International Workshop on Transverse Spin
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SSA in SIDIS & DY

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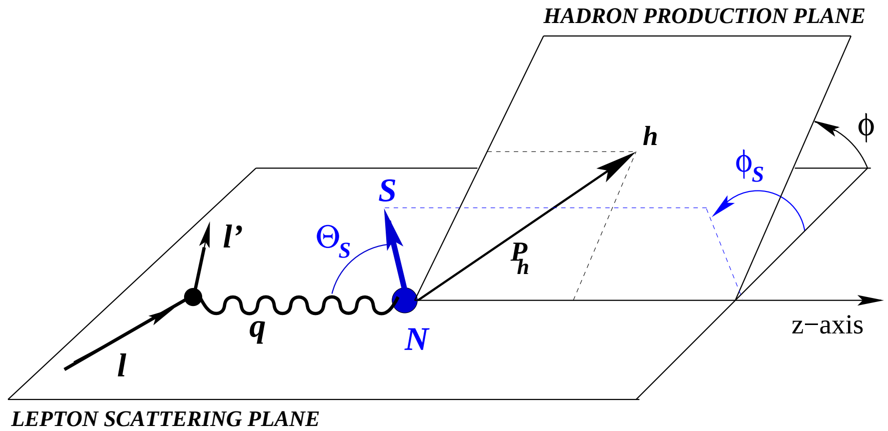
Overview:

- Sivers effect in SIDIS
- *Preliminary* HERMES data on $A_{UT}^{\sin(\phi-\phi_S)P_{h\perp}/M_N}$ & *final* HERMES data on $A_{UT}^{\sin(\phi-\phi_S)}$
  - Use & test(!) large N_c (= number of colours) QCD limit for Sivers function
  - Gauss model for distribution of transverse parton momenta
  - COMPASS (deuteron) vs. HERMES (proton) data
- Drell-Yan process
- Conclusions

HERMES & COMPASS data

$$\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \propto \underbrace{\ldots\ \sin(\phi - \phi_S)}_{\text{Sivers}} + \underbrace{\ldots\ \sin(\phi + \phi_S)}_{\text{Collins effect}}$$

Sivers and Collins effect



- **Sivers effect**: first *unambiguous* evidence for "naively/artificially T-odd" distribution in SIDIS
- Sivers SSA $\propto \sum_a e_a^2 f_{1T}^{\perp a}\, D_1^a$ and $D_1^a(z)$ known, e.g. Kretzer, Leader, Christova, EPJC 22 (2001) 269
- $f_{1T}^{\perp a}$ only unknown, i.e. possible to extract direct information on Sivers function
- subject to considerable interest in literature:

  Efremov, Goeke, Menzel, Metz and PS, PLB 612 (2005) 233, hep-ph/0412353

  Anselmino, Boglione, D'Alesio, Kotzinian, Murgia and Prokudin, PRD 71 (2005) 074006, hep-ph/0501196

  Anselmino, Boglione, D'Alesio, Kotzinian, Murgia and Prokudin, hep-ph/0507181

  Vogelsang and Yuan, hep-ph/0507266

  Collins, Efremov, Goeke, Menzel, Metz and PS, hep-ph/0509076

- **Collins effect** $\propto \sum_a e_a^2 h_1^a\, H_1^{\perp a}$ equally interesting, first *unambiguous* evidence in SIDIS.
  Data indicate fascinating properties $\longrightarrow$ favoured vs. unfavoured $H_1^\perp$.
  But: Two unknowns, more difficult. See Vogelsang and Yuan, *op. cit.*; Efremov et al., talk at SIR'05

- ***FINAL*** HERMES & COMPASS data PRL 94 (2005) 012002 & PRL 94 (2005) 202002

$$A_{UT}^{\sin(\phi-\phi_S)} \equiv \frac{\int \mathrm{d}\phi\, \sin(\phi-\phi_S)(N^\uparrow - N^\downarrow)}{\frac{1}{2}\int \mathrm{d}\phi\,(N^\uparrow + N^\downarrow)}$$

- "preferable" ***PRELIMINARY*** HERMES data Makins, *"Transversity Workshop", Oct. 2003, Athens.* Seidl, *DIS'2004, April 2004, Štrbské Pleso.* Gregor, Acta Phys. Pol. B 36 (2005) 209

$$A_{UT}^{\sin(\phi-\phi_S)P_{h\perp}/M_N} \equiv \frac{\int \mathrm{d}\phi\, \sin(\phi-\phi_S)P_{h\perp}/M_N(N^\uparrow - N^\downarrow)}{\frac{1}{2}\int \mathrm{d}\phi\,(N^\uparrow + N^\downarrow)} = (-2)\,\frac{\sum_a e_a^2\, x f_{1T}^{\perp(1)a}(x)\, z D_1^{a/\pi}(z)}{\sum_a e_a^2\, x f_1^a(x)\, D_1^{a/\pi}(z)}$$

with $f_{1T}^{\perp(1)a}(x) \equiv \int \mathrm{d}^2\mathbf{p}_T\, \frac{\mathbf{p}_T^2}{2M_N^2}\, f_{1T}^{\perp a}(x,\mathbf{p}_T^2)$ Boer and Mulders, PRD 57 (1998) 5780

- In which sense is $A_{UT}^{\sin(\phi-\phi_S)}$ "not preferable"? See later in detail.

- **WARNING!** Keep in mind: In any case **approximation** – neglect soft factors **(!)**
Ji, Ma and Yuan, PRD 71 (2005) 034005, PLB 597 (2004) 299. Collins and Metz, PRL 93 (2004) 252001.

