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Understanding SSA in SIDIS

on basis of chiral quark soliton model and large N_c limit

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Overview:

- Solid basis: Chiral quark soliton model & instanton vacuum
- Early (and premature) success: $A_{UL}^{\sin\phi}$ at HERMES & $A_{UL}^{\sin 2\phi}$ at CLAS
- Lessons from HERMES and COMPASS A_{UT} data on Collins and Sivers effect
- If we understood lessons: New predictions & estimates

  $\longrightarrow$ to be checked in experiments
- Conclusions

typically $\{$**SSA in SIDIS**$\} = \{h_1^a(x),\, h_L^a(x),\, \ldots\} \times \{H_1^\perp(z),\, \ldots\}$

$\Longrightarrow$ desirable to know at least some ingredients as reliably as possible

Chiral quark soliton model

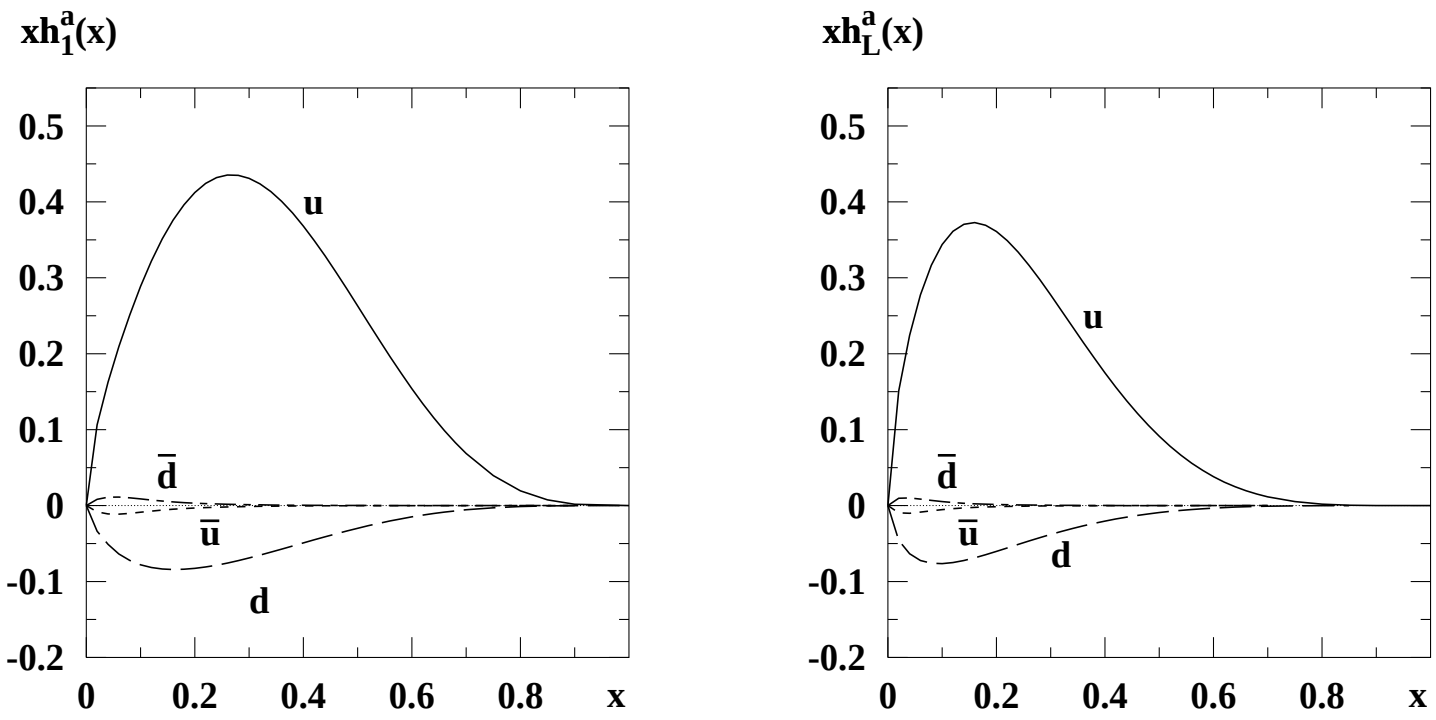
- nucleon = N_c quarks bound in static pion mean field as $N_c \to \infty$
- derived from instanton vacuum ($\to$ chiral symmetry breaking)
- wide range of applications: mass splittings, form factors, ..., Θ^+ (?)
- most recent: chiral extrapolation of lattice data, hep-lat/0505010
- twist-2 q and $\bar{q}$ distribution functions, GPDs, D-term at $\mu \approx 0.6\,\mathrm{GeV}$

  some highlights

  $\to$ Gottfried "sum rule" $\int \mathrm{d}x\, (f_1^{\bar{u}} - f_1^{\bar{d}})(x) \neq 0$

