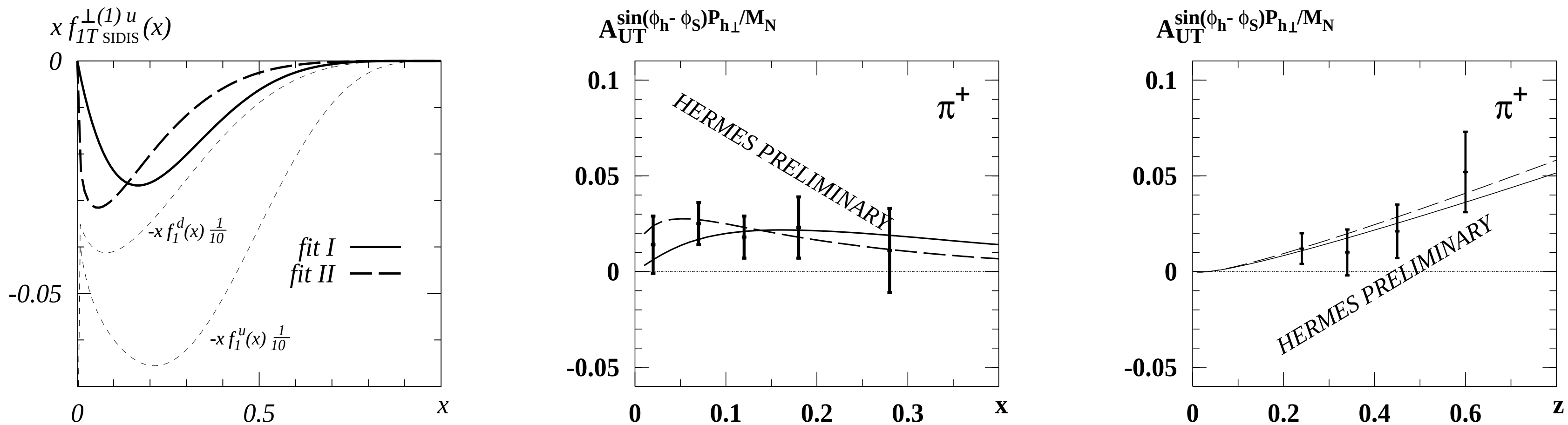
$$= (-2)\frac{a_{\rm Gauss}\sum_a e_a^2 f_{1T}^{\perp(1)a}(x) D_1^a(z)}{\sum_a e_a^2 f_1^a(x) D_1^a(z)}$$

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

experimentally preferable, but model-dependent
(no acceptance effects)
presently published PRL 94 (2005) 012002
more preliminary (recommended) data available
AIP Conf. Proc. **792** (2005) 933

$A_{UT}^{\sin(\phi-\phi_S)P_{h\perp}/M_N}$ model-independent information on $f_{1T}^{\perp(1)a}(x)$ PLB 612 (2005) 233, hep-ph/0412353

- sizeable error bars → minimize # of free parameters in fit → **theoretical constraints:**
- use large-N_c $f_{1T}^{\perp u} = -f_{1T}^{\perp d}$ modulo $1/N_c$ corrections Pobylitsa hep-ph/0301236 (★)
- respect positivity $\frac{|\mathbf{p}_T|}{M_N}\,|f_{1T}^{\perp a}(x,\mathbf{p}_T^2)| \le f_1^a(x,\mathbf{p}_T^2)$ Bacchetta, *et al.*, PRL 85 (2000) 712
- large-N_c-motivated fit Ansatz: $x f_{1T}^{\perp(1)u} = -x f_{1T}^{\perp(1)d} = A x^b (1-x)^5$ neglect $\bar{q}$, s, ...
- fit result: $x f_{1T}^{\perp(1)u} = \begin{cases} -0.4x\,(1-x)^5 & \text{for } b=1 \text{ fixed} \\ -0.1x^{0.3}(1-x)^5 & \text{both } A,\ b \text{ free} \end{cases}$



positivity ok! good (input!) cross check!

Where are $1/N_c$ corrections?

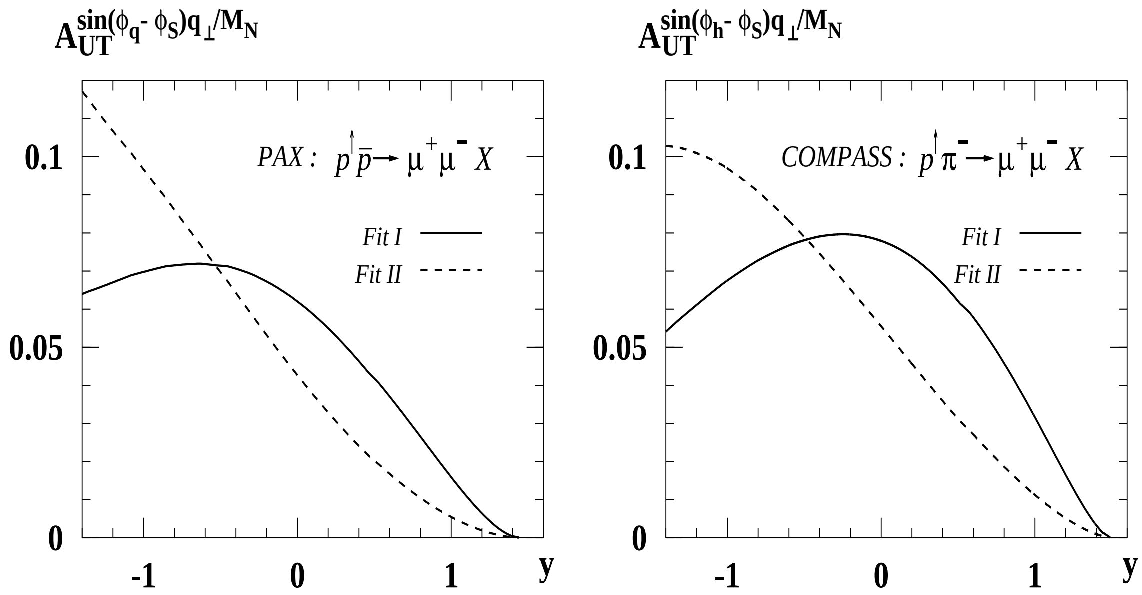
- Good place to see: $f_{1T}^{\perp u/\text{deuteron}} \approx f_{1T}^{\perp u/p} + f_{1T}^{\perp u/n} \approx f_{1T}^{\perp u} + f_{1T}^{\perp d}$
- $A_{UT,\,\text{deuteron}}^{\sin(\phi-\phi_s)} \sim 1/N_c \sim 0$ at COMPASS

