Recent transverse spin results from COMPASS

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On behalf of the COMPASS Collaboration

2009 RHIC & AGS Annual Users' Meeting

longitudinally polarised muon beam

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

beam momentum: 160 GeV/*c*

longitudinally or transversely polarised target

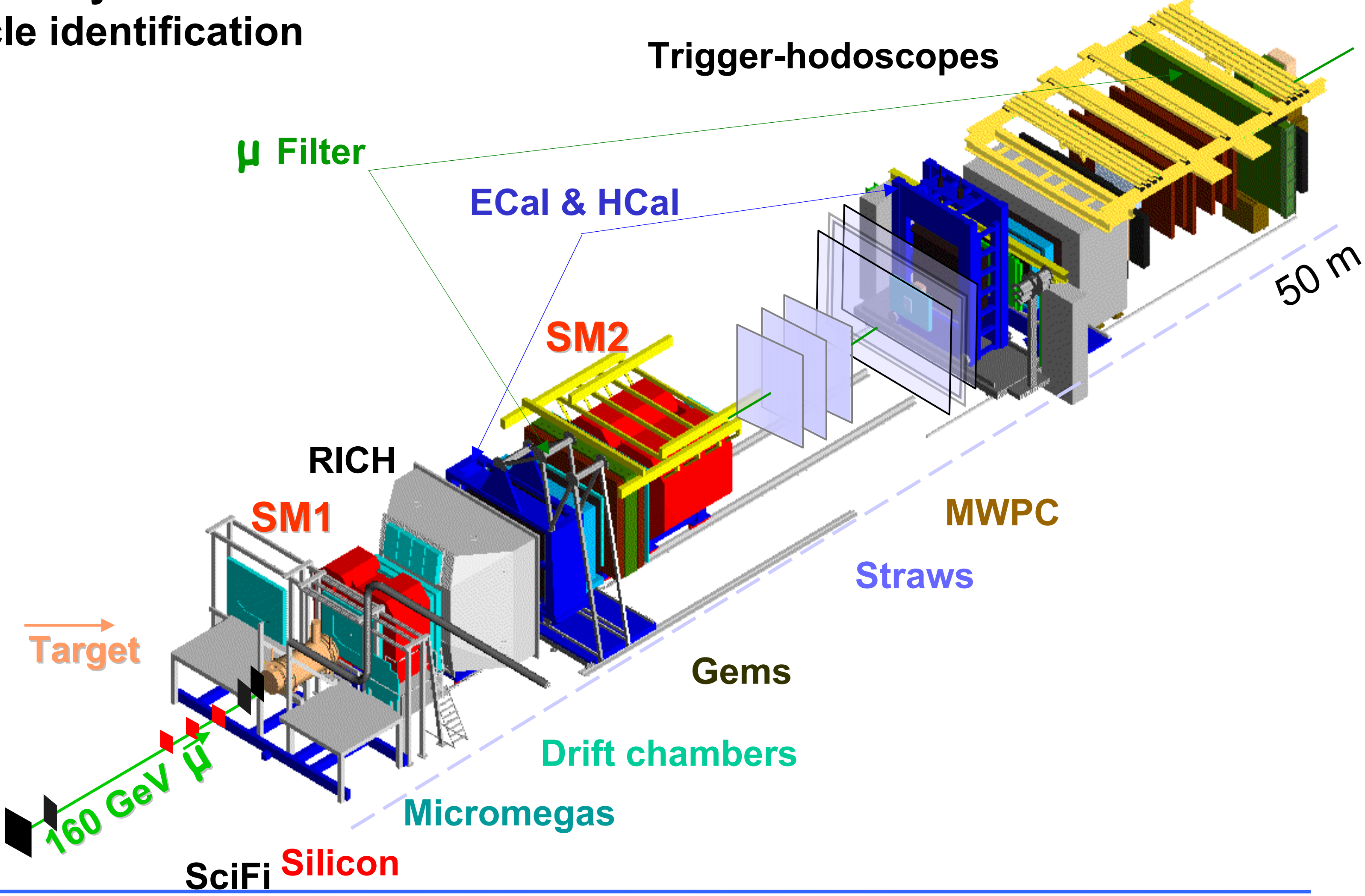
luminosity: $\sim 5 \cdot 10^{32}$ cm^{-2} s^{-1}

The COMPASS spectrometer

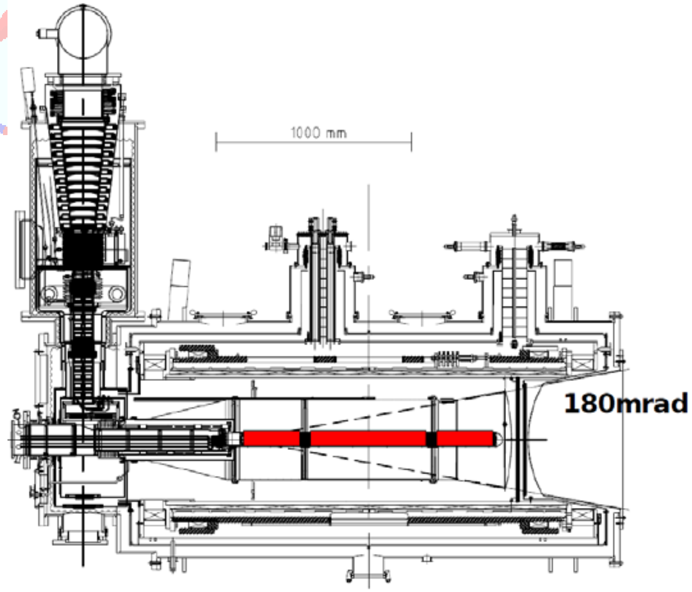
TWO STAGE SPECTROMETER

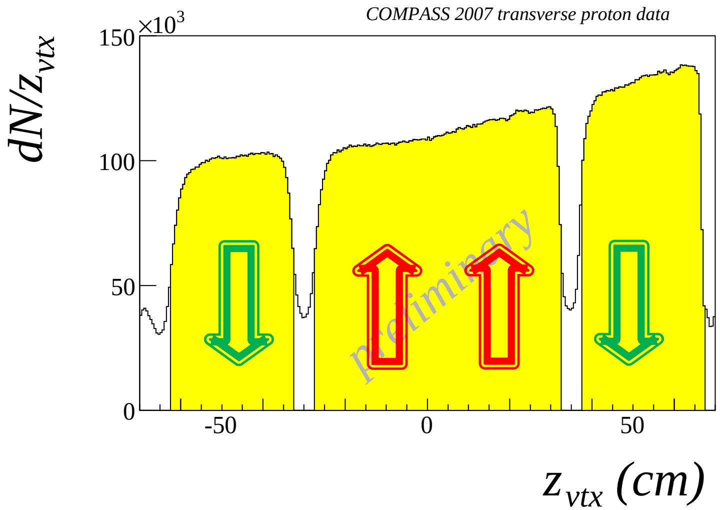
calorimetry

particle identification



Polarized Target in 2007





New COMPASS target magnet:

- 180 mrad geometrical acceptance

Target material: NH_3

- high polarisation: ~90%
- dilution factor f~0.15
- very long relaxation time (~ 4000 h)
- Target Polarization reversed every week

Transverse data taking

2002-4: ^{6}LiD target, 20% time dedicated to transverse data taking.
Many results: Collins, Sivers, other 6 SSA, 2h, Λ, unpolarized SSA.

2007: NH_3 target, 50% time dedicated to transverse data taking;
preliminary results on Collins, Sivers, 2h, Λ.

SIDIS cross section: Collins and Sivers SSA

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

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

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

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

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

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

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

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

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

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

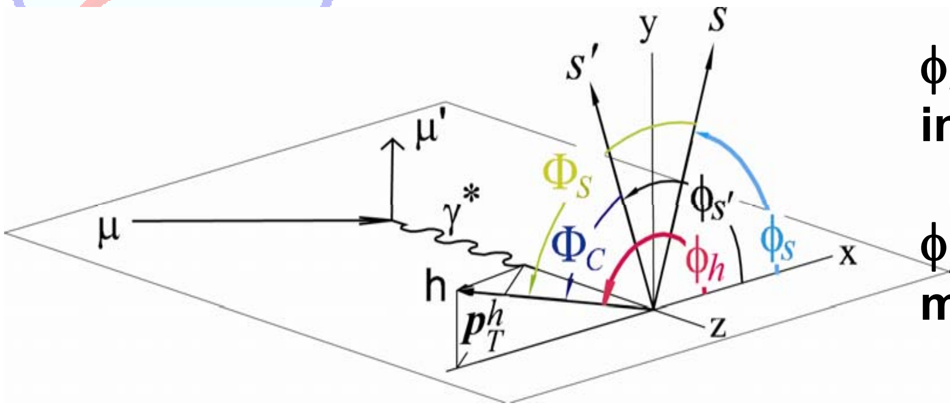
Sivers

Collins

SIDIS cross section:
18 structure functions,
8 transverse target dependent spin asymmetries
with different azimuthal dependences

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

Azimuthal modulations: Sivers SSA



ϕ_S azimuthal angle of spin vector of initial quark

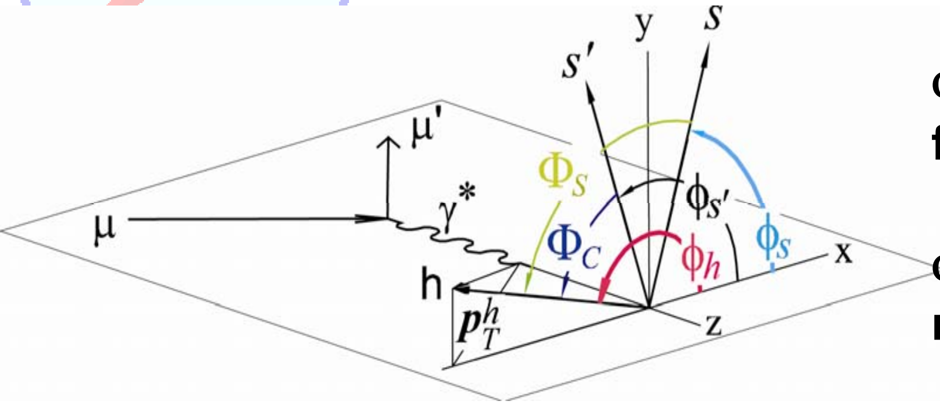
ϕ_h azimuthal angle of hadron momentum

$\Phi_S = \phi_h - \phi_S$ Sivers angle

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

Sivers PDF ⊗ FF

Azimuthal modulations: Collins SSA



$\phi_{S'}$ azimuthal angle of spin vector of fragmenting quark ($\phi_{S'} = \pi - \phi_S$)

ϕ_h azimuthal angle of hadron momentum

$\Phi_C = \phi_h - \phi_{S'} = \phi_h + \phi_S - \pi$ Collins angle

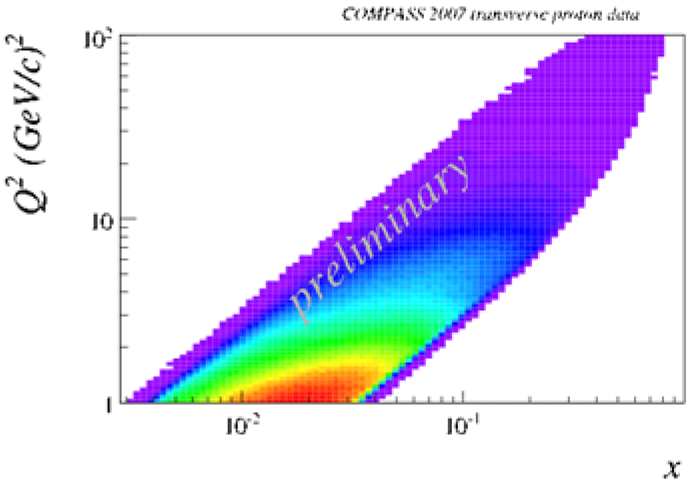
$$A_{Coll} = \frac{A_C^h}{f \cdot P_T \cdot D_{nn}} = \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

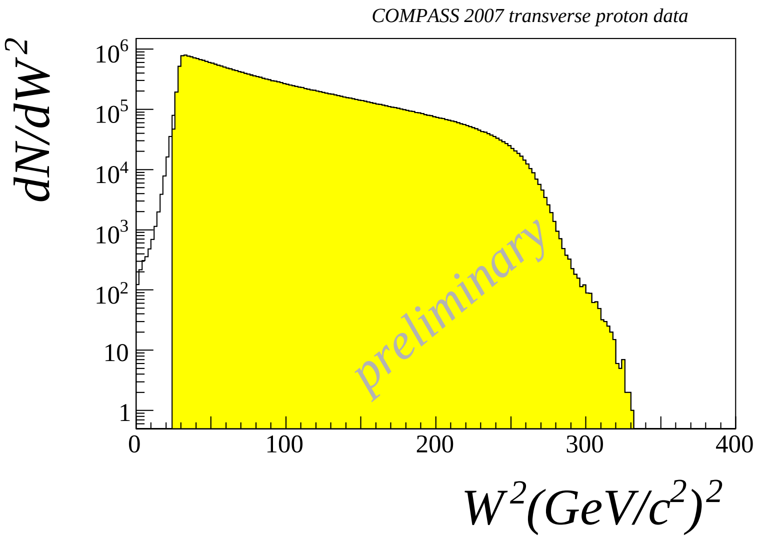
← "transversity" PDF ⊗ Collins FF

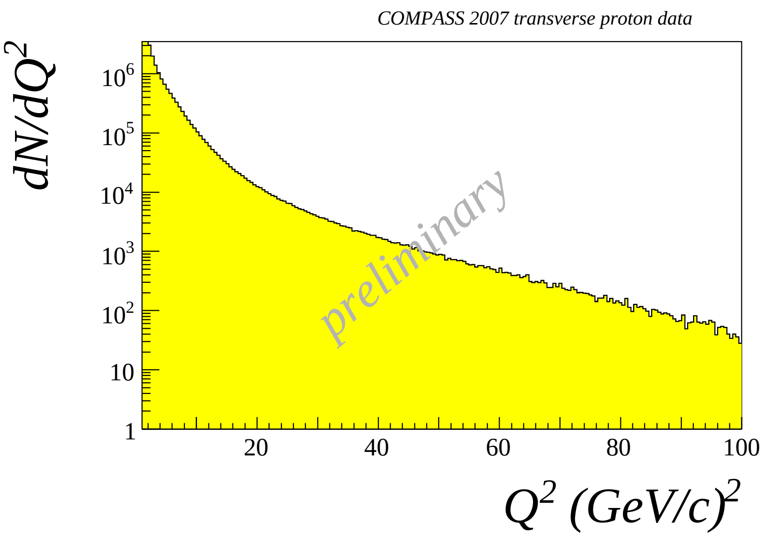
Data Selection

DIS event selection:

