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Sivers effect in semi-inclusive DIS & in the Drell–Yan process

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in collaboration with

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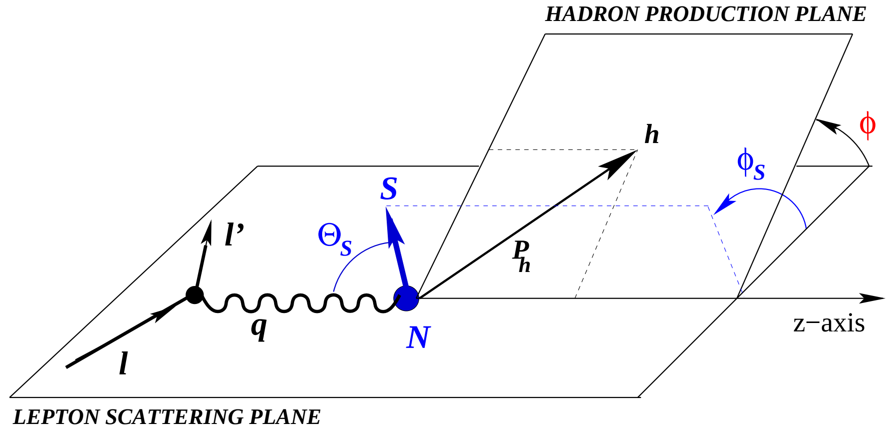
based on PRD 73 (2006) 094023, PRD 73 (2006) 014021, PLB 612 (2005) 233.

Overview:

- What is Sivers effect?
- Sivers effect in SIDIS & Drell-Yan $\longrightarrow$ testing QCD predictions
- Sivers effect for kaons — daily impact of new data!
- Summary & conclusions

SIDIS on transv. polarized target

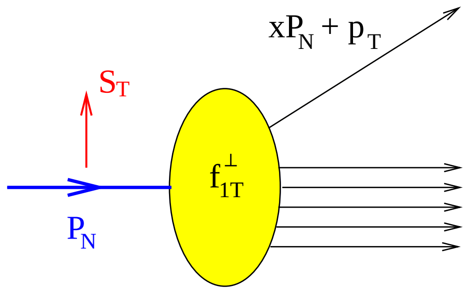


expressions in LO $1/Q$ Boer, Mulders, ... 1990s
factorization with k_T Ji, Ma, Yuan & Collins, Metz 2004

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

- Sivers function $f_{1T}^{\perp}(x, \mathbf{p}_T^2)$ "twist-2", naively/artificially "T-odd"

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



Sivers 1991, Brodsky, Hwang, Schmidt & Collins 2002
Belitsky, Ji, Yuan & Boer, Mulders, Pijlman 2003

- remarkable **universality** property $\boxed{f_{1T}^{\perp}\big|_{DIS} = -f_{1T}^{\perp}\big|_{DY}}$ Collins 2002

Of absolute importance to be tested experimentally!

Sivers effect in SIDIS

HERMES	**proton**	**clearly seen**	PRL 94 (2005) 012002, AIP Conf.Proc.792 (2005) 933
COMPASS	**deuteron**	$\sim$ **0** within error bars	PRL 94 (2005) 202002

Questions:

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

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

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

Answers: Yes. Yes. Yes.

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

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

- neglect soft factors

- Gaussian $f_{1T}^{\perp a}(x,\mathbf{p}_T^2) \equiv f_{1T}^{\perp a}(x)\frac{\exp(-\mathbf{p}_T^2/p_{\rm Siv}^2)}{\pi\, p_{\rm Siv}^2}$ & $D_1^a(z,\mathbf{K}_T^2)$ analog $\longrightarrow$ describes well $\langle P_{h\perp}(z)\rangle$ at HERMES

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

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

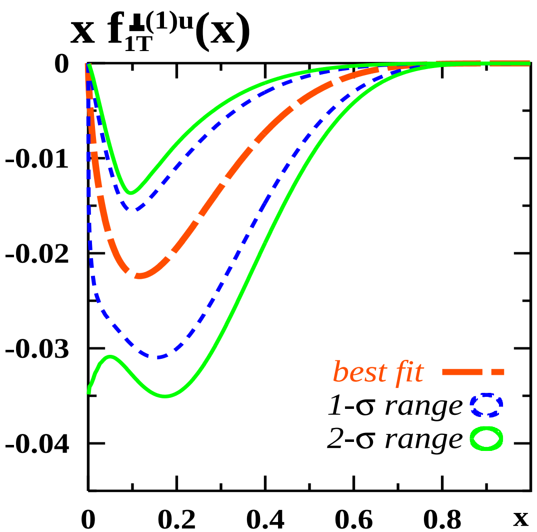
& $0.72 < a_{\rm Gauss} = \frac{\sqrt{\pi}\, M_N}{\sqrt{p_{\rm Siv}^2 + K_{D_1}^2/z^2}} < 0.83$