Application

- important prediction
  Collins, PLB 536 (2002) 43

$$f_{1T}^{\perp a}|_{\text{DIS}} = -\, f_{1T}^{\perp a}|_{\text{DY}}$$

- check in experiment!
- PAX at GSI $p^\uparrow\bar{p} \to \mu^+\mu^- X$
- COMPASS $p^\uparrow\pi^- \to \mu^+\mu^- X$
- possible to confirm (or ...)



Efremov et al., PLB 612 (2005) 233, hep-ph/0412353
confirmed with MC by Bianconi, Radici PRD (2006)

But though theoretically preferable, data uncorrected for acceptance & preliminary
repeat excersize with **final** data PRL 94 (2005) 012002

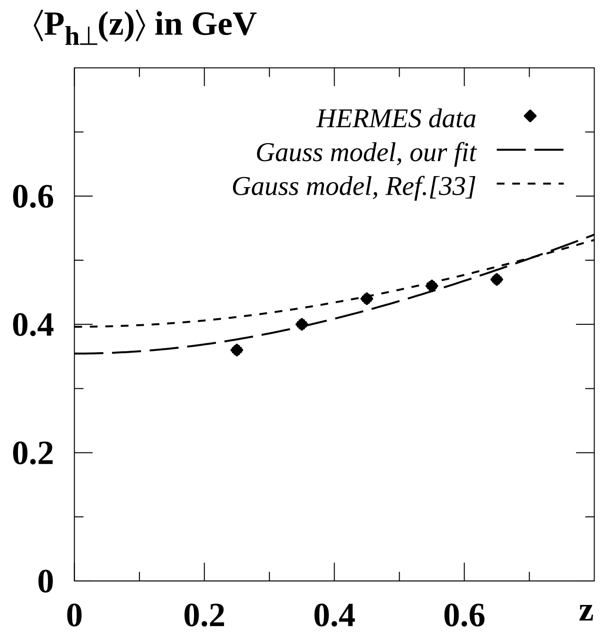
$A_{UT}^{\sin(\phi-\phi_S)}$ $\underbrace{\text{model-dependent}}_{\text{Gauss}}$ information on $f_{1T}^{\perp(1)a}(x)$ PRD 73 (2006) 094023, hep-ph/0509076

Gauss: $f(x,\mathbf{p}_T^2) \equiv f(x)\dfrac{\exp(-\mathbf{p}_T^2/p_{\rm av}^2)}{\pi\, p_{\rm av}^2}$ for $f = f_1^a,\ f_{1T}^{\perp a},\ D_1^a$

describes well HERMES $\langle P_{h\perp}(z)\rangle = \dfrac{\sqrt{\pi}}{2}\sqrt{z^2 p_{\rm unp}^2 + K_{D_1}^2}$

with $p_{\rm unp}^2 = 0.33\,{\rm GeV}^2$ and $K_{D_1}^2 = 0.16\,{\rm GeV}^2$

agrees with EMC "Cahn effect" Anselmino et al.
In numerous processes reasonable **model**,
provided transv. momenta $\ll$ hard scale
D'Alesio and Murgia, PRD 70 (2004) 074009.
At HERMES $\langle P_{h\perp}\rangle \sim 0.4\,{\rm GeV} \ll \sqrt{\langle Q^2\rangle} \sim 1.5\,{\rm GeV}$



$\langle P_{h\perp}(z)\rangle$ of hadrons produced from deuterium HERMES, PLB 562 (2003) 182

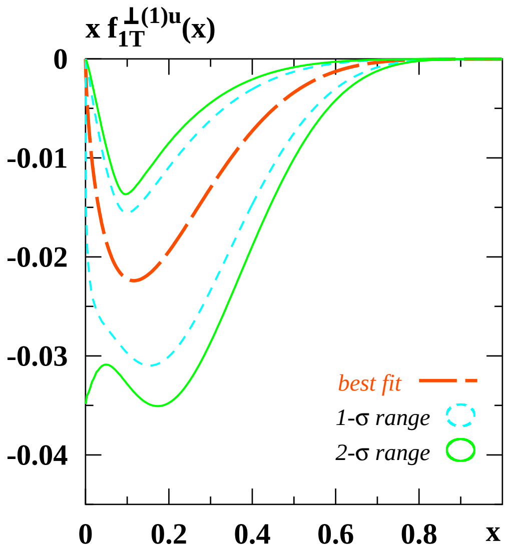
$$\Longrightarrow \quad A_{UT}^{\sin(\phi-\phi_S)} = (-2)\frac{a_{\rm Gauss}\sum_a e_a^2\, f_{1T}^{\perp(1)a}(x)\, D_1^a(z)}{\sum_b e_b^2\, f_1^b(x)\, D_1^b(z)}$$