$A_{UT}^{\sin(\phi-\phi_S)P_{h\perp}/M_N} \overset{\text{directly}}{\longleftrightarrow} f_{1T}^{\perp(1)a}(x)$ explored by Efremov *et al.*, PLB 612 (2005) 233, hep-ph/0412353

- error bars sizeable $\rightarrow$ minimize # of free parameters in fit Ansatz $\rightarrow$ theoretical constraints

I use large-N_c limit $\boxed{f_{1T}^{\perp u} = -f_{1T}^{\perp d}}$ modulo $1/N_c$ corrections Pobylitsa hep-ph/0301236 (★)

II satisfy sum rule $\sum_{a=g,u,d,\dots} \int dx\, f_{1T}^{\perp(1)a}(x) = 0$ Burkardt, PRD 69 (2004) 057501 and 091501

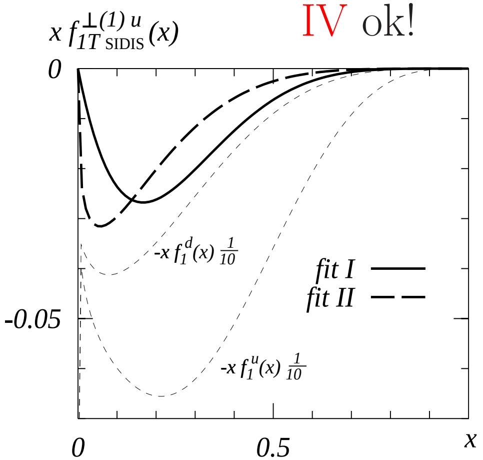
III explore "connection" of $f_{1T}^{\perp a}$ to GPD, $E^q(x,0,0) \propto (1-x)^4$ or $(1-x)^5$ Brodsky et al, Burkardt

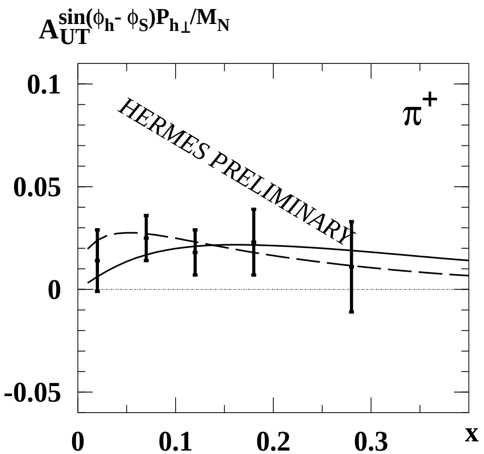
IV respect positivity $\frac{|\mathbf{p}_T|}{M_N}\,|f_{1T}^{\perp a}(x,\mathbf{p}_T^2)| \le f_1^a(x,\mathbf{p}_T^2)$ Bacchetta, *et al.*, PRL 85 (2000) 712

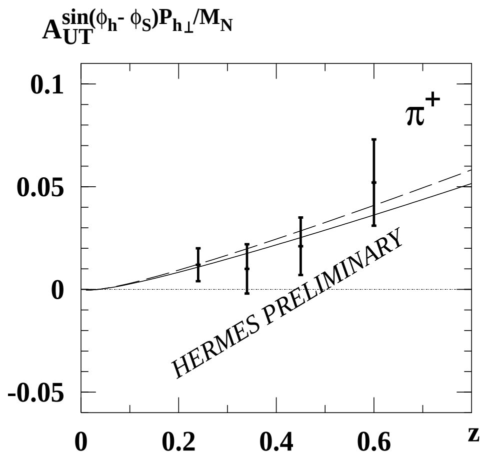
- fit Ansatz: $x f_{1T}^{\perp(1)u} = -x f_{1T}^{\perp(1)d} = A x^b (1-x)^5$ neglect $\bar{q}$, s, ... Respects I, II, III!
- fit result: $x f_{1T}^{\perp(1)u} = \begin{cases} -0.4x\,(1-x)^5 & \text{for } b=1 \text{ fixed} \\ -0.1x^{0.3}(1-x)^5 & \text{both } A,\, b \text{ free} \end{cases}$

Cross check!

IV ok!







★ Footnote for historical correctness:

- M. Anselmino, V. Barone, A. Drago and F. Murgia,
  "Non-standard time reversal for particle multiplets and the spin-flavor structure of hadrons,"
  Nucl. Phys. Proc. Suppl. **105** (2002) 132, hep-ph/0111044
- M. Anselmino, V. Barone, A. Drago and F. Murgia,
  "Non-standard time reversal and transverse single-spin asymmetries",
  hep-ph/0209073
- P. V. Pobylitsa,
  "T-odd quark distributions: QCD versus chiral models",
  hep-ph/0212027
- P. V. Pobylitsa,
  "Transverse-momentum dependent parton distributions in large-N_c QCD",
  hep-ph/0301236.
- A. Drago,
  "Time-reversal odd distribution functions in chiral models with vector mesons",
  Phys. Rev. D **71** (2005) 057501, hep-ph/0501282