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

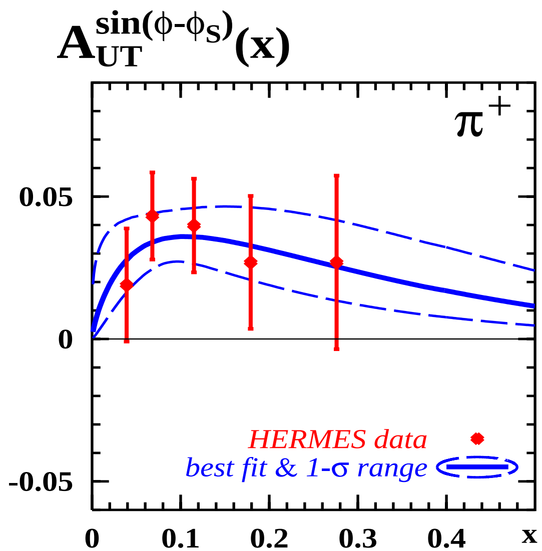
  in large-N_c limit Pobylitsa 2003, and neglect $\bar{q}$, s, ...

Results:

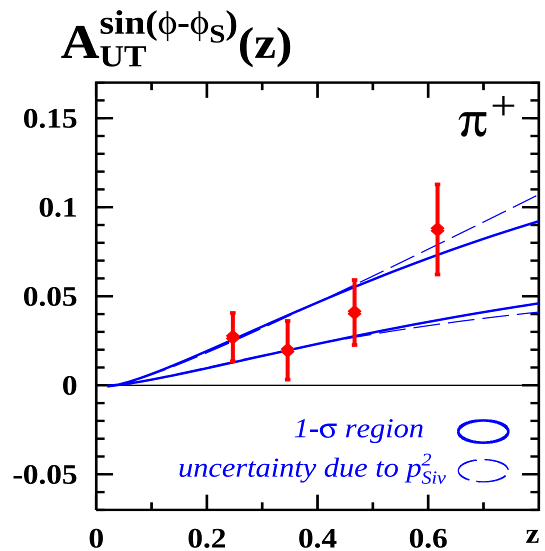
$\chi^2_{/\rm d.o.f.} \sim 0.3$



Sivers function



x-dependence (input)
Good description!



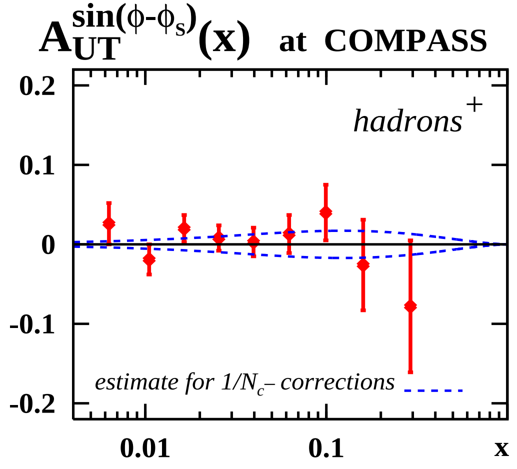
z-dependence (not used)
Cross-check: Ok!

What do we learn?

- good fit to HERMES **possible** with large-N_c $f_{1T}^{\perp u} = -f_{1T}^{\perp d}$

- COMPASS: deuteron target

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



$\longrightarrow$ **$1/N_c$ useful for HERMES & COMPASS**
. . . at present stage!

- supports intuitive picture by Burkardt 2002 $\int dx\, f_{1T\,\mathrm{SIDIS}}^{\perp(1)u}(x) \propto -\kappa^u < 0,\quad \int dx\, f_{1T\,\mathrm{SIDIS}}^{\perp(1)d}(x) \propto -\kappa^d > 0$

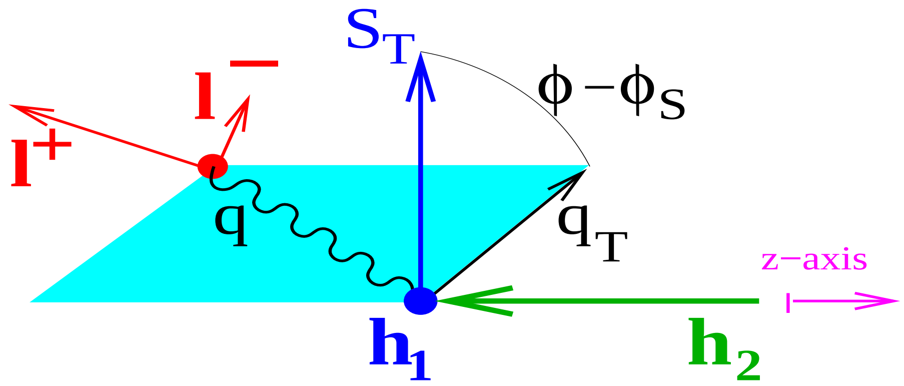
Suspicion: Maybe large-N_c works even *particularly well* for Sivers function because it *happens to work* particularly well for the anomalous magnetic moments ???

