# Transverse spin results at COMPASS

*Stefano Levorato*
*INFN Trieste and Trieste University*

*On behalf of COMPASS Collaboration*

*Outlook:*
*Transversity*
*COMPASS spectrometer*
*Collins effect*
*Results and Predictions*
*Sivers Effect*
*Results and Predictions*
*A flash on Unpolarised azimuthal asymmetries*

*Conclusion*

# Complete SIDIS cross section

*In the complete SIDIS cross section several terms are present:*
*18 structure functions, 8 transverse target dependent spin asymmetries with different azimuthal dependences*

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

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{$$

Sivers

Collins

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

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

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

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

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

All 8 asymmetries measured at COMPASS

6 further modulations

From **A. Bacchetta et al., JHEP 0702:093,2007 . e-Print: hep-ph/0611265**

# Transversity in SIDIS.

**Transversity DF is chiral-odd:**

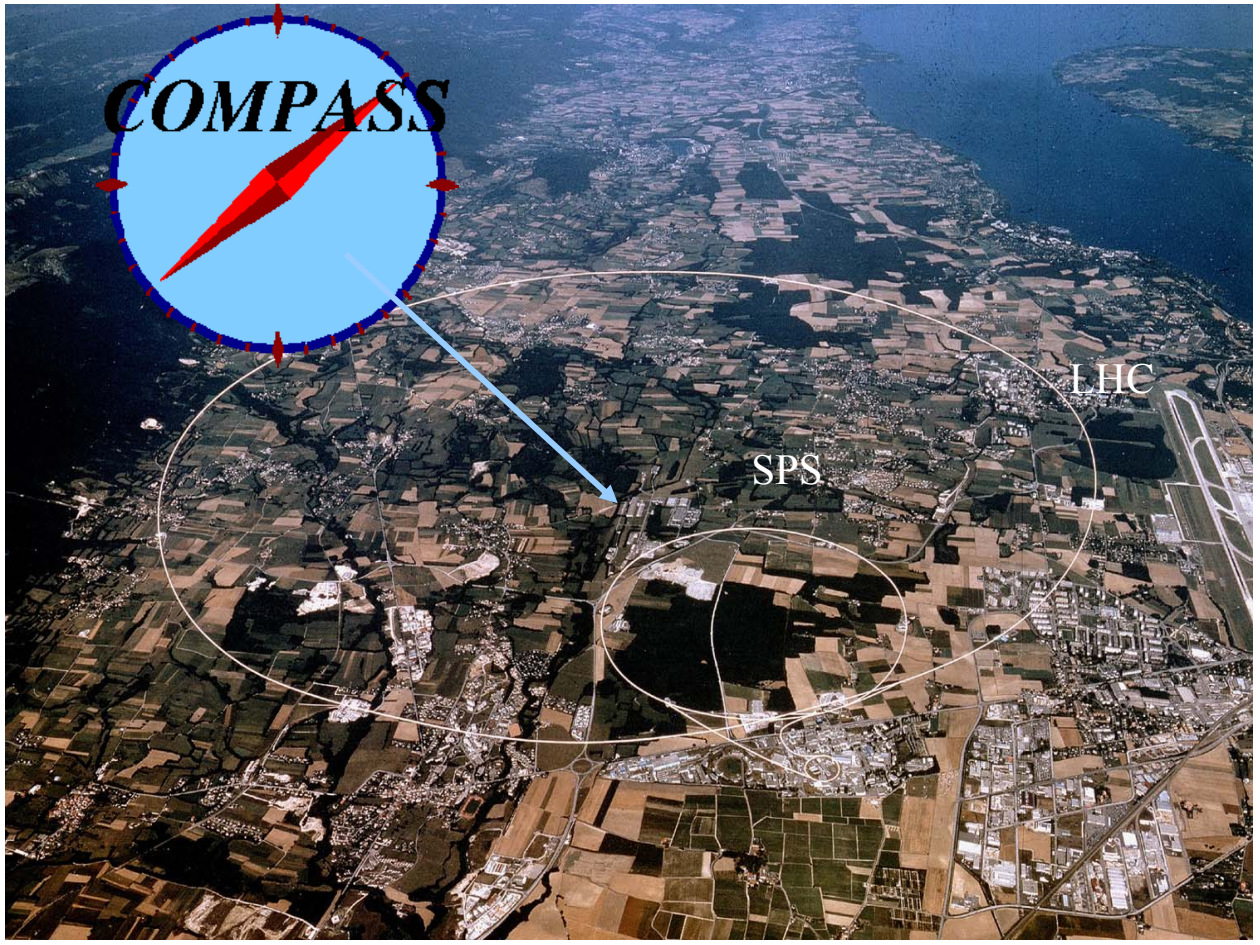
**→observable effects are given only by the product of ΔT q (x) and another chiral-odd function**

**→can be measured in SIDIS on a transversely polarized target via "quark polarimetry"**

| | |
|---|---|
| $\ell\, N^{\uparrow} \to \ell'\, h\, X$ | Collins Asymmetry (Collins FF) |
| $\ell\, N^{\uparrow} \to \ell'\, \Lambda\, X$ | $\Lambda$ polarization (FF of $q^{\uparrow} \to \Lambda$) |
| $\ell\, N^{\uparrow} \to \ell'\, hh\, X$ | Two hadrons asymmetry (Interference FF) |

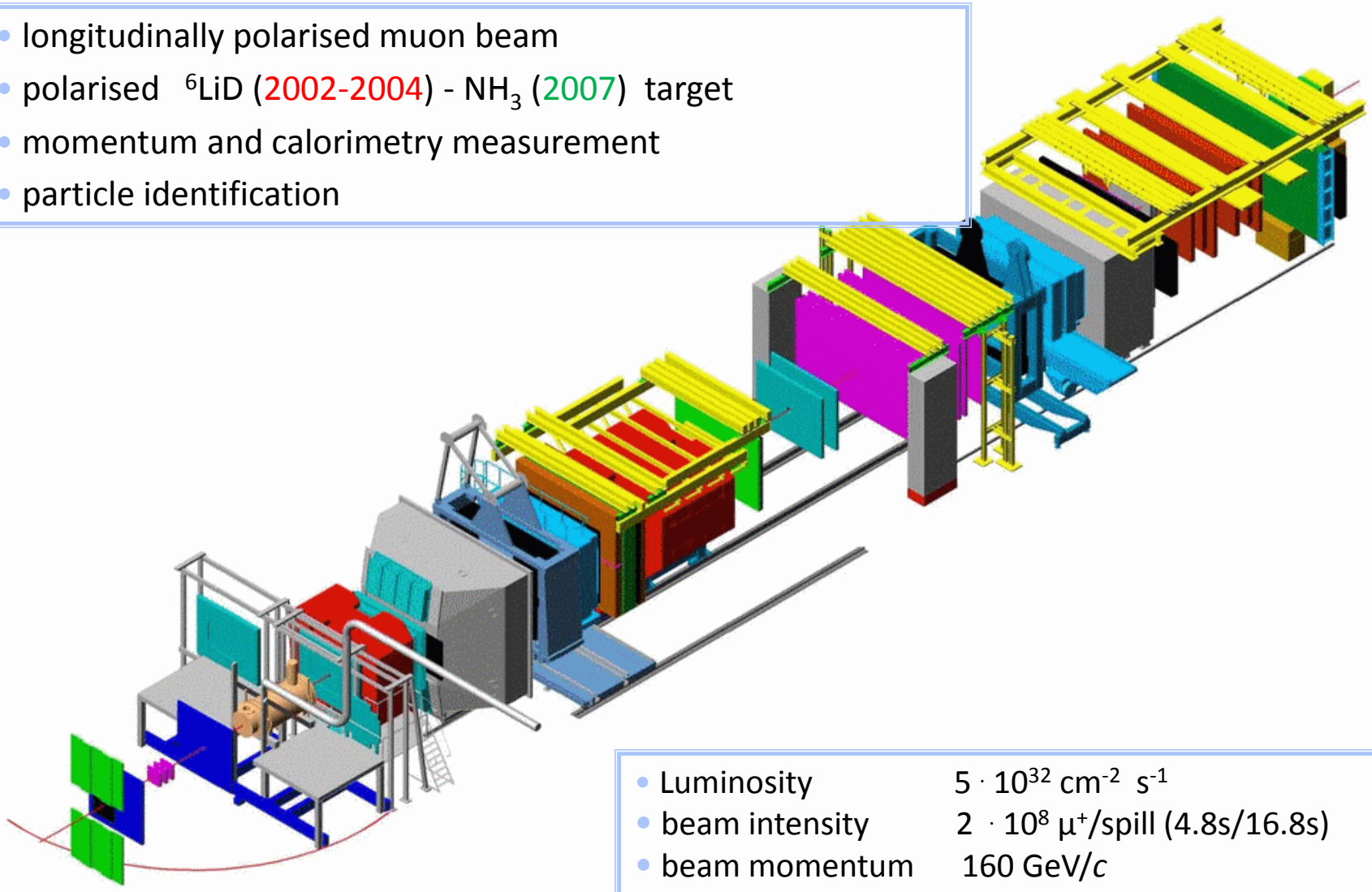
**All these channels measured at COMPASS**

