Transverse SSA in semi-inclusive DIS and DY

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Outline

- The Sivers effect in SIDIS
- Extraction of the Sivers function

  - in a model independent way
  - in a Gauss model

- Antiquark Sivers function
- Transverse SSA @ RHIC
- Consistency Check of Large N_C - ansatz
- Conclusions

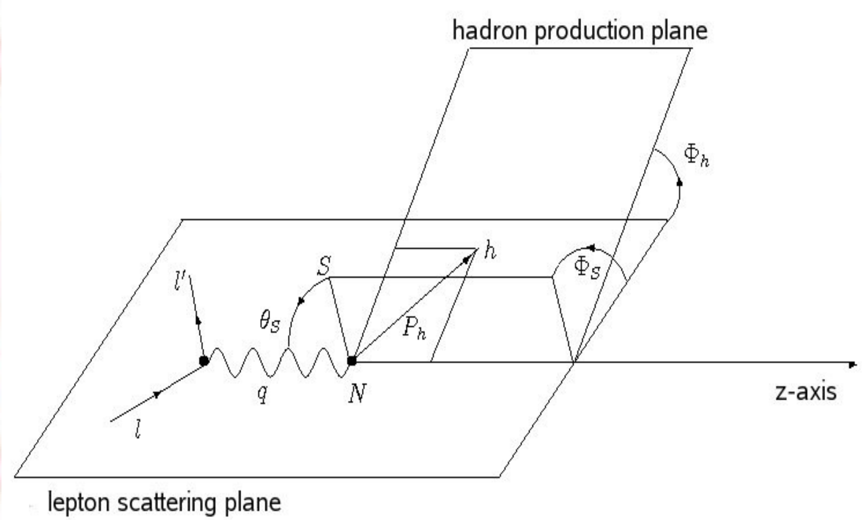
Sivers Effect

- introduced to explain large transverse SSA @FNAL (1990's)
- first evidence for „naively“ T-odd distributions in SIDIS (HERMES)
- $\propto (\mathbf{S}_T \times \mathbf{p}_T)\,\mathbf{P}_N$

(transverse component of) Nucleon spin

nucleon momentum

(transverse component of) parton momentum



- Gauge-link is necessary for the existence of the Sivers effect
- Sivers effect is quantified in terms of the Sivers function $f_{1T}^{\perp}\left(x, \mathbf{p}_T^2\right)$

Sivers function in SIDIS

- SIDIS: SSA generated by Sivers and Collins Effect, but

$$A_{UT} = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \propto \underbrace{sin\,(\phi_h - \phi_S)\, f_{1T}^{\perp} D_1}_{Siverseffect} + \underbrace{sin\,(\phi_h + \phi_S)\, h_1 H_1^{\perp}}_{Collinseffect} + sin\,(3\phi_h - \phi_S) \ldots$$

- ➡ Effects can be seen seperately !
- Sivers Asymmetry ➡ direct extraction possible!
  (Kretzer,Leader,Christova...)
- Collins Asymmetry ➡ both unkown ➡ extraction difficult !

Extraction (weighted data)

- use first transverse moment of Sivers function (Boer,Mulders)
- advantage: Model independent extraction possible

$$A_{UT} = \frac{\int d\phi_h sin\,(\phi_h - \phi_S)\,\frac{P_{h\perp}}{M}\left(N^{\uparrow} - N^{\downarrow}\right)}{\frac{1}{2}\int d\phi\,(N^{\uparrow} + N^{\downarrow})} = -2\frac{\sum e_a^2 x\, f_{1T}^{\perp(1)a}(x) z D_1^a(z)}{\sum_a e_a^2 f_1^a(x) D_1^a(z)}$$

- FIT:
  - use Large-N_C (Pobylitsa)
    $$f_{1T}^{\perp(1)u} = -f_{1T}^{\perp(1)d} \qquad f_{1T}^{\perp(1)\bar{q},g,s\ldots} = 0$$
  - obey Burkardt sum-rule (Burkardt)
    $$\sum_a \int dx\, f_{1T}^{\perp(1)a} = 0$$
  - explore connection of Siversfunction to GPD (Brodsky et al, Burkardt)
    $$E^q(x,0,0) \propto (1-x)^5$$
  - Check Positivity condition (Bacchetta)
    $$\frac{|\mathbf{p}_T|}{M}\left|f_{1T}^{\perp a}\left(x,\mathbf{p}_T^2\right)\right| \leq f_1^a\left(x,\mathbf{p}_T^2\right)$$

Results I

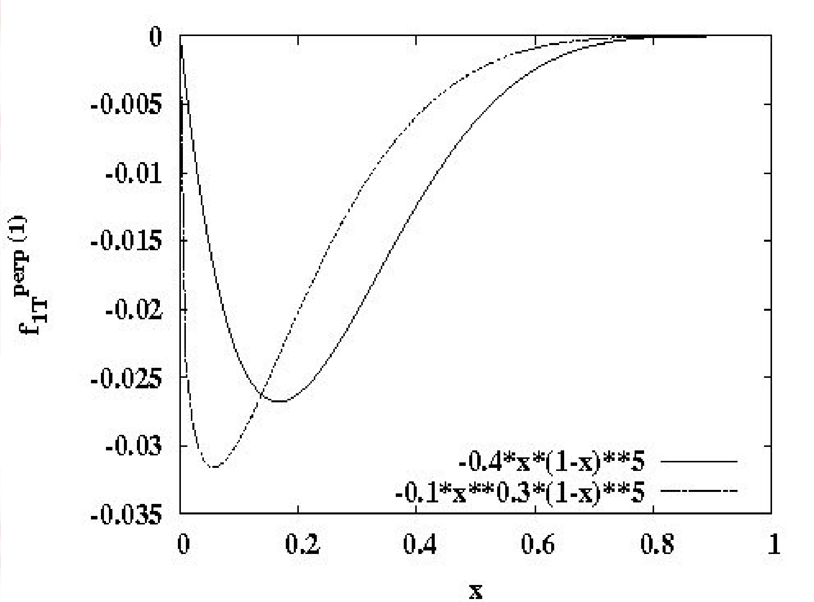
$$x f_{1T}^{\perp(1)u} = A x^b (1-x)^5$$