Comments

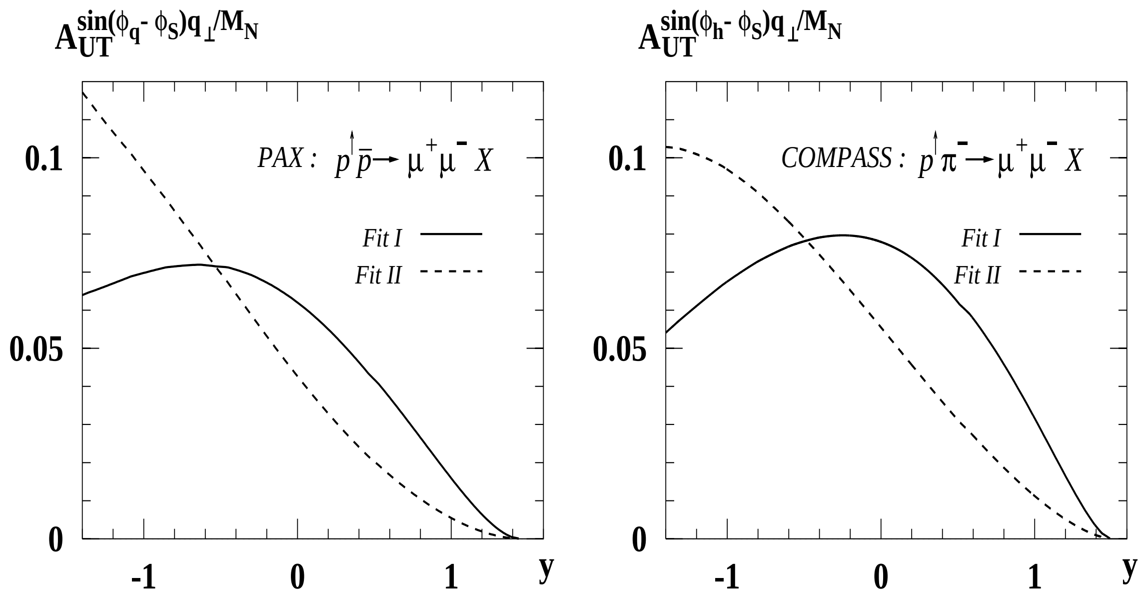
- supports picture by Burkardt, *op. cit.* $\int dx\, f^{\perp(1)u}_{1T\,\mathrm{SIDIS}}(x) \propto -\kappa^u < 0, \quad \int dx\, f^{\perp(1)d}_{1T\,\mathrm{SIDIS}}(x) \propto -\kappa^d > 0$
- Where are $1/N_c$ corrections? Good place to see: $f_{1T}^{\perp u/\mathrm{deuteron}} \approx f_{1T}^{\perp u/p} + f_{1T}^{\perp u/n} \approx f_{1T}^{\perp u} + f_{1T}^{\perp d}$
- COMPASS $A_{UT,\,\mathrm{deuteron}}^{\sin(\phi-\phi_s)} \sim 1/N_c \sim 0$ within error bars
- Thus HERMES & COMPASS compatible, $f_{1T}^{\perp a}|_{\mathrm{SIDIS}}$ obeys large N_c predictions

Application

- important prediction
  Collins, PLB 536 (2002) 43

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

- 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 ...)



Complication at the present stage: Status of used HERMES data *PRELIMINARY*.
Not recommended to use these data, because analysis of possible error correlations not finished
HERMES Collaboration, private communication

Necessary to solidify our conclusions $\longrightarrow$ study the ***FINAL*** but "less preferably" weighted data.

$$A_{UT}^{\sin(\phi_h-\phi_S)} = (-2)\,\frac{\sum_a e_a^2 \int d^2\mathbf{P}_{h\perp}\int d^2\mathbf{p}_T\int d^2\mathbf{K}_T \sin(\phi_h-\phi_S)\,\sin(\phi_{\mathbf{p}_T}-\phi_S)\,\frac{|\mathbf{p}_T|}{M_N}\,\delta^{(2)}(\mathbf{p}_T-\mathbf{K}_T-\mathbf{P}_{h\perp}/z)\,x f_{1T}^{\perp a}(x,\mathbf{p}_T^2)\,D_1^a(z,\mathbf{K}_T^2)}{\sum_b e_b^2\,x f_1^b(x)\,D_1^b(z)}$$

$\longrightarrow$ Have to assume some **model** for transverse parton momenta to solve convolution integrals.

Already commited a crime: soft factors $\longrightarrow \delta^{(2)}(\dots)$. Why not another?

Let us use **Gaussian model**

$$f_1^a(x,\mathbf{p}_T^2) \equiv f_1^a(x)\,\frac{\exp(-\mathbf{p}_T^2/p_{\rm unp}^2)}{\pi\, p_{\rm unp}^2}\,,$$

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

$$D_1^a(z,\mathbf{K}_T^2) \equiv D_1^a(z)\frac{\exp(-\mathbf{K}_T^2/K_{D_1}^2)}{\pi\, K_{D_1}^2} \qquad \text{with}\quad a_{\rm Gauss} = \frac{\sqrt{\pi}}{2}\,\frac{M_N}{\sqrt{p_{\rm Siv}^2+K_{D_1}^2/z^2}}\,.$$

Mulders and Tangerman, NPB 461 (1996) 197. Efremov, Goeke and PS, PLB 568 (2003) 63.

Price to pay: 2 free parameters $p_{\rm unp}^2$, $\underbrace{p_{\rm Siv}^2,\ K_{D_1}^2}_{\text{How to fix?}}$ if we assume them flavour- and x- or z-independent.

Note: In numerous processes reasonable **model**, if: transv. momenta $\ll$ hard scale

D'Alesio and Murgia, PRD 70 (2004) 074009.

- In HERMES experiment $\langle P_{h\perp}\rangle \sim 0.4\,\text{GeV} \ll \sqrt{\langle Q^2\rangle} \sim 1.5\,\text{GeV}$.

- more precisely: $\langle P_{h\perp}(z)\rangle$ of hadrons produced from a deuterium target HERMES, PLB 562 (2003) 182

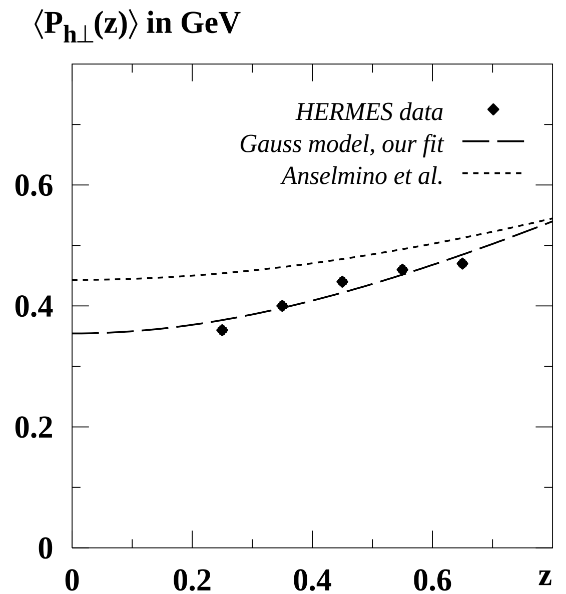
- $\langle P_{h\perp}(z)\rangle \overset{\text{Gauss}}{=} \frac{\sqrt{\pi}}{2}\sqrt{z^2 p^2_{\text{unp}} + K^2_{D_1}}$

- $p^2_{\text{unp}} = 0.33\,\text{GeV}^2$ and $K^2_{D_1} = 0.16\,\text{GeV}^2 \longrightarrow$ Ok!