# COmmon Muon and Proton Apparatus for Structure and Spectroscopy



# Our tool the COMPASS spectrometer.

- longitudinally polarised muon beam
- polarised $^6$LiD (2002-2004) - $NH_3$ (2007) target
- momentum and calorimetry measurement
- particle identification

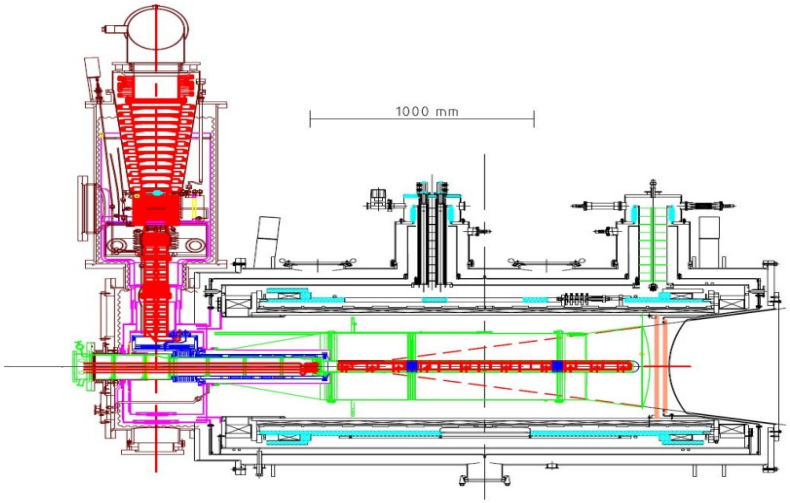


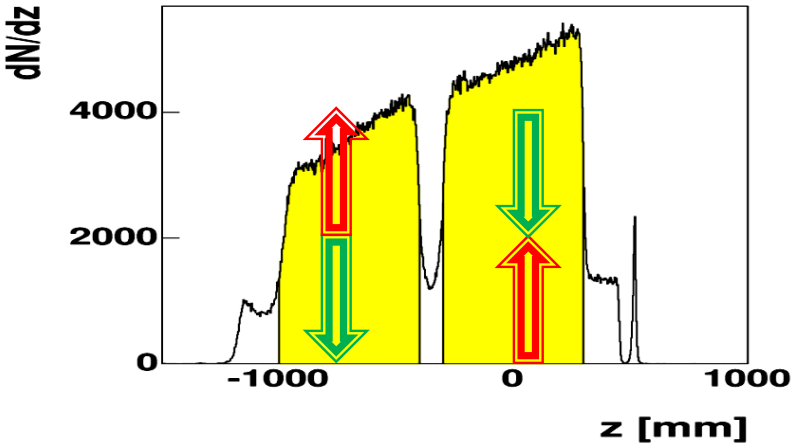
- Luminosity $5 \cdot 10^{32}$ cm$^{-2}$ s$^{-1}$
- beam intensity $2 \cdot 10^8$ $\mu^+$/spill (4.8s/16.8s)
- beam momentum 160 GeV/*c*

## Solid state target operated in frozen spin mode

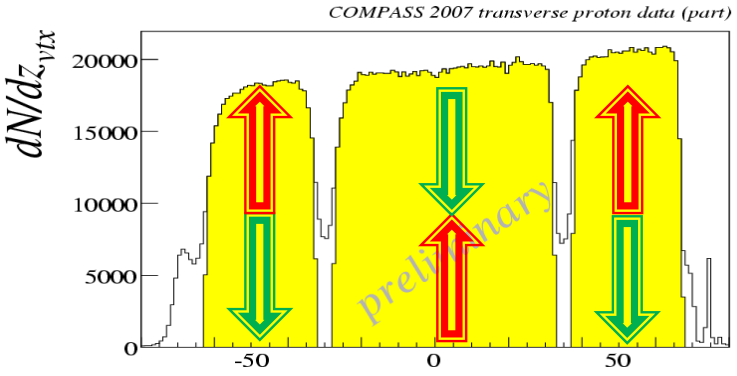
**2002-2004: $^6$LiD (polarised deuteron)**
**dilution factor f = 0.38**
**polarization $P_T$ = 50%**

