TMDs at COMPASS

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on behalf of
the COMPASS Collaboration

TMD2010 ECT*, Trento, June 21 - 25, 2010

OUTLINE

- **the COMPASS experiment**
- **results on azimuthal asymmetries**
  - unpolarised d target
  - longitudinally polarised d target
  - transversely polarised d and p targets
    - Collins asymmetry, 2h asymmetry, Λ polarisation
    - Sivers asymmetry
- **future measurements**

the Common Muon and Proton Apparatus for Structure and Spectroscopy Experiment

the COMPASS Experiment

broad physics program – data taking stated in 2002

- **hadron spectroscopy (hadron beams)**

  (2004) 2008 2009 runs

- **nucleon spin structure with high energy muon beam**

2002
2003 } **polarised deuteron** (^{6}LiD) **target** — **L & T** (20%)
2004

2006 polarised deuteron (^{6}LiD) target — L only

2007 **polarised proton** (NH_3) **target** — **L & T** (50%)

2010 polarised proton (NH_3) target — T only

2011 polarised proton (NH_3) target — L only

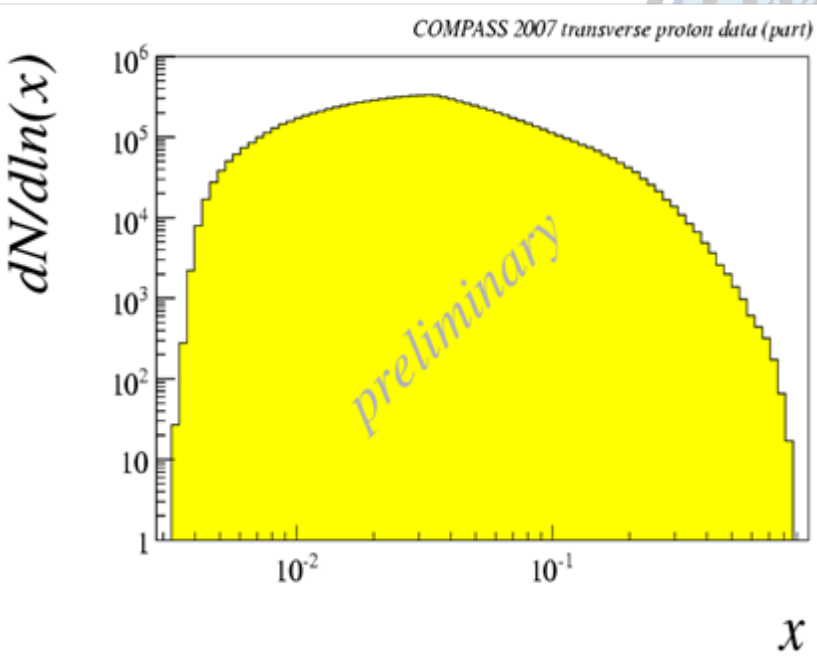
muon beam: 160 GeV/c

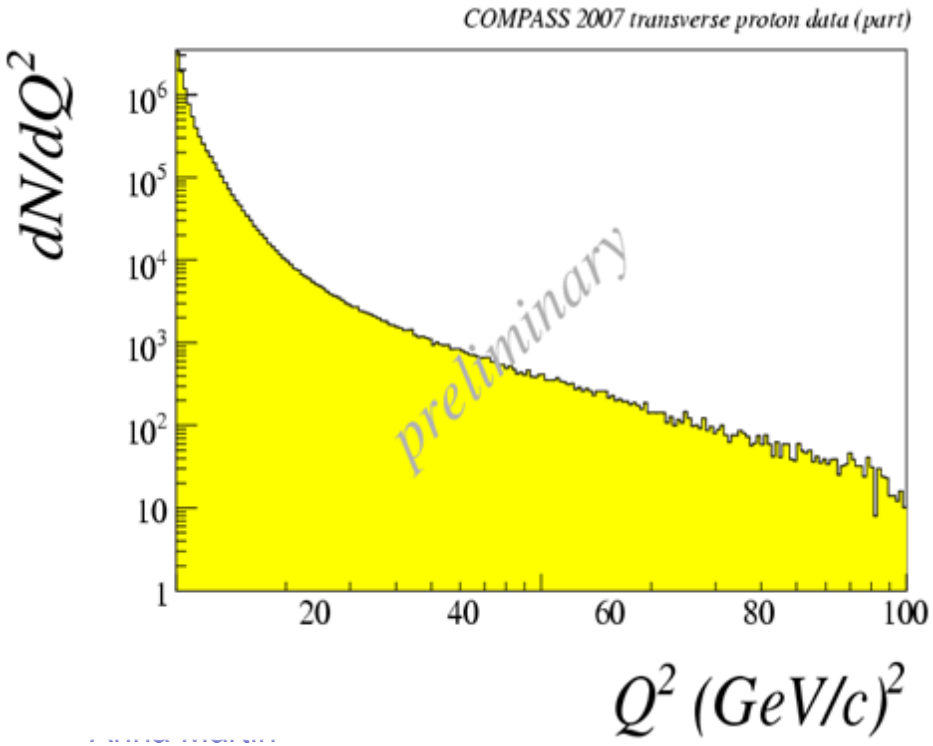
longitudinal polarisation -80%

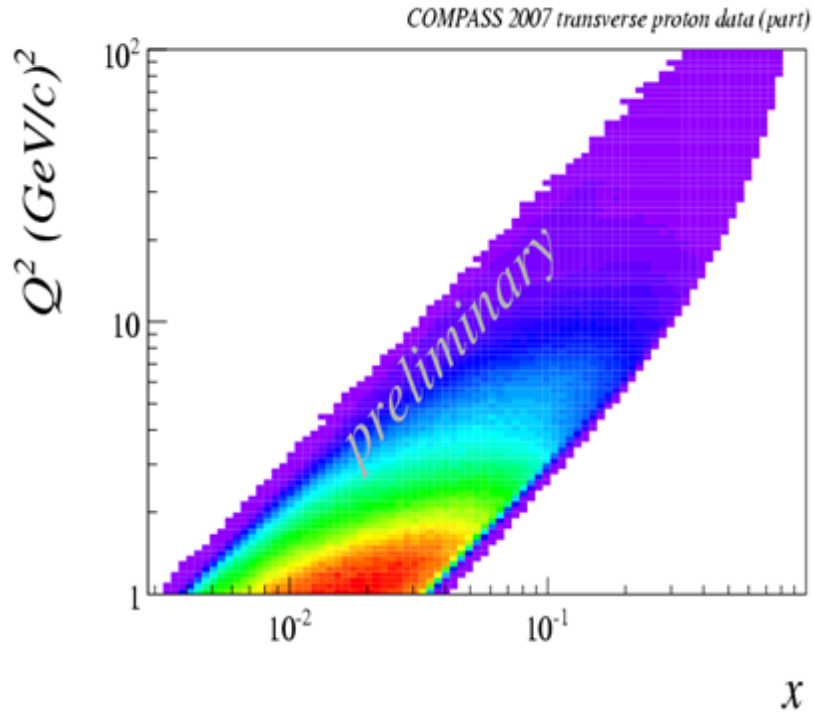
intensity $2 \cdot 10^8$ μ^+/spill (4.8s/16.2s)

SIDIS event selection

DIS cuts: $Q^2 > 1$ (GeV/c)^2
$0.1 < y < 0.9$
$W > 5$ GeV/c^2



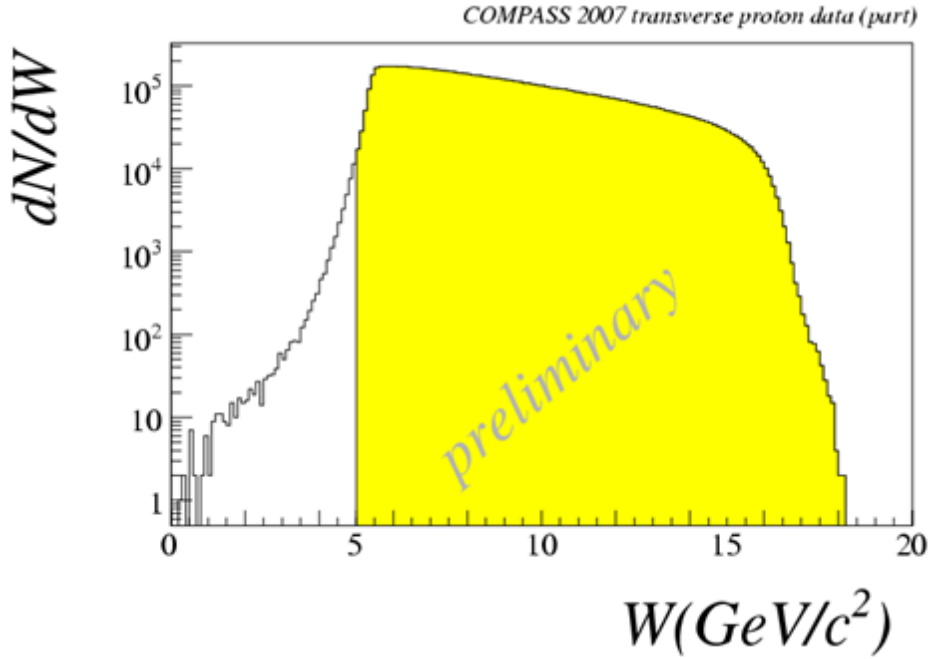


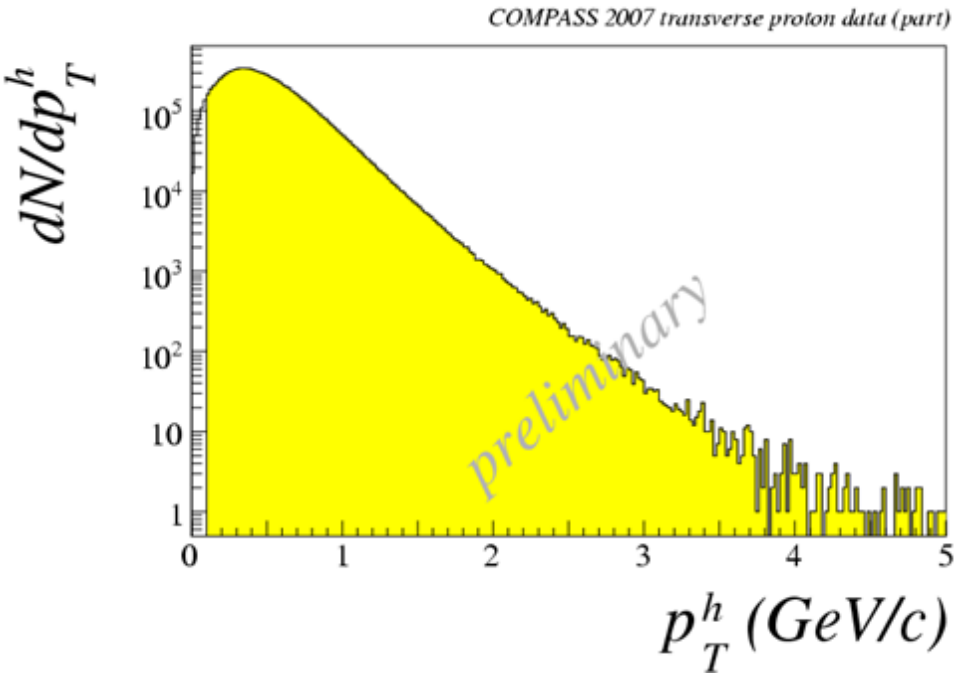


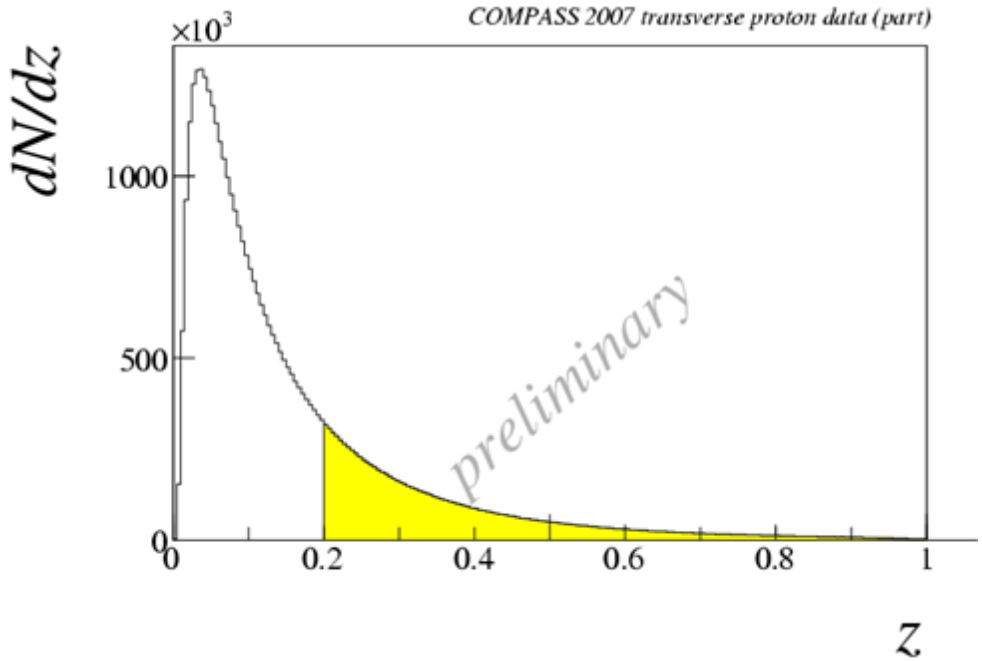
SIDIS event selection

DIS cuts: $Q^2 > 1$ (GeV/c)^2
$0.1 < y < 0.9$
$W > 5$ GeV/c^2

hadron selection: $p^h > 1.5$ GeV/c,
$p_T^h > 0.1$ GeV/c,
$z > 0.2$







results

SIDIS cross-section

18 structure functions

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$+S_\parallel\Big[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]+S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big]$$

$$+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

3 modulations with **unpol** target

3 modulations with **L pol** target

8 modulations (4 LO) with **T pol** target

$$\gamma=\frac{2Mx}{Q}\qquad\varepsilon=\frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$$

$\phi_{h\,(S)}$ hadron (nucleon spin) azimuthal angle in GNS

A Bacchetta, M Diehl, K Goeke, A Metz, P Mulders, M Schlegel (06)

The Structure of the Nucleon

three distribution functions are necessary to describe the quark structure of the nucleon at LO in the collinear case

taking into account the quark intrinsic transverse momentum k_T, at leading order 8 PDFs are needed for a full description

"TMDs"

nucleon polarisation

quark polarisation

	U	L	T	
U	f_1 *number density* q		$f_{1T}^{\perp}$	$\Delta_0^T q$ ***Sivers function***
L		g_1 *helicity* Δq	g_{1T}	
T	$h_1^{\perp}$	$h_{1L}^{\perp}$	h_1 ***transversity*** $h_{1T}^{\perp}$	$\Delta_T q$

SIDIS gives access to all of them

SIDIS cross-section

18 structure functions

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$+\,S_\parallel\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]+S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big]$$

$$+\,|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\,\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

3 modulations with **unpol** target

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$\phi_{h\,(S)}$ hadron (nucleon spin) azimuthal angle in GNS

all measured at COMPASS

A Bacchetta, M Diehl, K Goeke, A Metz, P Mulders, M Schlegel (06)

SIDIS cross-section: unpolarised target

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+ \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + \ldots$$

twist3

3 independent azimuthal modulations

Boer-Mulders DF — **Cahn effect**

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x h H_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{D}^\perp}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x f^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{H}}{z}\right)\right]$$

$$xh = x\tilde{h} + \frac{p_T^2}{M^2}h_1^\perp \qquad xf^\perp = x\tilde{f}^\perp + f_1 \qquad F_{UU}^{\cos\phi_h} \approx \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M} f_1 D_1\right]$$

$$F_{UU}^{\cos 2\phi_h} = \mathcal{C}\left[-\frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h} h_1^\perp H_1^\perp\right]$$

Boer-Mulders DF x Collins FF
+ Cahn effect (twist 4, $1/Q^2$)

SIDIS cross-section: unpolarised target

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}\quad+\ldots$$

measurable from the data collected with polarised target

- both target orientation configurations are used to cancel possible polarisation effects

to extract the asymmetries the azimuthal distributions have to be corrected by the apparatus acceptance

→ **MC simulations**

the final azimuthal distributions are fitted with the function:

$$N_{corr}(\phi_h)=N_0\left(1+A_{\sin\phi_h}\sin\phi_h+A_{\cos\phi_h}\cos\phi_h+A_{\cos 2\phi_h}\cos 2\phi_h\right)$$