- compare to study of Cahn effect by Anselmino *et al.* where

  $p^2_{\text{unp}} = 0.2\,\text{GeV}^2$ and $K^2_{D_1} = 0.25\,\text{GeV}^2$ obtained.

  $\Longrightarrow$ Good qualitative agreement!



Ok, p^2_{unp}, $K^2_{D_1}$ fixed. But what is p^2_{Siv} ?

- Of course, cannot be zero! Otherwise $f_{1T}^{\perp}(x,\mathbf{p}_T^2) \to f_{1T}^{\perp}(x)\delta^{(2)}(\mathbf{p}_T) \Longrightarrow A_{UT}^{\sin(\phi-\phi_S)} \to 0$

- Also, cannot be arbitrarily large. To satisfy positivity in Gauss Ansatz

$$p^2_{\text{Siv}} \le \frac{p^2_{\text{unp}}}{1 + \dfrac{2M_N^2 p^2_{\text{unp}}}{e\; p^4_{\text{Siv}}}\left(\dfrac{f_{1T}^{\perp(1)a}(x)}{f_1^a(x)}\right)^2}.$$

Parameter restricted $\quad 0 < p^2_{\text{Siv}} < p^2_{\text{unp}}$. Admittedly vague. But, which is astonishing, ...

- $0 < p_{\rm Siv}^2 < 0.33\,{\rm GeV}^2$ **sufficient**, if we extract $f_{1T}^{\perp(1)a}(x) = \dfrac{p_{\rm Siv}^2}{2M_N^2}\, f_{1T}^{\perp a}(x)$ and not $f_{1T}^{\perp a}(x)$ itself.

$\Rightarrow$ needed only in $a_{\rm Gauss} = \dfrac{\sqrt{\pi}}{2}\, \dfrac{M_N}{\sqrt{p_{\rm Siv}^2 + K_{D_1}^2/z^2}}$ $\Rightarrow$ $0.72 < a_{\rm Gauss} < 0.83$ $\Rightarrow$ 10% uncertainty!

Procedure

- Ansatz $x f_{1T}^{\perp(1)u}(x) = -x f_{1T}^{\perp(1)d}(x) = A x^b (1-x)^5$, neglect anti- and heavier quarks.
- Choose some $p_{\rm Siv}^2 \in [0, 0.33\,{\rm GeV}^2]$
- Fit to *FINAL* HERMES data
- Check (within 2-σ) positivity $p_{\rm Siv}^2 \le \dfrac{p_{\rm unp}^2}{1 + \dfrac{2M_N^2 p_{\rm unp}^2}{e\, p_{\rm Siv}^4} \left(\dfrac{f_{1T}^{\perp(1)a}(x)}{f_1^a(x)} \right)^2}$