BEST FIT:

1 parameter fit $\quad x f_{1T}^{\perp(1)u} = -0.4x(1-x)^5$

2 parameter fit $\quad x f_{1T}^{\perp(1)u} = -0.1x^{0.3}(1-x)^5$

(Efremov, Goeke, Menzel, Metz, Schweitzer)



Problem: Weighted data still *preliminary* (acceptance problems), use *published* unweighted data instead

Unweighted Sivers asymmery

- need model for p_T- dependence of distribution functions !

$$A_{UT} = (-2)\frac{\sum_a e_a^2 \int d^2P_{hT} \int d^2p_T \int d^2K_T sin(\phi_h - \phi_S) \frac{|p_T|}{M_N} \delta^{(2)}(zp_T + K_T - P_{hT}) x f_{1T}^{\perp a}(x, p_T^2) D_1^a(z, K_T^2)}{\sum_a e_a^2 x f_1^a(x) D_1^a(z)}$$

$$f_1^a(x, \mathbf{p}_T^2) = f_1^a(x)\frac{exp\left(\frac{-\mathbf{p}_T^2}{p_{unp}^2}\right)}{\pi p_{unp}^2}$$

$$f_{1T}^{\perp a}(x, \mathbf{p}_T^2) = f_{1T}^{\perp a}(x)\frac{exp\left(-\frac{\mathbf{p}_T^2}{p_{siv}^2}\right)}{\pi p_{siv}^2}$$

$$D_1^a(z, \mathbf{K}_T^2) = D_1^a(z)\frac{exp\left(-\frac{\mathbf{K}_T^2}{K_{D1}^2}\right)}{\pi K_{D1}^2}$$

→ 3 additional parameters need to be fixed

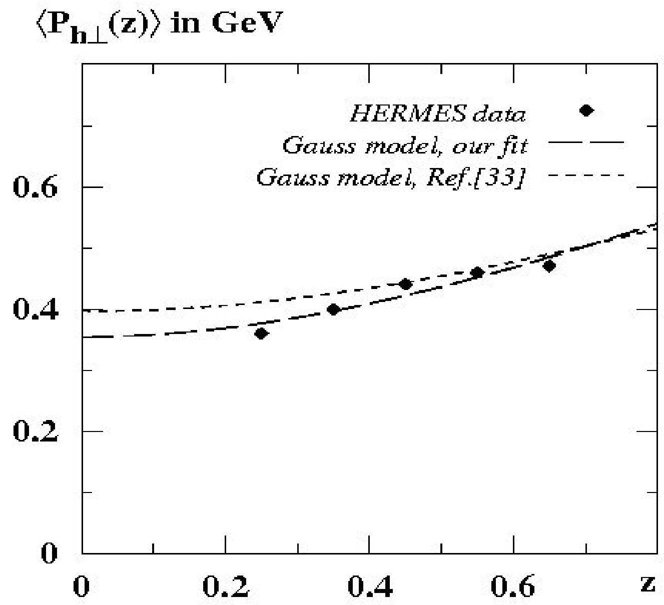
$$p_{unp}^2, p_{siv}^2, K_{D1}^2$$

→ fix from external conditions

- p^2_{unp} K^2_{D1} ⟶ HERMES $\mathrm{P}_{h\perp}$ data

$$\langle \mathbf{P}_{h\perp}(z)\rangle \stackrel{Gauss}{=} \frac{\sqrt{\pi}}{2}\sqrt{z^2 p^2_{unp} + K^2_{D1}}$$

$$\begin{aligned} p^2_{unp} &= 0.33\ \mathrm{GeV}^2 \\ K^2_{D1} &= 0.16\ \mathrm{GeV}^2 \end{aligned}$$



- ⟶ use positivity condition

$$\frac{|\,\mathbf{p}_T\,|}{M}\left|f_{1T}^{\perp a}\left(x,\mathbf{p}_T^2\right)\right| \le f_1^a\left(x,\mathbf{p}_T^2\right) \stackrel{Gauss}{\Rightarrow} p^2_{siv} \le \frac{p^2_{unp}}{1+\frac{2M_N^2 p^2_{unp}}{e p^4_{siv}}\left(\frac{f_{1t}^{\perp a}(x)}{f_1^a(x)}\right)^2}$$

- must be valid for all x ⟶ $0 < p^2_{siv} < p^2_{unp}$

because $p^2_{siv} \longrightarrow 0 \Rightarrow A_{UT} \longrightarrow 0$

Extraction II

- positivity condition gives us only a vague value for p^2_{siv}

BUT: If we use the first Sivers moment instead of the unweighted Sivers function, one gets

$$A_{UT}^{\sin(\phi_h-\phi_S)} = (-2)\frac{a_{Gauss}\sum_a e_a^2 x f_{1T}^{\perp(1)a}(x) D_1^a(z)}{\sum_a e_a^2 x f_1^a(x) D_1^a(z)} \quad , \quad a_{Gauss} = \frac{\sqrt{\pi}}{2}\frac{M_N}{\sqrt{p^2_{siv} + \frac{K^2_{D1}}{z^2}}}$$

and 0.72 < a_{Gauss} < 0.83 only 10% uncertainty !!!