**two 60 cm long cells**
**with opposite polarisation**




**2007: $NH_3$ (polarised protons)**
**dilution factor f = 0.14**
**polarization $P_T$ = 90%**



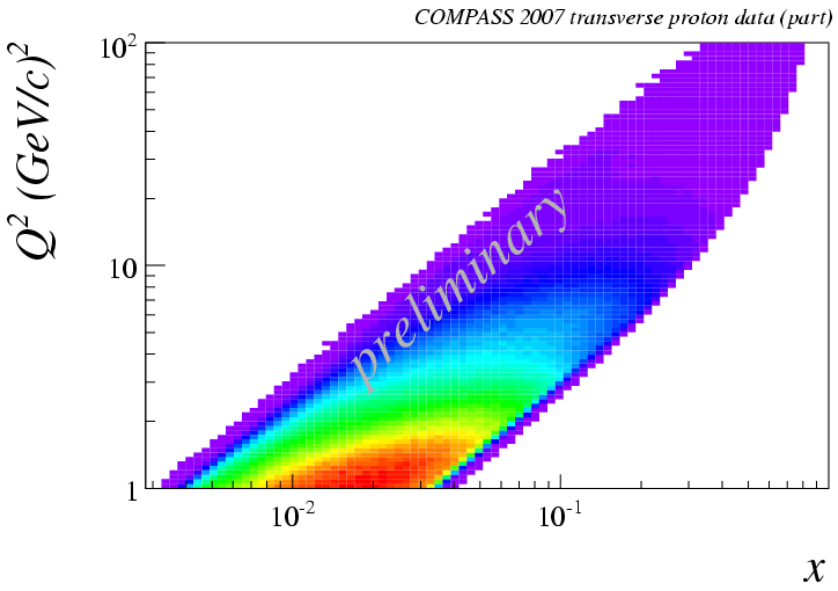

Polarisation of $NH_3$: $z_{vtx}$ (cm)
-92%, +88%, -83%

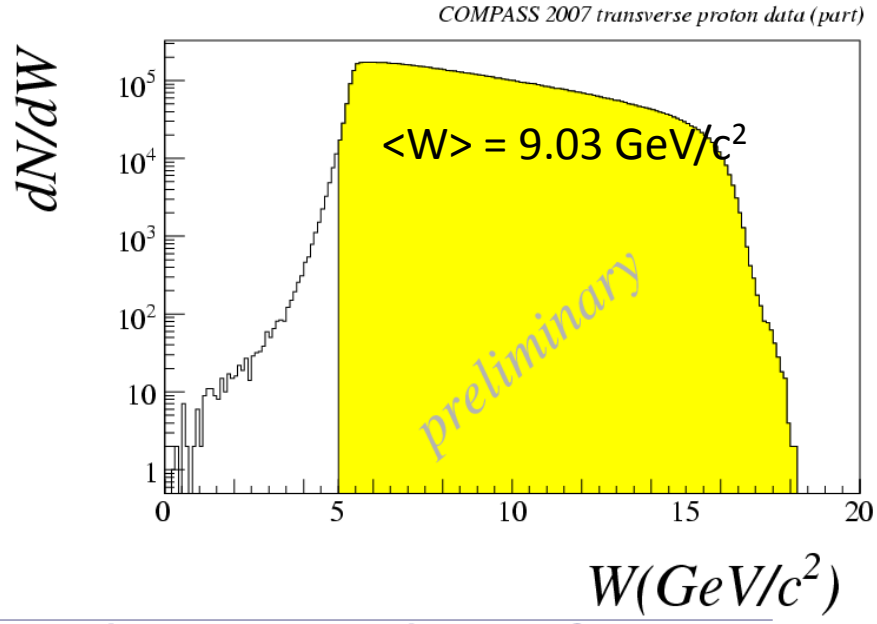
**during data taking with transverse polarisation,**
**polarisation reversal in the cells after ~ 4-5 days** (systematics)

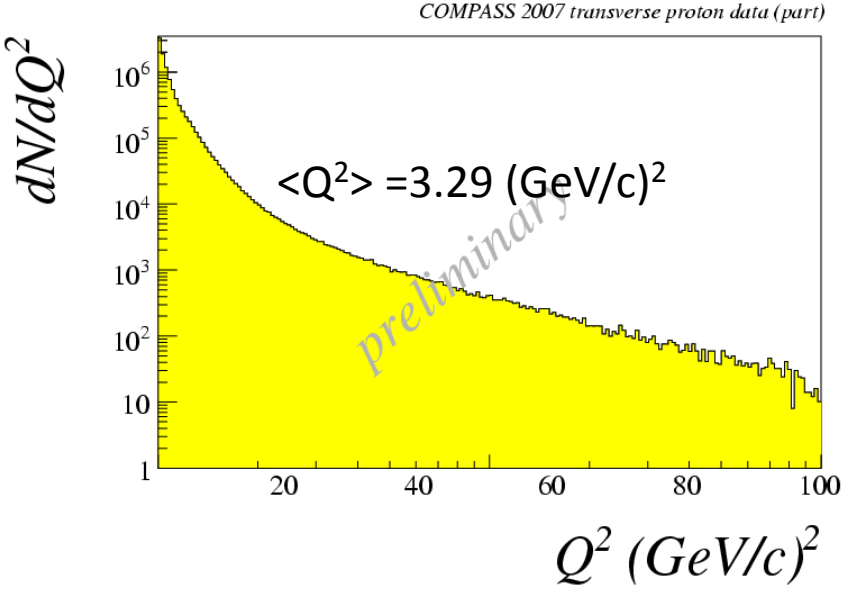
# DATA selection, DIS cut.

DIS cuts:

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



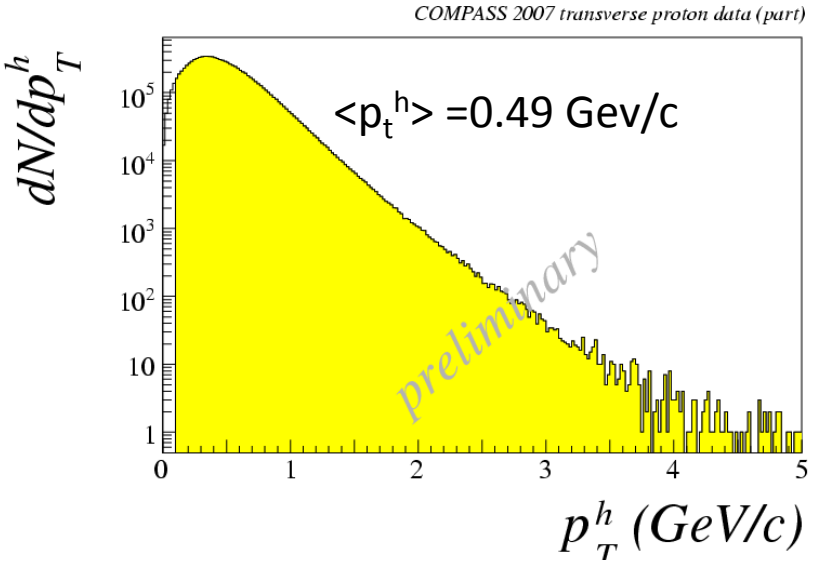



# DATA: hadron selection.

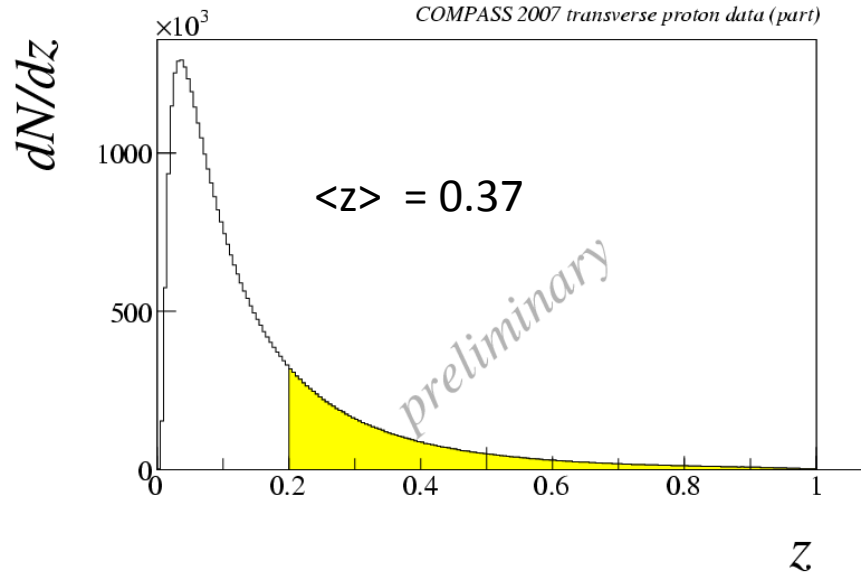
**All hadrons**

- Energy Deposit HCALs>Thr. ( ~5 GeV )
- $p_T$>0.1 GeV/c
- z>0.2



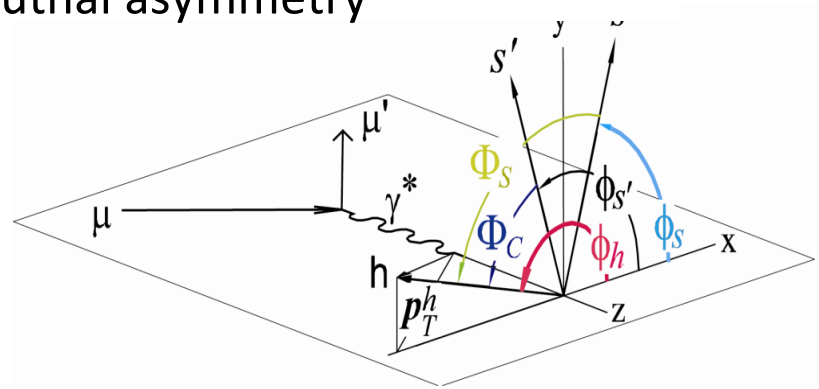

| 2002-2004 | Positive hadrons | Negative hadrons |
|---|---|---|
| Total statistic | 8.5M | 7M |

| 2007 | Positive hadrons | Negative hadrons |
|---|---|---|
| Total statistic Prel. Result | 5.7M | 4.5M |