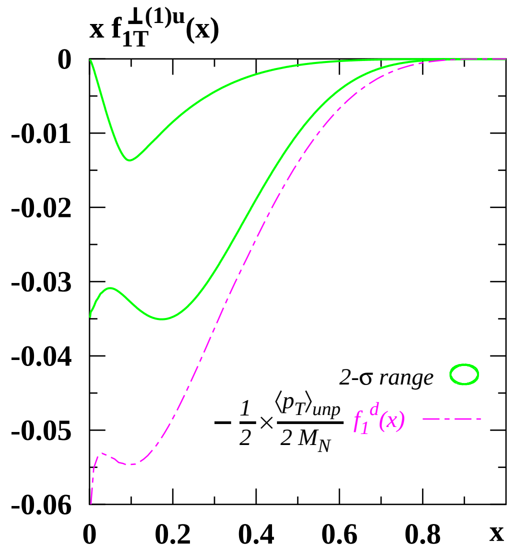
positivity $\frac{|\mathbf{p}_T|}{M_N}\,|f_{1T}^{\perp a}(x,\mathbf{p}_T^2)| \le f_1^a(x,\mathbf{p}_T^2)$ in Gauss: $p_{\rm Siv}^2 = (0.10\ldots0.32)\,{\rm GeV}^2$ i.e. $0.36 < a_{\rm Gauss} < 0.41$

Same procedure as before:

$$xf_{1T}^{\perp(1)u} = -xf_{1T}^{\perp(1)d} = Ax^b(1-x)^5 = -0.18x^{0.66}(1-x)^5 \quad \text{with } \chi^2/\text{d.o.f.} \sim 0.3$$

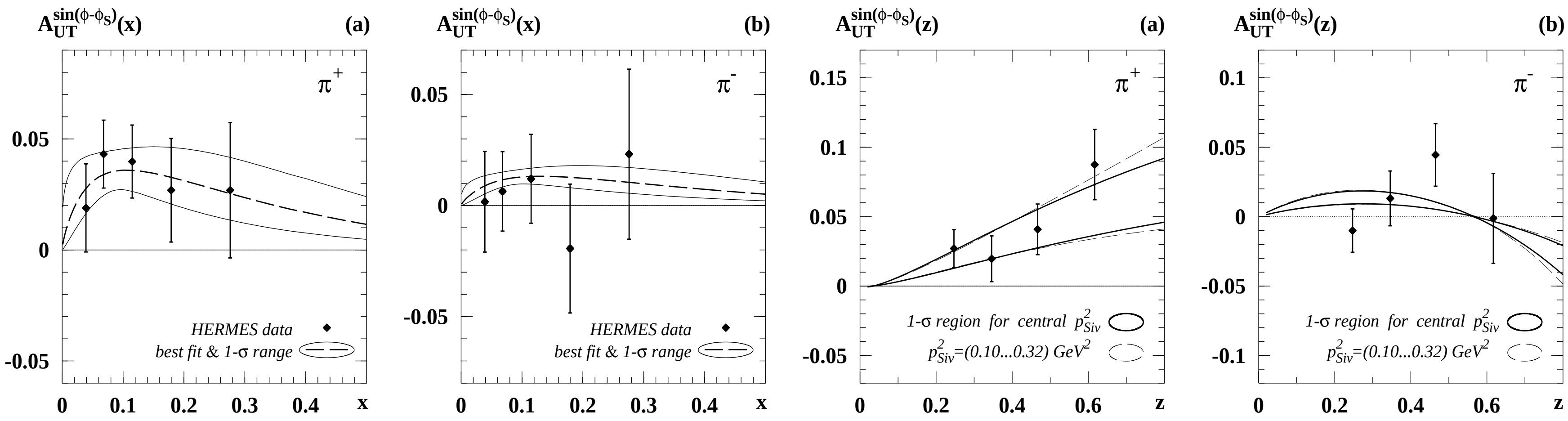
Results:





Positivity ok! **Not small!!!**

How does it describe the HERMES data? Well!



x-dependence (input)
Good description!

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

Satisfactory description.

We estimated that

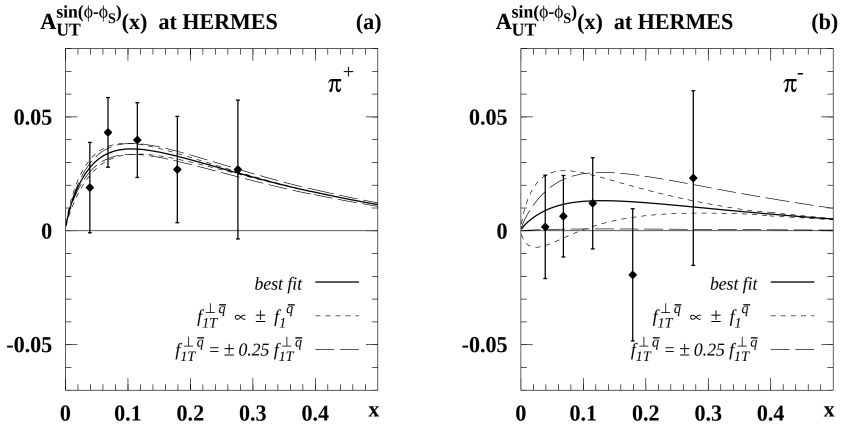
- Sivers sea quarks
- $1/N_c \sim 30\%$ corrections

within error bars.