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







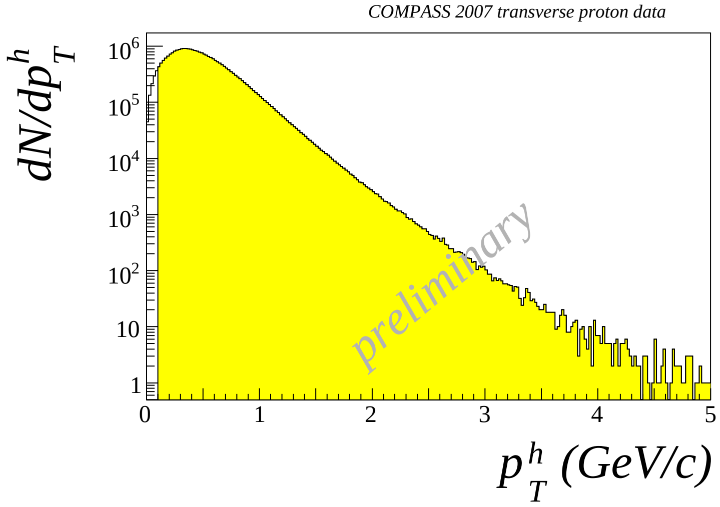
Data Selection

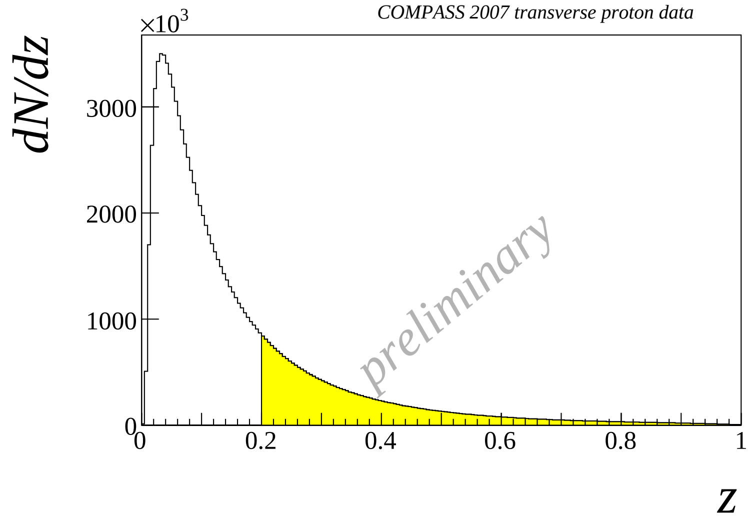
DIS event selection:

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

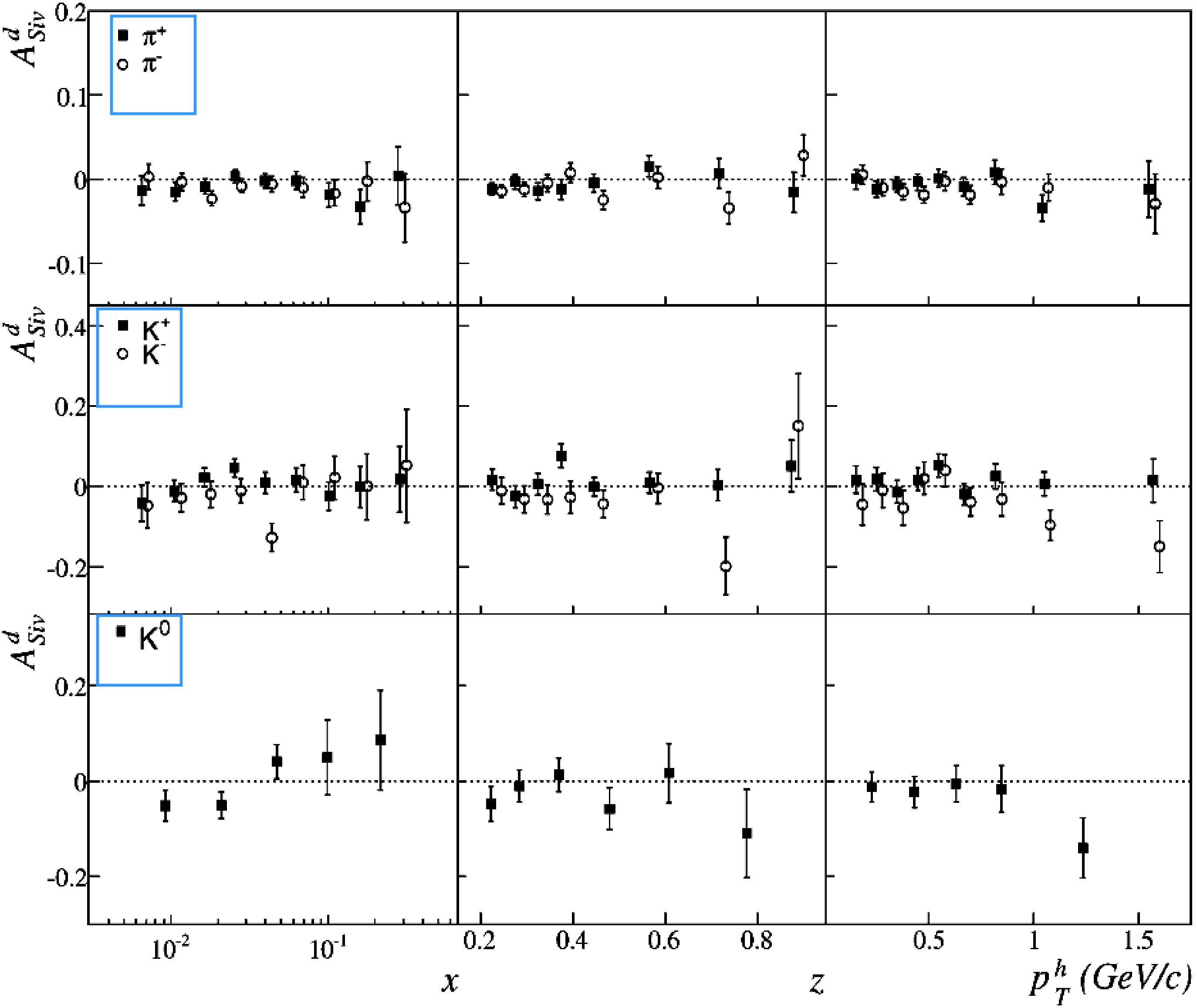
Hadron selection

- $p_T>0.1$ GeV/c
- $z>0.2$





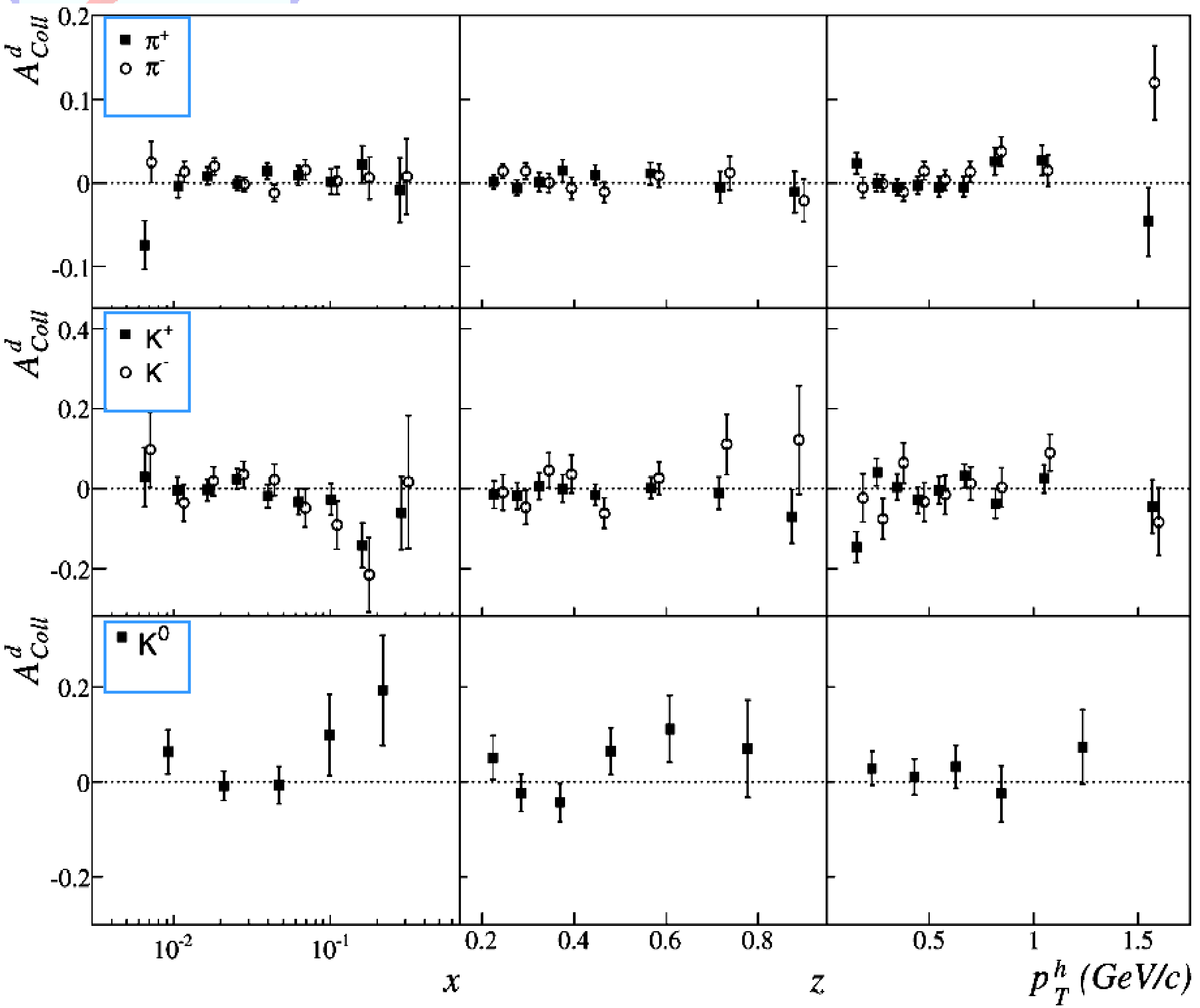
Results: Sivers asymmetries on deuteron



COMPASS Collaboration Physics Letters B 673 (2009) 127–135

Values corrected for the purity;
systematic error below 30% of the statistical one

Results: Collins asymmetries on deuteron

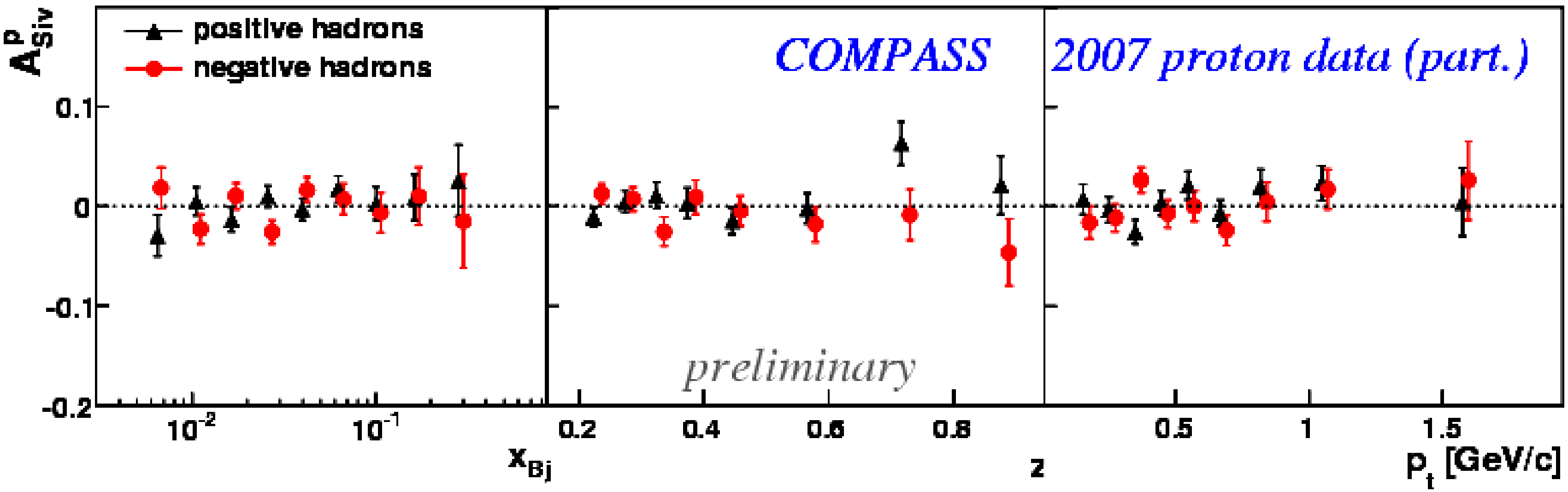


COMPASS Collaboration Physics Letters B 673 (2009) 127–135

Values corrected for the purity;
systematic error below 30% of the statistical one