In the hadronization process from transversely polarized quarks, the produced hadrons show an azimuthal asymmetry

$$N_h^{\pm}(\Phi_C) = N_h^0 \cdot \{ 1 \pm A_C^h \cdot \sin\Phi_C \}$$




$\Phi_C = \phi_h - \phi_{s'}$ is the "Collins angle"

$$A_{Coll} = \frac{A_C^h}{f \cdot P_T \cdot D_{nn}} = \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

transversity distribution function

Collins fragmentation function

$\phi_h$ azimuthal angle of the hadron

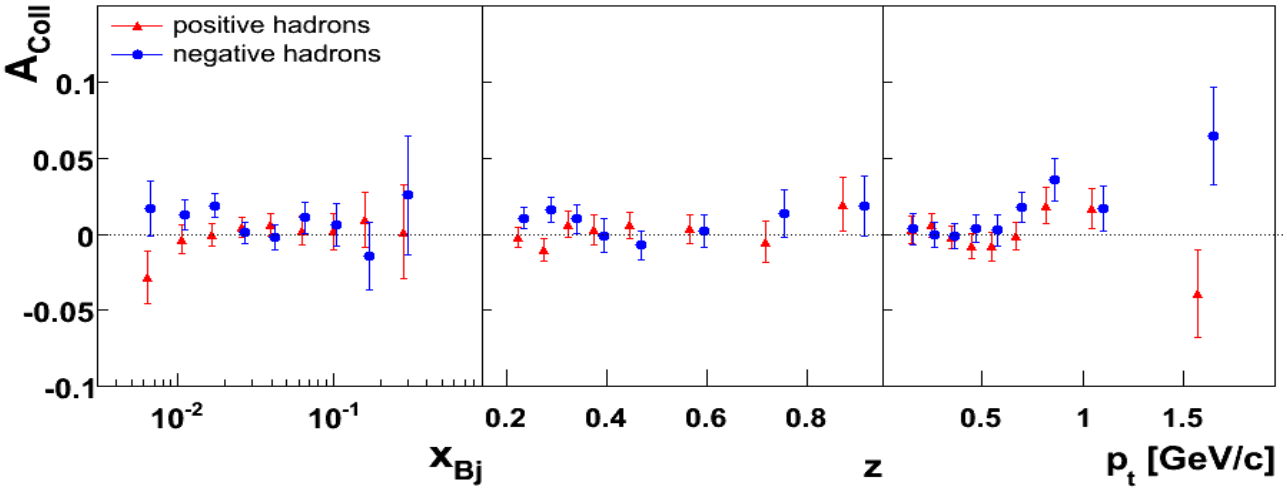
$\phi_s$ azi. angle of the transverse spin of the initial quark

$\phi_{s'}$ azi. angle of the transverse spin of the fragmenting quark

$\phi_{s'} = \pi - \phi_s$ *(spin flip)*

# Asymmetries, Collins effect Deuteron data, Naïve interpretation, (Parton Model, Valence Region)

*COMPASS: 2002-2004*




- only statistical errors shown, systematic errors considerably smaller
- small asymmetries compatible with 0 for both + and – hadrons

[NP B765 (2007) 31-70]

$$A_{Coll}^{d,\pi^+} \simeq \frac{\Delta_T u_v + \Delta_T d_v}{u_v + d_v} \frac{4\Delta_T^0 D_1 + \Delta_T^0 D_2}{4D_1 + D_2}$$

$$A_{Coll}^{d,\pi^-} \simeq \frac{\Delta_T u_v + \Delta_T d_v}{u_v + d_v} \frac{\Delta_T^0 D_1 + 4\Delta_T^0 D_2}{D_1 + 4D_2}$$

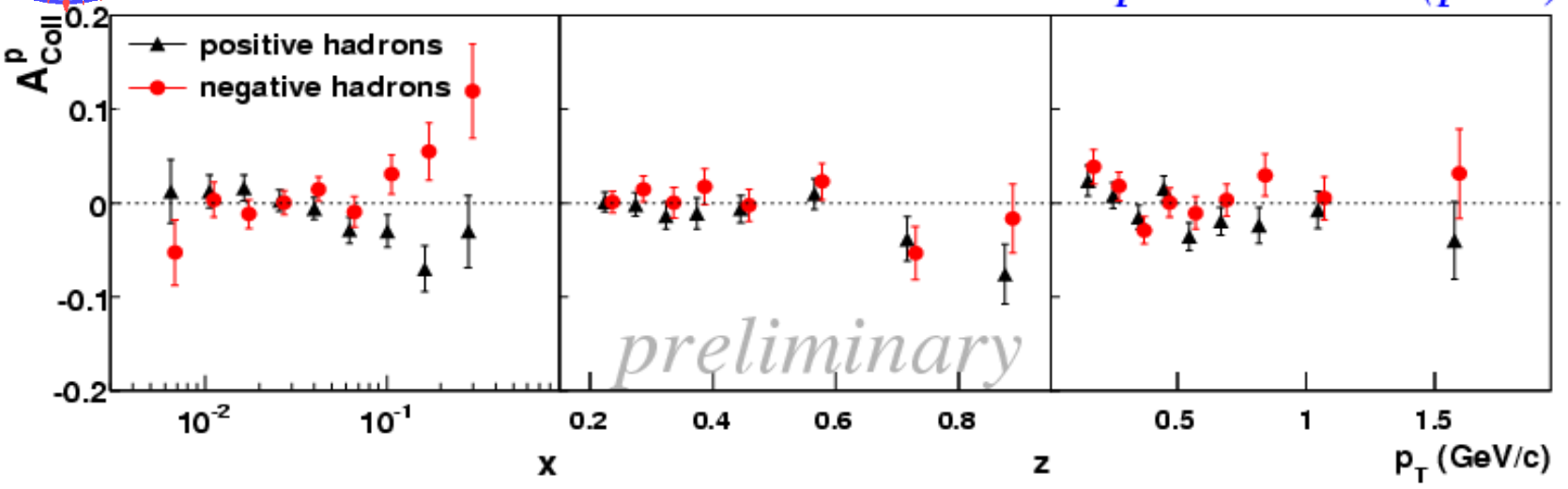
Small asymmetries → $\Delta_T u(x) + \Delta_T d(x) \sim 0$