Sivers-$\bar{q}$

- Let us simulate

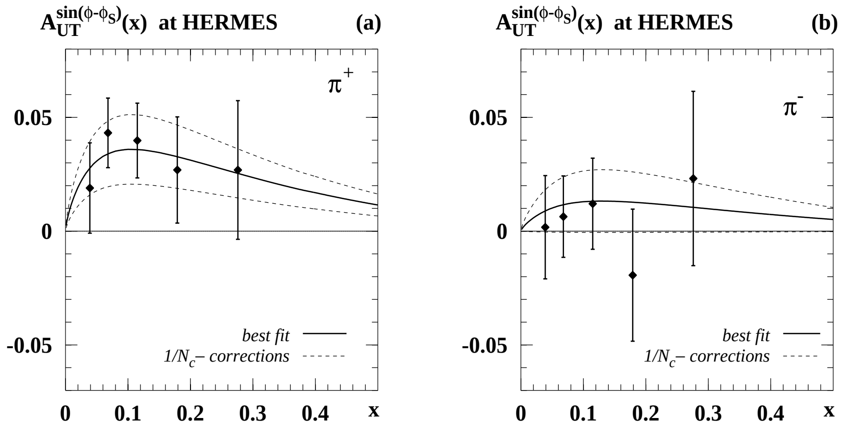
$$f_{1T}^{\perp(1)\bar{q}}(x) = \underbrace{f_{1T}^{\perp(1)q}(x)}_{\text{best fit}} \times \begin{cases} \pm 25\% \\ \pm \dfrac{f_1^{\bar{q}}(x)}{f_1^{q}(x)} \end{cases}$$



$1/N_c$-corrections

- $\underbrace{|(f_{1T}^{\perp u} + f_{1T}^{\perp d})(x)|}_{\mathcal{O}(N_c^2)} \ll \underbrace{|(f_{1T}^{\perp u} - f_{1T}^{\perp d})(x)|}_{\mathcal{O}(N_c^3)}$

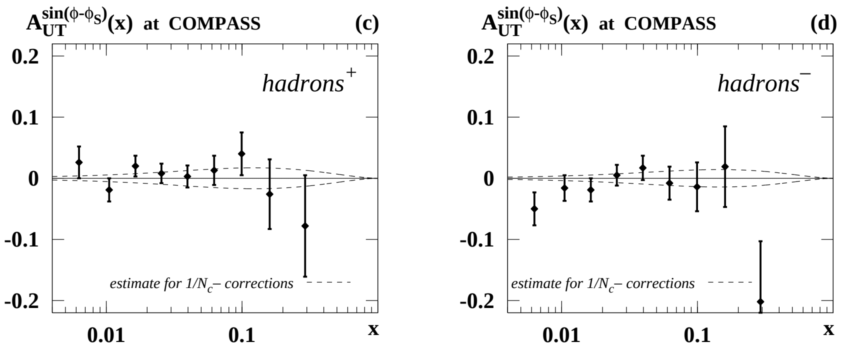
  $$(f_{1T}^{\perp u} + f_{1T}^{\perp d})(x) = \pm\frac{1}{N_c}\underbrace{(f_{1T}^{\perp u} - f_{1T}^{\perp d})(x)}_{\text{best fit}} \neq 0$$



- $f_{1T}^{\perp u/\text{deuteron}} = (f_{1T}^{\perp u} + f_{1T}^{\perp d})$, etc.

  Sivers SSA on deuterium $\stackrel{!}{=}$"$1/N_c$-correction"

  (Beware: Small x!)



Conclusion: Neglect of $\bar{q}$-effects and $1/N_c$-corrections in fit Ansatz good for present data

$f_{1T}^{\perp(1)q}$ **from** **FINAL** **HERMES data analysed without** $P_{h\perp}$**-weight**
PRD 73 (2006) 014021, hep-ph/0509076

vs.

$f_{1T}^{\perp(1)q}$ **from** **PRELIMINARY** **but "more preferably"** $P_{h\perp}$**-weighted data**
PLB 612 (2005) 233, hep-ph/0412353

FINAL data on $A_{UT}^{\sin(\phi-\phi_S)}$ $\xrightarrow{\text{Gauss}}$ … constrain parameters … $\xrightarrow{\text{etc.}}$ $f_{1T}^{\perp(1)q}(x)|_{\text{model-dependent}}$

$\updownarrow$?

PRELIMINARY data on $A_{UT}^{\sin(\phi-\phi_S)P_{h\perp}/M_N}$ $\xrightarrow{\text{directly}}$ $f_{1T}^{\perp(1)q}(x)|_{\text{“model-independent”}}$

Does the Gauss Ansatz work?

- The same events with/without $P_{h\perp}$-weight!

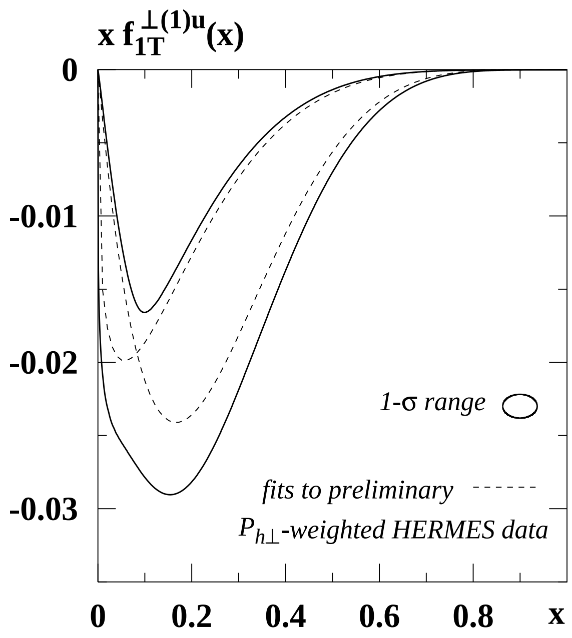
  If Gauss ok $\Longrightarrow$ the same $f_{1T}^{\perp(1)q}(x)$