Results:
Sivers asymmetries on proton

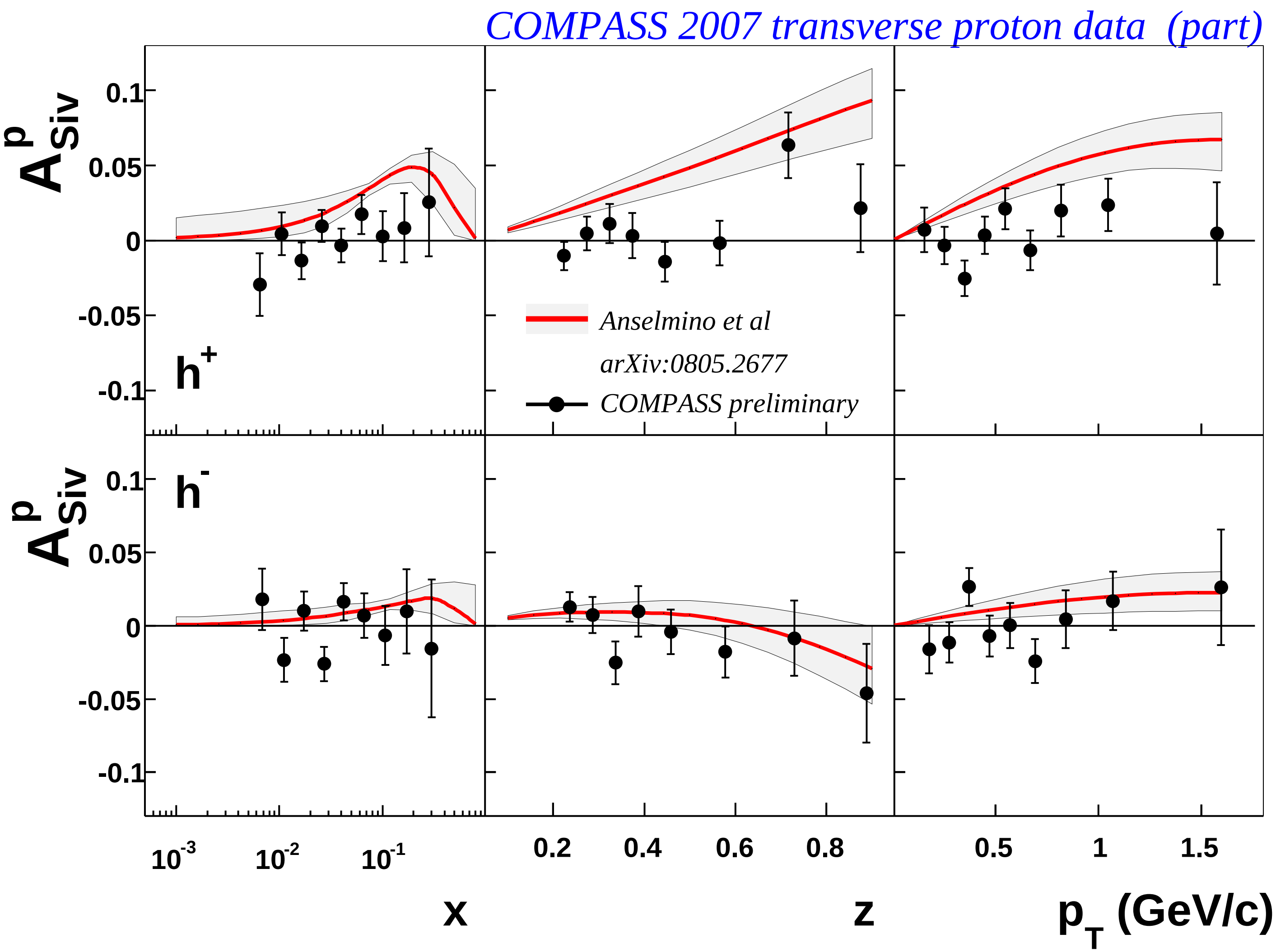
Results on the second half of the collected data (Transversity 2008).



systematic errors ~ 0.5 σ_{stat}

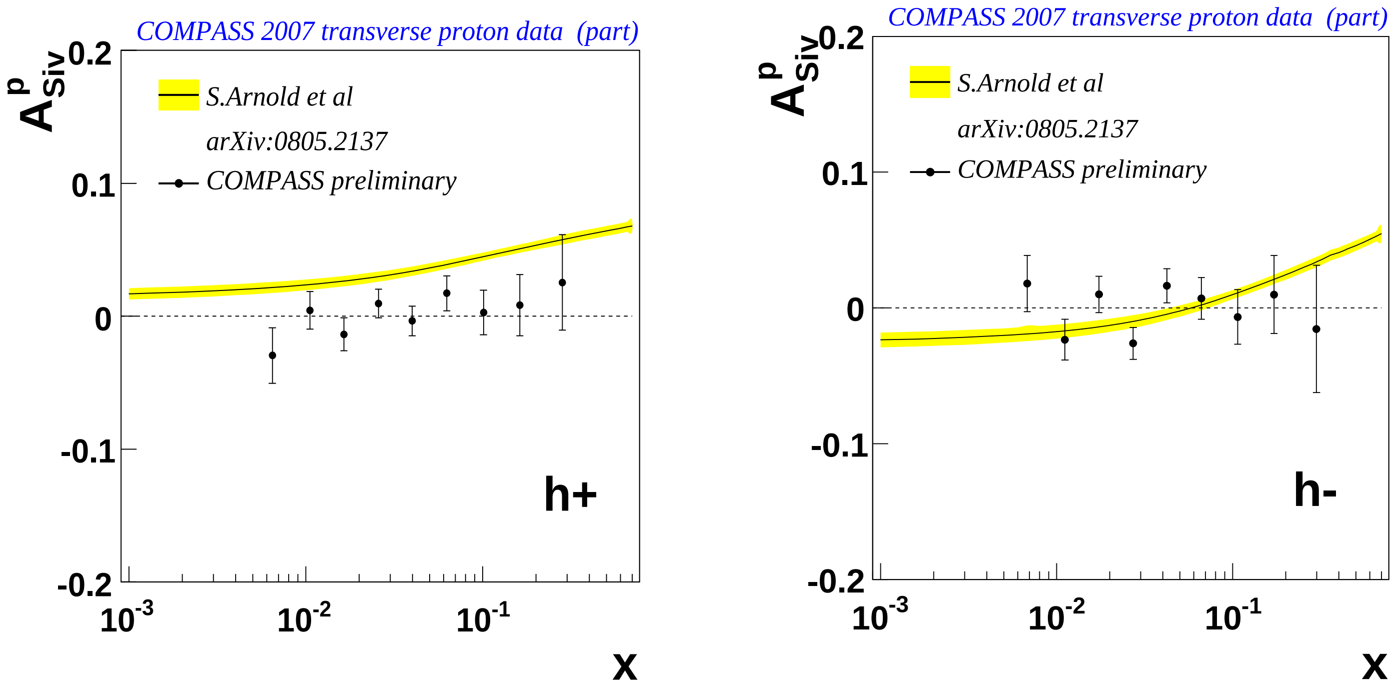
the measured asymmetries are small, compatible with zero

Sivers asymmetry: comparison with predictions



comparison with predictions from

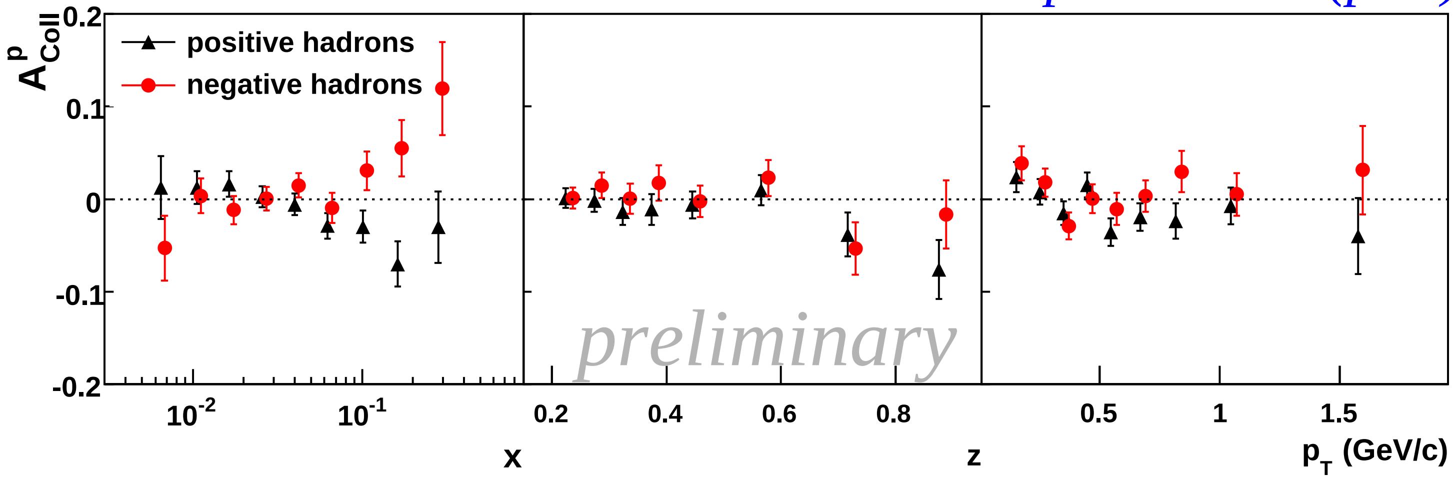
S.Arnold, A.V.Efremov, K.Goeke, M.Schlegel and P.Schweitzer, arXiv:0805.2137



Results: Collins asymmetry on proton

Results on the second half of the collected data (Transversity 2008).

COMPASS 2007 proton data (part)

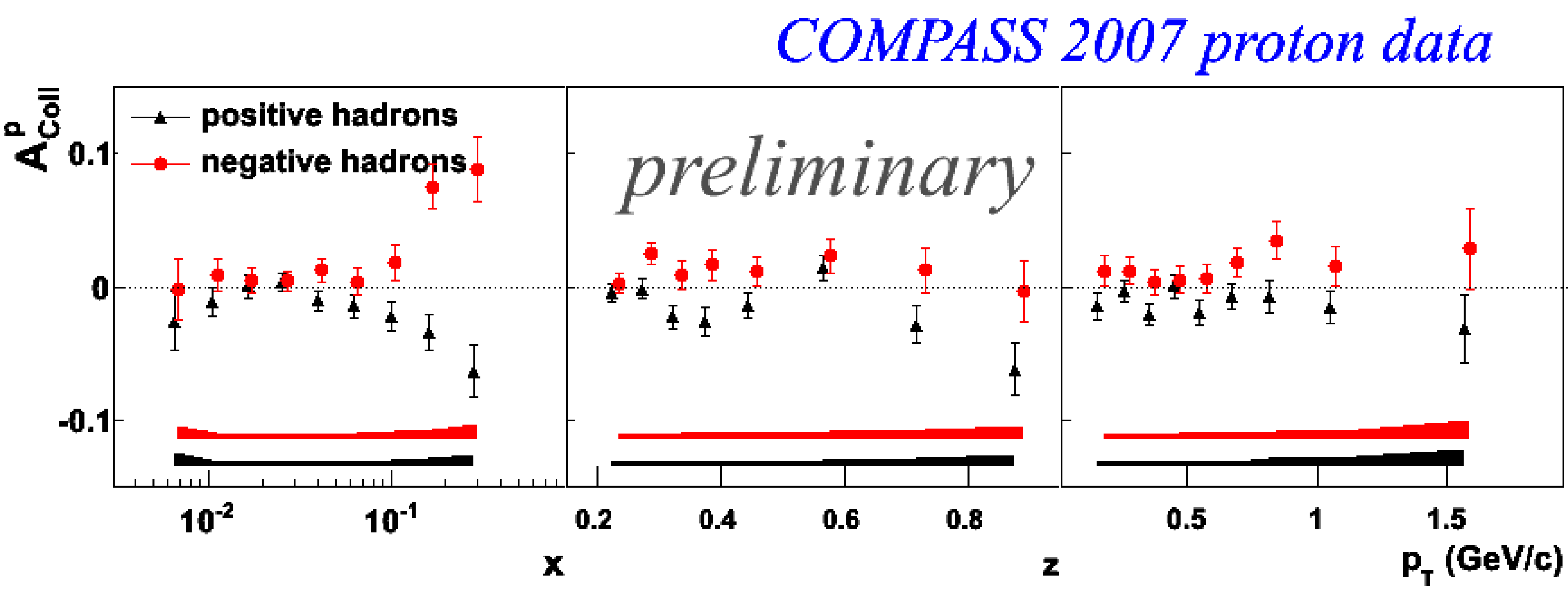


systematic errors ~ 0.3 σ_{stat}

at small x, the asymmetries are compatible with zero
in the valence region the asymmetries are different from zero,
of opposite sign for positive and negative hadrons,
and have the same strength and sign as HERMES