Also expected if $\Delta_T^0 D_2 \approx -\Delta_T^0 D_1$

$$A_{Coll}^{p,\pi^+} \simeq \frac{4\Delta_T u_v \Delta_T^0 D_1 + \Delta_T d_v \Delta_T^0 D_2}{4u_v D_1 + d_v D_2} \qquad A_{Coll}^{p,\pi^-} \simeq \frac{4\Delta_T u_v \Delta_T^0 D_2 + \Delta_T d_v \Delta_T^0 D_1}{4u_v D_2 + d_v D_1}$$

suggested by data on proton target – HERMES experiment

# Asymmetries, Collins effect Proton data (2007)



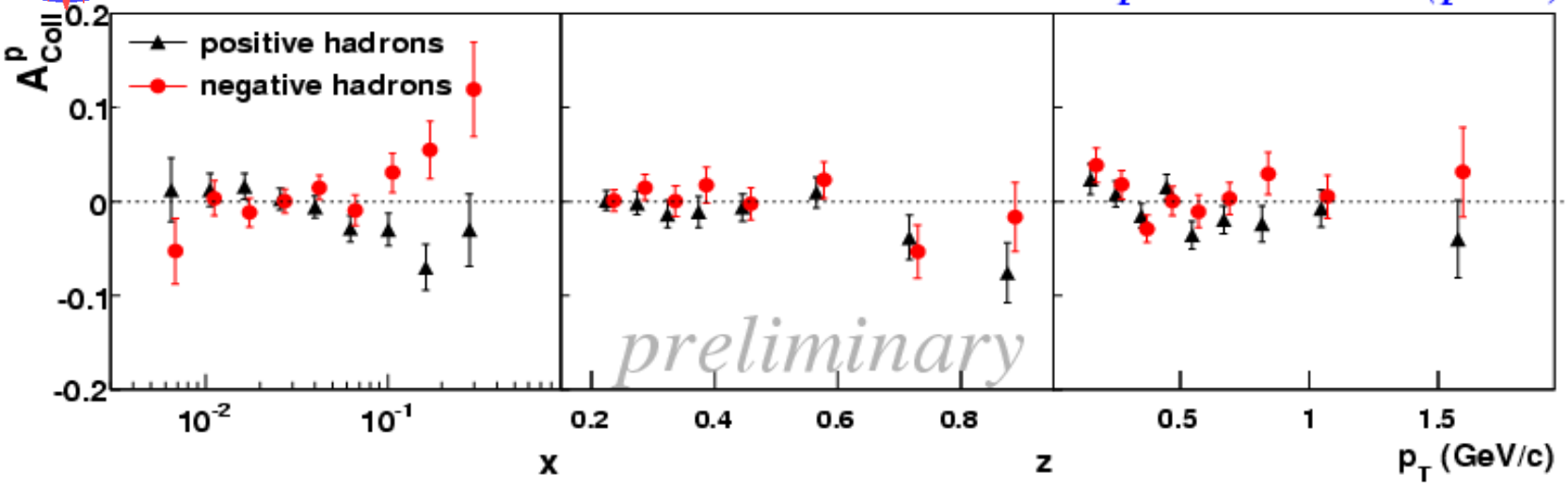

*Clear effect, asymmetry different from zero,*

- ✓ *Small asymmetry at small x, compatible with zero*
- ✓ *Asymmetry of opposite sign for positive and negative hadrons, same strength and sign of HERMES, result which is not obvious due the different kinematic range of the two experiments.*

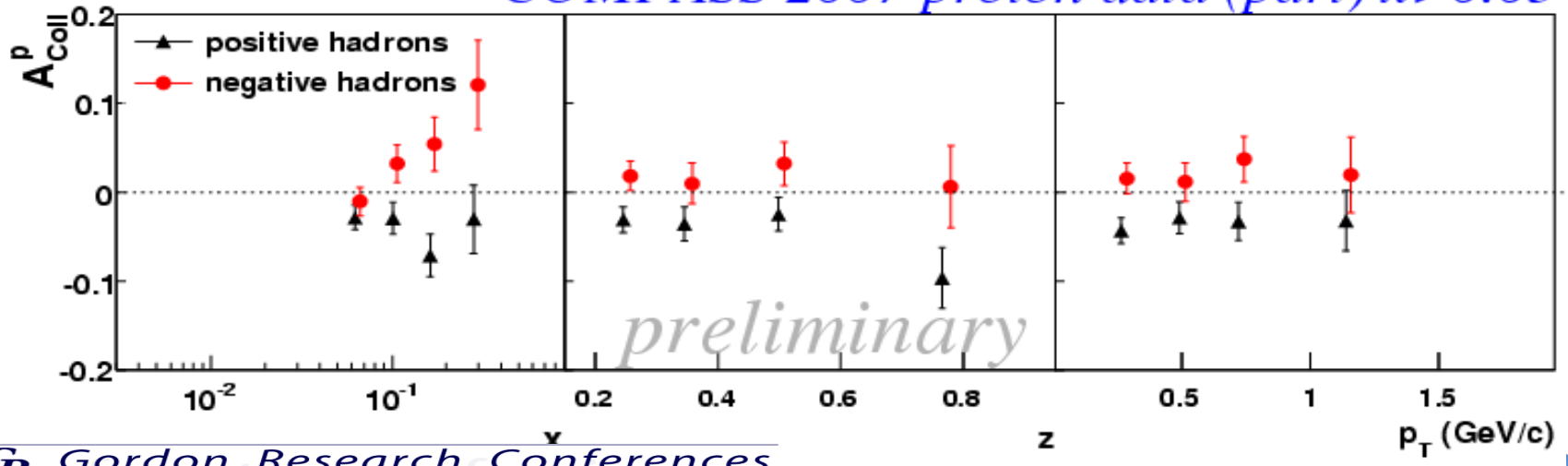
Statistical error only, systematic error has been evaluated to be 0.3 $\sigma_{stat}$ for Collins asymmetry.