  $\Longrightarrow$ **Yes, it works!**

Keep in mind:

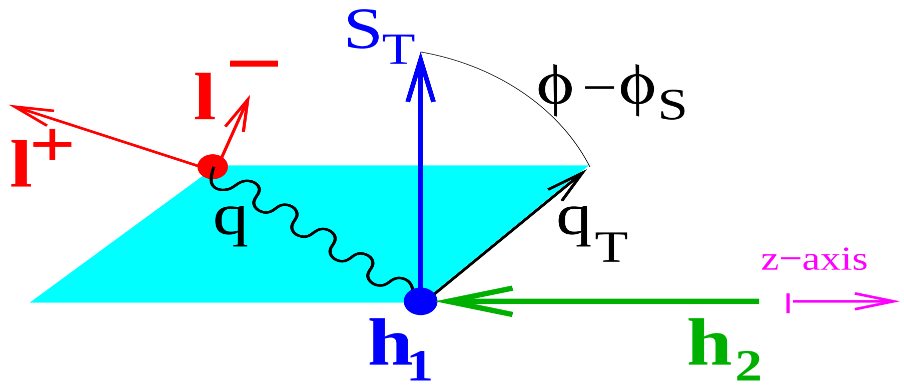
- *Preliminary, uncorrected* data.

  Does this indicate that for *these data* systematic errors due to acceptance less dominant than statistical error of data?



We have first idea of $f_{1T\,\mathrm{DIS}}^{\perp(1)}$!

Apply to DY $\quad h_1^{\uparrow} h_2 \to l^+ l^- X$



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

$$y = \frac{1}{2}\ln\Big(p_1\cdot q/p_2\cdot q\Big), \quad x_{1,2} = (Q^2/s)^{1/2} e^{\pm y}$$

Sivers-$\bar q$ *may* matter! Assume

$$\left.\begin{aligned} f_{1T}^{\perp\bar q} &= \pm 25\,\%\; f_{1T}^{\perp q} \\ \frac{f_{1T}^{\perp\bar q}(x)}{f_{1T}^{\perp q}(x)} &= \frac{f_1^{\bar q}(x)}{f_1^q(x)} \end{aligned}\right\}$$

just for illustrative purposes

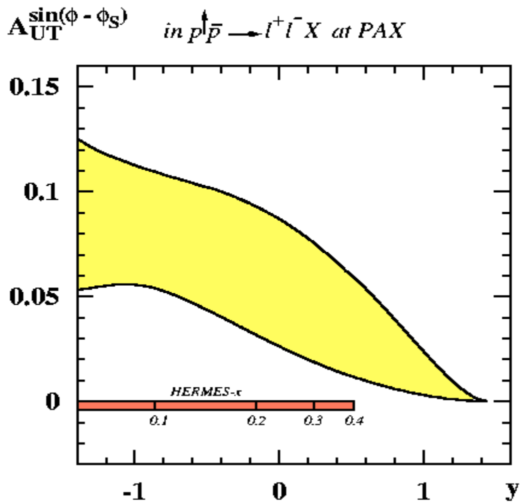
- **PAX at GSI**

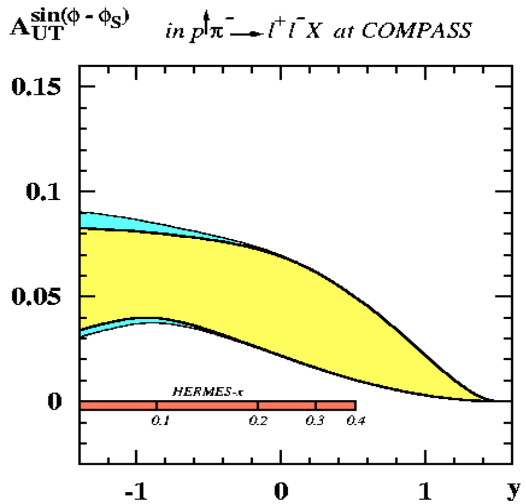
$$p^{\uparrow}\bar p \;\to\; l^+ l^- X \quad \text{(byproduct)}$$

- **COMPASS**

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

annihilations of valence q & $\bar q$ dominate
$\Rightarrow$ not sensitive to Sivers-$\bar q$, good!