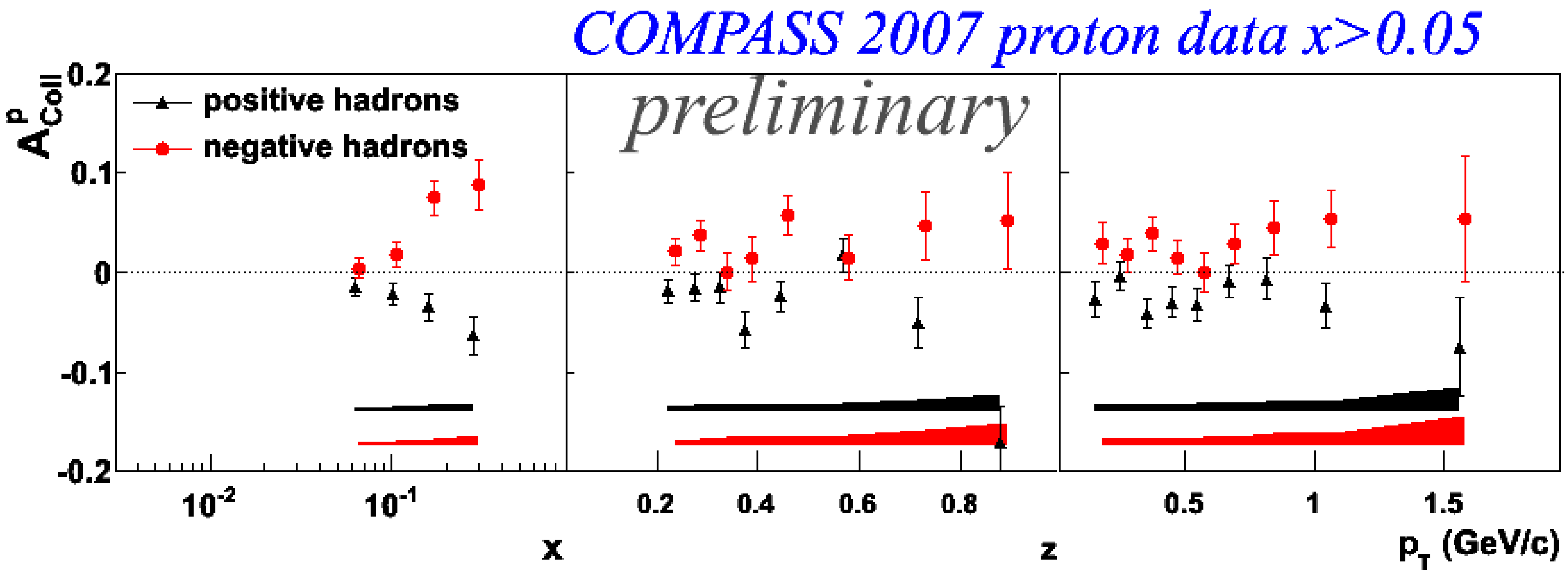
Results:
Collins asymmetry on proton

1 year spent to further analyse the data collected in the first part of 2007 data taking; results in an increase of usable statistics for the Collins asymmetries by ~ a factor 3,
while previous results for Sivers have been confirmed

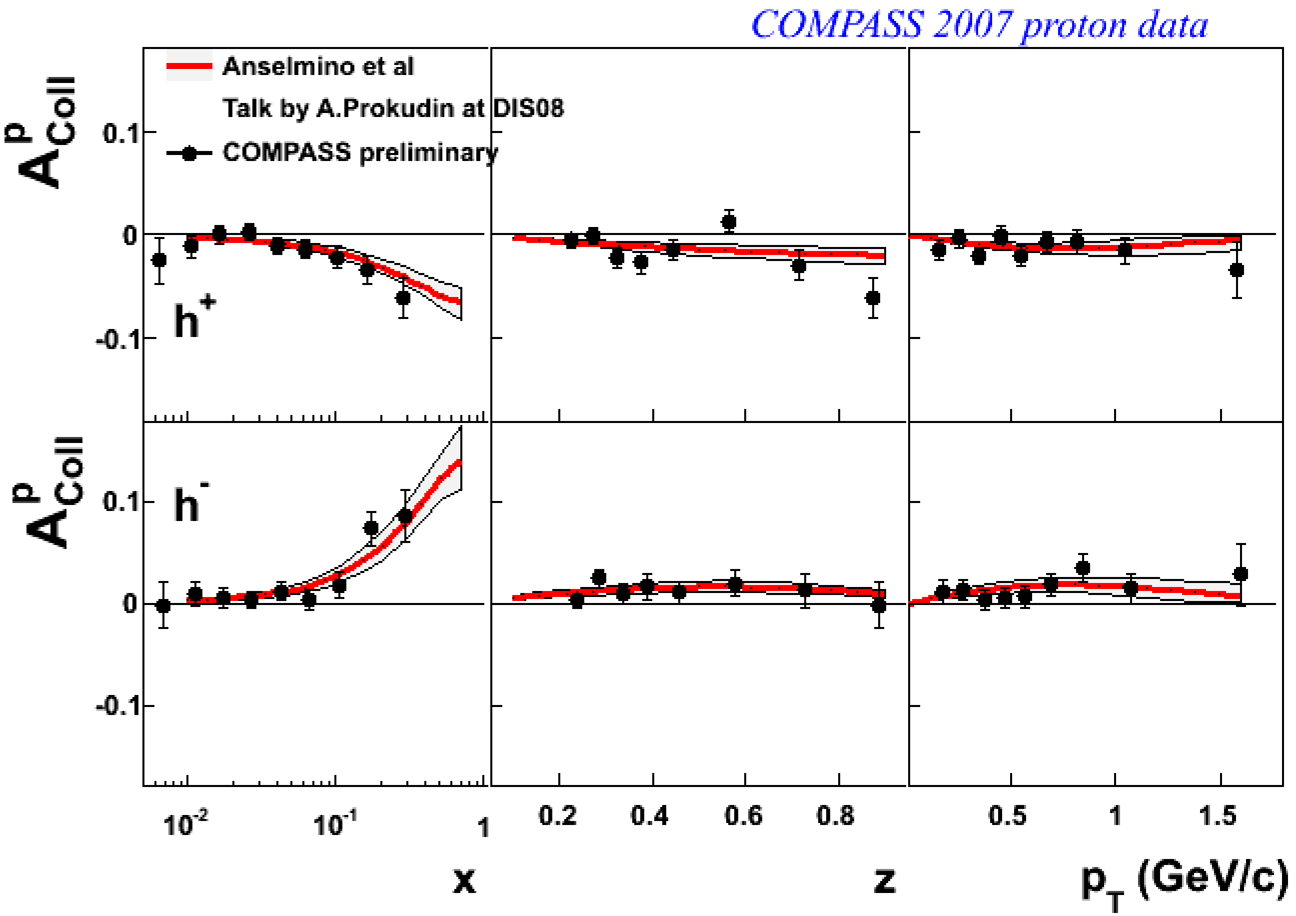


DIS09

Results:
Collins asymmetry on proton



Collins asymmetry: comparison with predictions



SIDIS cross section: other SSA

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

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

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

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

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

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

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

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

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

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

Sivers

Collins

twist-2 contribution

Remaining four can be interpreted as twist-3 contributions

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

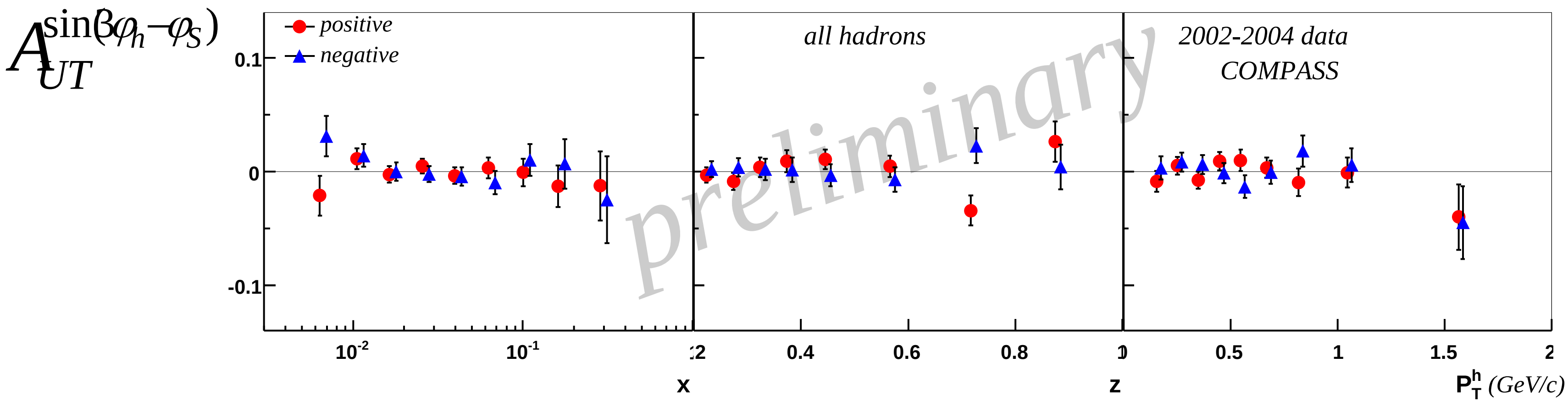
Other single spin asymmetries, deuteron target

$$F_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$

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

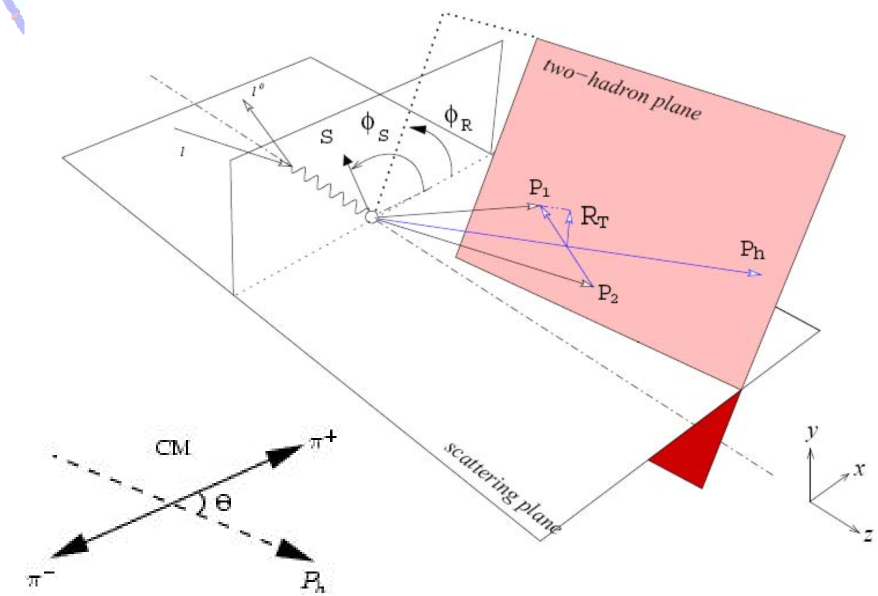
Two twist-2 asymmetries can be interpreted in QCD parton model and will allow to extract unexplored DFs.

"pretzelosity" ⊗ Collins FF



asymmetries found compatible with zero on deuteron: again cancellation between proton and neutron?

Two Hadron Asymmetries



Another channel that can be used to access transversity is the inclusive production of hadron pairs.