# Asymmetries, Collins effect Proton data (2007)

## COMPASS 2007 proton data (part)

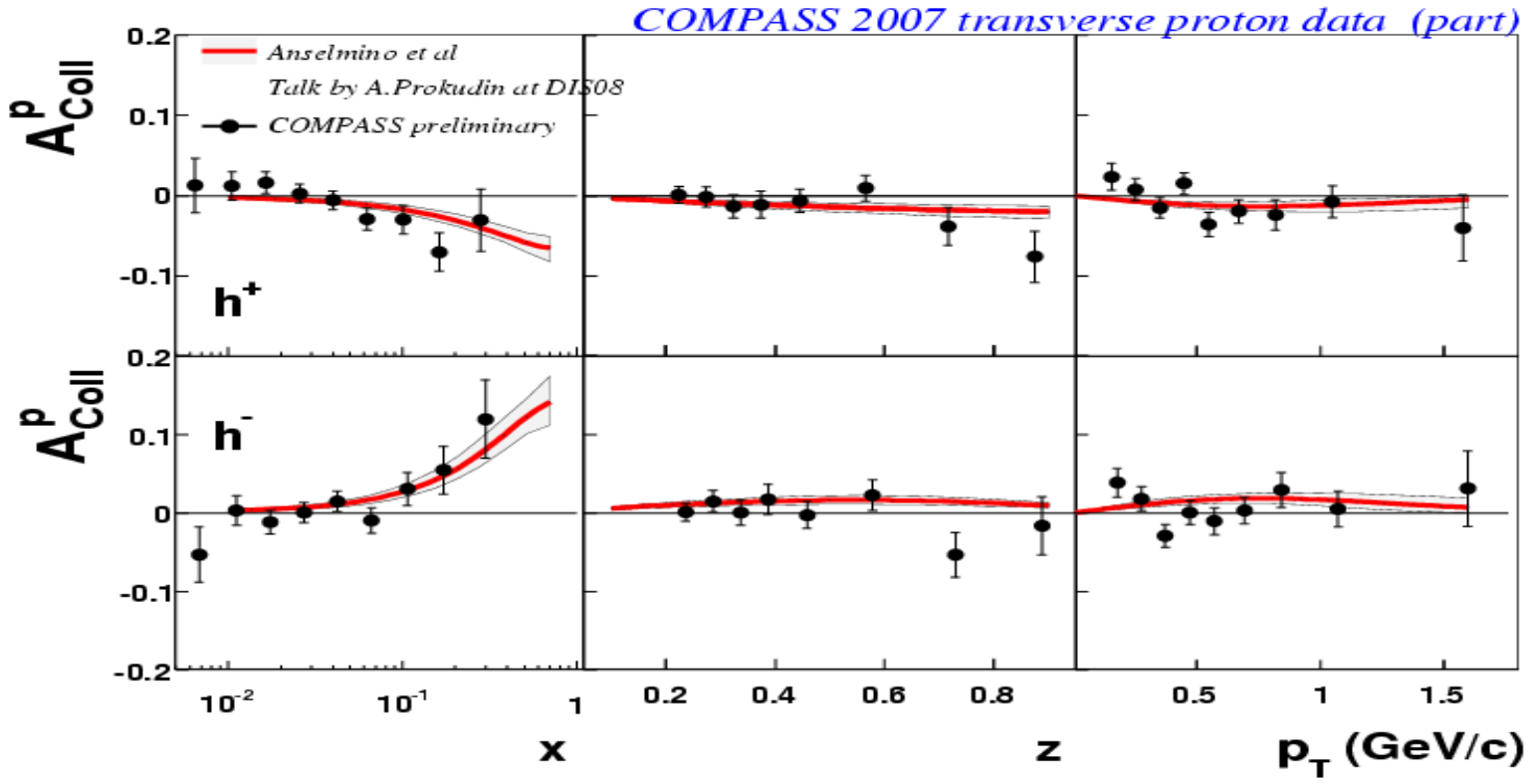



## COMPASS 2007 proton data (part) x>0.05



# Collins Effect, comparison with predictions

*Update of the analysis with the most recent*
*COMPASS Deuteron*, *HERMES Proton*, *BELLE* $e^+ e^-$ data




COMPASS proton data for h+ and h-, with the *very last* predictions of Anselmino et al. *(DIS08 by A.Prokudin. )*

# Asymmetries, Sivers effect

*A different mechanism can also produce azimuthal asymmetries*
*…in SIDIS Collins and Sivers effects are decoupled!*

The Sivers DF $\Delta_0^T q$ is probably the most famous among TMDs…
*gives a measure of the correlation between the intrinsic transverse momentum of unpolarised quarks and the spin in a transversely polarized nucleon*

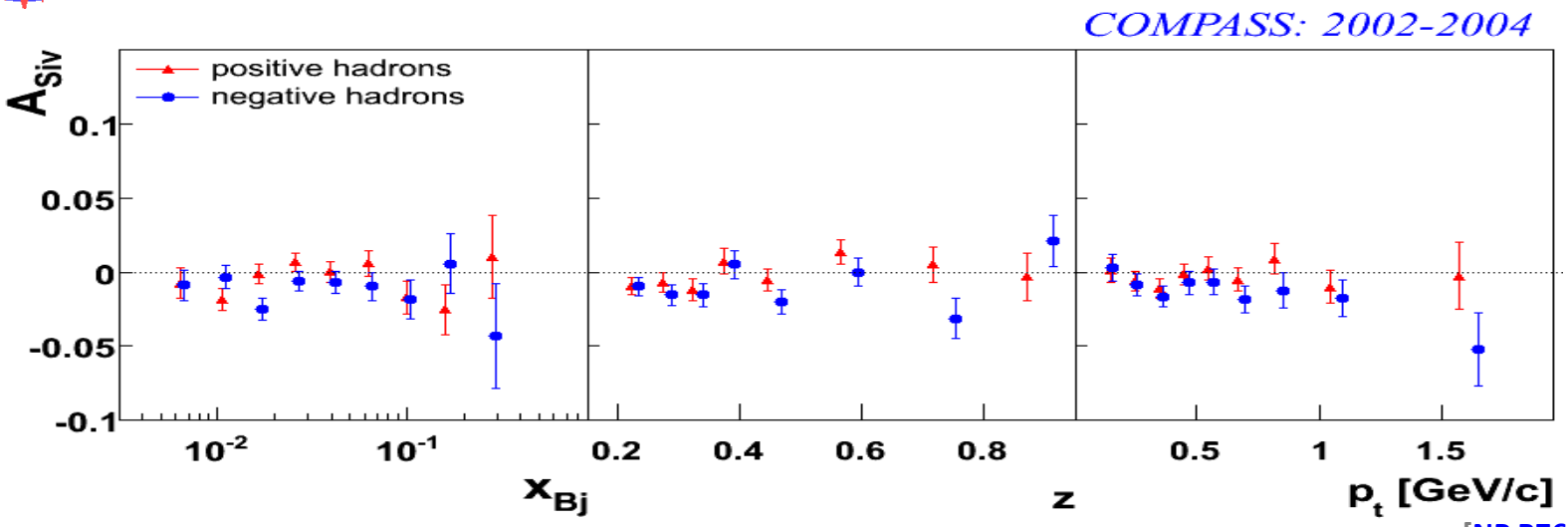
$$N_h^{\pm}(\Phi_S) = N_h^0 \cdot \left\{ 1 \pm A_S^h \cdot \sin\Phi_S \right\}$$

Sivers DF

$$A_{Siv} = \frac{A_S^h}{f \cdot P_T} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

"Sivers angle" $\Phi_S = \phi_h - \phi_s$

# Asymmetries, Sivers effect Deuteron data, Naïve interpretation, (Parton Model, Valence Region)




[NP B765 (2007) 31-70]

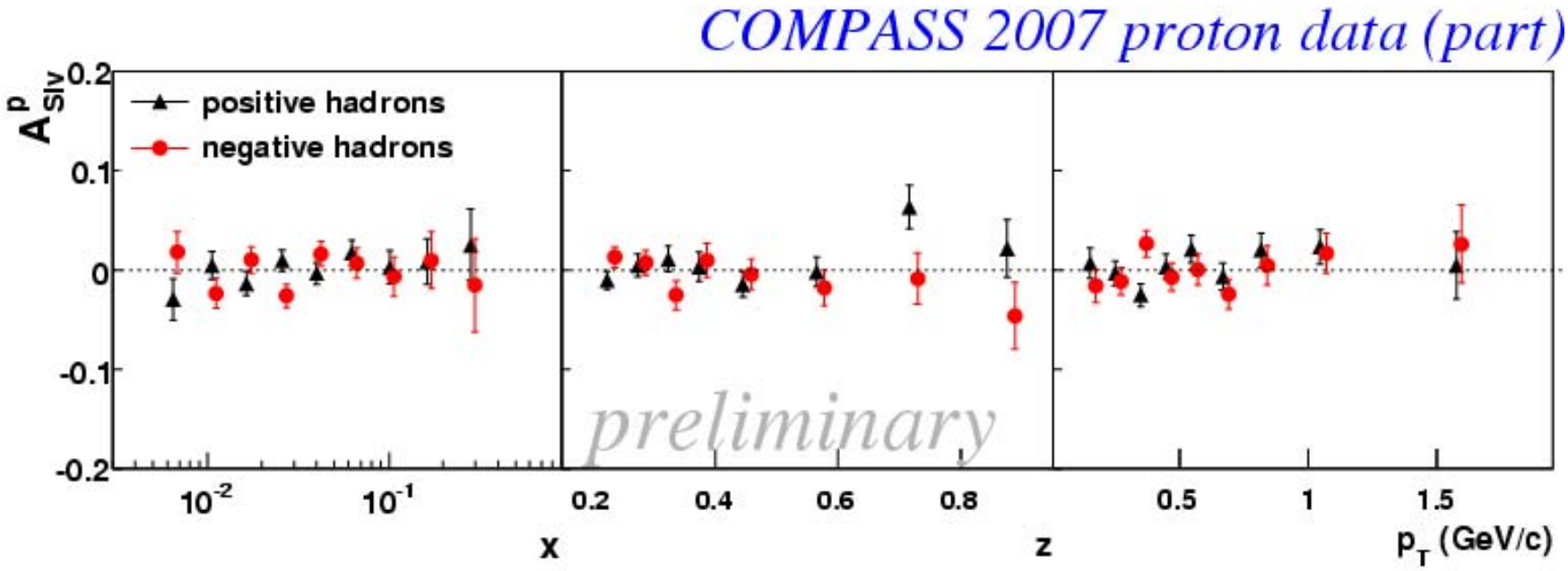
**Only statistical errors shown (systematic errors considerably smaller)**
**Small asymmetries**