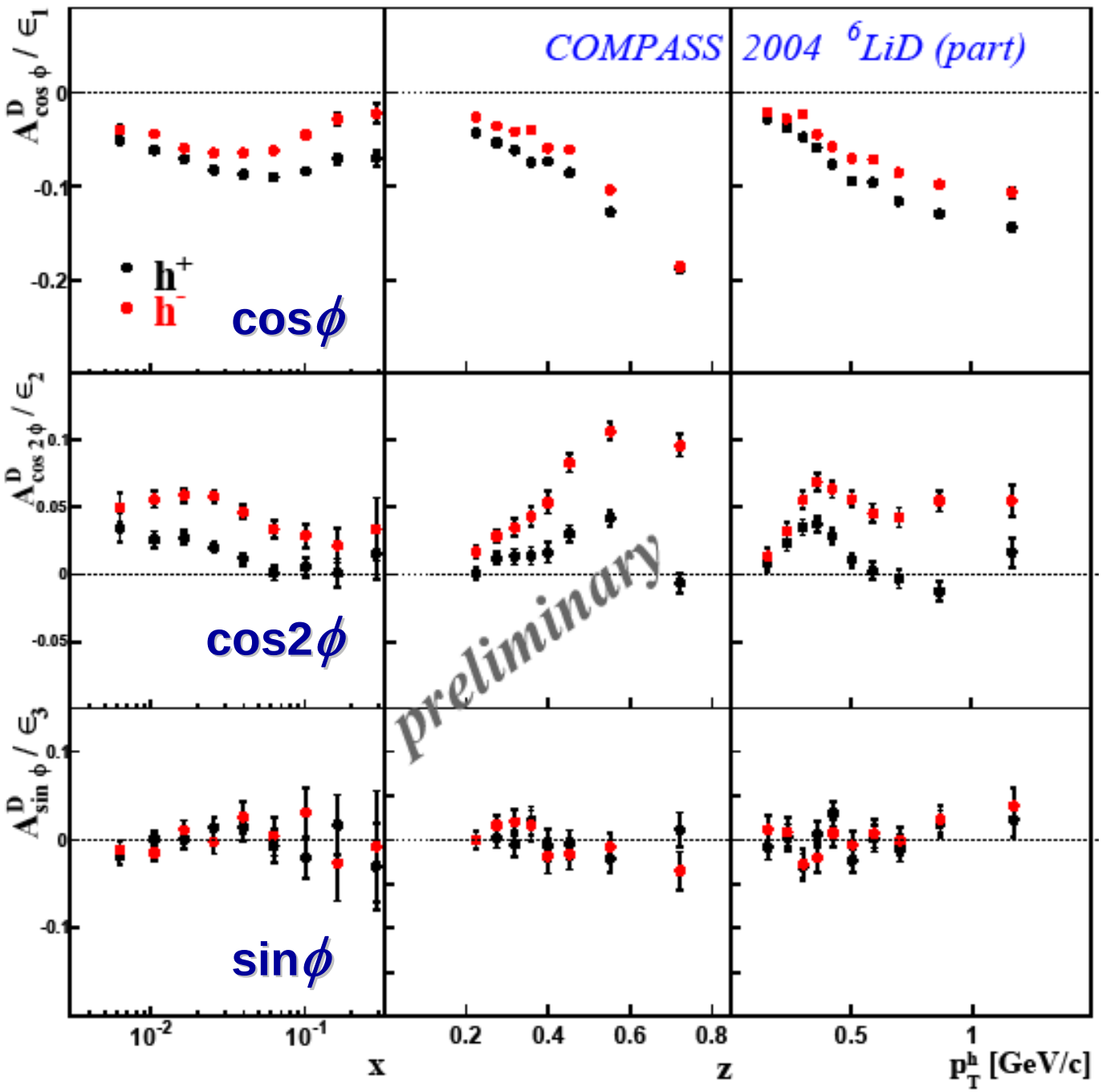
preliminary results from data collected with L and T polarisation of the ^{6}LiD (~d) target

summary of results for d

(Transversity 2008)

clear signal,
different for h^+ and h^-:
non negligible contribution of BM term, different $<k_T>$ for u and d quarks…

clear signal,
different for h^+ and h^-:
important contribution of BM term

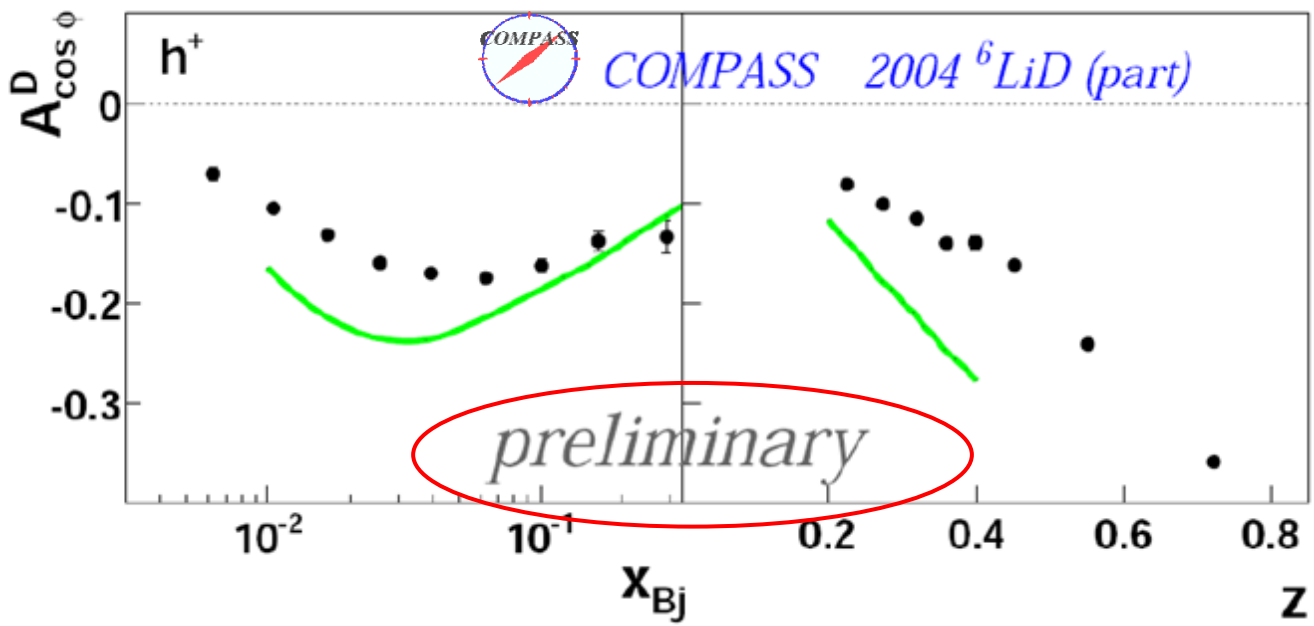


error bars:
statistical errors only

$$\varepsilon_c = \frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2} \qquad \varepsilon_{c2} = \frac{2(2-y)}{1+(1-y)^2} \qquad \varepsilon_s = \frac{2y\sqrt{1-y}}{1+(1-y)^2}$$

comparison with theory

cosϕ amplitude



final results soon

presently, indication that the cos ϕ amplitude will somewhat change

M. Anselmino, M. Boglione, A. Prokudin, C. Türk
Eur. Phys. J. A 31, 373-381 (2007)
does not include Boer – Mulders contribution

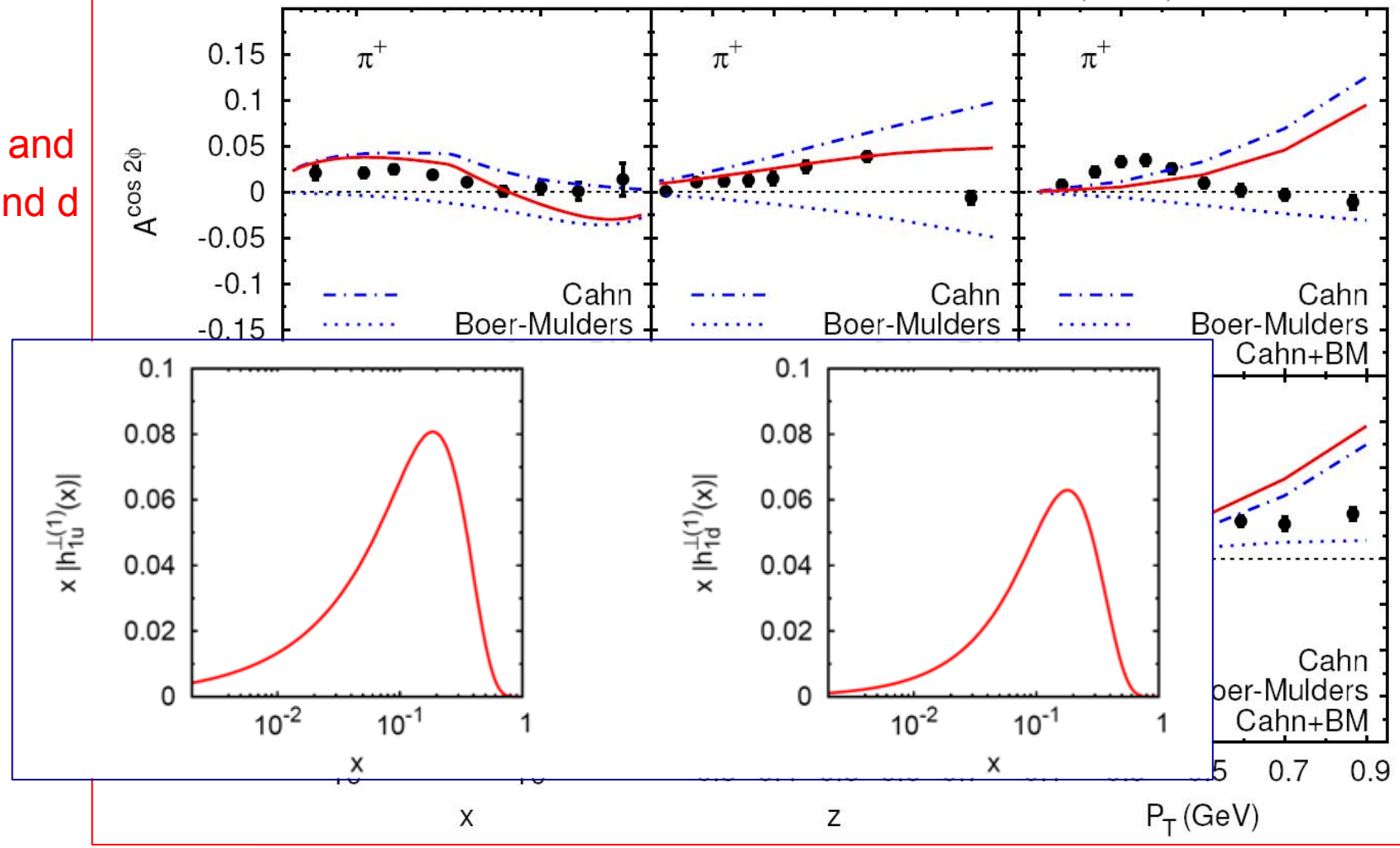
comparison with theory

cos 2ϕ amplitude

fit to COMPASS d and HERMES p and d data

→ *S. Melis*

V. Barone, S. Melis, and A. Prokudin, (2009), 0912.5194



$H_1^{\perp q}(z, p_T^2) = \rho_q^C(z)\,\eta^C(p_T)\,D_1(z, p_T^2)$ M. Anselmino *et al.*, Nucl. Phys. Proc. Suppl. **191**, 98 (2009), 0812.4366

$h_1^{\perp q} = \lambda_q f_{1T}^{\perp q}$ M. Anselmino *et al.*, Eur. Phys. J. **A39**, 89 (2009), 0805.2677

$\langle k_T^2 \rangle = 0.25\ \text{GeV}^2\,, \quad \langle p_T^2 \rangle = 0.20\ \text{GeV}^2$ M. Anselmino *et al.*, Phys. Rev. **D71**, 074006 (2005)

unpolarised azimuthal Asymmetries

- **deuteron: final results soon**
- **proton: COMPASS II proposal**

longitudinal Spin Asymmetries

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \ldots$$

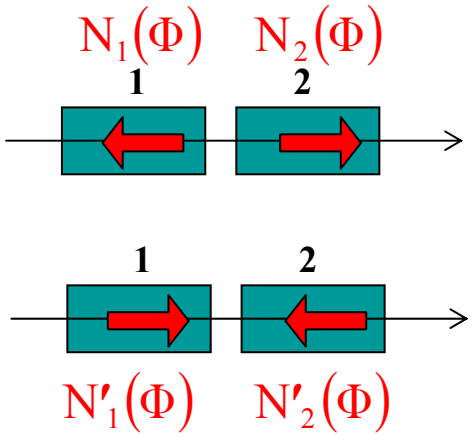
$$+ S_\parallel \lambda_e \left[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos\phi_h\, F_{LL}^{\cos\phi_h} \right]$$

$$+ S_\parallel \left[\sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon \sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h} \right] + \ldots$$

$$\frac{d\sigma^{\leftarrow\Rightarrow} - d\sigma^{\leftarrow\Leftarrow}}{|S_\parallel|(d\sigma^{\leftarrow\Rightarrow} + d\sigma^{\leftarrow\Leftarrow})}$$

extraction of the L Spin Asymmetries

"standard" COMPASS method of the "ratio products"



$$F(\phi_h)=\frac{N_1(\phi_h)}{N'_1(\phi_h)}\cdot\frac{N'_2(\phi_h)}{N_2(\phi_h)}$$

$$a(\phi_h)=\frac{1}{S_{\|,1}+S_{\|,2}+S'_{\|,1}+S'_{\|,2}}\cdot\{F(\phi_h)-1\} \quad \cong \quad \frac{\sigma_L(\phi_h)}{\sigma_U(\phi_h)}$$

$$a(\phi_h)= a^{\text{const}} + a^{\sin\phi_h}\sin\phi_h + a^{\sin 2\phi_h}\sin 2\phi_h + a^{\sin 3\phi_h}\sin 3\phi_h + a^{\cos\phi_h}\cos\phi_h$$

- $a^{\text{const}} \rightarrow F_{LL}$: helicity $g_{1L}D_1$
- $a^{\sin\phi_h}\sin\phi_h \rightarrow F_{UL}^{\sin\phi_h}$ (twist 3)
  - Sivers $f_{1T}^{\perp}D_1$: $F_{UT,T}^{\sin(\phi_h-\phi_S)}$
  - transversity $h_1 H_1^{\perp}$: $F_{UT}^{\sin(\phi_h+\phi_S)}$
- $a^{\sin 2\phi_h}\sin 2\phi_h \rightarrow F_{UL}^{\sin 2\phi_h}$: worm-gear $h_{1L}^{\perp}H_1^{\perp}$
- $a^{\sin 3\phi_h}\sin 3\phi_h \rightarrow F_{UT}^{\sin(3\phi_h-\phi_S)}$: pretzelosity $h_{1T}^{\perp}H_1^{\perp}$
- $a^{\cos\phi_h}\cos\phi_h \rightarrow F_{LL}^{\cos\phi_h}$ (twist 3)
  - $\sin\theta_\gamma \sim \frac{M}{Q}$
  - $F_{LT}^{\cos(\phi_h-\phi_S)}$: worm-gear $g_{1T}D_1$

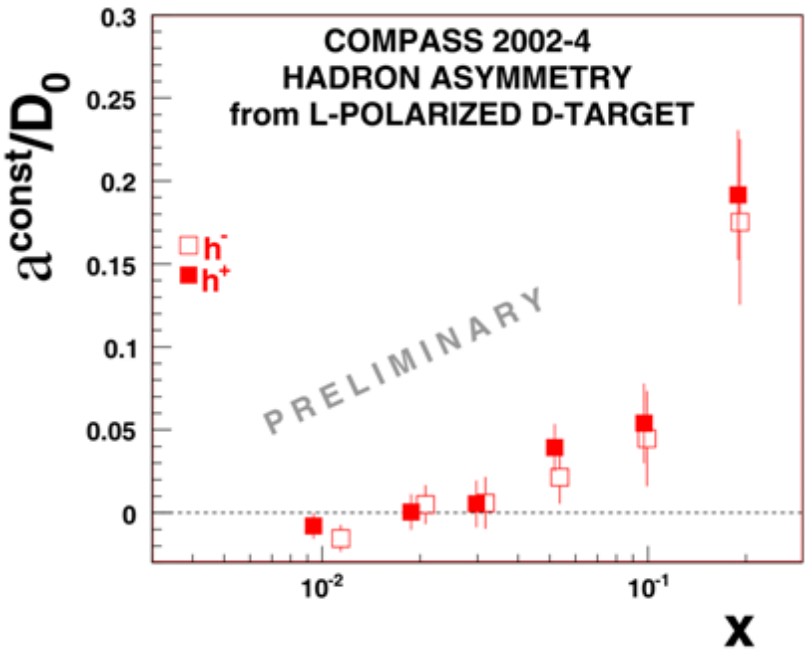
preliminary results from the 2002-2004 d data (Dubna-Spin 2009)