  $\to$ predicts even larger flavour asymmetry in helicity sea $(g_1^{\bar{u}} - g_1^{\bar{d}})(x) > |(f_1^{\bar{u}} - f_1^{\bar{d}})(x)|$
- phenomenologically **<u>successful</u>** within accuracy of (10-30)% no free parameters
- theoretically **<u>consistent</u>**: PDFs $\to$ inequalities and sum rules, GPDs $\to$ polynomiality
- Good model, but not perfect. No gluons. Sivers function = 0 suppressed Pobylitsa hep-ph/0212027.

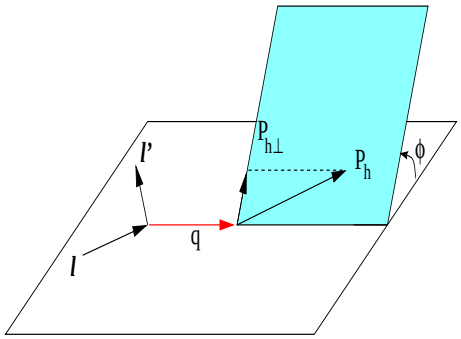
Predictions for $h_1^a(x)$ and $h_L^a(x)$ LO-evolved to 2.5 GeV^2

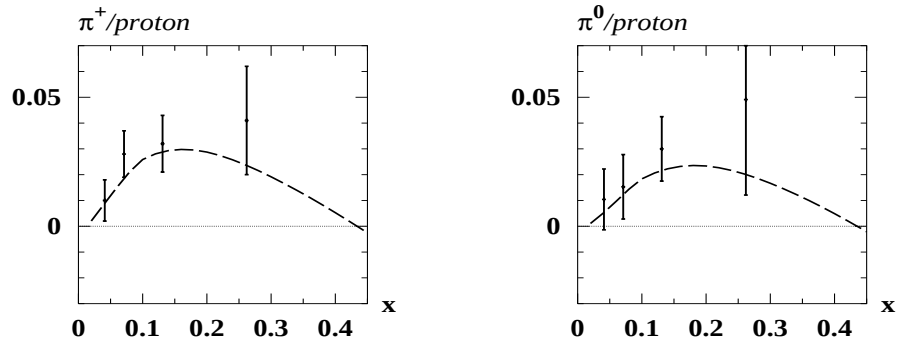


- twist-2 $h_1^a(x)$ directly computed in model PS, Urbano, Pobylitsa, Polyakov, Weiss, Goeke PRD64 (2001) 034013
- twist-3 $h_L^a(x) = 2x \int_x^1 \mathrm{d}y \, \frac{h_1^a(y)}{y^2} + \tilde{h}_L^a(x)$ with $|\tilde{h}_L(x)| \ll |h_1(x)|$ from instanton vacuum

  Dressler and Polyakov, PRD61 (2000) 097501
- reliable within accuracy of the model $\sim$ (10-30)%

$$A_{UL}^{\sin\phi} = \text{“twist-3” at tree-level} \propto h_L(x)H_1^\perp - h_1(x)H_1^\perp + \ldots + \text{Sivers effect}$$