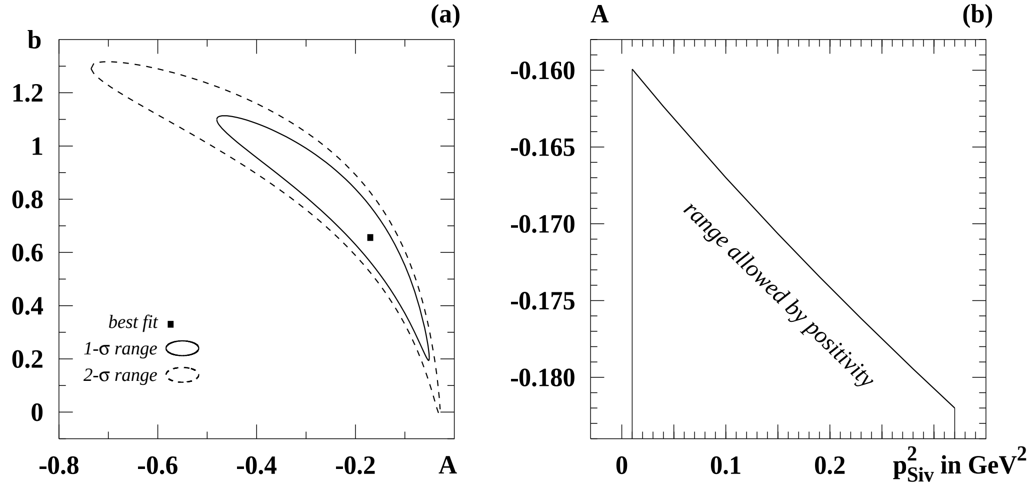
Result

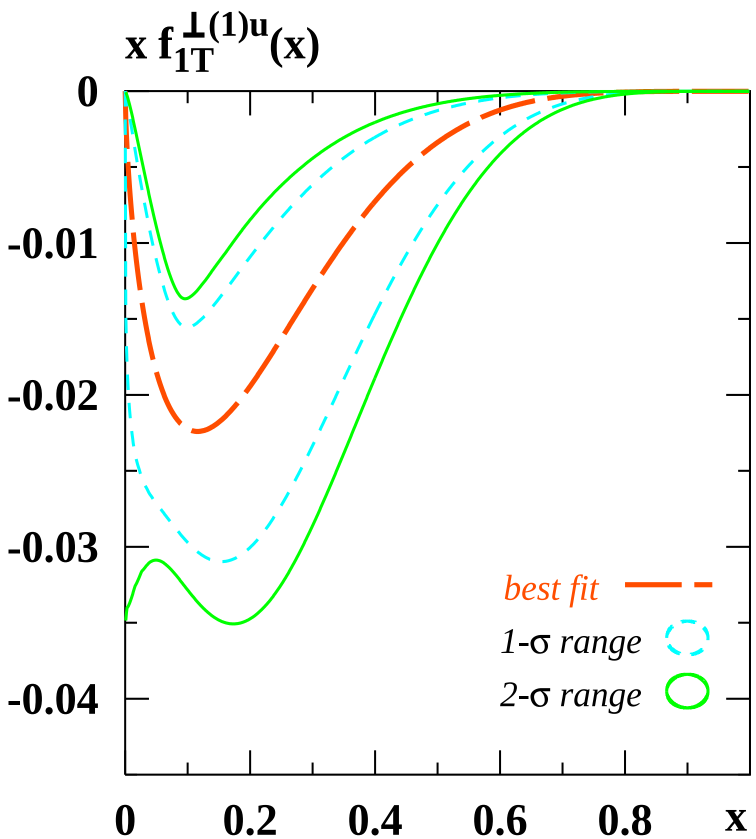
- Best fit ($\chi^2 \sim 2.2$)

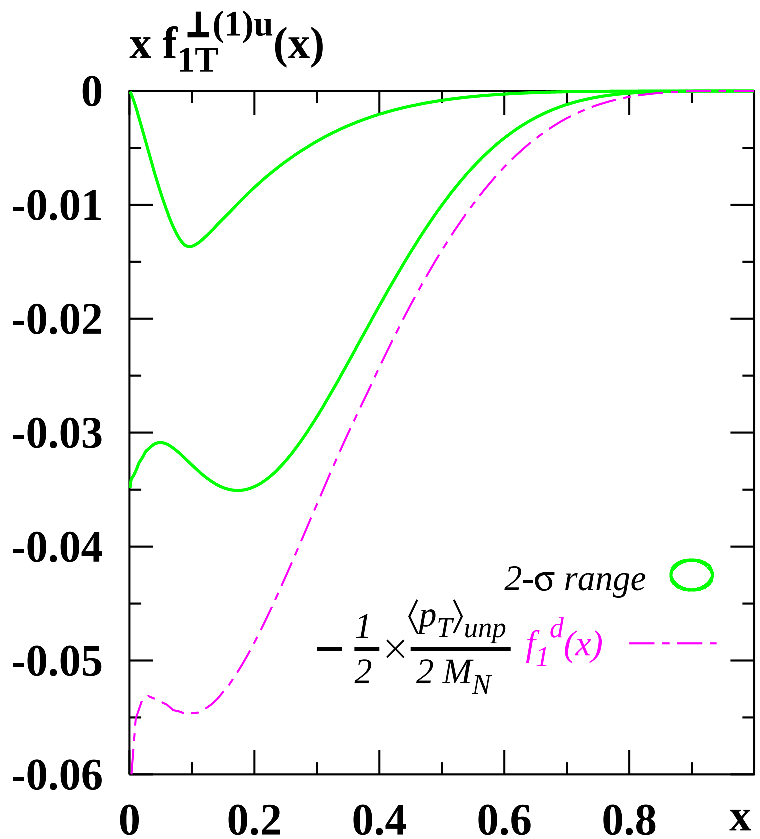
$$x\, f_{1T}^{\perp(1)u}(x) = -(0.16\ldots0.18)\, x^{0.66}(1-x)^5$$

for $p_{\rm Siv}^2 = (0.01\ldots0.32)\,{\rm GeV}^2$

- refers to scale $\sim 2.5\,{\rm GeV}^2$







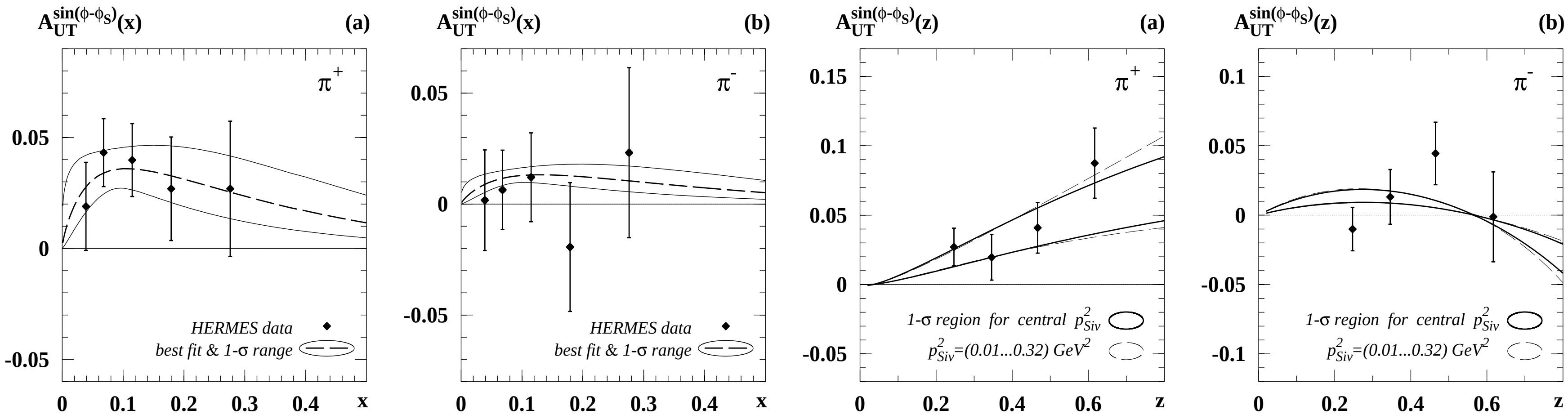
Positivity ok! & Not small!!!