Will see!

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

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

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



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

$$y = \frac{1}{2} \ln\big(p_1 \cdot q / p_2 \cdot q\big)$$

$$x_{1,2} = (Q^2/s)^{1/2} e^{\pm y}$$

Sivers-$\bar q$ matter! Assume

$$\left. \begin{array}{l} f_{1T}^{\perp \bar q} = \pm 25\,\%\ f_{1T}^{\perp q} \\[1ex] \dfrac{f_{1T}^{\perp \bar q}(x)}{f_{1T}^{\perp q}(x)} = \dfrac{f_1^{\bar q}(x)}{f_1^{q}(x)} \end{array} \right\}$$

just for illustrative purposes

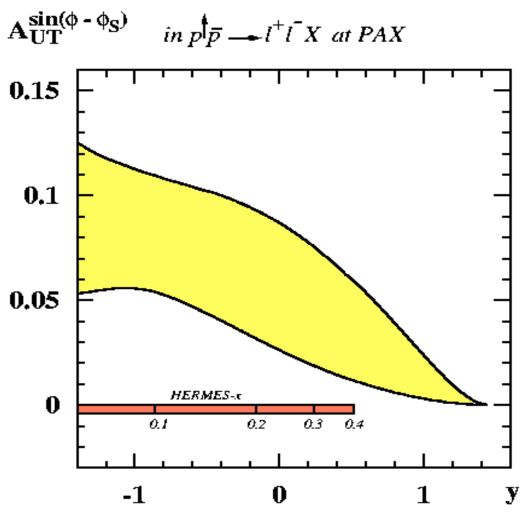
- **PAX at GSI**

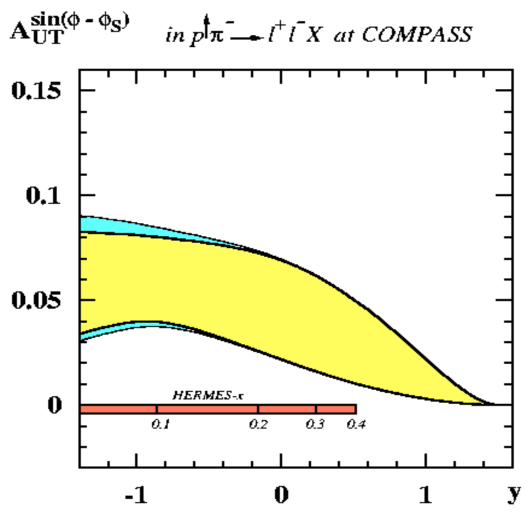
$$p^{\uparrow} \bar p \quad \to \quad l^+ l^- X \quad \text{(byproduct)}$$