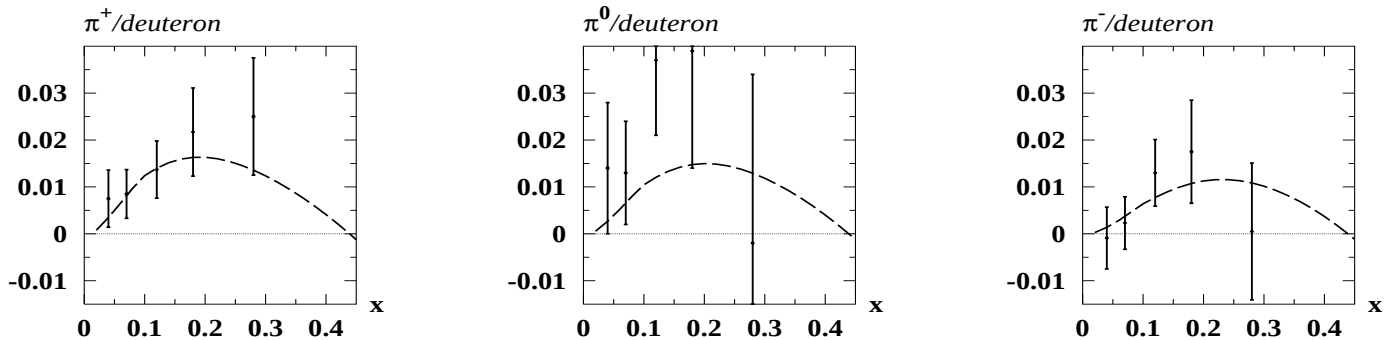
HERMES data:

A. Airapetian *et al.*

PRL **84** (2000) 4047,

PRD **64** (2001) 097101,

PLB **562** (2003) 182.



Our approach:

Efremov, Goeke and P.S.,

PLB **522** (2001) 37,

and **544** (2002) 389E,

EPJC **24** (2002) 407.

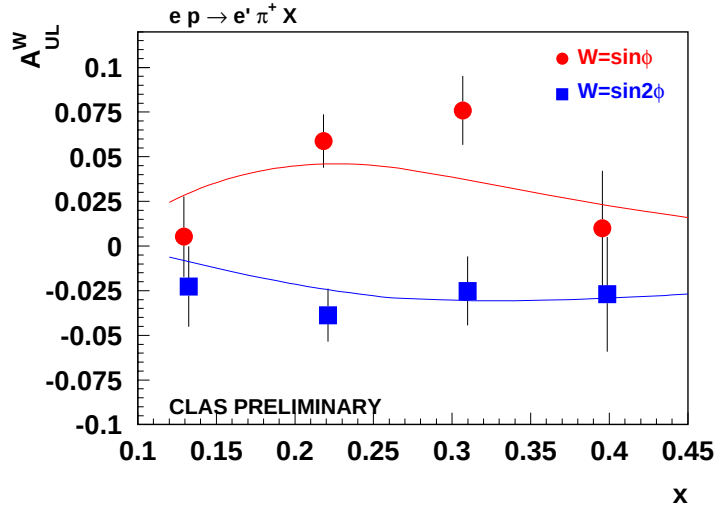
Also other approaches ...

- simplified description of transverse momenta $f(x, k_T^2) = f(x)\,\mathcal{G}(k_T^2)$, k_T-weighting (!)
- $\dfrac{\langle H_1^{\perp\text{fav}}\rangle}{\langle D_1^{\text{fav}}\rangle} = (12-14)\%$ assuming $\langle H_1^{\perp\text{unf}}\rangle \approx 0$ [DELPHI Efremov *et al.*, NPB **74** (1999) 49c $\rightarrow$ BELLE!]
- reasonable description without free adjustable parameters

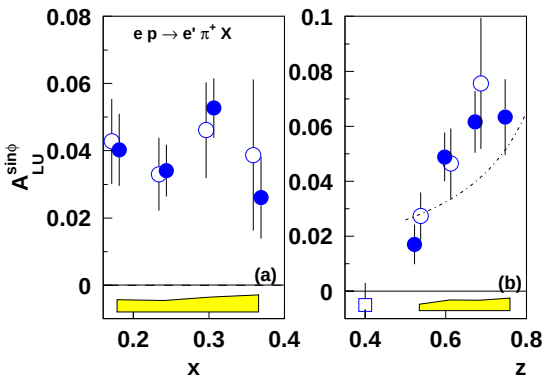
Test: $A_{UL}^{\sin 2\phi}(x)$ independent observable!

- $\propto h_{1L}^{\perp} H_1^{\perp}$ with $h_{1L}^{\perp(1)}(x) = -x^2 \int_x^1 \mathrm{d}y \, \frac{h_1^a(y)}{y^2}$
- Indication: sign and magnitude seem ok

  [Avakian, CIPANP 2003, New York.]