- In large-N_c: $\frac{|\mathbf{p}_T|}{M_N}\,|f_{1T}^{\perp u}(x,\mathbf{p}_T^2)| = \frac{|\mathbf{p}_T|}{M_N}\,|f_{1T}^{\perp d}(x,\mathbf{p}_T^2)| \le f_1^u(x,\mathbf{p}_T^2) = f_1^d(x,\mathbf{p}_T^2)$
- In nature $f_1^u(x,\mathbf{p}_T^2) > f_1^d(x,\mathbf{p}_T^2) \Rightarrow$ for d-quark stronger. To check multiply by $|\mathbf{p}_T|$ & integrate

$$|f_{1T}^{\perp(1)u,d}(x)| \le \frac{\langle p_T\rangle_{\rm unp}}{2M_N} f_1^d(x)$$

$$\langle p_T\rangle_{\rm unp} = \frac{\int {\rm d}^2\mathbf{p}_T\,|\mathbf{p}_T|\,f_1^q(x,\mathbf{p}_T^2)}{\int {\rm d}^2\mathbf{p}_T\,f_1^q(x,\mathbf{p}_T^2)} \stackrel{\rm Gauss}{=} \frac{\sqrt{\pi}}{2}\,p_{\rm unp} = 0.51\,{\rm GeV}$$

How does it describe the HERMES data? Well!



x-dependence (input)
Good description!

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

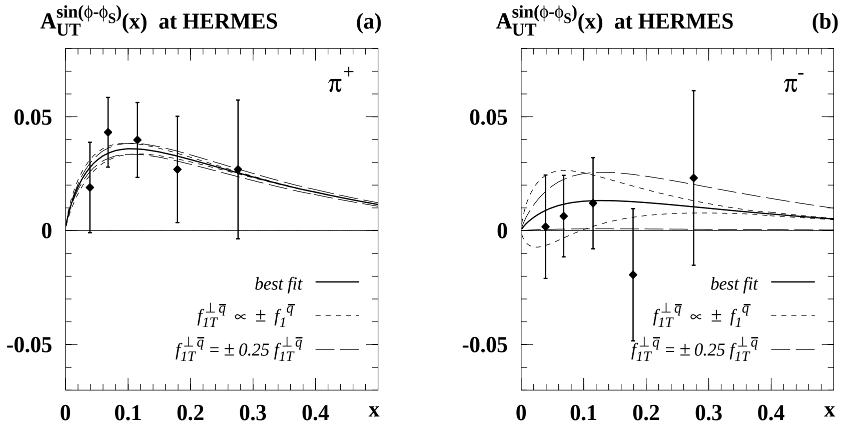
Good description. However, two questions arise:

- $f_1^{\bar{d}}(x)/f_1^d(x) \sim 25\%$ at small HERMES-x. Justified to neglect Sivers-$\bar{q}$?
- Where are $1/N_c \sim 30\%$ corrections?

Sivers-$\bar{q}$

- Let us simulate

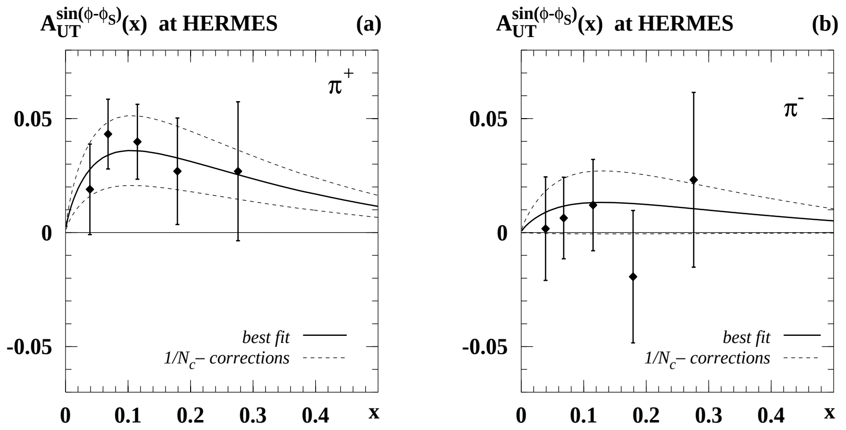
$$f_{1T}^{\perp(1)\bar{q}}(x) = \underbrace{f_{1T}^{\perp(1)q}(x)}_{\text{best fit}} \times \begin{cases} \pm 25\% \\ \pm \dfrac{(f_1^{\bar{u}} + f_1^{\bar{d}})(x)}{(f_1^{u} + f_1^{d})(x)} \end{cases}$$



$1/N_c$-corrections

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

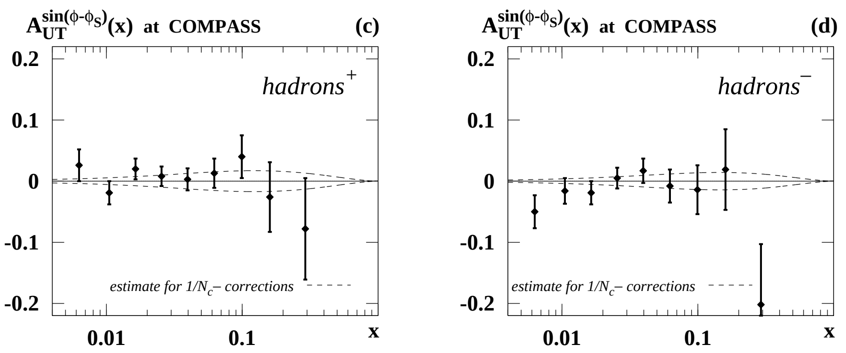
$$(f_{1T}^{\perp u} + f_{1T}^{\perp d})(x) = \pm \frac{1}{N_c} \underbrace{(f_{1T}^{\perp u} - f_{1T}^{\perp d})(x)}_{\text{best fit}} \neq 0$$



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

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

(Beware: Small x!)