The measurement is based on a an azimuthal asymmetry in the angle $\phi_{RS} = \phi_{R\perp} - \phi_S$, in which $\phi_{R\perp}$ is the angle of the plane containing the two hadrons

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

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

Transversity distribution function

Interference fragmentation function

A. Bacchetta, M. Radici, hep-ph/0407345
X. Artru, hep-ph/0207309

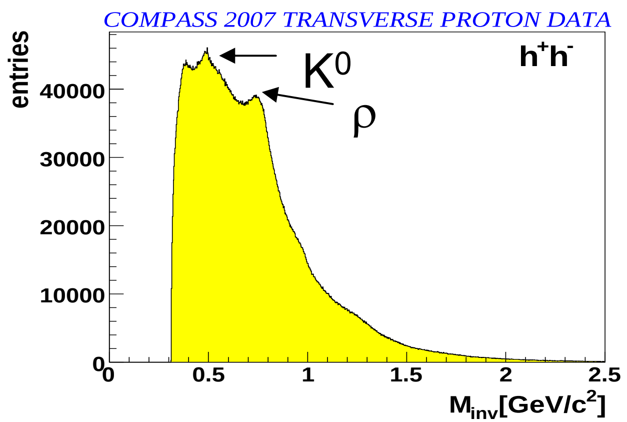
Two Hadron Asymmetries : results on proton

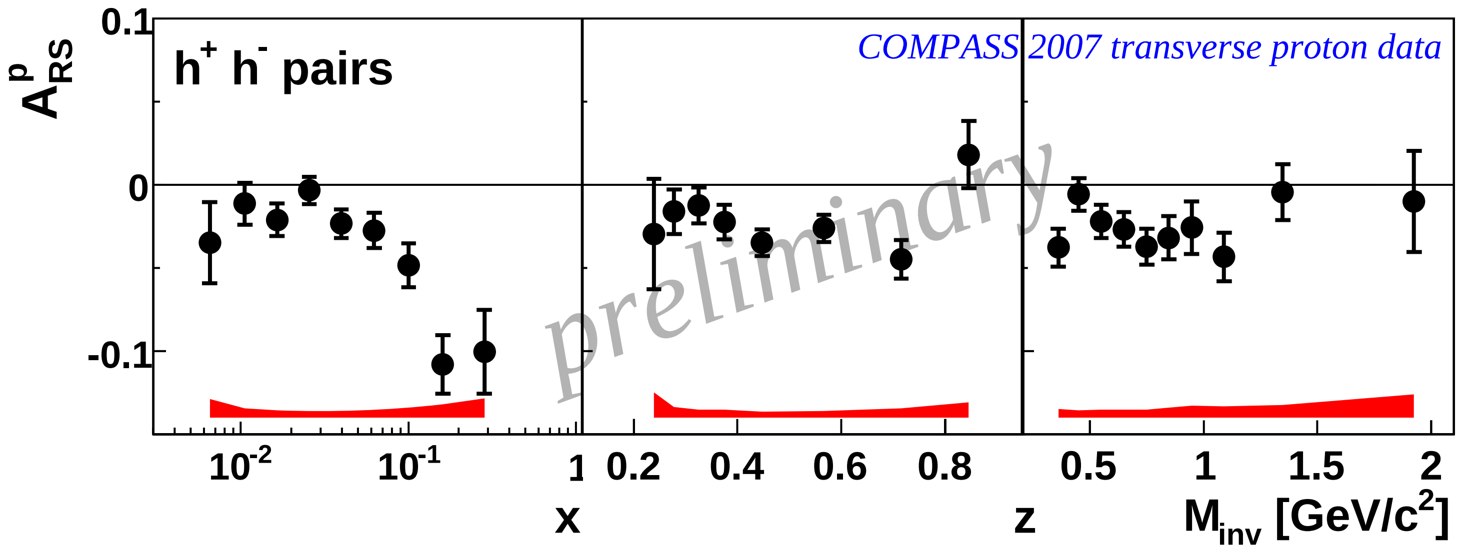
$x_F>0.1$

$z>0.1$

Zsum = $z1+z2<0.9$

R_T >0.07GeV/c

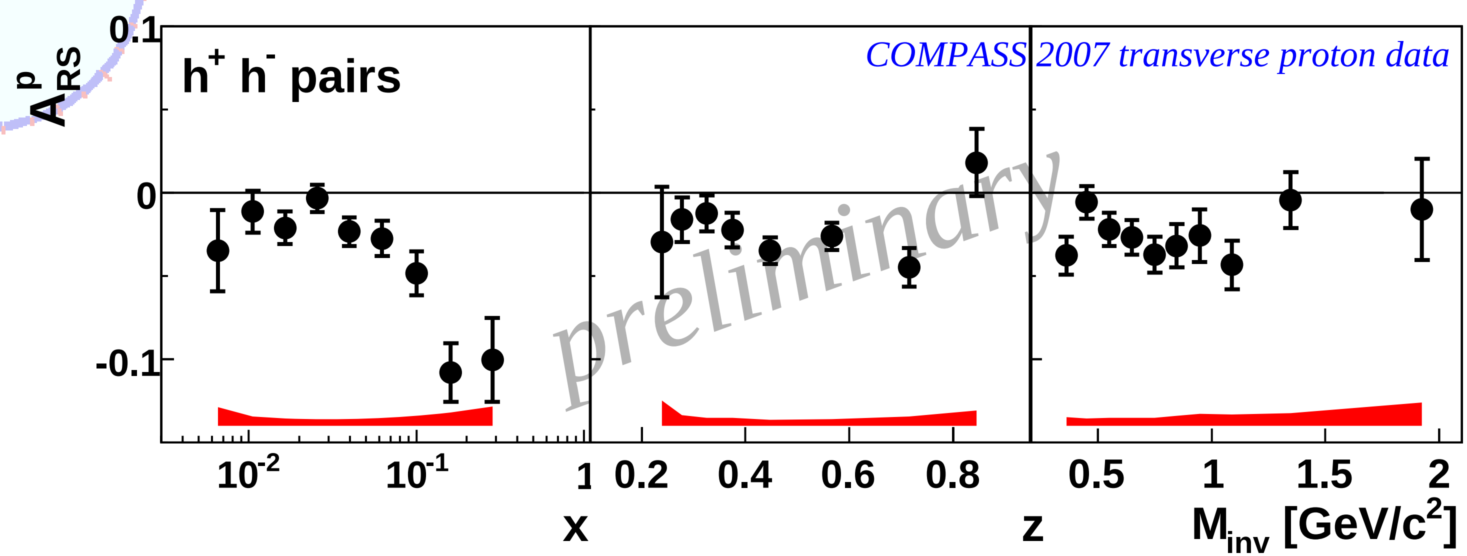


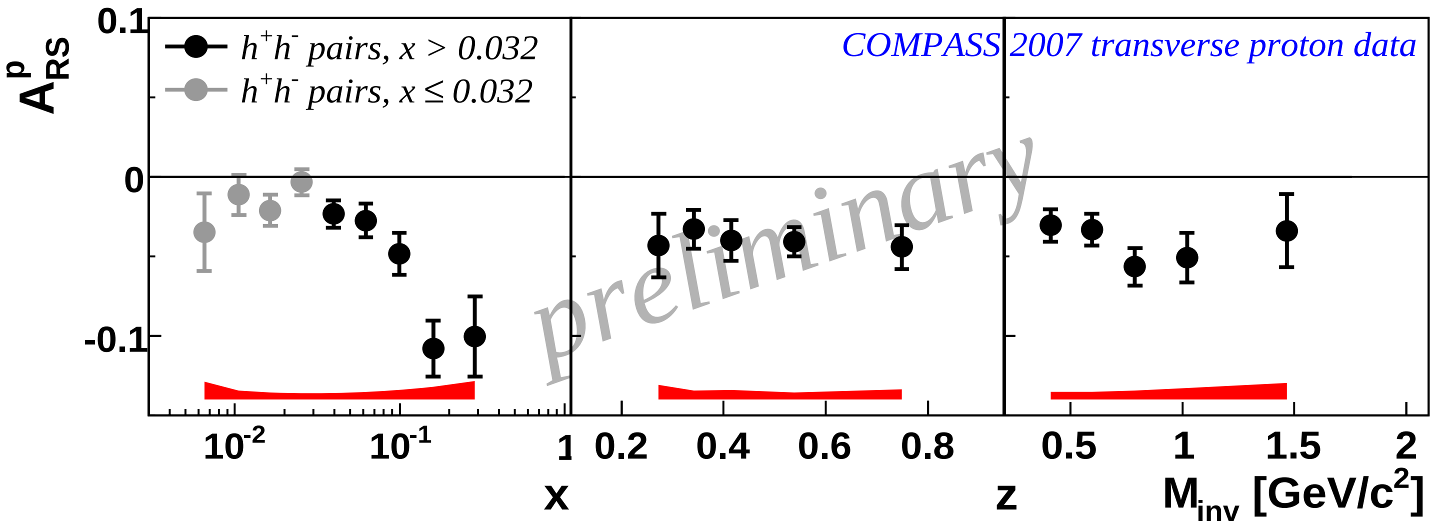


DIS09

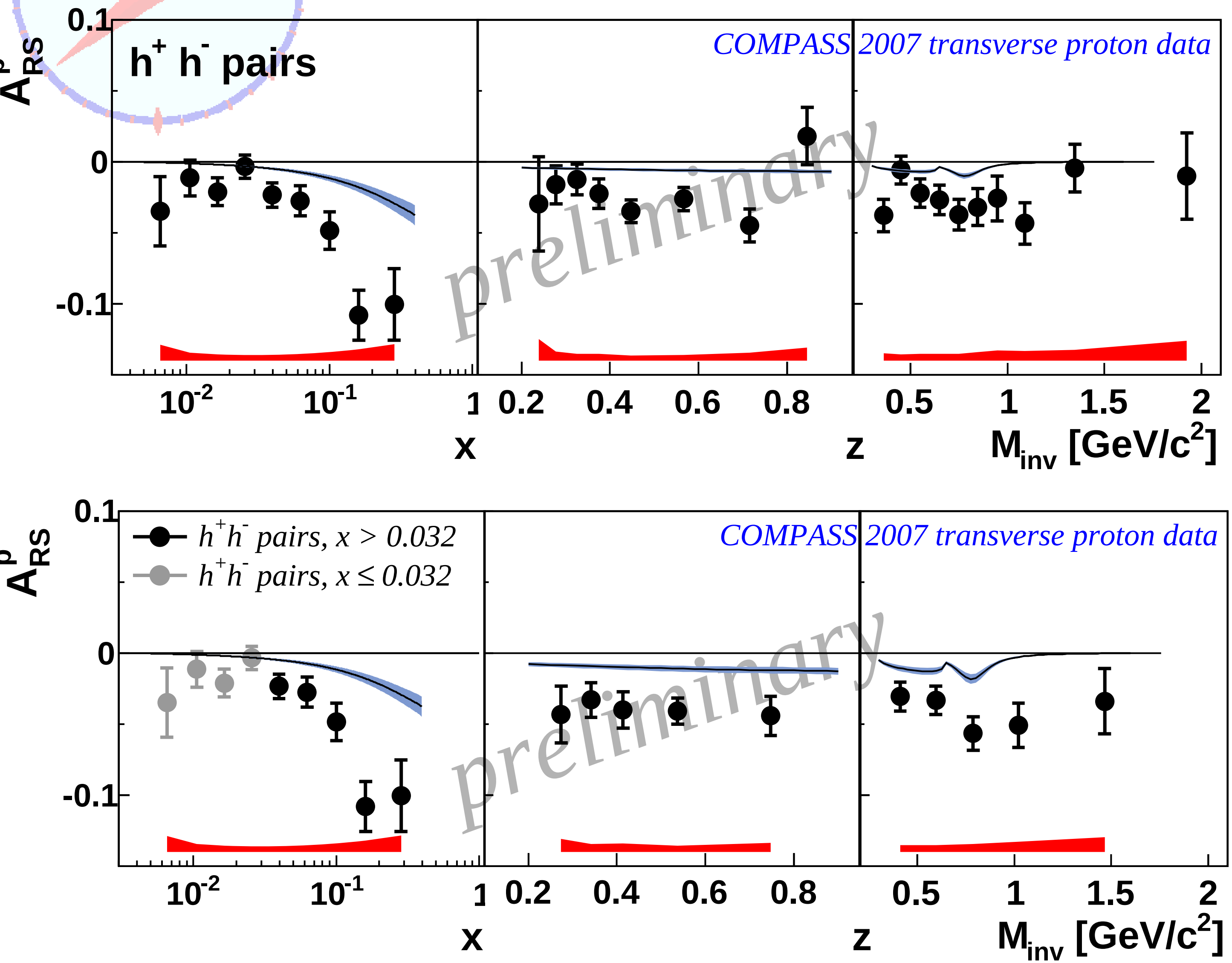
in the valence region the asymmetries are different from zero, signal larger than measured by HERMES

Two Hadron Asymmetries : results on proton





Two Hadron Asymmetries : comparison with predictions



Courtesy of A.Bacchetta

SIDIS cross section: unpolarized part

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = {} & \\
\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right) \Big\{ & F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\, F_{UU}^{\cos\phi_h} \\
& + \varepsilon\cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\, F_{LU}^{\sin\phi_h} \\
& + S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h}\right] \\
& + S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\, F_{LL}^{\cos\phi_h}\right] \\
& + |\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
& \quad + \varepsilon\,\sin(\phi_h+\phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} \\
& \quad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
& + |\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\, F_{LT}^{\cos\phi_S} \\
& \quad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
$$

3 independent modulations in the hadron azimuthal distribution

Sivers

Collins

twist-2 contribution

Remaining four can be interpreted as twist-3 contributions

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

SIDIS cross section: unpolarized part

Also the azimuthal asymmetries in the unpolarized cross section give information on TMD effects...