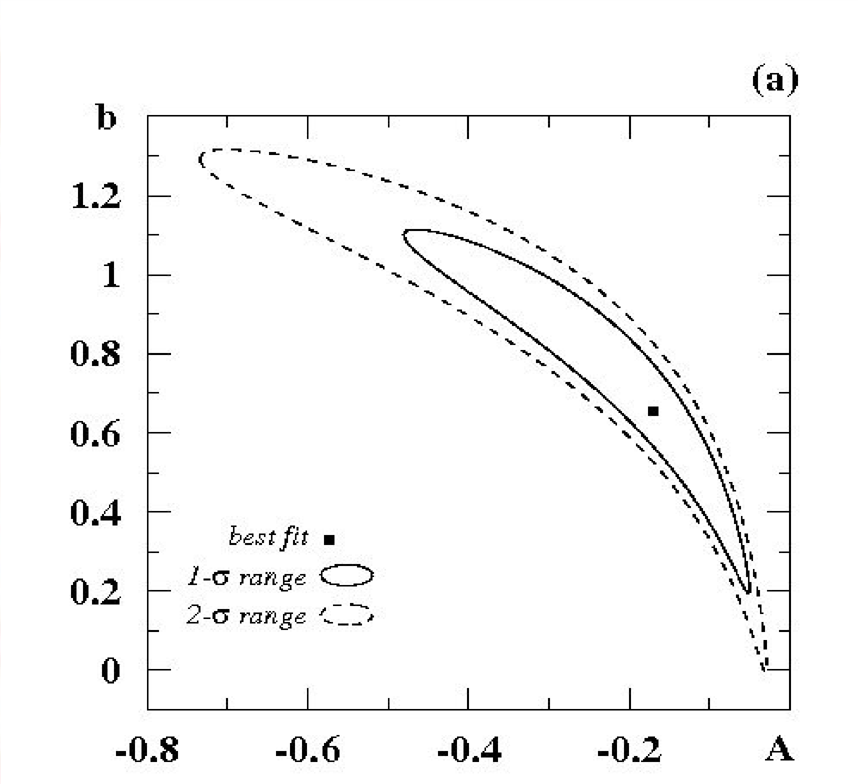
FIT:

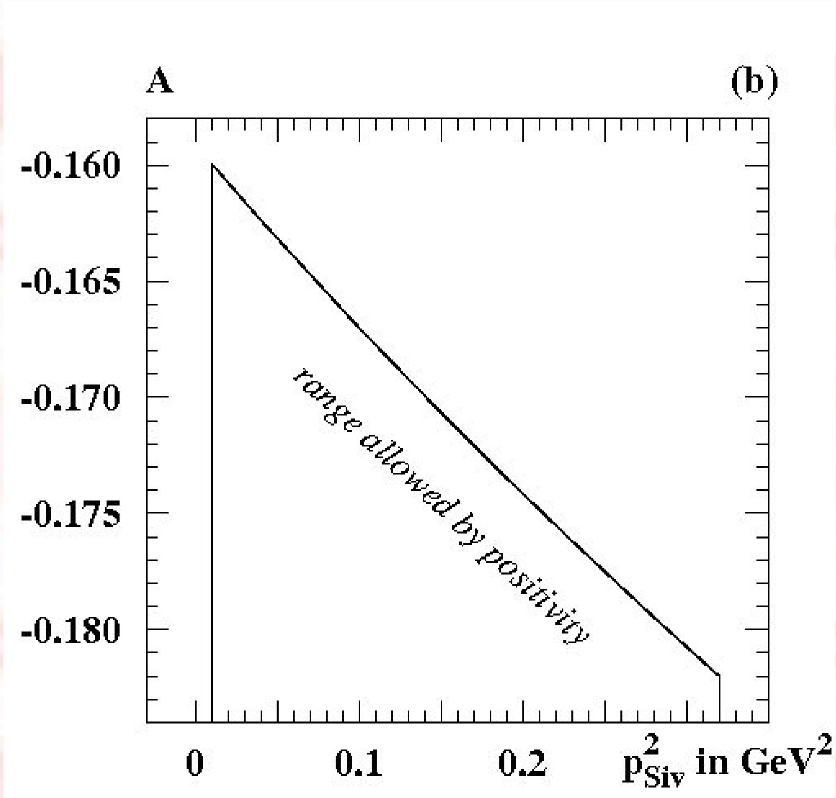
$$\begin{aligned} x f_{1T}^{\perp(1)u}(x) &= -x f_{1T}^{\perp(1)d}(x) = A x^b (1-x)^5 \\ f_{1T}^{\perp(1)\bar{q},g}(x) &= 0 \end{aligned}$$