Conclusion: Neglect of $\bar{q}$-effects and $1/N_c$-corrections in fit Ansatz <u>not unjustified</u> for present data

Maybe, suspicion(!), large-N_c works even *particularly well* for Sivers function because it *happens to work* particularly well for the anomalous magnetic moments "related" by $\int \mathrm{d}x\, f_{1T\,\mathrm{SIDIS}}^{\perp(1)q}(x) \propto -\kappa^q$, Burkardt, *op. cit.*

Recall: $\kappa^u = 1.673$ and $\kappa^d = -2.033$

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

Is this an additional reason why large-N_c useful for Sivers effect? The future will show.

There are large-N_c predictions also for all the other novel twist-2 functions. E.g. Boer-Mulders function

$h_1^{\perp u} = h_1^{\perp d}$ modulo $1/N_c$ corrections, ... Pobylitsa hep-ph/0301236 Worthile to be keept in mind.

Where else is large-N_c useful?

Worthwhile recalling $\dfrac{\Delta G(x)}{G(x)} \sim \dfrac{1}{N_c}$ Efremov, Goeke and Pobylitsa, PLB 488 (2000) 182, hep-ph/0004196

$(\Delta\bar{u} - \Delta\bar{d})(x) > |(\bar{u} - \bar{d})(x)| \neq 0$ Diakonov, NPB 480 (1996) 341, hep-ph/9606314 Being tested ...

$f_{1T}^{\perp(1)q}$ from FINAL HERMES data analysed without $P_{h\perp}$-weight
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

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

$\updownarrow$?

There 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!

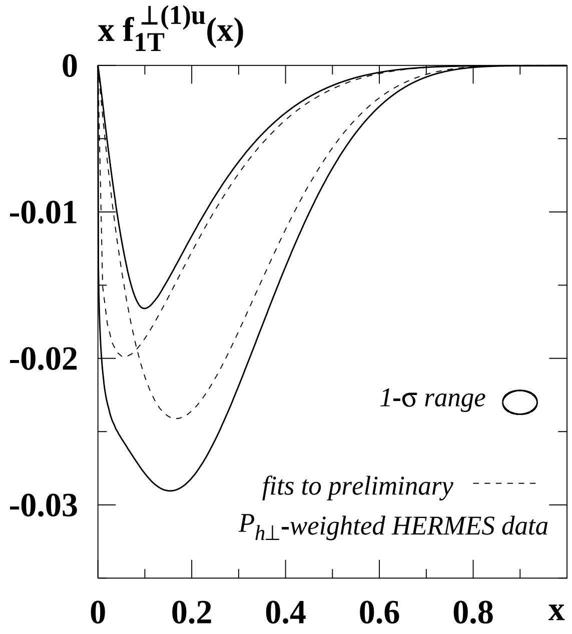
  If Gauss ok $\Longrightarrow$ the same $f_{1T}^{\perp(1)q}(x)$

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

Grain of salt:

- Be careful: *Preliminary* data.

  "Indication": Effects of error correlations less dominant than statistical error of data



Intermediate conclusion:

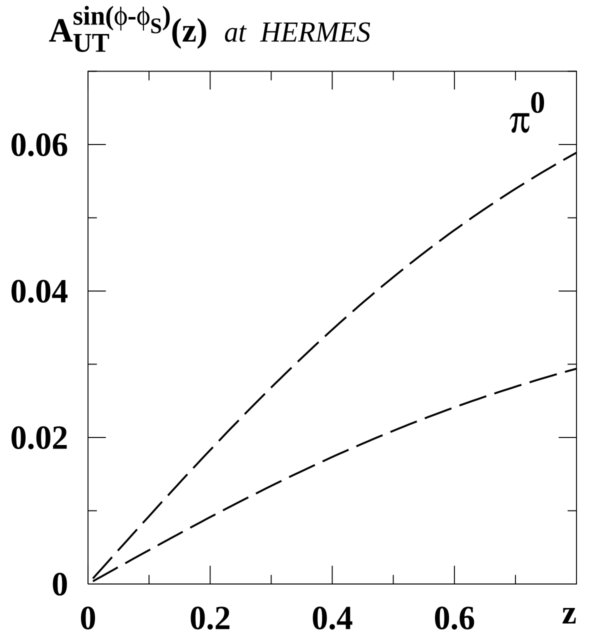
- Gauss Ansatz & large-N_c presently useful tools
- Extraction of $f_{1T}^{\perp(1)q}(x)$ from preliminary data "confirmed"
- Previous conclusions solidified (DY, change of sign, PAX & COMPASS, etc.)

  see also Anselmino *et al.*, and Vogelsang and Yuan, *op. cit.*

How to test further Gauss model?

- Range of reliability? Limitations?
- e.g. for π^0 (neglecting s, ...)

$$A_{UT\,\pi^0}^{\sin(\phi-\phi_S)}(z) = a_{\rm Gauss}(z)\frac{\sum_a e_a^2\,\langle x f_{1T}^{\perp(1)a}\rangle}{\sum_b e_b^2\,\langle x f_1^b\rangle} \propto \frac{z}{\sqrt{\underbrace{z^2 p_{\rm Siv}^2}_{\text{smaller}} + \underbrace{K_{D_1}^2}_{\text{larger}}}}$$



How to see $1/N_c$ corrections?

- More precise deuteron & proton data

  most recent *PRELIMINARY* HERMES data Diefenthaler, DIS'05, hep-ex/0507013 still compatible

How to see Sivers-$\bar{q}$?