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(xe\,H_1^\perp + \frac{M_h}{M}\,f_1\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{h}\cdot p_T}{M}\left(xg^\perp D_1 + \frac{M_h}{M}\,h_1^\perp\frac{\tilde{E}}{z}\right)\right]$$

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(xh\,H_1^\perp + \frac{M_h}{M}\,f_1\frac{\tilde{D}^\perp}{z}\right) - \frac{\hat{h}\cdot p_T}{M}\left(xf^\perp D_1 + \frac{M_h}{M}\,h_1^\perp\frac{\tilde{H}}{z}\right)\right]$$

Cahn effect +
Boer-Mulders DF

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

Boer- Mulders x Collins FF
+ Cahn effect

Cahn effect
kinematical effect due to
quark intrinsic momentum

$$\frac{d\sigma}{d\phi_h} \propto 1 - 4\frac{\langle k_t^2\rangle z P_t}{Q\langle P_t^2\rangle} D_{\cos\phi_h}(y)\cos\phi_h + \ldots$$

Boer-Mulders PDF

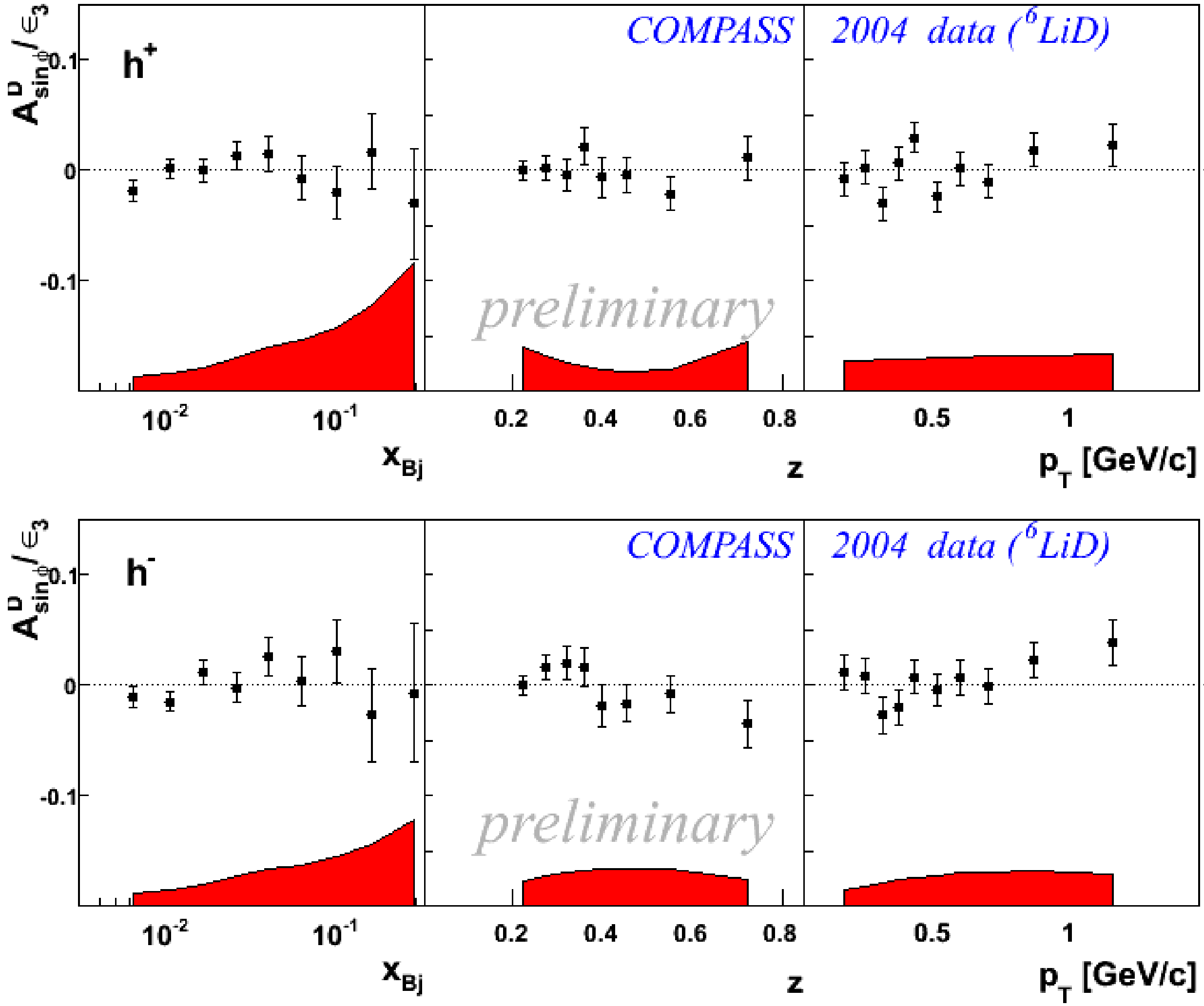
quark with spin parallel to the nucleon spin in an unpolarised nucleon

pQCD contributions expected to be important for pT>1GeV/c

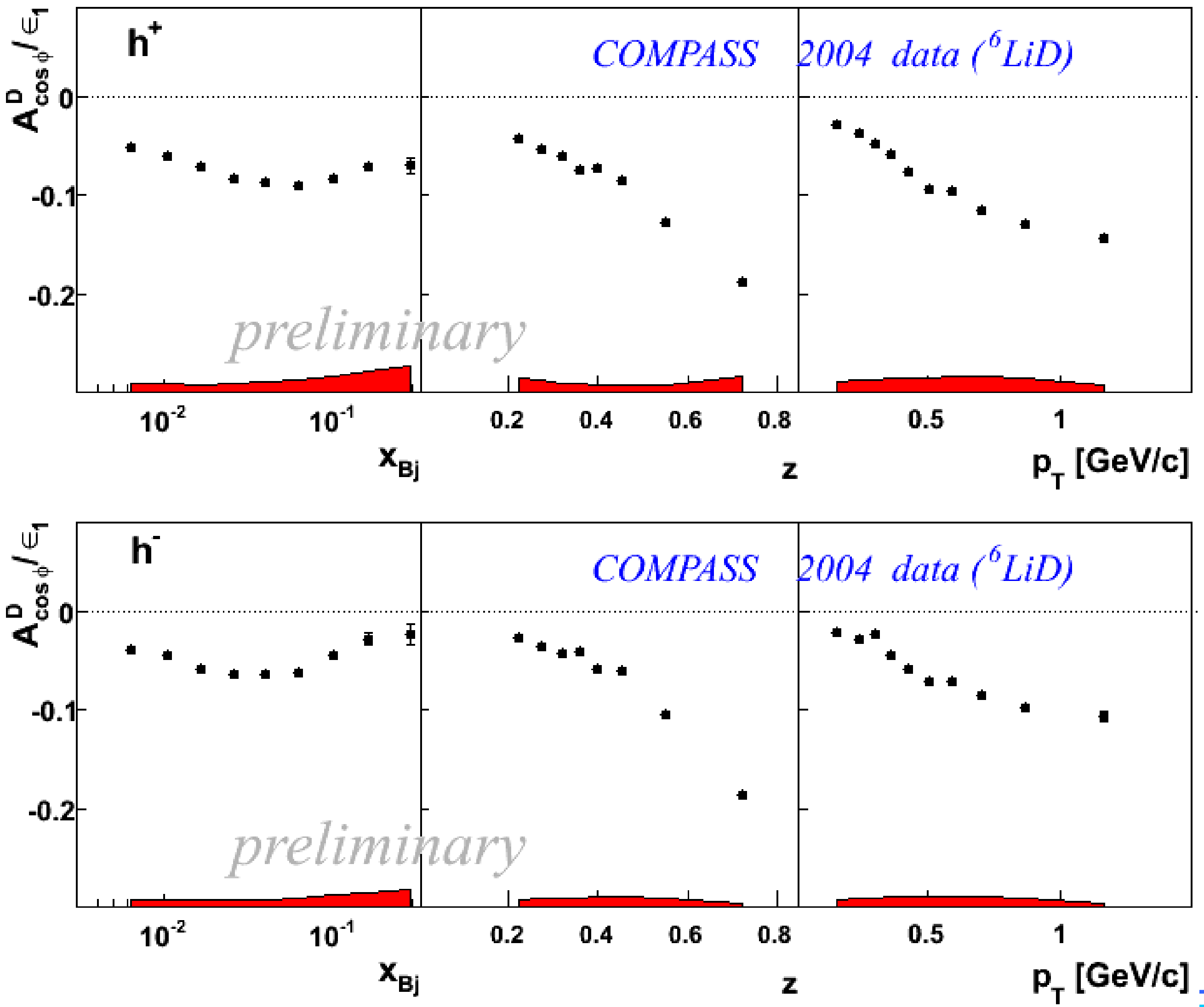
Results: sinϕ asymmetries on deuteron

$A_{\sin\phi} / \varepsilon_s$

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



cosϕ asymmetries on deuteron



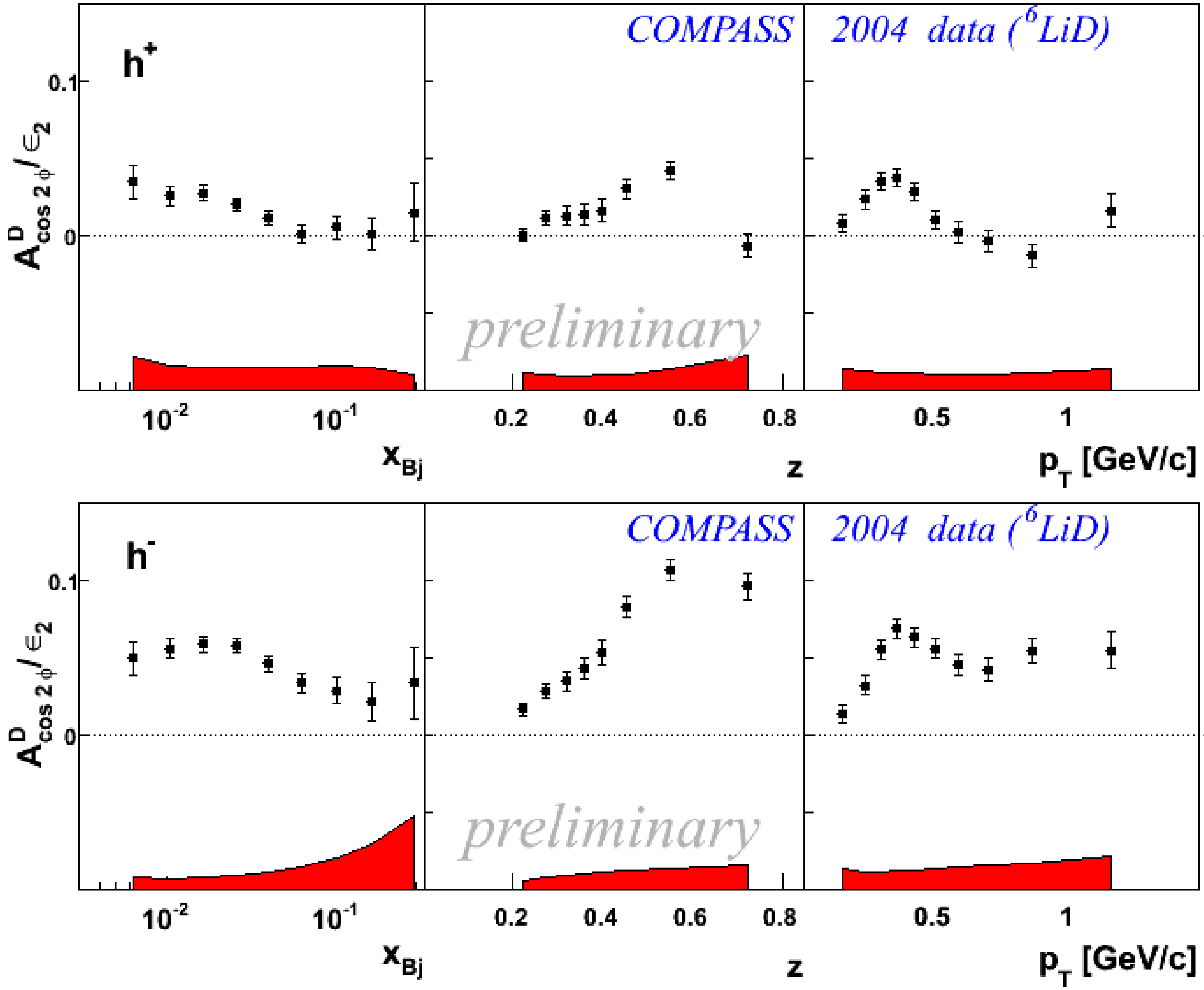
$A_{\cos\phi} / \varepsilon_c$

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

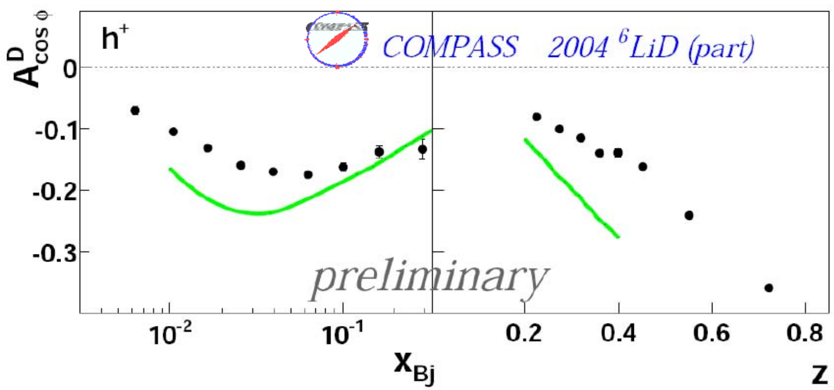
Results: cos2ϕ asymmetries on deuteron

$$A_{\cos 2\phi} / \varepsilon_2$$

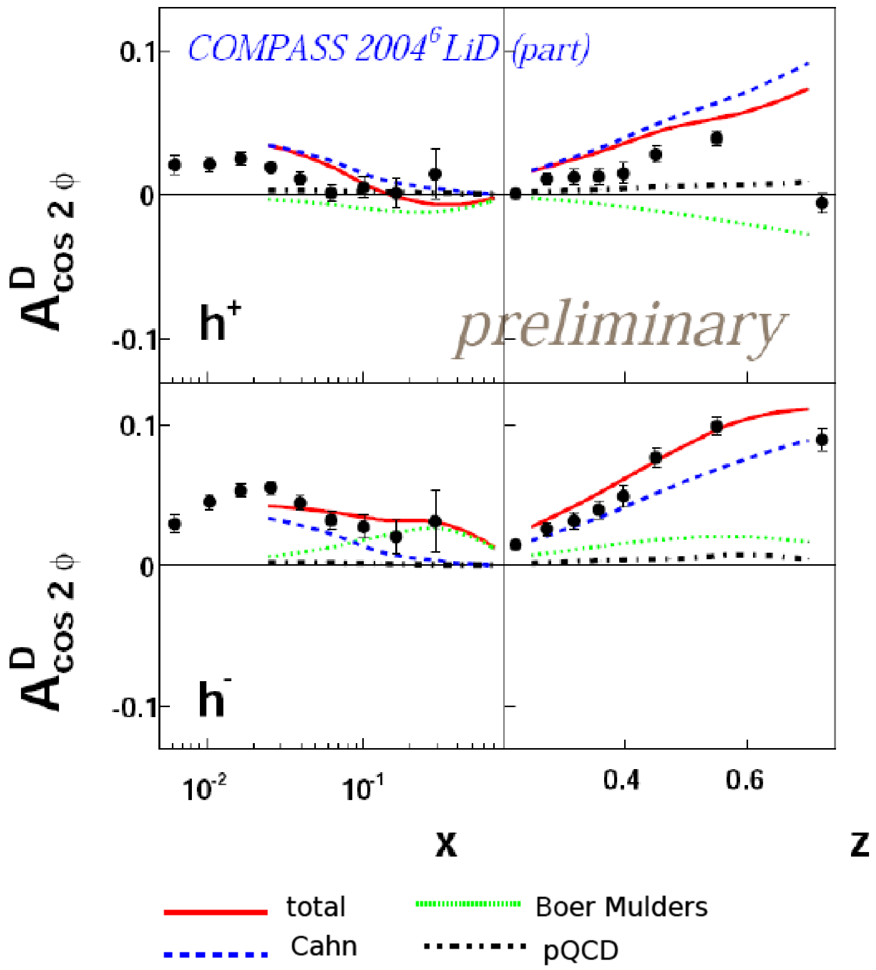
$$\varepsilon_2 = \frac{2(2-y)}{1+(1-y)^2}$$



cosϕ and cos2ϕ comparison with predictions



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



V.Barone, A.Prokudin, B.Q.Ma
arXiv:0804.3024 [hep-ph]