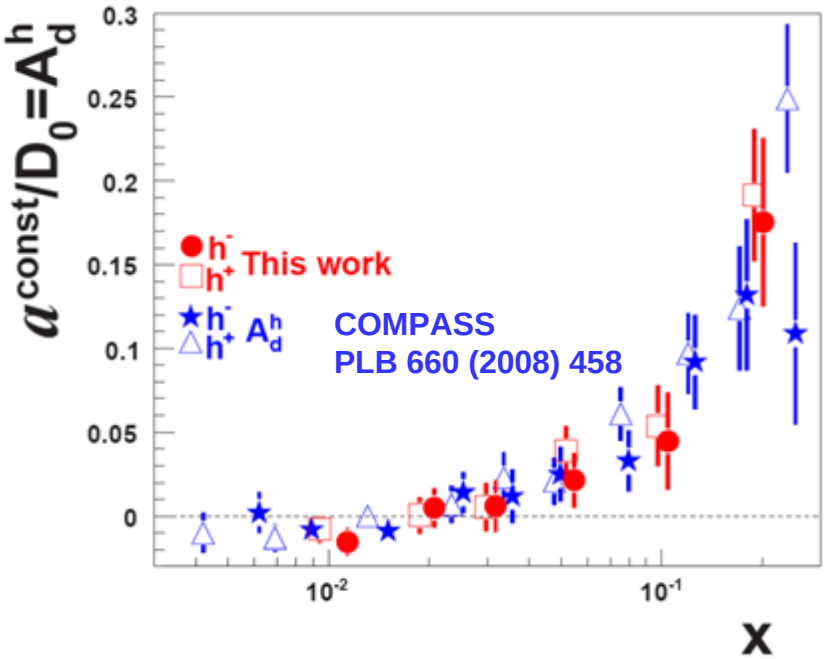
deuteron results

a^{const} F_{LL}

helicity $g_{1L} D_1$

$$\frac{a^{const}(x)}{D_0} = A_d^h(x) \qquad D_0 = |P_\mu| \sqrt{1-\varepsilon^2}$$





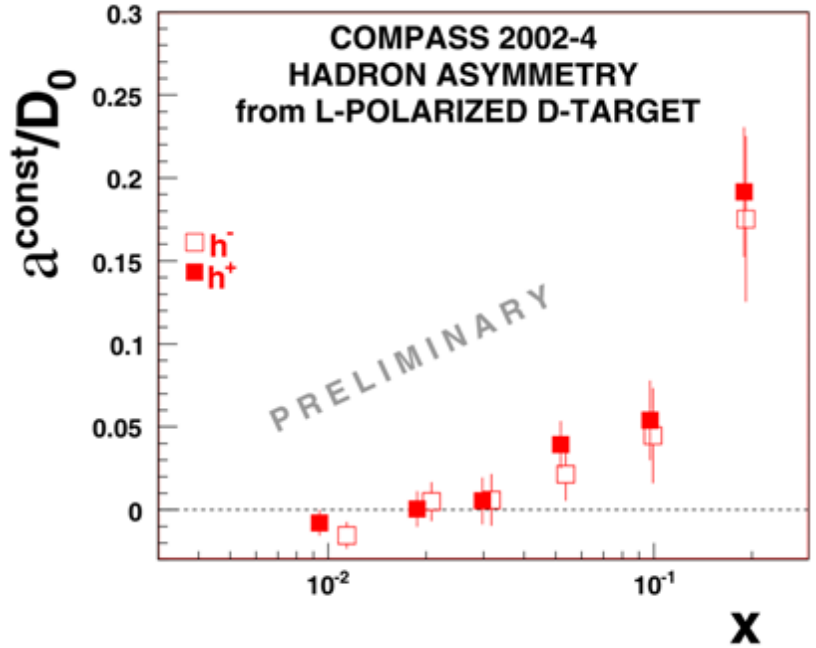
good agreement → internal consistency of the COMPASS results

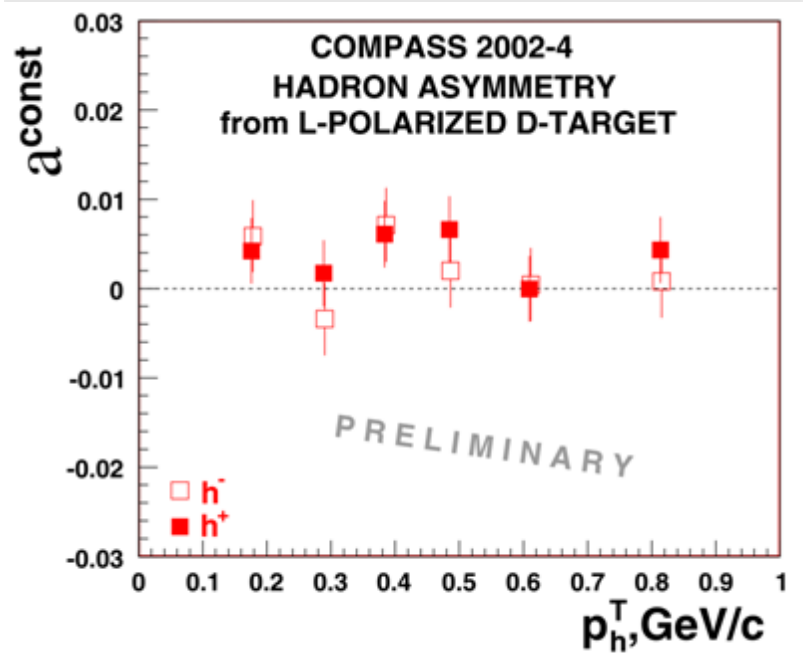
deuteron results

a^{const} $\quad F_{LL}$

helicity $g_{1L} D_1$

$$\frac{a^{\text{const}}(x)}{D_0} = A_d^h(x) \qquad D_0 = |P_\mu| \sqrt{1-\varepsilon^2}$$





good agreement → internal consistency of the COMPASS results

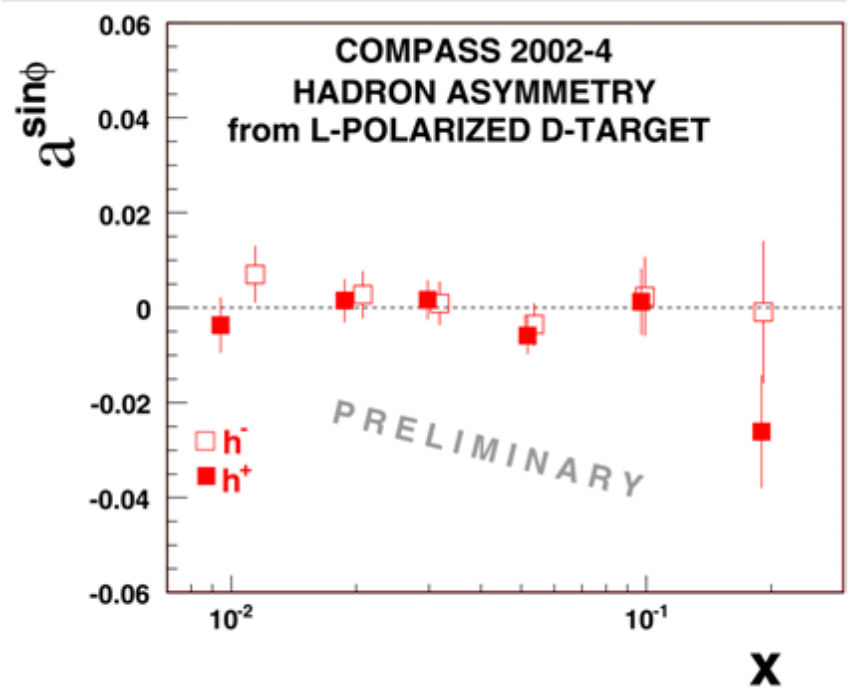
no strong z or p_h^T dependence

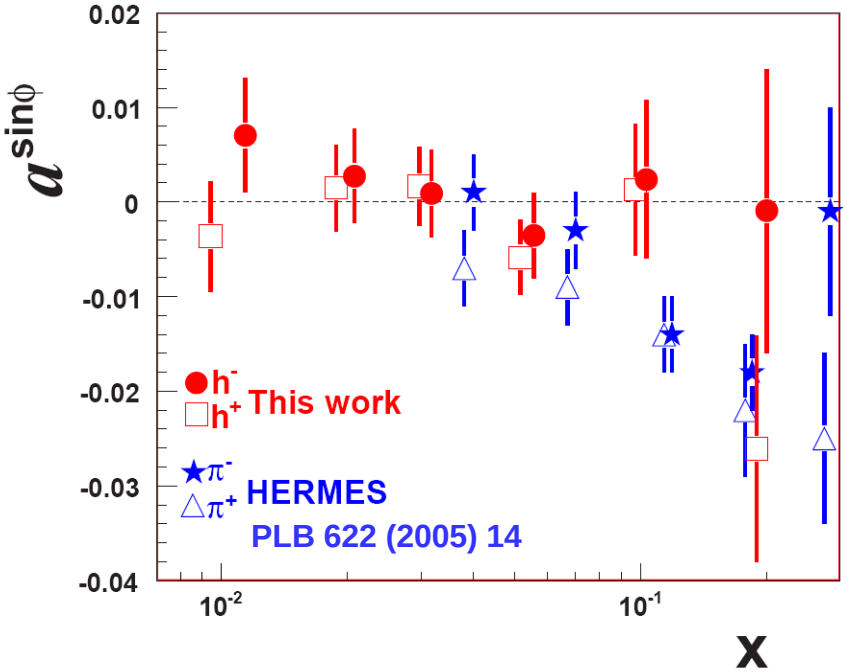
deuteron results

$a^{\sin\phi_h}$ $\quad F_{UL}^{\sin\phi_h}$ (twist 3)

$F_{UT,T}^{\sin(\phi_h-\phi_S)}$ Sivers $f_{1T}^{\perp} D_1$

$F_{UT}^{\sin(\phi_h+\phi_S)}$ transversity $h_1 H_1^{\perp}$



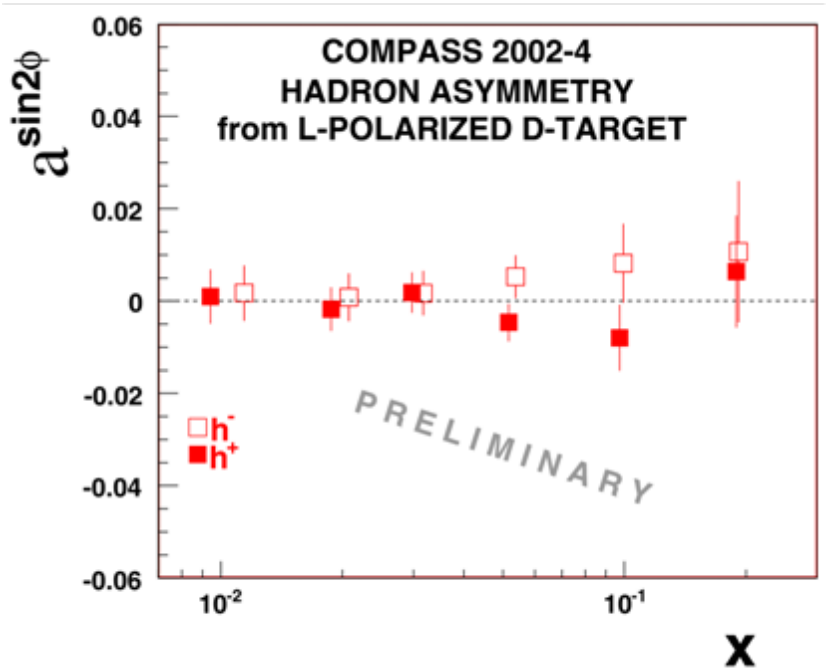


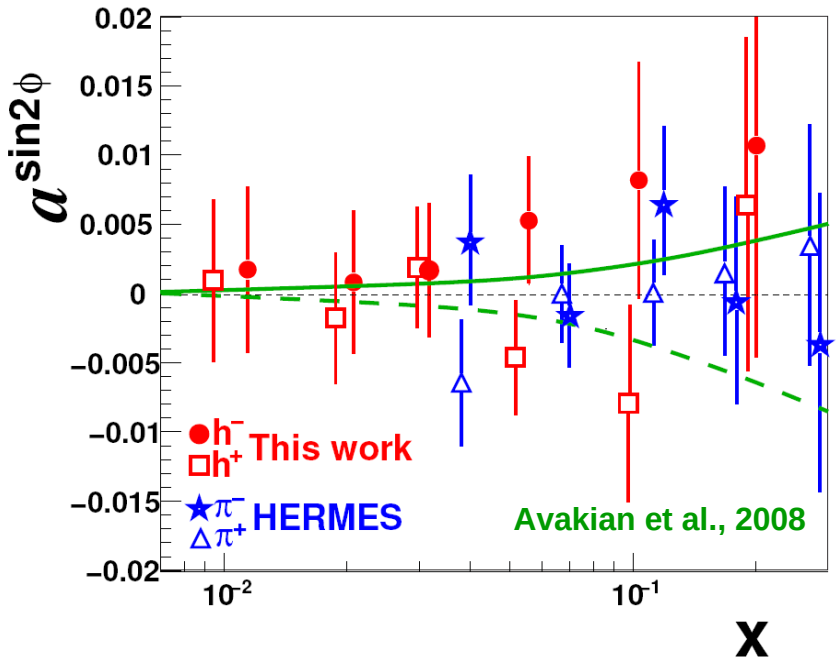
no evident x dependence

different kinematics

deuteron results

$a^{\sin 2\phi_h}$ $F_{UL}^{\sin 2\phi_h}$ worm-gear $h_{1L}^{\perp} H_1^{\perp}$





small, consistent with zero within the errors

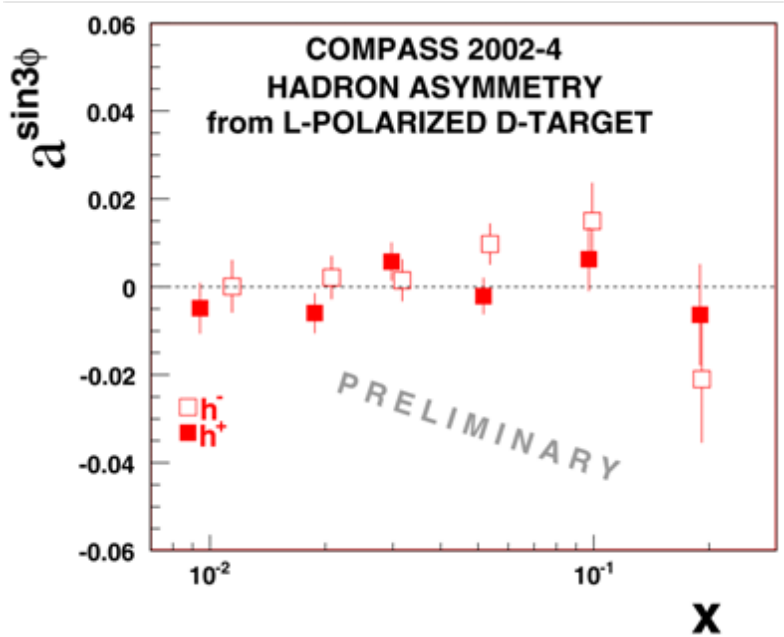
deuteron results

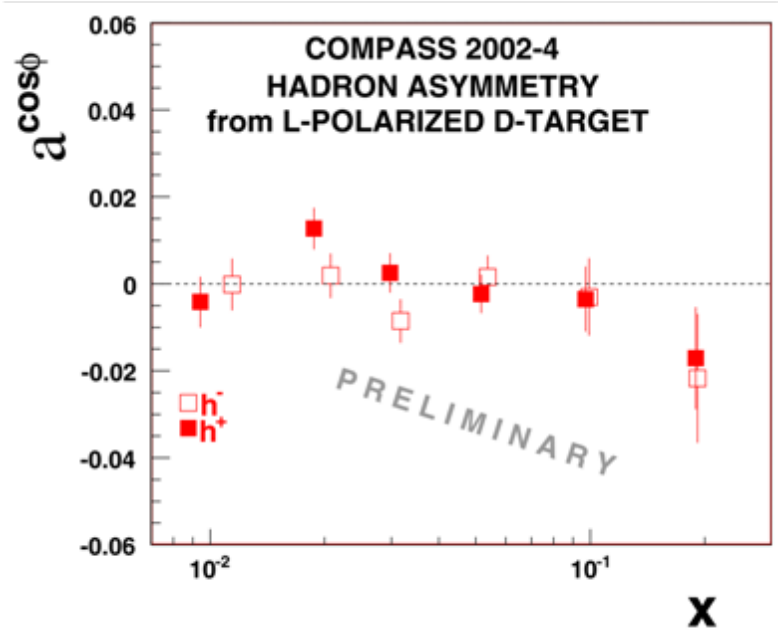
$a^{\sin 3\phi_h}$ $F_{UT}^{\sin(3\phi_h-\phi_S)}$

pretzelosity $h_{1T}^{\perp} H_1^{\perp}$

$a^{\cos\phi_h}$ $F_{LL}^{\cos\phi_h}$ (twist 3) $F_{LT}^{\cos(\phi_h-\phi_S)}$

worm-gear $g_{1T} D_1$





compatible with zero, in agreement with the COMPASS measurements with the T polarised d target

next: extract the same asymmetries from the 2007 p data

transverse Spin Asymmetries

8 modulations
(4 LO)