$$A_{Siv}^{d,\pi^+} \simeq A_{Siv}^{d,\pi^-} \simeq \frac{\Delta_0^T u_v + \Delta_0^T d_v}{u_v + d_v}$$

Small asymmetries suggest $\Delta_0^T d_v \simeq -\Delta_0^T u_v$

**The measured** *asymmetry on deuteron compatible with zero* **has been interpreted as Evidence for the** ***Absence of Gluon Orbital Angular Momentum in the Nucleon***
***S.J. Brodsky and S. Gardner, PLB643 (2006) 22***

# Asymmetries, Sivers effect Proton data (2007)

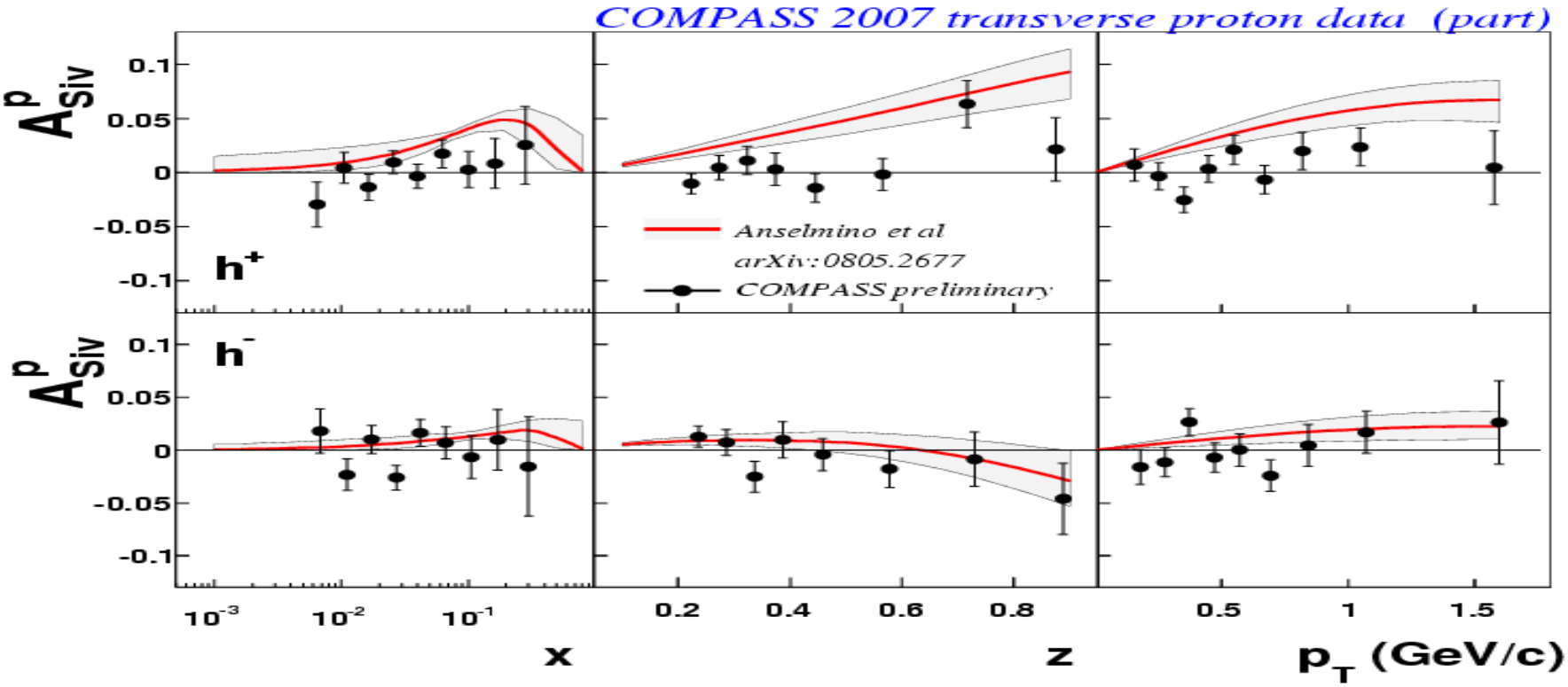



Asymmetry small, compatible with zero within present statistical error

**statistical errors only; systematic errors ~ 0.5 $\sigma_{stat}$**

# Sivers Effect, comparison with predictions

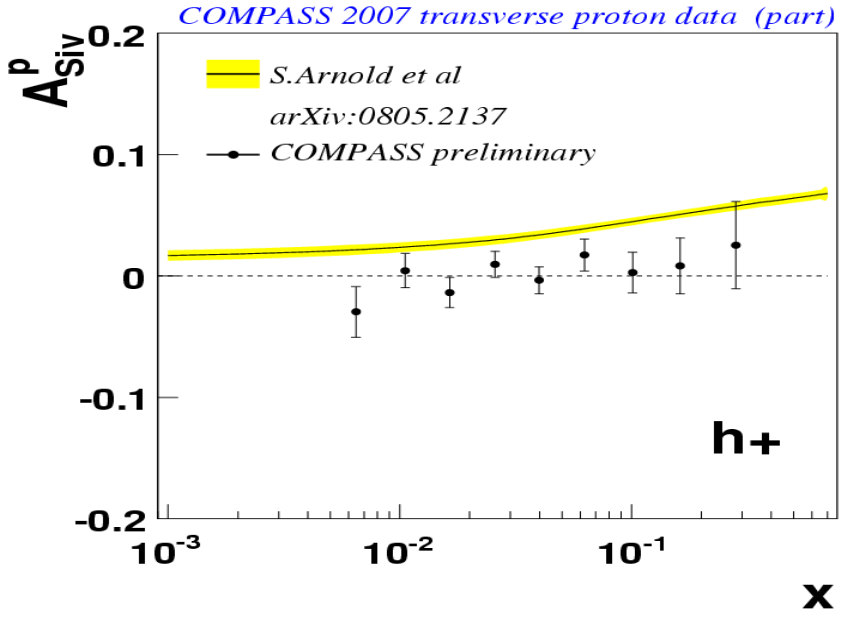
Latest prediction of
M. Anselmino et *al.*