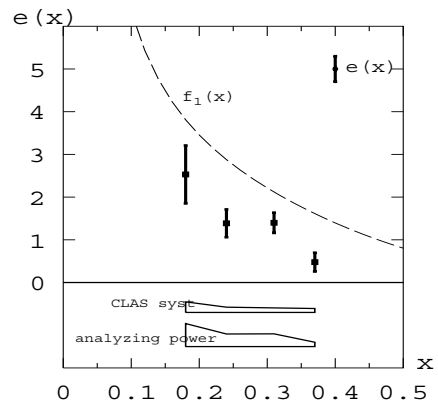
Application: $A_{LU}^{\sin\phi} \propto e(x) H_1^{\perp}$ CLAS PRD69, 112004 (2004) (c.f. HERMES, E. Avetisyan)



$\Longrightarrow$

Efremov, Goeke, P.S., PRD67 (2003) 114014

... is there $\delta(x)$?



- **But** twist-3 "T-odd" distributions/fragmentation functions Afanasev and Carlson, hep-ph/0308163; Yuan, PLB 589 (2004) 28; Gamberg et al. PLB 2004; Metz and Schlegel, EPJA 22 (2004) 489; Bacchetta, Mulders and Pijlman, PLB 595 (2004) 309; Goeke, Metz and Schlegel, hep-ph/0504130
- More promising to access $e(x)$: interference functions Bacchetta and Radici, PRD 69 (2004) 074026.

Satisfactory description of $A_{UL}^{\sin\phi}(x)$ without Sivers and other effects, how possible?

- Sivers function suppressed in instanton vacuum?

  Efremov, Goeke and P.S., PLB **568** (2003) 63;

  Ostrovsky and Shuryak, PRD71, 014037 (2005);

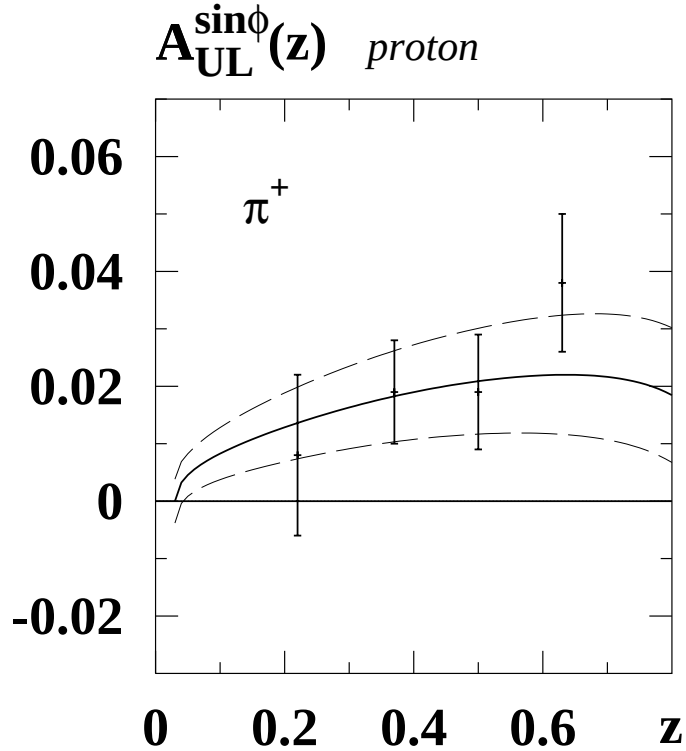
  Boer et al., EPJC40, 55 (2005)

- $f_{1T}^{\perp}$ as large as allowed by positivity bounds* could be hidden in statistical error bars!

  Bacchetta and P.S., NPA **732** (2004) 106,

  using model calculation for $H_1^{\perp}$ by

  Bacchetta et al., PRD **65** (2002) 094021.**



* Bacchetta *et al.*, PRL **85** (2000) 712.