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \quad ...$$

Collins asymmetry

$$+ |\boldsymbol{S}_\perp| \Big[\sin(\phi_h - \phi_S) \left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \right)$$

$$+ \varepsilon \sin(\phi_h + \phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon \sin(3\phi_h - \phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+ \sqrt{2\,\varepsilon(1+\varepsilon)} \sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)} \Big]$$

$$+ |\boldsymbol{S}_\perp| \lambda_e \Big[\sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)} \cos\phi_S\, F_{LT}^{\cos\phi_S}$$

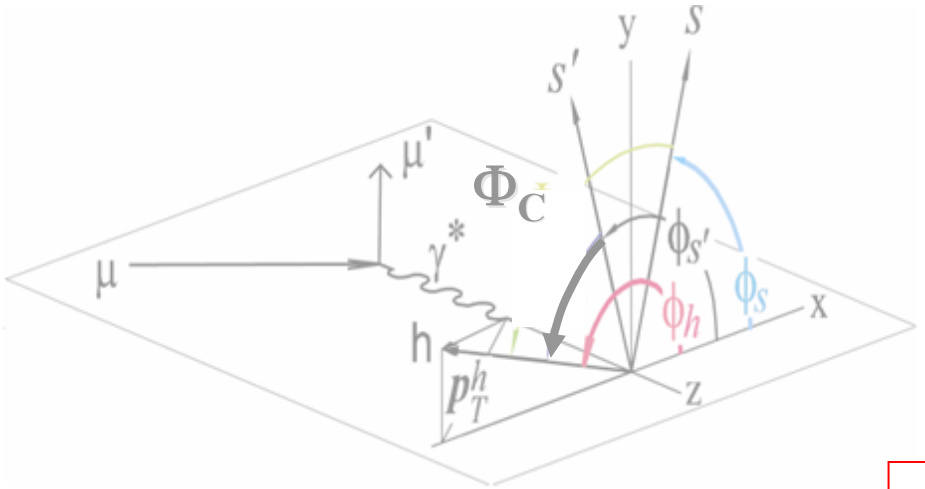
$$+ \sqrt{2\,\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)} \Big] \Big\},$$

Collins asymmetry

if transversity PDFs and Collins FFs different from zero

modulation in the azimuthal distribution of the final state hadrons

$$N_h^{\pm}(\Phi_C) = N_h^0 \cdot \left[1 \pm P_T \cdot D_{NN} \cdot A_{Coll} \cdot \sin\Phi_C\right]$$



$$\Phi_C = \phi_h + \phi_S - \pi$$

ϕ_h azimuthal angle of the hadron,

ϕ_S azimuhtal angle of the spin of the nucleon

transversity — "Collins FF"

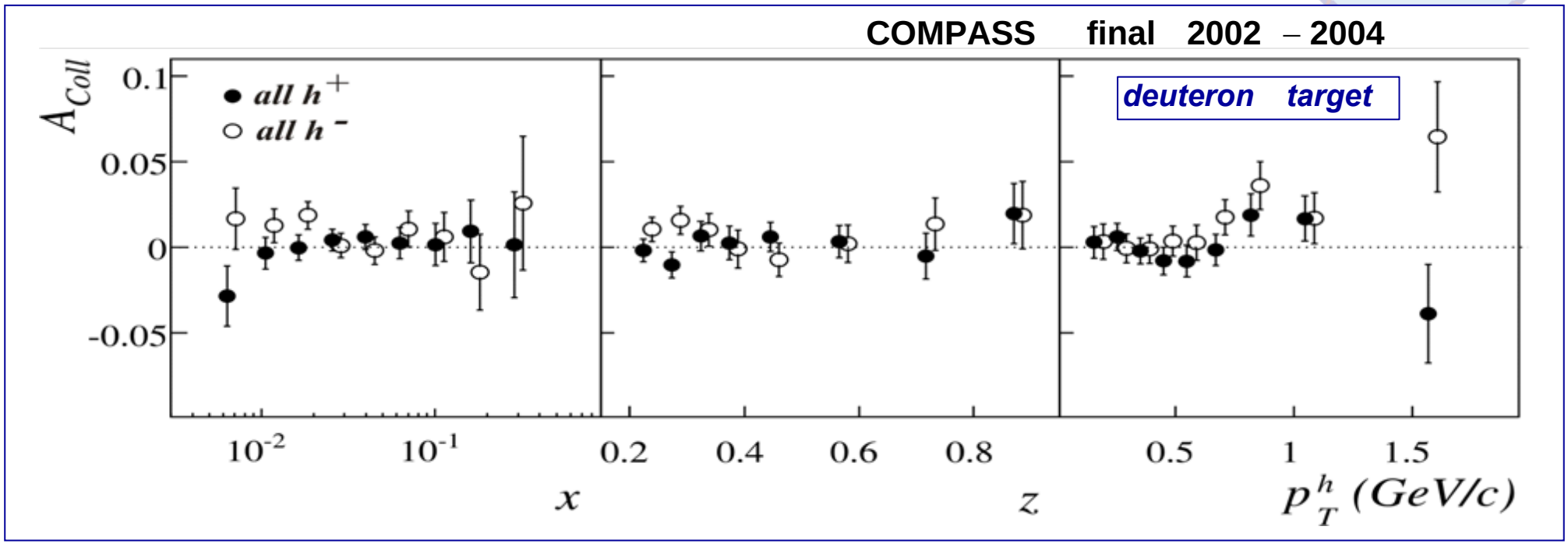
$$A_{Coll} \approx \frac{\sum_q e_q^2 \, \Delta_T q \otimes \Delta_T^0 D_q^h}{\sum_q e_q^2 \, q \otimes D_q^h}$$

first measured by HERMES (proton target) and COMPASS (deuteron target)

different from zero ***compatible with zero***

Collins asymmetry

COMPASS d results: *PRL 94 (2005) 202002, NPB 765 (2007) 31, PLB 673 (2009) 127*



understood as u – d cancellation

the COMPASS d, HERMES p, and BELLE $e^+e^- \to \pi^+\pi^- X$ **data**

are well described in global fits [M. Anselmino et al.]

→ first extractions of the Collins FFs and the transversity PDFs, and tensor charge

energy dependence?

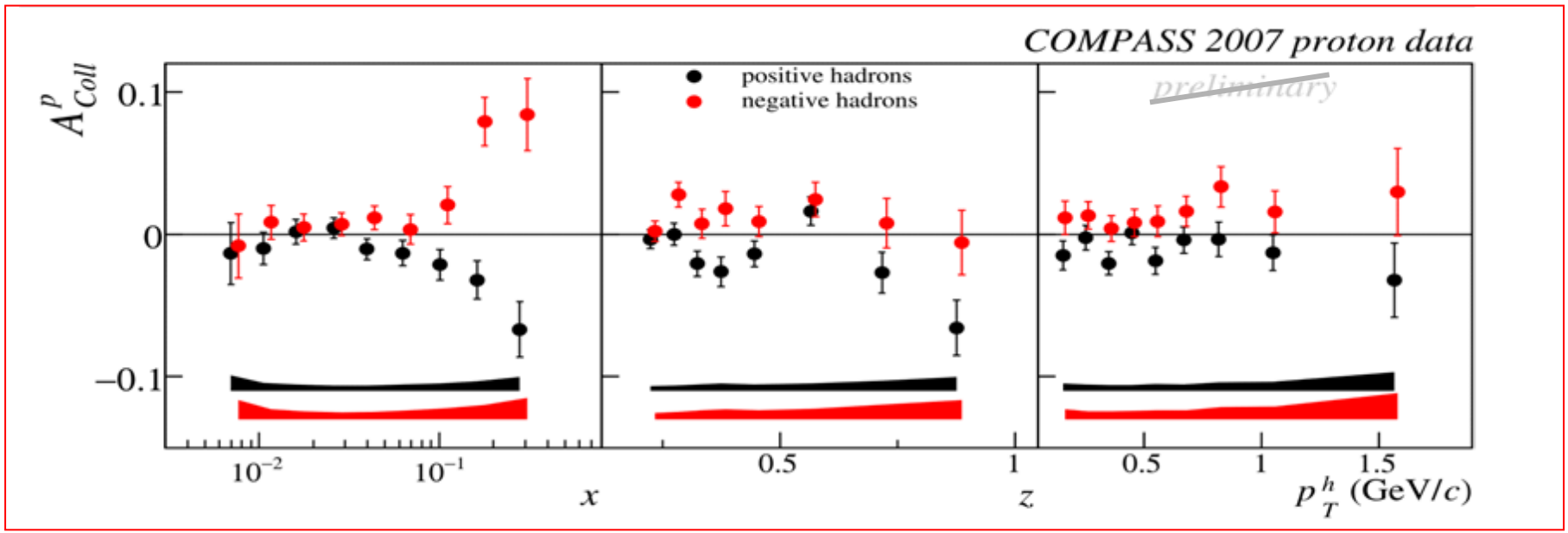
COMPASS p results

Collins asymmetry - proton

the analysis of the 2007 proton run is over

the paper has been submitted **CERN-PH-EP-2010-013, May 2010, arXiv:1005.5609 [hep-ex]**

final results very much the same as presented at DIS 2009



- **at small x,** the asymmetries are **compatible with zero**
- **large signal in the valence region** of opposite sign for positive and negative hadrons

same sign and ~ strength as HERMES: ***not obvious!***

Collins asymmetry - proton

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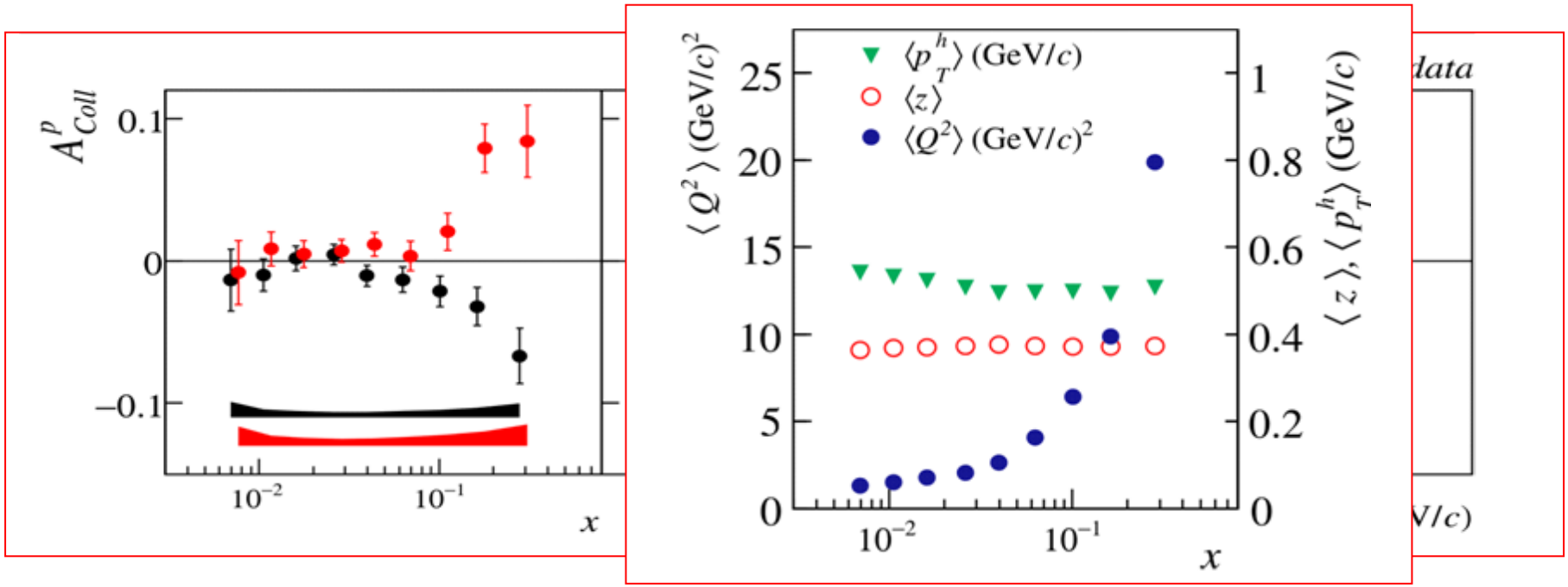

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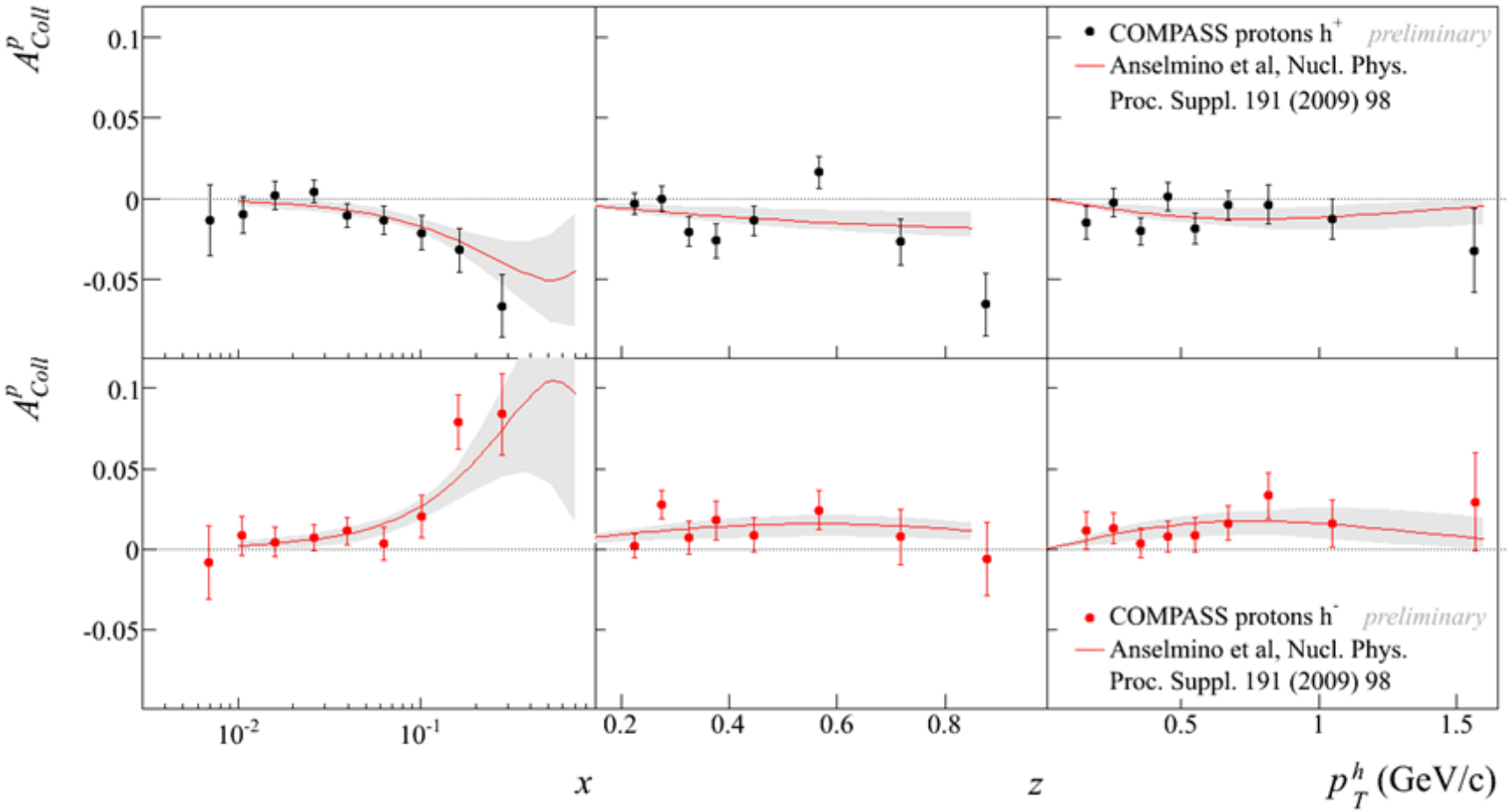
- **large signal in the valence region** of opposite sign for positive and negative hadrons

same sign and ~ strength as HERMES: ***not obvious!***

Collins asymmetry - proton

comparison with predictions from fit to the HERMES proton, COMPASS deuteron, BELLE data



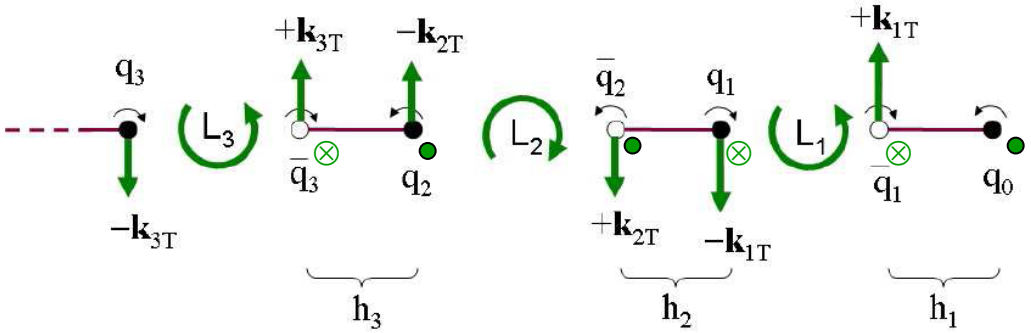
our data **support the assumption of a weak Q^2 dependence in the present energy range**