choose 0 < p^2_{siv} < 0.33

check positivity

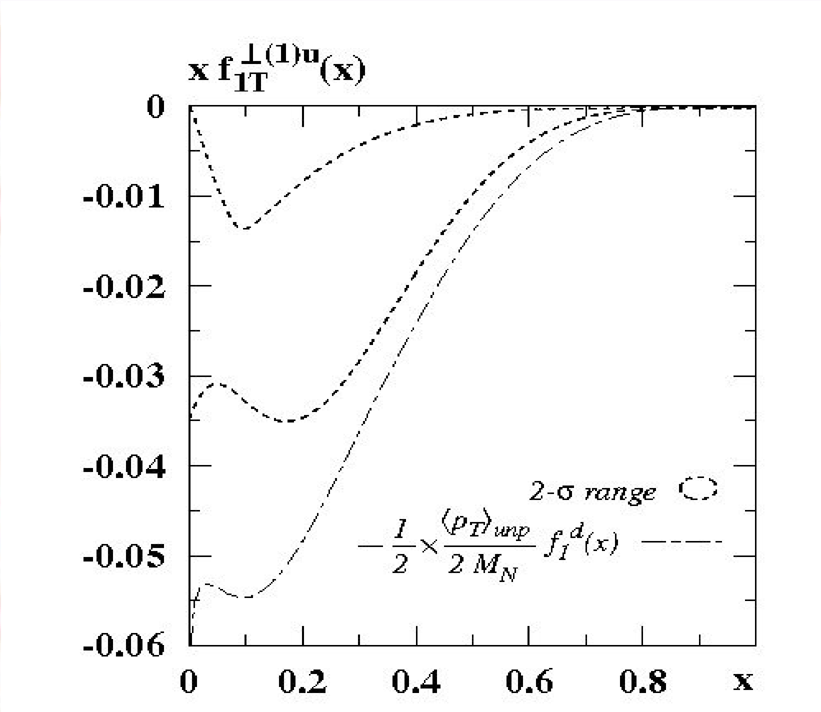
Results II

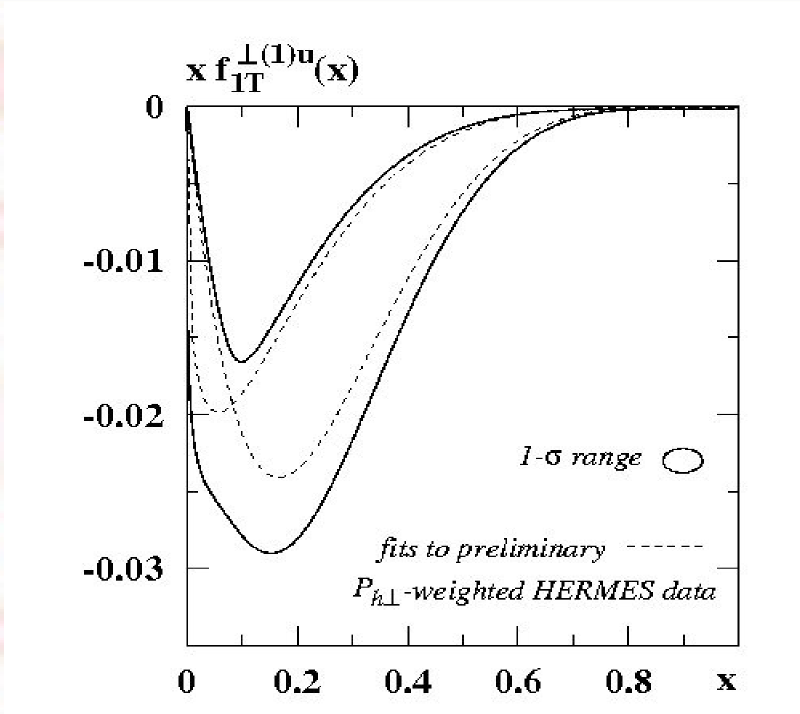




Best fit: $x f_{1T}^{\perp(1)u} = -0.17 x^{0.66} (1-x)^5$

Results II





Extraction of Sivers function from weighted data is justified afterwards !

Antiquarks

- up to now $f_{1T}^{\perp\bar{q}} = 0$

<u>QUESTION</u>: Is it justified to neglect the antiquark distributions?

invent two models for Sivers antiquark distributions

(1) <u>simple model</u>:
Antiquarks have the same distribution like quarks, but only with 25% amplitude

(2) <u>advanced model</u>:
The ratio of antiquarks Sivers function is the same as the unpolarized ratio

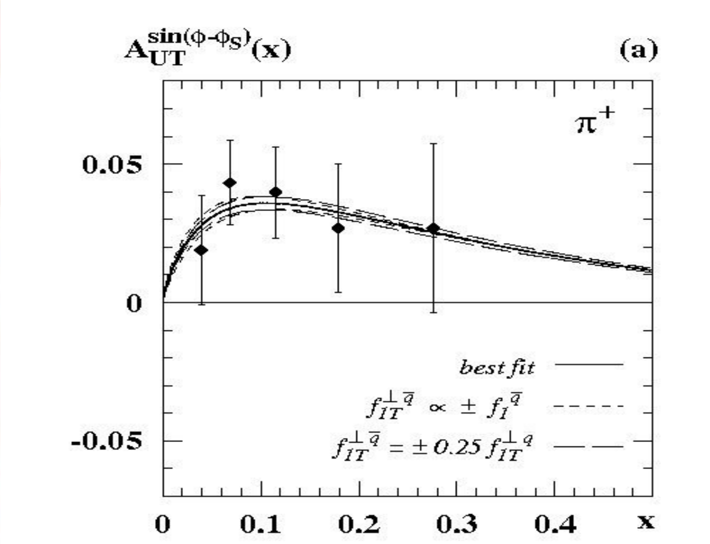
$$f_{1T}^{\perp\bar{q}}(x) = \epsilon(x) f_{1T}^{\perp q}$$

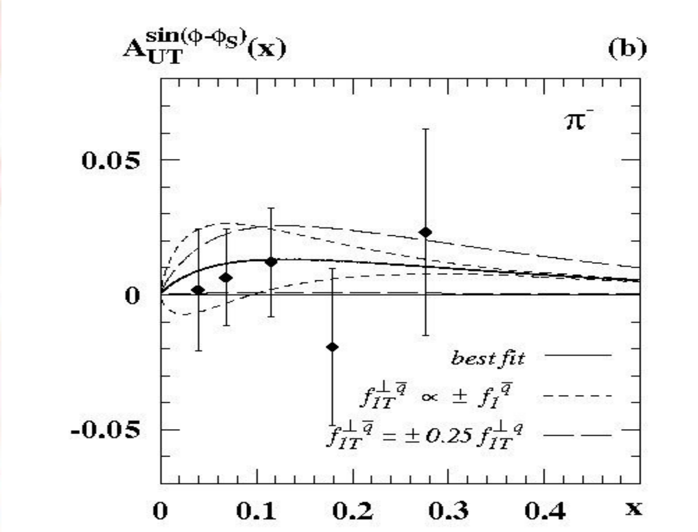
$$\epsilon(x) = \pm \begin{cases} 0.25 & \text{Model I} \\ \dfrac{\left(f_1^{\bar{u}}+f_1^{\bar{d}}\right)(x)}{\left(f_1^{u}+f_1^{d}\right)(x)} & \text{Model II} \end{cases}$$

Burkardt sum rule is automatically obeyed!

Antiquarks @ HERMES

QUESTION: Can we see antiquarks @ HERMES ?





ANSWER: We can not!

Size of errorbars does not allow one to extract Sivers antiquark distribution functions!