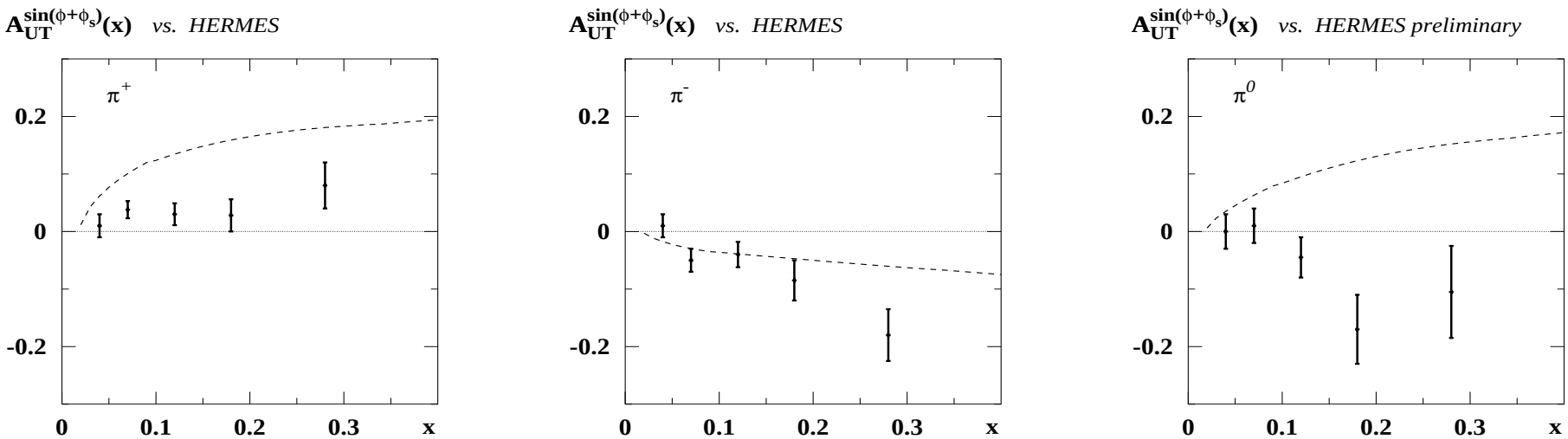
** Amrath, Bacchetta and Metz, hep-ph/0504124.

Certain success! But error bars large. Strong & unambiguous test $\Longrightarrow$ A_{UT}

Remark: Caution! Preliminary A_{UT}^{Col} SMC data [Bravar, NPB 79 (1999) 520c]: Opposite sign!

Transverse Collins SSA: $A_{UT}^{\sin(\phi+\phi_S)} \propto h_1(x) H_1^{\perp}$ twist-2 and "clean" & "simple"

- HERMES data [PRL94, 012002, 2005] $\leftrightarrow$ our approach [Efremov, Goeke, P.S., EPJC32, 377, 2004].



Looks much different $\longrightarrow$ Exciting! What went wrong?

<u>First lesson:</u>

- If we

  believe in models for $h_1^a(x)$, stick to simplified description of p_T, continue neglecting soft factors

  $\Longrightarrow$ the only suspicion is: $H_1^{\perp \mathrm{unf}} \not\approx 0$.

Collins SSA $A_{UT}^{\sin(\phi+\phi_S)}$

- define analyzing power $B^a = \dfrac{\langle k_{\perp\pi}\rangle}{m_\pi\sqrt{1+\frac{\langle p_{\perp\mathrm{N}}^2\rangle}{\langle k_{\perp\pi}^2\rangle}}} \cdot \langle H_1^{\perp a}\rangle$

  for Gaussian distribution of $p_{\perp\mathrm{N}}$ in target and $k_{\perp\pi}$ fragmentation process $\rightarrow$ $P_{\pi\perp}$-weighting!