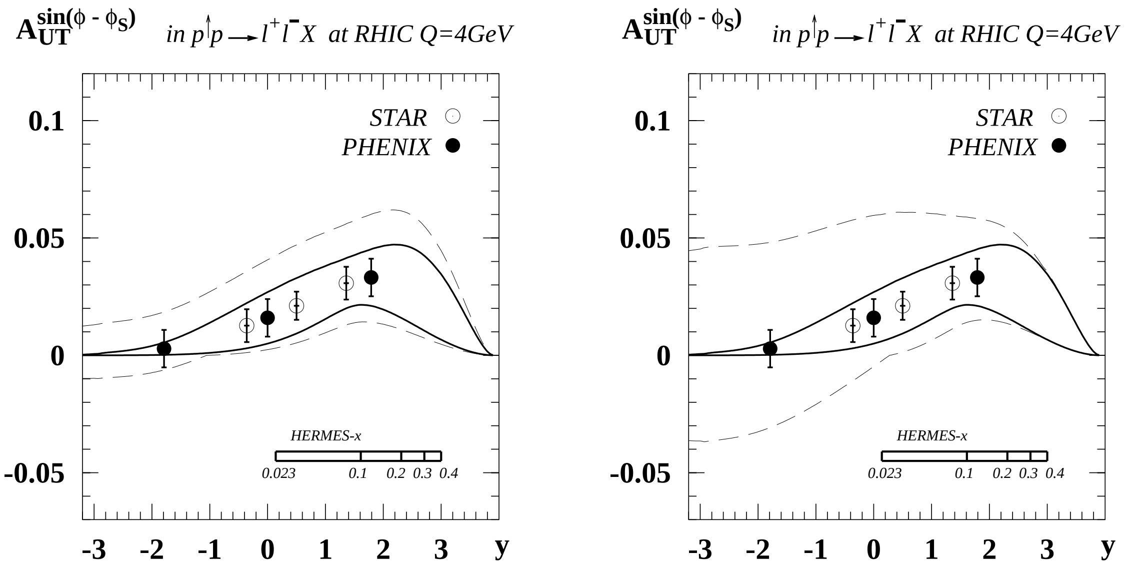


- **RHIC**

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

can test "change of sign" Sivers-q at $y > 0$
& provide information on Sivers-$\bar{q}$ at $y < 0$

error bars (thanks to Beau & Matthias)
$\int dt\, \mathcal{L} \sim 125\,\mathrm{pb}^{-1}$ realistic till 2012
RHIC & RHIC II



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

Why so important?

If $f_{1T}^{\perp a}|_{\mathrm{SIDIS}} = -\, f_{1T}^{\perp a}|_{\mathrm{DY}}$

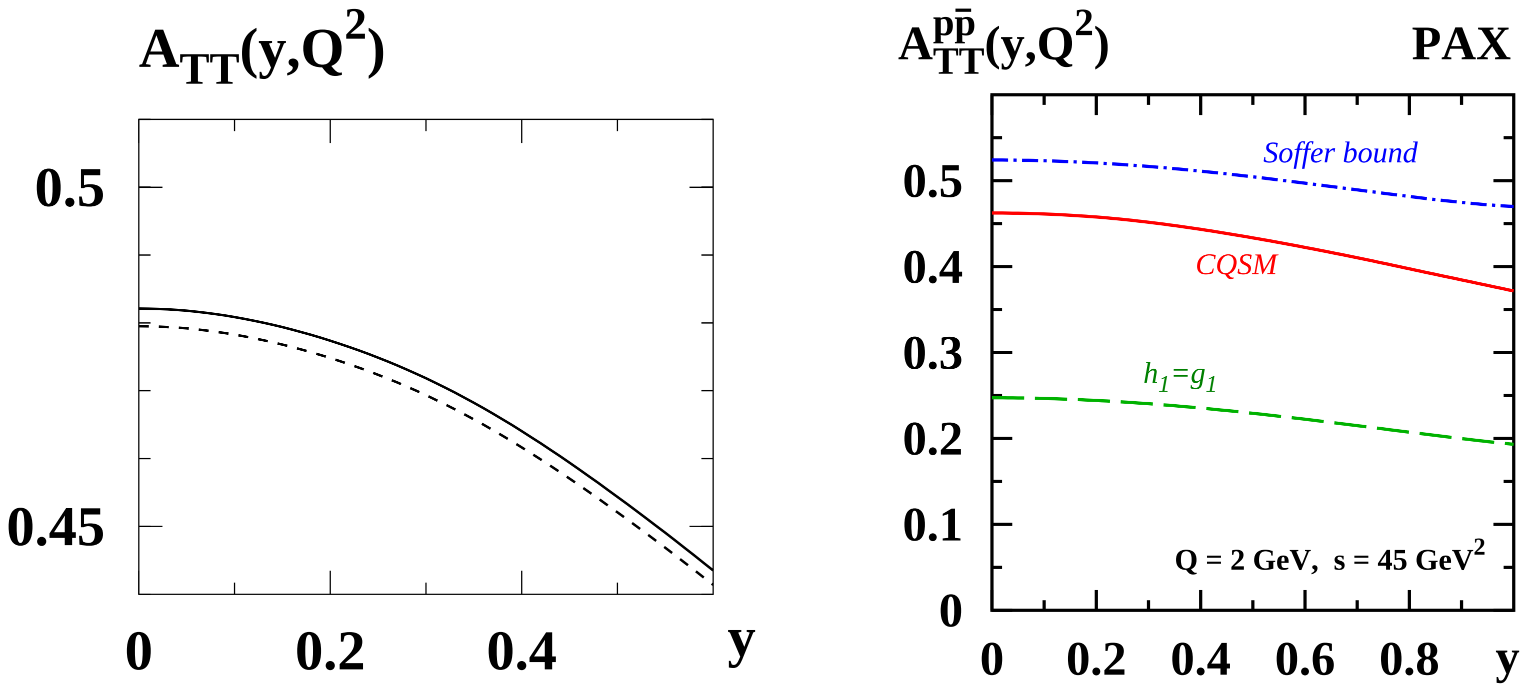
- **experimentally confirmed: fine! Are on the right treck!**
- **experimentally disproved: No factorization!**
  No understanding of intrinsic k_T-effects!

Experiment (as always) crucial!