$f_{1T}^{\perp\bar{q}} = 0$?? → is not fixed. (Anselmino et al, Vogelsang, Yuan)

Sivers asymmetry in Drell-Yan

based on the present understanding of T-odd distribution functions, one can make a QCD prediction:

Collins 2002:

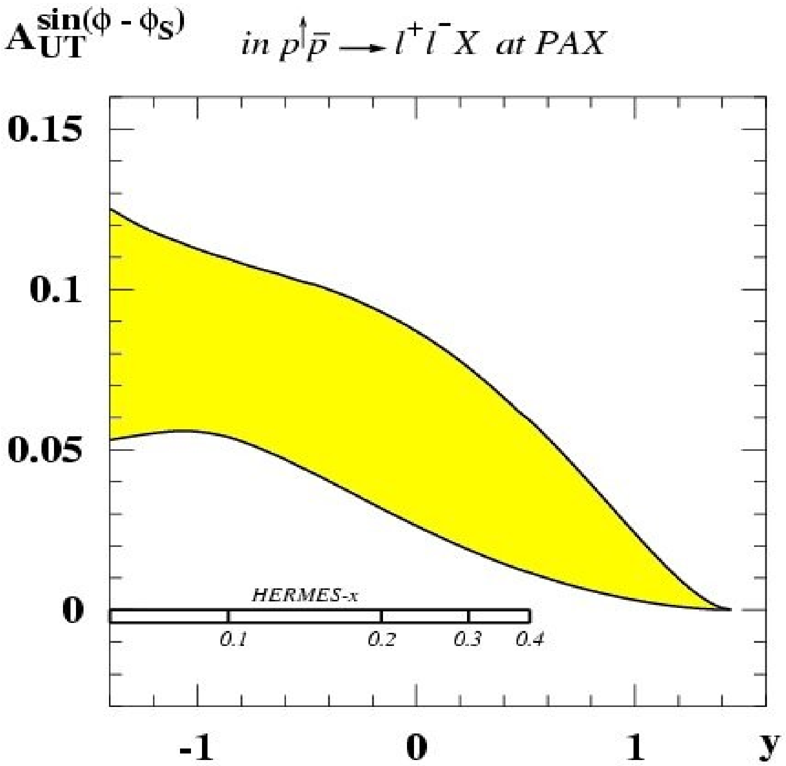
$$\boxed{f_{1T}^{\perp}(x)\Big|_{SIDIS} = -\, f_{1T}^{\perp}(x)\Big|_{DY}} \qquad (\#)$$

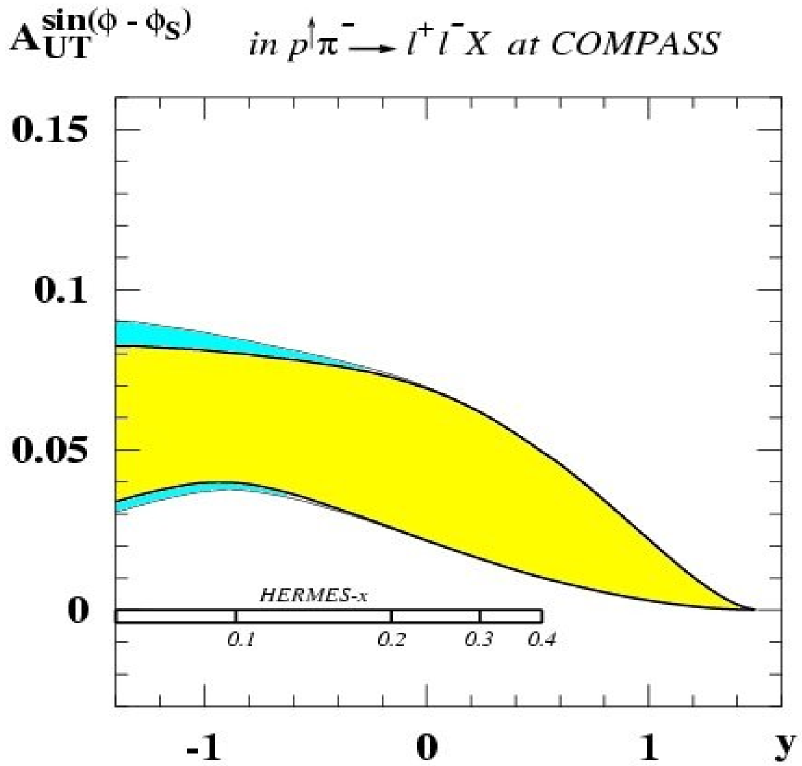
→ Can make predictions for DY based on (#) and

$$f_{1T}^{\perp\bar{q}}(x) = \epsilon(x) f_{1T}^{\perp q}$$

$$\epsilon(x) = \pm \begin{cases} 0.25 & \text{Model I} \\ \dfrac{\left(f_1^{\bar{u}}+f_1^{\bar{d}}\right)(x)}{\left(f_1^{u}+f_1^{d}\right)(x)} & \text{Model II} \end{cases}$$

Predictions for Drell-Yan





! change of sign visible

→ Check of present transverse SSA understanding!

Visibility of Sivers antiquarks

- PAX: collision of protons and antiprotons
- COMPASS: collision of protons and negative pions