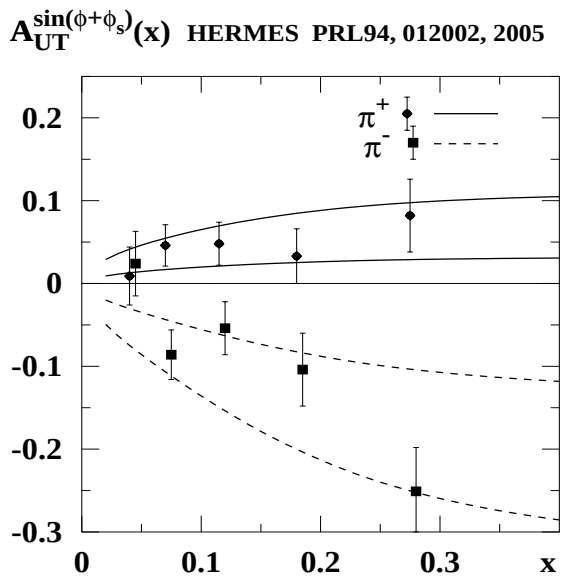
- to explain $\pi^\pm$ data we need

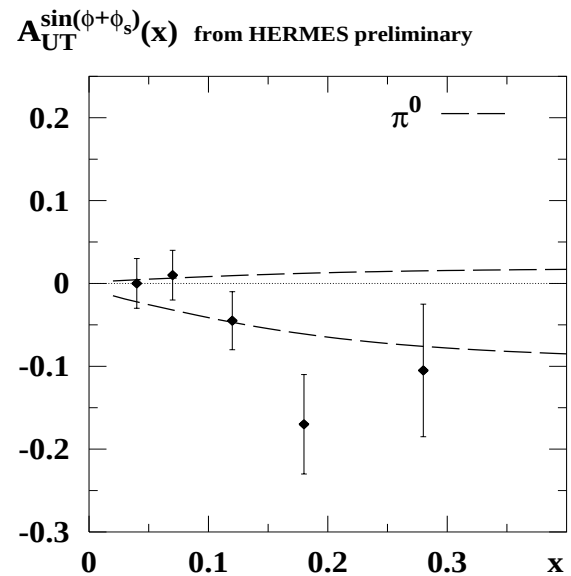
$$0.02 \leq \quad B^{\mathrm{fav}} \quad \leq 0.07$$
$$0.05 \leq \; -B^{\mathrm{unf}} \; \leq 0.12$$

- $H_1^{\perp\mathrm{unf}}$

  opposite sign to $H_1^{\perp\mathrm{fav}}$, and

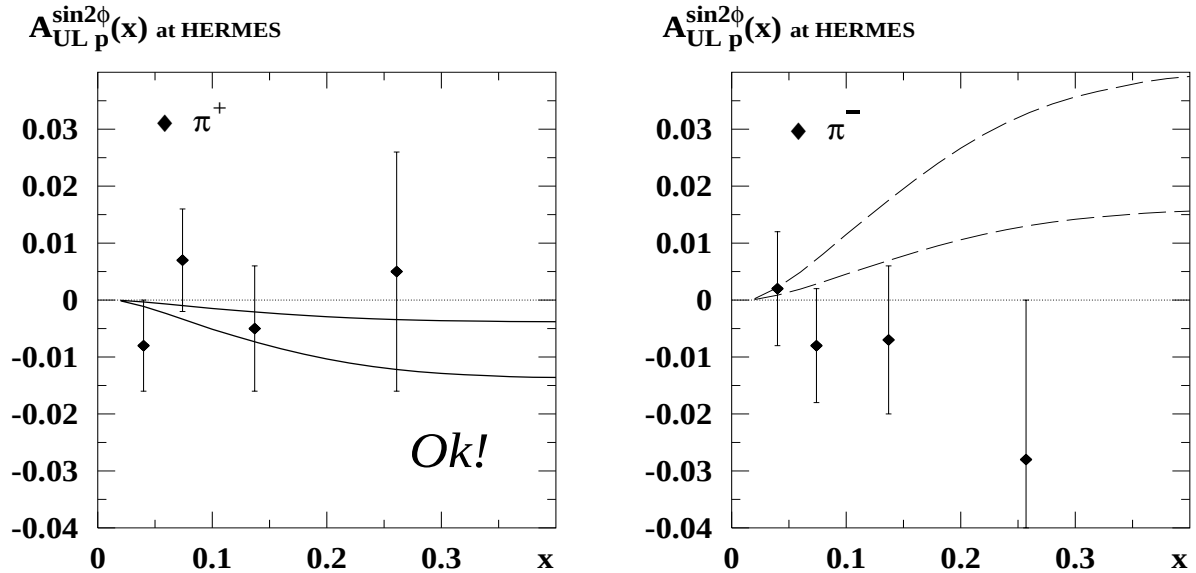
  factor 2 larger absolute value!