Conclusions

COMPASS investigated transverse spin and TMD effects using a **deuterium target in 2002-2004:**

- Collins and Sivers compatible with zero
- cosϕ strong effect, cos2ϕ up to 10%

From the analysis of **2007 data, with a NH_3 target**:

- Collins asymmetries are different from zero also in COMPASS kinematic domain
- no evidence of Sivers signal within the statistical errors
- 2h asymmetries are different from zero, signal stronger than Hermes

...more work ongoing to produce results on the other 6 SSA and on identified hadrons.

Conclusions

COMPASS investigated transverse spin and TMD effects using a **deuterium target in 2002-2004:**

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Future:

•Request to take data a full year with a proton target to

•improve statistics for Collins to investigate evolution and better measure both valence and low x region (COMPASS unique!)

•clarify the situation with Sivers, statistical errors expected to be similar to those of Hermes.

•Drell-Yan measurements (longer term project)

backup

Lambda asymmetries

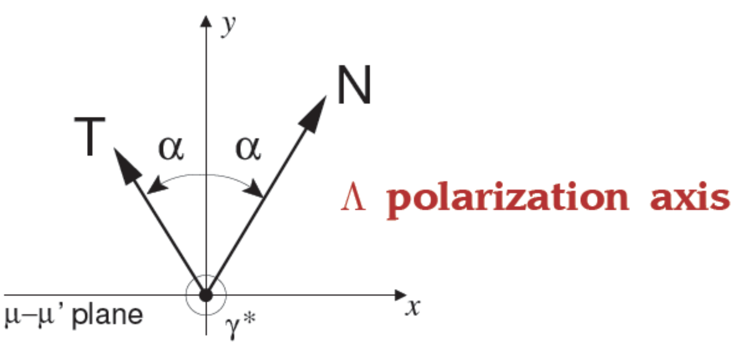
Information on $\Delta_T q$ can be accessed in the processes:

$$\mu\, N^{\uparrow} \rightarrow \mu'\, \Lambda\, X$$

$$\mu\, N^{\uparrow} \rightarrow \mu'\, \overline{\Lambda}\, X$$

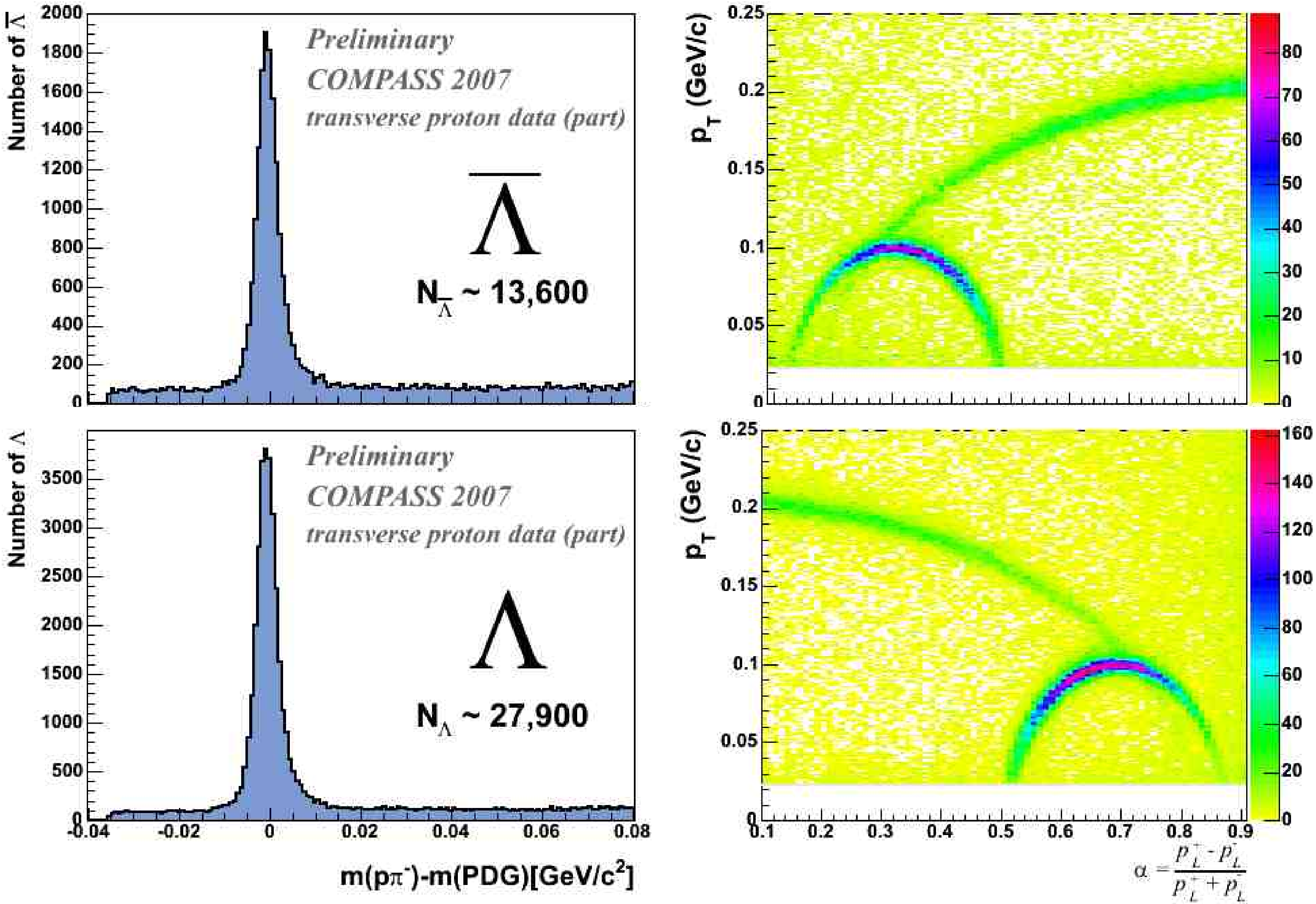
$$P^{\Lambda}_{T,exp} = \frac{d\sigma^{\mu N^{\uparrow}\rightarrow\mu'\Lambda^{\uparrow}X} - d\sigma^{\mu N^{\downarrow}\rightarrow\mu'\Lambda^{\uparrow}X}}{d\sigma^{\mu N^{\uparrow}\rightarrow\mu'\Lambda^{\uparrow}X} + d\sigma^{\mu N^{\downarrow}\rightarrow\mu'\Lambda^{\uparrow}X}}$$

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

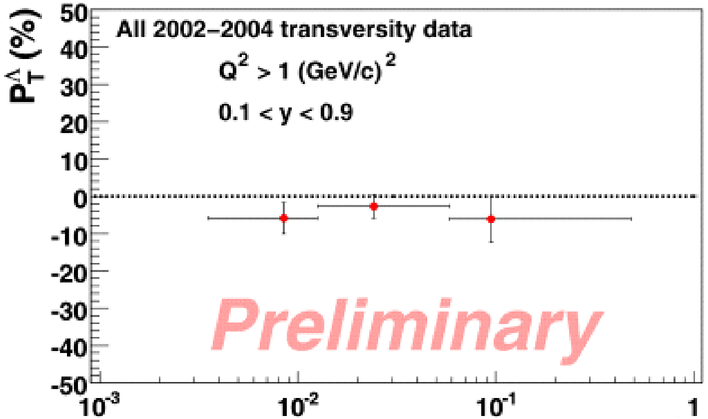


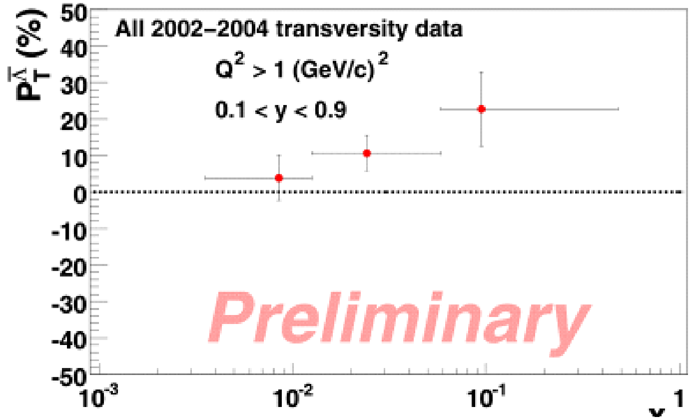
- Secondary vertex downstream of primary vertex.
- P_T > 23 MeV/c to exclude e^+e^- pairs
- *Proton* and pion momenta > 1 GeV/c
- $Q^2 > 1\ (GeV/c)^2$
- $0.1 < y < 0.9$
- Use of RICH (2007 data)
- Λ decay distance $D_\Lambda > 7\ \sigma_D$
- Collinearity < 10 mrad