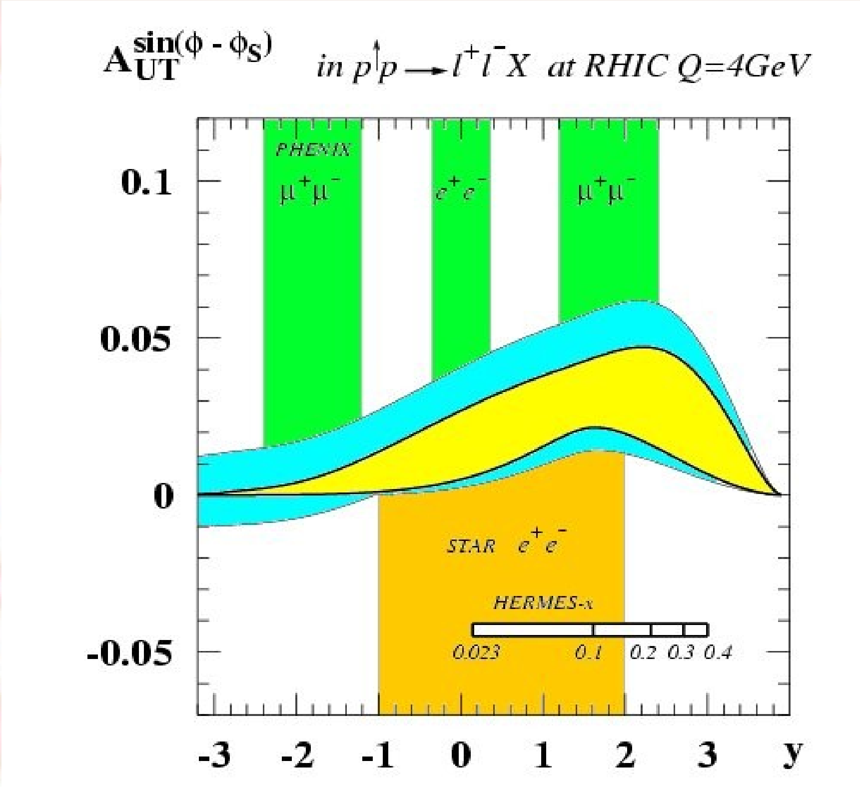
$\longrightarrow$ sivers antiquark distribution hardly visible !

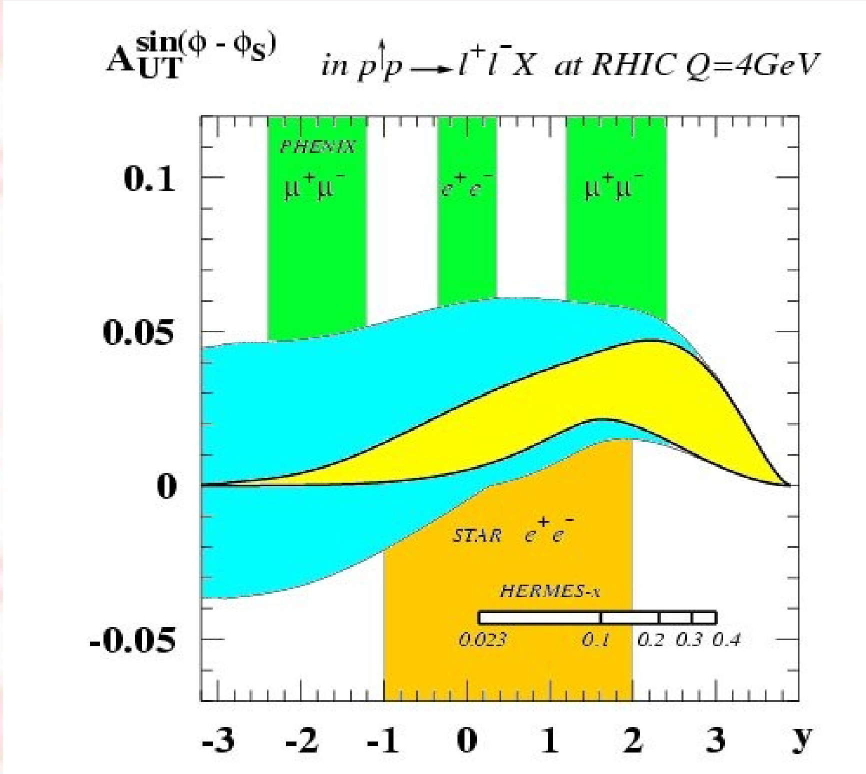
- RHIC: DY process with pp - Collisions:

  sensetive to on equal footing $f_{1T}^{\perp(1)q}(x_1) f_1^{\bar{q}}(x_2)$ and $f_1^{q}(x_1) f_{1T}^{\perp(1)\bar{q}}(x_2)$

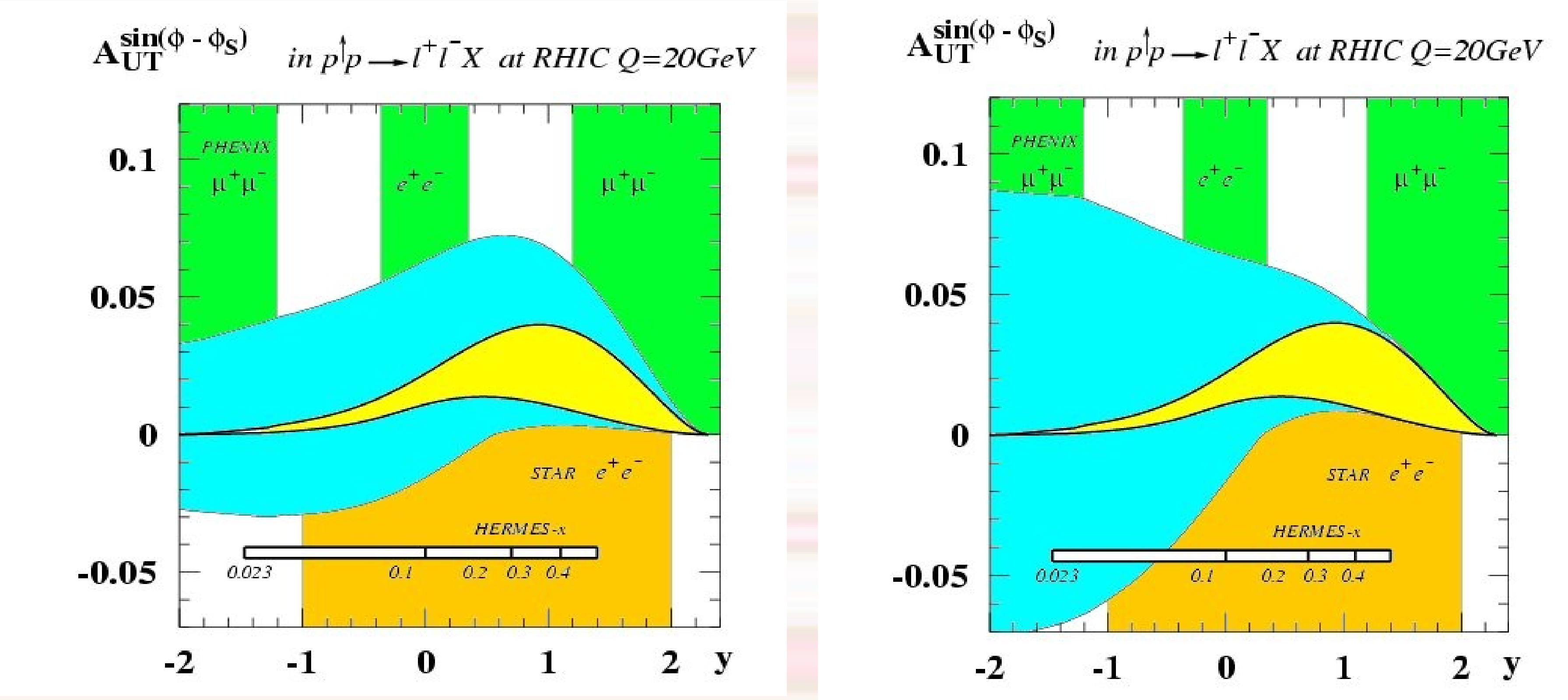
- Sivers antiquark distributions should be visible @ RHIC