- rather interesting and unexpected properties of Collins fragmentation function (string model?)
- not inconsistent with preliminary HERMES data for π^0

Such behaviour of Collins function consistent with $A_{UL}^{\sin 2\phi} \propto h_{1L}^{\perp a} H_1^{\perp a}$?



- π^+ ok!
- π^- much more sensistive to $H_1^{\perp \mathrm{unf}}$ $\longrightarrow$ consistent?

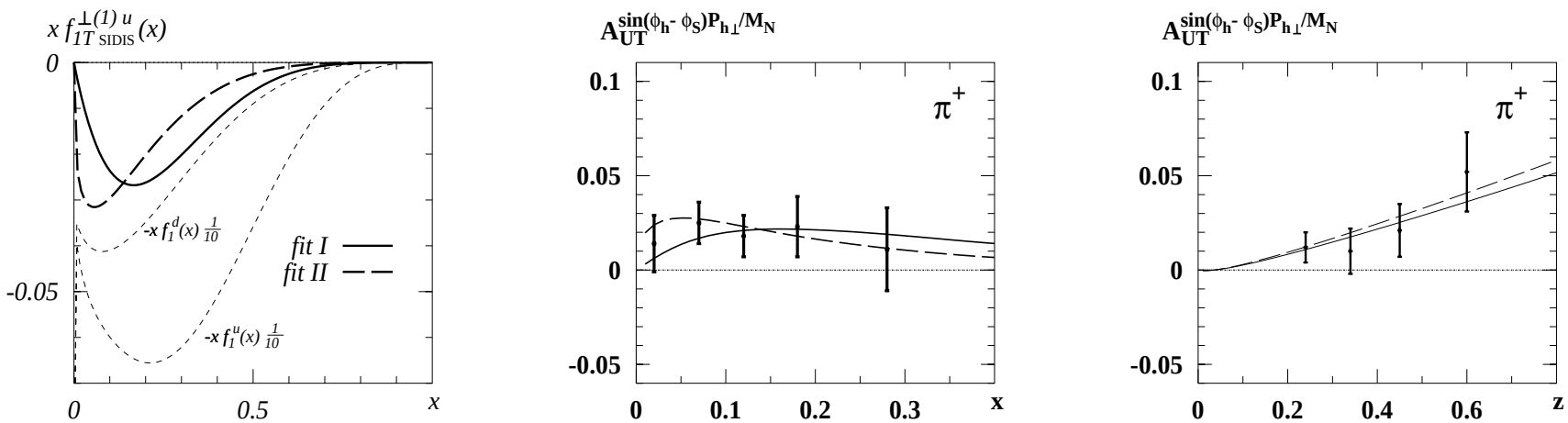
  Remark: "Lorentz invariance relation" $h_{1L}^{\perp(1)}(x) = -x^2 \int_x^1 \mathrm{d}y \, \frac{h_1(y)}{y^2}$ in general incorrect

  Goeke, Metz, Pobylitsa, Polyakov PLB 567 (2003) 27

  spoiled by "gluonic effects" $\sim$ suppressed in instanton vacuum $\rightarrow$ deserves further investigation
- seems consistent with CLAS $A_{UL}^{\sin 2\phi} \neq 0$. Since measured in different z-range, need $H_1^{\perp \mathrm{fav,unf}}(z)$ ...

<u>Second lesson:</u> Sivers SSA $A_{UT}^{\sin(\phi-\phi_S)\frac{P_{h\perp}}{M_N}} \propto f_{1T}^{\perp(1)a}(x) D_1^a(z)$

- unambiguous evidence for T-odd distribution, consider (preliminary) data weighted with $P_{h\perp}$
- z-dependence dictated by $D_1^a(z)$ e.g. Kretzer, Leader, Christova, EPJC 22 (2001) 269
- use large-N_c limit $\boxed{f_{1T}^{\perp u} = -f_{1T}^{\perp d}}$ modulo $1/N_c$ corrections Pobylitsa hep-ph/0301236 (Drago in model)
- fit: $x f_{1T}^{\perp(1)u} = -0.4x(1-x)^5$ or $-0.1x^{0.3}(1-x)^5$ neglect s, $\bar{q}$