By the way:

PAX: main goal $\bar{p}^{\uparrow} p^{\uparrow} \to l^+ l^- X$

$$A_{TT} = \frac{\sum_{a=u,d,\bar{u},\dots} e_a^2 h_1^a(x_1) h_1^a(x_2)}{\sum_{a=u,d,\bar{u},\dots} e_a^2 f_1^a(x_1) f_1^a(x_2)}$$

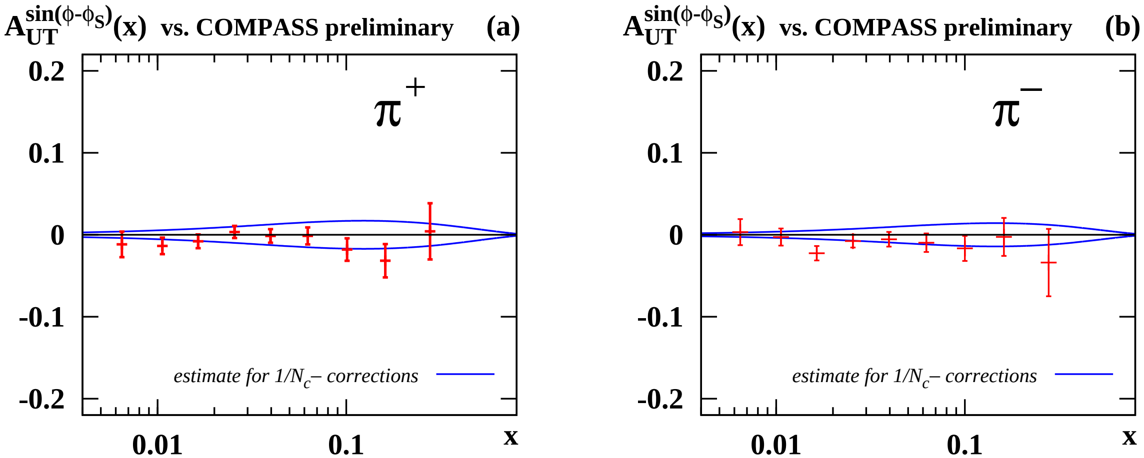


to good approximation $h_1^u(x)$
using $h_1^a(x)$ from chiral quark soliton model & other models

LO order, corrections there but asymmetry stable Ratcliffe & Shimizu, Sterman, Vogelsang, Yokoya

New developments

- deviations from large-N_c constraint $\longrightarrow$ deuteron, COMPASS.Most recent & precise data still compatible:

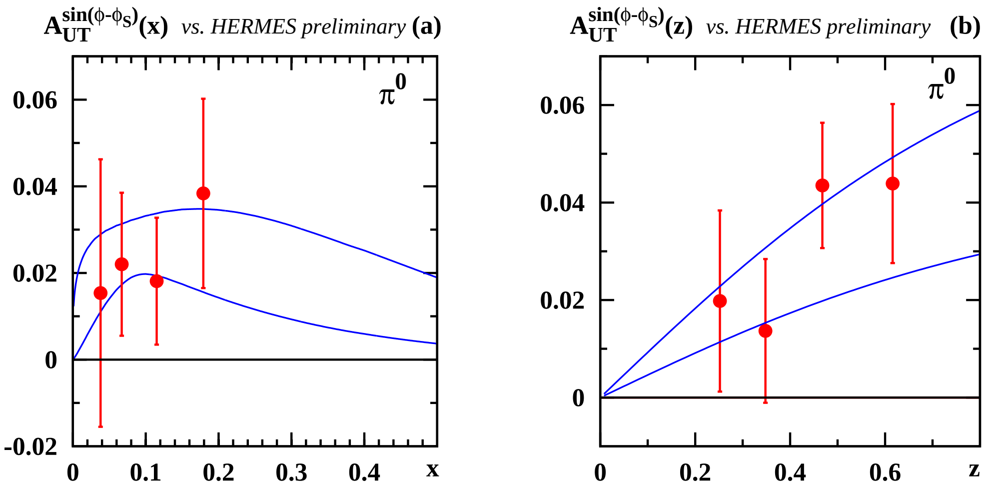


error bars $= \mathcal{O}(1/N_c)$

$f_{1T}^{\perp u} \approx \;\; -f_{1T}^{\perp d}$ (our constraint)
$f_{1T}^{\perp u} \approx -2 f_{1T}^{\perp d}$ (Anselmino et al, fit)

equally supported by COMPASS!
(but not necessarily by HERMES
precise data $\longrightarrow$ give up constraint)

- π^0 from HERMES



- kaons at HERMES: issue **?** Preliminary data, preliminary considerations (appendix)
  $\longrightarrow$ talk by Alexei!

Conspiracy of nature against D? Or: large-N_c, Burkardt, and all that

- Large-N_c: All flavour-singlet (deuteron!) spin effects $\sim \mathcal{O}(1/N_c)$ Pobylitsa hep-ph/0301236

  Includes polarization of gluon $\dfrac{\Delta G(x)}{G(x)} \sim \dfrac{1}{N_c}$ Efremov, Goeke, Pobylitsa, PLB 488 (2000) 182

  But Boer-Mulders function $h_1^{\perp u} = h_1^{\perp d}$ (not cancelled in D) Pobylitsa hep-ph/0301236

- supports Burkardt 2002: signs! $\int \mathrm{d}x\ f_{1T\,\mathrm{DIS}}^{\perp(1)u}(x) \propto -\kappa^u < 0, \quad \int \mathrm{d}x\ f_{1T\,\mathrm{DIS}}^{\perp(1)d}(x) \propto -\kappa^d > 0$

- supports Burkardt 2002: magnitude! $\dfrac{\int \mathrm{d}x\ f_{1T\,\mathrm{DIS}}^{\perp(1)u}(x) + \int \mathrm{d}x\ f_{1T\,\mathrm{DIS}}^{\perp(1)d}(x)}{\int \mathrm{d}x\ f_{1T\,\mathrm{DIS}}^{\perp(1)u}(x) - \int \mathrm{d}x\ f_{1T\,\mathrm{DIS}}^{\perp(1)d}(x)} \simeq \dfrac{\kappa^u + \kappa^d}{\kappa^u - \kappa^d} \simeq -\dfrac{1}{10}$