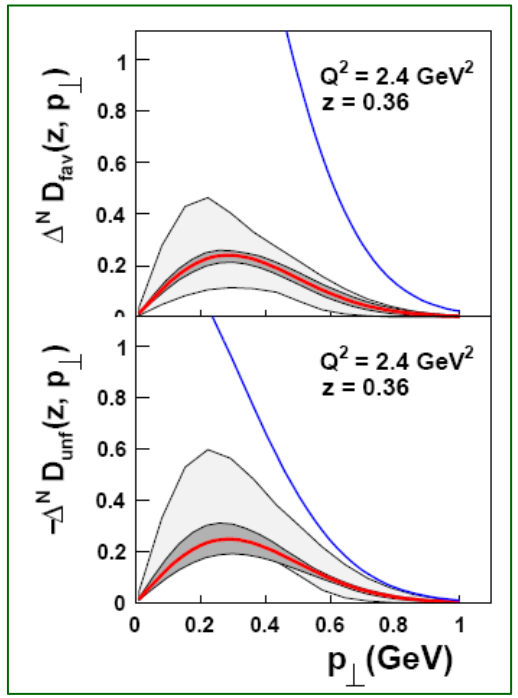
Collins asymmetry - proton

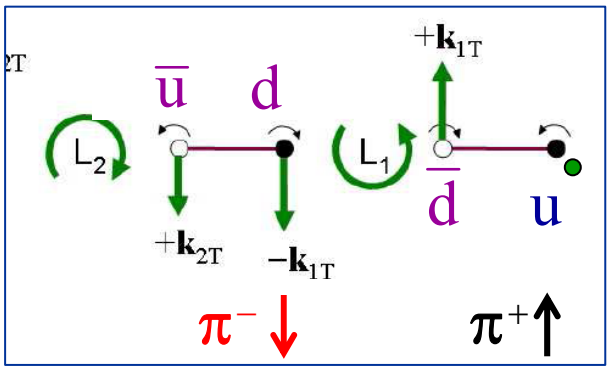
SIGN in agreement with the

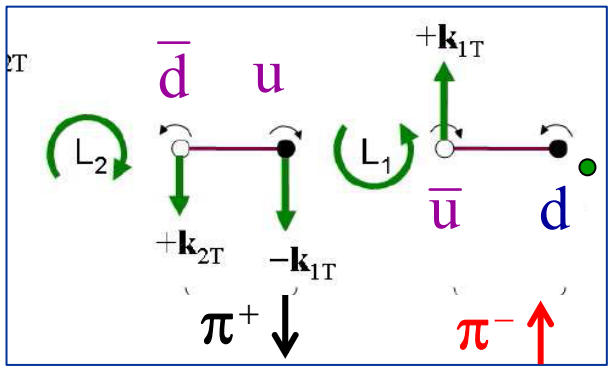
“recursive fragmentation model with quark spin”

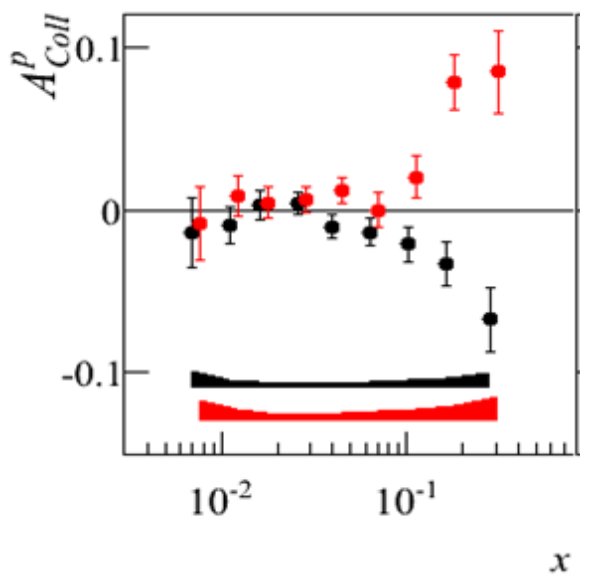
[X. Artru, arXiv:1001.1061] $^3P_0$











Collins FFs: favored ~ - unfavored

transversity PDFs: substantially different for u and d

Transversity PDF

can be measured in SIDIS off transversely polarised targets via
"quark polarimetry"

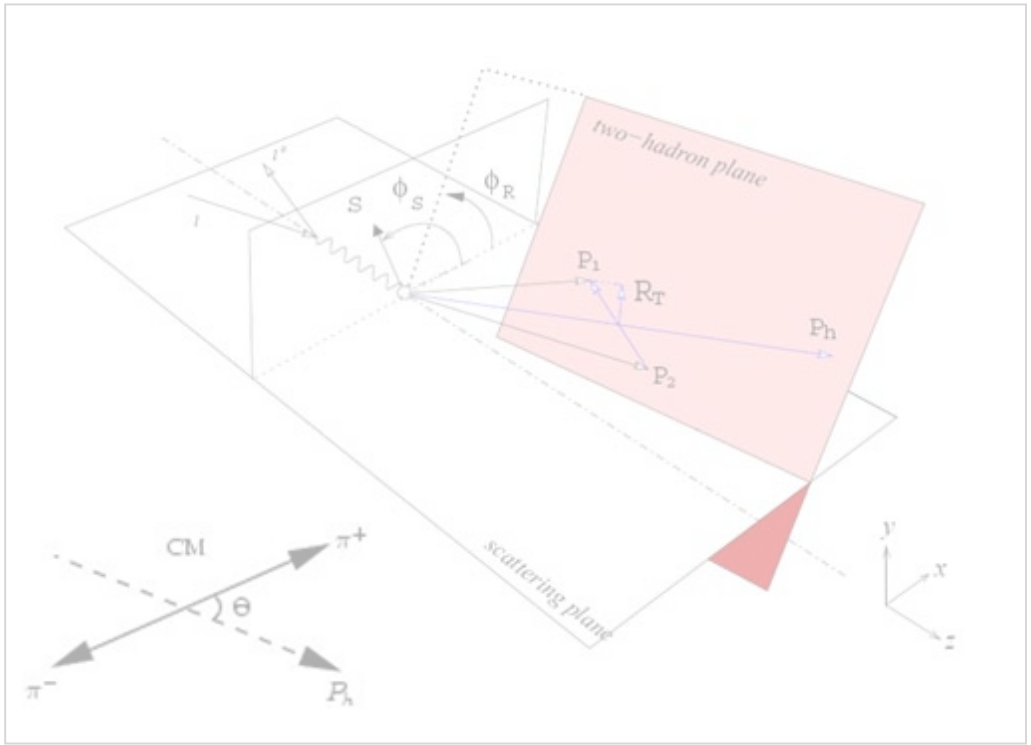
$l\,N^{\uparrow} \to l'\,h\,X$ **"Collins" asymmetry**
"Collins" Fragmentation Function

$l\,N^{\uparrow} \to l'\,hh\,X$ **"two-hadron" asymmetry**
"Interference" Fragmentation Function

$l\,N^{\uparrow} \to l'\,\Lambda X$ **Λ polarisation**
Fragmentation Function of $q^{\uparrow} \to \Lambda$

all explored in COMPASS

Two Hadron Asymmetry



azimuthal asymmetry in

$$\phi_{RS} = \phi_{R\perp} - \phi_S,$$

$\phi_{R\perp}$ is the azimuthal angle of the plane defined by the two hadrons

$R = (z_1 p_2 - z_2 p_1)/(z_1 + z_2)$

$$N^{\pm}(\Phi_{RS}) = N^0 \cdot \{1 \pm A \cdot \sin\Phi_{RS}\}$$

Interference Fragmentation Function

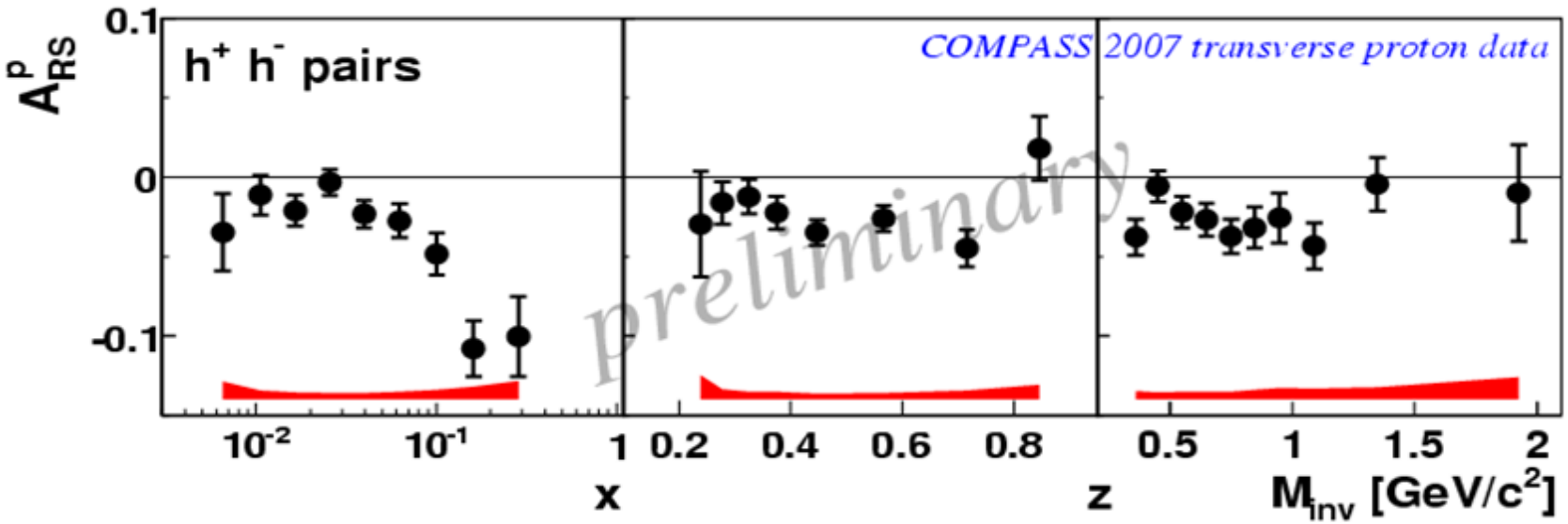
BELLE

$$A_{RS} = \frac{1}{f \cdot P_T \cdot D_{NN}} \cdot A = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_q^{2h}(z, M_h^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^{2h}(z, M_h^2)}$$

Two Hadron Asymmetry

deuteron: compatible with zero at all x, for all the combinations we have tested

proton preliminary results (DIS2009)



$x_F > 0.1$
$z_{1,2} > 0.1$
$Z = z_1 + z_2 < 0.9$
$R_T > 0.07$ GeV/c

large signal in the valence region, no particular trend in z and M_{inv}

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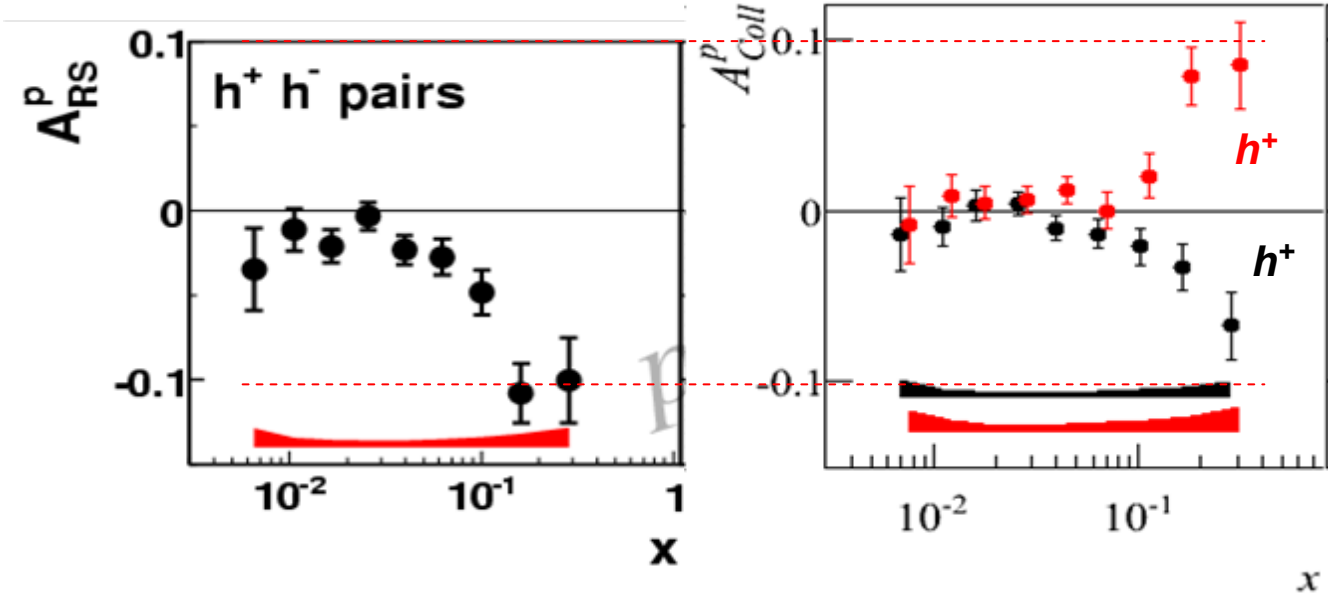

large signal in the valence region, no particular trend in z and M_{inv}

sign in agreement with the Collins asymmetry,
strengh ~ larger than the Collins asymmetry

in qualitative agreement with the "recursive model" if $\Delta_T u \sim -\Delta_T d$

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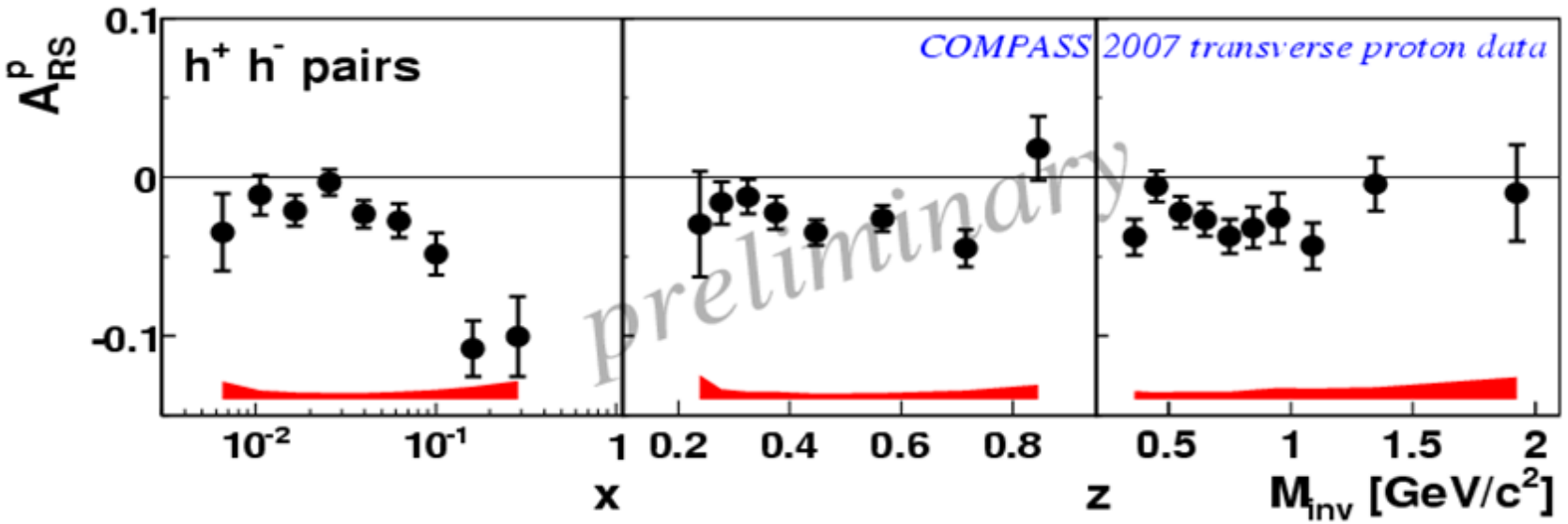

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in qualitative agreement with the "recursive model" if $\Delta_T u \sim -\Delta_T d$

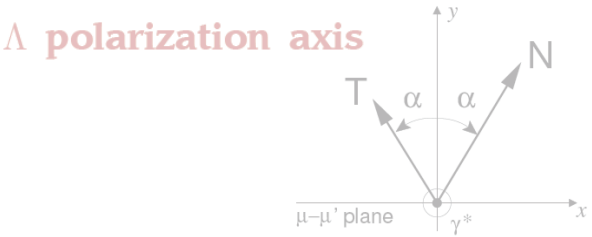
larger than measured by HERMES

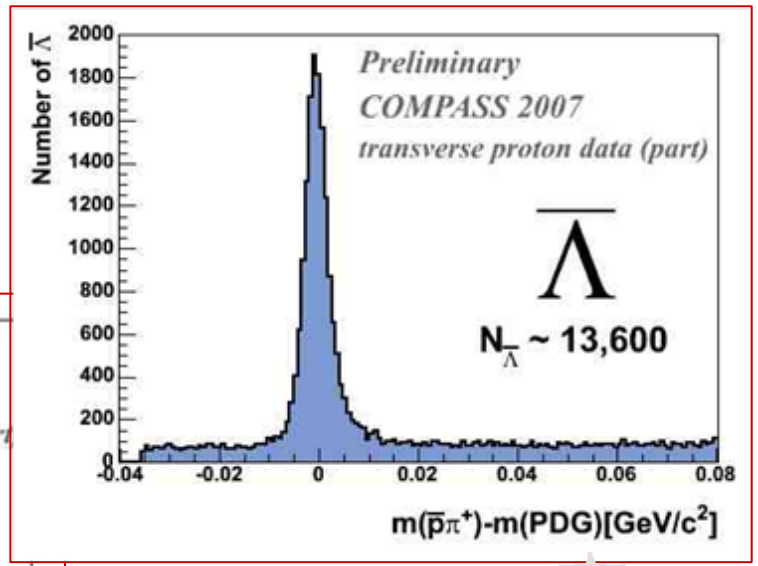
difficult to describe both sets of results at the same time
[Bacchetta et al., Mah et al.]