- Drell-Yan

Sivers effect in DY

PAX & COMPASS

- $\left.\begin{array}{l} p^{\uparrow}\bar{p} \\ p^{\uparrow}\pi^{-} \end{array}\right\}\rightarrow l^{+}l^{-}X$

  dominated by annihilations of

  valence q and valence $\bar{q}$

  $\Rightarrow$ not sensitive to Sivers-$\bar{q}$, good!

RHIC

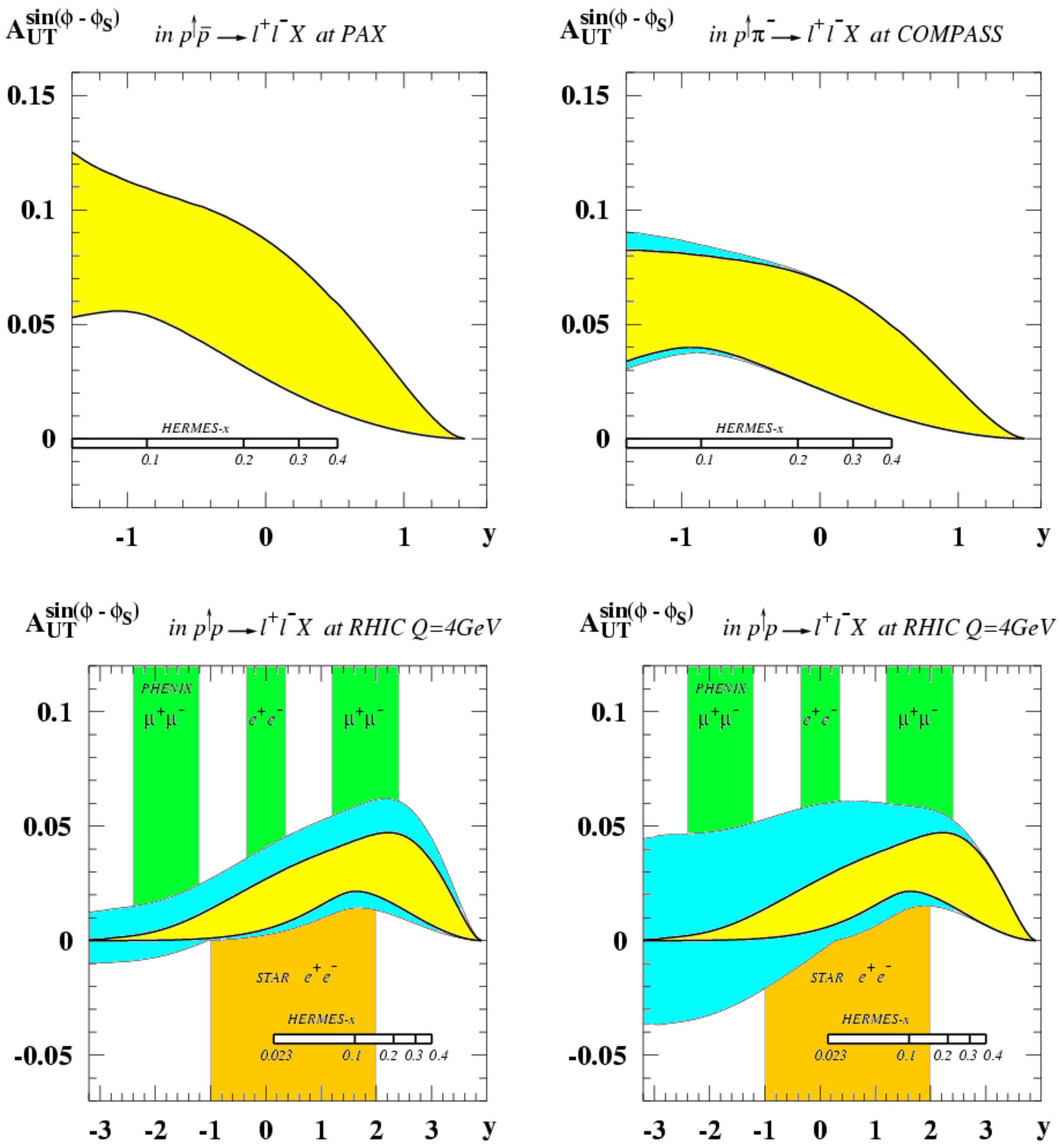
- $p^{\uparrow}p \rightarrow l^{+}l^{-}X$

  valence q and sea $\bar{q}$ on equal footing

  sensitive to Sivers-$\bar{q}$ in certain y-region

- RHIC can test "change of sign"

  & provide information on Sivers-$\bar{q}$!



yellow $= 1$-σ region

blue $=$ effects due to Sivers-$\bar{q}$

Conclusions

- Previous study of ***preliminary*** HERMES data on $A_{UT}^{\sin(\phi-\phi_S)P_{h\perp}/M_N}$
  solidified by study of ***final*** HERMES data on $A_{UT}^{\sin(\phi-\phi_S)}$
- Gaussian model $\Rightarrow$ parameters constrained in terms of HERMES data $\Rightarrow$ consistent with data
- Large-N_c predictions used (and: tested!). Useful guideline!

  $\Rightarrow$ naturally explains compatibility of HERMES (proton) and COMPASS (deuteron) data
- Obtained fit satisfies all presently known theoretical constraints
  (large-N_c, Burkardt sum-rule, "connection" to GPD, positivity)
- Consistent (of course) with fits by Anselmino *et al.*, Vogelsang and Yuan (but different assumptions!)
- Change of sign $f_{1T}^{\perp a}|_{\rm SIDIS} = - \, f_{1T}^{\perp a}|_{\rm DY}$ can be tested at COMPASS & PAX (byproduct) for Sivers-q ...
- ... also at RHIC, where first glimpse on Sivers-$\bar{q}$ possible
- Most recent & more precise ***preliminary*** HERMES data somehow larger Sivers effect.
  Still compatible with large-N_c. $\Rightarrow$ even more optimistic estimates for Drell-Yan

Thank you!