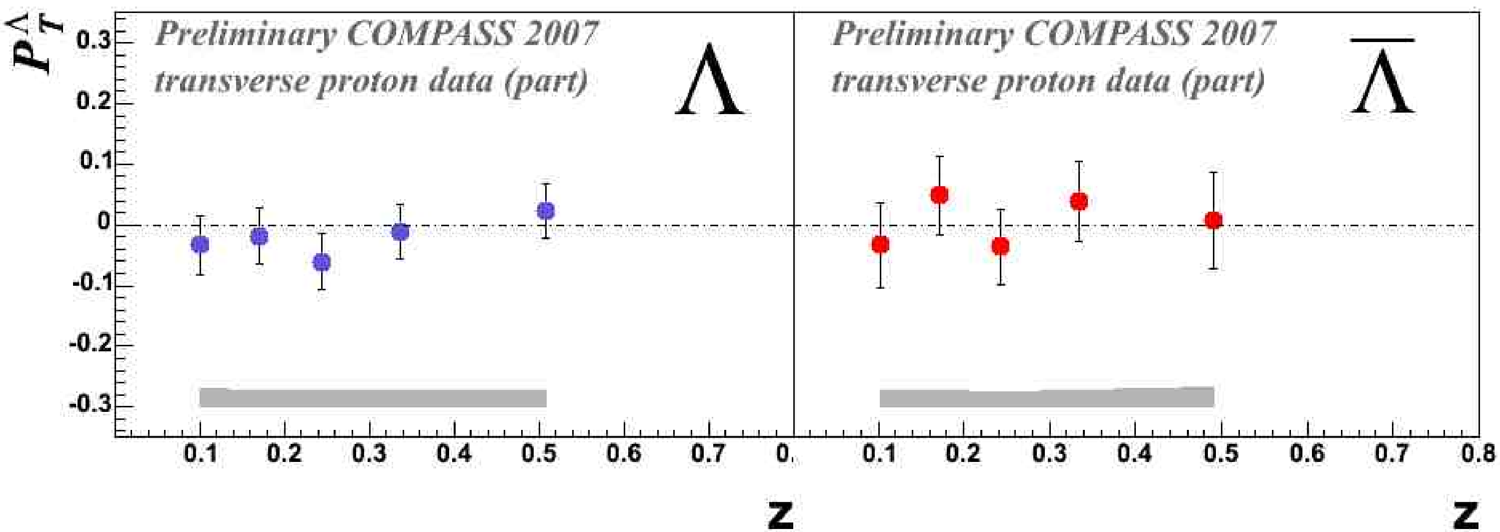
Data Selection



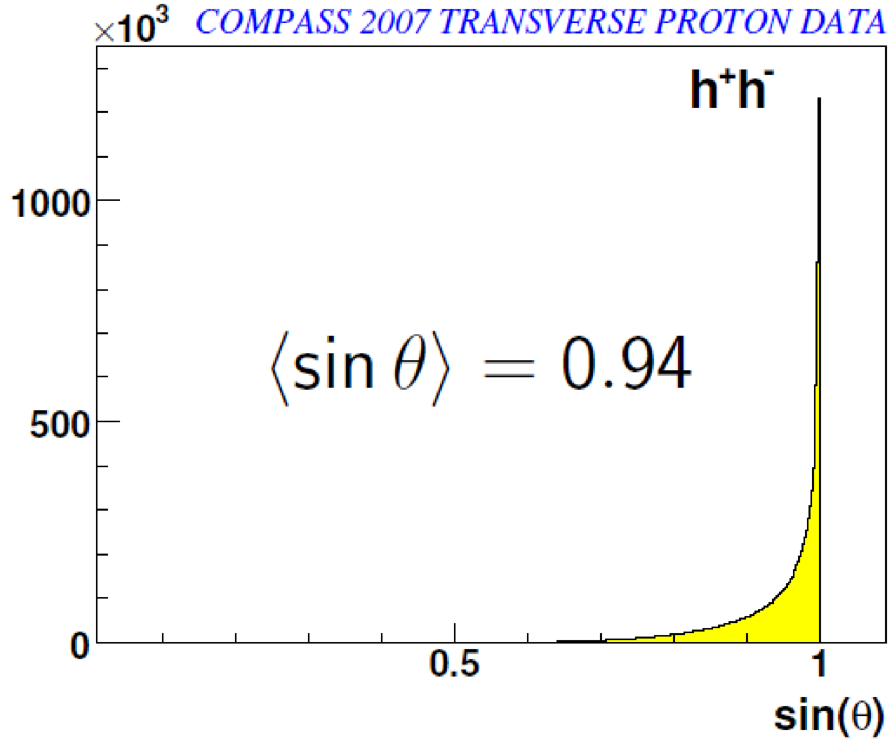
Lambda asymmetries





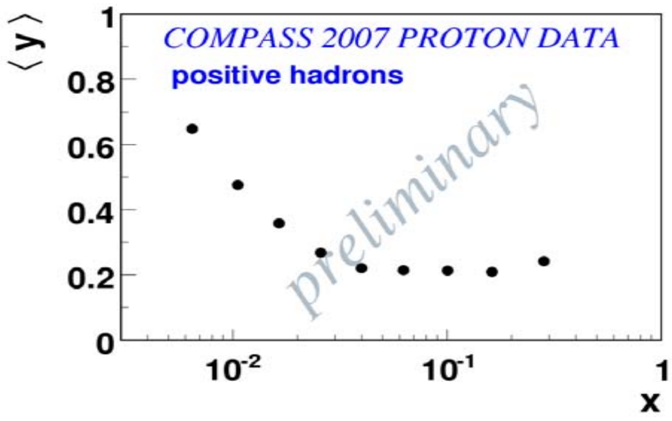


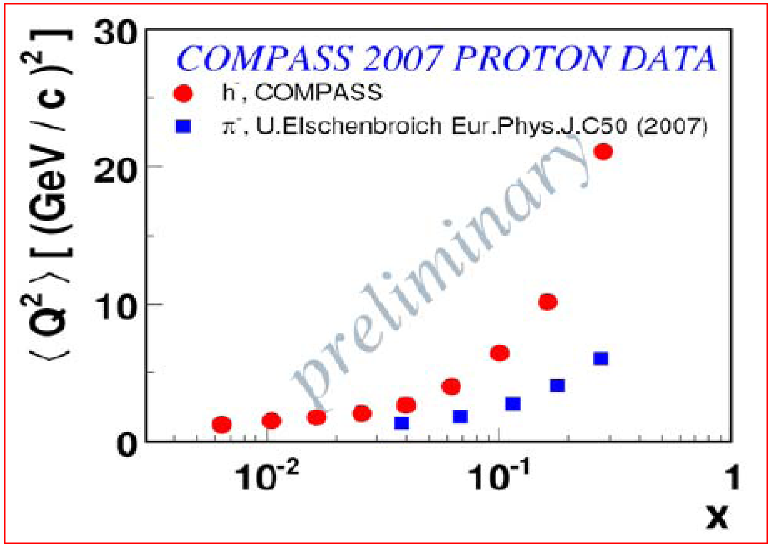
~60% higher statistics with respect deuteron data (after)
Systematic errors have been estimated to be smaller than statistical errors from false polarization.
No dependence on *x*.

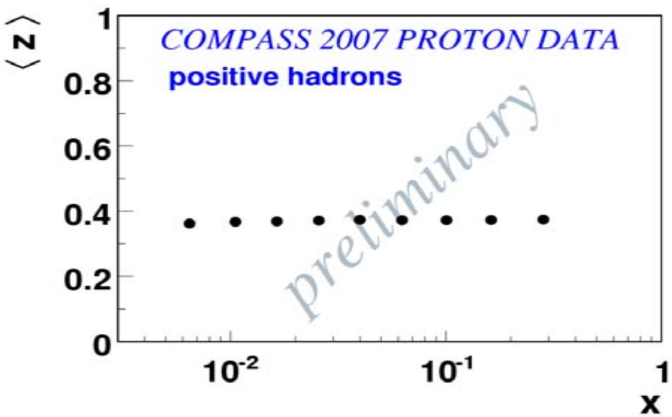


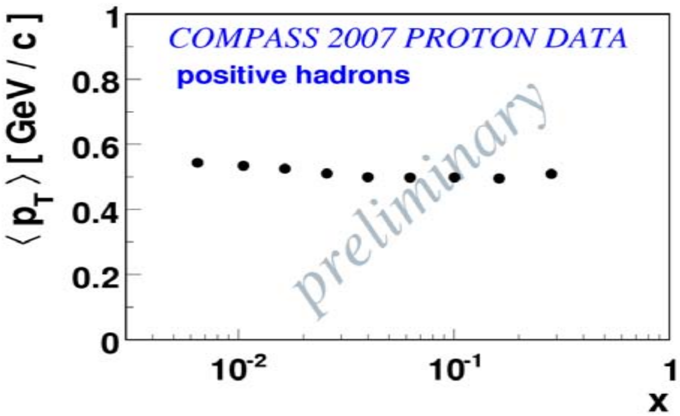
COMPASS 2007 TRANSVERSE PROTON DATA
×10³
h⁺h⁻
$\langle \sin\theta \rangle = 0.94$
1000
500
0
0.5
1
sin(θ)

Mean of kinematical quantities

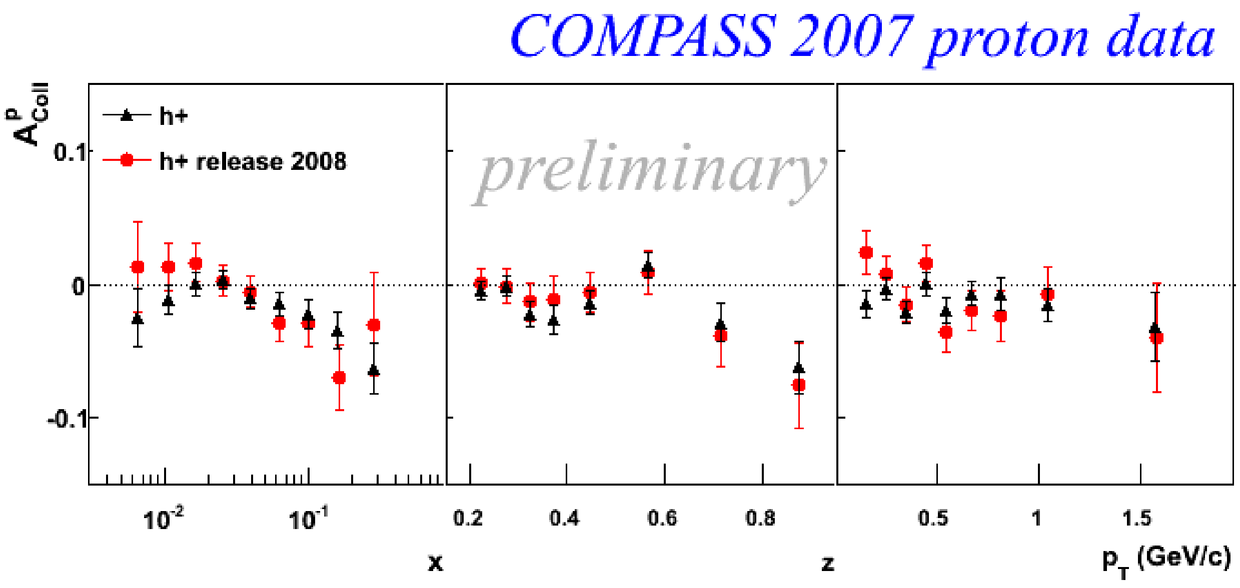


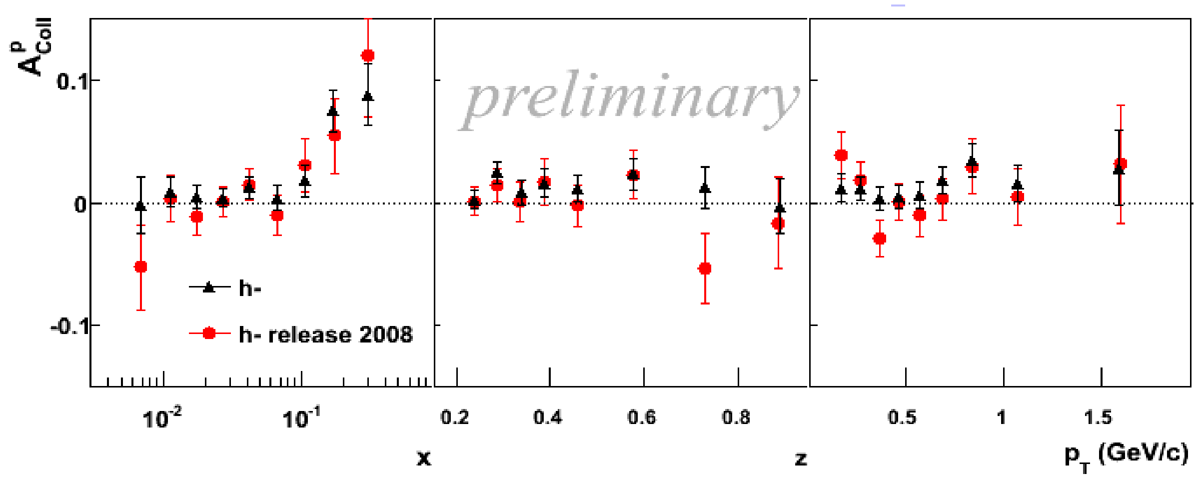




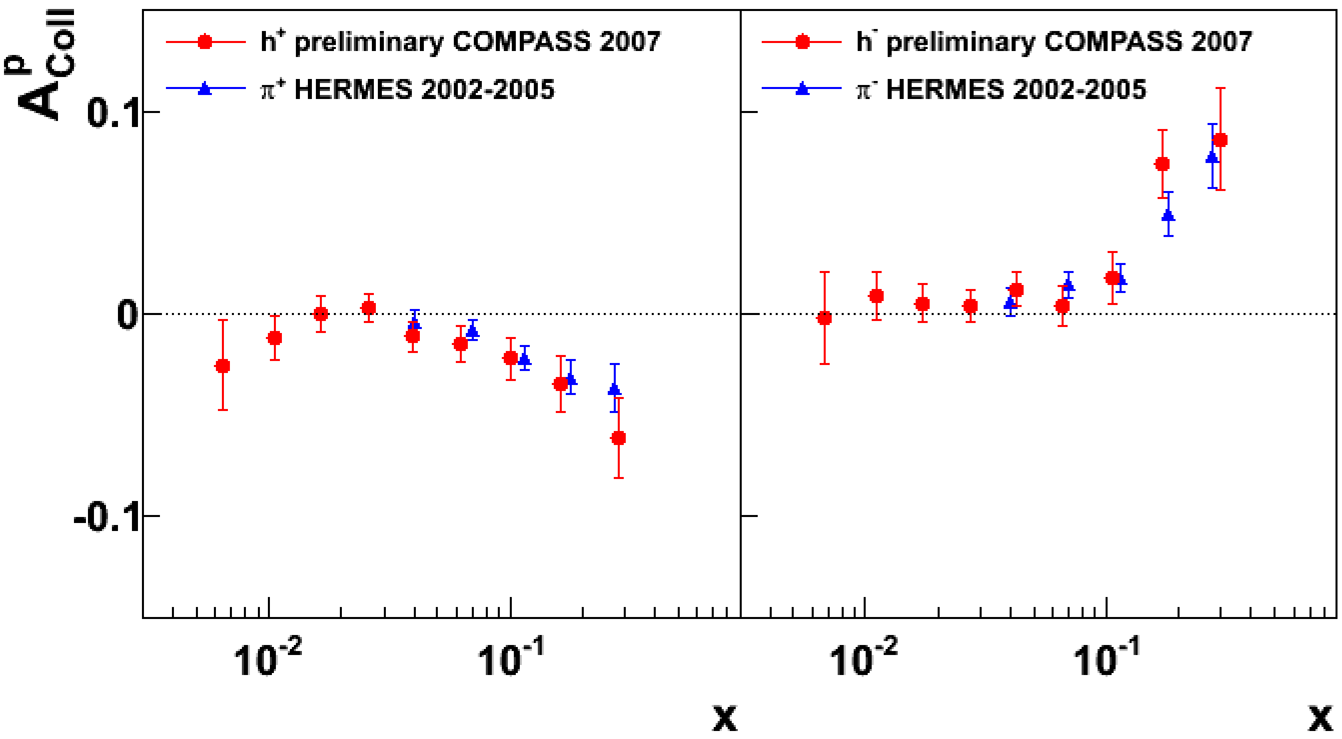


Comparison previous release





Collins asymmetry: comparison with Hermes



Hermes: lepton-beam asymmetries