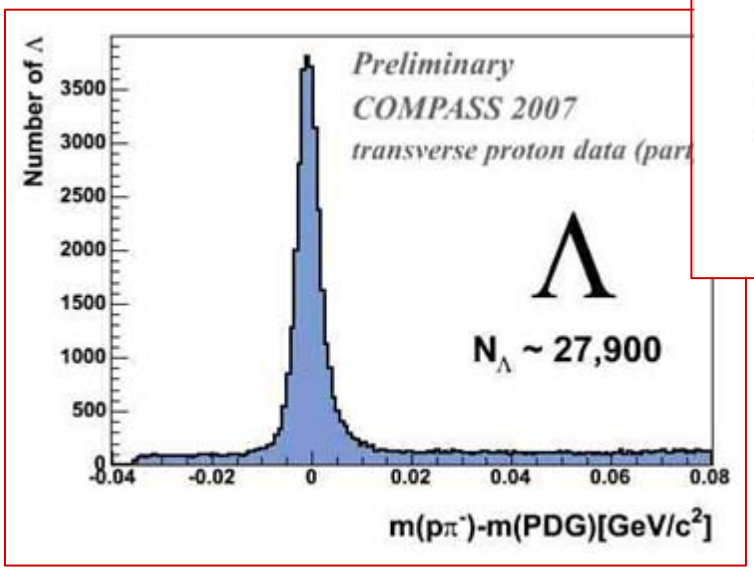
Λ polarisation

$\mu N^{\uparrow} \to \mu' \Lambda X \qquad \mu N^{\uparrow} \to \mu' \bar{\Lambda} X$

$$P_{T,exp}^{\Lambda} = f P_N D(y) \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T D_{\Lambda/q}(z)}{\sum_q e_q^2 q(x) D_{\Lambda/q}(z)}$$



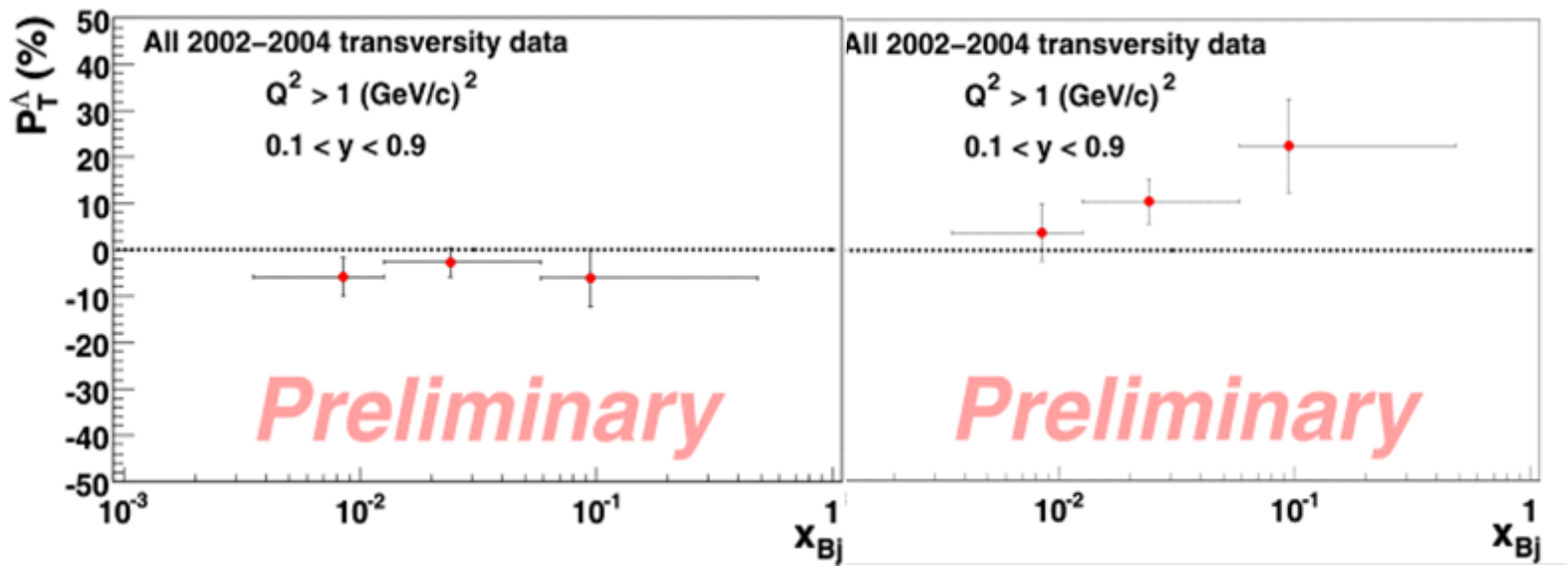




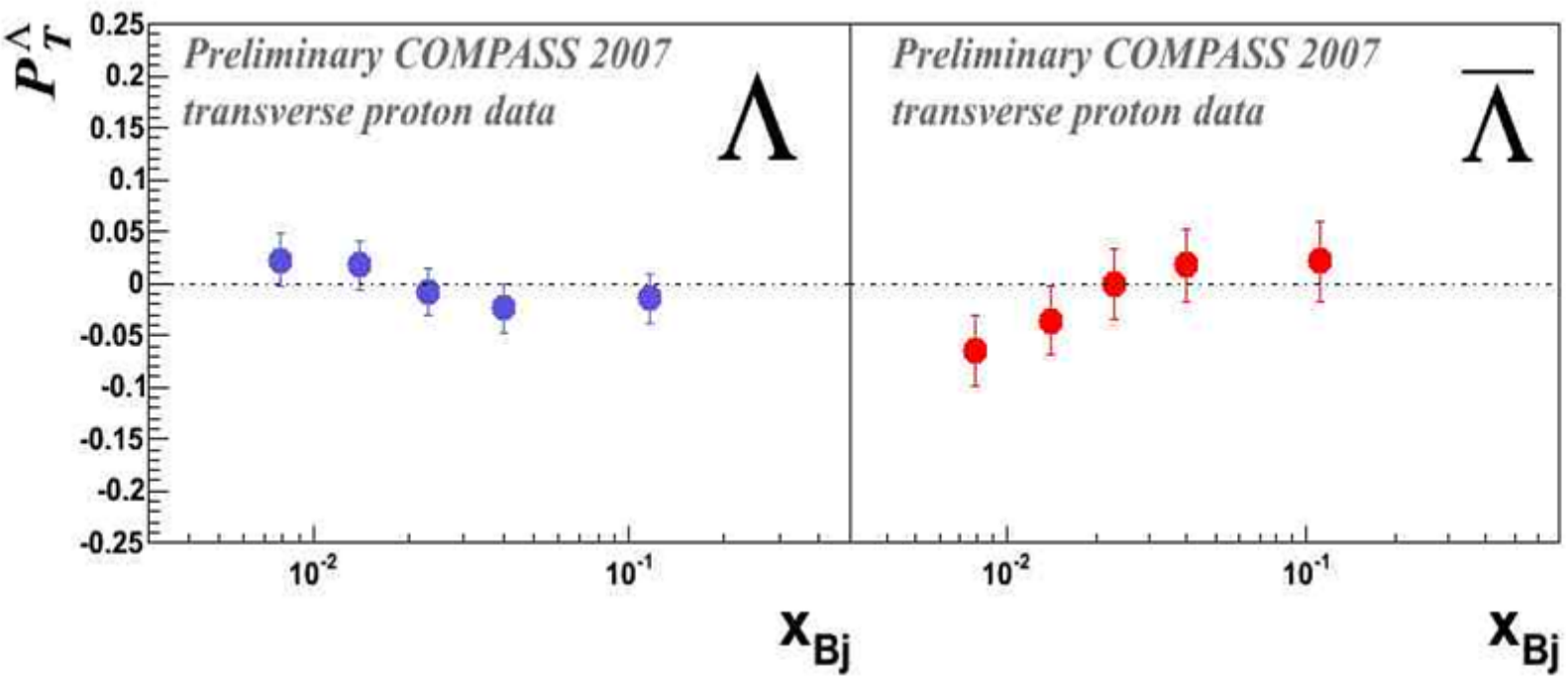
2007 proton data

p_T > 23 MeV/c to exclude e^+e^- pairs
p and pion momenta > 1 GeV/c
Q^2 > 1 (GeV/c)^2
0.1 < y < 0.9
Use of RICH (2007 data)
Λ decay distance $D_\Lambda > 7\ \sigma_D$
Collinearity < 10 mrad

Λ polarisation



deuteron



proton

transverse Spin Asymmetries

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \quad ...$$

$$+ |\boldsymbol{S}_\perp| \Big[\sin(\phi_h - \phi_S) \Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \Big)$$

$$+ \varepsilon \sin(\phi_h + \phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon \sin(3\phi_h - \phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+ \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin(2\phi_h - \phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)} \Big]$$

$$+ |\boldsymbol{S}_\perp| \lambda_e \Big[\sqrt{1-\varepsilon^2}\, \cos(\phi_h - \phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos\phi_S\, F_{LT}^{\cos\phi_S}$$

$$+ \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos(2\phi_h - \phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)} \Big] \Big\},$$

Sivers asymmetry

Collins asymmetry

Sivers asymmetry

$$A_{Siv} \approx \frac{\sum_q e_q^2 \, f_{1T}^{\perp q} \otimes D_1^q}{\sum_q e_q^2 \, f_1 \otimes D_1^q}$$

- **strong signal seen by HERMES for π^+ and K^+ on protons**
- **no signal seen by COMPASS on deuterons**
  interpreted as u- and d-quark cancellation (as for the Collins asymmetry)

→ **first extractions of the Sivers function from HERMES (and COMPASS) data**
good description of the experimental results

no energy dependence expected

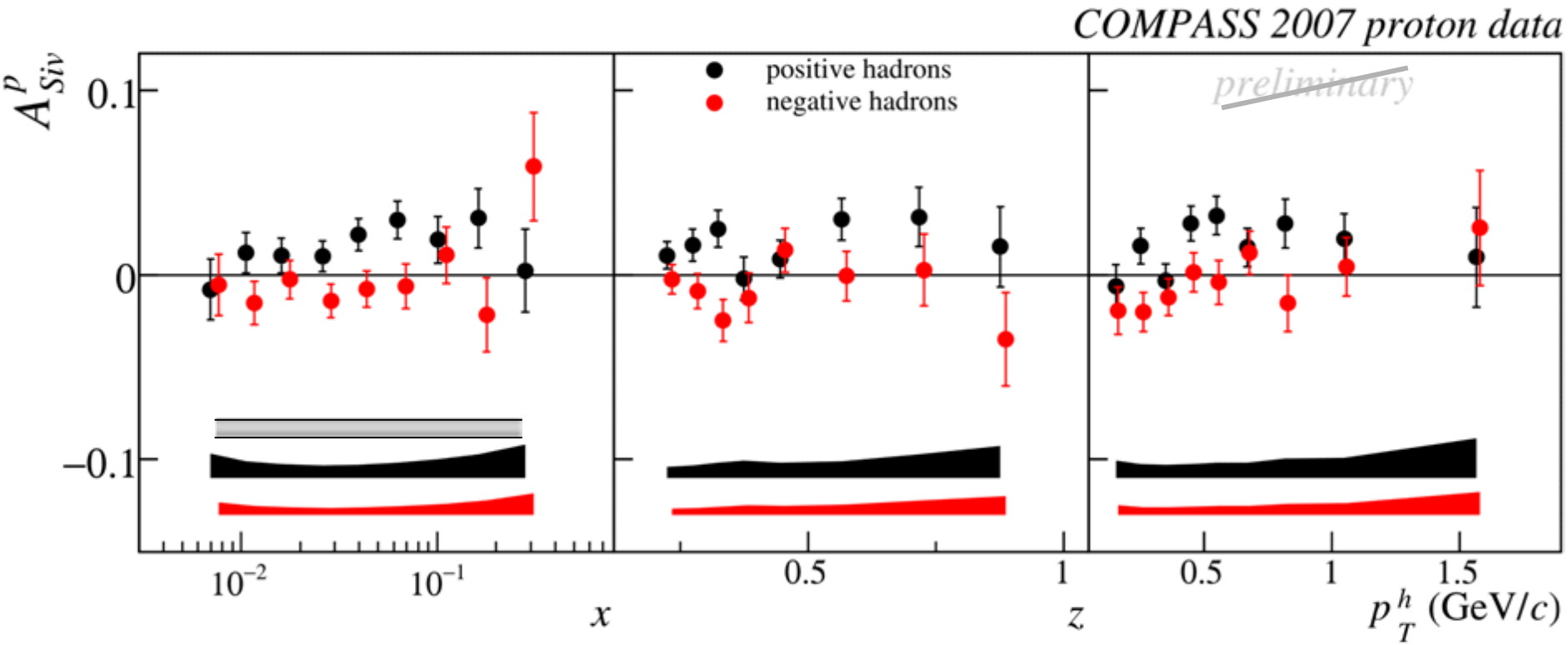
first COMPASS results on p
from part of the 2007 data presented at Transversity 2008**:**
compatible with zero

now the analysis of the 2007 data is over

new final results (DIS2010)
more statistics, further data taking periods
paper sent for publication CERN-PH-EP-2010-013, arXiv:1005.5609 [hep-ex]

Sivers asymmetry - proton

new final results CERN-PH-EP-2010-013

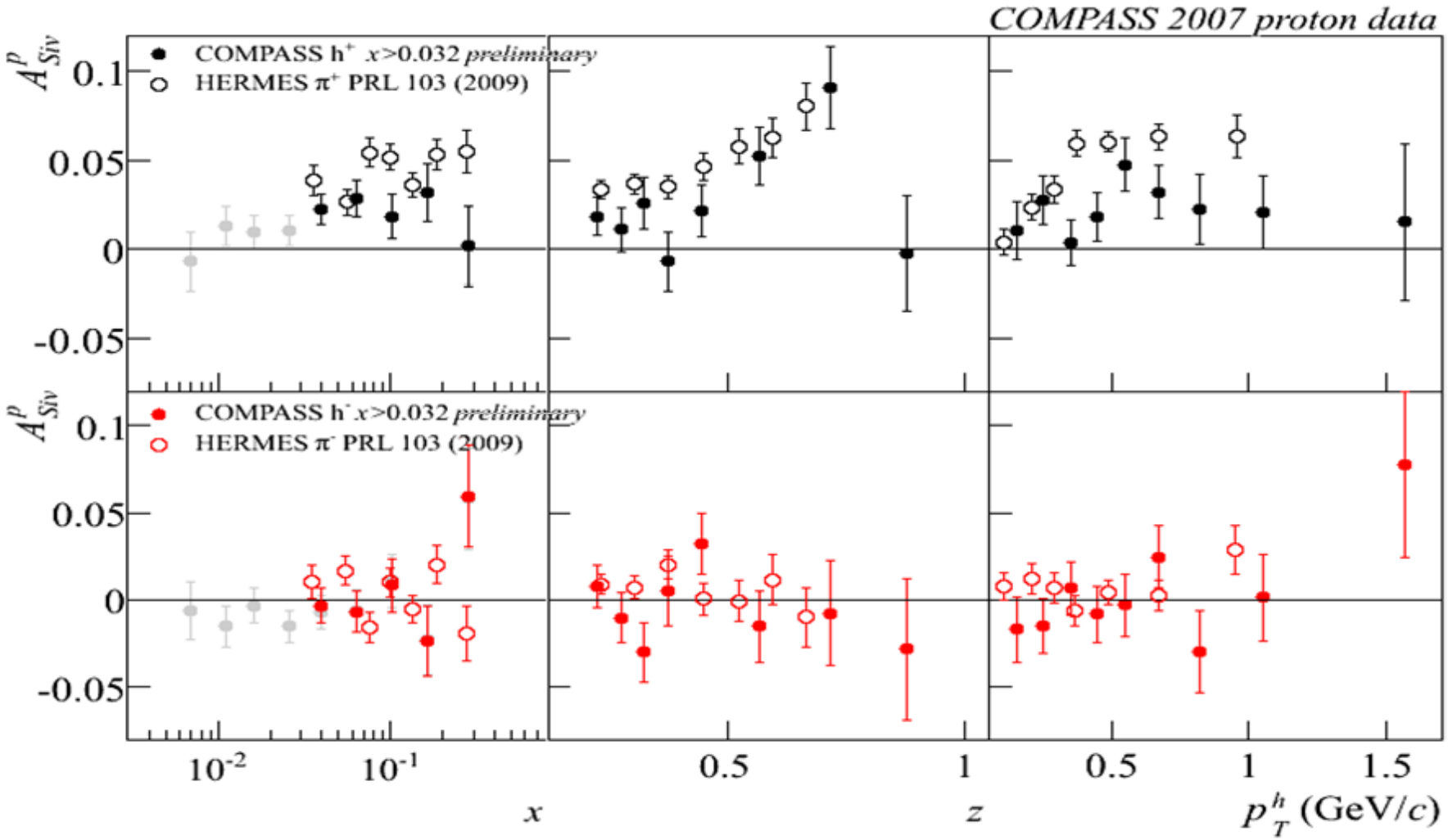


evidence for a positive signal for h^+,
which extends to small x, in the region not measured before

systematic errors **h^- ~ 0.5 σ_{stat}**
h^+ ~ 0.8 σ_{stat} plus a scale (abs) uncertainty of ± 0.01