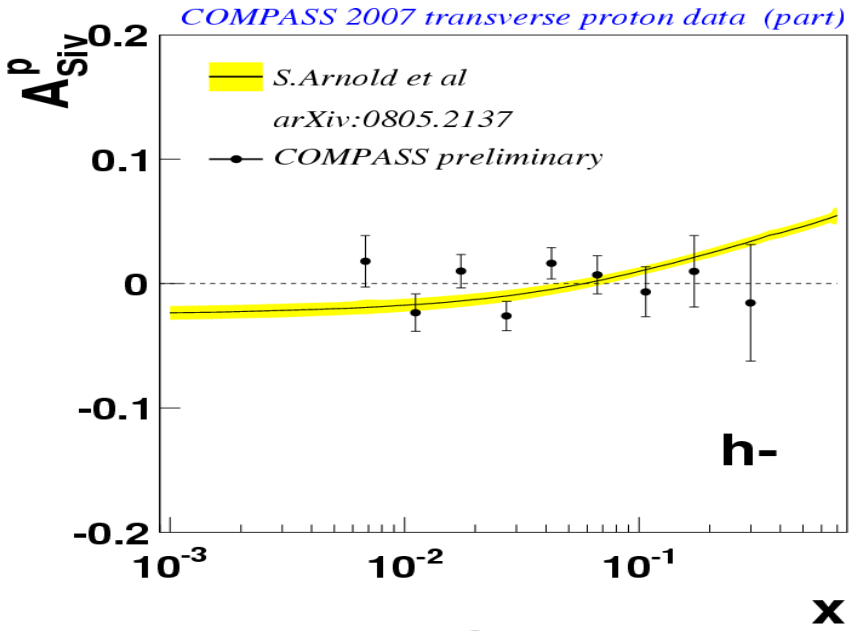



COMPASS proton data for h+ and h-, with the latest prediction of Anselmino et al.
M. Anselmino et al. ``Sivers Effect for Pion and Kaon Production in Semi-Inclusive Deep Inelastic Scattering,'' arXiv:0805.2677 [hep-ph].

## Comparison with predictions from

*S.Arnold, A.V.Efremov, K.Goeke, M.Schlegel and P.Schweitzer, arXiv:0805.2137*




$$A_{UT\,\text{measured}}^{\sin(\phi-\phi_S)} = \left\{ \text{'twist-2 Sivers effect' in Eqs. (11, 15)} \right\} + C(Q)\frac{M_N^2}{Q^2}$$

Maybe such corrections are irrelevant for $Q^2 > 1\,\text{GeV}^2$ which is typically used as DIS-cut. In any case, a careful comparison of all (present and future) data from COMPASS, HERMES and JLab will shed light on the possible size of power corrections.

*3 further independent modulations in the hadron azimuthal distribution*

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

*Cahn, Boer Mulder, pQCD*

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

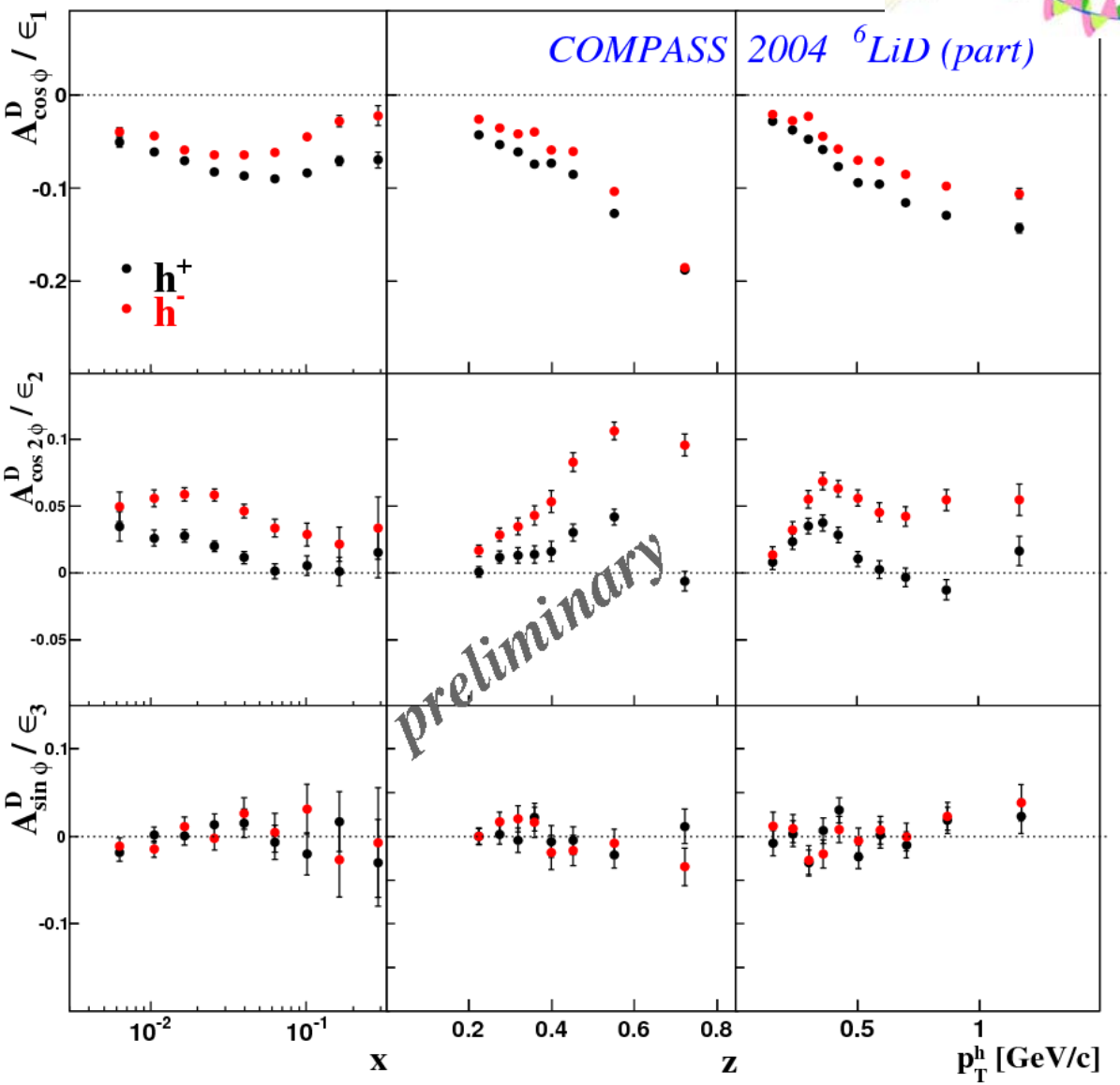
$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

*Beam polarisation effect*

# Just a flash on unpolarized azimuthal asymmetries in SIDIS at COMPASS

- *positive hadrons*
- *negative hadrons*

- sinϕ compatible with zero
- cosϕ strong effect (up to 40%),
- cos2ϕ up to 10%
  (good general agreement
  with predictions)
- Differences between asymmetries from positive and negative hadrons (cosϕ and cos2ϕ) → hint of BM PDF
- New input for theoretical work and the better understanding of the nucleon structure



# Conclusions

Full set of measurements on the data collected on a deuterium target in 2002-2004→ analysis finalized

New result Collins and Sivers asymmetries on protons (polarized)

- Collins asymmetry different from zero
  →the effect is there at COMPASS energies
- Sivers asymmetry: small, compatible with zero
  →to be understood

New result of unpolarised asymmetries

Near future: analysis of the whole 2007 proton data sample

Identified hadron results coming soon

Longer terms project (after 2010)

Precision SIDIS measurements for flavor separation

Drell-Yan measurements (first test done during 2007 data taking)

Thank you