  Recall: $\kappa^u = 1.673$ and $\kappa^d = -2.033$ $\quad \underbrace{|\kappa^u - \kappa^d|}_{\mathcal{O}(N_c^2)} \sim 3.706 \gg \underbrace{|\kappa^u + \kappa^d|}_{\mathcal{O}(N_c)} \sim 0.360$

Conclusions

- HERMES & COMPASS: first & compatible data on Sivers effect $\longrightarrow$ first insights

- 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

- first predictions for Drell–Yan SSA observable at RHIC, COMPASS, PAX, JPARC, U70
  experimental test of $\boxed{f_{1T}^{\perp}|_{DIS} = -f_{1T}^{\perp}|_{DY}}$ possible. Prediction true? **crucial!!!**

- situation improving due to further/new data from HERMES, COMPASS & JLAB

- lots of work, these are (bright? dark?) exciting times

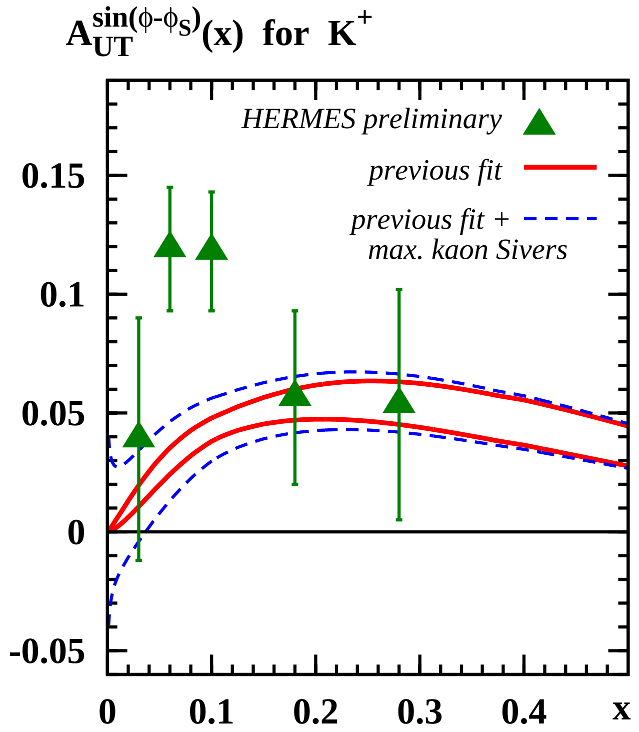
Thank you!

Appendices

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 $\bar{d} \leftrightarrow \bar{s}$.
- masses different, fragmentation functions different
- but in the ratio (SSA!) largely cancel!
- include previously neglected strangeness Sivers function!?
- let s, $\bar{s}$ Sivers functions saturate positivity bound
  Bacchetta, Boglione, Henneman and Mulders, PRL 85 (2000) 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!

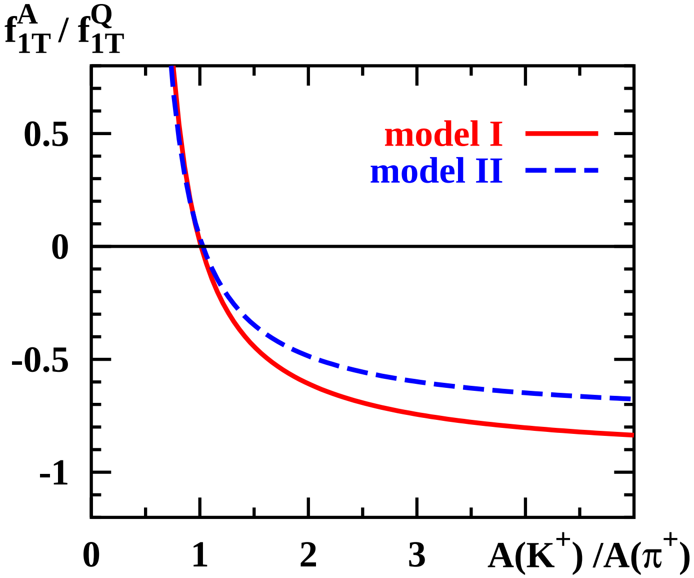
$\Longrightarrow$ Consider all of them $f_{1T}^{\perp u}$, $f_{1T}^{\perp d}$, $f_{1T}^{\perp \bar{u}}$, $f_{1T}^{\perp \bar{d}}$, $f_{1T}^{\perp s}$, $f_{1T}^{\perp \bar{s}}$

Understand K^+ Sivers effect qualitatively sufficient at this stage

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., Vogelsang & Yuan
A just some model

$\Rightarrow$ at given x ratio $\dfrac{(K^+ \text{ Sivers SSA})(x)}{(\pi^+ \text{ Sivers SSA})(x)}$ function of $\dfrac{f_{1T}^{\perp A}(x)}{f_{1T}^{\perp Q}(x)}$

$\Leftrightarrow$ how much Sivers-$\bar{q}$ needed to explain HERMES observation?

- at large x: observation $A(K^+) \approx A(\pi^+)$; thus $f_{1T}^{\perp A}(x) \approx 0$
- at small x: observation $\dfrac{A(K^+)}{A(\pi^+)} \approx (2-3)$; then $f_{1T}^{\perp A}(x) \approx -(0.5-0.7) f_{1T}^{\perp Q}$ not unusual in small-x region

$\Rightarrow$ **illustrates:**

1. K^+ data show importance of Sivers sea quarks

2. even sizeable K^+ Sivers SSA compatible with Sivers-$\bar{q}$ & s of natural size

illustrative study to be confirmed later by simultaneous fit of $\pi^\pm$ and $K^\pm$ SSAs

★ Footnote for historical correctness:

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