Sivers asymmetry - proton

comparison with the **HERMES** 2002-2005 final results



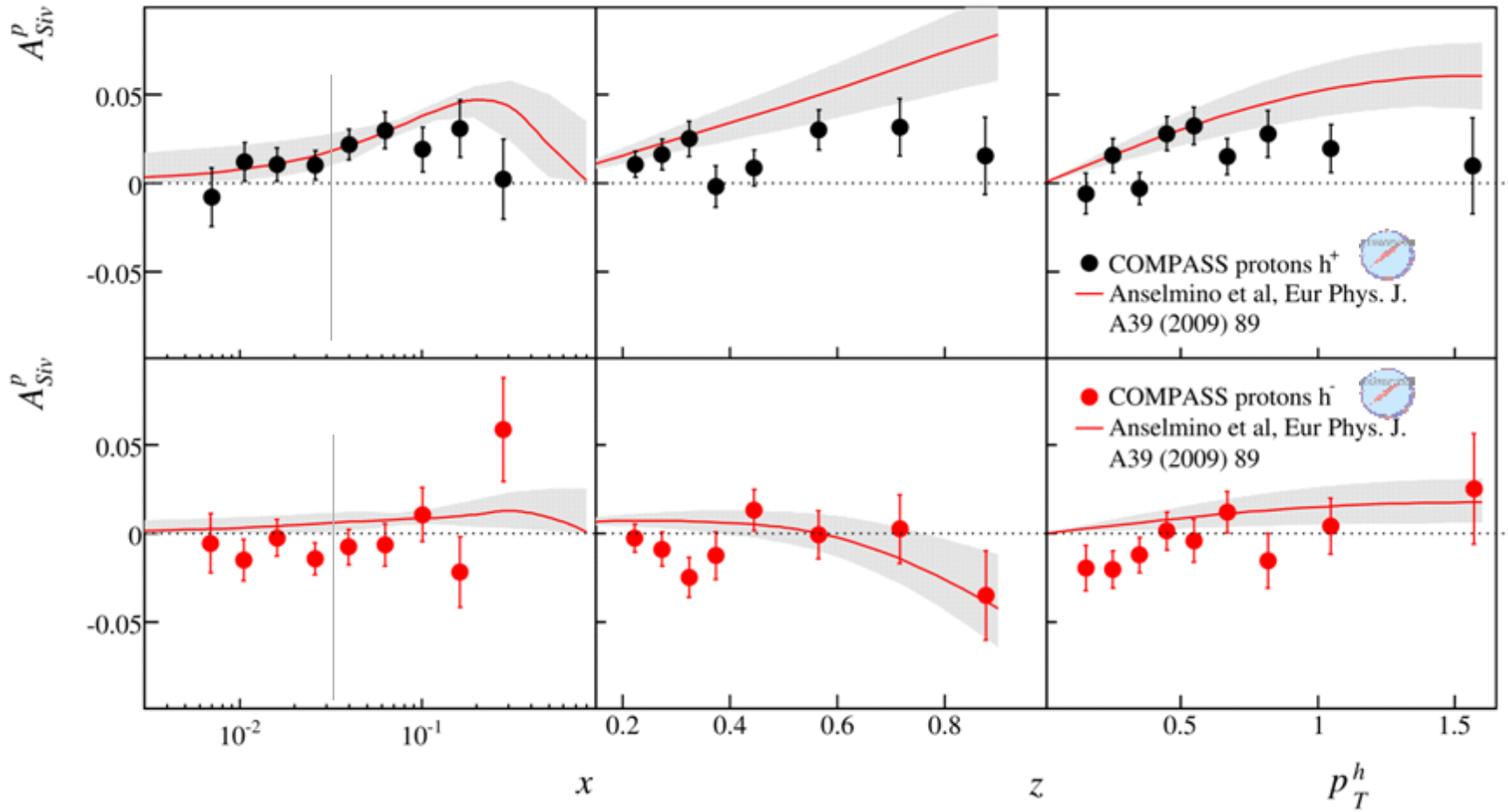
h⁺ COMPASS asymmetry: same sign
smaller by a factor ~ 2

Sivers asymmetry - proton

comparison with theory

… **most recent predictions from *M. Anselmino et al.***

based on the fit of HERMES proton and COMPASS deuteron data

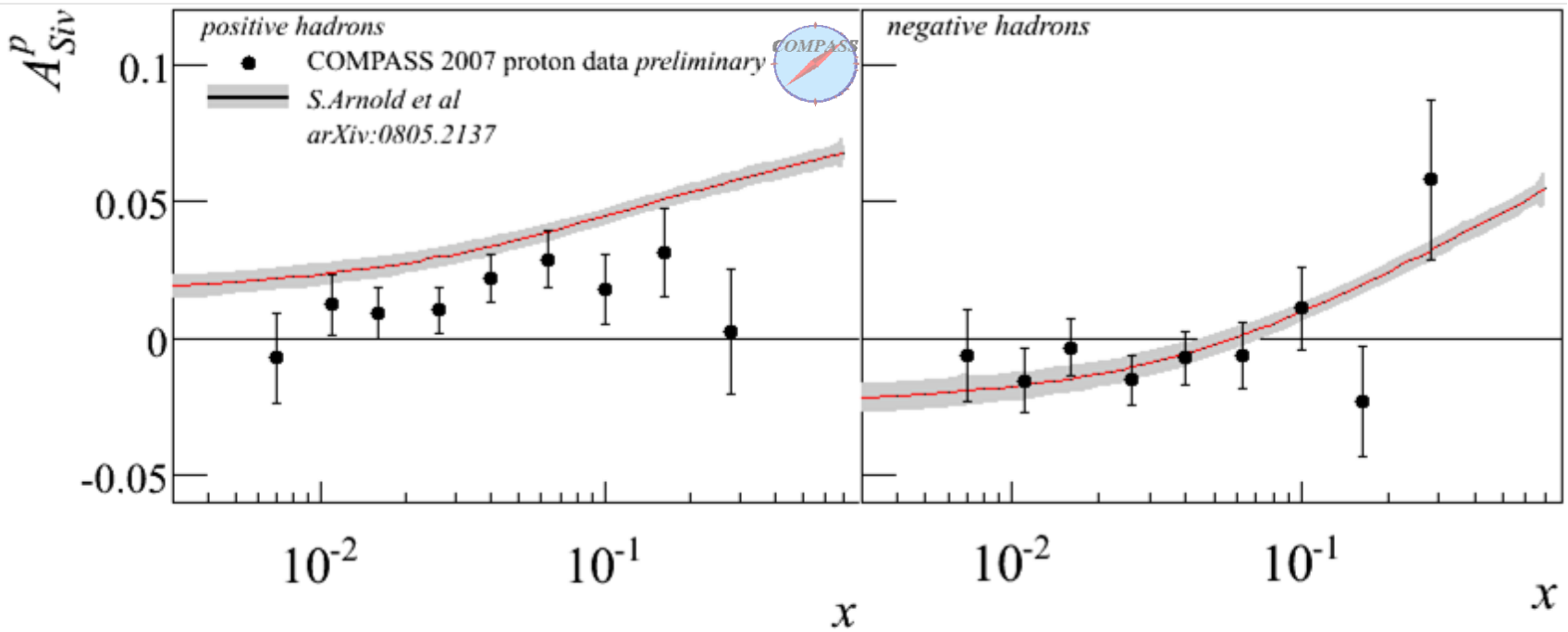


Sivers asymmetry - proton

comparison with theory

… calculations from *S.Arnold et al.*

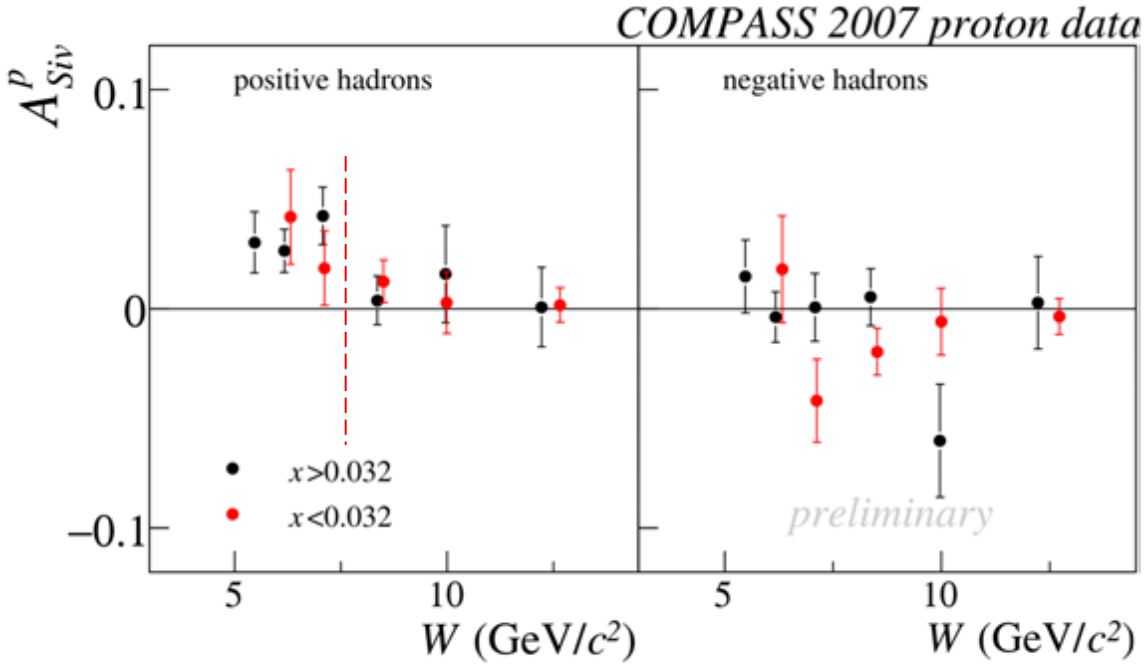
in agreement with HERMES preliminary results



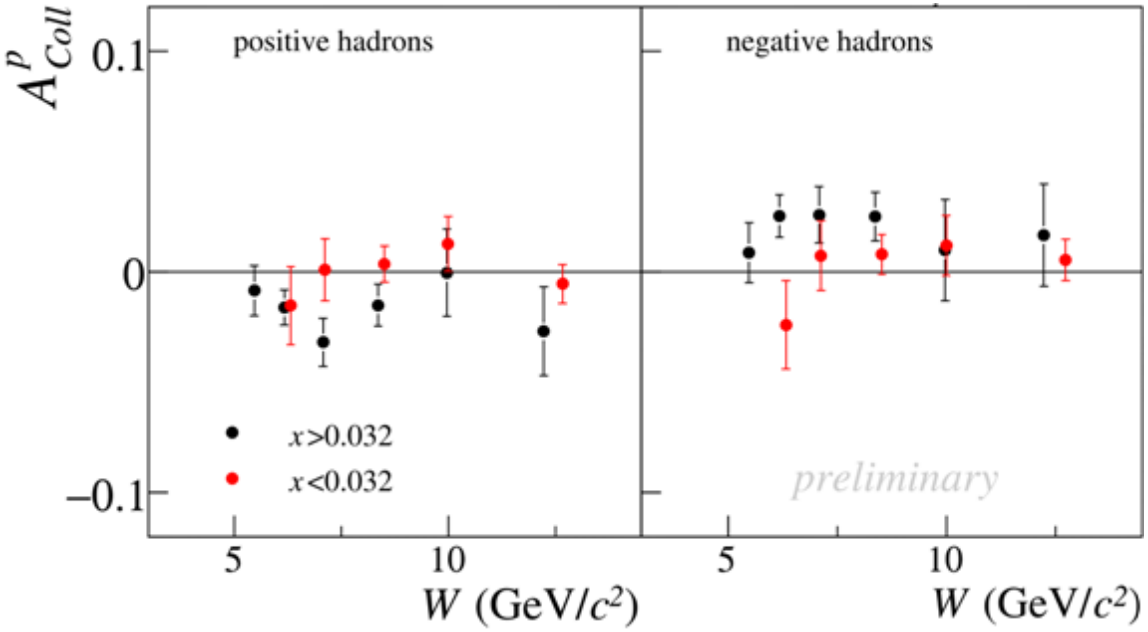
Sivers asymmetry - proton

a lot of investigations to understand the results (systematic effects)