- **COMPASS**

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

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



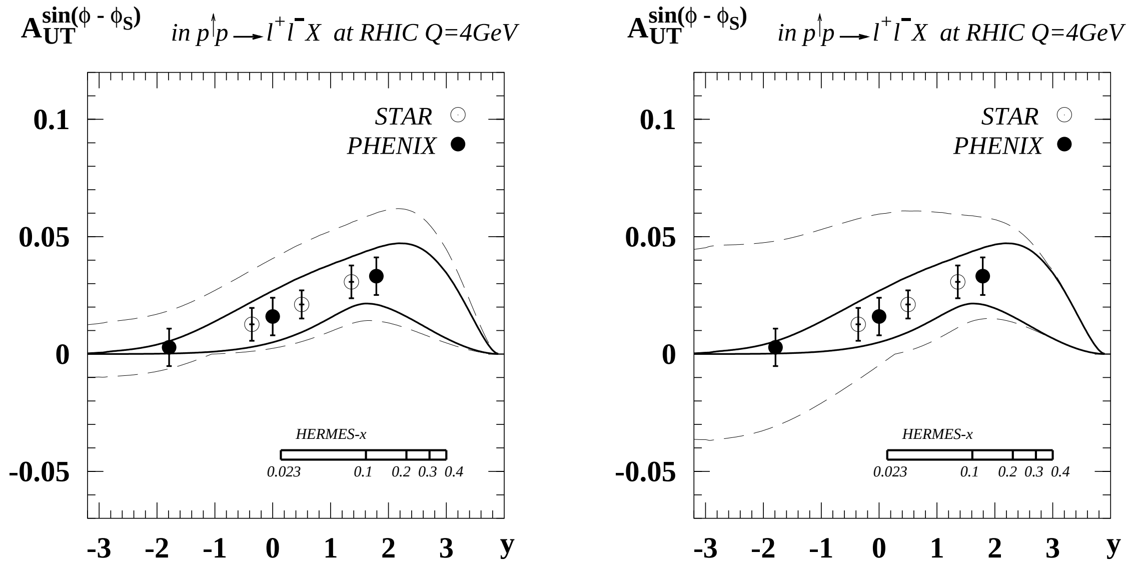


- **RHIC**

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

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)
$\int dt\, \mathcal{L} \sim 125\,\text{pb}^{-1}$ realistic till 2012
later RHIC II
$\longrightarrow$ talk by Matthias, tomorrow



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

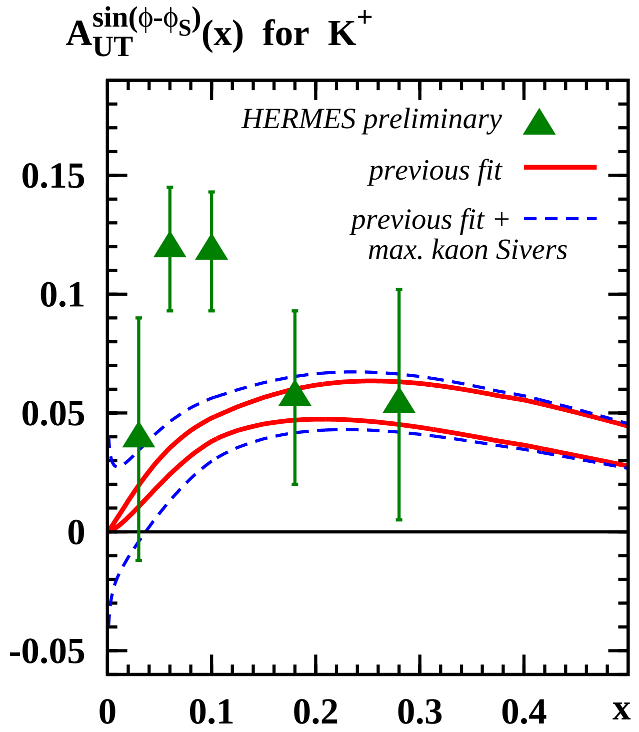
For some while (Como workshop September 2005 — DIS'06 in Tsukuba April 2006)
happy with situation: first rough understanding of Sivers in SIDIS, predictions for DY done, wait till 2012

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 $\bar{d} \leftrightarrow \bar{s}$.
- 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!

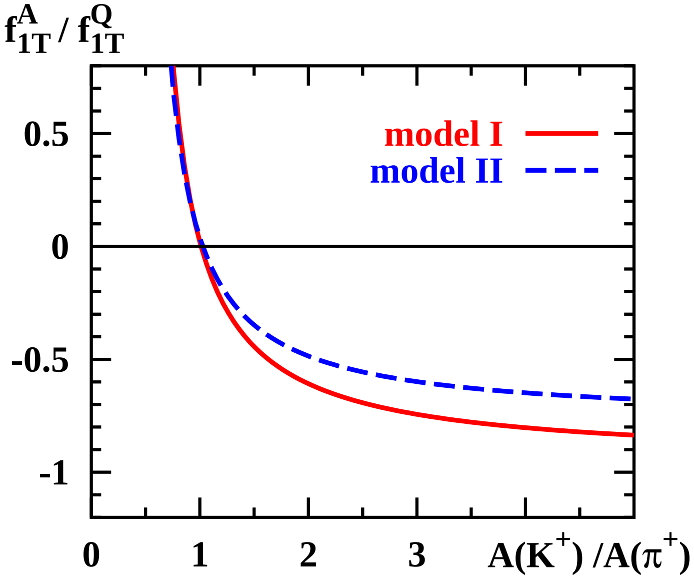
$\Longrightarrow$ Consider all of them $f_{1T}^{\perp u}$, $f_{1T}^{\perp d}$, $f_{1T}^{\perp \bar{u}}$, $f_{1T}^{\perp \bar{d}}$, $f_{1T}^{\perp s}$, $f_{1T}^{\perp \bar{s}}$

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

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 further/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, JPARC

  experimental test of $\boxed{f_{1T}^{\perp}|_{DIS} = -f_{1T}^{\perp}|_{DY}}$ possible. Prediction true?
- lots of work: e.g. what about SSA in $p^{\uparrow}p \rightarrow \pi X$? Sivers, Anselmino et al.
- in any case — on short and long term exciting future

Thank you!