- compatible with positivity, respects $\sum_a \int \mathrm{d}x f_{1T}^{\perp(1)a}(x) = 0$, supports picture by M.Burkardt
- small & not inconsistent with idea of instanton suppression
- similar result without large-N_c Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin hep-ph/0501196

- Of course, expect $1/N_c$ corrections $\rightarrow$ deuteron $f_{1T}^{\perp u/D} \approx f_{1T}^{\perp u/p} + f_{1T}^{\perp u/n} \approx f_{1T}^{\perp u} + f_{1T}^{\perp d}$

- COMPASS $A_{UT,D}^{\sin(\phi-\phi_s)} \sim 1/N_c \sim 0$ within error bars

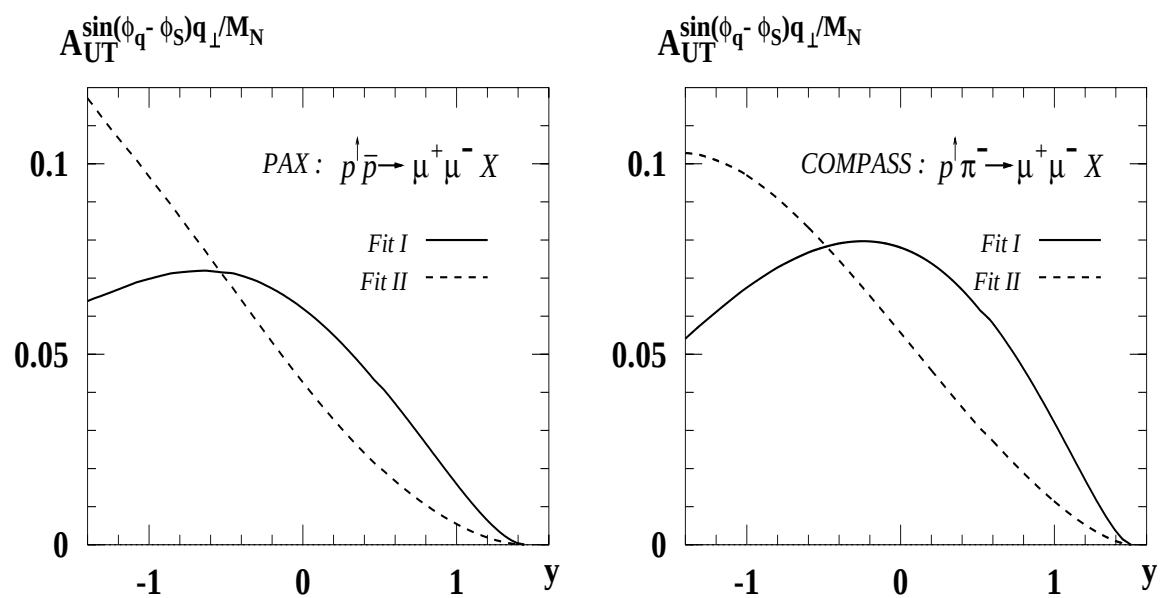
  HERMES $A_{UT,p}^{\sin(\phi-\phi_s)} \sim N_c^0$ some effect, although comparable statistics

- **Conclusion:** HERMES & COMPASS compatible, $f_{1T}^{\perp a}|_{\rm SIDIS}$ compatible with large N_c

- crucial prediction

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

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



Conclusions

- first data $A_{UL}^{\sin\phi}$ most complicated $\longrightarrow$ first understanding needs revision

- new data Collins $A_{UT}^{\sin(\phi+\phi_S)}$

  $\longrightarrow$ exciting & unexpected properties of Collins fragmentation function

  $\longrightarrow$ need more information from CLAS, HALL A on $A_{UT}^{\sin(\phi+\phi_S)}$ and $A_{UL}^{\sin 2\phi}$

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

  $\longrightarrow$ first insight into $f_{1T\,\mathrm{SIDIS}}^{\perp(1)a}$ compatible with large N_c

  $\longrightarrow$ test change of sign in Drell-Yan at PAX, COMPASS

- predictions & estimates are made

  $\longrightarrow$ wait for next data

  $\longrightarrow$ and (most likely) revise the revised understanding – and learn something new!!!

THANK YOU!