Prediction for RHIC

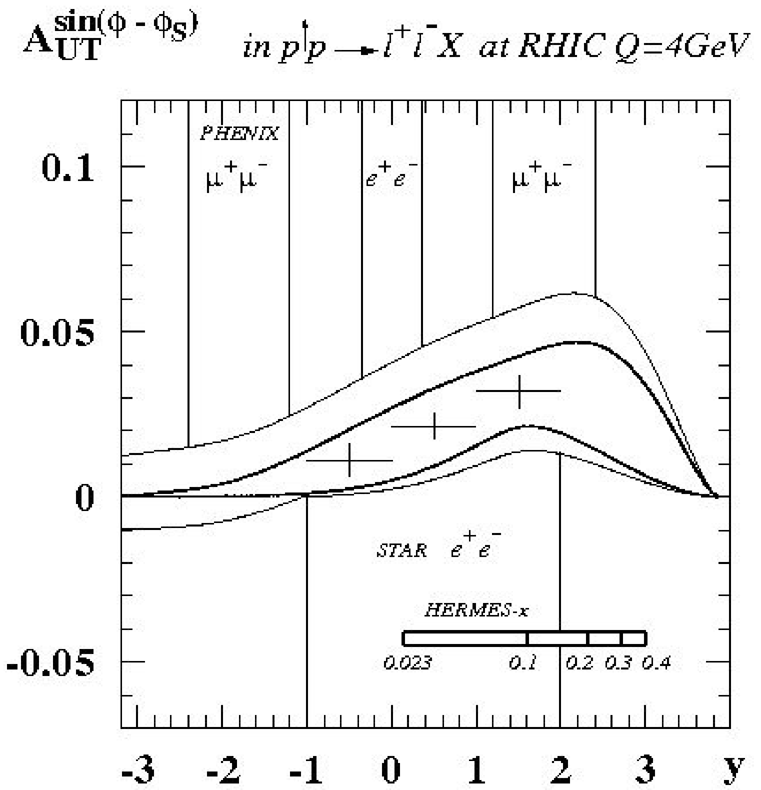


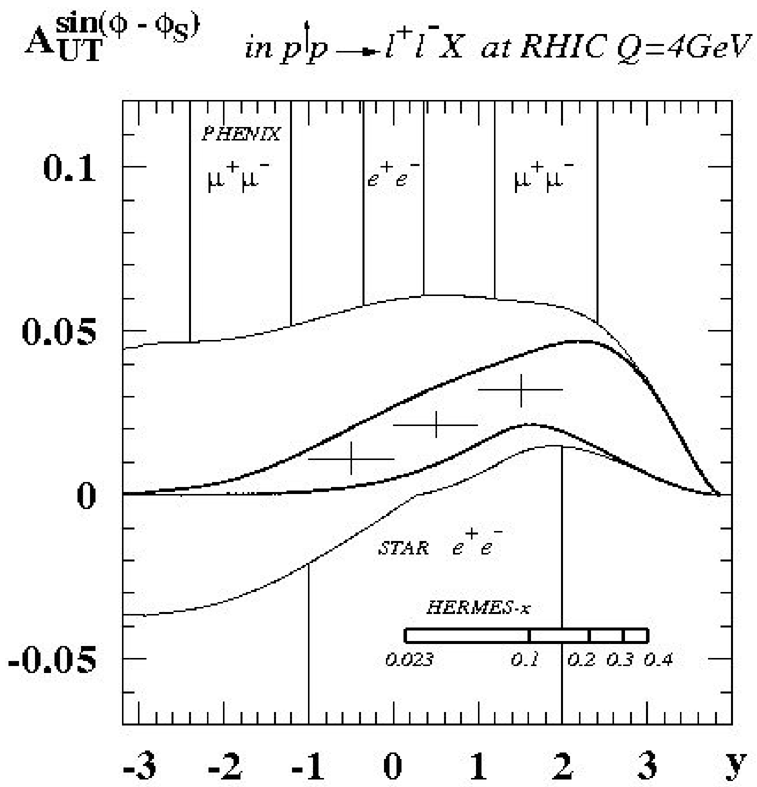


Prediction for RHIC



statistical uncertainties @ STAR





Large - N_C

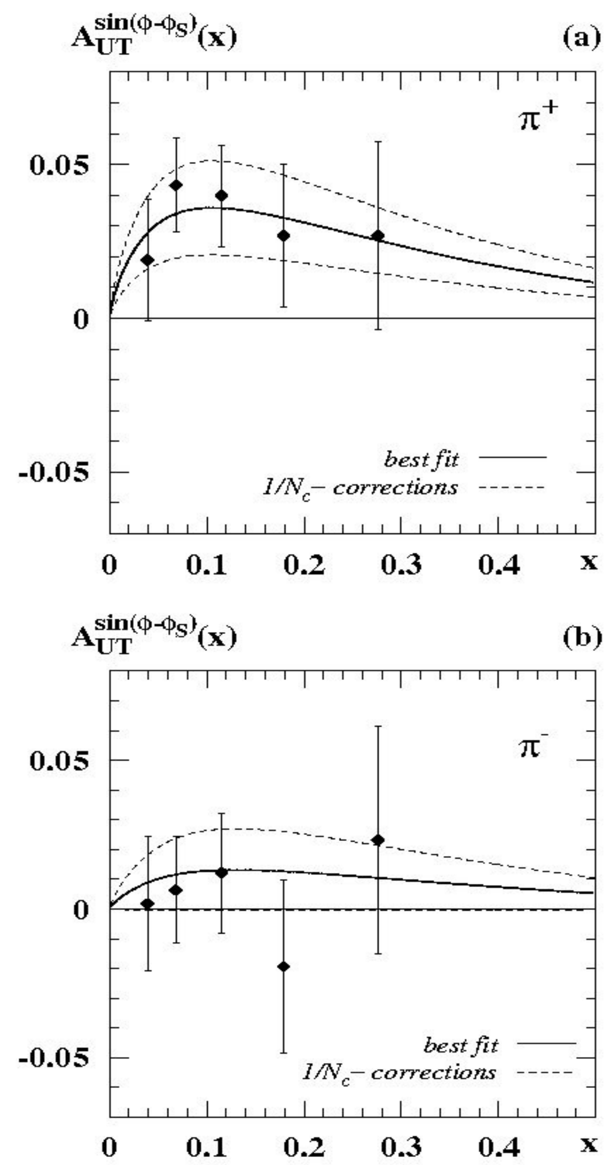
QUESTION: How reliable is the Large – N_C ansatz?

Ansatz: $$\left|\left(f_{1T}^{\perp u}+f_{1T}^{\perp d}\right)(x)\right| \ll \left|\left(f_{1T}^{\perp u}-f_{1T}^{\perp d}\right)(x)\right|$$

$$\rightarrow \quad \left(f_{1T}^{\perp u}+f_{1T}^{\perp d}\right)(x)=\pm\frac{1}{N_C}\left(\left(f_{1T}^{\perp u}-f_{1T}^{\perp d}\right)(x)\right)$$

ANSWER: Large – N_C ansatz ist compatible with present data

HERMES: →



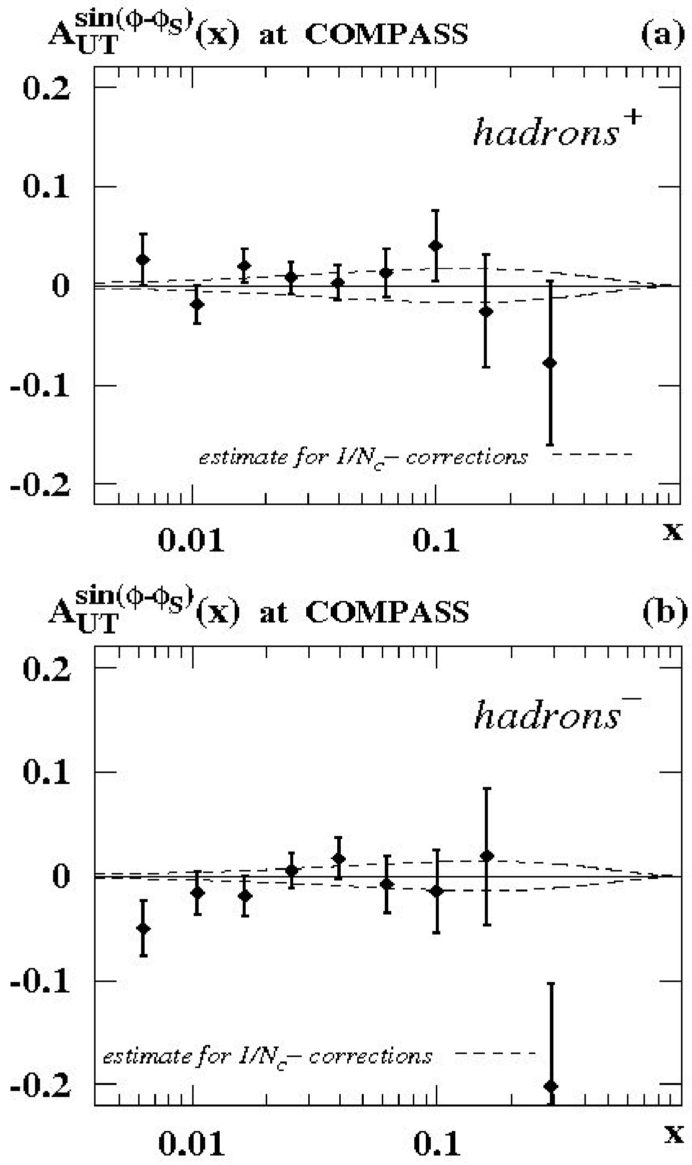
Large - N_C

COMPASS:

$$f_{1T}^{\perp u/deuteron} = f_{1T}^{\perp u/proton} + f_{1T}^{\perp d/proton} = \mathcal{O}\left(\frac{1}{N_C}\right)$$

$$\longrightarrow \quad A_{UT} \approx 0$$

Future data: Maybe Large - N_C constraint has to be relaxed



Conclusions

- A parameterization of the u-quark Sivers function has been extracted
- Change of sign of Sivers asymmetry visible in DY
- A parameterization of the antiquark Sivers function can not be extracted from COMPASS or HERMES data
- Can be extracted from RHIC data (PHENIX, STAR, PHOBOS, BRAHMS)
- Errors @ STAR should be small enough to get a good parameterization
- Large – N_C Model ist compatible with present data