hints for a possible W dependence of the h^+ Sivers asymmetry



no evidence of dependence of the Collins asymmetry on W



Sivers asymmetry - proton

hints for a possible W dependence of the h^+ Sivers asymmetry

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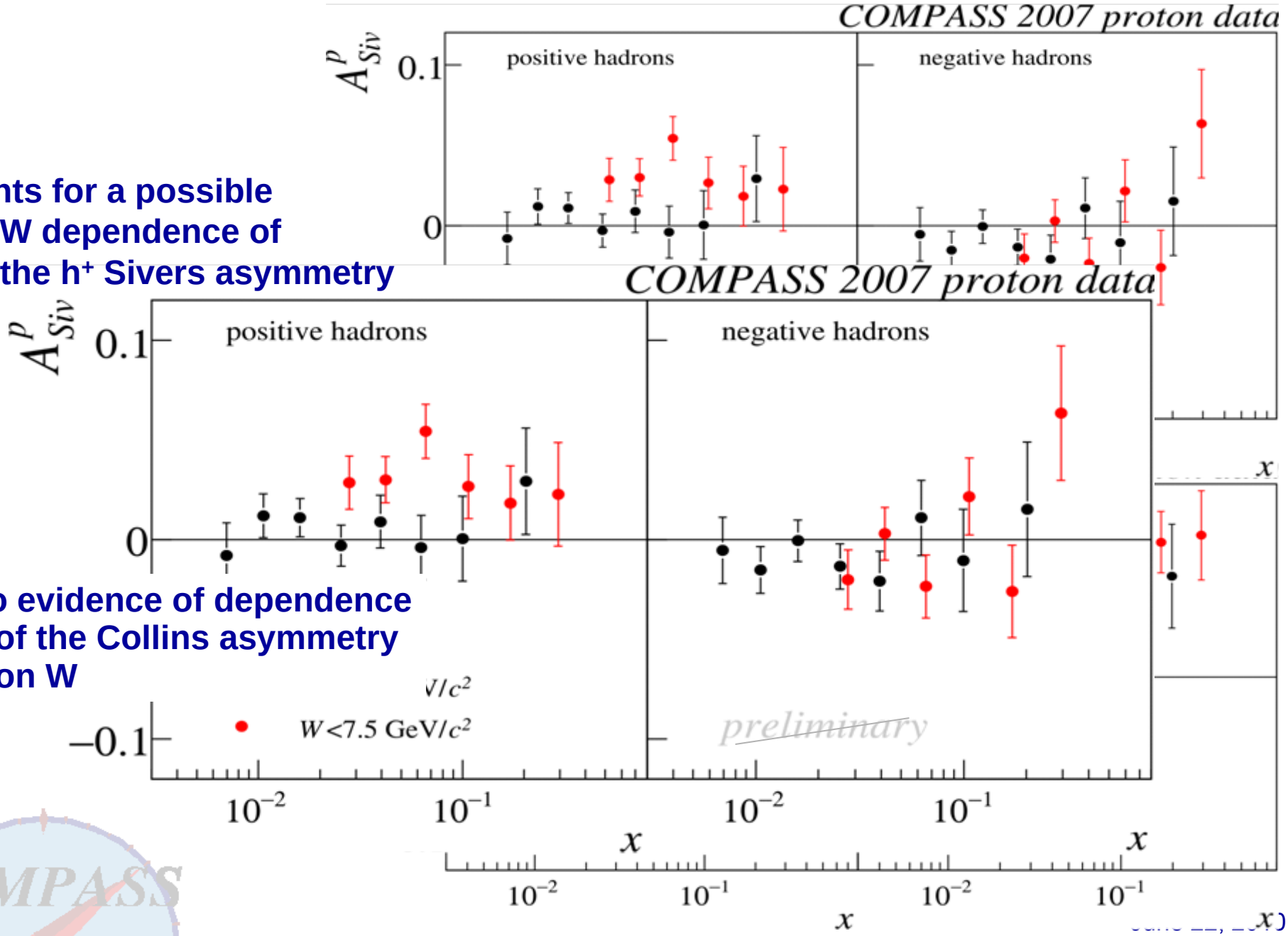
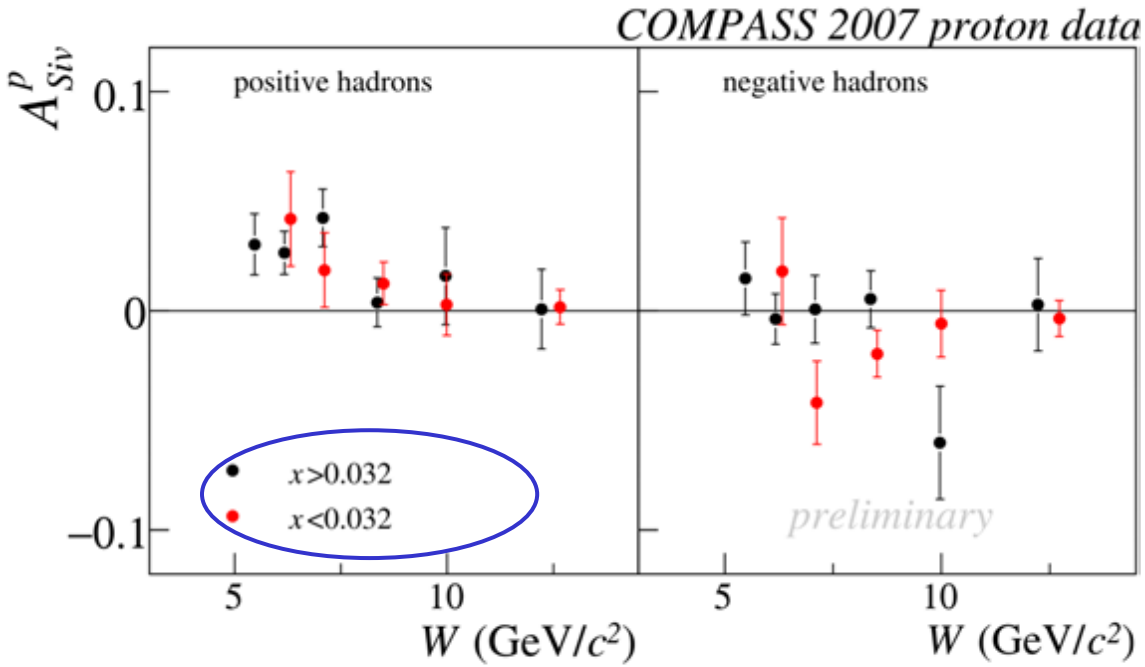
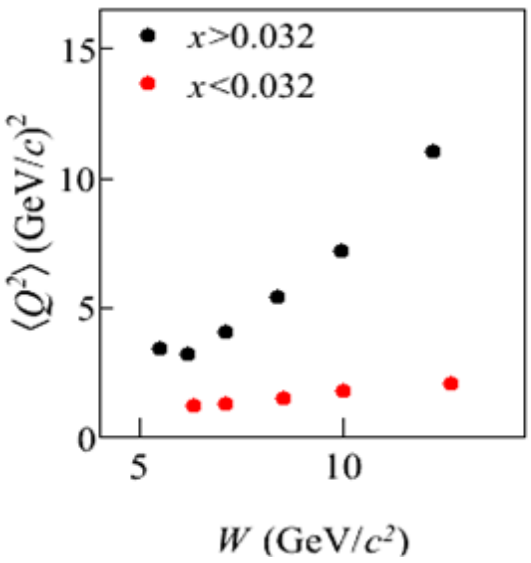


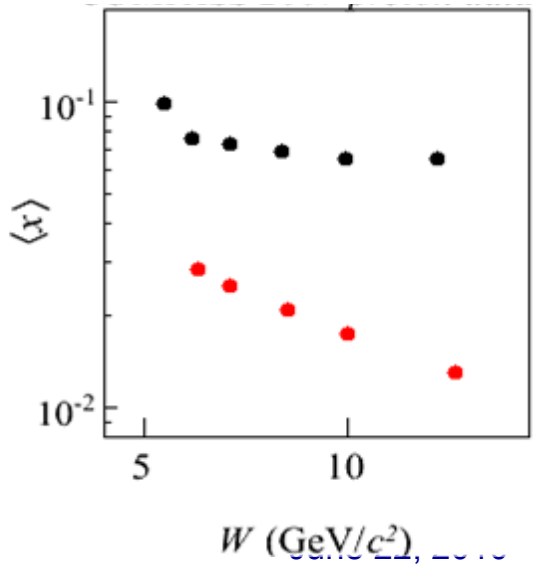
Sivers asymmetry - proton

hints for a possible
W dependence of
the h^+ Sivers asymmetry

not due to
different <x> vs W





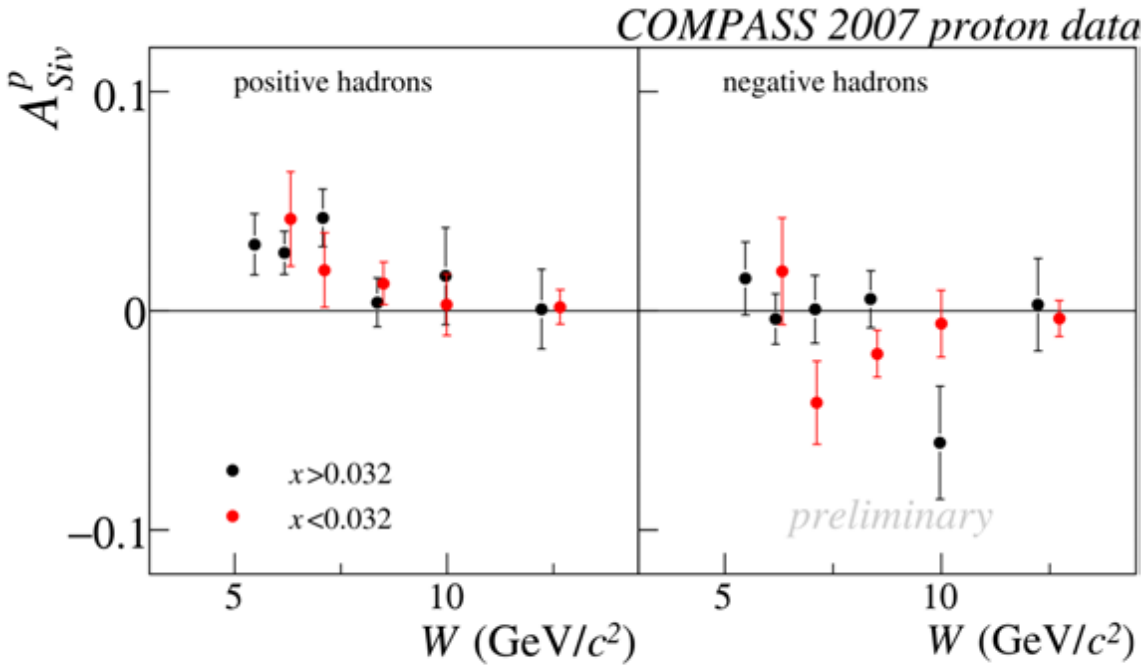


Sivers asymmetry - proton

hints for a possible
W dependence of
the h^+ Sivers asymmetry

not due to
different <x> vs W

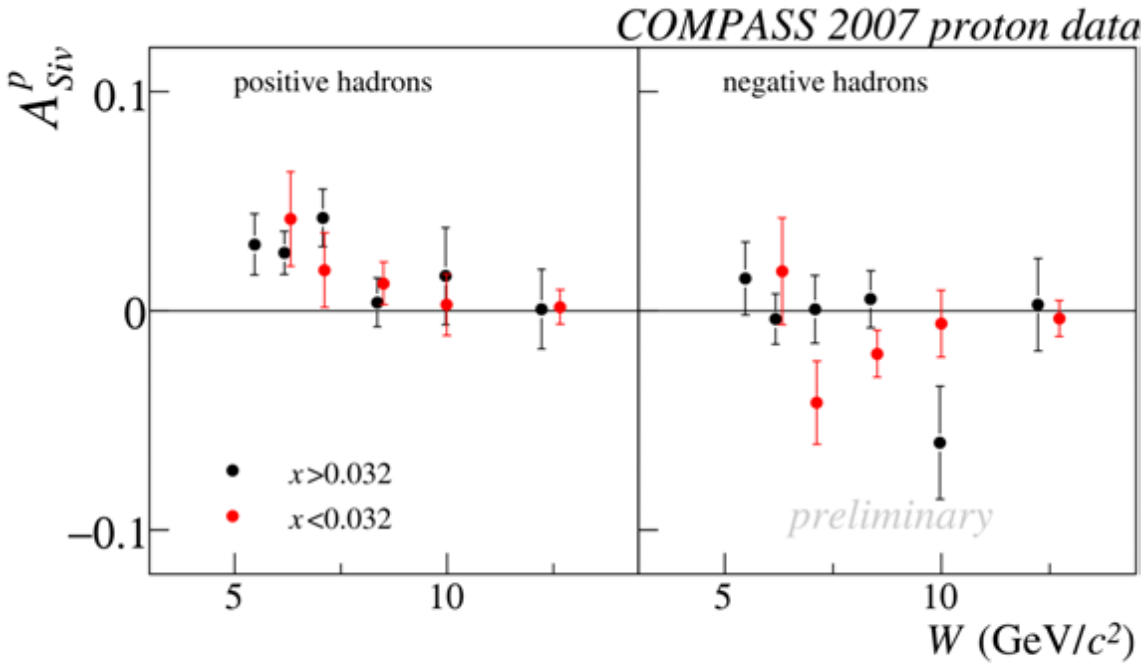
unexpected ...

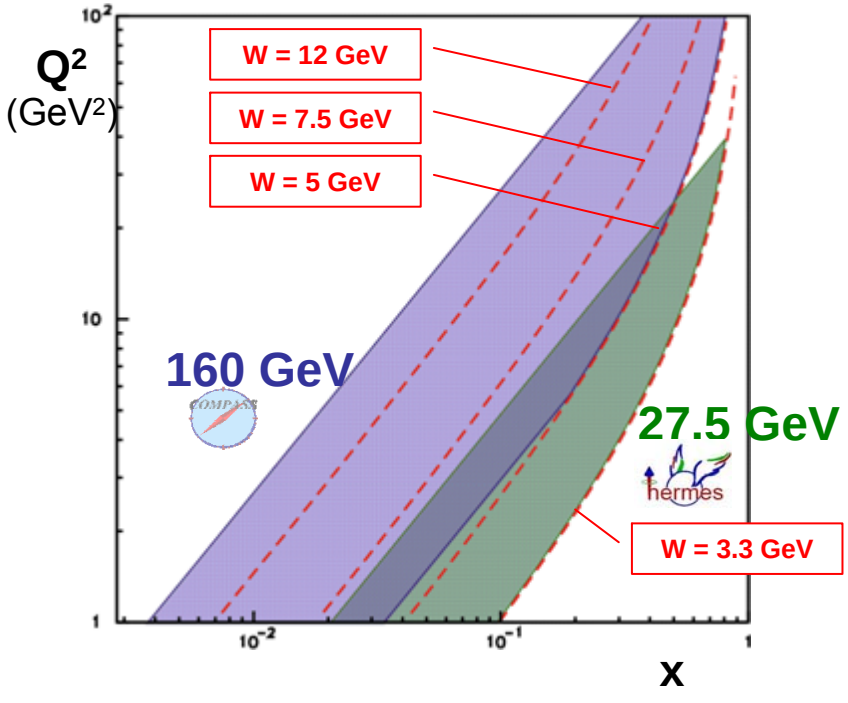


but W and z cuts sometimes are applied to select the current fragmentation region

Sivers asymmetry - proton

hints for a possible W dependence of the h^+ Sivers asymmetry





no definite conclusion with the present accuracy:

higher precision measurements needed

→ 2010 data

transverse Spin Asymmetries

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \quad \ldots$$

further two twist 2 asymmetries

four twist 3 asymmetries

$$+ |\boldsymbol{S}_\perp| \Big[\sin(\phi_h - \phi_S) \Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \Big)$$

$$+ \varepsilon \sin(\phi_h + \phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+ \sqrt{2\,\varepsilon(1+\varepsilon)} \sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h-\phi_S)} \Big]$$

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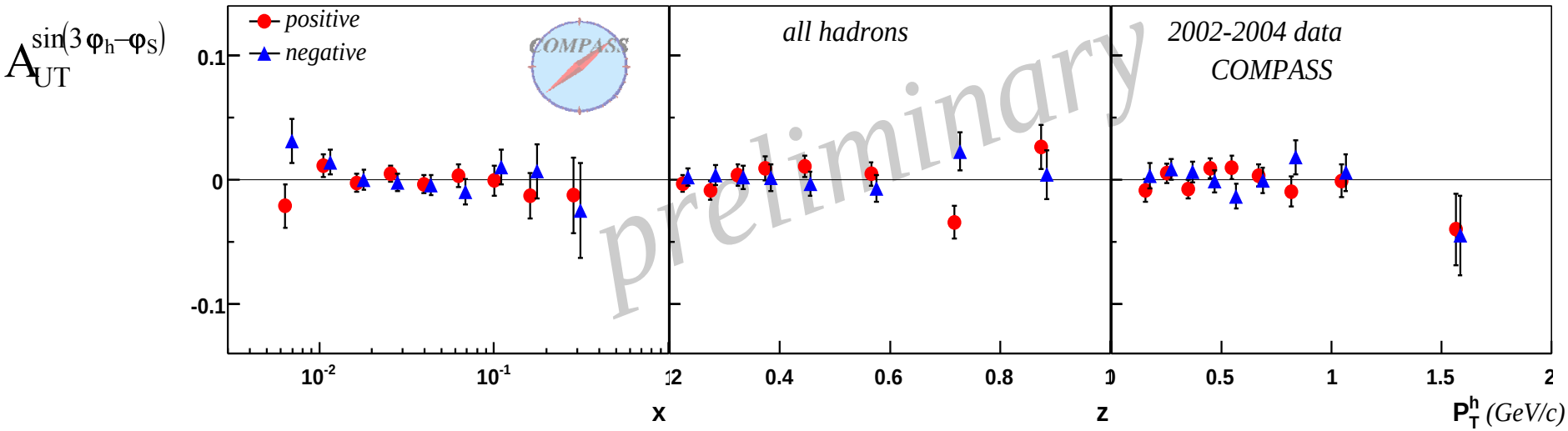
$$+ \sqrt{2\,\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h-\phi_S)} \Big] \Big\},$$

all measured by COMPASS on d (DIS2007)**: an example**

other T SAs - deuteron data

$$F_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

"pretzelosity" ⊗ Collins FF



on deuteron asymmetries compatible with zero :

again because of cancellation between u and d quark contributions?

COMPASS results: summary

deuteron data:

- **unpolarised azimuthal asymmetries:** large effects, different for h^+ and h^-
  finalised soon
- **all spin asymmetries (T&L)** compatible with zero
  Collins and Sivers asymmetries: constrain for d quark PDFs
  final results already published

proton, 2007 data:
final results for Collins and Sivers at high energy

- Q^2 and W ranges extended at large values
- x range extended to considerably smaller values

Collins asymmetry:

- clear signal both for positive and negative hadrons in the valence region
- SIDIS as appropriate tool to investigate the transversity PDF

Sivers asymmetry:

- signal for positive hadrons, also at small x values
- indication for a possible (and unexpected) W dependence

more statistic needed asap

next **from the 2007 p data:** PID for Collins, Sivers and the other T SSA LR asymmetries

from the d data: unpolarised SIDIS differential cross-sections

future

2010: transversely polarised NH_3 target and 160 GeV muon beam

data taking started on June 12

→ **higher precision measurements of the Collins, the Sivers, and the other T spin asymmetries**

0.004< x < 0.3, in valence region Q^2 up to 20 GeV^2

2011: longitudinally polarised NH_3 target and the 190 GeV muon beam

→ **higher precision measurements of the L spin asymmetries**

COMPASS II Proposal: submitted in May 2010

- Primakoff
- DY on transversely polarised target → *O. Denissov*
- DVCS on LH2 → **unpolarised azimuthal asymmetries and cross-sections**

high energy SIDIS: a special tool to investigate transversity and TMDs

complementary to JLab experiments

future:

- **fixed target with higher intensity high energy beams**
- **high energy colliders**

thank you!